Physics 661

Particle Physics Phenomenology

November 18, 2003

Quarks in Hadrons

- Charm and beauty
- Quarkonium
- Baryon decuplet
- Quark spin and color
- Baryon octet
- Pseudoscalar mesons
- Vector mesons
- Other tests of the quark model
- Mass relations and hyperfine splitting
- EM mass differences and isospin symmetry
- Baryon magnetic moments
- Heavy quark mesons
- The top quarks

Charm and Beauty

- By the early 1970's, three quarks had been discovered.
- During the 1970's, two more quarks were discovered
  - charm, 1974
  - bottom, 1977
- In 1995, the top quark was finally observed

Flavor	I	I_3	S	C	B*	T	Q/e
u	1/2	1/2	0	0	0	0	+2/3
d	1/2	-1/2	0	0	0	0	-1/3
s	0	0	-1	0	0	0	-1/3
c	0	0	0	1	0	0	+2/3
b	0	0	0	0	-1	0	-1/3
t	0	0	0	0	0	1	+2/3

Discovery of Charm

- 1974
  - two complementary experiments
  - SLAC: $e^+e^- \to \psi \to$ hadrons

    $\quad\quad\quad\quad\quad\quad\quad\quad\hookrightarrow e^+e^-, \mu^+\mu^-$
  - BNL: $p + Be \to J/\psi +$ anything

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

Discovery of Charm

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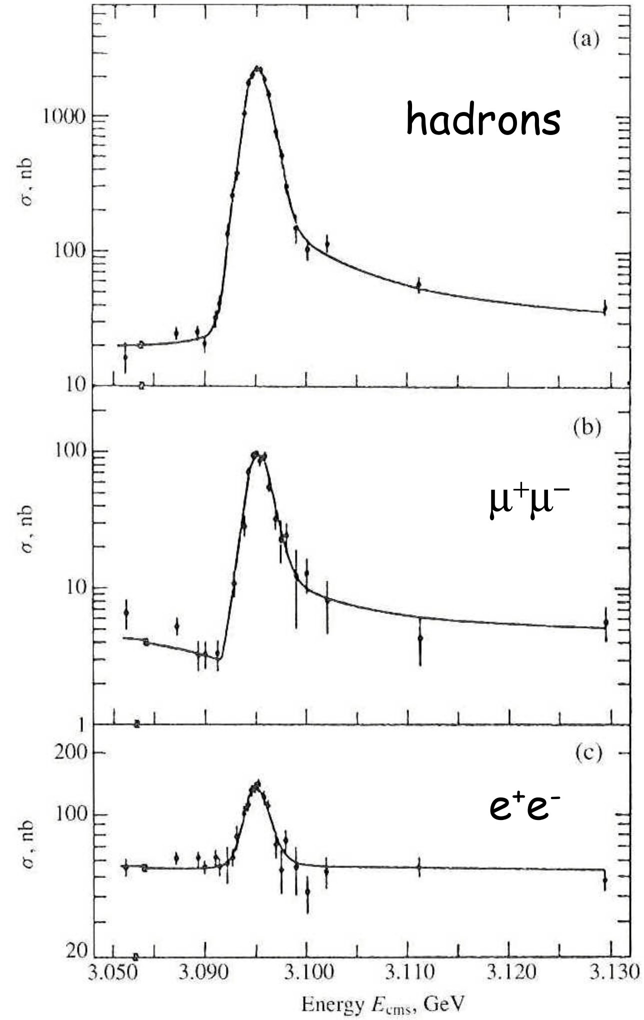
    $\hookrightarrow e^+e^-, \mu^+\mu^-$

  width dominated by experimental resolution

  Also observed second peak at 3.7 GeV (ψ')



Discovery of Charm

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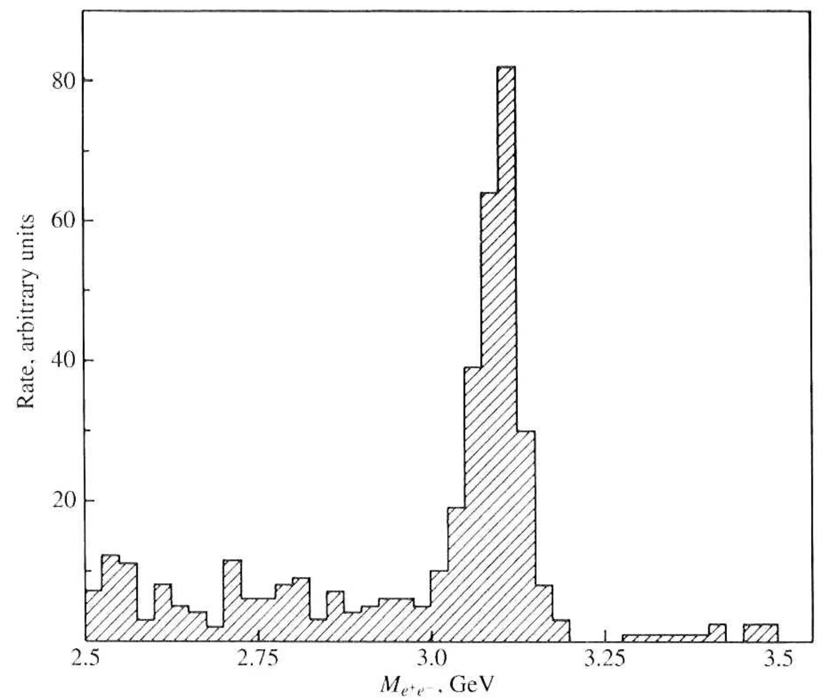


Discovery of Charm

- Total width from integral of the cross section:

$$\int \sigma(E)\, dE = 3\pi^2/2\ \lambda\!\!\!^{-2}\ (\Gamma_{ee}/\Gamma)^2\, \Gamma = 800 \text{ nb MeV}$$

$$\Gamma_{ee}/\Gamma = 0.06$$

$$\lambda\!\!\!^{-} = \hbar c/pc = 197 \text{ fm}/1500$$

$$\Gamma = 0.087 \text{ MeV} \qquad (\underline{\text{very narrow}})$$

Discovery of Charm

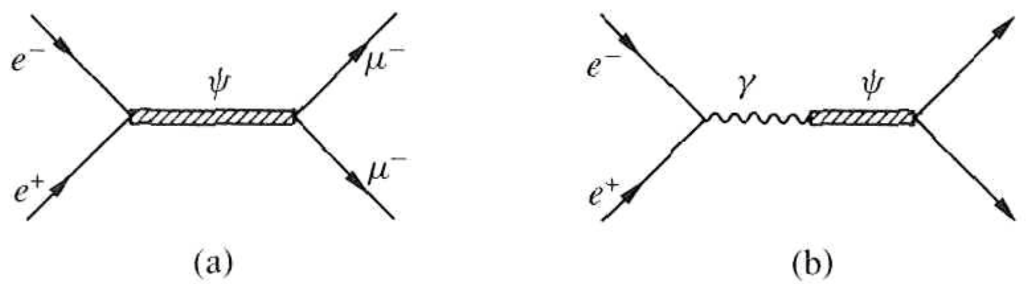
- Vector mesons:

	Γ	
ρ(776 MeV)	150	MeV
ω(784 MeV)	8.4	MeV
J/ψ(3100 MeV)	0.087	MeV

	Γ_{ee}	
ϕ(1020 MeV)	1.4	keV
ω(784 MeV)	0.6	keV
J/ψ(3100 MeV)	5	keV

Discovery of Charm

- Shape of the resonance was consistent with $J^p = 1^-$
  - interference of the direct and virtual photon channels



  - ratio of decay modes (such as $\rho^0\pi^0$ and $\rho^-\pi^+$) shows J/ψ is I=0 state

Discovery of Charm

- $\psi(3700) \rightarrow \psi(3100)\,\pi^+\,\pi^-$

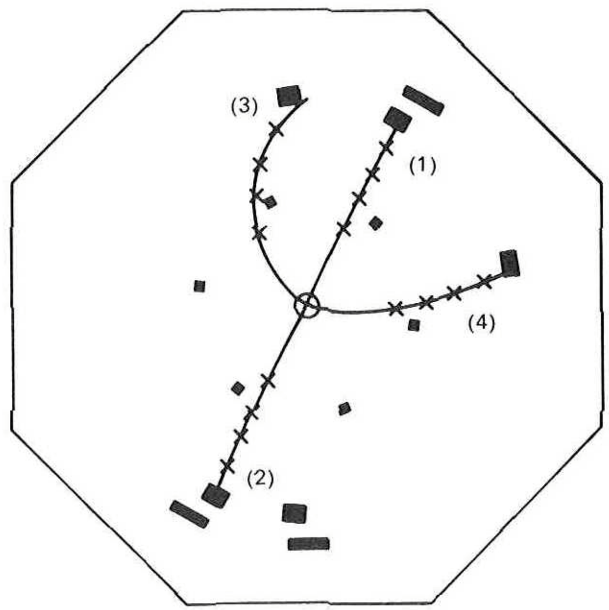
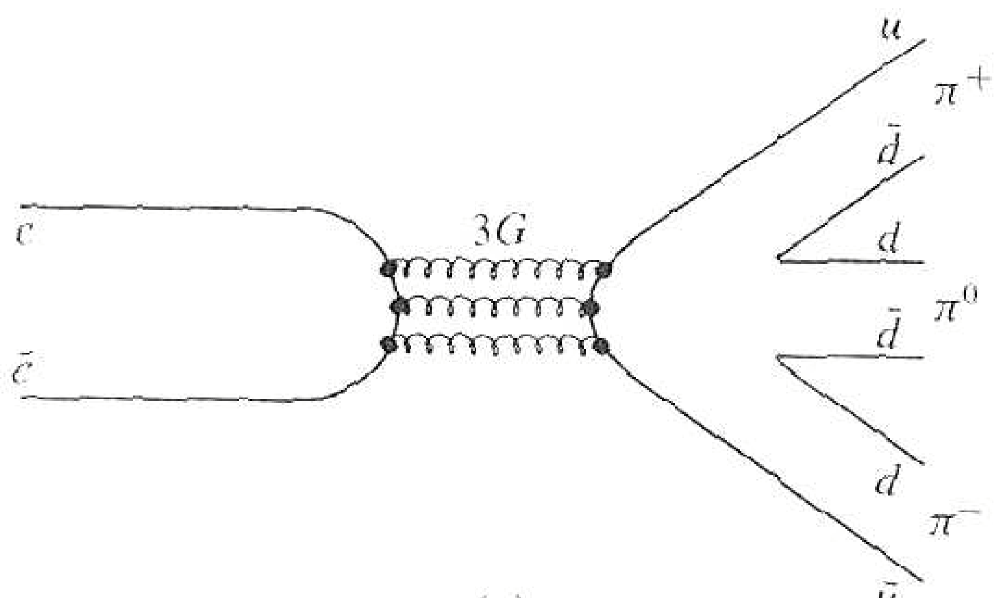


Fig. 4.4. Example of the decay $\psi(3.7) \rightarrow \psi(3.1) + \pi^+ + \pi^-$ observed in a spark chamber detector. The $\psi(3.1)$ decays to $e^+ + e^-$. Tracks (3) and (4) are due to the relatively low energy (150 MeV) pions, and (1) and (2) to the 1.5 GeV electrons. The magnetic field and the SPEAR beam pipe are normal to the plane of the figure. The trajectory shown for each particle is the best fit through the sparks, indicated by crosses. (From Abrams *et al.* 1975.)

Discovery of Charm

- Narrowness of $\psi(3100)$ and $\psi(3700)$ explained by QCD, 3G exchange required

Colorless,
and C parity odd



(a)

Discovery of Charm

- For heavier charmion states, open charm decay modes open up -> broader resonances

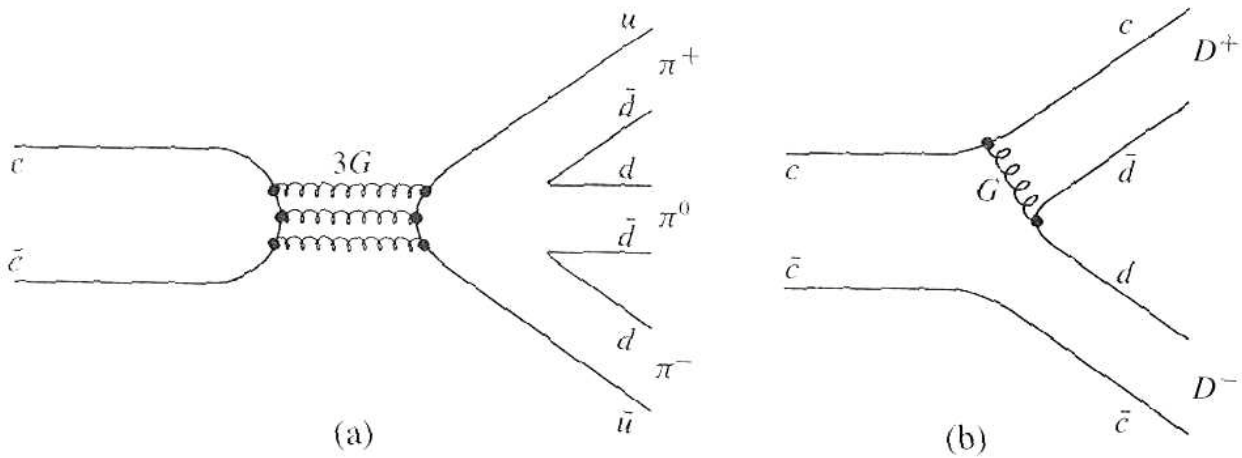


Fig. 4.5. Quark diagrams for charmonium decay. (a) $\Psi(3100) \to 3\pi$, $\Gamma = 0.076$ MeV; (b) $\Psi(3770) \to D\bar{D}$, $\Gamma = 24$ MeV. Diagram (b) is favoured but forbidden by energy conservation for charmonium states $\psi(3.1)$ and $\psi(3.7)$ with masses below threshold $2M_D = 3.75$ GeV. The 'OZI forbidden' diagram (a) is therefore the only one allowed for hadronic decay of these low-mass states.

Discovery of Charm

$\psi(3100)$	Γ = 0.087 MeV
$\psi(3700)$	Γ = 0.28 MeV
$\psi(3770)$	$\Gamma = 23.6 \pm 2.7$ MeV
$\psi(4040)$	$\Gamma = 52 \pm 10$ MeV
$\psi(4160)$	$\Gamma = 78 \pm 20$ MeV
$\psi(4415)$	$\Gamma = 43 \pm 15$ MeV

Discovery of Beauty

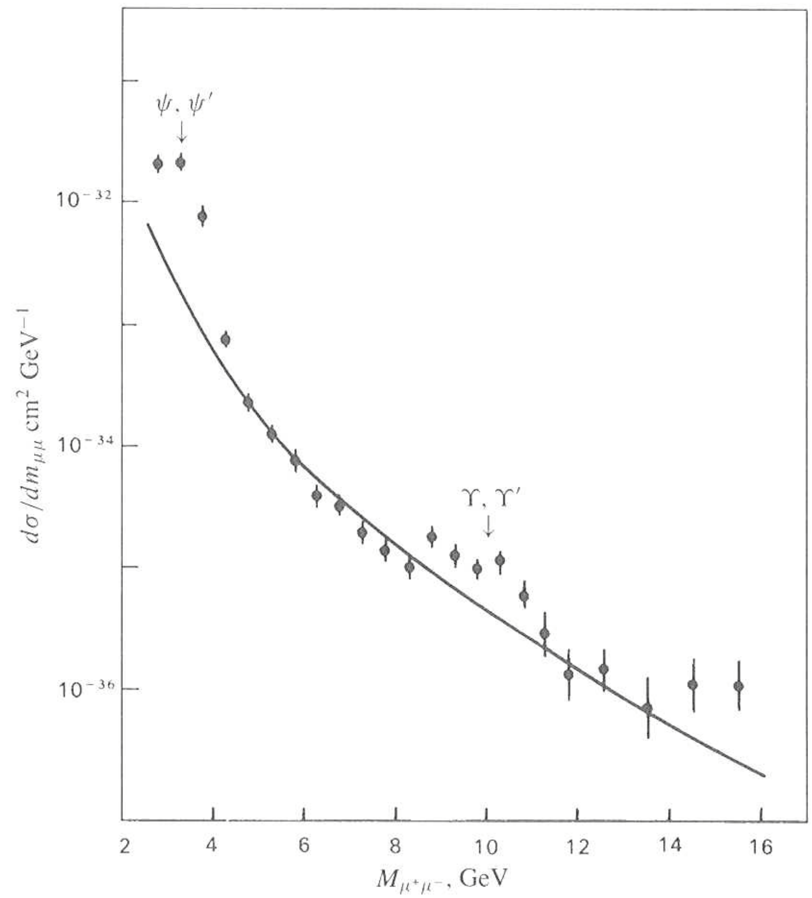
- 1977
  - history repeats itself
  - another narrow resonance

  - this time at Fermilab
  - p+Be -> $\mu^+\mu^-$ + anything

    p+Cu -> $\mu^+\mu^-$ + anything

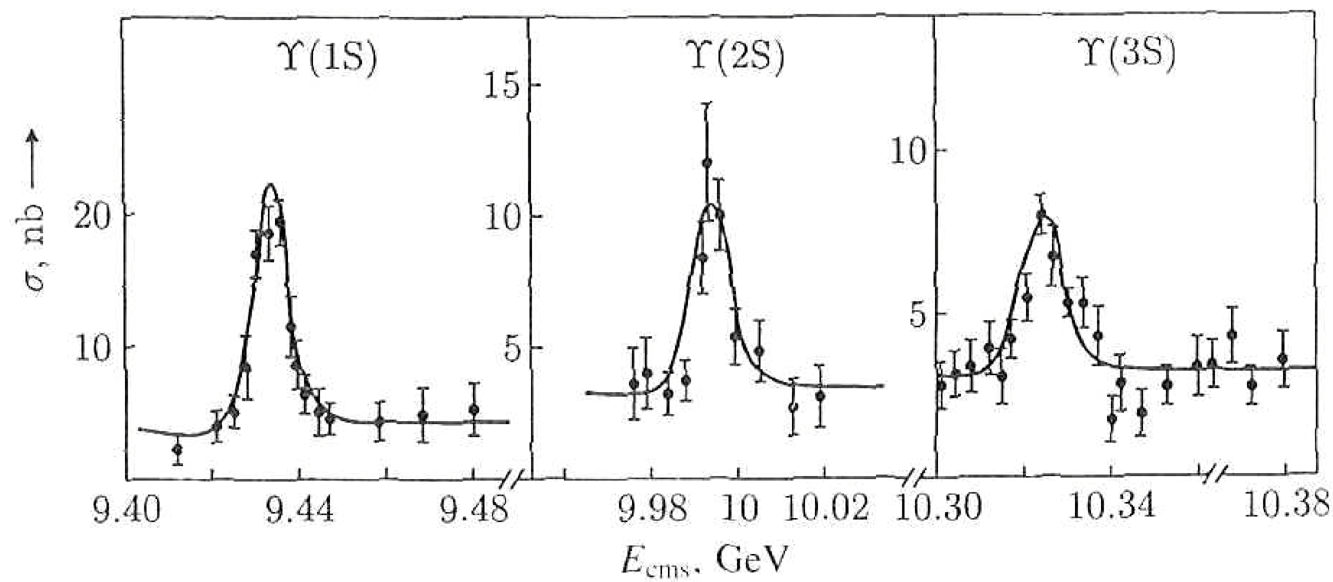
    p+Pt -> $\mu^+\mu^-$ + anything

    400 GeV protons



Discovery of Beauty

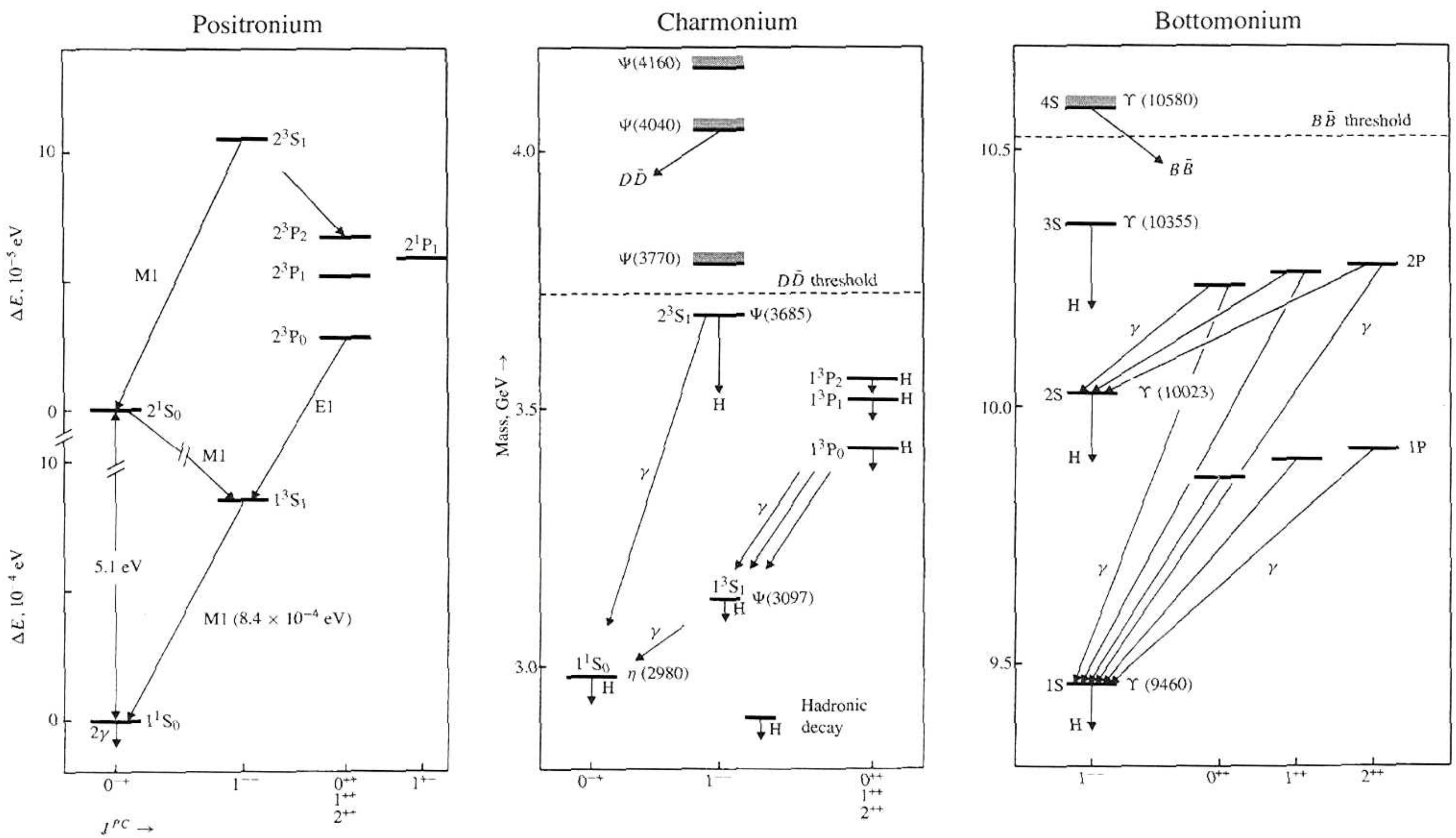
- Electron-positron colliders refine measurements:
  - DORIS at DESY, CLEO at Cornell



Discovery of Beauty

	Mass (MeV)	Γ_{ee} (keV)	Γ (MeV)
$\Upsilon(1S)$	9460	1.32	0.053
$\Upsilon(2S)$	10023	0.52	0.044
$\Upsilon(3S)$	10355		0.026
$\Upsilon(4S)$	10580	0.25	10 ± 4

Quarkonium and Positronium



Positronium

- e^+e^- -> $\gamma\gamma$
  - $\tau = 1.25 \times 10^{-10}$ sec
  - singlet state
  - even ang. momentum -> $J=0$ -> $C = (-1)^{L+S} = (-1)^0 = +1$
  - $C = (-1)^{n\gamma}$ -> $C = +1$

- e^+e^- -> $\gamma\gamma\gamma$
  - $\tau = 1.4 \times 10^{-7}$ sec
  - triplet state -> $J=1$ -> $C = (-1)^{L+S} = (-1)^{0+1} = -1$
  - $C = (-1)^{n\gamma}$ -> $C = -1$

C of particle/antiparticle

- Interchange of space and spin

is equivalent to Charge Conjugation

Positronium

- Principal energy levels from non-relativistic Schroedinger equation in a Coulomb potential

$$E_n = -\alpha^2 \mu c^2 / 2n^2, \quad \mu = m/2$$

- Relativistic corrections:
  - spin-orbit
    - S, P, D
  - spin-spin
    - $^3S_1$, $^1S_0$, ……

  - these are about the same size in positronium:
    $\Delta E \sim \alpha^4 mc^2 / n^3$

Positronium

- Lifetimes:
  - Two photon
    - two photons means rate is to order α^2
    - overlap of wavefunctions at origin to annihilate
      - $|\psi(0)|^2 = 1/\ \pi\ a^3$
      - $a = 2\ h/(2\pi\ mc\ \alpha)$
    - exact result:

      $\Gamma = \alpha^5\ m/2$

  - Two photon
    - rate at higher order

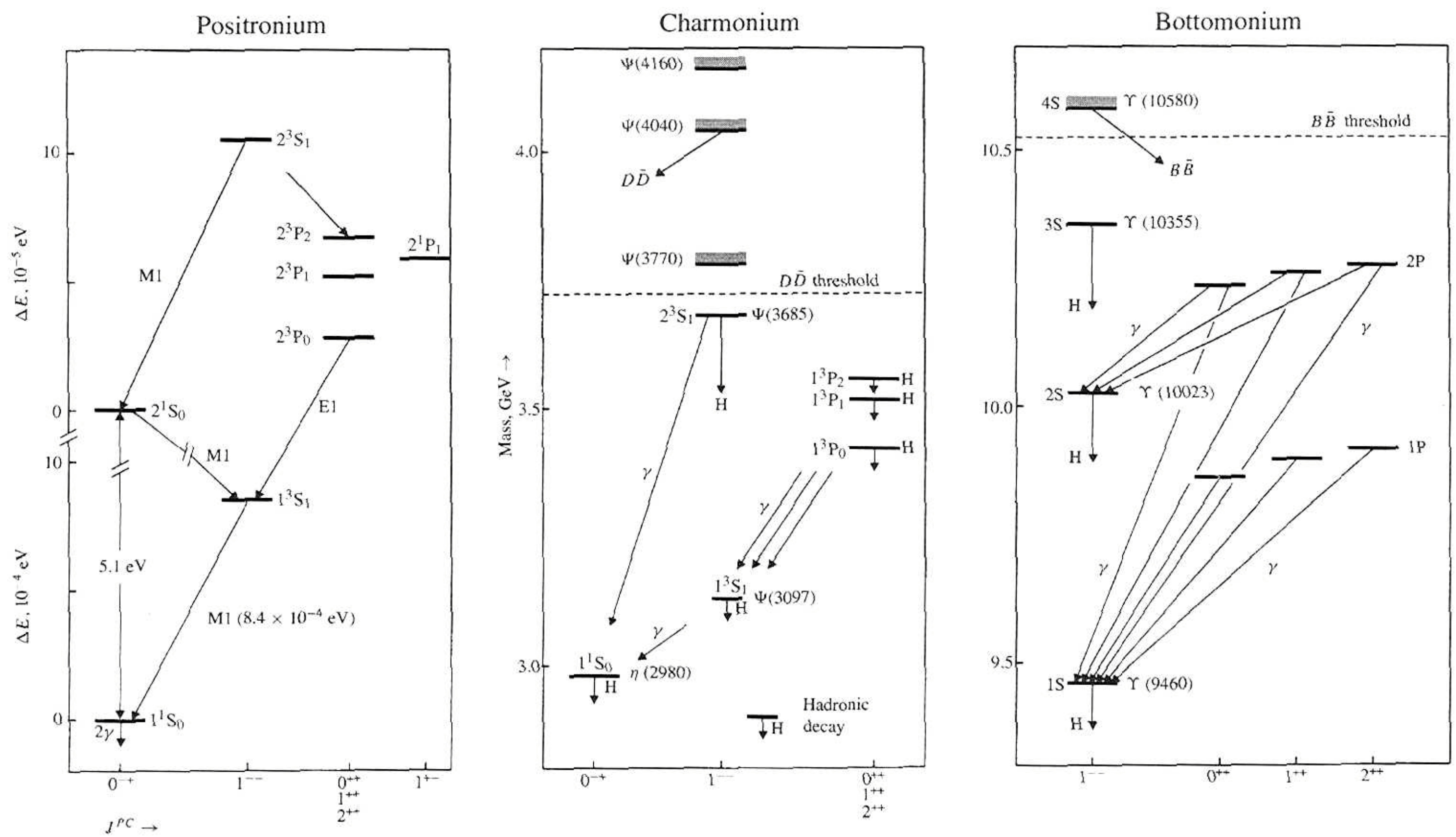
      $\Gamma = 2(\pi^2-9)\ \alpha^6\ m/(9\pi)$

Positronium

- Excellent agreement on Theory and Experimental results for lifetimes and energy levels
  - (see textbook)

Quarkonium

- Similar energy levels to positronium



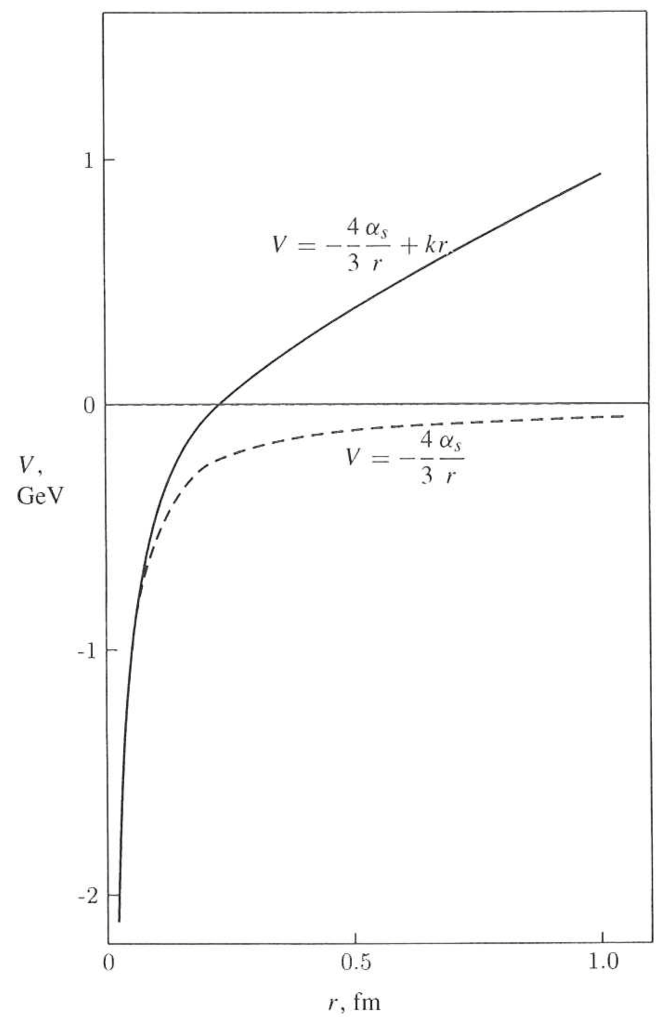
Quarkonium

- Different potential:
  - positronium -> Coulomb
  - $V = - \alpha / r$

  - quarkonium -> potential from QCD
  - expected potential of the form
  - $V = -(4/3)\, \alpha_s / r + kr$

Quarkonium

- $\alpha_s = 0.2$
- $k \approx 1$ GeV fm^{-1}



Quarkonium

- For the heavy quarks, a non-relativistic approximation is valid:
  - $p/m \sim 0.13$

- Fine structure is of order α_s, and therefore coarser than for positronium, as observed