The Search for Charm
My Recollections*

- A brief pre-history
- The charmed quark mass
- Gaillard, Lee & Rosner
- The November revolution
- The interim: where is open charm?
- Charm is found

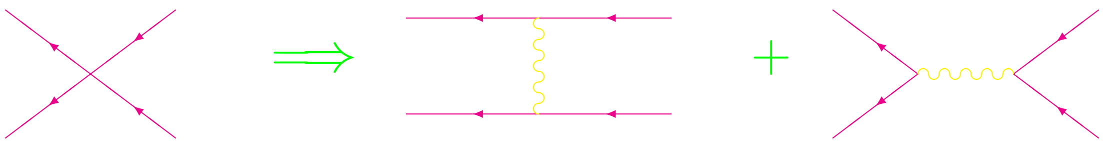
*A detailed, carefully referenced, account of these developments can be found in

Jon Rosner, The Arrival of Charm AIP Conf. Proc. 459:9-27 (1999)

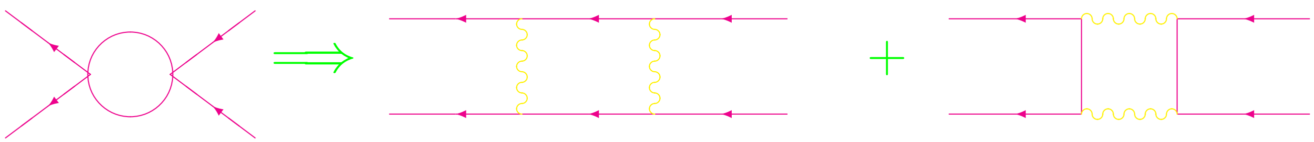
The Interplay of Theory and Experiment

Low energy data

Spectroscopy, V-A, $\Delta S = \Delta Q, \ldots \Longrightarrow$ quark model



because



$$\sim G_F^2 \Lambda^2 \Longrightarrow \quad \sim G_F^2 m_W^2 \sim g^2/m_W^2$$

Full renormalizability $\Longrightarrow$ GWS

Meanwhile

$$\left.\begin{array}{lcl} \text{soft pion theorems} & \Longrightarrow & \text{chiral symmetry} \\ \text{scaling in } e^+e^-\text{, DIS} & \Longrightarrow & \text{asymptotic freedom} \end{array}\right\} \Longrightarrow \quad \text{QCD}$$

Flashback: Spectroscopy Before Gauge Theories

Many (integrally charged) 4-constituent models (GM)

Bjorken & Glashow 1964

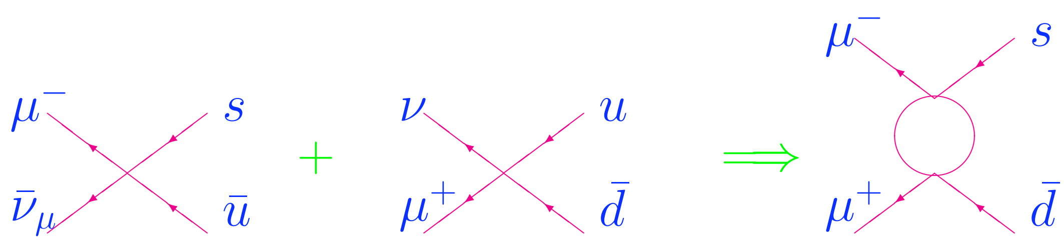
- Coined the word charm: new Q-no
- Noted flavor conserving neutral current

"The baryon current us thus $\bar{\psi}\gamma_\mu(1-\gamma_5)W\psi$, with the 4 by 4 matrix W given by

$$W = \begin{pmatrix} 0 & 0 & \sin\theta & \cos\theta \\ 0 & 0 & \cos\theta & -\sin\theta \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

The relation $[W, W^+] = 2Q - 1$, independent independent of θ, suggests a possible intimate connection between weak and electromagnetic interactions."

Strangeness Changing Neutral Currents



$K^- \to \mu^- \bar{\nu}_\mu$ $\quad$ $\pi^+ \to \mu^+ \nu_\mu$ $\quad$ $K_L \to \mu^+ \mu^-$

$\sim G_F^2 \Lambda^2 \left(\frac{1}{16\pi^2}\right)$

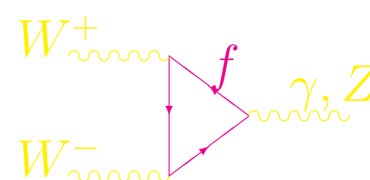
$\Lambda \sim$ a few GeV(4π)

Mohapatra, Subbba & Marshak 1968 also Δm_K

GIM 1970:

- u, c cancellation: $\Lambda \to m_c$
- If $W^\pm \to W^\pm, W^0$ neutral current conserves flavor

BIM 1972: Anomaly cancellation

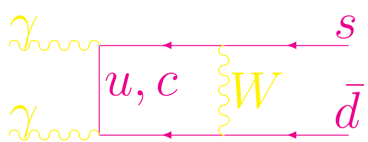


The Mass of the Charmed Quark

Rare K-decays in GWS/GIM

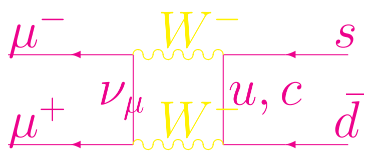
MKG & BW Lee 1974

$K_L \to \gamma\gamma$:



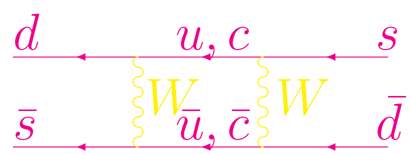
$\overset{\propto}{\sim} \ln\left(\frac{m_c}{m_u}\right)$ allowed $\Longrightarrow m_u^2 \ll m_c^2$

$K_L \to \mu^+\mu^-$:



$\propto \frac{m_c^2 - m_u^2}{m_W^2}$ forbidden $\Longrightarrow m_c \lesssim 9\text{GeV}$

$m_u^2 \ll m_c^2 \ll m_W^2$: $|m_{K_L} - m_{K_S}|$:



$\propto \frac{m_c^2}{m_W^2} \Longrightarrow$

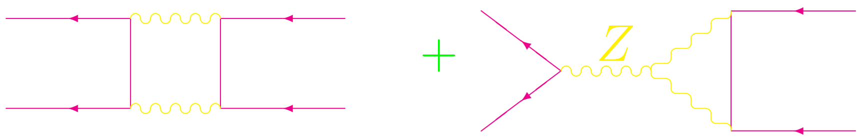
$$m_c \approx \begin{cases} 1.5\text{GeV} & \text{no QCD} \\ 2\text{GeV} & \text{QCD } (\surd) \text{ color factors } (\times) \end{cases}$$

Historical notes

- AI Vainstein & IB Khriplovich 1973: $K_L \to \mu^+\mu^-, \Delta m_K : \Delta m \sim 1$ GeV

  Scooped! Ma 1974 $K \to 2\mu, 2\gamma : m_c \approx 5\text{GeV}$

- $K_L \to \mu^+\mu^-$:



$$\propto \frac{m_c^2 - m_u^2}{m_W^2}\left[a \ln\left(\frac{m_W}{m_c}\right) + b\right]$$

cancellation: $a = 0 \Longrightarrow$ weak bound on Δm^2 $[K_L \to \gamma\gamma \to \mu\mu]$

GL FOUND ALSO $b = 0$: SYMMETRY? $\epsilon^{\mu\nu\rho\sigma} \to -\epsilon^{\mu\nu\rho\sigma}$ GL & Shrock

- GL Abstract:

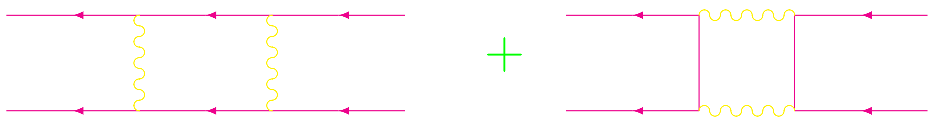
TO EXPLAIN THE SMALL K_L-K_S MASS DIFFERENCE AND NONSUPPRESSION OF $K_L \to \gamma\gamma$, IT IS FOUND NECESSARY TO ASSUME $m_{\mathcal{P}}/m_{\mathcal{P}'} << 1$, WHERE $m_{\mathcal{P}}$ IS THE MASS OF THE PROTON QUARK AND $m_{\mathcal{P}'}$, THE MASS OF THE CHARMED QUARK, AND $m_{\mathcal{P}'} < 5$ GEV.

Text:

EQUATION (2.8) IS COMPATIBLE WITH EITHER WITH $m_{\mathcal{P}'} \simeq m_{\mathcal{P}}$ AND LARGE, AND $m_{\mathcal{P}'} - m_{\mathcal{P}} \simeq 1$ GEV, OR $m_{\mathcal{P}} \ll m_{\mathcal{P}'}$ AND $m_{\mathcal{P}'} \simeq 1.5$ GEV.

MS version 1: $1.5 \to 2$ (J-M G) $2 \to 1.5$

Appendix:

$K_L \leftrightarrow K_S$:  $\Longrightarrow 1.5 \to 2$

color factor $1/3$

(London July 1974: 1.5)

GL & Rosner

FERMILAB-PUB-74-086-THY, Aug. 1974

Our discussion is largely based on intuition gained from the familiar, but not necessarily understood, phenomenology of known hadrons, and predictions must be interpreted only as guidelines for experimenters.

- $SU(3)_F \to SU(4)_F$ linear vs quadratic mass sum rules? $m(^3S_1) < 2m_D$
- Zweig rule $\Longrightarrow$ narrow $^3S_1$: $\Gamma \simeq 2$ MeV
- weak coupling selection rules: $\begin{cases} \Delta C = \Delta Q = +1 & \text{production} \\ \Delta C = \Delta S = -1 & \text{decay} \end{cases}$

  signal for $\nu \to$ charm
- chiral symmetry wrong $F_\pi = \sqrt{2} f_\pi$! L Quigg & R, QR
- parton model for DIS

Carlson & Freund 1972, Snow 1973, Glashow 1974

GLR Conclusions: Look for

- DIRECT LEPTON PRODUCTION
- LARGE NUMBERS OF STRANGE PARTICLES
- NARROW PEAKS IN MASS SPECTRA OF HADRONS
- APPARENT STRANGENESS VIOLATIONS $(c \longrightarrow s,\ \bar{c} \longrightarrow d)$
- SHORT TRACKS, ... LIFETIME $\sim 10^{-13}$ SEC
- DI-LEPTON PRODUCTION IN NEUTRINO REACTIONS
- NARROW PEAKS IN e^+e^- OR $\mu^+\mu^-$ SPECTRA
- TRANSIENT THRESHOLD PHENOMENA IN DI LEPTOPRODUCTION
- APPROACH OF $(e^+e^- \longrightarrow \text{hadrons})/(e^+e^- \longrightarrow \mu^+\mu^-)$ RATIO TO $3\frac{1}{3}$, PERHAPS FROM ABOVE
- ANY OTHER PHENOMENA THAT MAY INDICATE A MASS SCALE OF 2-10 GeV

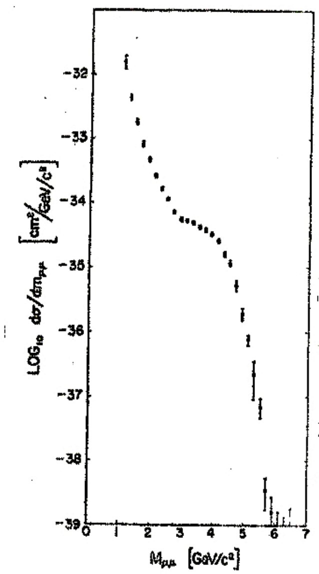
HINTS OF CHARM?

Abstract: MUON PAIRS IN THE MASS RANGE $1 < m_{\mu\mu} < 6.7$ GEV/c^2 HAVE BEEN OBSERVED . . . THE CROSS SECTION . . . EXHIBITS NO RESONANT STRUCTURE.

Text: INDEED, IN THE MASS REGION NEAR 3.5 GEV/c^2, THE OBSERVED SPECTRUM MAY BE REPRODUCED BY A COMPOSITE OF A RESONANCE AND A STEEPER CONTINUUM.

Christenson et al. 1970

$p + U \to \mu^+ + \mu^- + X$



Niu et al. 1971

$X \to \pi^0 + \pi^+$

$m_X = 1.78$ GeV

$\tau_X = 2.2 \times 10^{-14}$ sec

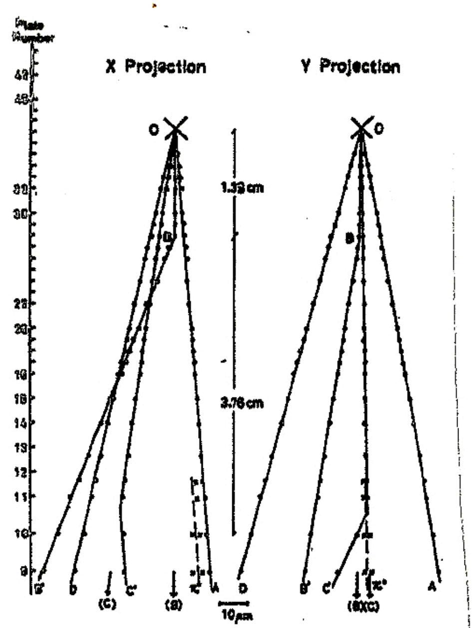


Fig. 3(a). Fig. 3(b).

HINTS OF CHARM?

Rubbia for Aubert et al. London, July, 1974

$\nu + Z \rightarrow \mu + X$

TWO EVENTS HAVE BEEN OBSERVED IN WHICH THERE IS AN APPARENT SIMULTANEOUS PRODUCTION OF TWO PENETRATING PARTICLES OF OPPOSITE SIGN (MUONS).

Litke et al. 1973

Tarnopolsky et al. 1973

Richter et al. 1974

$e^+e^- \rightarrow$ hadrons

(from GLR)

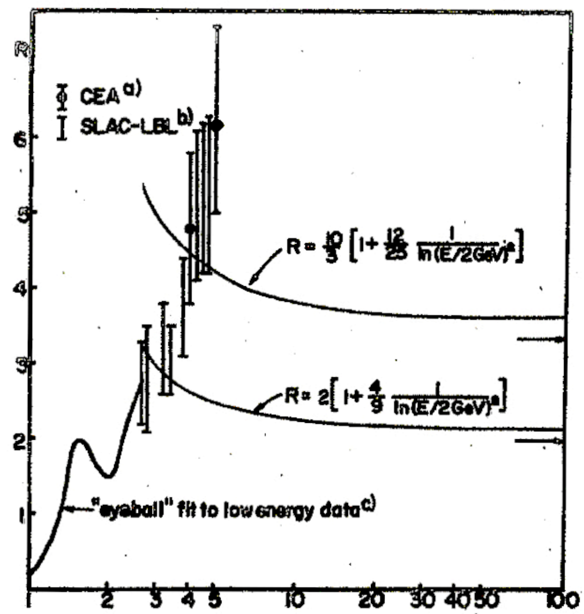


FIG. 8. Data on the ratio $R = \sigma(e\bar{e} \rightarrow \text{hadrons})/\sigma(e\bar{e} \rightarrow \mu\bar{\mu})$, and predictions of the asymptotically free quark model without charm (lower curve) and with charm (upper curve). (a) CEA data: Litke *et al.*, 1973. Tarnopolsky *et al.*, 1973. (b) SLAC–LBL data: Richter, 1974. (c) This is taken from Adler, 1974.

November 1974

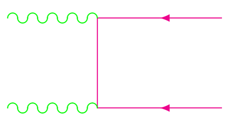
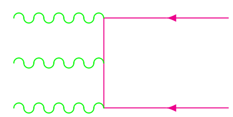
Aubert et al. $p + Z \to {}^3S_1 + X$ Augustin et al. $e^+ + e^- \to {}^3S_1$

G<u>LR</u> Appendix: $m({}^3S_1) = 3.1$ GeV, decay widths, excited states $\Longrightarrow$

more precise predictions for spectrum, couplings

Enter QCD

Zweig rule $\Longrightarrow$ asymptotic freedom Appelquist & Politzer Dec 1974

${}^1S_0$:  $\propto g^2$ ${}^3S_1$:  $\propto g^3$ $|\psi(0)| \propto g^3$

$\Gamma \simeq .6$ MeV

$SU(4)$ mass sum rules $\Longrightarrow$ quarks in coulomb-like chromomagnetic field

Better predictions for fermion masses De Rújula, Georgi & Glashow March 1975

Waiting for open charm: a view from Europe

COLOR VS CHARM (CERN): WARD (LRG) VS ELLIS & GAILLARD

CERN TOWER

CARGÈSE 1975: WHERE ARE P-WAVE CHARMONIUM STATES? Rudaz

$$R = \frac{\sigma(\text{hadrons})}{\sigma(\mu\mu)}$$ too high τ confusion!

WHERE IS $D \to \bar{K} + \pi$?

GLR wrong f_π LQR, QR resonance production Einhorn & Q etc

COUNTING K'S IN $e^+e^- \to$ HADRONS

When will you stop believing in charm? CERN cafeteria

Charm is found

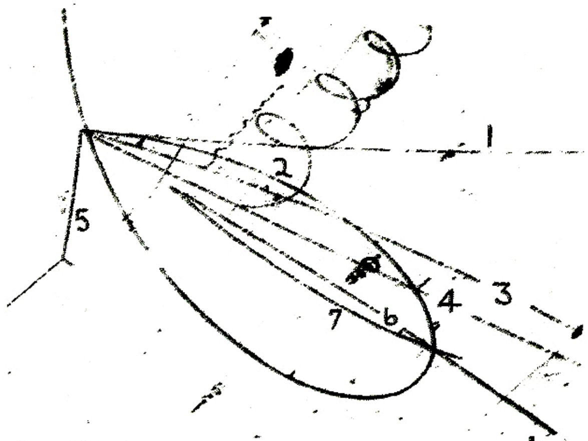
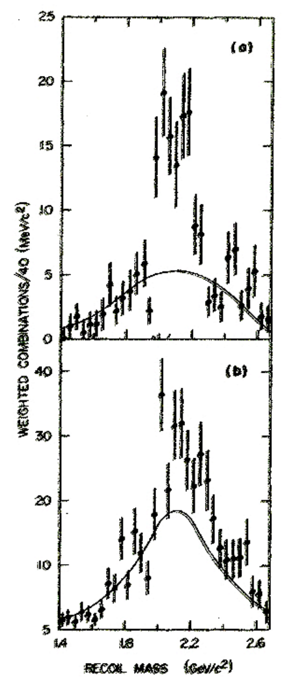


FIG. 1. View of event as seen in camera 3.

$\Delta S = -\Delta Q$ observed

Cazzoli et al, March 1975

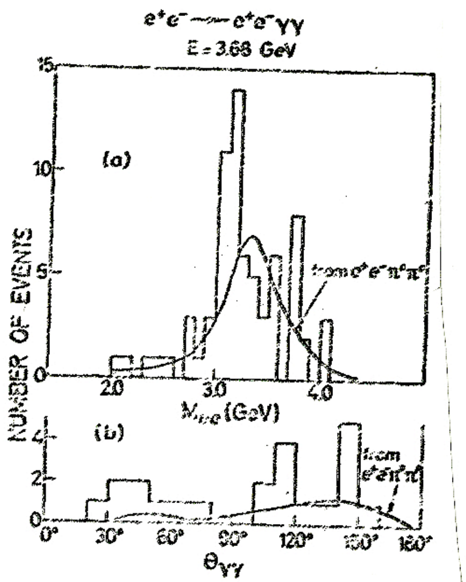
$$\nu p \to \mu^- + (\Lambda\pi^+\pi^+\pi^+\pi^-)_{2462\ \mathrm{MeV}}$$



$e^+e^- \to D^\pm + X$ observed

Goldhaber et al, June 1976

$$e^+e^- \to (K\pi, K3\pi)_{1865\ \mathrm{MeV}} + X$$



First P-state observed

Braunschweig et al, July 1975

$$\psi'(3.7) \to \gamma + (\gamma J/\psi)_{3.52\ \mathrm{GeV}}$$

IN MEMORIAM

Benjamin W. Lee 1935-1977

Bruce Winstein 1943-2011

Conclusions

Well, those were great days. The 1960s and 1970s were a time when experimentalists and theorists were really interested in what each other had to say, and made great discoveries through their mutual interchange. We have not seen such great days in elementary particle physics since that time, but I expect that we will see good times return again in a few years, with the beginning of a new generation of experiments at this laboratory.

The Making of the Standard Model

S. Weinberg

Eur. Phys. J. C 34, 5 (2004)

LET'S HOPE SO!

HAPPY RETIREMENT JON!