Quarkonium Spectroscopy

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Outline

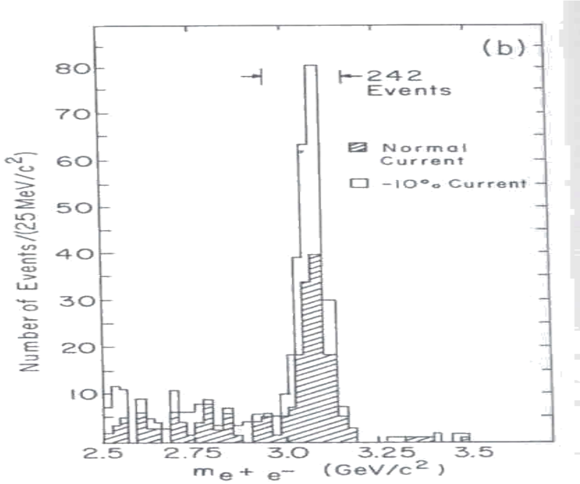
- Discoveries of Charmonium and Bottonium
- Importance of Charmonium and Bottonium
- Analogy to Positronium
- Charmonium and Bottonium Spectra
- Potential Models for Quarkonium
- Charmonium States

Charmonium - The Discovery

In 1974 two experimental groups at BNL and SLAC found a new particle, J/Ψ. Mass ~ 3100 MeV/c^2 , the state was extremely narrow (Γ=91keV).

The BNL group investigated

$p + Be \rightarrow e^+ + e^- + X$



<u>interpretation:</u>

new bound state: cc→ e+e-

At SLAC, cross-sections for

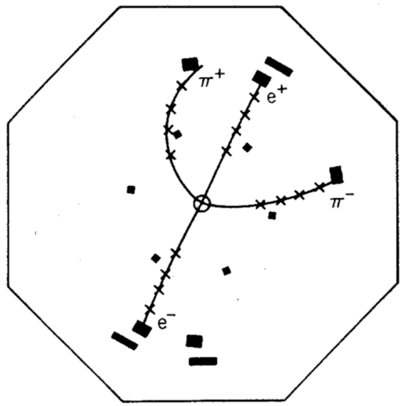
$e^+ + e^- \rightarrow$ hadrons

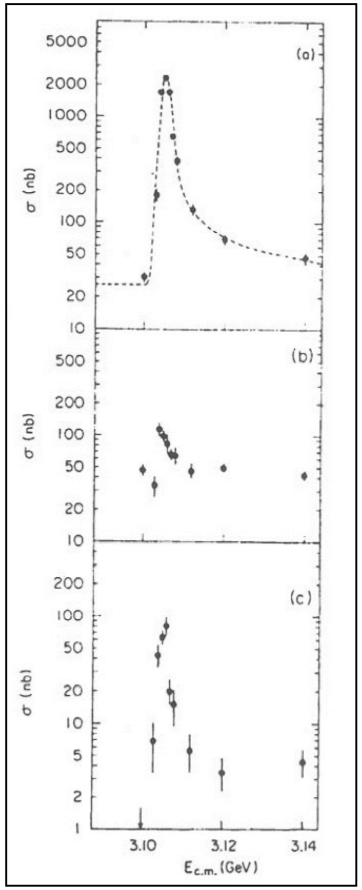
$e^+ + e^- \rightarrow e^+ + e^-$

$e^+ + e^- \rightarrow \mu^+ + \mu^-$

measured

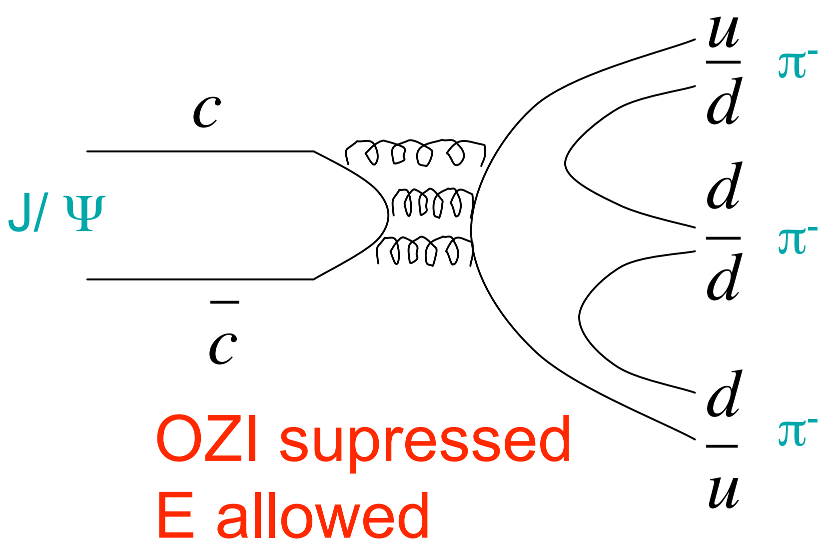
$e^+e^- \rightarrow \Psi' \rightarrow J/\Psi \rightarrow \pi^+\pi^-e^+e^-$

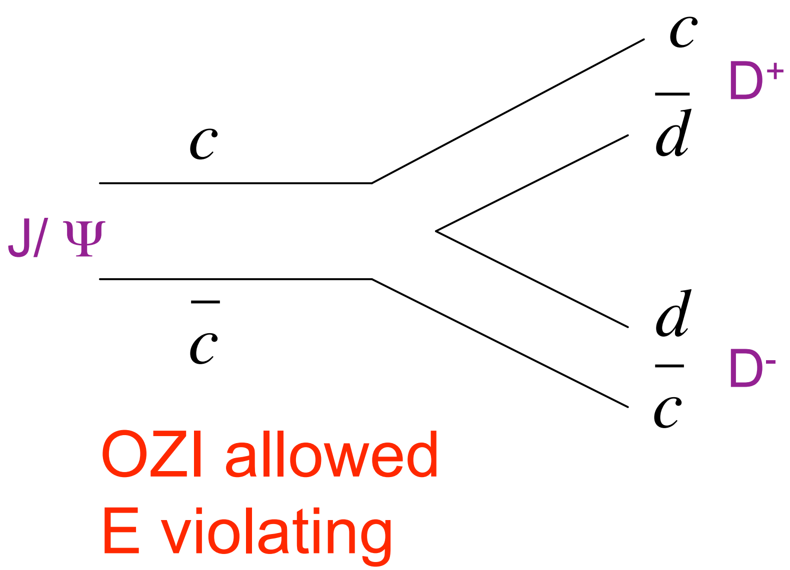




J/ Ψ and Ψ’ formed directly in e^+e^- annihilation → quantum numbers of the photon, $J^{PC} = 1^{--}$. The narrow width led scientists to believe that the state was a $c\bar{c}$ state.

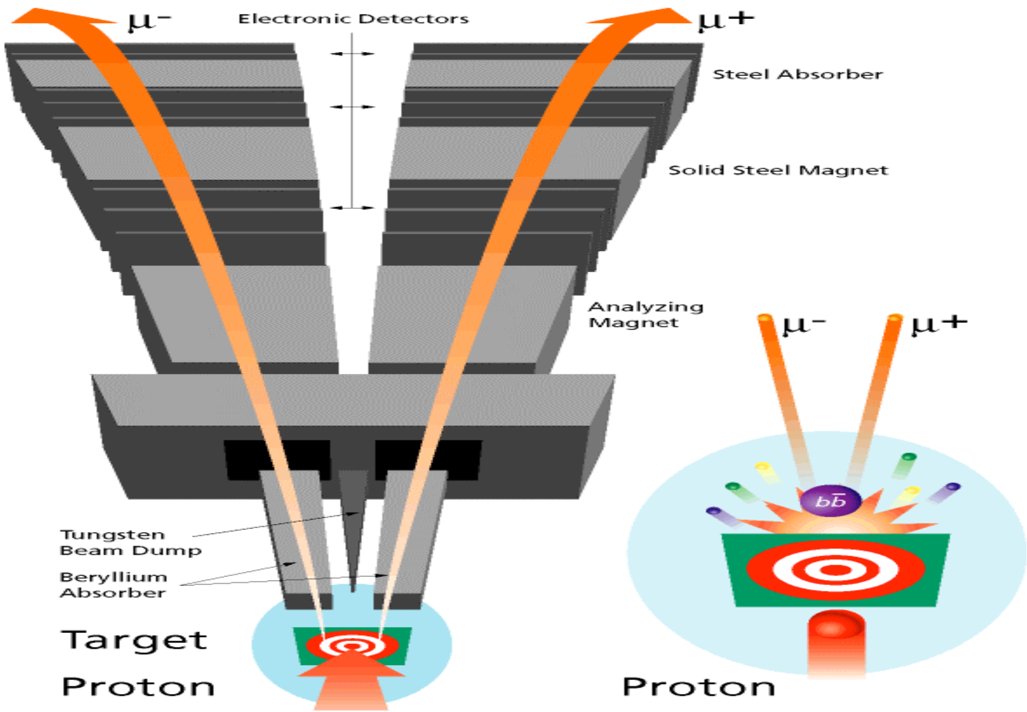
Narrowness of states explained by OZI-rule (decay rates described by diagrams with unconnected quark lines suppressed).





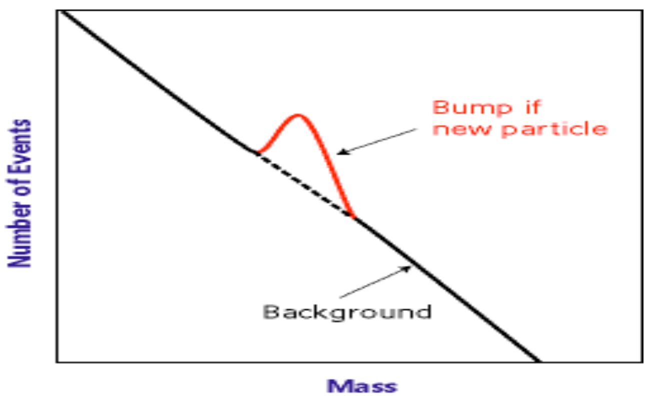
Bottonium - The Discovery

1977 @ Fermilab, Bottonium $p + Be, Cu, Pt \to \mu^+ \mu^- + anything$



Get mass of short lived particles produced with muon pairs by measuring E and direction of muons.

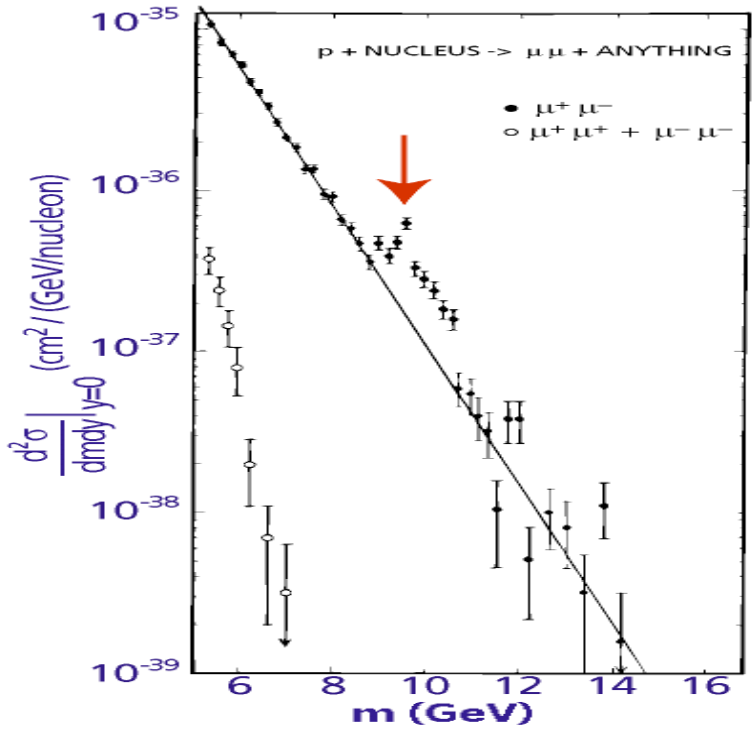
Mass plot of muon pairs will show a bump.



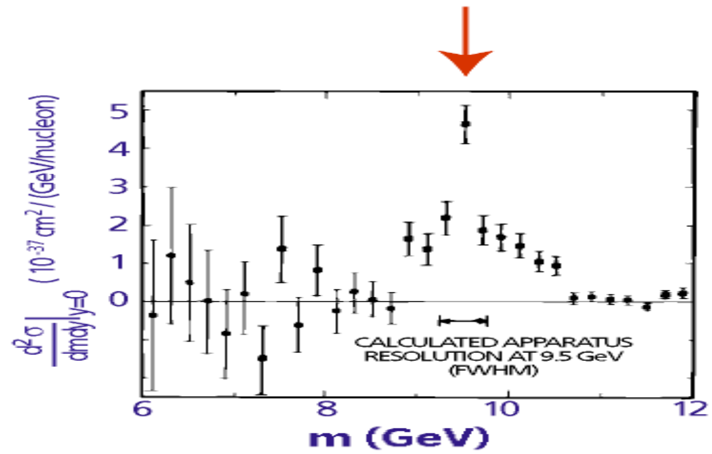
Very broad peak around 10 GeV found (width 1.2 GeV).

Three resonances claimed, at m = 9.4, 10 and 10.4 GeV

(ϒ, ϒ', ϒ'').



Results published in Physical Review Letters August 1, 1977



Why are Charmonium & Bottonium Important?

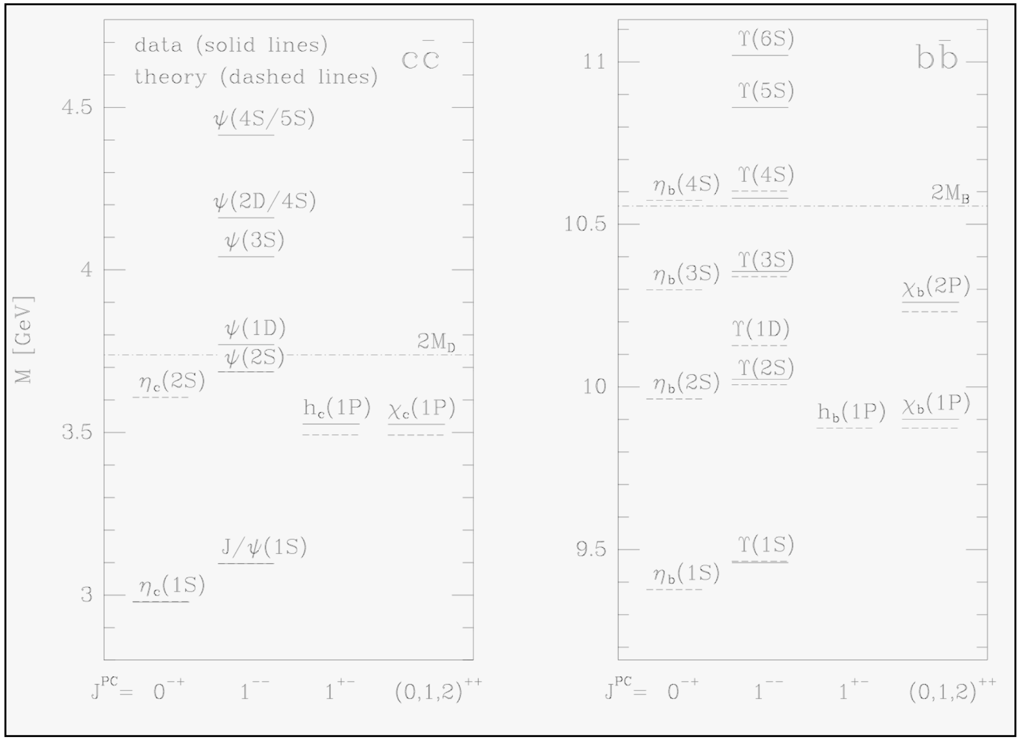
Quark masses large compared to kinetic energy (1.5, 4.5 GeV) → non relativistical treatment (β^2=0.2 and 0.1). Non-relativistic potential models chosen for reproduction of the asymptotic properties of the strong interaction. Non-relativistic correction terms needed.

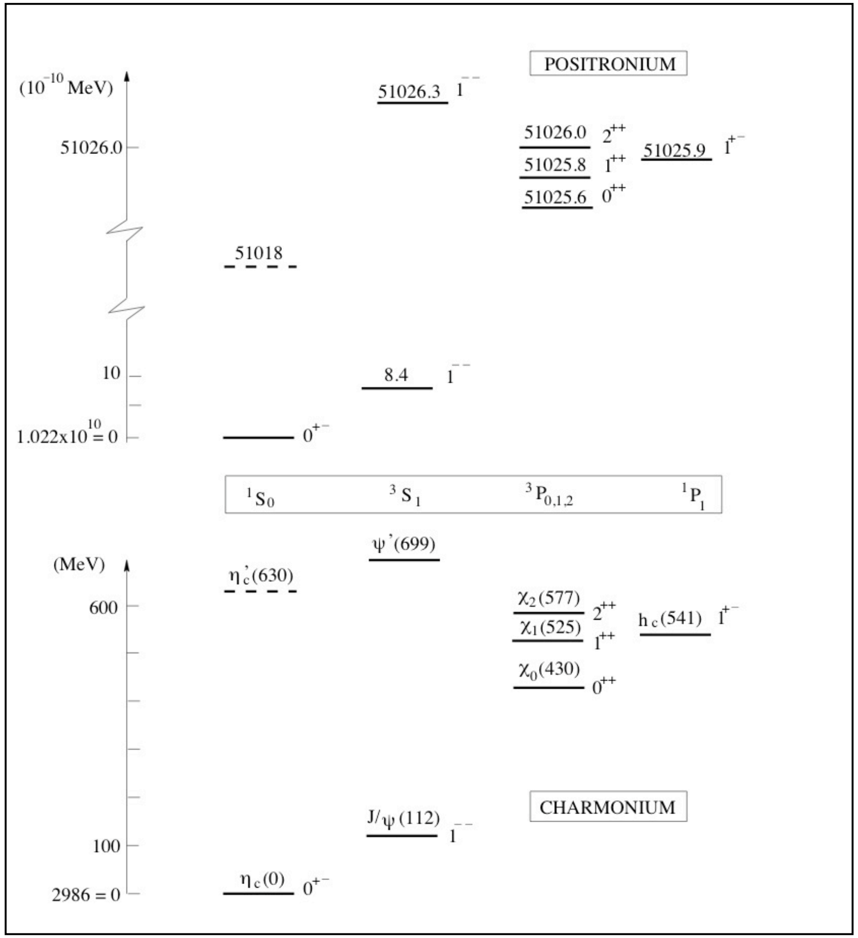
Another interesting property is that the strong coupling constant, α, is approximately 0.25 and 0.16 for $c\bar{c}$ and $b\bar{b}$ respectively → possible to use perturbative QCD (with non-perturbative effects).

Positronium Analogies

Strong analogy to positronium. States labelled by:

- Principal quantum number n
- Angular mom q. n.
  - J $(= \bar{L} + \bar{S})$
  - L (≤n-1)
  - S (=0,1)





Similarities between states

Positronium

n	L	S	J^{PC}	$^{2S+1}L_J$
1	0	0	0^{-+}	$^1S_0$
1	0	1	1^{--}	$^3S_1$
2	0	0	0^{-+}	$^1S_0$
2	0	1	1^{--}	$^3S_1$
2	1	0	1^{+-}	$^1P_1$
2	1	1	2^{++}	$^3P_2$
2	1	1	1^{++}	$^3P_1$
2	1	1	0^{++}	$^3P_0$

Charmonium and Bottonium

n	J^{PC}	$^{2S+1}L_J$	$c\bar{c}$ state	$b\bar{b}$ state
1	0^{-+}	$^1S_0$	$\eta_c(2980)$	—
1	1^{--}	$^3S_1$	$J/\psi(3097)$	$\Upsilon(9460)$
2	0^{-+}	$^1S_0$	—	—
2	1^{--}	$^3S_1$	$\psi(3686)$	$\Upsilon(10023)$
2	0^{++}	$^3P_0$	$\chi_{c0}(3415)$	$\chi_{b0}(9860)$
2	1^{++}	$^3P_1$	$\chi_{c1}(3511)$	$\chi_{b1}(9892)$
2	2^{++}	$^3P_2$	$\chi_{c2}(3556)$	$\chi_{b2}(9913)$
2	1^{+-}	$^1P_1$	—	—

Just like for positronium, connection between radial wave function of lowest lying s-wave state ($R_{L=0}(r) \propto \left(\frac{1}{a_0}\right)^{3/2} e^{\frac{-r}{a_0}}$, a_0=Bohr radius~1/($\alpha\mu$)) and width of states.

For J/Ψ and Υ ($^3S_1$-states):
$$\Gamma(^3S_1 \to 3g) = \frac{5}{18}\frac{\alpha_s^3}{m^2}\frac{4\left(\pi^2 - 9\right)}{9\pi}\left|R_0(0)\right|^2$$

For η_c and η_b ($^1S_0$-states) :
$$\Gamma(^1S_0 \to hadrons) = \frac{2}{3}\frac{\alpha_s^3}{m^2}\left|R_0(0)\right|^2$$

Gluons → hadrons with probability 1 ⇔ equations above describe width of $^3S_1$/$^1S_0$→hadrons. Difference in width for $^3S_1$ and $^1S_0$ in spectrum:

$$\frac{\Gamma(J/\Psi \to light\ \ hadrons)}{\Gamma(\eta_c \to light\ \ hadrons)} = \alpha_S \frac{5\left(\pi^2 - 9\right)^2}{27\pi}$$

Based on non-relativistic potential model.

Quarkonium Potential

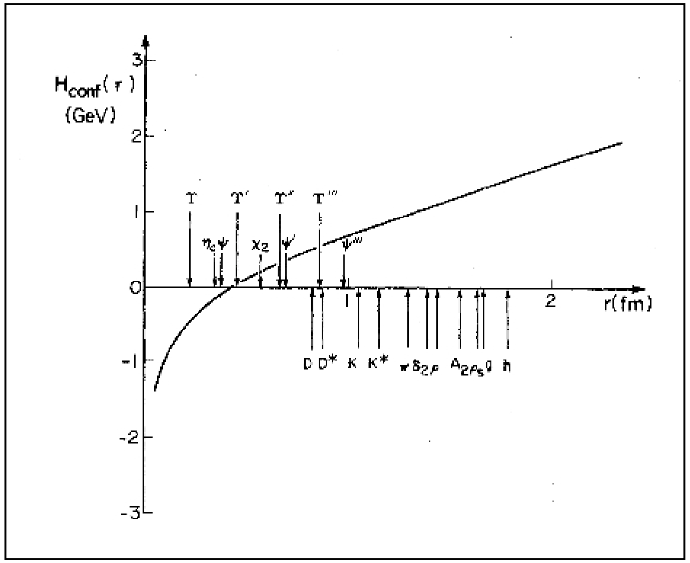
States not well described with only Coulomb pot as for positronium - new potential!

- At small distances: Asymptotic freedom
  The strong force weaker as the energy scale increases, allowing for a perturbative treatment of QCD at high energies. In this regime, the potential is Coulomb like:

$$V(r) = -\frac{4}{3}\frac{\alpha_s(\mu)}{r} \text{ with } \alpha_s(\mu) = \frac{4\pi}{\left(11 - \frac{2}{3}n_f\right)\ln\left(\frac{\mu^2}{\Lambda^2}\right)}$$

- At large distances: Confinement
  The strong force increases with larger distances and confines quarks within hadrons. Linear potential

$$V(r) = kr$$



The sum of the two potentials is called the Cornell potential. V(r) well determined for 0.2 fm ≤ r ≤ 0.8 fm.

Spin Dependent Terms

The spin dependent potential consists of three parts:

- Spin-orbit potential splitting levels with the same orbital angular momentum L but different total spin S (splits the ^3P_J χ states).

$$V_{LS} = \frac{\left(\overline{L} \bullet \overline{S}\right)}{2m_c^2 r}\left(3\frac{dV_V}{dr} - \frac{dV_S}{dr}\right)$$

Index V and S stand for vector and scalar components of the non-relativistic potential.

- Spin-spin which gives the hyperfine splitting, ie the splitting between singlet and triplet states (splitting of J/Ψ, $^3S_1$, and η_c, $^1S_0$)

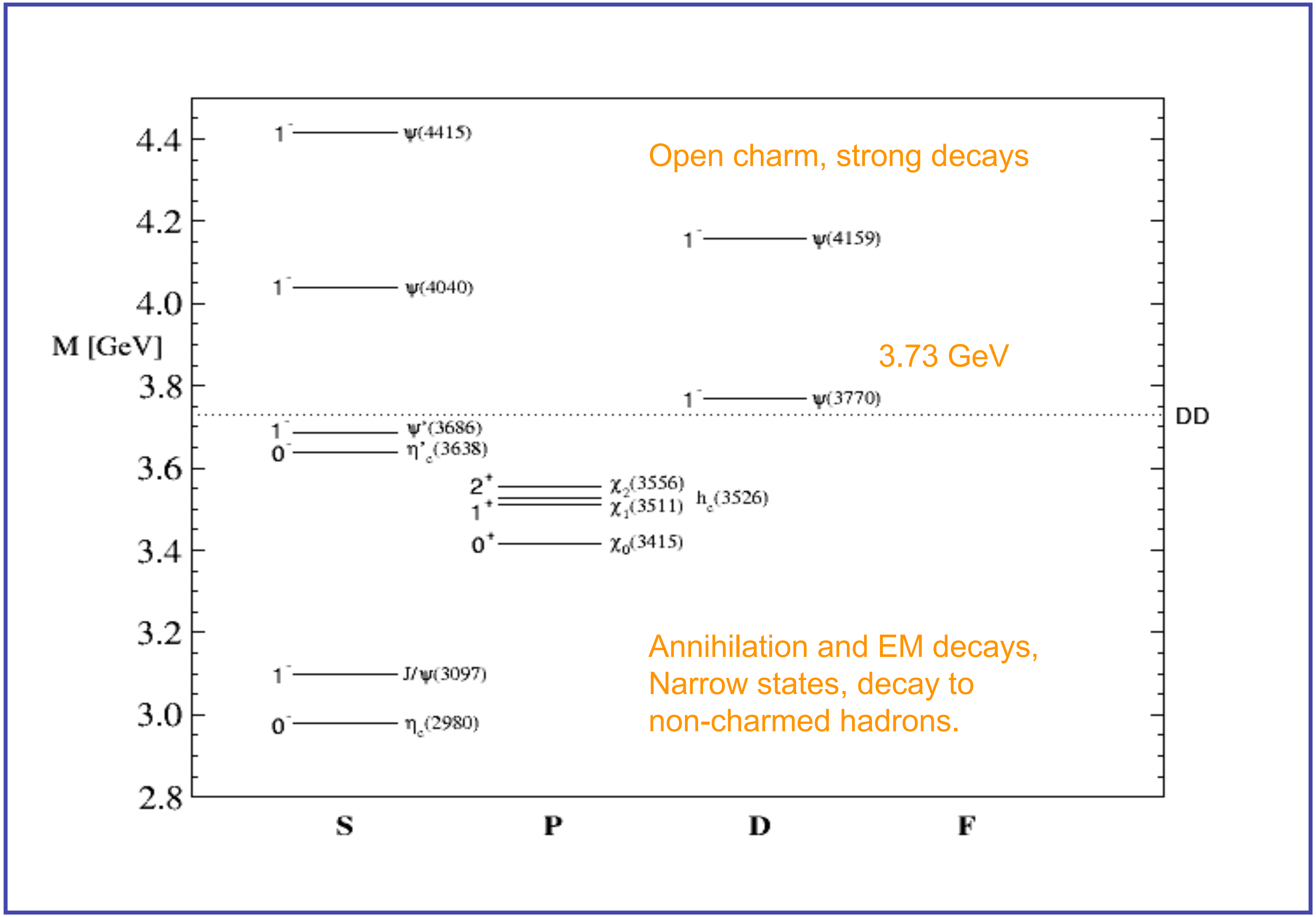
$$V_{SS} = \frac{2\left(\overline{S_1} \bullet \overline{S_2}\right)}{3m_c^2} \cdot \nabla^2 V_V(r)$$

- Tensor interaction term

$$V_T = \frac{2\left(3\left(\overline{S} \bullet \hat{r}\right)\left(\overline{S} \bullet \hat{r}\right) - S^2\right)}{12m_c^2}\left(\frac{1}{r}\frac{dV_V}{dr} - \frac{d^2V_V}{dr^2}\right)$$

Splits the χ states by mixing states with same J^π but different combinations of L and S.

Charmonium Spectrum



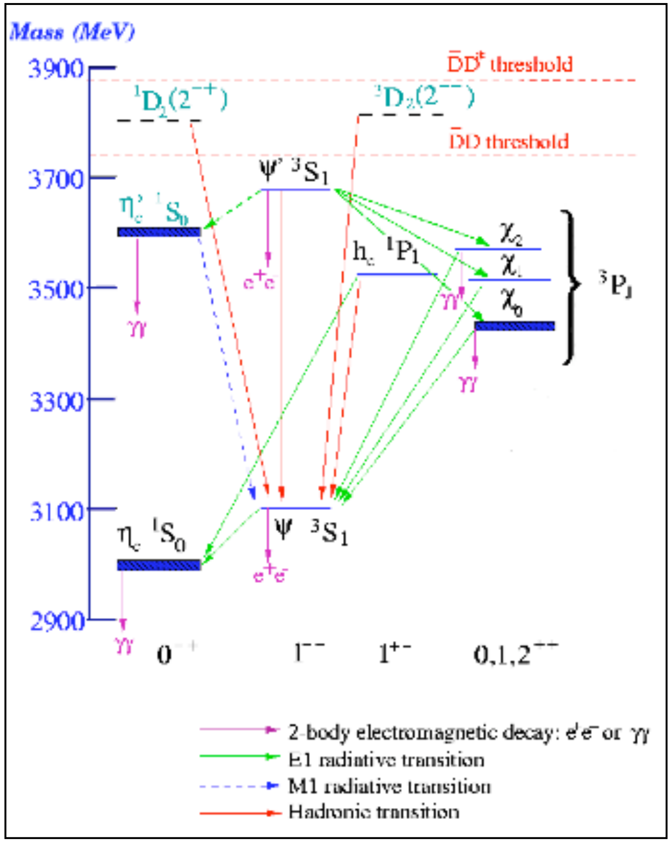
Known (Old) States

Below threshold:

$J/\Psi(3097)$	1^3S_0	1^{--}	1974
$\Psi'(3686)$	2^3S_0	1^{--}	shortly after
$\eta_c(2980)$	1^1S_0	0^{-+}	
$\eta_c'(3638)$	2^1S_0	0^{-+}	2002
$\chi_{c0}(3415)$	$^3P_0$	0^{++}	
$\chi_{c1}(3510)$	$^3P_1$	1^{++}	
$\chi_{c2}(3456)$	$^3P_2$	2^{++}	
$h_c(3526)$	1^1P_1	1^{-+}	1992

Above threshold:

$\psi(3770)$	1^3D_1	1^{--}	1977
$\psi(4040)$	3^3S_1	1^{--}	1978
$\psi(4160)$	$^3S_1$	1^{--}	1978
$\psi(4415)$	$^3S_1$	1^{--}	1978



Most recent:

Belle 2003: $B^{\pm} \to$ X(3872) $\to K^{\pm}(\pi^+ \pi^- J/\Psi)$. No assignment.
Molecule, diquark-antidiquark, hybrid?

Belle 2005: $e^+e^- \to$ X(3943)=η_c'' $\to J/\Psi\, \bar{D}D^*$ 3^1S_0?
χ_{c1}', η_c'', η_{c2}?

Belle 2004: $B \to K$Y(3943)=χ'_{c1}?, $Y \to \omega J/\Psi$. 2^3P_1?
Above $\bar{D}D^*$ thresh, but no $\bar{D}D^*$ or $D\bar{D}$ decay! ccg?

Belle 2005: $\gamma\gamma \to$ Z(3931)=χ'_{c2}? $\to D\bar{D}$

BaBar/CLEO 2005: $e^+e^- \to$ Y(4260) $\to \pi^+ \pi^- J/\Psi$. Glueball? 4q? Hybrid?
$\omega\chi_{c1}$-molecule?