Experimental Elementary Particle Physics Group at the University of Arizona + Searching for Quark Compositeness at the LHC

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The Large Hadron Collider (LHC), near Geneva, Switzerland, is the “Hubble Telescope” for High Energy Physics, and Arizona is there!

(Proton-Proton Collisions at 14 TeV)

The high energy group at The University of Arizona joined the ATLAS experiment in 1994, and had major impact—from the start—on the design of the experiment!

M. Shupe - ATLAS Collaboration
ATLAS, In Its Underground Cavern
Arizona was the only U.S. group to make a major change in the ATLAS design. We conceived the integrated FCal and shield design, adopted by ATLAS in June, 1994.
Constructing the ATLAS Integrated Forward Calorimeter in a clean room in the basement of the PAS building. Arizona conceived, engineered and supervised this $16M project for ATLAS.
Some of our research group, at CERN, during the installation of the ATLAS Integrated Forward Calorimeter
Quarks are the building blocks of protons, neutrons, and hundreds of other similar (short-lived) particles.

Are quarks themselves made of even smaller building blocks?
The only particles needed to build the periodic table of the elements are protons, neutrons, and electrons! (Plus photons and gluons!)

The only quarks needed to build up protons and neutrons are u and d.

u has charge $\frac{2e}{3}$, and d has charge $-\frac{e}{3}$. What quarks do neutrons contain?

Who ordered this one?

What else can we make from the six quarks? Thousands of other not-so-stable particles!
Particle “multiplets”: “periodic tables” of the strongly interacting particles.
The known quarks and leptons also look like a periodic table! Are they made of smaller particles?

- **Electromagnetic Force**
- **Strong (Nuclear) Force**
- **Weak Force (Changes particle types)**
- **Gravity (Gravitons?)**
A composite model may explain parameters such as particle mass, electric charge, and color charge - which the Standard Model of particle physics does not.
Direct route to shortest distance scales?

It’s all in the momentum!

The de Broglie equation:

$$\lambda = \frac{h}{p}$$
The momentum of the “force carrying” particle (here a gluon) determines its wavelength, and the distance scale that can be probed.
Each proton is a chaotic mix of 3 “valence quarks” + other quarks + gluons.

The two that collide typically carry a small fraction of the proton momentum: parton distribution functions (PDF’s).

Outgoing quarks, or gluons, barely escape the protons before they cascade in to more quarks and gluons (a parton shower). And this is just the start!
Dijets seen in the detector:

- Without pile-up
- With design luminosity pile-up
Search With Angular Distributions

- Angular distributions are sensitive to s-channel vs. t-channel (QCD) production of dijets
  - The variable $\chi$ is convenient – it’s flat for Rutherford scattering, and almost flat for QCD
  - s-channel exchange peaks at low $\chi$.

- We require (depending on mass bin)
  - $p_T(j_1) > 80$–150 GeV (trigger)
  - $p_T(j_2) > 30$ GeV (reconstruction)
  - $|y_1 + y_2| < 1.5$
  - $|y_1 - y_2| < 4.9$

- No significant deviation from QCD is observed
  - Expressed as our benchmark, a contact interaction $\Lambda$, this works out to $\Lambda > 3.4$ TeV (at 95%), with an expected sensitivity of 3.5 TeV
  - Previous best limit is from D0, $\Lambda > 2.8$ TeV

$\Lambda_{qqqq} > 3.4$ TeV
A Composite Model of Leptons and Quarks

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A heuristic model is presented, treating leptons and quarks as composites of spin 1/2 fields with charges 0, ±1/3. A distinguishability assumption leads to the emergence of three quark colors. The model is extended to consideration of the force-mediating bosons.

1. Introduction. In the past few years, experiment and theory have converged on a description of the submicroscopic world which is astounding in its simplicity and regularity. All known matter can be built from fundamental fermions — the leptons and quarks — arranged and structured by four interactions which themselves are surprisingly similar. Gauge field theories may well describe all of these interactions, and their attendant mediating bosons.

The leptons have something akin to a "level" structure. Each charged lepton joins with a corresponding neutrino in obeying a number conservation principle. This effectively decomposes the six leptons into three groups of two, with considerable mass splitting between the charged leptons. The quarks also show level structure. Each level holds one quark of charge +2/3 and one of charge —1/3. The levels are split in mass by the same order of magnitude as the lepton splittings, and the levels would be disconnected — obeying a "quark number" conservation principle — if the Cabibbo angle were zero, instead of 15°.

To date, no direct connection has been observed between quarks and leptons. If the proton were observed to decay, the connection would be established. Nevertheless, all the observed similarities suggest that the leptons and quarks should be grouped together in a pattern of "generations", split according to mass and number conservation. The first generation consists of e, νe, u, and d; the second, of μ, νμ, c, and s; and the third, of τ, ντ, t, and b. This grouping is the basis of the Georgi–Glashow scheme of grand unification based on SU(5) [1], and has been discussed in detail by Harari [2], among others. As with the periodic table or the hadron multiplets, there is a regular, repeating pattern with no indication that the states of large mass have been exhausted. There is strong suggestion, therefore, that a composite model should be attempted.

In the following sections we consider objections to the composite view, possible properties of constituents, states describing quarks and leptons, states describing the bosons which mediate the various interactions, problems occurring in the present model, and paths for ongoing investigation.

2. Barriers to the composite view. The main objection to describing the leptons and quarks as composite is the success of formulations which treat them as Dirac point particles. The Lamb shift, electron and muon magnetic moments, high-energy electromagnetic scattering, and Bjorken scaling (with QCD corrections) are all accounted for without introducing lepton or quark form factors.

There are two possible escapes from the uncomfortable prospect of doing physics at a point. The first is to assume that all present experiments are at pre-asymptotic values of momentum transfer; that, at smaller distances, quarks and leptons will start to show structure. The second escape is to envision a new kind

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Conclusion

• The LHC is rapidly pushing to shorter distance scales. The full dataset from 2010 is ~10 times larger than the data shown here. Within a few weeks we will publish a result which greatly increases the excluded energy range and reduces the distance scale further.

• If you are interested in this research, this is the perfect time to join. The 2011 data sample will be another huge increase over the existing data, and many Ph.D. theses will be based on studies of these highest-energy collisions!