From the Revolution to the Standard Model

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Introduction

- We have relived the scientific event of a lifetime with the announcements of the discovery of the J/psi on Monday, November 11, 1974.

- By the early summer of 1975, the additional states that had been discovered with the quantum numbers expected for a set of quark-antiquark bound states strongly supported adding a charm quark, c, to the u, d, and s quarks known beforehand. That summer brought us not just a new quark, but two new leptons, jets, and the first statement of the standard model.

- However, before describing how the rest of the standard model of particle physics came into existence, let's go back a little bit to set the stage and to see where we were just before the November Revolution.

The XVII International Conference on HEP
July 1 - 10, 1974 @ London

- Enormous progress had been made in understanding the strong, electromagnetic, and weak interactions.
- QCD was just a couple of years old, and asymptotic freedom and infrared slavery merely a year old. However, the non-Abelian gauge theory with $SU(3)_C$ acting on the color quantum number of quarks had been generally accepted as the theory describing the strong interactions.
- Consequently, QCD corrections to scaling were being successfully applied to deep inelastic electron-proton scattering for the first time.

The XVII International Conference on HEP
Electroweak Interactions

- The Gargamelle Collaboration observed neutral weak currents in 1973, and the additional data on neutral currents was another area of high interest.

- As proposed by Weinberg in 1967, the candidate theory to unify weak and electromagnetic interactions was a spontaneously broken gauge theory with the gauge group SU(2) x U(1).

- The ~ 25-year journey to understand the strong, electromagnetic, and weak interactions in terms of relativistic, local quantum field theories was essentially over. The incredibly simple answer: SU(3) x SU(2) x U1)

The XVII International Conference on HEP
Deep Inelastic Scattering of Neutrinos

- After years of unconvincing data on deep inelastic (charged current) neutrino interactions, the first results from a new Caltech-Fermilab experiment were presented. The data demonstrated scaling and consistency of the structure functions and corresponding quark distributions inside the nucleon measured in deep inelastic electron nucleon scattering.
- One expression of the consistency of the two deep inelastic data sets is to express the average charge-squared of the quark constituents in the electron data in terms of all the other measured quantities and constants.
- With equal numbers of u and d quarks, the answer should be

$$[\ (2/3)^2 + (-1/3)^2\ ]\ /2\ = [\ 4/9 + 1/9\ ]/\ 2 = 5\ /18$$

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Deep Inelastic Neutrino Scattering (continued)

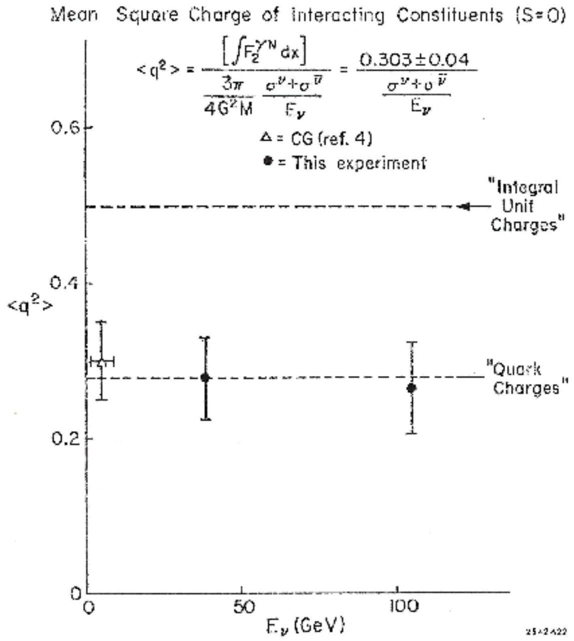


Fig. 23

The XVII International Conference on HEP

- “Who would have thought six years ago in Vienna, that the data presented there, plus the idea of three, point quarks in the nucleon, would permit one to predict to within 20% or better the results of the electron, muon, and neutrino deep inelastic scattering experiments performed since then, which now extend over almost two orders of magnitude in ν and q^2 ? ” (FJG, ICHEP74)

The XVII International Conference on HEP
Along With Great Understanding, Apparent Failure

- An historic achievement in discovering the quantum field theories for the strong, electromagnetic and weak interactions.
- The u, d, and s quarks bound together as constituents of hadrons,
- The leptons: electron, muon, and their neutrino
- An understanding of the deep inelastic scattering of the leptons in terms of scaling due to quark constituents of the neutron and proton, <u>and</u> the corrections to scaling from QCD, calculable to arbitrary order

- **BUT, how can it be that all of this "works" so beautifully, but @ SPEAR $e^+ e^- \rightarrow$ hadrons isn't at all as expected for $e^+ e^- \rightarrow$ quark + antiquark ? We understand all the interactions; are we missing something?**

How Lucky Can You Be?

- SPEAR was an incredible match to the physics. The range of energies allowed not only finding and exploring the physics of a new quark AND a new lepton, but to find evidence for jets, see the polarization of the beams, …
  The Mark I detector was capable of finding and characterizing the new physics, and became the paradigm for generations of collider detectors to come.

- Even more amazing was having both a new quark and a new lepton nearby in mass, thereby creating major confusion. It reminds one of the 1930s and 1940s, with the pion (expected) and the muon (totally unexpected = "who ordered that") were in the same mass range.

How Unlucky Can You Get?

- The initial set of center of mass energies to measure systematically the total hadronic cross section was in steps of 0.2 GeV, for example, 3.0, 3.2, ..., 3.8, 4.0, … GeV. With the same spacing it could have been 2.9, 3.1, …, 3.7, 3.9 … While you would not have discovered the ψ (as the original energy calibration for SPEAR had its mass as 3.105 GeV), the ψ′ (at 3.695 GeV with the original energy calibration) radiative tail couldn't be missed with a run at $E_{cm} = 3.7$ GeV.

- Suppose the E_{cm} calibration had not been too high by 8 MeV − after all, it could have just as easily been close to the correct value or too low by 8 MeV. Months before it's actual discovery in November, the ψ with a mass of 3.097 GeV would have blown you out of the water when you started to run at the actual 3.100 GeV.

How Unlucky Can You Get? (continued)

- In the 4 to 4.5 GeV region, almost any choice of energies aside from 4.0, 4.2, and 4.4 GeV would have shown that the total hadronic cross section changes by one or even two units of R with modest changes in the beam energy.

  You couldn’t then escape from exploring further, finding the resonances above and then below the threshold for producing charmed mesons.

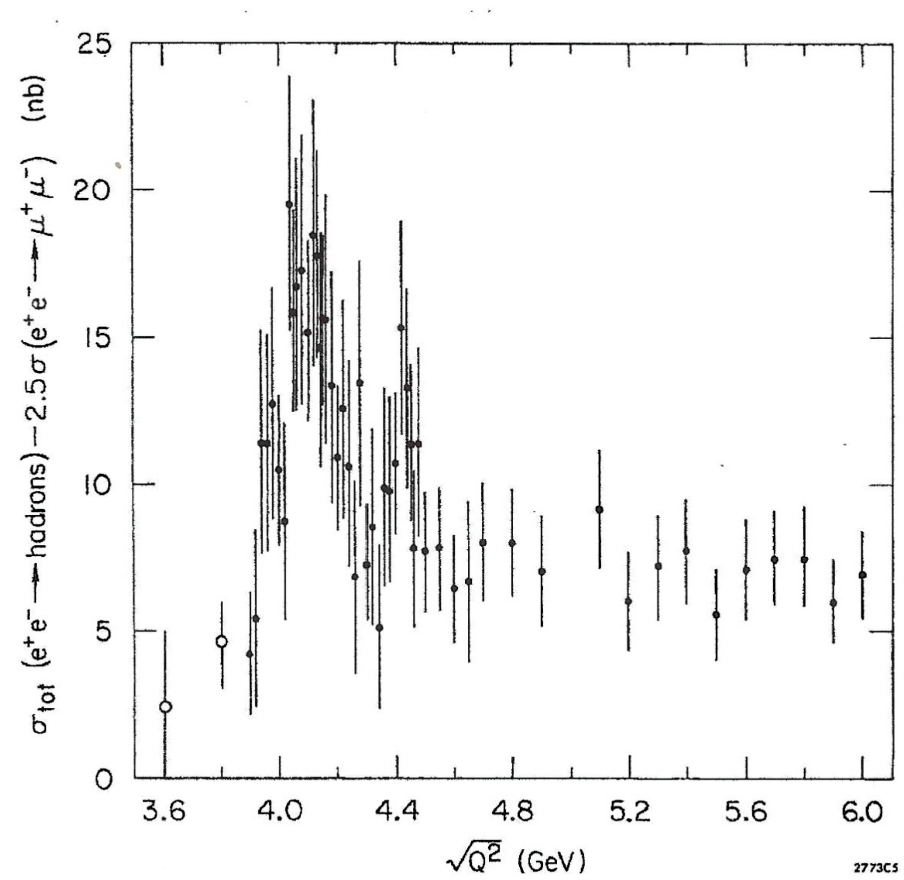


Fig. 2--The cross section for new physics, $\sigma_{total}(e^+e^- \to hadrons) - 2.5\sigma(e^+e^- \to \mu^+\mu^-)$ from SPEAR I (open circles)[20] and SPEAR II (closed circles) data.[22]

The Run-up to the 1975 ISLPIHE

- In the early summer of 1975, the three charmonium states between the ψ and ψ′ were found at SLAC and DESY.
- Evidence for jets at the higher SPEAR energies was found.

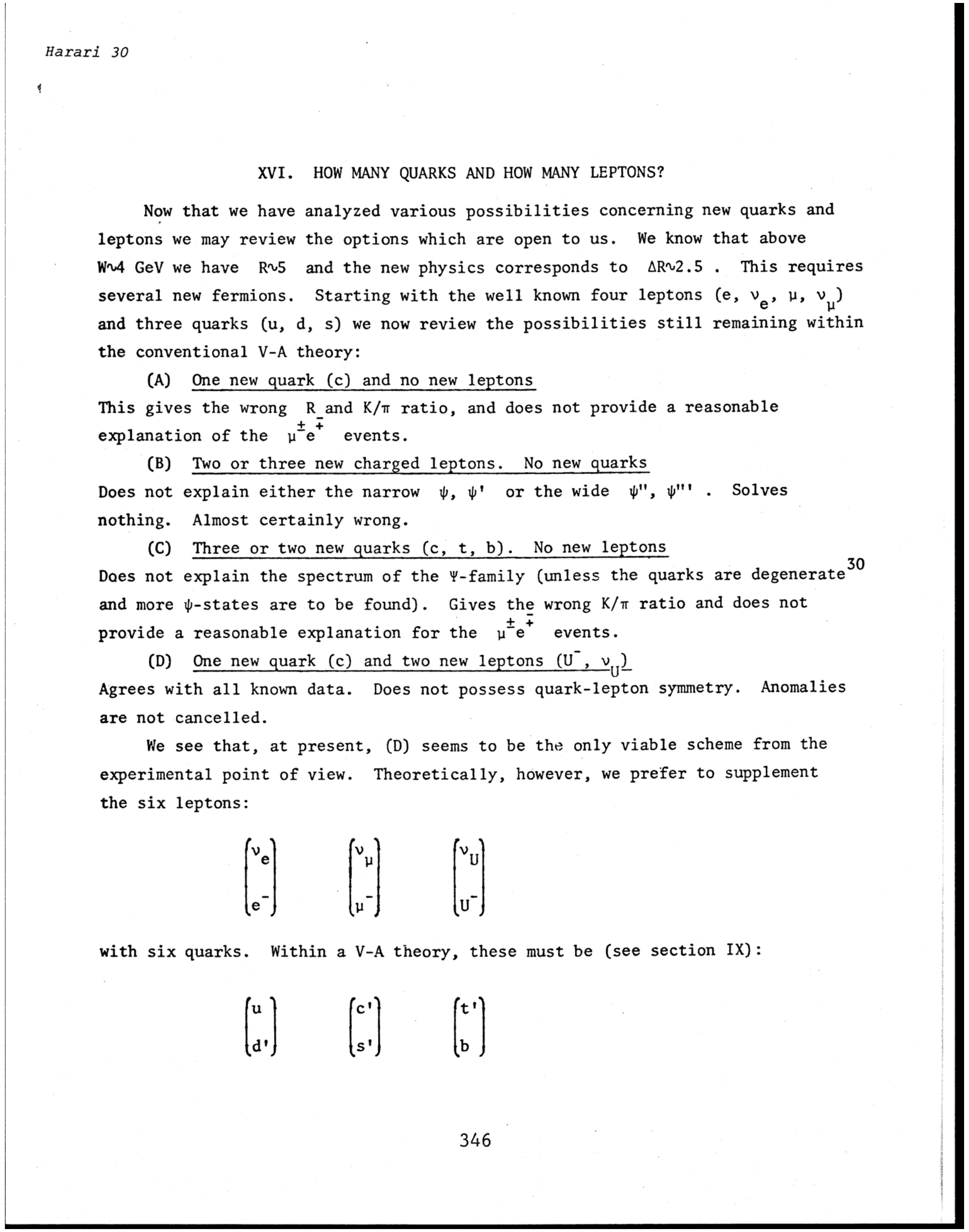
  Resonant depolarization was seen, allowing determination of E_{beam} using g_e - 2
- The azimuthal distribution of the jets corresponded to spin ½ quarks.
- The sphericity (from momenta) of the jets at the highest SPEAR energies matched my then-sphericity in 3D. At the higher energy accelerators being and to be built, they would be increasingly obvious to the eye.
- e μ events were observed, at a level beyond known sources and charm.

  Could be explained with a new charged lepton and a neutrino: U^- and ν_U .
- Meanwhile, Haim Harari and (separately) Michael Barnett proposed theories with six quarks. The weak mixing involved three independent mixing angles plus a phase that gave rise to CP violation.

The Int. Symposium on Lepton Photon Interactions at HE August, 1975 @ Stanford

Plenary Talk of Harari

The 6 quarks and 6 leptons
of the Standard Model
U, for "unknown" → τ)



Harari 30

XVI. HOW MANY QUARKS AND HOW MANY LEPTONS?

Now that we have analyzed various possibilities concerning new quarks and leptons we may review the options which are open to us. We know that above $W \sim 4$ GeV we have $R \sim 5$ and the new physics corresponds to $\Delta R \sim 2.5$. This requires several new fermions. Starting with the well known four leptons (e, ν_e, μ, ν_μ) and three quarks (u, d, s) we now review the possibilities still remaining within the conventional V-A theory:

(A) <u>One new quark (c) and no new leptons</u>

This gives the wrong R and K/π ratio, and does not provide a reasonable explanation of the $\mu^\pm e^\mp$ events.

(B) <u>Two or three new charged leptons. No new quarks</u>

Does not explain either the narrow ψ, ψ' or the wide ψ'', ψ''' . Solves nothing. Almost certainly wrong.

(C) <u>Three or two new quarks (c, t, b). No new leptons</u>

Does not explain the spectrum of the Ψ-family (unless the quarks are degenerate[30] and more ψ-states are to be found). Gives the wrong K/π ratio and does not provide a reasonable explanation for the $\mu^\pm e^\mp$ events.

(D) <u>One new quark (c) and two new leptons (U^-, ν_U)</u>

Agrees with all known data. Does not possess quark-lepton symmetry. Anomalies are not cancelled.

We see that, at present, (D) seems to be the only viable scheme from the experimental point of view. Theoretically, however, we prefer to supplement the six leptons:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_U \\ U^- \end{pmatrix}$$

with six quarks. Within a V-A theory, these must be (see section IX):

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c' \\ s' \end{pmatrix} \quad \begin{pmatrix} t' \\ b \end{pmatrix}$$

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The Remaining Discoveries Are Made
Charmed Mesons and Baryons

- There was evidence for a charmed baryon in a bubbe chamber event published in May 1975
- The searches at SPEAR published before 1977 did not show a statistically significant evidence for charmed mesons to Glashow's consternation
- At the 1974 ICHEP, the speakers were given bottles of wine. John Iliopoulos opened his bottle during the discussion after his plenary talk. He bet a whole case of wine (to any taker) if charm was not discovered by the 1976 ICHEP.
- In the spring of 1976 both the D^0 and then the D^+ were found by the LBL – SLAC Collaboration.
- John Iliopoulos won his bet just before the 1976 ICHEP at Tbilisi.
- The Ds and the Λc were found soon after the D^0 and D^+.

The Remaining Discoveries Are Made
The Tau Lepton and Tau Neutrino

- DASP at DESY and DELCO at SLAC provided early parts of the confirmation of the τ; later were experiments at PEP and PETRA.
- Vertex detectors at higher energy colliders (or emulsions) provided direct evidence by measuring the lifetime.
- Direct observation of the tau neutrino was made at Fermilab in 2000
- Both a confirmation and a precise mass of the τ could have been obtained by running below and through the ψ′ (see the figure from FJG ISLPIHE75 with a τ mass of 1.75 GeV).

  Decades later, Beijing and Novosibirsk colliders found a precission τ mass of 1.7769 GeV in this way.

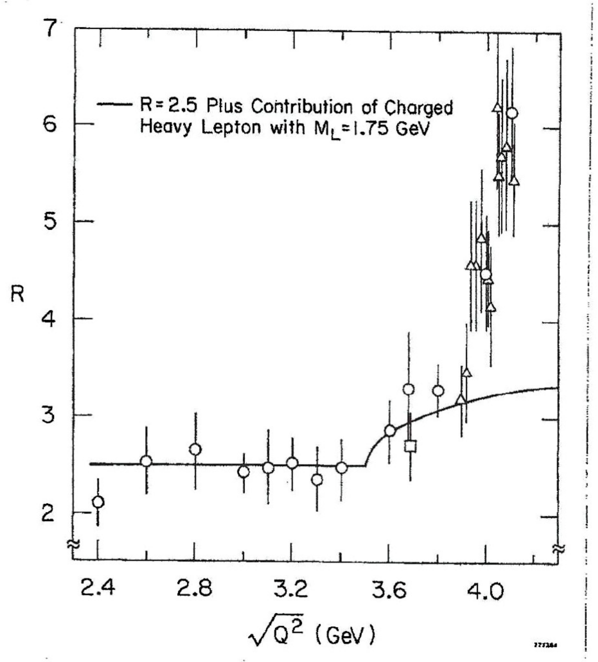

Fig. 10--Measurements of R near the threshold from SPEAR I[20] (open circles), SPEAR II[22] (triangles), and data[41] just below (open circle) and at (square) the ψ′.

The Remaining Discoveries Are Made
The Bottom Quark, b

- The discovery of the Upsilon at Fermilab was announced mid-1977, followed later by two higher mass members of the Upsilon family .
- B mesons were fully reconstructed in 1983 by CLEO, and their lifetimes from the mid-80s onward. Baryons with a b quark are known with all possible combinations of u, d, and s quarks.
- The mixing of neutral B mesons gave us an enormous and decisive program to determine the CKM matrix in multiple ways and test whether the different determinations are consistent and whether it describes all the experimentally accessible manifestations of CP violation.

The Remaining Discoveries Are Made
The Top Quark, t

- Discovered at Fermilab by CDF and D0 in 1995.
- Through two decades of searching for the top quark, the experimental lower limit on its mass increased more than an order of magnitude.

Unlike all the other quarks and leptons, it is of order the weak scale.

$M_t = 172.5$ GeV.

The Remaining Discoveries Are Made
The Gluon

- The gluon was discovered in 1979 using the PETRA collider at DESY. As the gluon carries net color and, like quarks, is confined, it was found by establishing the existence of quark-antiquark-gluon three-jet events.

The November Revolution as Part of the History Particle Physics

- The November Revolution and what followed in the next few years taught us that we could employ electron-positron annihilation to systematically discover and characterize all the quarks, leptons, and any other particles (such as the W and Z) that have electroweak interactions.
- The Z gave rise to precision measures of the electroweak parameters at the SLC and LEP. The tau-charm factories and B factories gave us detailed understanding of parts of tau, charm, and b physics plus the nature of CP violation in the SM.
- proton-proton colliders provide a key alternate route to discovery, with much higher collision energies and mass range explored for possible new physics. .
- The Mark I at SPEAR, is the progenitor of generations of collider detectors.

November 1974 was the tipping point