Heavy Quarks and Charmonium Spectroscopy

Introduction to Elementary Particle Physics

Diego Bettoni

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The Discovery of Charm

The charmonium system was discovered in November 1974, when two experimental groups at Brookhaven and SLAC announced almost simultaneously the discovery of a new, narrow resonance, later to be called J/ψ.

The new resonance had a mass of roughly 3100 MeV/c^2 and an extremely narrow width. Present values from PDG 2004 edition:

$$M(J/\psi)=(3096.916 \pm 0.011)\ \mathrm{MeV}/c^2$$

$$\Gamma(J/\psi) =(91.0\pm3.2)\ \mathrm{keV}$$

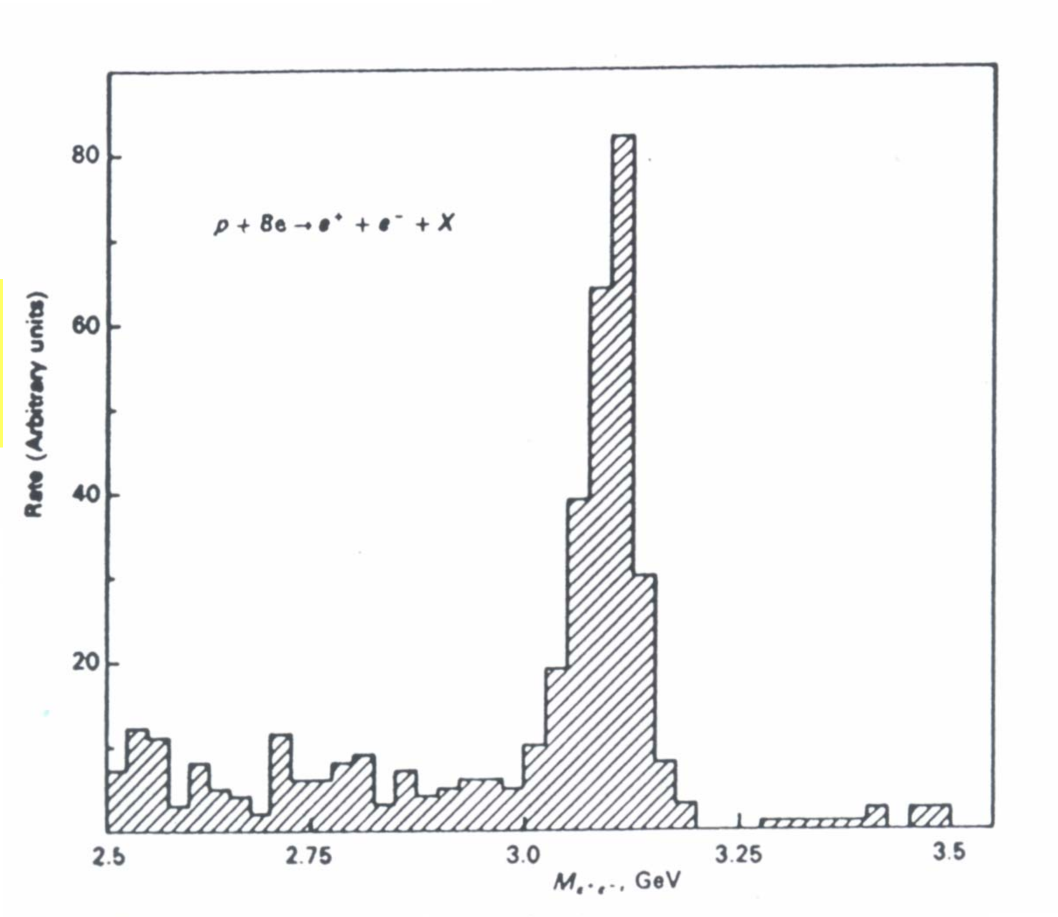
This was followed very shortly by the discovery, by the SLAC group, of another narrow state, called ψ'.

$$M(\psi')=(3686.093 \pm 0.034)\ \mathrm{MeV}/c^2$$

$$\Gamma(\psi') =(277\pm22)\ \mathrm{keV}$$

The Brookhaven Signal

$$p + Be \rightarrow \underbrace{e^{+} + e^{-}}_{J} + X$$

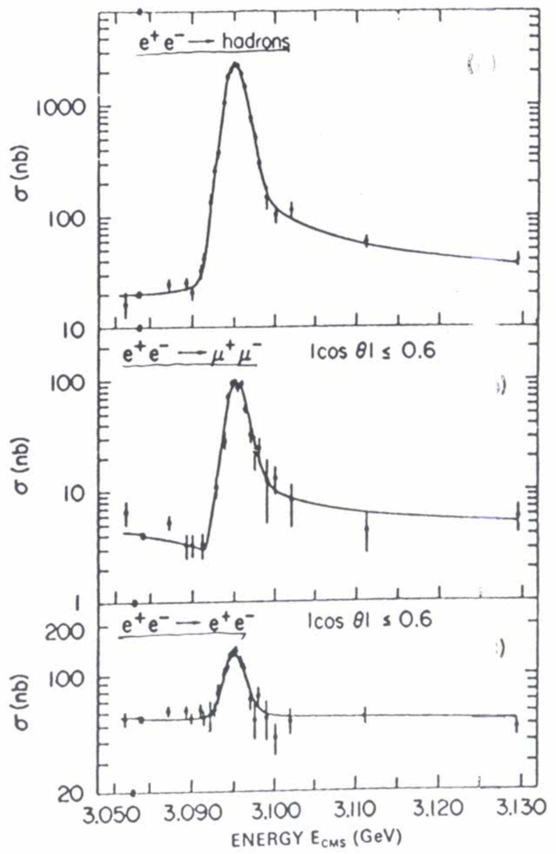


The SLAC Signals

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

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

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



Measurement of the J/ψ Total Width - I

The cross section for the process a+b$\rightarrow$R$\rightarrow$c+d is given by the Breit-Wigner formula:

$$\sigma_{BW}(E) = \frac{2J+1}{(2s_1+1)(2s_2+1)}\frac{\pi}{k^2}\frac{\Gamma_{ab}\Gamma_{cd}}{(E-M_R^2)+\frac{\Gamma^2}{4}}$$

where k, s_1 and s_2 are the CMS momentum and spins of a and b;
J, M_R and Γ are the resonance spin and mass and total width, E is the CMS energy, Γ_{ab} and Γ_{cd} are the partial widths for R$\rightarrow$ab and R$\rightarrow$cd.
If G(E) is the beam distribution function, the measured cross section is:

$$\sigma(E) = \int_0^\infty \sigma_{BW}(E')G(E'-E)dE'$$

Measurement of the J/ψ Total Width - II

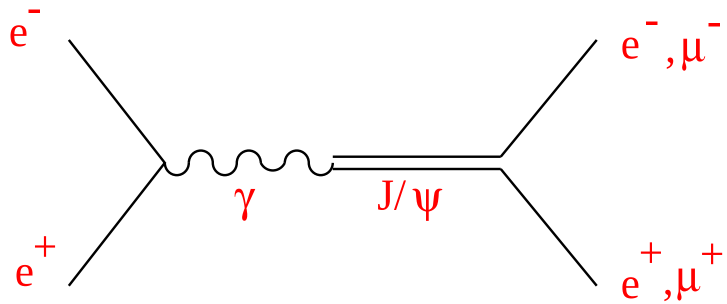
The area under the resonance is given by:

$$A = \int_0^\infty \sigma(E)dE = \frac{\pi}{2}\sigma_{peak}\Gamma$$

where σ_{peak} is the value of the Breit-Wigner cross section at $E=M_R$.
The area under the resonance is thus independent of the form of G(E): if G(E) is unknown, then the value of the resonance width Γ can be obtained from the measured area (indirect determination of Γ). **This is how the J/ψ and ψ' total widths were determined at SLAC.**
On the other hand, if G(E) is known, than Γ can be determined directly from the analysis of the shape of the measured excitation function (i.e. the measured cross section as a function of the CMS energy).

The J/ψ and ψ′ as c $\bar{c}$ states

The J/ψ and the ψ′ are formed directly in e^+e^- annihilation, therefore they have the quantum numbers of the photon: $J^{PC}=1^{--}$.

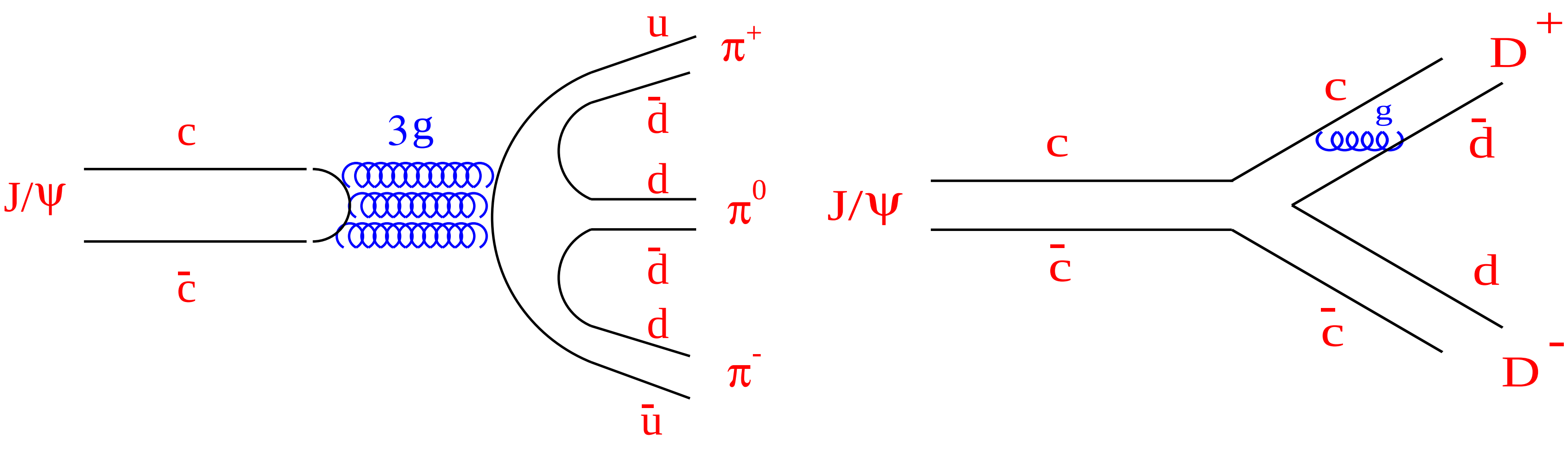


Their extremely narrow width makes it impossible to understand these new states in terms of the light u,d,s quarks.

They are interpreted as bound states of a new quark (c) and its antiquark ($\bar{c}$), whose existence had been predicted in 1970 to account for the non existence of Strangeness Changing Neutral Currents.

The J/ψ Width and the OZI rule

Decay rates described by diagrams with unconnected quark lines are suppressed.



OZI suppressed

OZI allowed
forbidden by
energy conservation

Why is Charmonium Interesting ?

Charmonium is a powerful tool for the understanding of the strong interaction. The high mass of the c quark ($m_c \sim 1.5\ \mathrm{GeV}/c^2$) makes it plausible to attempt a description of the dynamical properties of the ($c\bar{c}$) system in terms of non-relativistic potential models, in which the functional form of the potential is chosen to reproduce the known asymptotic properties of the strong interaction. The free parameters in these models are determined from a comparison with experimental data.

$$\beta^2 \approx 0.2 \quad \alpha_s \approx 0.3$$

Non-relativistic potential models + Relativistic corrections + PQCD

The Non-Relativistic Potential

The functional form of the potential is chosen to reproduce the known asymptotic properties of the strong interaction.

- At small distances asymptotic freedom, the potential is coulomb-like:

$$V(r) \xrightarrow[r \to 0]{} -\frac{4}{3}\frac{\alpha_s(r)}{r}$$

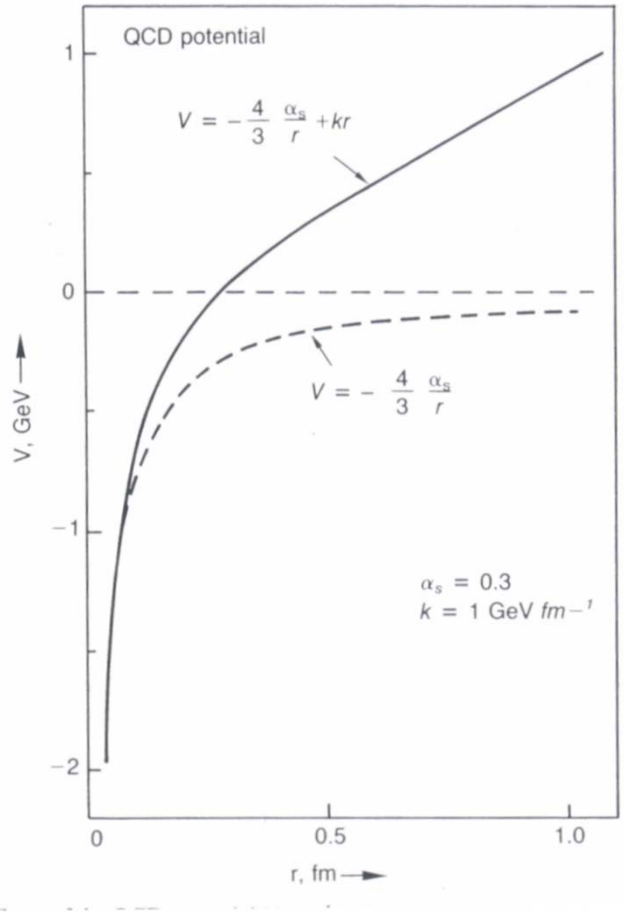
- At large distances confinement:

$$V(r) \xrightarrow[r \to \infty]{} kr$$

The Non-Relativistic Potential II

$$\alpha_s(\mu) = \frac{4\pi}{(11 - \frac{2}{3} n_f) \ln(\frac{\mu^2}{\Lambda^2})}$$

n_f = number of flavours
Λ ~ 0.2 GeV QCD scale parameter
k string constant (~ 1 GeV/fm)



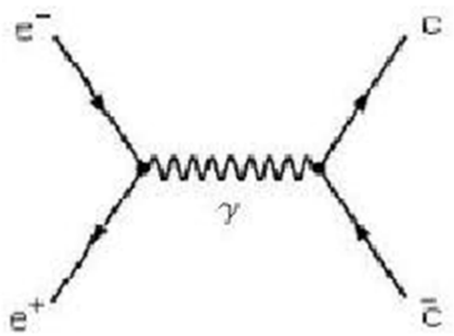
Charmonium Decay

- One of the key features of charmonium states below $D\bar{D}$ threshold is the narrow width. These states decay violating the OZI rule.
- States above threshold can generally decay to open charm, except if forbidden by some conservation rule: in this case these states are also narrow.
- Electromagnetic decays are calculable with high accuracy in QED, but it is the strong interaction which describes the $c\bar{c}$ bound state.
  - e^+e^- decay of vector states.
  - $\gamma\gamma$ decay of J-even states.
  - $\gamma\gamma\gamma$ decay
  - radiative transitions
- Strong decays must be calculated in QCD. Due to the high value of α_s, QCD cannot always be treated as a perturbative theory.

Experimental Methods for the Study of Charmonium

- e^+e^- collisions (SLAC: Mark I, II, III, TPC, Crystall Ball; DESY: DASP and PLUTO; LEP; CESR: CLEO, CLEO-c; BEPC BES; B-factories: BaBar and Belle).
  - direct formation
  - two-photon production
  - initial state radiation
  - B meson decay
  - double charmonium
- $p\bar{p}$ annihilations (CERN R704, FNAL E760 E835, GSI PANDA)
- hadroproduction (CDF, D0, LHC)
- electroproduction (HERA)

Direct Formation $e^+e^- \to c\bar{c}$

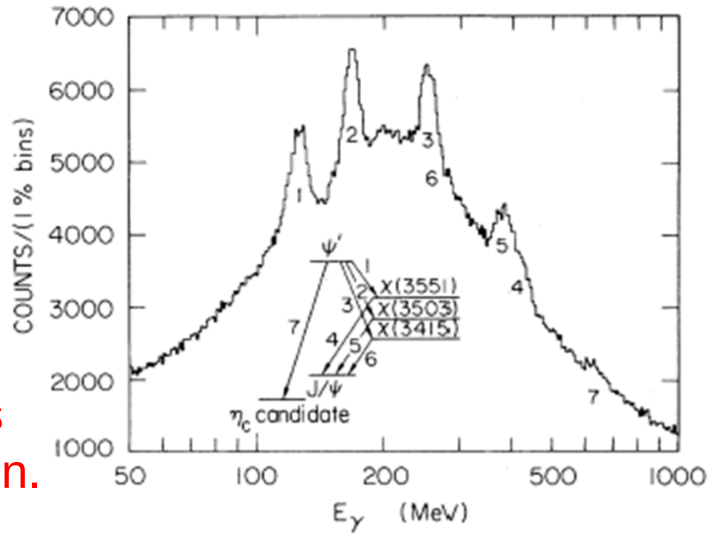


In e^+e^- annihilations direct formation is possible only for states with the quantum numbers of the photon $J^{PC}=1^{--}$: J/ψ, ψ' and $\psi(3770)$.

All other states can be produced in the radiative decays of the vector states. For example:

$$e^+ + e^- \to \psi'(2S) \to \gamma + X$$

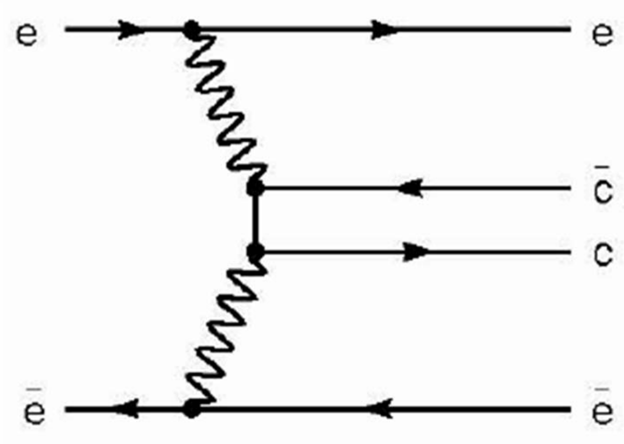
The precision in the measurement of masses and widths is limited by the detector resolution.



Crystal Ball inclusive photon spectrum

Two-photon Production $e^+e^- \to e^+e^- + (c\bar{c})$

J-even charmonium states can be produced in e^+e^- annihilations at higher energies through $\gamma\gamma$ collisions. The $(c\bar{c})$ state is usually identified by its hadronic decays. The cross section for this process scales linearly with the $\gamma\gamma$ partial width of the $(c\bar{c})$ state.



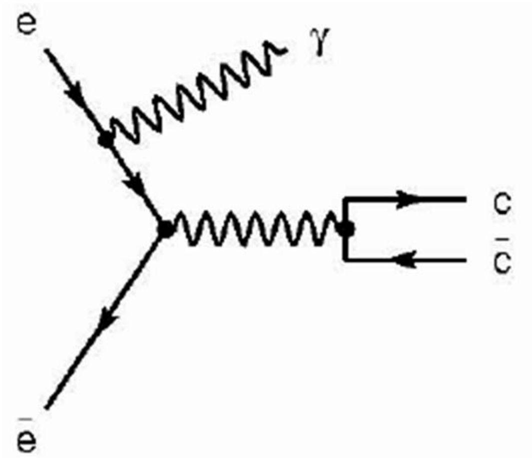
$$\sigma\left(e^+e^- \to e^+e^-(c\bar{c})\right) = \int d^5 L_{\gamma\gamma}(\alpha_i)\,\sigma\left(\gamma\gamma \to (c\bar{c})\right)$$

$$\sigma\left(\gamma\gamma \to (c\bar{c})\right) = 8\pi \frac{2J+1}{M}\Gamma_{\gamma\gamma}\frac{M\Gamma}{\left(s-M^2\right)^2 + M^2\Gamma^2} F\left(q_1^2, q_2^2\right)$$

L = Luminosity function
α= e.g. 4-momenta of out going leptons.
J,M,Γ = spin, mass ,total width of $c\bar{c}$ state.
s = cm energy of $\gamma\gamma$ system
$\Gamma_{\gamma\gamma}$ two-photon partial width
q_1,q_2 photon 4-momenta
F = Form Factor describing evolution of cross section.

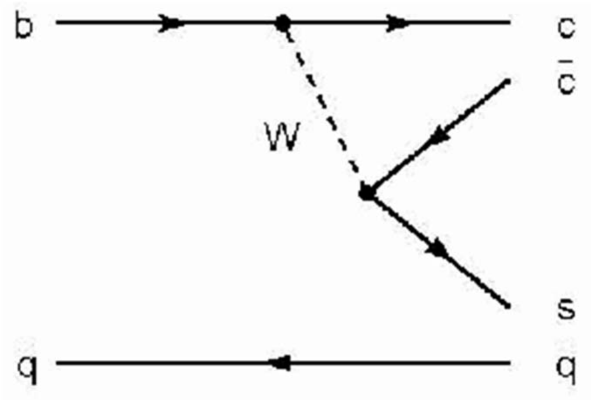
Limititations: knowledge of hadronic branching ratios and form factors used to extract the $\gamma\gamma$ partial width.

Initial State Radiation (ISR)



- Like in direct formation, only $J^{PC}=1^{--}$ states can be formed in ISR.
- This process allows a large mass range to be explored.
- Useful for the measurement of $R = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-)$.
- Can be used to search for new vector states.

B-Meson Decay



$J/\psi,\psi',\psi(3770),\ \eta_c,\eta'_c,\chi_{c0},\chi_{c1},D^{(*)},\ \bar{D}^{(*)},X(3872)$

$K^{\pm},K_S,K_L,K^*(890),K(1270)...$

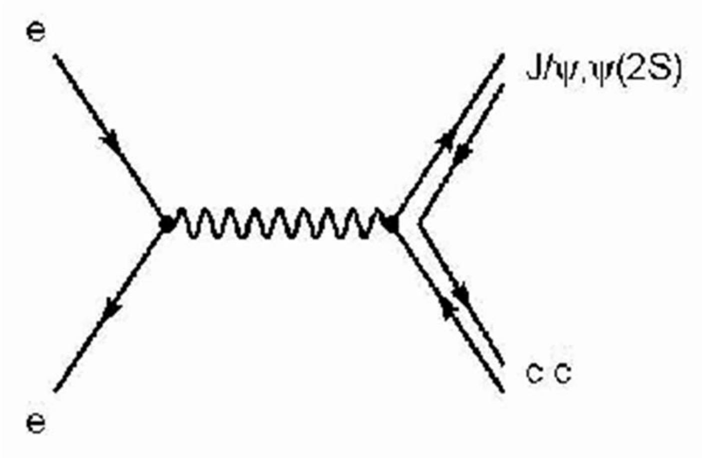
Charmonium states can be produced at the B-factories in the decays of the B-meson.

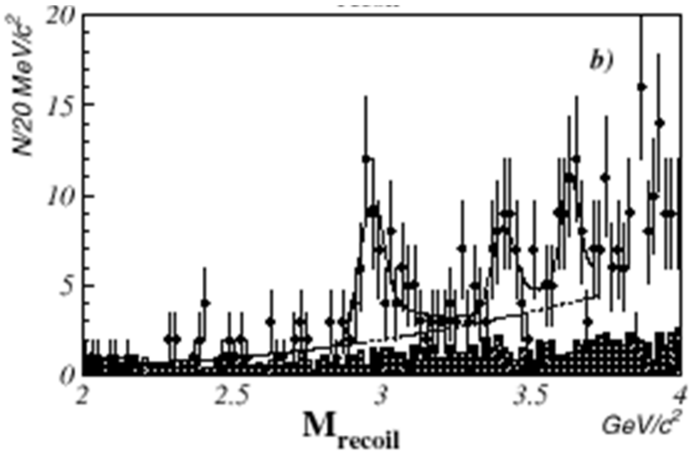
The large data samples available make this a promising approach.

States of any quantum numbers can be produced.

η'_c and X(3872) discoveries illustrate the capabilities of the B-factories for charmonium studies.

Double Charmonium





Discovered by Belle in $e^+e^- \to J/\psi + X$

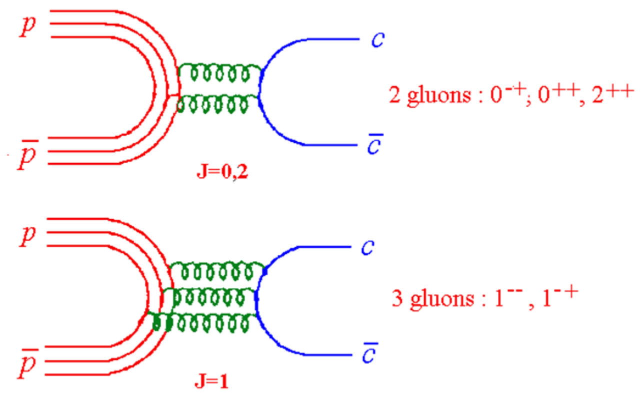
The measured cross section for this process is about one order of magnitude larger than predicted by NRQCD.

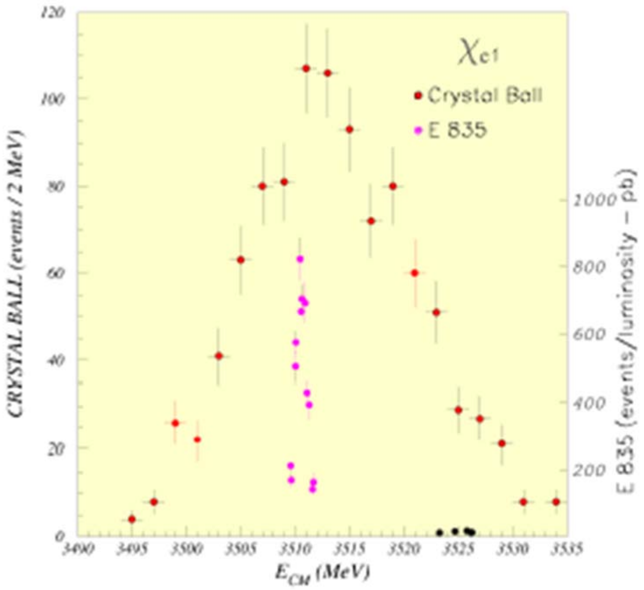
$$\sigma\left(e^+e^- \to J/\psi + \eta_c\right) \times B(\geq 4) = \left(0.033^{+0.007}_{-0.006} \pm 0.009\right) pb$$

Enhances discovery potential of B-factories: states which so far are unobserved might be discovered in the recoil spectra of J/ψ and η_c.

$\bar{p}p$ Annihilation

In $\bar{p}p$ collisions the coherent annihilation of the 3 quarks in the p with the 3 antiquarks in the $\bar{p}$ makes it possible to form directly states with all quantum numbers.





The measurement of masses and widths is very accurate because it depends only on the beam parameters, not on the experimental detector resolution, which determines only the sensitivity to a given final state.

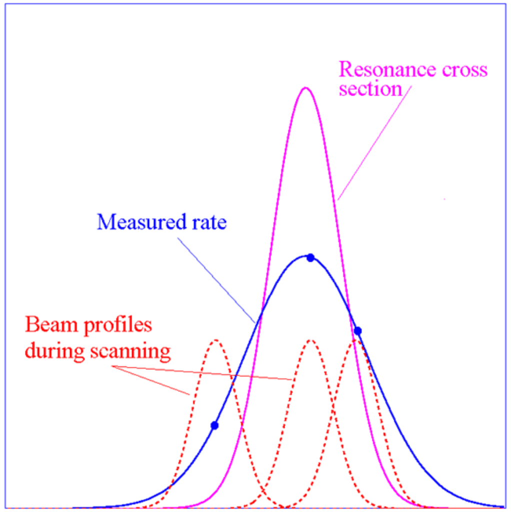
Experimental Method

The cross section for the process:

$$\bar{p}p \rightarrow c\bar{c} \rightarrow \text{final state}$$

is given by the Breit-Wigner formula:

$$\sigma_{BW} = \frac{2J+1}{4} \frac{\pi}{k^2} \frac{B_{in} B_{out} \Gamma_R^2}{(E - M_R)^2 + \Gamma_R^2 / 4}$$



The production rate ν is a convolution of the BW cross section and the beam energy distribution function $f(E,\Delta E)$:

$$\nu = L_0 \left\{ \varepsilon \int dE f(E, \Delta E) \sigma_{BW}(E) + \sigma_b \right\}$$

The resonance mass M_R, total width Γ_R and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy E.

Beam Energy and Width Measurement

In $\bar{p}p$ annihilation the precision in the measurement of mass and width is determined by the precision in the measurement of the beam energy and beam energy width, respectively.

$$E_{cm} = \sqrt{2} m_p (1+\gamma)^2 \qquad \gamma = \frac{E_{beam}}{m_p} = \frac{1}{\sqrt{1-\beta^2}} \qquad \beta = f \cdot L$$

$$\frac{\delta E_{cm}}{E_{cm}} = \frac{\beta^2 \gamma^3}{2(1+\gamma)} \sqrt{\left(\frac{\delta f}{f}\right)^2 + \left(\frac{\delta L}{L}\right)^2}$$

η is a machine parameter which can be measured to ~ 10 %

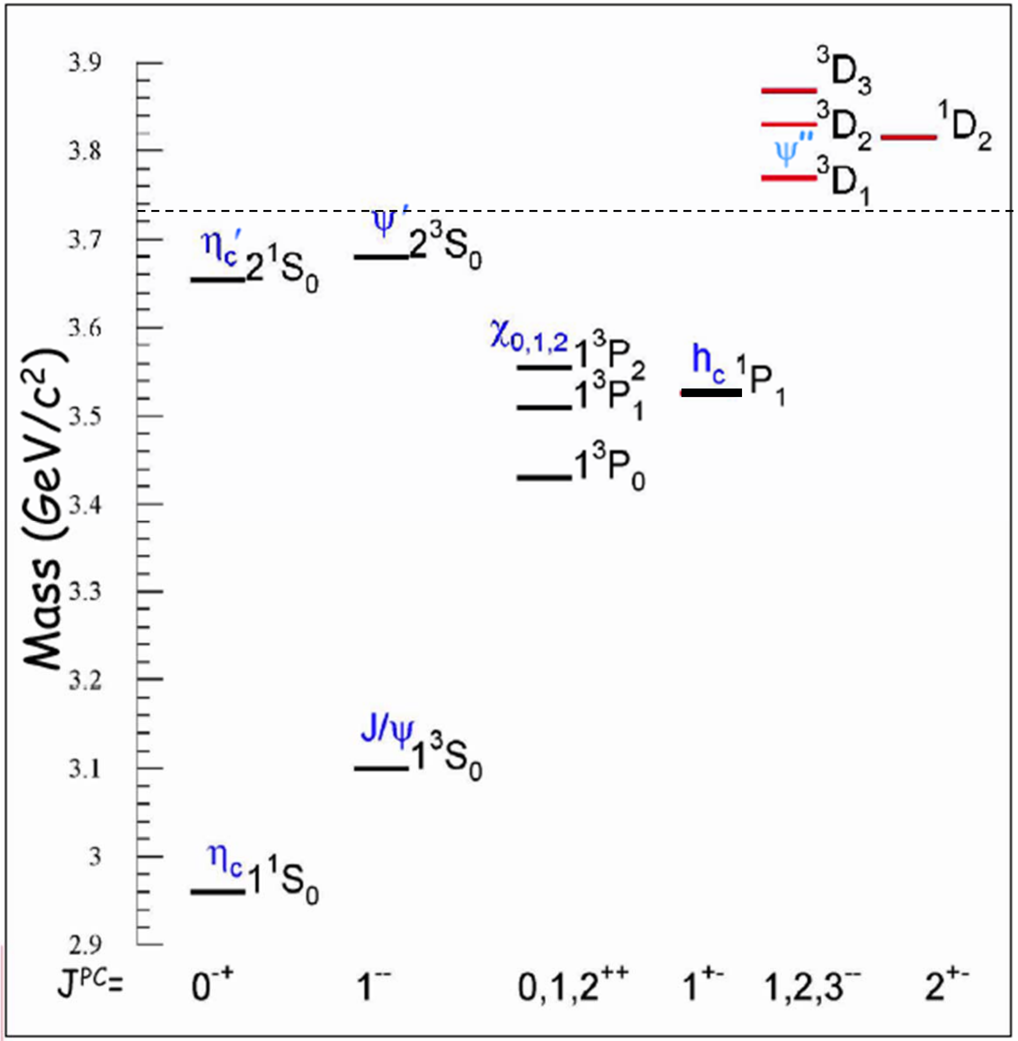
$$\frac{\delta p}{p} = \frac{1}{\eta} \frac{\delta f}{f}$$

The beam revolution frequency *f* can be measured to 1 part in 10^7 from the beam current Schottky noise. In order to measure the orbit length L to the required precision (better than 1 mm) it is necessary to calibrate using the known mass of a resonance, e.g. the ψ′ for which ΔM = 34 keV.

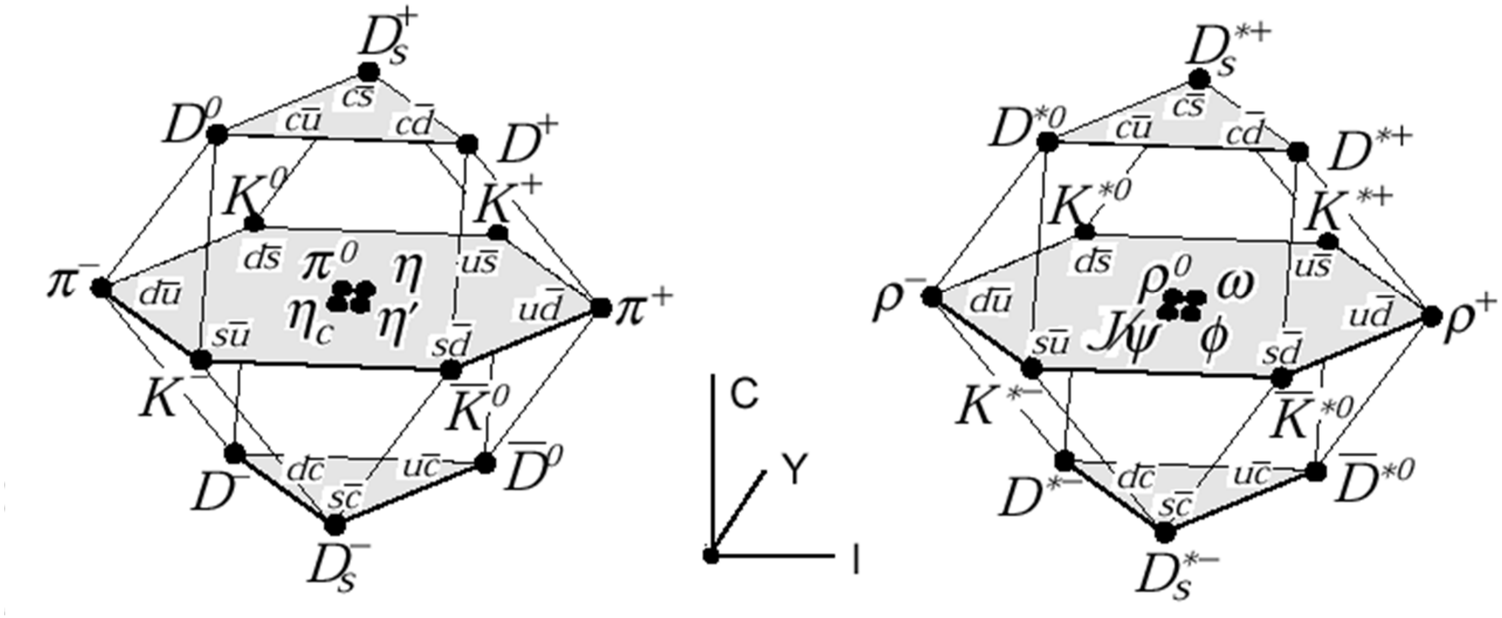
The Charmonium Spectrum

Spectroscopic Notation

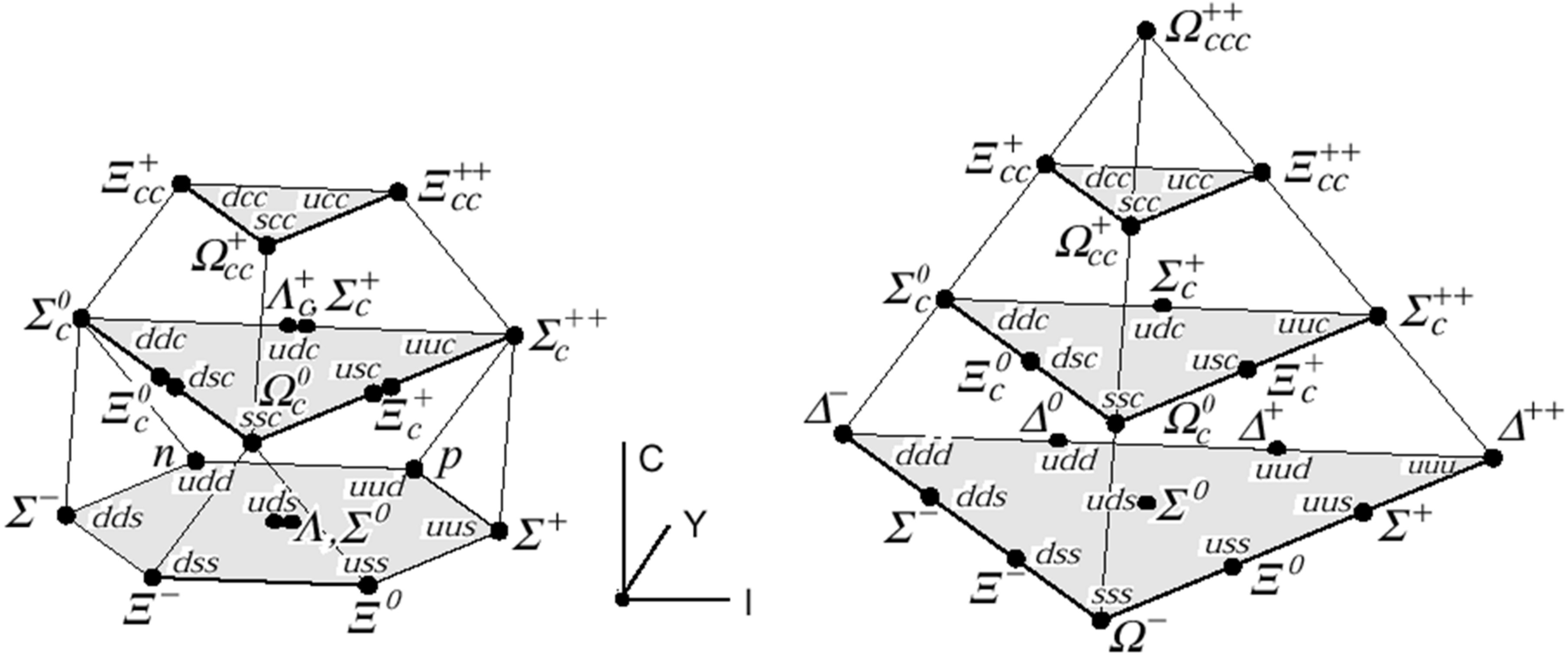
$n^{2S+1}L_J$



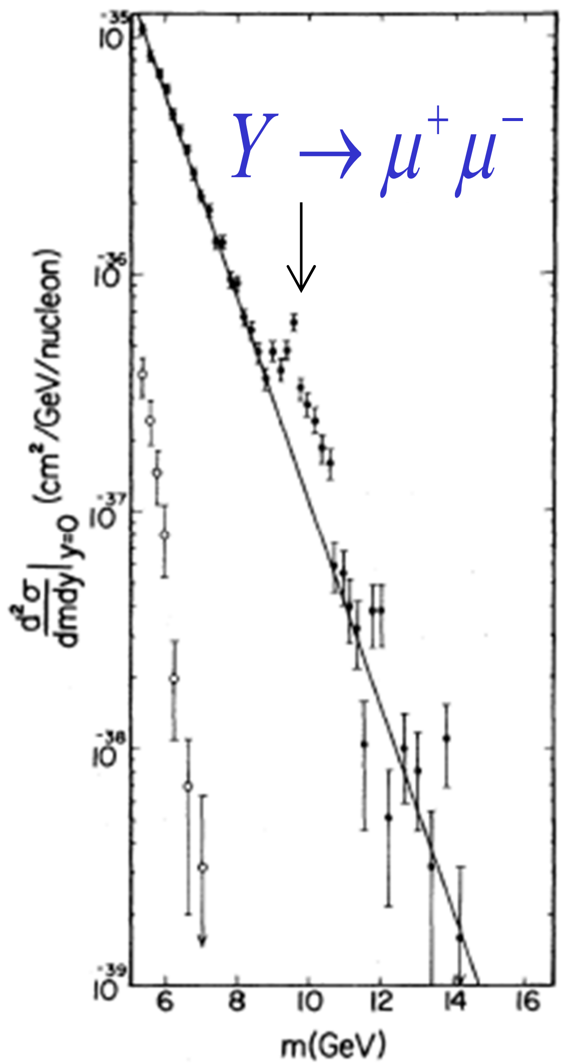
Meson States with 4 Flavours



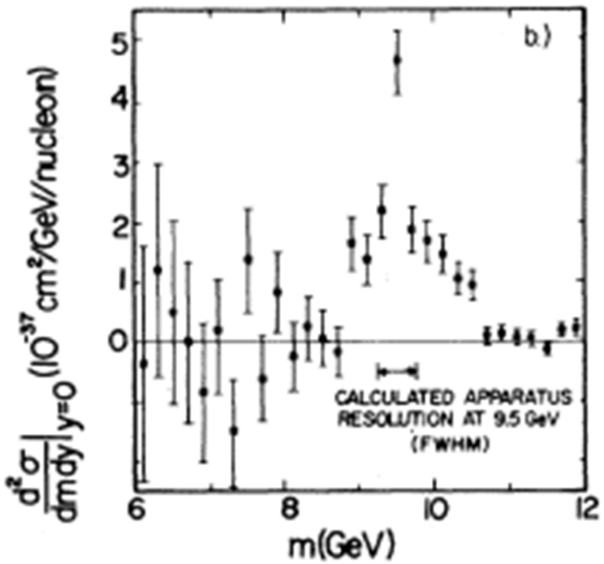
Baryon States with 4 Flavours



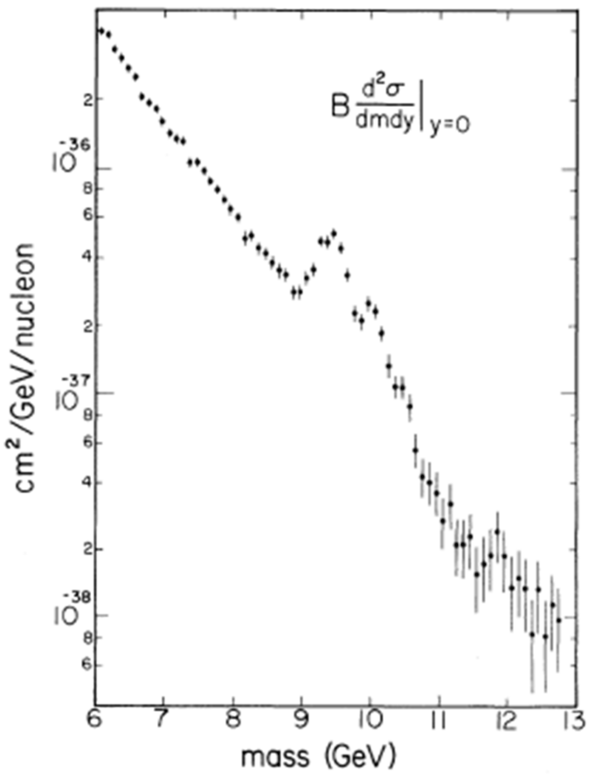
The Discovery of the Bottom (b) Quark



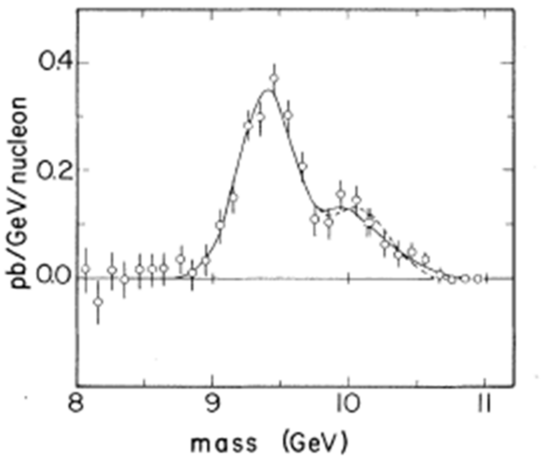
$$p + A \to \mu^+ + \mu^- + X$$



The same data with three times the statistics



Fit with two or three resonances:



	M(MeV/c^2)	Γ(keV)
Υ(1S)	9460.30 $\pm$ 0.26	53.0 $\pm$ 1.5
Υ(2S)	10023.26 $\pm$ 0.31	43 $\pm$ 6
Υ(3S)	10355.2 $\pm$ 0.5	26.3 $\pm$ 3.4