Charming and Beautiful: A Short History of Heavy Quarks

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Overview

- Historical context and why we needed charm
- The J/Psi and open charm
- Why we needed a 3rd generation of quarks
- The Upsilon and open bottom

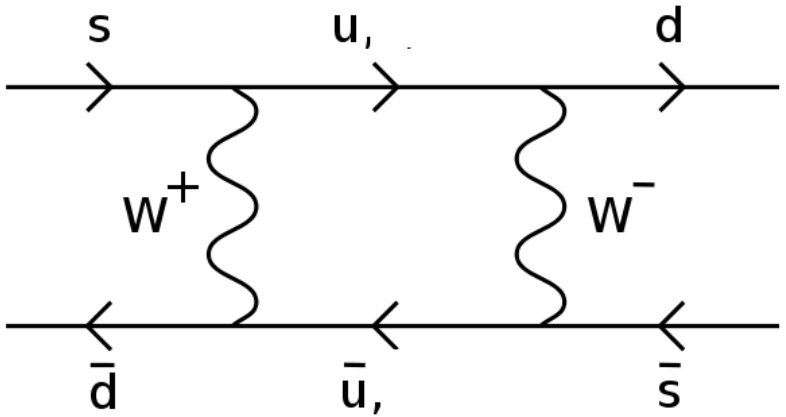
Where we were around 1970

- Early 1970's
  - We have quarks, and an explanation of light hadron spectra
- Hadronic weak charge changing currents in SU(3) broken into Cabibbo components
  - $J^{\mu(+)} = \cos\theta J^{\mu(+)}_{\Delta S=0} + \sin\theta J^{\mu(+)}_{\Delta S=1}$
  - This introduces a mysterious "strangeness changing" piece not understood
- One experimental puzzle, neutral kaon oscillation

$$K^0 \rightarrow \overline{K}^0$$

Neutral Kaons and an Incomplete Theory

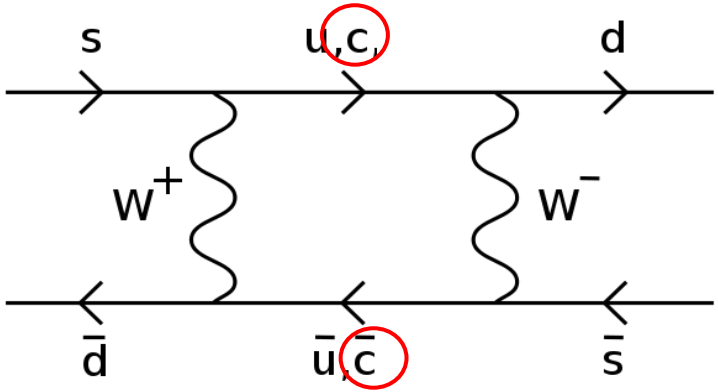
- Introduce box diagrams
- Uh Oh, with 3 quarks, this process is not well controlled
- Solution: Go back to “strangeness changing” part of hadronic current
- Coupled with a strong symmetry argument with leptons



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

A 4th Quark

- Glashow-Iliopoulos-Maiani (GIM) Mechanism Introduced
- Kaon oscillations cut off by mass of new quark
- Provided upper limit of 2 GeV on the mass
- Lots of other predictions:
  - Strongly produced cc pairs
  - D^0 -> Kpi predicted
  - Direct lepton production in charm
  - Charm production in neutrino interactions
  - And more!



Berkeley Angle: Mary K. Gaillard Predictions

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 [''R''] to $3\frac{1}{3}$, perhaps from above, and
(h) any other phenomena that may indicate a mass scale of 2 - 10 GeV.

A Pregnant Pause and the Birth of Charm

- GIM paper in 1970 with many predictions from the theory
- Hints in 1972 at Cambridge Electron Accelerator (CEA)
  - Pointlike quarks and ratio of hadrons in e+e- rises with energy
- CEA results confirmed at SPEAR at SLAC
- By 1974 lots of hints and lots of expectations

Dualing Discoveries of the J/Ψ

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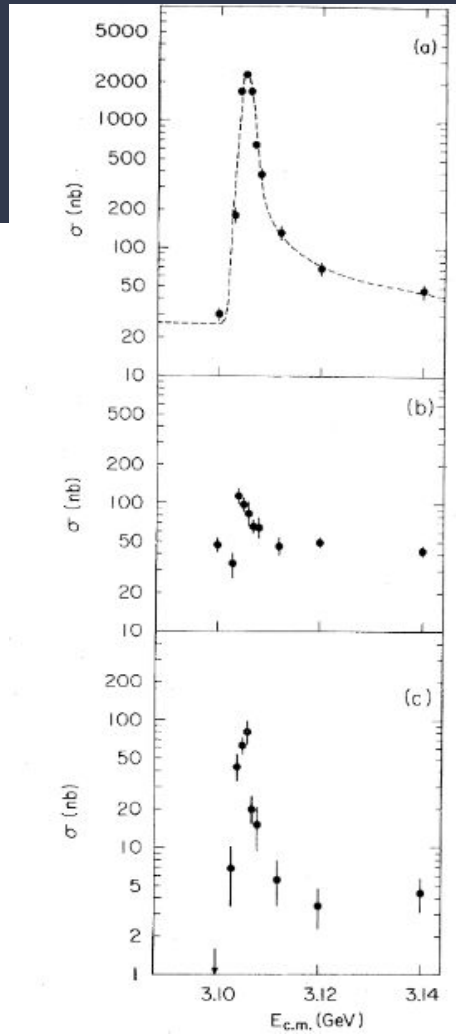
- By 1974 lots of hints and lots of expectations
- And finally, direct, simultaneous confirmation on the West and East coasts

November Revolution of the J/Ψ: SLAC

- SPEAR at SLAC: e+e-
- Factor of 100 enhancement of the cross section!!
  - Plots shows (top to bottom) e+e- to
    - Multi hadrons
    - e+e-
    - pipi, KK, and mu mu

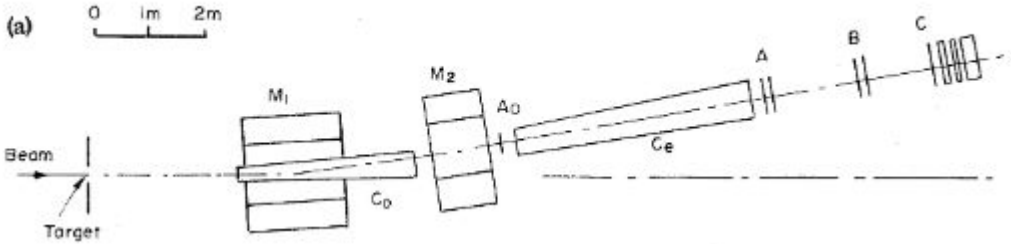
$E = 3.105 \pm 0.003$ GeV,

$\Gamma \leq 1.3$ MeV

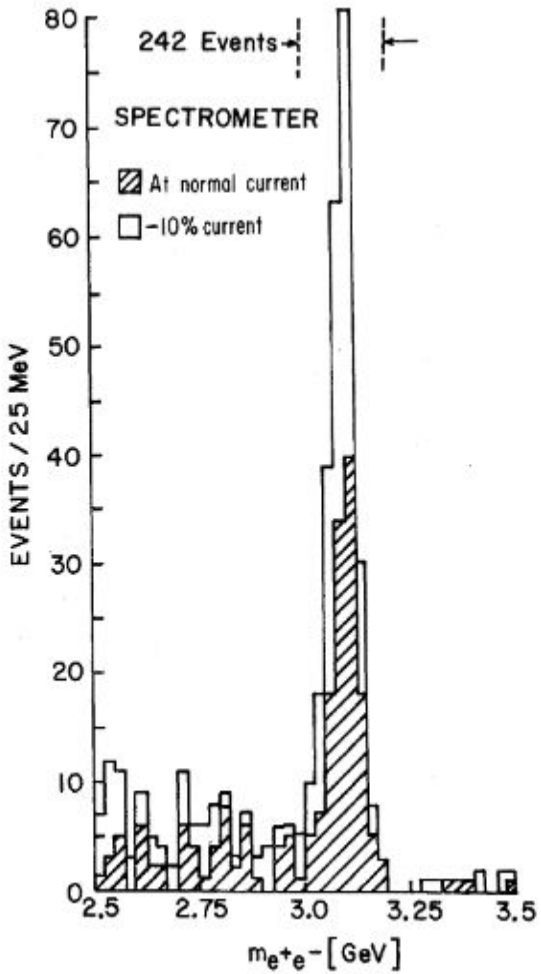


November Revolution of the J/Ψ: BNL

- AGS at BNL with p + Be to e+e-
- Peak for “J” confirmed
- BNL and SLAC results perfectly consistent
- 7 Cross check performed to cross check results

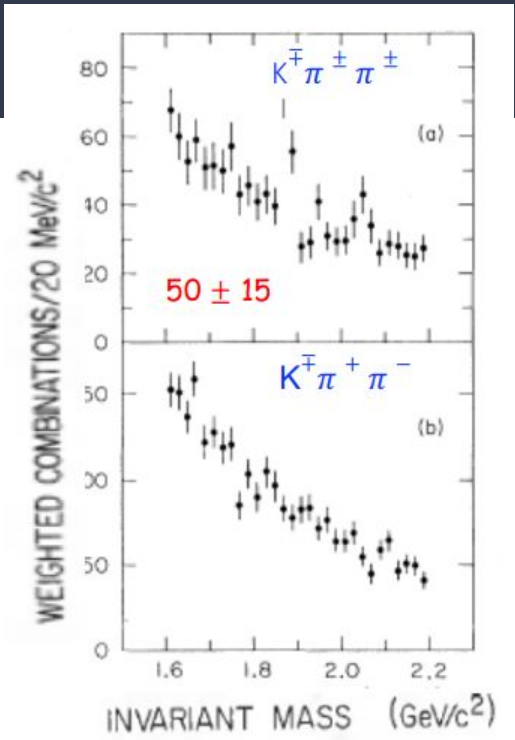


Simplified AGS spectrometer arm



Open Charm

- Discovery of J/Psi, but where is the Open Charm?
- Theoretical Mass Estimates 1.8 - 1.9 GeV
- Why weren't D mesons found at SLAC?
- Glashow urged Goldhaber to reexamine SPEAR data
- D0 pairs found in 1976
  - Mass 1865 ± 15 MeV
- Charged D mesons found shortly after (pictured)
  - Mass 1867 ± 15 MeV
  - Excellent example of Caibibbo supression



What About CP Violation?

- Indirect CP violation discovered with netural Kaon oscillation
- K0 transitions to its antiparticle have slightly different rates than the reverse
- 1973: proposal of CKM matrix, requiring 3 generations of quarks
  - Note this was even before charm discovery

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

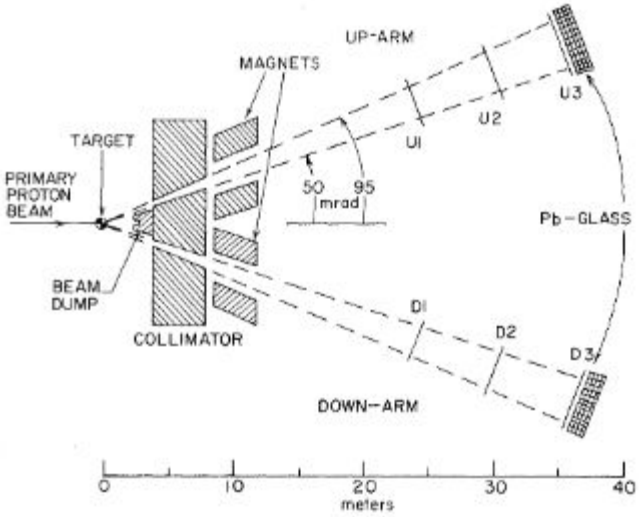
Not So Spontaneous Symmetry Breaking

- Tau discovered at MARK I in 1975
- The great symmetry of the quarks and leptons is fully broken

$$[\tau] \quad \begin{bmatrix} \nu_e \\ e^- \end{bmatrix} \begin{bmatrix} \nu_\mu \\ \mu^- \end{bmatrix} \Leftrightarrow \begin{bmatrix} u \\ d \end{bmatrix} \begin{bmatrix} c \\ s \end{bmatrix} \quad [?]$$

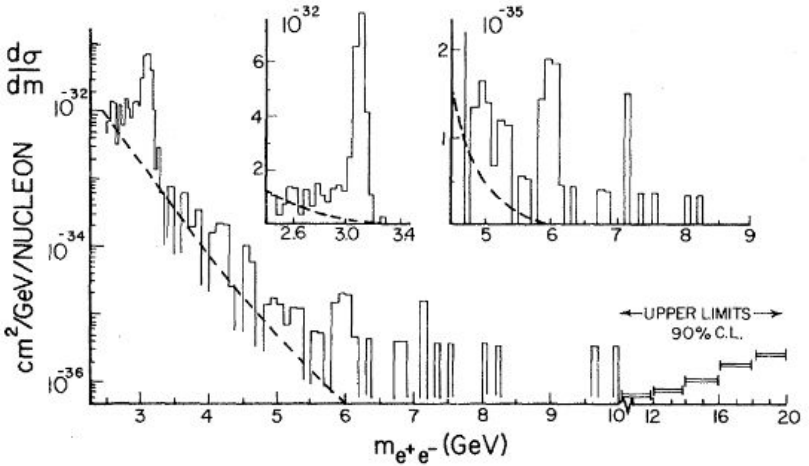
Back to Experiments: A New World of Dileptons

- Lederman lead active program of lepton studies at BNL accelerators
- Lots of experimental interest in this channel before J/Psi discovery
- “Missed the Boat” on charmonium due to superior technology of Ting’s experiment
  - Multiwire Proportional Chambers
- New experiment, CFS, expected to have results with electrons, hadrons, and muons in that order
- 400 GeV protons on Be



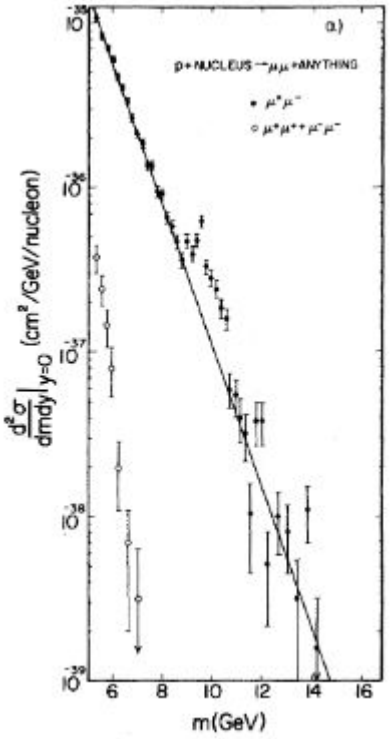
Statistical Errors and the Oops-Leon

- 1976: Large amount of dielectron data with a “peak” around 6.0 GeV
- “1 chance in 50 to see such a clustering”
- By the spring of ‘76, 5 times as much sensitivity in dimuon channel
- Peak entirely disappeared!
- Lederman has an impressive record of both discovery and missing things



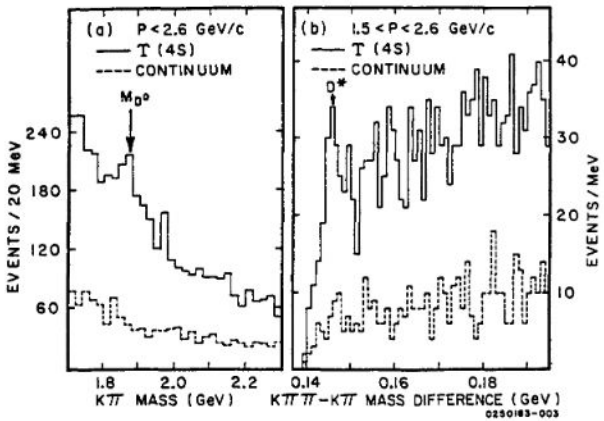
Is There Anything in this Dilepton Spectrum?

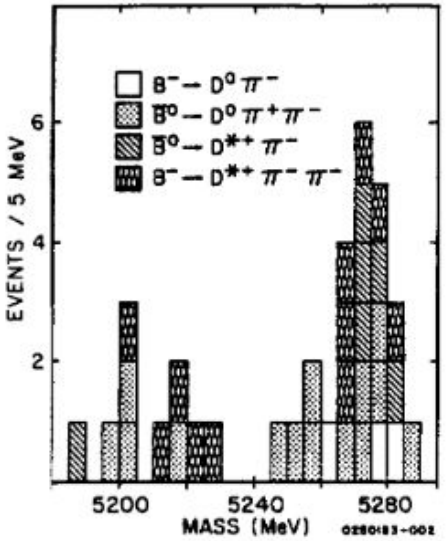
- November 1976 (still) clustering of dielectron events near 9.5 GeV
- Hadronic debris greatly reduced by implementing downstream absorbers
- Charmonium used to test resolution, normalization and uniformity over the detector
- Discovery of peak at 9.54 ±0.04 GeV
- Proof of b quarks!



For Completeness, A Bare Bottom

- Higher bottomonium resonances discovered by 1983
- B mesons were seen through charm cascade decays
- Exploit similar techniques as are used today when reconstructing charm decays





What Did This All Mean

- Discovery of b quark cemented understanding of 3 generations
- Launched program of precision B physics which continues through today
- Implication of the existence of the top quark
    - Deep understand of b's integral to this discovery in the mid 1990's
- Rich field in b and c physics to this day at the LHC and beyond

Sources

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Dueling Discoveries of the J/Ψ

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