THE ARRIVAL OF CHARM

Heavy Quarks at Fixed Target Workshop

J. Rosner Fermilab Oct. 9, 1998

Electroweak unification

Currents

Quark-lepton analogies

Exhortations

Hidden charm

Open charm

Further progress | Examples

Current questions | Examples

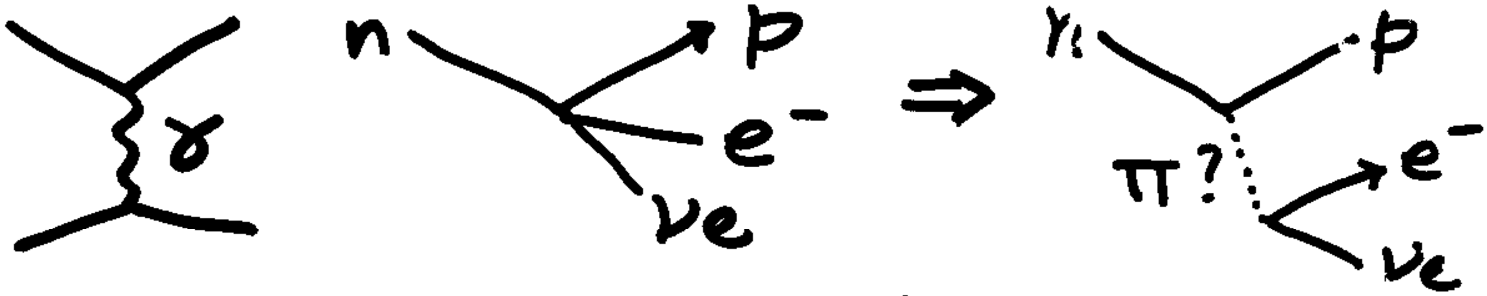
Lessons ?

One ref: V. Fitch + J. L. Rosner, <u>Twentieth Century Physics</u> (AIP/IOP, 1995), Ch. 9

Comments welcome (2nd ed. in preparation)

ELECTROWEAK UNIFICATION

QED | **Fermi** | **Yukawa**



O. Klein (1938): $W^\pm$, γ
(predecessor of Yang-Mills 1954)

1950's: Schwinger, ... SU(2)?

Problems:	γ	V	massless
	$W^\pm$	V-A	massive

Glashow (1961):	γ	V	massless
$SU(2) \times U(1)$	$W^\pm$	V-A	massive
	Z	mixture	massive

Salam-Ward 1964
Weinberg 1967
Salam 1968

Higgs mechanism:
spontaneous
$SU(2) \times U(1) \to U(1)_{e.m.}$

't Hooft 1971
Lee-Zinn-Justin 1972 | Renormalizability

Abers + Lee 1973 · Electroweak review

CURRENTS, QUARKS, & LEPTONS

Gell-Mann & Levy (1960)

Normalize weak currents:

$Q^{(+)}$: $e \to \nu$

$n\cos\theta + \Lambda\sin\theta \to p$

$[Q^{(+)}, Q^{(-)}] = 2Q_3$
$[Q_3, Q^{(\pm)}] = \pm Q^{(\pm)}$ | An SU(2) algebra

Cabibbo (1963)

Matrix elements $\langle B'|J^\mu|B\rangle$ and $\langle M'|J^\mu|M\rangle$ via SU(3)

In quark language $\begin{bmatrix} u \\ d \\ s \end{bmatrix}$:

$$Q^{(+)} = \begin{bmatrix} 0 & \cos\theta & \sin\theta \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad Q^{(-)} = Q^{(+)\dagger}$$

$2Q_3 = [Q^{(+)}, Q^{(-)}]$ has $\Delta S \neq 0$ pieces!
("Pay no attention...")

Quartet models (1964) (Bj-Glashow, Gell-Mann, Hara, Maki-Ohnuki)

$$\begin{bmatrix} \nu_e \\ e^- \end{bmatrix} \begin{bmatrix} \nu_\mu \\ \mu^- \end{bmatrix} \Longleftrightarrow \begin{bmatrix} u \\ d \end{bmatrix} \begin{bmatrix} c \\ s \end{bmatrix}$$

THE GIM MECHANISM

$Q^{(+)}$: $d\cos\theta + s\sin\theta \rightarrow u$

$-d\sin\theta + s\cos\theta \rightarrow c$

$2Q_3 = [Q^{(+)}, Q^{(-)}]$ is flavor-diagonal

Glashow-Iliopoulos-Maiani (1970)

This structure banished flavor-changing neutral currents to leading order of momentum in higher orders of perturbation theory.

Example: K^0-$\bar{K}^0$ mixing

Now cut off by m_{charm}

$$\Rightarrow \boxed{\begin{array}{c} m_c \lesssim 2\text{ GeV} \\ \tau_{charm} \sim 10^{-13}\text{ s} \end{array}}$$

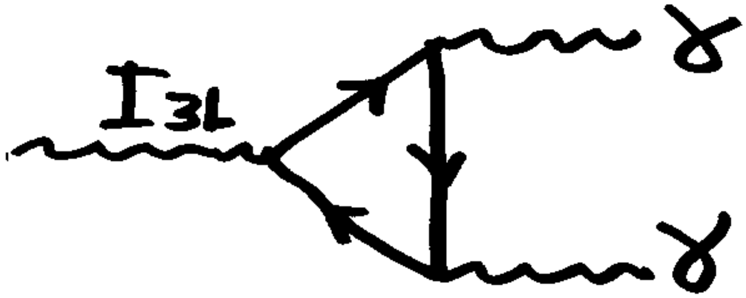
Predictions: • Strong pair prod.

- Direct leptons
- Production in ν reactions
- Neutral currents
- Z^0 in e^+e^- annihilations

GAUGE THEORY RESULTS

Anomalies (1972)

Bouchiat-Iliopoulos-Meyer; Gross-Jackiw



Well-behaved gauge theory requires

$$\boxed{\sum I_{3L} Q^2 = 0}$$

$\nu_e + e + u + d$:

$$\tfrac{1}{2}(0)^2 - \tfrac{1}{2}(-1)^2 + \tfrac{1}{2}\cdot 3\cdot\left(\tfrac{2}{3}\right)^2 - \tfrac{1}{2}\cdot 3\cdot\left(-\tfrac{1}{3}\right)^2 =$$

$$= -\tfrac{1}{2} + \tfrac{2}{3} - \tfrac{1}{6} = 0$$

$\nu_\mu + \mu + (c) + s$: charm needed for cancellation

Rare kaon decays: Gaillard-Lee

(1973)

Take charm seriously in $K^0-\overline{K^0}$ mixing, rare processes (e.g. $K_L \to \mu^+\mu^-$, $\gamma\gamma$, $\pi^0 e^+e^-$, $\pi^0 \nu\bar{\nu}$, ...)

$m_c^2 \gg m_u^2$

$m_c^2 - m_u^2$ limited

$m_c \lesssim 2$ GeV supported; stronger result than Lee, Primack, Treiman

EXHORTATIONS

1972 Freund-Carlson Narrow $c\bar{c}$

1973 G. Snow Production, decays

With M.K. Gaillard & B.W. Lee - started in late '73 to look at charm production in hadron, ν, e^+e^- reactions - quickly became clear that a 2 GeV quark could have been overlooked.

1974 Glashow (Meson conference)

$10^{-13}\,s \lesssim \tau \lesssim 10^{-12}\,s$

Semileptonic, hadronic decays comparable

Strange particles in final state

Prompt leptons in hadron reacts.

ν's → dileptons

WHAT TO EXPECT AT EMS-76

There are just three possibilities:

1. Charm is not found, and I eat my hat.
2. Charm is found by hadron spectroscopers, and we celebrate.
3. Charm is found by outlanders, and you eat your hats.

MORE EXHORTATIONS

S. Treiman to B. Lee (1974): "It's getting urgent"

Gaillard-Lee-Rosner wrote up results for Rev. Mod. Phys. ('75!)

Conclusions: (most at 8/74 Gordon Conf.)

We have suggested some phenomena that might be indicative of charmed particles. These include:

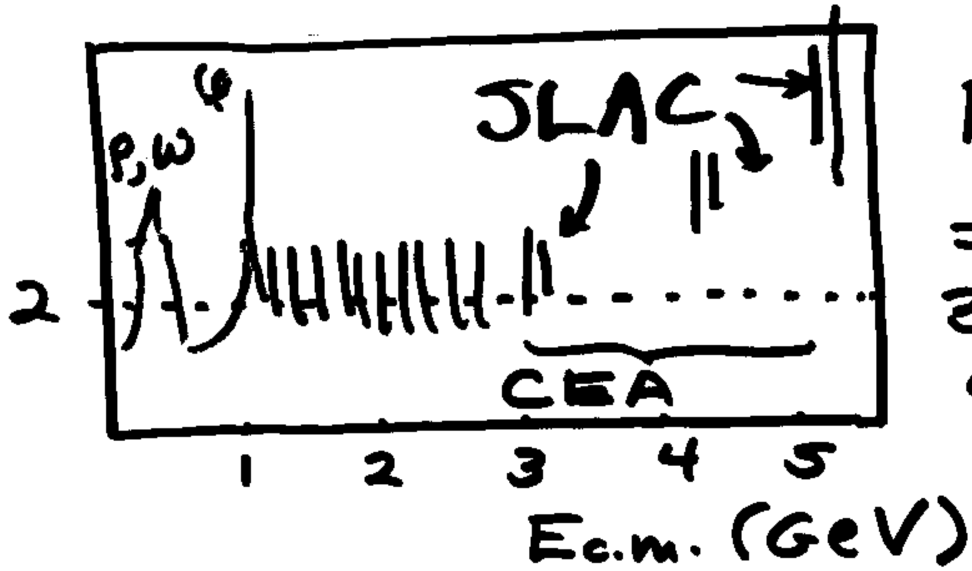
(a) "direct" lepton production,
(b) large numbers of strange particles,
(c) narrow peaks in mass spectra of hadrons,
(d) apparent strangeness violations,
(e) short tracks, indicative of particles with lifetime of order 10^{-13} sec.,
(f) di-lepton production in neutrino reactions,
(g) narrow peaks in e^+e^- or $\mu^+\mu^-$ mass spectra,
(h) transient threshold phenomena in deep inelastic leptoproduction,
(i) approach of the $(e^+e^- \rightarrow \text{hadrons})/(e^+e^- \rightarrow \mu^+\mu^-)$ ratio to $3\frac{1}{3}$, perhaps from above, and
(j) any other phenomena that may indicate a mass scale of 2–10 GeV.

Glashow in Minnesota (10/74): charm and much else (SU(5), SO(10), ...)

Appelquist-Politzer (1974): <u>really</u> narrow $c\bar{c}$ (QCD)

HIDDEN (?) CHARM: '74-'75

The rise of $R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$



$R = \Sigma Q^2$

$= 2$ for 3 colors of u, d, s

Dimuons in ν interactions

Indicative of a prompt decay

The J and the ψ (11/74)

Ting +:

$p + Be \to J$

$\quad \hookrightarrow e^+e^-$

$M = 3.1$ GeV

Richter +:

$e^+e^- \to \psi \to \ldots$

peak at

$E_{c.m.} = 3.1$ GeV

Interpret as 1^3S_1 $c\bar{c}$ state

THE RISE IN R (PRE-J/ψ)
B. Richter - 17th Int. Conf. on HEP. London 7/74

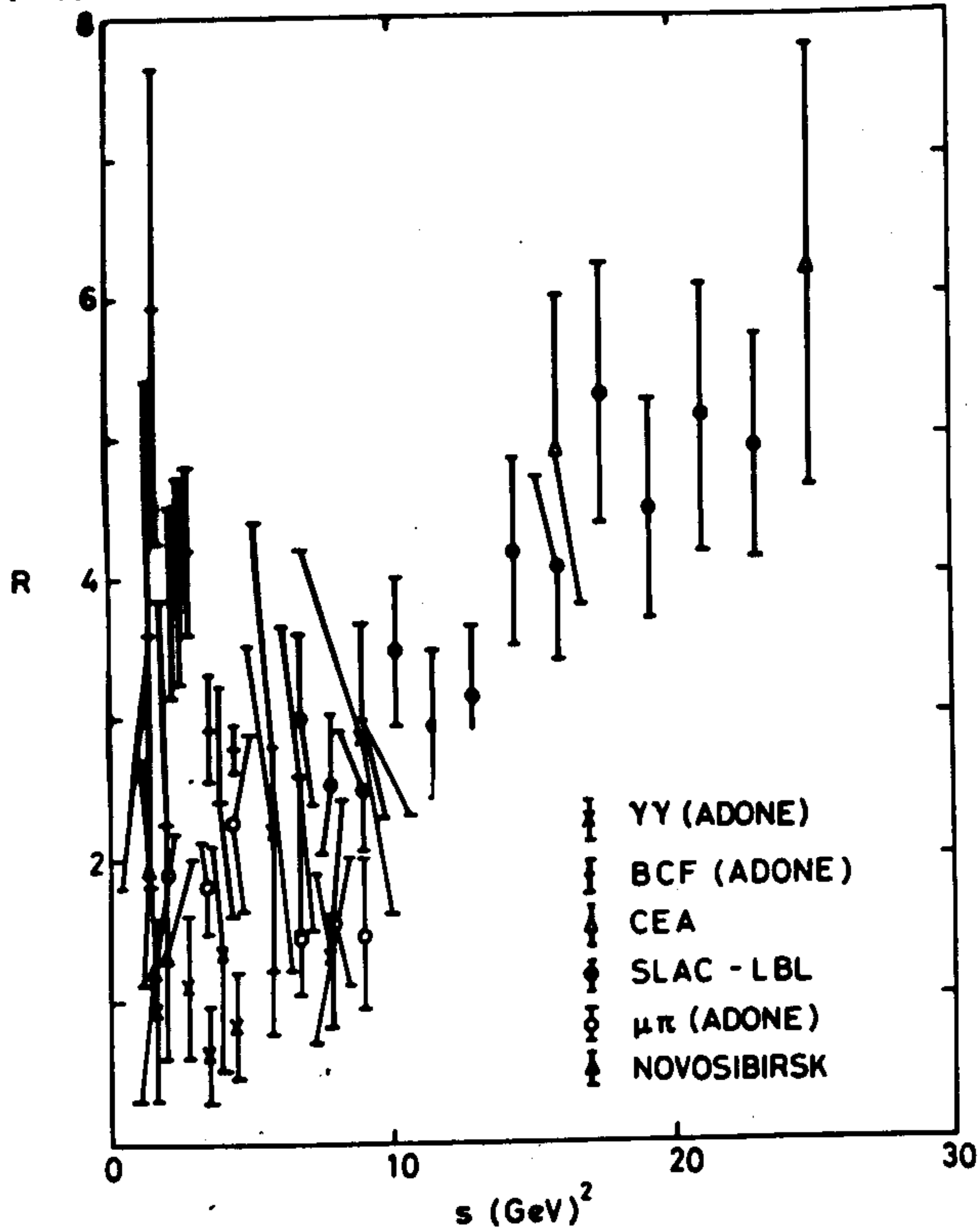
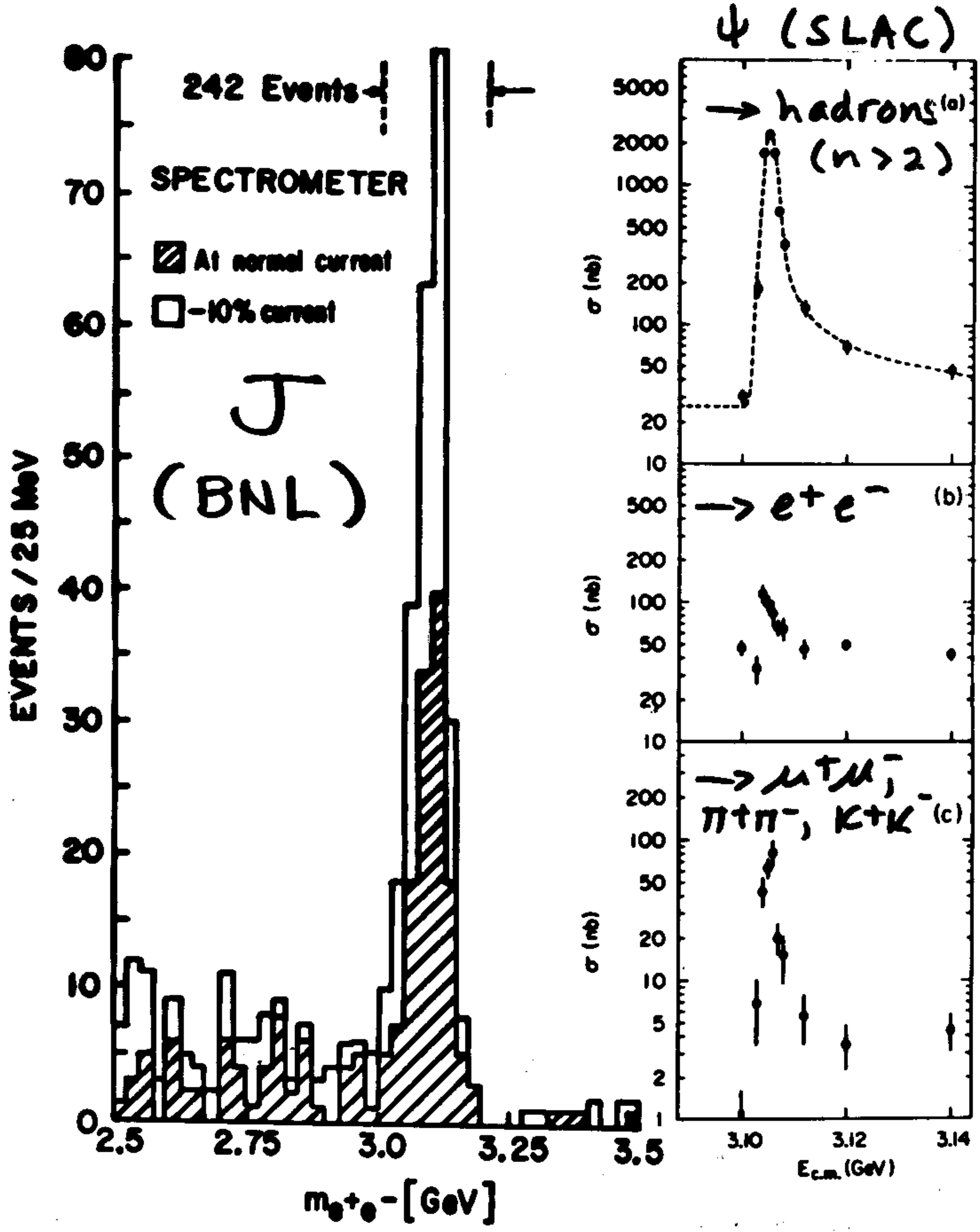


Fig. 4. All measurements of the ratio of σ_{TOT} to $\sigma_{\mu\mu}$ vs S, for S ≥ 1.5 (GeV)^2.

INITIAL J/ψ PEAKS 11/74



WAS CHARM THE ANSWER?

R. Blankenbecler (3/75): "Don't give up the ship. It has just begun to sink..."

K. Niu + (1971) Candidates in emulsion

N. Samios + (1975) Charmed baryon cand.

However:

① $D \to \bar{K}\pi$? $\begin{cases} D^+ = c\bar{d} \to K^-\pi^+\pi^+, \ldots \\ D^0 = c\bar{u} \to K^-\pi^+, \ldots \end{cases}$

2-body decays rare for a 2 GeV object. GIM ⇒ b.r. = few %.

② Rise in R was too big

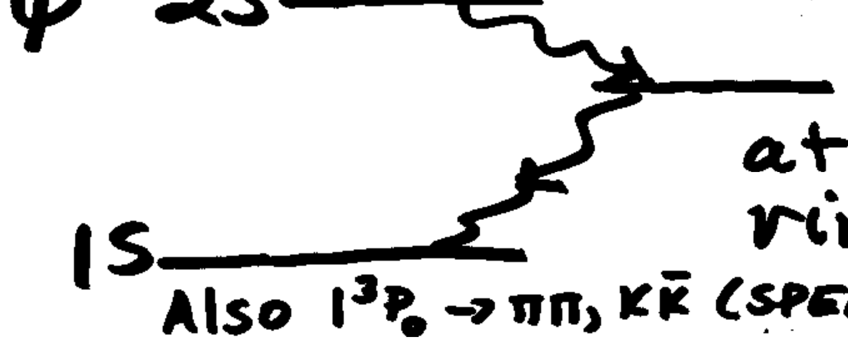
$\tau\bar{\tau}$ pairs also being produced

They diluted the expected rise in kaon multiplicity

SPEAR $\mathcal{L}$ later recalibrated

③ Electric dipole transitions were slow to appear in charmonium

NaI(Tl)



Eventually 1P discovered at DORIS storage ring (DESY) (DASP)

Also $1^3P_0 \to \pi\pi, K\bar{K}$ (SPEAR)

"OPEN" CHARM DISCOVERY

Predictions

Eichten +
De Rújula + } M(D) ~ 1.8 to 1.9 GeV
Rise in R ⟺
$D\bar{D}$ threshold

D^0, D^+ at SPEAR

Glashow to G. Goldhaber (1976):
"Try harder!" TOF info
$\Delta t < 0.5$ ns

$D^0 \to K^- \pi^+$: peak at 1.863 GeV
b.r. ≃ 4%   Also in $K^- \pi^+ \pi^- \pi^+$

Announced 6/76. No meson conference in 4/76. Participants in 1977 meson conference eat their (candy) hats.

Interloper: the τ

$m_\tau \simeq 1.78$ GeV ⟹ ΔR (not quite 1)
Destroyed anomaly cancellation!
Needed new quark pair (top / bottom)
Invented earlier by Kobayashi & Maskawa for CP violation

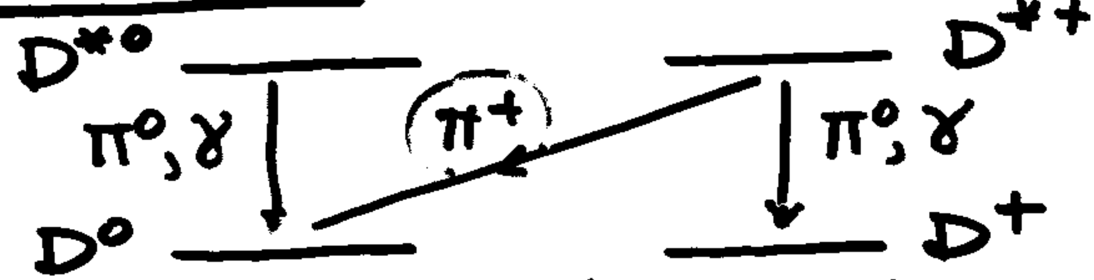
TOTAL RATE VS. PURITY

$e^+e^- \to \gamma^* \to c\bar{c}$: $\Delta R = \frac{4}{3}$ above threshold
"fullstrength"

pp @ 400 GeV/c: $\sigma_{c\bar{c}} \lesssim 10^{-3}\,\sigma_{TOT}$
overall rate greater

How to pick out charm?

① <u>$D^* \to D\pi$</u> (Nussinov)



Soft π^+ "tags" D^0 flavor, helps one see it.

② <u>Vertex detection</u>

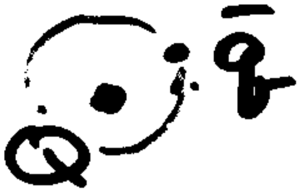
- Emulsions (Niu, 1971; searches, 1975)
  Systematic errors; must scan
- Attempts at high resolution
  Streamer, bubble chambers
- Silicon vertex detectors
  Fast; excellent resolution
  <u>The</u> technique of choice in hadro-, photoproduction

FURTHER PROGRESS

Emulsion - automatic scanning

Fermilab E-531, E-653 lifetimes, f_{D_s}
CERN CHORUS oscillation search

Excited charmed mesons



Like hydrogen atoms
$s(\bar{q}) \times (L=1) \Rightarrow j = \underline{1/2}, \underline{3/2}$
$\times\, S_Q$

$J = 0, 1$	$J = 1, 2$
Broad	Narrow
Not yet seen	D(2420, 2460)

Charmonium with antiprotons

CERN R-704 }
Fermilab E-760, 865 } $\bar{p}p \to \eta_c, J/\psi, (h_c), \chi_c, \cdots$

Discovery of 1^1P_1 state
Precise mass, decay width measurements

Photo- and hadroprod., vtx. detection

CERN WA-62, 89, ⋯
Fermilab E-516, 691, 791, ⋯ | Lifetime hierarchy

e^+e^- production (ARGUS, CLEO)

D_s, charmed baryons (spectroscopy!)

SOME CURRENT QUESTIONS

Lifetime hierarchies

$\tau(\Omega_c) < \tau(\Lambda_c) < \tau(D^0, D_s) < \tau(D^+)$

Vary by > factor of 10 (cf. 600 for kaons!)

Differences expected to be < 10% for B's but $\tau(\Lambda_b) \simeq 0.8\,\tau(B^{+,0})$

Decay constants

$f_{D_s} = 255 \pm 21 \pm 28$ MeV | $D_s \to \mu\nu$, $\to \tau\nu$

What about f_D, f_B, f_{B_s}?

(Lattice predictions exist)

Excited D mesons

Heavy quark symmetry: know how to go from Q = c to Q = b. P-wave $b\bar{q}$ meson properties would be useful for "tagging" neutral B's: $\begin{cases} b\bar{u} \to \pi^- \bar{B}^0 \\ \bar{b}u \quad \pi^+ B^0 \end{cases}$

$D^0 \leftrightarrow \bar{D}^0$, CP violation

Both mixing & CP̸ expected to be smaller than for B's (but easier to study!) Ideal for beyond-standard-model physics searches.

LESSONS ?

(Fighting the last war? History useful?)

Theory

- Optimism was justified: $m_c \simeq 1.5$ GeV
- Perturbative QCD was a good guide
- Quarks needed to be taken seriously

Experiment

- Many searches were harder than people thought
- Instrumental "overkill" sometimes helped (e.g. J)
- Choice of fortunate channel also helped: $e^+e^- \to \psi$
  $J \to e^+e^-$
- Instrumentation is crucial (vertex detection)

Future searches

- Supersymmetry? Looks very different!