APPLICATION OF HIGH QUALITY ANTIPROTON BEAM WITH MOMENTUM RANGING FROM 1 GeV/c TO 15 GeV/c TO STUDY CHARMONIUM AND EXOTICS

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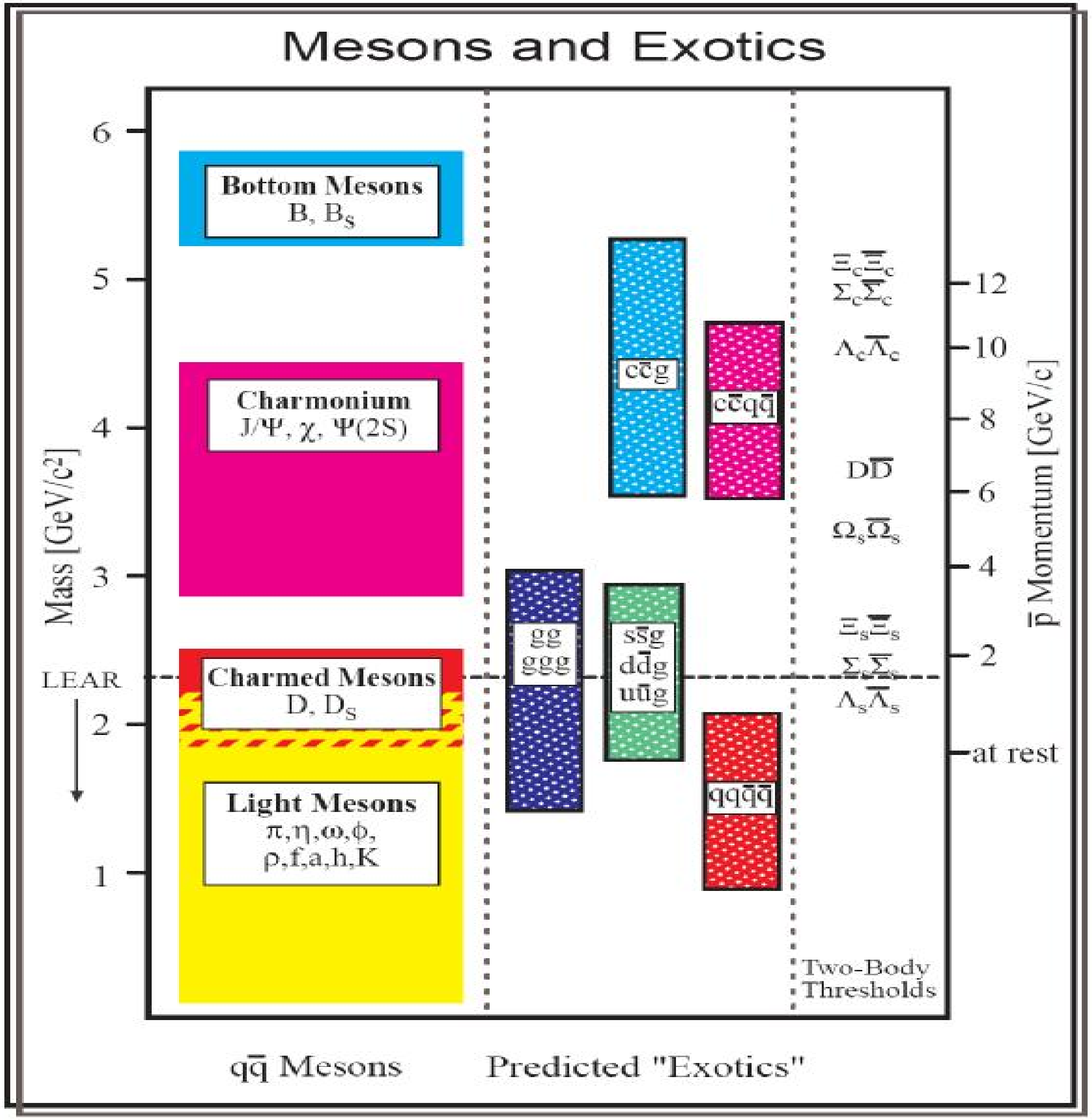
WHY WE CONCENTRATE ON PHYSICS WITH ANTIPROTONS:



Ulrich Wiedner

Expected masses of $\overline{q}q$-mesons, glueballs, hybrids and two-body production thresholds.

PREAMBLE

1. STUDY OF THE MAIN CHARACTERISTICS OF CHARMONIUM & CHARMED HYBRIDS SPECTRUM (MASS, WIDTH & BRANCH RATIOS) BASED ON THE QUARKONIUM POTENTIAL MODEL AND RELATIVISTIC TOP MODEL FOR CHARMONIUM DECAY PRODUCTS.

2. ANALYSIS OF SPECTRUM OF SCALAR AND VECTOR CHARMONIUM STATES IN MASS REGION OVER D$\bar{D}$-THRESHOLD. A BRIEF REVIEW OF THE NEW *XYZ*-CHARMONIUMLIKE MESON STATES AND ATTEMPTS OF THEIR POSSIBLE INTERPRETATION. THE EXPERIMENTAL DATA FROM DIFFERENT COLLABORATIONS (CLEO, CDF, BELLE & BABAR) WERE ELABORATELY ANALIZED.

3. DISCUSSION OF THE RESULTS OF CULCULATION FOR THE RADIAL EXCITED SCALAR AND VECTOR STATES OF CHARMONIUM AND THEIR COMPARISON WITH THE RECENTLY REVEALED EXPERIMENTAL DATA OVER D$\bar{D}$-THRESHOLD.

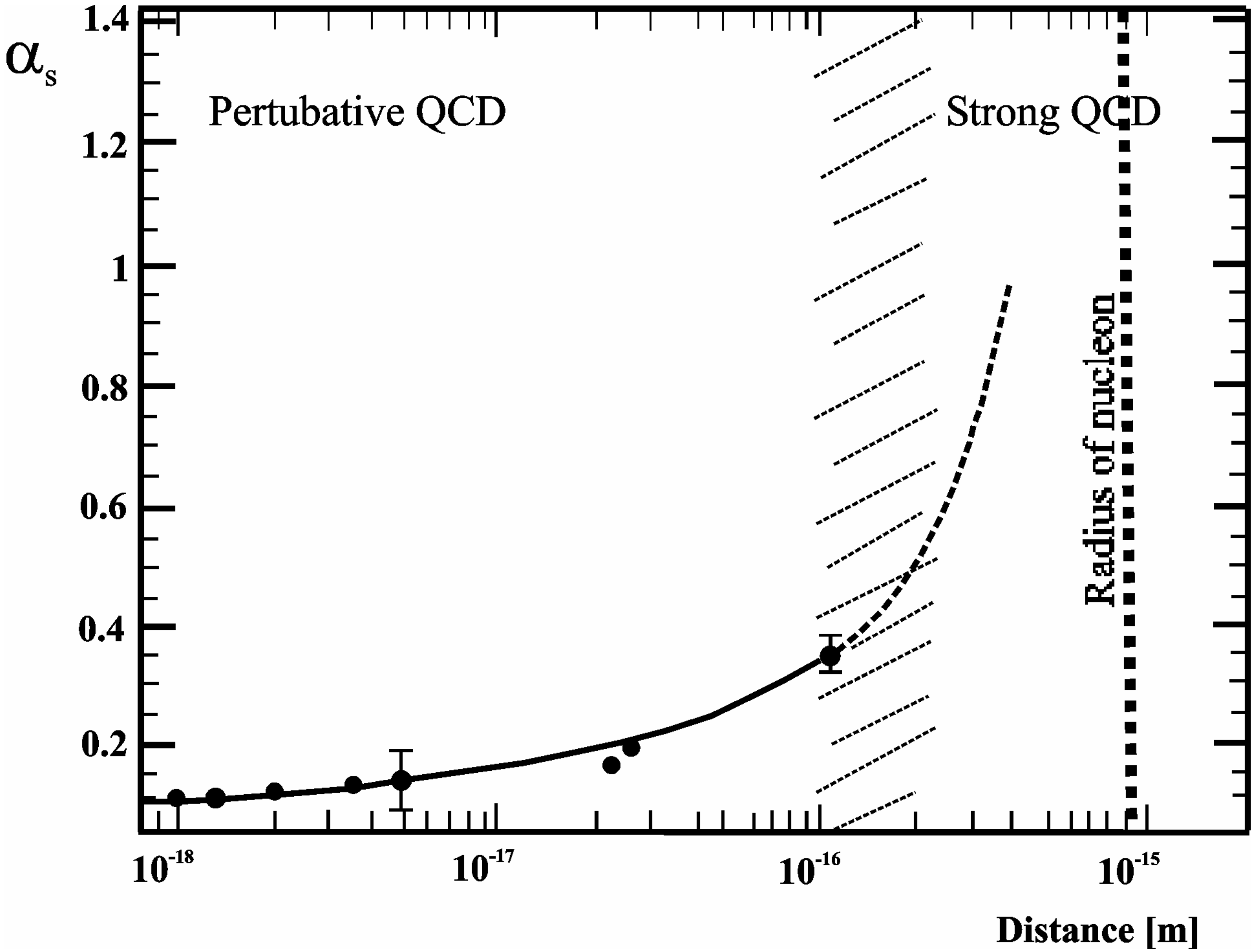
4. APPLICATION OF THE INTEGRAL FORMALISM FOR DECAY OF HADRON RESONANCES TO CALCULATE THE WIDTHS OF CHARMONIUM AND CHARMED HYBRIDS. ANALYSIS OF THE RESULTS OF CALCULATION FOR THE WIDTHS OF SCALAR AND VECTOR CHARMONIUM STATES IN THE FRAMEWORK OF INTEGRAL FORMALISM.

Why is charmonium chosen!?
Charmonium possesses some well favored characteristics:

- Charmonium – is the simplest two-particle system consisting of quark & antiquark;
- Charmonium – is a compact bound system with small widths varying from several tens of keV to several tens of MeV compared to the light unflavored mesons and baryons;
- Charm quark *c* has a large mass (1.27 ± 0.07 GeV) compared to the masses of *u, d* & *s* (~ 0.1 GeV) quarks, that makes it plausible to attempt a description of the dynamical properties of $c\bar{c}$ – system in terms of non-relativistic potential models, where the functional form of potential is chosen to reproduce the assymptotic properties of strong interaction;
- Quark motion velocities in charmonium are non-relativistic (the coupling constant, $\alpha_s \approx 0.3$ is not too large, and relativistic effects are manageable ($v^2/c^2 \approx 0.2$));
- The size of charmonium is of the order of less than 1 Fm $(R_{c\bar{c}} \sim \alpha_s \cdot m_q)$ so that one of the main doctrines of QCD – asymptotic freedom is emerging;

<u>Therefore</u>:

- ■ charmonium studies are promising for understanding the dynamics of quark interaction at small distances;
- ■ charmonium spectroscopy is a good testing ground for the theories of strong interactions:
    - QCD in both perturbative and nonperturbative regimes
    - QCD inspired purely phenomenological potential models
    - non-relativistic QCD and Lattice QCD



Coupling strength between two quarks as a function of their distance. For small distances ($\leq 10^{-16}\ m$) the strengths α_s is ≈ 0.1, allowing a theoretical description by perturbative QCD. For distances comparable to the size of the nucleon, the strength becomes so large (strong QCD) that quarks can not be further separated: they remain confined within the nucleon. For charmonium states $\alpha_s \approx 0.3$ and $\langle v^2/c^2 \rangle \approx 0.2$.

In QCD-motivated quark potential models, quarkonium states are described as a quark-antiquark pair bound by an inter-quark force (potential) that includes a Coulomb-like one-gluon exchange potential dominates at small separation and a linearly increasing confining potential dominates at large separation.

The energy levels are found by solving a non-relativistic Schrodinger equation:

$$-\frac{\hbar^2}{2m}\nabla^2\psi(\vec{r})+\{V(\vec{r})-E\}\psi(\vec{r})=0.$$

In central symmetric potential field *V(r)* the Schrodinger-type equation can be written:

$$U''(r)+\frac{2m}{\hbar^2}\{E-V(r)-\frac{l(l+1)\hbar^2}{2mr^2}\}U(r)=0$$

where *U(0) = 0* and *U' (0) = R(0),* and *U(r) = rR(r),* $m_c \approx m_{\bar{c}} \approx 1.27$ GeV, *R(r)* – radial wave function, *r* – distance between quark and antiquark in quarkonium.

These properties underlie the choice most of potentials: $\begin{cases} V(r)\big|_{r\to 0} \sim 1/r & \text{or } \dfrac{1}{r\ln(1/r\Lambda)} \\ V(r)\big|_{r\to\infty} \sim kr \end{cases}$

The Cornel potential: $V(r) = -a/r + kr$; $a = 0.52$ GeV; $k = 0.18$ GeV.

The orbital levels are labeled by *S, P, D,…* corresponding to *L = 0,1,2,….* The quark and antiquark spins couple to give the total spin *S = 0* (scalar) or *S = 1* (vector). Whole momentum of quark-antiquark system *J = L+S.* Quarkonium states are generally denote by $^{2S+1}L_J$ with quantum numbers J^{PC}, where parity $P = (-1)^{L+1}$ and charge parity $C = (-1)^{L+S}$.

* A.A. Bykov et al. Physics – Uspekhi, V.143, N1, 1 (1984)

The quark potential models have successfully described the charmonium spectrum, which generally assumes short-range coulomb interaction and long-range linear confining interaction plus spin dependent part coming from one gluon exchange and the confining interaction. The zero-order Hamiltonian is:

$$H_0 = \frac{p^2}{m_c} - \frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\,\tilde{\delta}_\sigma(r)\,\mathbf{S}_c \cdot \mathbf{S}_{\bar{c}}$$

where $\tilde{\delta}_\sigma(r) = (\sigma/\sqrt{\pi})^3\ e^{-\sigma^2 r^2}$ which is a gaussian-smeared hyperfine interaction. Solution of this equation with above H_0 gives the zero order charmonium wavefunctions.

**T. Barnes, S. Godfrey, E. Swangon, Phys. Rev. D 72, 054026 (2005), hep-ph/ 0505002.*

The splitting between the multiplets is determined by taking the matrix element of the H_{sd} taken from one-gluon exchange Breit-Fermi-Hamiltonian between zero-order wavefunctions:

$$H_{sd} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\mathbf{L}\cdot\mathbf{S} + \frac{4\alpha_s}{r^3}\mathbf{T}\right]$$

where α_s - coupling constant, *b* - string tension, s - hyperfine interaction smear parameter.

Izmestev A. has shown **Nucl. Phys., V.52, N.6 (1990) & *Nucl. Phys., V.53, N.5 (1991)* that in the case of curved coordinate space with radius *a* (confinement radius) and dimension *N* at the dominant time component of the gluonic potential the quark-antiquark potential defines via Gauss equations. If space of physical system is compact (sphere S^3), the harmonic potential assures confinement:

$$\Delta V_N(\vec{r}) = \mathrm{const}\ G_N^{-1/2}(r)\,\delta(\vec{r}), \quad V_N(r) = V_0 \int D(r) R^{1-N}(r)\,dr/r, \ V_0 = \mathrm{const} > 0.$$

$$R(r) = \sin(r/a),\ D(r) = r/a, \qquad V_3(r) = -V_0\,\mathrm{ctg}(r/a) + B, \qquad V_0 > 0, \qquad B > 0.$$

When cotangent argument in $V_3(r)$ is small: $r^2/a^2 << p^2$,

we get: $ctg(r/a) \approx a/r - r/3a$,

where *R(r), D(r)* and $G_N(r)$ are scaling factor, gauging and determinant of metric tensor $G_{\mu\nu}(r)$.

Let us define the set of generators of *SO*(4) group → $\vec{M} = [\vec{r} \times \vec{p}];\ \vec{N} = r_4 \vec{p} - \vec{r} p_4$

where $\vec{r}$ and $\vec{p}$ are coordinate and momentum operators, $\vec{M}$ is angular momentum operator.

Dilatation operator $\vec{N}$ defined on the sphere S^3 has the form → $\vec{N} = R\vec{p} + \vec{r}(\vec{r}, \vec{p})/R$

The linear combinations of these orthonormal operators → $\vec{m}_\pm = (\vec{M} \pm \vec{N})$

contribute two set of generators of the SU(2) group. Thus the *SU*(2) group generates the action on a three-dimensional sphere S^3. This action consists of the translation with whirling around the direction of translation. We get a Hamiltonian:

$$H = \frac{1}{2mR^2}\{2\hbar + (\vec{m}_\pm, \vec{s})\}\{2\hbar + (\vec{m}_\pm, \vec{s})\}$$

where $\vec{s}$ - spin operator, *m* - mass of the top.

When radius of the sphere: $R \to \infty$ → $\vec{m}_\pm / R = (\vec{M} \pm \vec{N})/R \to \pm \vec{p}$

the Hamiltonian tends to the Pauli operator for the free particle motion: $H = \frac{1}{2mR^2}\{2\hbar + (\vec{m}_\pm, \vec{s})\}\{2\hbar + (\vec{m}_\pm, \vec{s})\} \to \frac{1}{2m}(\vec{p}, \vec{s})^2.$

The spectrum is:

$$H\Psi_n = \frac{\hbar^2}{2mR^2}(n+1)^2\Psi_n,\ n = 0, 1, 2...$$

The wave function:

$$\Psi_n = |LSJM_J\rangle$$

was taken as eigenfunction of total momentum → $\vec{J}^2 = ((\vec{m}_\pm + \vec{s})/2)^2$ of the top.

* Advances in Applied Clifford Algebras, V.8, N.2, p.235-254 (1998) & V.8, N.2, p.255-270 (1998) .

In the framework of this approach in the relativistic case the Hamiltonian of a decaying resonance is defined with the equation ($R \to a + b$ is a binary decay channel):

$$H = \sqrt{m_a^2 + \frac{1}{R^2}\left(\left(\vec{\mu}_{\pm},\vec{\sigma}\right)+2\hbar\right)^2} + \sqrt{m_b^2 + \frac{1}{R^2}\left(\left(\vec{\mu}_{\pm},\vec{\sigma}\right)+2\hbar\right)^2}$$

were m_a and m_b are the masses of resonance decay products (particles a and b).
The spectrum of the Hamiltonian is:

$$E = \sqrt{m_a^2 + \frac{\hbar^2(n+1)^2}{R^2}} + \sqrt{m_b^2 + \frac{\hbar^2(n+1)^2}{R^2}}, \quad n = 0, 1, 2...$$

Finally, the formula for resonance mass spectrum can be written in the following form (we used the system in which $\hbar = c = 1$):

$$E = M_{th} = \sqrt{m_a^2 + P_n^2} + \sqrt{m_b^2 + P_n^2} = \sqrt{m_a^2 + (nP_0)^2} + \sqrt{m_b^2 + (nP_0)^2} =$$

$$= \sqrt{m_a^2 + \left[\frac{n}{R_0}\right]^2} + \sqrt{m_b^2 + \left[\frac{n}{R_0}\right]^2}$$

where P_0 – is the basic momentum. The momentum of relative motion of decay products P_n (particles a and b in the center-of-mass system of decaying resonance) is quantized relatively P_0. R_0 is the parameter with dimension of the length conjugated to P_0.

The $c\bar{c}$ system has been investigated in great detail first in e^+e^--reactions, and afterwards on a restricted scale ($E_{\bar{p}} \leq 9$ GeV), but with high precision in $\bar{p}p$-annihilation (the experiments R704 at CERN and E760/E835 at Fermilab).

The number of unsolved questions related to charmonium has remained:

- **scalar $^1D_2$ and vector ^3D_J charmonium states are not determined yet;**
- **higher laying scalar $^1S_0$, $^1P_1$ and vector $^3S_1$, ^3P_J – charmonium states are poorly investigated;**
- only few partial widths of ^3P_J-states are known (some of the measured decay widths don't fit theoretical schemes and additional experimental check or reconsideration of the corresponding theoretical models is needed, more data on different decay modes are desirable to clarify the situation);
- the domain over $D\bar{D}$ - threshold of 3.73 GeV/c^2 is poorly studied.

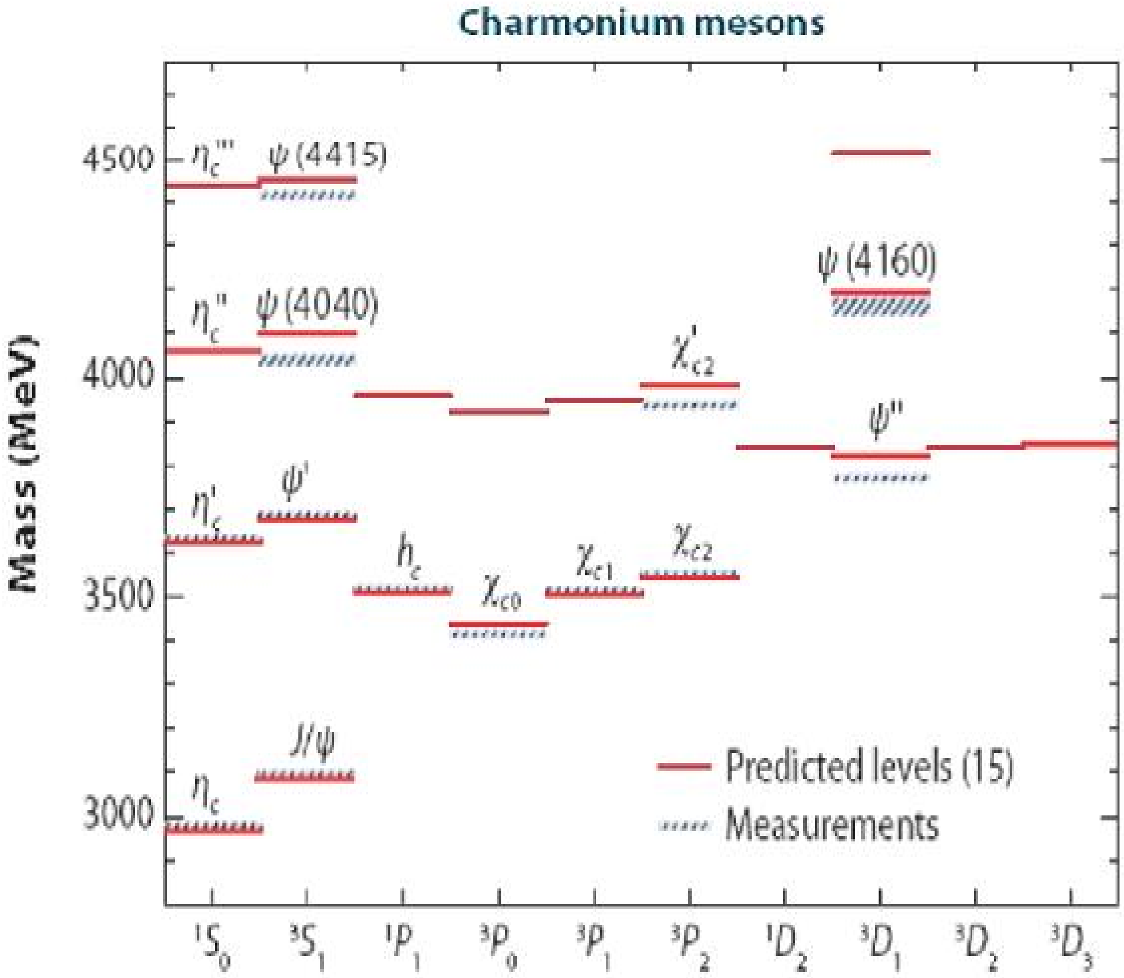
AS RESULT:

- **little is known on charmonium states above the the $D\bar{D}$ – threshold (S, P, D,….);**
- **many recently discovered states above $D\bar{D}$ - threshold (*XYZ*-states) expect their verification and explanation (their interpretation now is far from being obvious).**

IN GENERAL ONE CAN IDENTIFY FOUR MAIN CLASSES OF CHARMONIUM DECAYS:

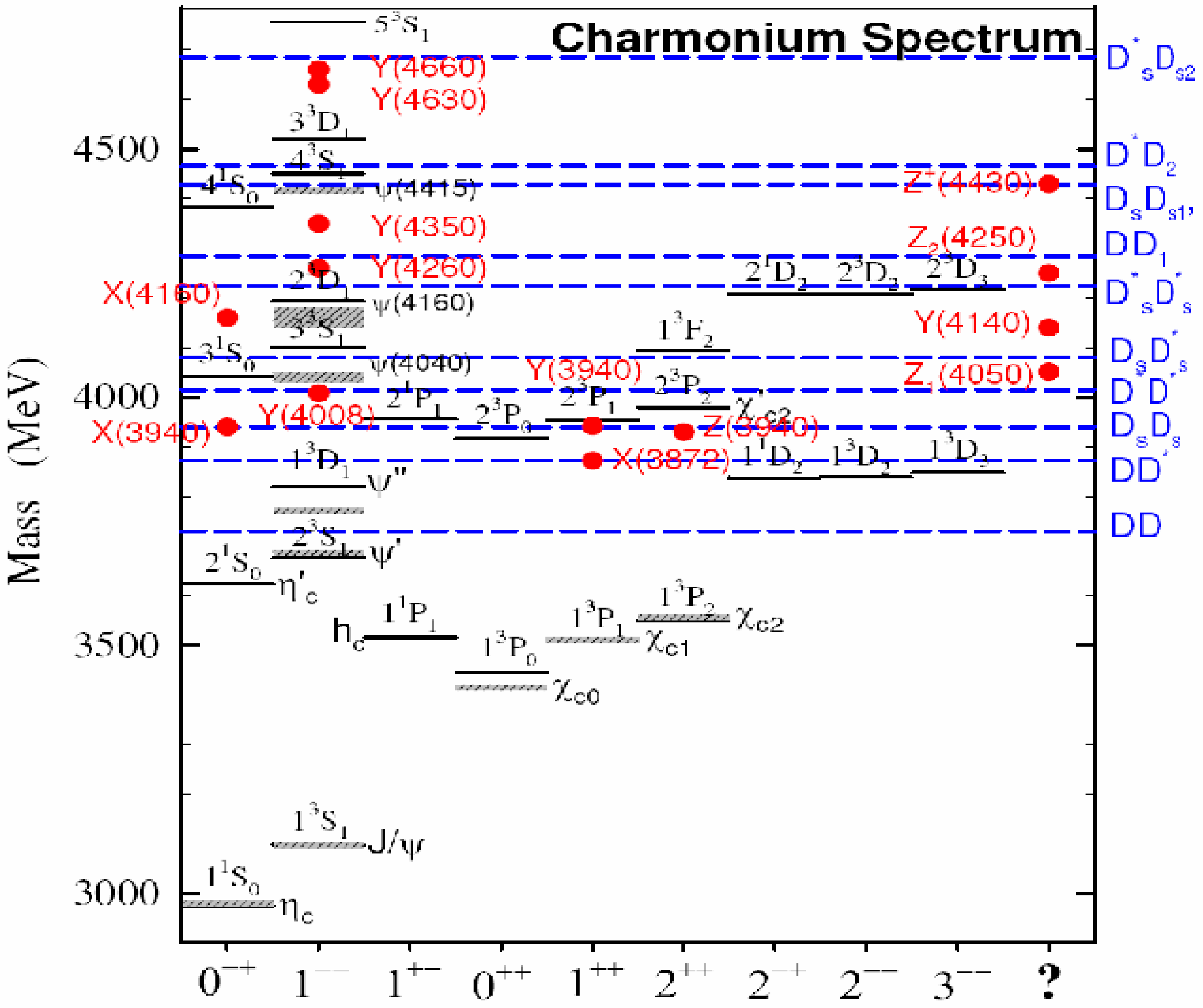
- decays into particle-antiparticle or $D\bar{D}$-pair: $\bar{p}p \rightarrow (\Psi, \eta_{c'}, \chi_{cJ}) \rightarrow$ barion-antibaryon or $D\bar{D}$
- decays into light hadrons: $\bar{p}p \rightarrow (\Psi, \eta_c) \rightarrow \rho\pi$; $\bar{p}p \rightarrow \Psi \rightarrow \pi^+\pi^-$, $\bar{p}p \rightarrow \Psi \rightarrow \omega\pi^0$,…
- radiative decays: $\bar{p}p \rightarrow \gamma\eta_c, \gamma\chi_{cJ}$ …; (are employed for $h_{c'}$, η_c and their radial excitations study)
- decays with J/Ψ in the final state: $\bar{p}p \rightarrow J/\Psi + X \Rightarrow \bar{p}p \rightarrow J/\Psi\,\pi^+\pi^-$, $\bar{p}p \rightarrow J/\Psi\,\pi^0\pi^0$ (are employed mainly to study χ_{cJ} and radial excitations of Ψ and χ_{cJ}).

$c\bar{c}$ meson spectrum



- mass spectrum predicted by potential models and lattice calculations
- good agreement with data below $D\bar{D}$ threshold
- missing states above threshold
- defined basis to study meson structure

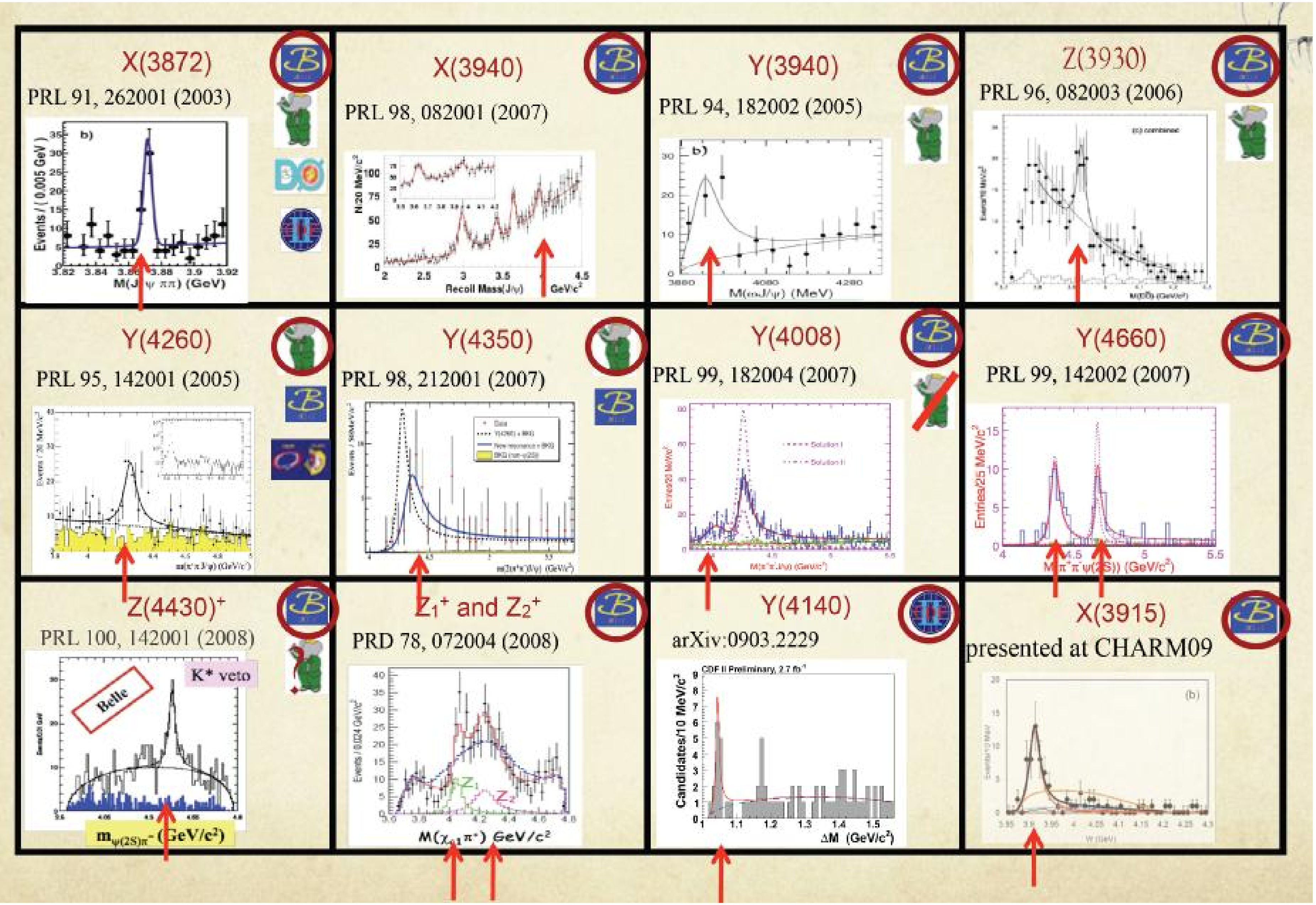
The figure was taken from S. Godfrey & S. Olsen, Annu. Rev. Nucl. Part. Sci., ***58****, 51 (2008).*



This figure was taken from S. Godfrey, Proc. Of the DPF-2009 Conf., Detroit, MI, July, 2009.

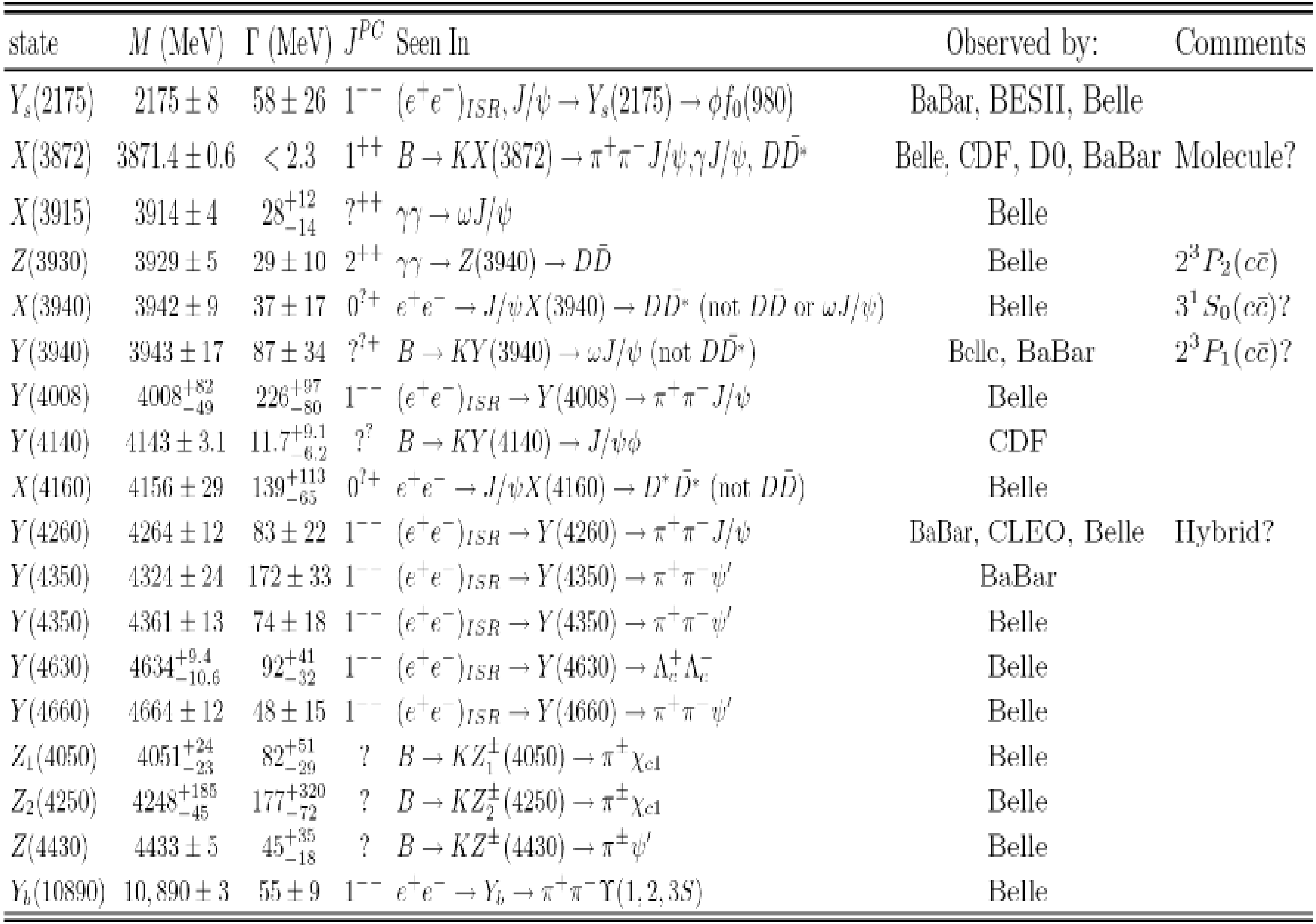
The solid lines are constituent quark model predictions; the shaded lines are the observed conventional charmonium states; the blue horizontal dashed lines represent various $D_S^{(*)}\overline{D}_S^{(*)}$ thresholds; the red dots are the newly discovered charmonium-like states placed in the column with the most probable spin assignment. The states in the last column don't fit elsewhere and appear to be truly exotics.

XYZ-STATES



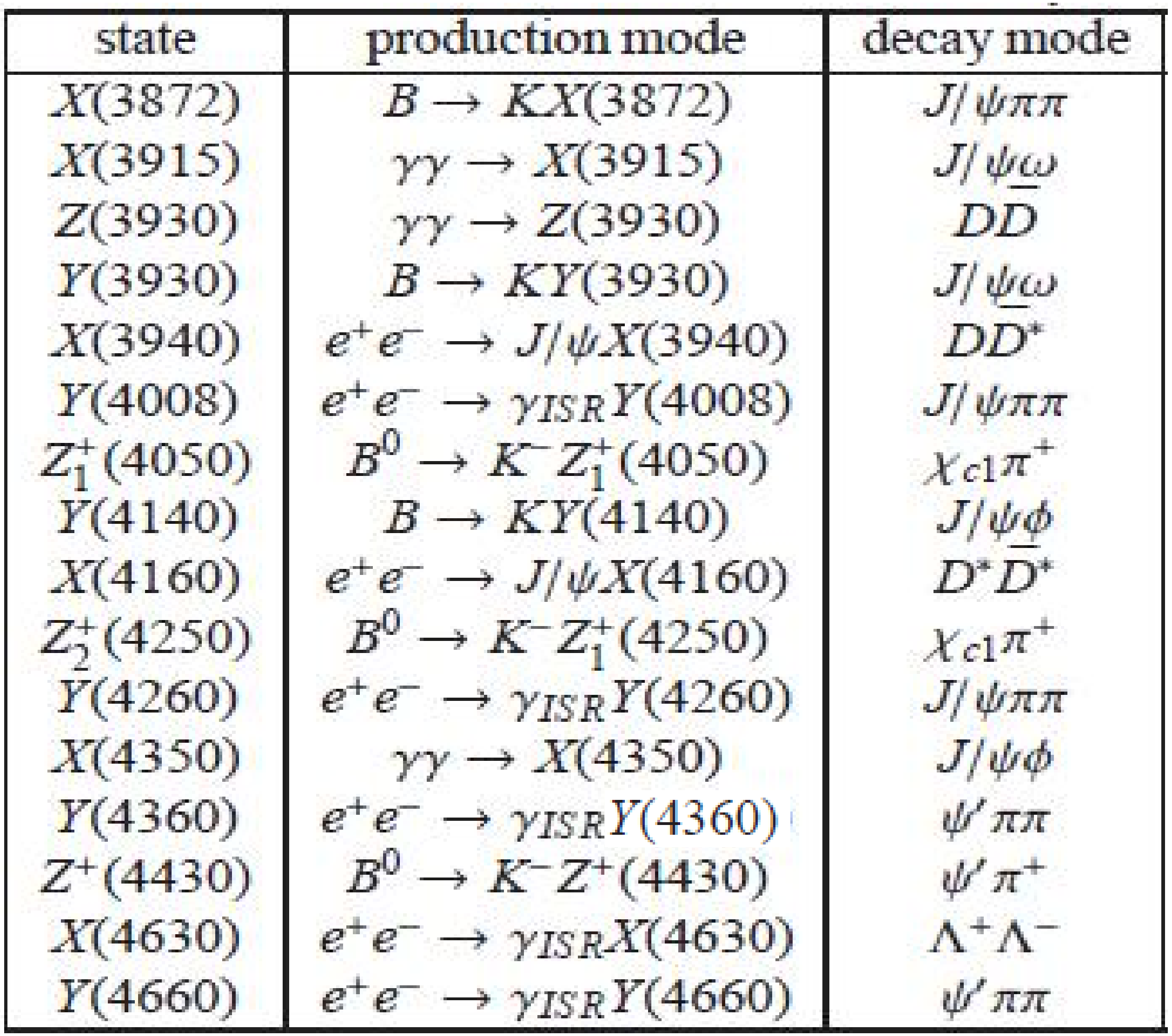
Many new states: above $D\bar{D}$ – threshold for the recent years were revealed in experiment.
Most of these heavy states are not explained by theory and wait for their verification and explanation.

Summary of *XYZ*-particles. Unusual strong decay into hidden charm.



state	M (MeV)	Γ (MeV)	J^{PC}	Seen In	Observed by:	Comments
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$(e^+e^-)_{ISR}, J/\psi \to Y_s(2175) \to \phi f_0(980)$	BaBar, BESII, Belle	
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$B \to KX(3872) \to \pi^+\pi^- J/\psi, \gamma J/\psi, D\bar{D}^*$	Belle, CDF, D0, BaBar	Molecule?
$X(3915)$	3914 ± 4	28^{+12}_{-14}	$?^{++}$	$\gamma\gamma \to \omega J/\psi$	Belle	
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$\gamma\gamma \to Z(3940) \to D\bar{D}$	Belle	$2^3P_2(c\bar{c})$
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$e^+e^- \to J/\psi X(3940) \to D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	Belle	$3^1S_0(c\bar{c})$?
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$B \to KY(3940) \to \omega J/\psi$ (not $D\bar{D}^*$)	Belle, BaBar	$2^3P_1(c\bar{c})$?
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$(e^+e^-)_{ISR} \to Y(4008) \to \pi^+\pi^- J/\psi$	Belle	
$Y(4140)$	4143 ± 3.1	$11.7^{+9.1}_{-6.2}$	$?^?$	$B \to KY(4140) \to J/\psi\phi$	CDF	
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$e^+e^- \to J/\psi X(4160) \to D^*\bar{D}^*$ (not $D\bar{D}$)	Belle	
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$(e^+e^-)_{ISR} \to Y(4260) \to \pi^+\pi^- J/\psi$	BaBar, CLEO, Belle	Hybrid?
$Y(4350)$	4324 ± 24	172 ± 33	1^{--}	$(e^+e^-)_{ISR} \to Y(4350) \to \pi^+\pi^- \psi'$	BaBar	
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$(e^+e^-)_{ISR} \to Y(4350) \to \pi^+\pi^- \psi'$	Belle	
$Y(4630)$	$4634^{+9.4}_{-10.6}$	92^{+41}_{-32}	1^{--}	$(e^+e^-)_{ISR} \to Y(4630) \to \Lambda_c^+\Lambda_c^-$	Belle	
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$(e^+e^-)_{ISR} \to Y(4660) \to \pi^+\pi^- \psi'$	Belle	
$Z_1(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$B \to KZ_1^{\pm}(4050) \to \pi^+ \chi_{c1}$	Belle	
$Z_2(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$B \to KZ_2^{\pm}(4250) \to \pi^{\pm} \chi_{c1}$	Belle	
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$B \to KZ^{\pm}(4430) \to \pi^{\pm} \psi'$	Belle	
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$e^+e^- \to Y_b \to \pi^+\pi^- \Upsilon(1,2,3S)$	Belle	

Charmonium states observed in the last years.



state	production mode	decay mode
$X(3872)$	$B \to KX(3872)$	$J/\psi\pi\pi$
$X(3915)$	$\gamma\gamma \to X(3915)$	$J/\psi\omega$
$Z(3930)$	$\gamma\gamma \to Z(3930)$	DD
$Y(3930)$	$B \to KY(3930)$	$J/\psi\omega$
$X(3940)$	$e^+e^- \to J/\psi X(3940)$	DD^*
$Y(4008)$	$e^+e^- \to \gamma_{ISR} Y(4008)$	$J/\psi\pi\pi$
$Z_1^+(4050)$	$B^0 \to K^- Z_1^+(4050)$	$\chi_{c1}\pi^+$
$Y(4140)$	$B \to KY(4140)$	$J/\psi\phi$
$X(4160)$	$e^+e^- \to J/\psi X(4160)$	D^*D^*
$Z_2^+(4250)$	$B^0 \to K^- Z_1^+(4250)$	$\chi_{c1}\pi^+$
$Y(4260)$	$e^+e^- \to \gamma_{ISR} Y(4260)$	$J/\psi\pi\pi$
$X(4350)$	$\gamma\gamma \to X(4350)$	$J/\psi\phi$
$Y(4360)$	$e^+e^- \to \gamma_{ISR} Y(4360)$	$\psi'\pi\pi$
$Z^+(4430)$	$B^0 \to K^- Z^+(4430)$	$\psi'\pi^+$
$X(4630)$	$e^+e^- \to \gamma_{ISR} X(4630)$	$\Lambda^+\Lambda^-$
$Y(4660)$	$e^+e^- \to \gamma_{ISR} Y(4660)$	$\psi'\pi\pi$

* N. Brambilla et al., Eur.Phys.J. C 71 (2011) 1534.

Y(4274) $J^{PC} = ?^{?+}$, $M = 4274 \pm 8.4$, $\Gamma = 32 \pm 22$, $B \to K\, Y(4274) \longrightarrow K(\phi J/\psi)$

May be radial excitation of $Y(4140)$ or what!? What is $Y(4140)$!?

CHARMONIUM PRODUCTION MECHANISMS RELEVANT TO THE *XYZ* – STATES:

- B → $K(c\bar{c})$ => $J^{PC} = 0^{-+}, 1^{--}, 1^{++}$. $\beta \approx 2 \times 10^{-3}$. $B^+ = u\bar{b}$, $B^0 = d\bar{b}$, $K^+ = u\bar{s}$, $K^0 = d\bar{s}$.
- Production of $J^{PC} = 1^{--}$ charmonium states via initial state radiation (ISR) => $J^{PC} = 1^{--}$.
- Charmonium associated production with J/Ψ mesons in e^+e^- annihilation. => $J^{PC} = 0^{-+}, 0^{++}$.
- Two photon collisions . => $J^{PC} = 0^{-+}, 0^{++}, 2^{-+}, 2^{++}$.

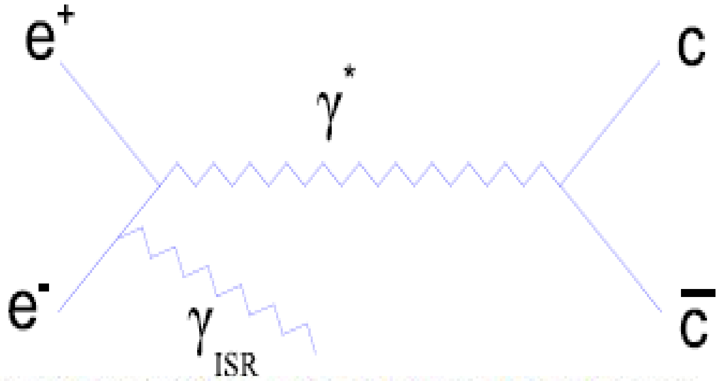
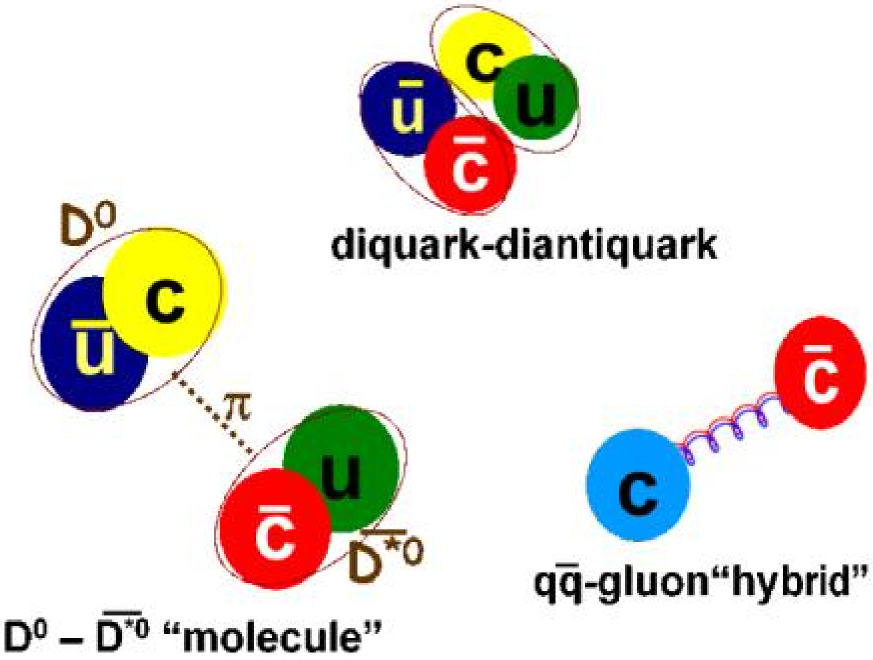


Illustration for the initial state radiation (ISR) process.

Structures besides $q\bar{q}$ quark model



CHARMONIUM PRODUCTION MECHANISMS RELEVANT TO THE *XYZ* – STATES (*XYZ* - PARTICLES)

■ $B \rightarrow K(c\bar{c}) \Rightarrow J^{PC} = 0^{-+}, 1^{--}, 1^{++}$. $\beta \approx 2 \times 10^{-3}$. $B^{+} = u\bar{b}$, $B^{0} = d\bar{b}$, $B^{-} = \bar{u}b$.

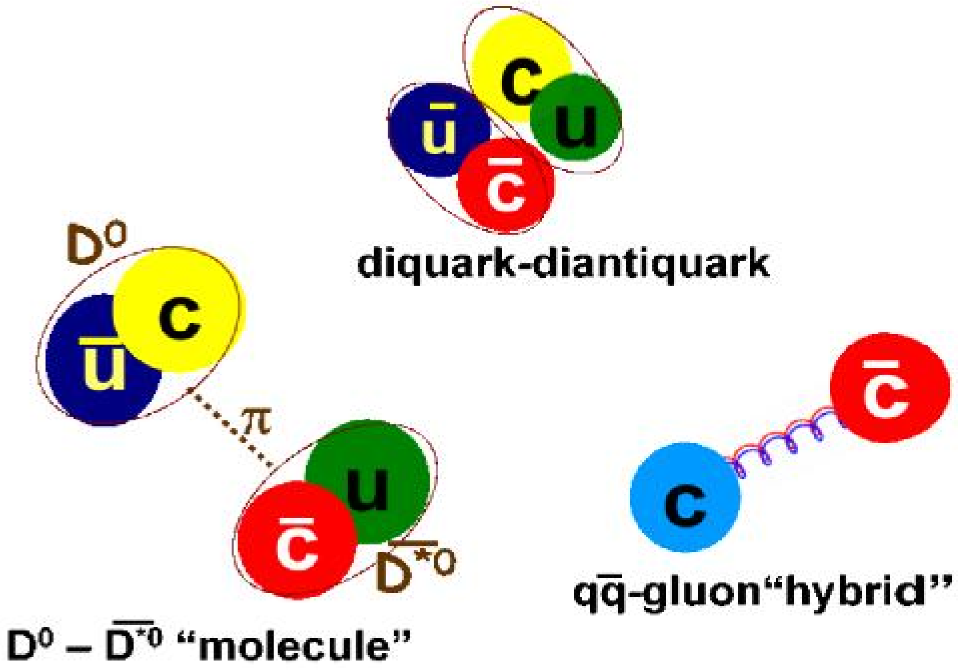
***B*-decays to final states containing $c\bar{c}$ mesons.** At the quark level, the dominant decay mechanism is the weak interaction transition of a *b* quark to *c* quark accompanied by the emission of a virtual W^{-} boson, the mediator of the weak interaction. Approximately half of the time, the W^{-} boson matirializes as a $s\bar{c}$ pair. So, almost half of all *B*-meson decays result in a final state that contains *c* and $\bar{c}$ quarks. When these final-state *c* and $\bar{c}$ quarks are produced close to each other in phase space, they can coalesce to form a $c\bar{c}$ meson. The simplest charmonium producing *B*-meson decays are those where the *s* quark from the W^{-} combines with the parent *B*-meson's $\bar{u}$ or $\bar{d}$ quark to form a *K*-meson ($K^{+} = u\bar{s}$; $K^{0} = d\bar{s}$).

■ **Production of $J^{PC} = 1^{--}$ charmonium states via initial state radiation (ISR).** In $e^{+}e^{-}$ collisions at a cm energy of 10580 MeV the initial-state e^{+} or e^{-} occasionally radiates a high-energy γ-ray (γ_{ISR} = 4000 MeV – 5000 MeV), and e^{+} and e^{-} subsequently annihilate at a reduced cm energy that correspond to the range of mass values of charmonium mesons. Thus, the ISR process can directly produce charmonium states with $J^{PC} = 1^{--}$.

■ **Charmonium associated production with J/Ψ mesons in $e^{+}e^{-}$ annihilation**. **$J^{PC} = 0^{-+}$ and 0^{++}.** In studies of $e^{+}e^{-}$ annihilations at cm energies near 10580 MeV => Belle discovered that in inclusive annihilation process => $e^{+}e^{-} \rightarrow J/\Psi + (c\bar{c}) \Rightarrow J/\Psi + \eta_{c}$ or $J/\Psi + \chi_{c0}$ (J=0≠1≠2).

■ **Two photon collisions.** In high energy $e^{+}e^{-}$ machines, photon-photon collisions are produced when both an incoming e^{+} and e^{-} radiate photons that subsequently interact with each other. Two photon interactions can directly produce particles with **$J^{PC} = 0^{-+}, 0^{++}, 2^{-+}, 2^{++}$.**

Structures besides $q\bar{q}$ quark model



Two generic types of multiquark states have been described in the recent literature:

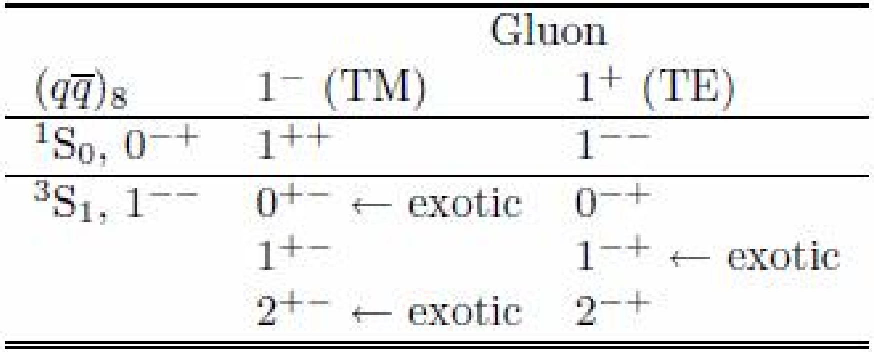
- molecular states, is comprised of two charmed mesons bound together to form a molecule. These states are by nature loosely bound. Molecular states are bound through two mechanisms: quark/colour exchange at short distances and pion exchange at large distances. Also pion exchange is expected to dominate. Because the mesons inside the molecule are weakly bound , they tend to decay as if they are free.

- tightly bound four-quark states, dubbed a tetraquark, that is predicted to have properties that are distinct from those of a molecular state. In the model of Maiani*, the tetraquark is described as a diquark-diantiquark structure in which the quarks group into colour-triplet scalar and vector clusters, and the interactions are dominated by a simple spin-spin interaction. A prediction that distinguishes multiquark states containing a $c\bar{c}$ pair from conventional charmonia is the possible existence of multiplets that include members with non-zero charge [cu$\overline{cd}$], strangeness [cd$\overline{cs}$], or both [cu$\overline{cs}$] (Z^+ - particles). * *Maiani, et al., Phys. Rev.,* ***D*** *71:014028.*

There are two different kinds of $\bar{p}p$ – annihilation experiments:

- production experiment – $\bar{p}p \to X + M$, where $M = \pi, \eta, \omega, \ldots$ (conventional states plus states with exotic quantum numbers)
- formation experiment (annihilation process) – $\bar{p}p \to X \to M_1 M_2$ (conventional states plus states with non-exotic quantum numbers)

The low laying charmonium hybrid states:



	Gluon	
$(q\bar{q})_8$	1^- (TM)	1^+ (TE)
$^1S_0, 0^{-+}$	1^{++}	1^{--}
$^3S_1, 1^{--}$	0^{+-} ← exotic	0^{-+}
	1^{+-}	1^{-+} ← exotic
	2^{+-} ← exotic	2^{-+}

Charmonium hybrids are the states with excited gluonic degree of freedom. Predominantly decay via electromagnetic and hadronic transitions and into the open charm final states:

- $c\bar{c}g \to (\Psi, \chi_{cJ})$ + light mesons $(\eta, \eta', \omega, \varphi)$ - these modes supply small widths and significant branch fractions;
- $c\bar{c}g \to DD^*$. In this case *S-wave (L = 0)* + *P-wave (L = 1)* final states should dominate over decays to and the partial width to should be very small.

The most interesting and promising decay channels of charmed hybrids have been, in particular, analyzed:

- $\bar{p}p \to \tilde{h}_{c0,1,2}\ (0^{-+}, 1^{-+}, 2^{-+})\, \eta \to \chi_{c0,1,2}\,(\eta, \pi\pi; \ldots);$
- $\bar{p}p \to \tilde{h}_{c0,1,2}\,(0^{+-}, 1^{+-}, 2^{+-})\, \eta \to \chi_{c0,1,2}\,(\eta, \pi\pi; \ldots);$
- $\bar{p}p \to \tilde{\Psi}\ (1^{--}) \to J/\Psi\,(\eta, \omega, \pi\pi, \ldots);$
- $\bar{p}p \to \tilde{h}_{c0,1,2},\ \tilde{h}_{c0,1,2},\ \tilde{c}_{c1}\ (0^{-+}, 1^{-+}, 2^{-+}, 0^{+-}, 1^{+-}, 2^{+-}, 1^{++})\, \eta \to D\bar{D}^*\eta\,.$

$$\frac{\mathcal{B}(X(3940)\to\omega J/\psi)}{\mathcal{B}(X(3940)\to D^{*0}\bar{D}^0)} < 0.60$$

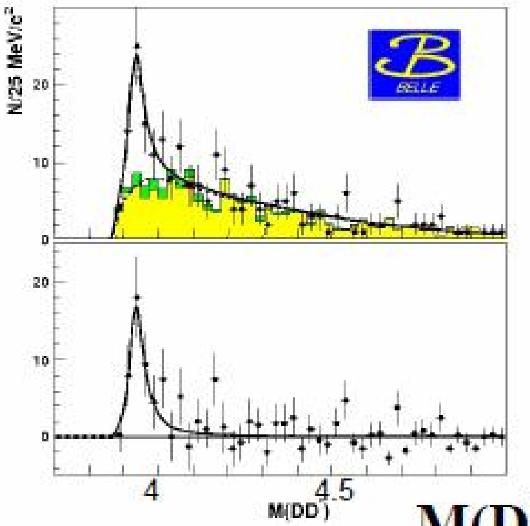
$$\frac{\mathcal{B}(Y(3940)\to\omega J/\psi)}{\mathcal{B}(Y(3940)\to D^{*0}\bar{D}^0)} > 0.75$$

The X,Y,Z near 3940 MeV

not seen in $\omega J/\psi$

X(3940)

$e^+e^- \to J/\psi\, D\bar{D}^*$



$M(D\bar{D}^*)$

M = 3942 $^{+7}_{-6}$ ± 6 MeV

Γ_{tot} = 37 $^{+26}_{-15}$ ± 12 MeV

Nsig =52 $^{+24}_{-16}$ ± 11evts

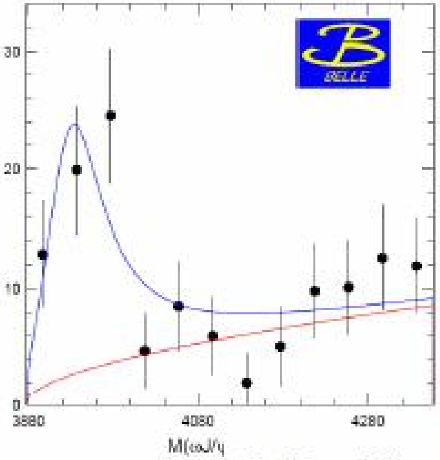
PRL 100, 202001 (2008)

probably different

not seen in DD^*

Y(3940)

$B \to K\,\omega J/\psi$



$M(\omega J/\psi)$

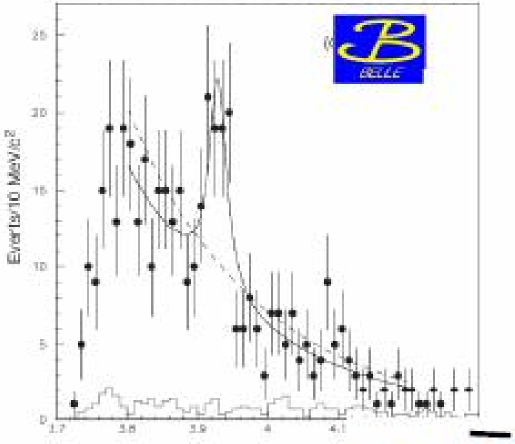
M≈3940 ± 11 MeV
Γ≈ 92 ± 24 MeV

PRL94, 182002 (2005)

Probably the χ_{c2}'

Z(3930)

$\gamma\gamma \to D\bar{D}$



$M(D\bar{D})$

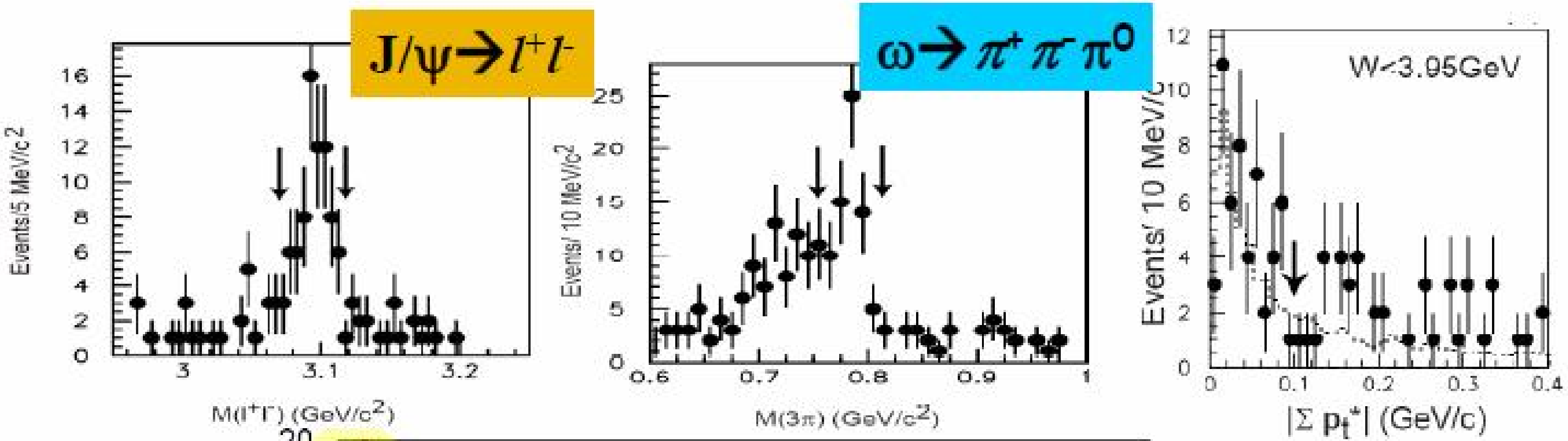
M = 3929±5±2 MeV

Γ_{tot} = 29±10±2 MeV

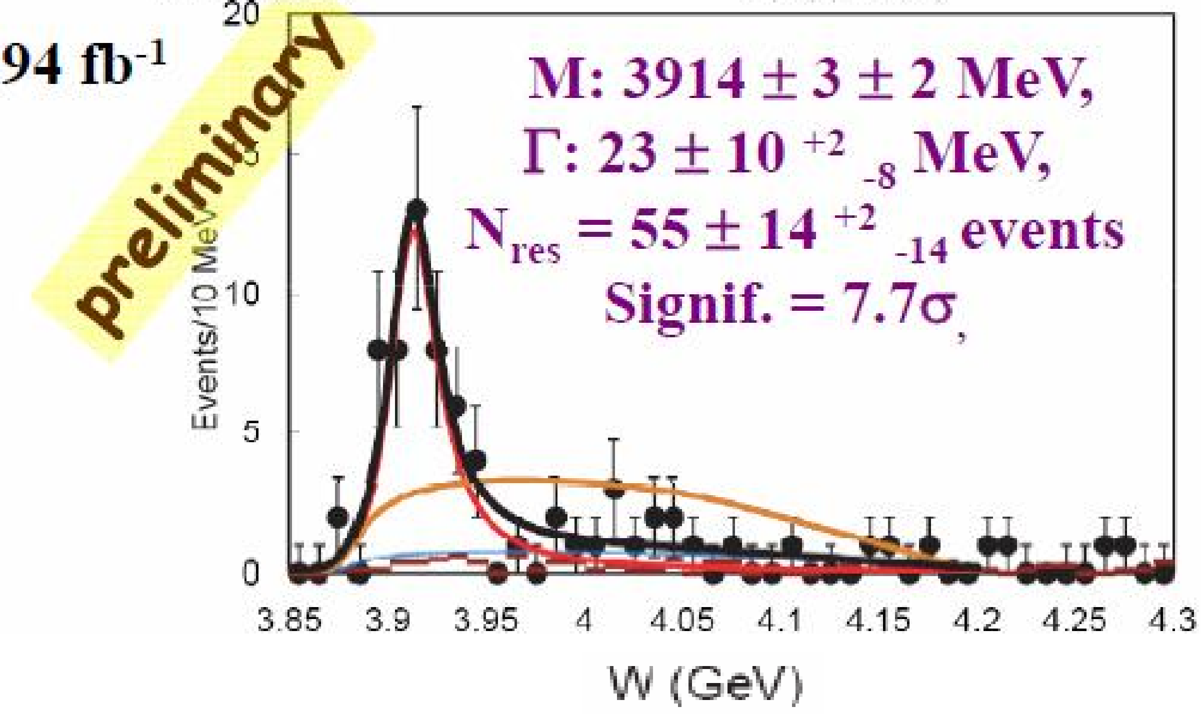
Nsig =64 ± 18evts

PRL 96, 082003 (2006)

New peak in $\gamma\gamma \to \omega J/\psi$ from Belle



694 fb^{-1}



M: 3914 ± 3 ± 2 MeV,
Γ: $23 \pm 10^{+2}_{-8}$ MeV,
$N_{res} = 55 \pm 14^{+2}_{-14}$ events
Signif. = 7.7σ,

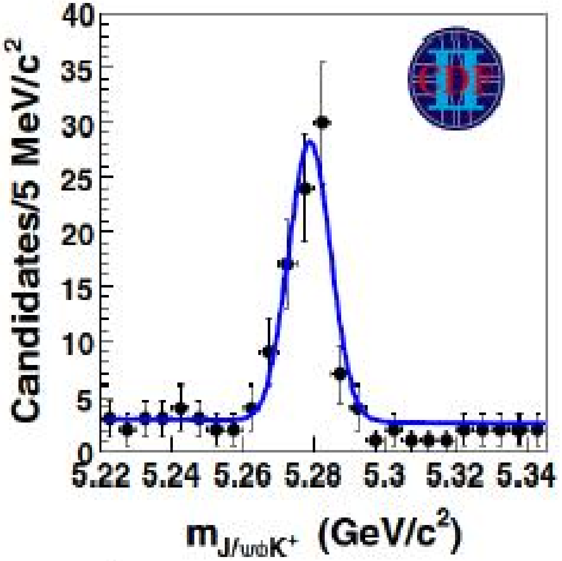
Two-photon production of Y(3940)?

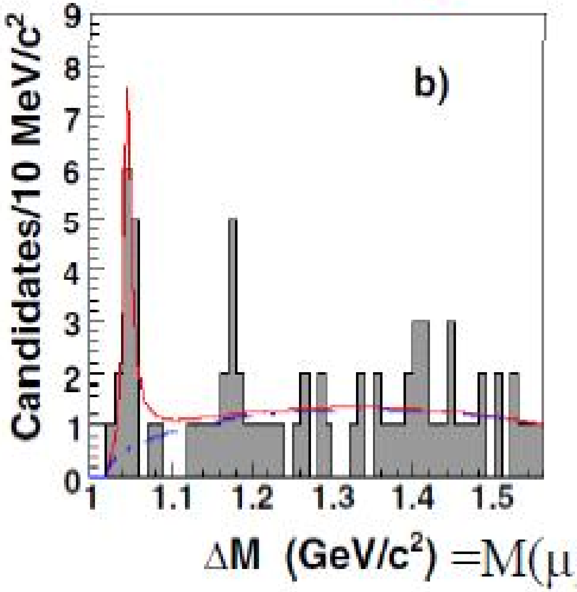
or New decay mode of Z(3930)?

$Y(4140) \to J/\psi\ \phi$

CDF, PRL 102, 242002 (2009)

CDF observed new charmonium-like particle

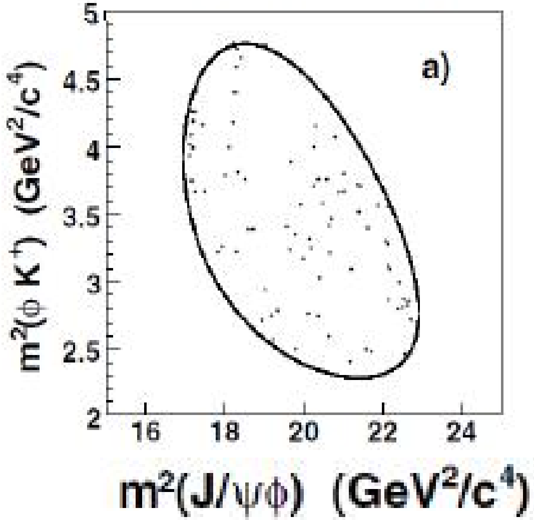




$\Delta M\ (\mathrm{GeV}/c^2) = M(\mu\mu KK) - M(\mu\mu)$

$B^+ \to J/\psi\ \phi\ K^+$

14 ± 5 events (3.8σ)
from 2.7 fb^{-1}



$M = 4143.0 \pm 2.9 \pm 1.2\ \mathrm{MeV}/c^2$

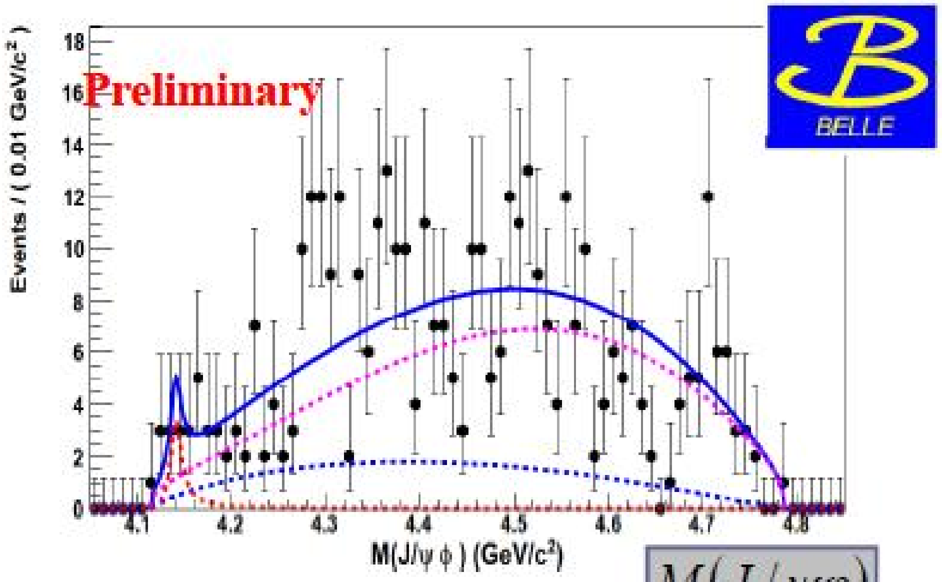
$\Gamma = 11.7\,^{+8.3}_{-5.0} \pm 3.7\ \mathrm{MeV}$

$D_s^* \overline{D_s}^*$ molecule or tetraquark ?

Searches at Belle

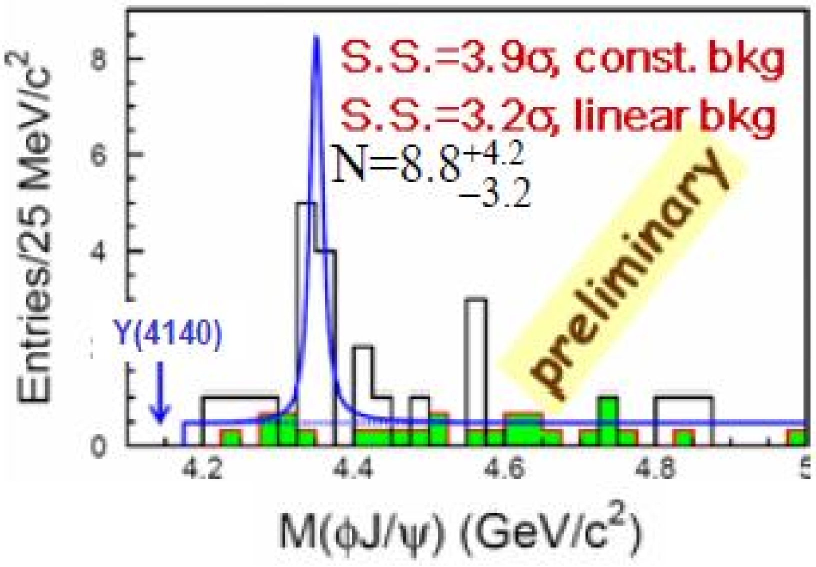
$B^+ \to J/\psi\ \phi\ K^+$ →

$BF(B \to YK)BF(Y \to J/\psi\phi)$
$< 6 \times 10^{-6}$ (@90%CL)



$M(J/\psi\varphi)$

$\gamma\gamma \to J/\psi\ \phi$ ↓



Belle: Y(4140) not seen in B decays or in two-photon

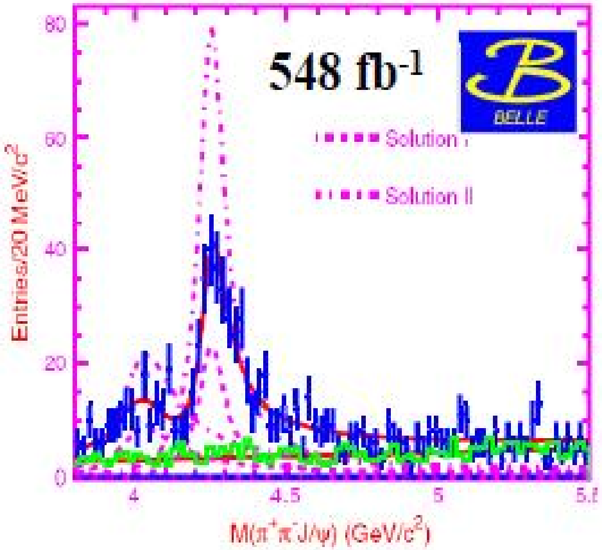
Instead, a new peak is seen at around 4.35 GeV in $\gamma\gamma \to J/\psi\phi$

$M = 4350.6^{+4.6}_{-5.1} \pm 0.7\ \mathrm{MeV}/c^2$

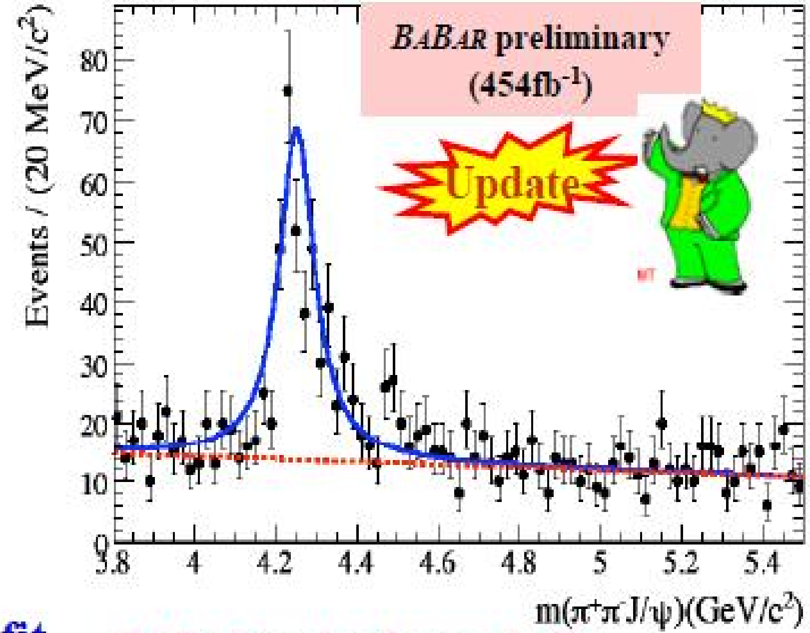
$\Gamma = 13.3^{+17.9}_{-9.1} \pm 4.1\mathrm{MeV}$

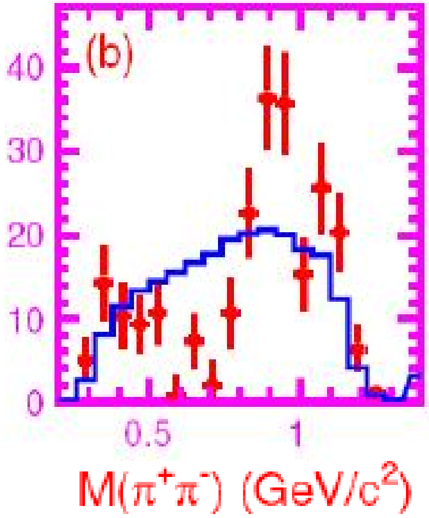
Updates of Y(4260)

Belle, PRL 99, 182004 (2007)



BaBar, arXiv:0808.1543(2008)





Belle's Two-peak fit

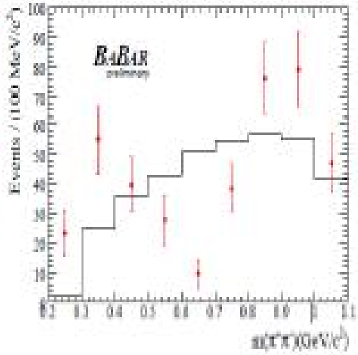
$M=4008 \pm 40\ ^{+114}_{-28}$ MeV
$\Gamma=226 \pm 44 \pm 87$ MeV

$M=4247 \pm 12\ ^{+17}_{-32}$ MeV
$\Gamma=108 \pm 19 \pm 10$ MeV

BaBar's single-peak fit

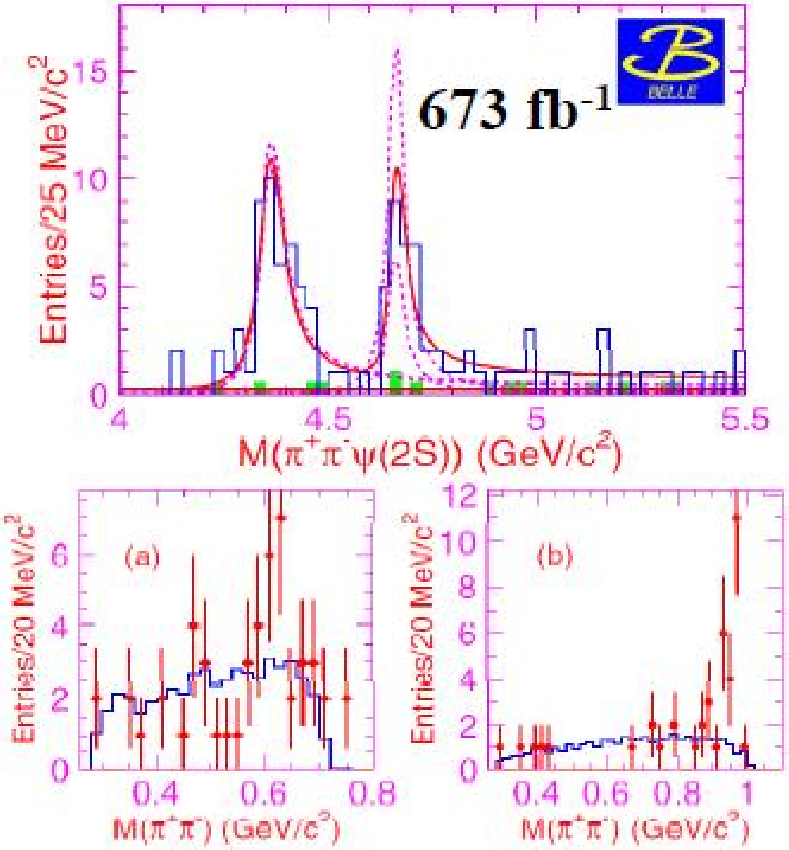
$M=4252 \pm 6\ ^{+2}_{-3}$ MeV
$\Gamma=105 \pm 18\ ^{+4}_{-6}$ MeV

Y(4008) is not evident.



Y(4320) and Y(4664), and X(4630) in $\Lambda c^+ \Lambda c^-$

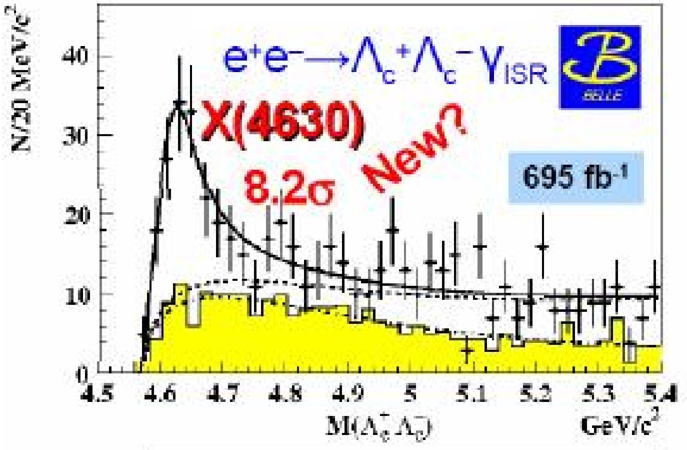
Belle, PRL 99, 142002 (2007)



M= 4361 ± 9 ± 9 MeV
Γ= 74 ± 15 ±10 MeV

M= 4664 ± 11 ± 5 MeV
Γ= 48 ± 15 ±3 MeV

Belle. PRL 101, 172001(2008)



State	M, MeV/c²	Γ$_{tot}$, MeV
X(4630)	4634^{+8+5}_{-7-8}	92^{+40+10}_{-24-21}
Y(4660)	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$

Or, a popular nature of
Baryon-antibaryon
near-threshold structures

The *XYZ* particles

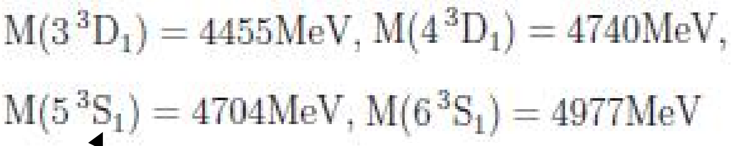
new state

- **X(3915) – γγ → ωJ/ ψ** (J^{PC} = $?^{++}$ **=>** may be $J^{PC} = 0^{++}$)
- **Z(3930) – γγ → $D\overline{D}$** (only $J^{PC} = 0^{++}$ and $J^{PC} = 2^{++}$)
- **Y(3940) – B → KωJ/ψ** ($J^{PC} = 1^{++}$)
- **X(3940) – e^+e^- → J/ψ $D\overline{D}^*$** ($J^{PC} = 0^{-+}$, not 0^{++})
- **X(4160) – e+e- → J/ ψ $D^*\overline{D}^*$** (JPC = 0^{-+}, not 0^{++})

double charmonium decay

new states

- **Y(4140) – B → KφJ/ ψ** (B → KωJ/ ψ)($J^{PC} = ??^{+}$)
- **X(4350) – γγ → φJ/ ψ** ($J^{PC} = 0, 2^{++}$)
- **Y(4274) – B → KφJ/ ψ** ($J^{PC} = ??^{+}$)


$M(3\,^3D_1) = 4455\text{MeV},\ M(4\,^3D_1) = 4740\text{MeV},$

$M(5\,^3S_1) = 4704\text{MeV},\ M(6\,^3S_1) = 4977\text{MeV}$

- **Y(4260) – e^+e^- → γ $\pi^+\pi^-$J/ψ** (no evidence for open charm decay $D\overline{D}$, …, $D^*\overline{D}^*$)
- **Y(4350) – e^+e^- → γ $\pi^+\pi^-$ψ(2*S*)** (no evidence for open charm decay $D\overline{D}$, …, $D^*\overline{D}^*$)
- **Y(4660) – e^+e^- → γ $\pi^+ \pi^-$ ψ(2S)**(no evidence for open charm decay $D\overline{D}$, …, $D^*\overline{D}^*$)
- **$Z^\pm$(4430) – B → K$\pi^\pm$ ψ(2*S*); $Z^\pm$(4050) – B → K $\pi^\pm\chi_{c1}$; $Z^\pm$(4250) – B → K $\pi^\pm\chi_{c1}$**
- ISR 1^{--} states => higher laying conventional $c\overline{c}$ states : Y(4350) <=> 3^3D_1 and Y (4660) <=> 5^3S_1 respectively: Ding G.J. et al., arXiV: 0708.3712 [hep-ph].

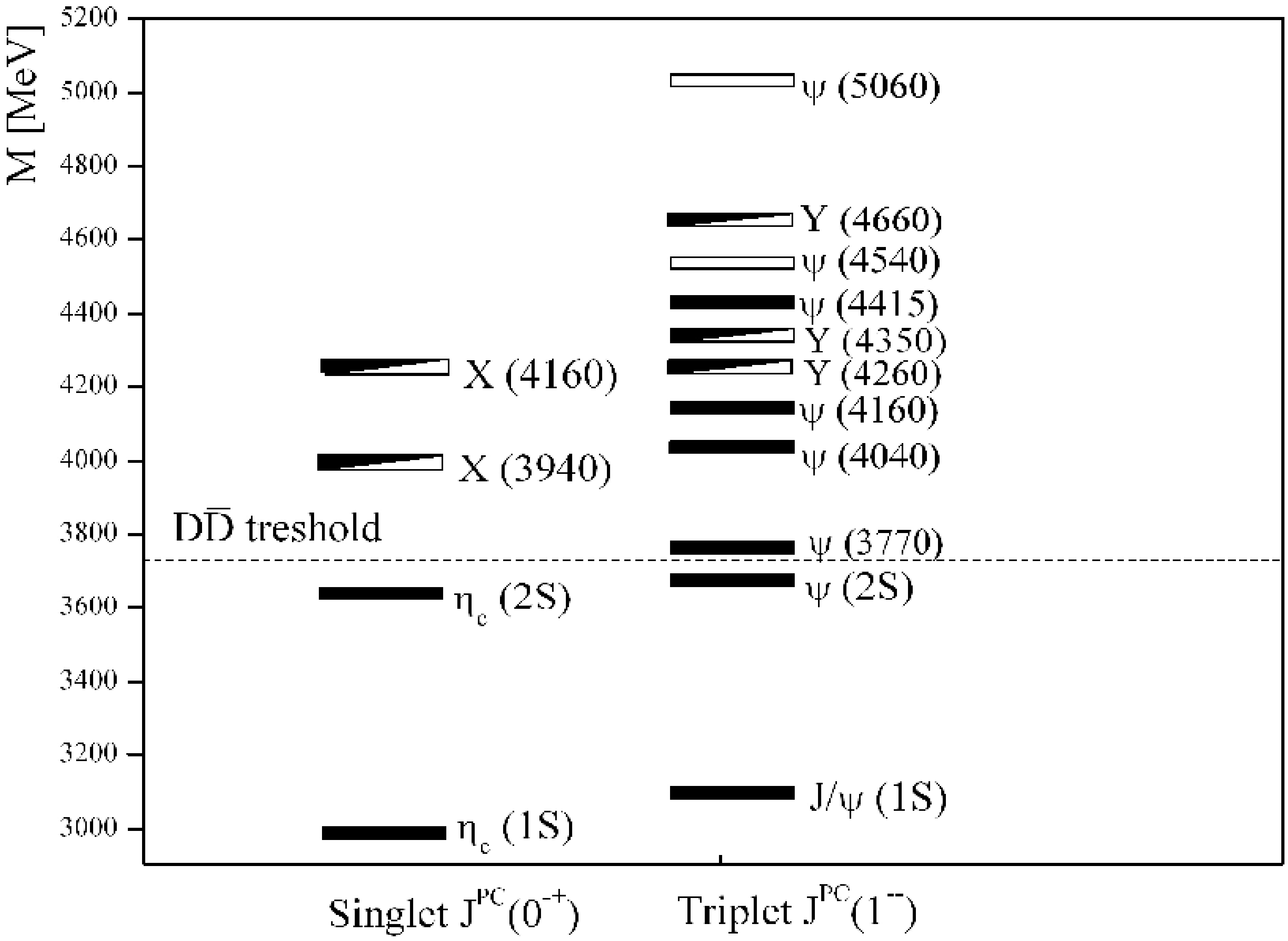
- **Theory referred many years for the lack of new data in hadron spectroscopy especially over $D\overline{D}$ - threshold.**
- **Now theory does not know where to put the new recently discovered states.**
- **Eight of the *XYZ* particles seems possible to interpret as radial excited scalar and vector states of charmonium in the framework of the combined approach considered above:**
  - X(3872) – $D^{*0}\overline{D}^{0}$ molecule or tetraquark $[(cq)\,(\overline{cq})]_{\text{S-wave}}$ $(q = u, d)$ *)
    The interpretation as $c_{c2}(2P)$ state X(3872) → $\omega J/\Psi$ seems to be interesting! *)
  - X(3915) – $\chi_{c0}(2P)$
  - Y(3940) – $\chi_{c1}(2P)$
  - Z(3930) – $c_{c2}(2P)$
  - X(3940) – $h_c(3S)$
  - Y(4140) – tetraquark state $[(cq)\,(\overline{cq})]_{\text{S-wave}}$ or $[(cs)\,(\overline{cs})]_{\text{S-wave}}$ or $D^{*+}_{s}\overline{D}^{*-}_{s}$ molecule *)
  - X(4160) – $h_c(4S)$
  - Y(4260) – Ψ''; charmed hybrid $(c\overline{c}g)$ or tetraquark $[(cs)\,(\overline{cs})]_{\text{S-wave}}$ or $D^{0}\overline{D}^{*}$, $D\overline{D}_{1}$ molecule*
  - Y(4350) – $\Psi'''\cdots$, charmed hybrid $(c\overline{c}g)$ or tetraquark $[(cs)\,(\overline{cs})]_{\text{P-wave}}$ *)
  - Y(4630) – tetraquark state $[(cd)\,(\overline{cd})]$ or baryonium $(\Lambda^{+}_{c}\Lambda^{-}_{c})$ *)
  - Y(4660) – $\Psi''''\cdots$, tetraquark $[(cs)\,(\overline{cs})]_{\text{2P-wave}}$ or baryonium *)
  - $Z^{\pm}$(4430) – charged tetraquark state $[(cu)][(\overline{cd})]$ or baryonium $\Lambda^{\pm}_{c}\overline{\Sigma}^{0}_{c}$ or $D^{*+}\overline{D}^{0}_{1}$ molecule*)

*) N. Brambilla et al., Eur.Phys.J. C 71 (2011) 1534.

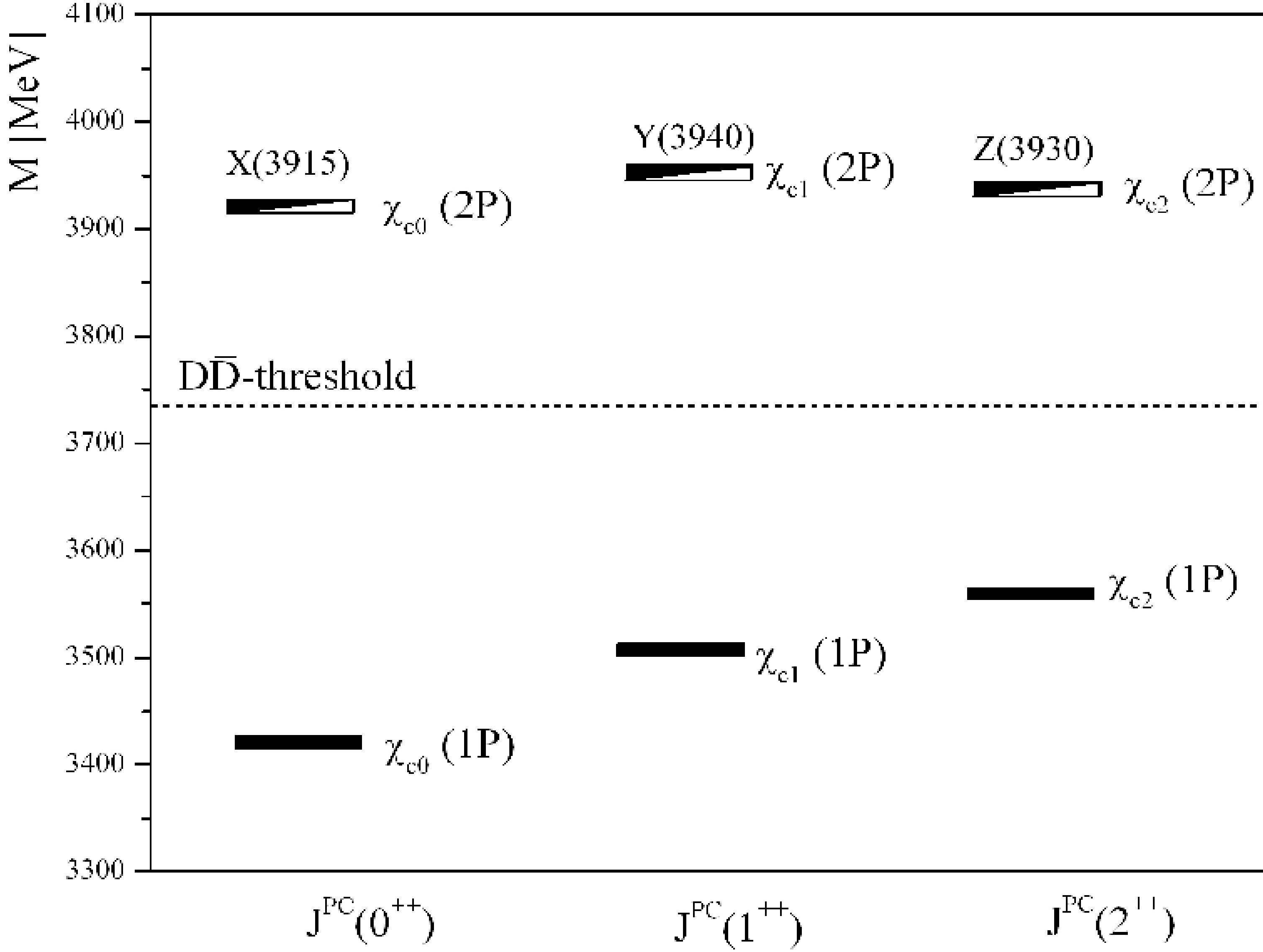
HADROCHARMONIUM

Y(4260) Y(4350) Y(4660) $Z^{\pm}$(4050) $Z^{\pm}$(4250) $Z^{\pm}$(4430)

THE SPECTRUM OF SCALAR ($^1S_0$) AND VECTOR ($^3S_1$) STATES OF CHARMONIUM



THE SPECTRUM OF VECTOR (^3P_J) STATES OF CHARMONIUM



The integral formalism (or in other words integral approach) is based on the possibility of appearance of the discrete quasi stationary states with finite width and positive values of energy in the barrier-type potential. This barrier is formed by the superposition of two type of potentials: short-range attractive potential $V_1(r)$ and long-distance repulsive potential $V_2(r)$.

Thus, the width of a quasi stationary state in the integral approach is defined by the following expression (integral formula):

$$\Gamma = 2p \left| \int_0^\infty f_L(r) V(r) F_L(r) r^2 dr \right|^2$$

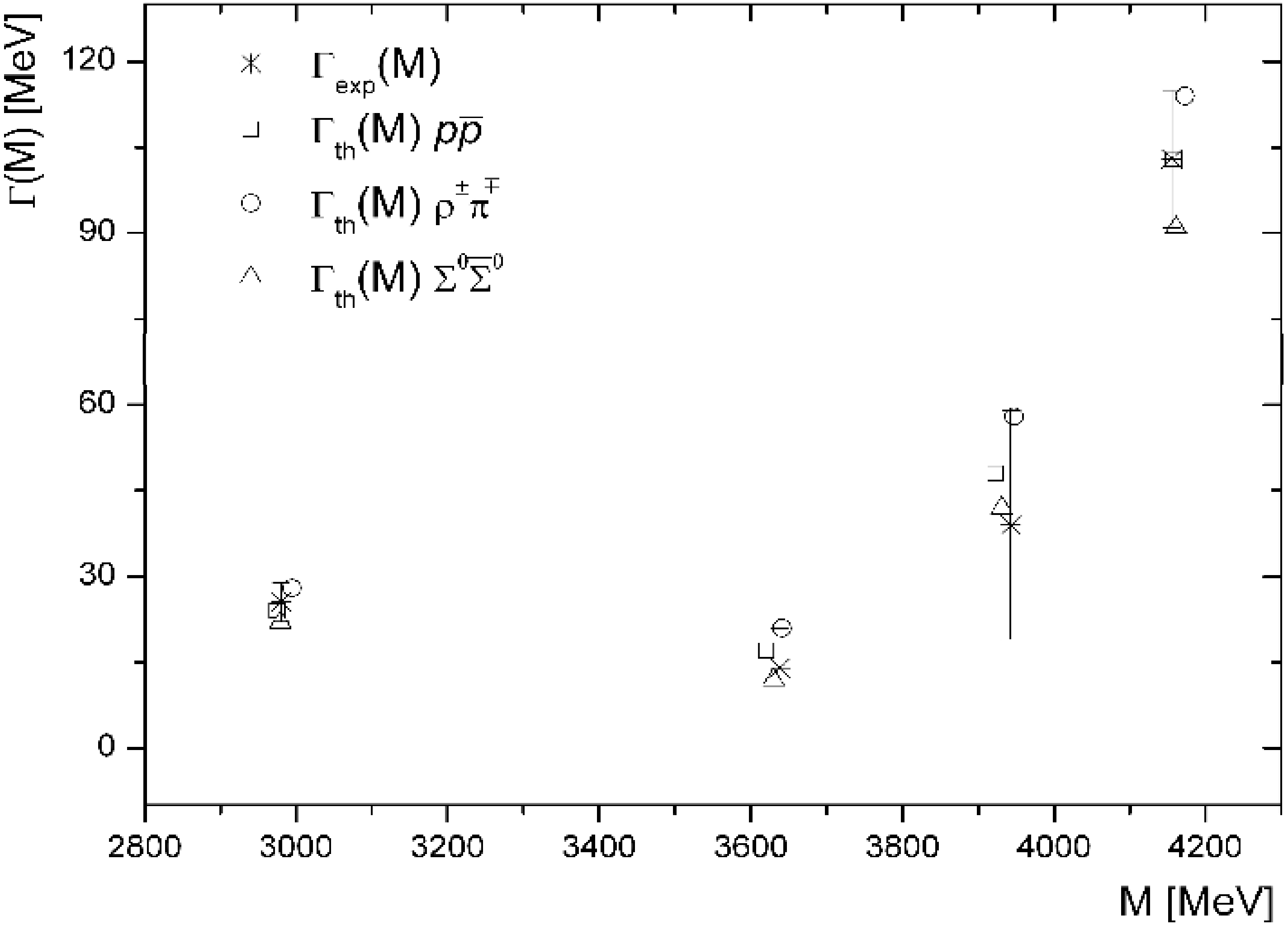
where

$$(r < R):\ \int_0^R \left| f_L(r) \right|^2 dr = 1$$

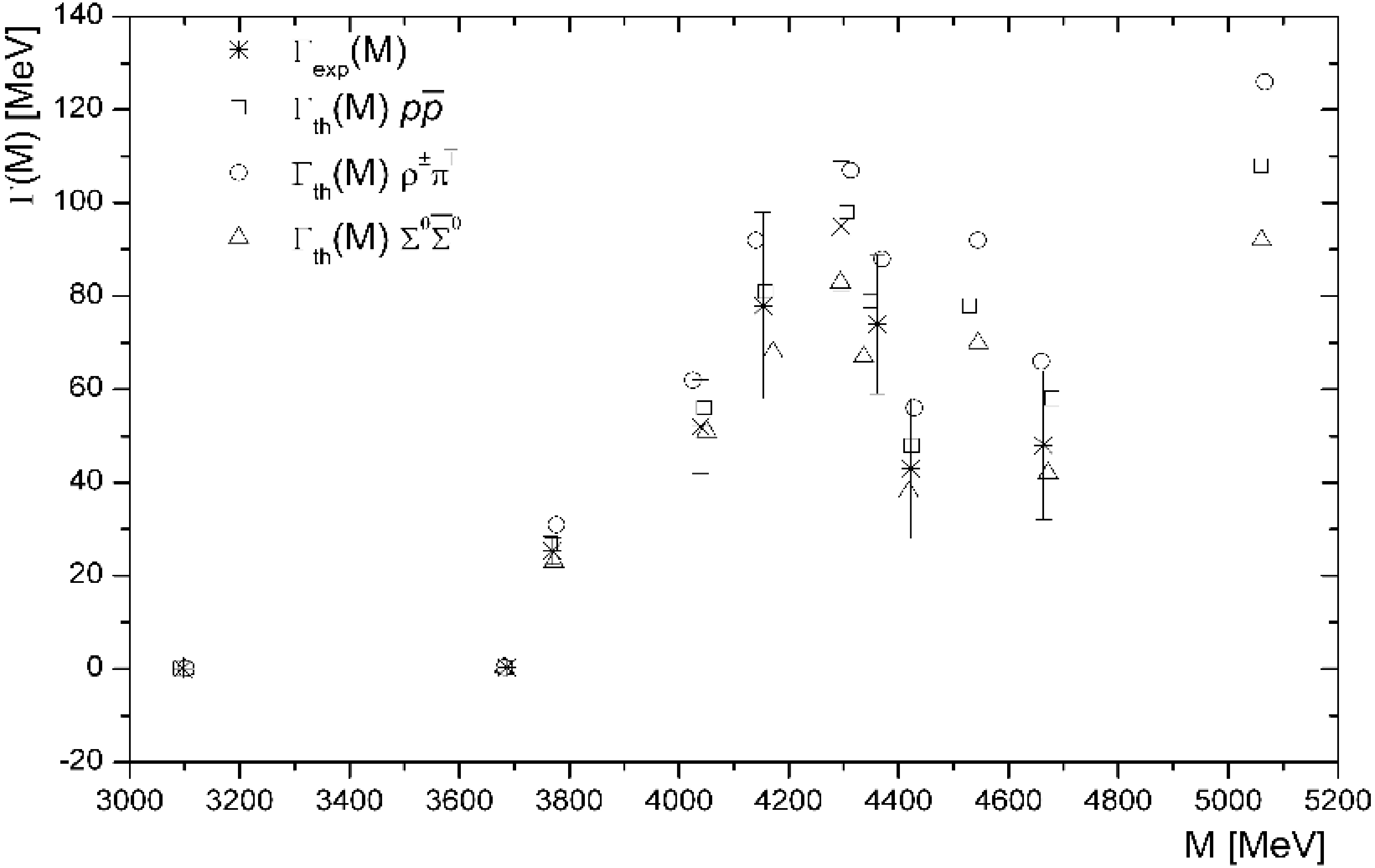
where $F_L(r)$ – is the regular decision in the $V_2(r)$ potential, normalized on the energy delta-function; $f_{L(}r)$ – normalized wave function of the resonance state. This wave function transforms into irregular decision in the $V_2(r)$ potential far away from the internal turning point.

The integral can be estimated with the well known approximately methods: for example, the saddle-point technique or the other numerical method.

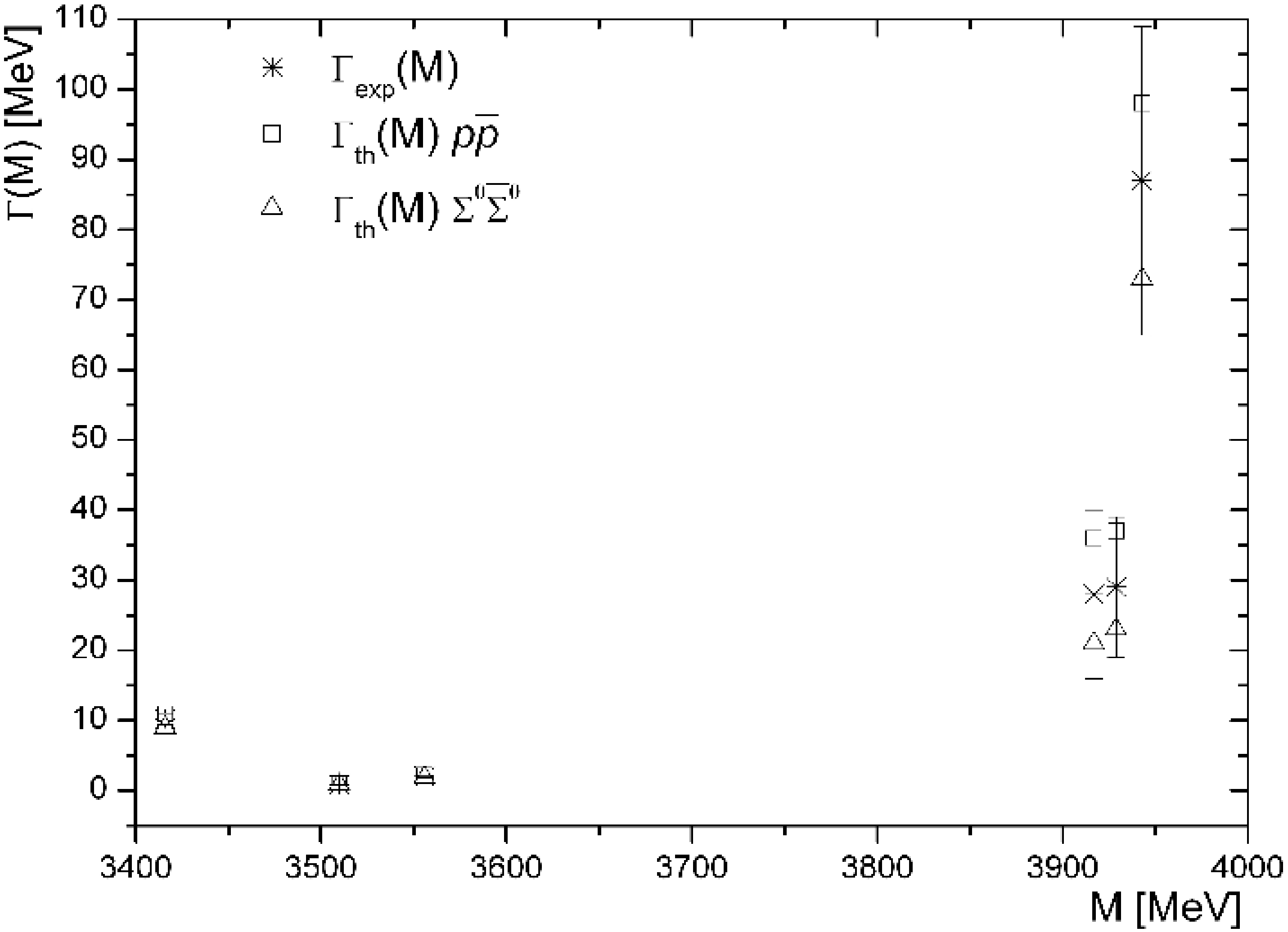
THE WIDTHS OF THE SCALAR $^{1}S_{0}$ CHARMONIUM STATES



THE WIDTHS OF THE VECTOR $^3S_1$ CHARMONIUM STATES



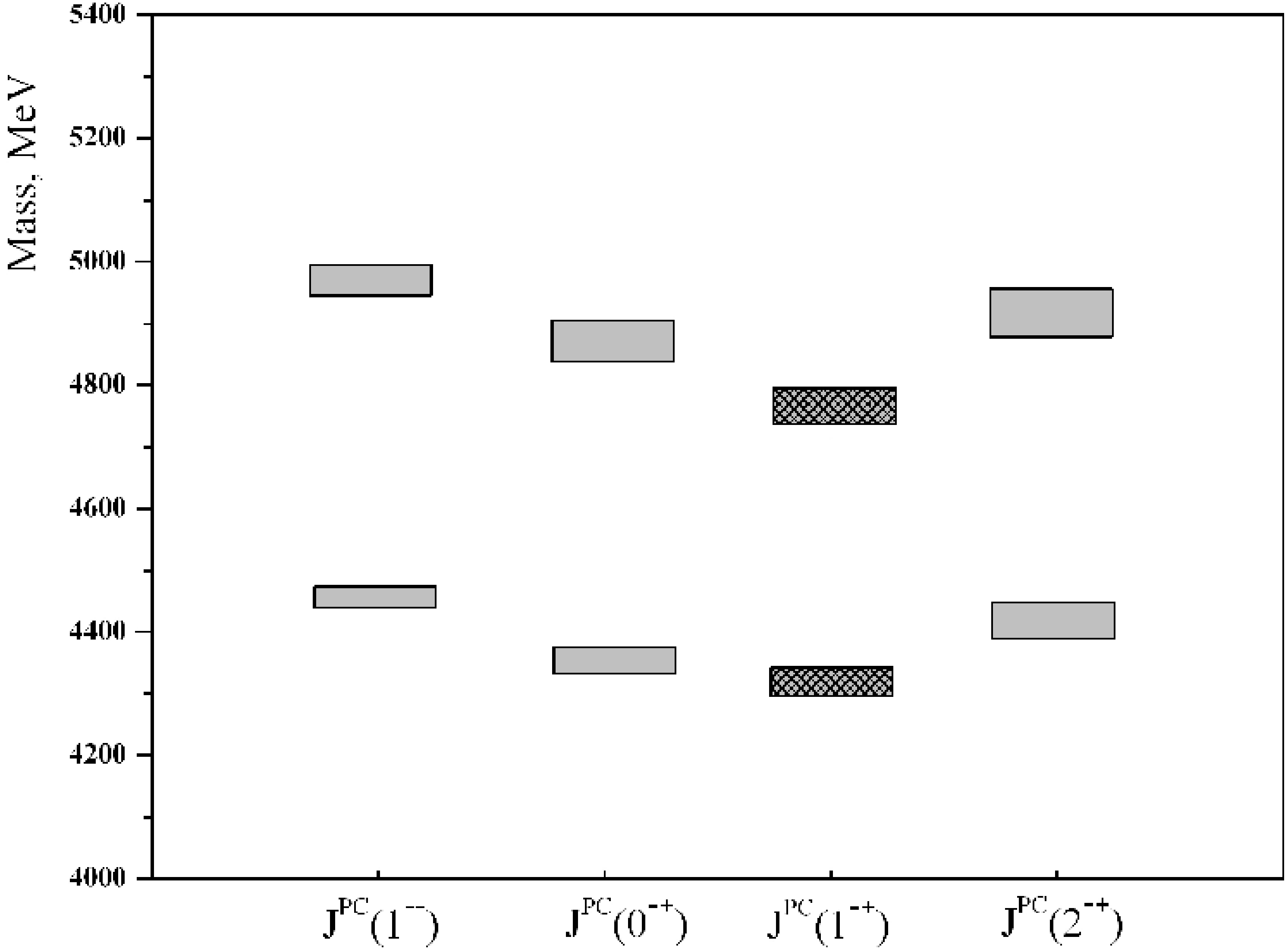
THE WIDTHS OF THE ^3P_J CHARMONIUM STATES



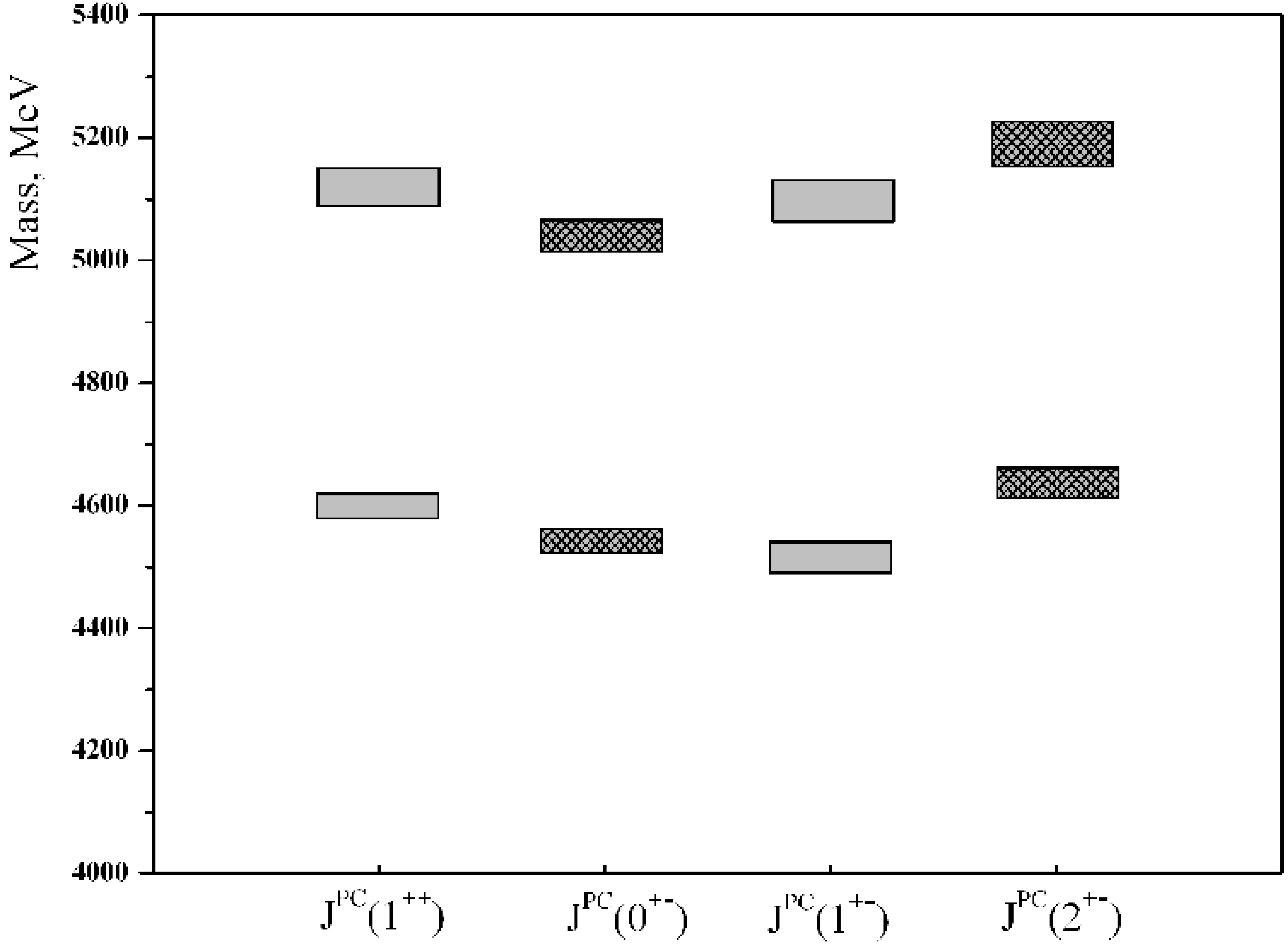
CONCLUSION

- A combined approach has been proposed to study the charmonium and charmed hybrids on the basis of the quarkonium potential model and the relativistic top model for decay products.
- Several promising decay channels of charmonium like $\bar{p}p \to c\bar{c} \to \rho\pi$, $\bar{p}p \to c\bar{c} \to \Sigma^0\bar{\Sigma}^0$, decays into $D\bar{D}$ - pair and decays with J/ψ in the final state $\bar{p}p \to J/\psi + X$ were, in particular, investigated.
- Ten radial excited states of charmonium (two scalar $^1S_0$, three vector $^3S_1$ and tree vector ^3P_J charmonium states) above $D\bar{D}$ - threshold are anticipated to exist in the framework of the combined approach.
- The recently discovered states above $D\bar{D}$ – threshold (*XYZ*-particles) have been elaborately analyzed. Some of these states can be interpreted as higher laying radial excited states of charmonium. This treatment seems to be perspective and needs to be carefully verified in the future PANDA experiment with its high quality antiproton beam. The necessity of further studying of *XYZ*-particles and their main characteristics (mass, width, branch ratios) in PANDA experiment was illustrated.
- Several promising decay channels of the charmed hybrids like decays into charmonium and light mesons in the final state $\bar{p}p \to c\bar{c}g \to \chi_{c0,1,2}$ $(\eta, \pi\pi; \ldots)$, $\bar{p}p \to c\bar{c}g \to J/\Psi$ $(\eta, \omega, \pi\pi; \ldots)$ and decays into $D\bar{D}^*$-pair $\bar{p}p \to c\bar{c}g \to D\bar{D}^*\eta$ are, in particular, analyzed at present.
- A possibility to confirm the existence of charmonium and charmed hybrids and verify their main characteristics in PANDA experiment with the high quality antiproton beam, has been demonstrated.
- Using the integral approach, the widths of the anticipated (and also well-established) states of charmonium were calculated. It has been demonstrated that their widths are also narrow and don't have anomalous large values.
- At present the simulation of the appropriate physical processes of charmonium formation and its decay through the considered above channels is started. This information is rather useful for the PANDA detector simulation.

SPECTRUM OF CHARMED HYBRIDS WITH QUANTUM NUMBERS $J^{PC} = 2^{-+}, 1^{-+}, 1^{--}, 0^{-+}$.



SPECTRUM OF CHARMED HYBRIDS WITH QUANTUM NUMBERS $J^{PC} = 2^{+-}, 1^{+-}, 1^{++}, 0^{+-}$.



THIS WORK WAS SUPPORTED BY

FAIR-RUSSIA RESEARCH CENTER

AFTERWORD

- DURING THE PAST SEVERAL YEARS (ESPECIALLY 2008-2010 YEARS) THERE HAVE BEEN MANY NEW DEVELOPMENTS IN HADRON SPECTROSCOPY. IN SOME CASES THE NEW RESULTS REINFORCED OUR UNDERSTANDING IN THE CONTEXT OF CONSTITUENT QUARK MODEL WHILE IN OTHER CASES THEY DEMONSTRATE THAT WE STILL HAVE MUCH TO LEARN.

- IT IS NOT AT ALL CLEAR WHAT MOST OF THE NEW CHARMONIUM-LIKE *XYZ*-STATES ARE. THERE ARE NOW SOMETHING LIKE 16 CHARMONIUM-LIKE STATES WITH NEW ONES, SEEMINGLY, DISCOVERED EVERY OTHER DAY.

- IT HAS BEEN SUGGESTED THAT MANY OF THE *XYZ*-STATES ARE HIGHER LAYING SCALAR AND VECTOR CHARMONIUM STATES, SOME OF THEM ARE MULTIQUARK STATES, EITHER TETRAQUARKS OR MOLECULES. THE POSSIBILITY THAT SOME OF THE *XYZ* – STATES ARE MOLECULES IS LIKELY INTERTWINED WITH THRESHOLD EFFECTS THAT OCCUR WHEN CHANNELS ARE OPENED UP.

- MANY OF THE *XYZ* – STATES NEED INDEPENDENT CONFIRMATION AND TO UNDERSTAND THEM WILL REQUIRE DETAILED STUDIES OF THEIR PROPERTIES. WITH BETTER EXPERIMENTAL AND THEORETICAL UNDERSTANDING OF THESE STATES WE WILL HAVE MORE CONFIDENCE IN BELIEVING THAT ANY OF THESE NEW STATES ARE CONVENTIONAL $c\bar{c}$ STATES OR NON-CONVENTIONAL $c\bar{c}$ STATES LIKE MOLECULES, TETRAQUARKS AND HYBRIDS.

- HADRON SPECTROSCOPY CONTINUES TO INTRIGUE WITH A BRIGHT FUTURE. THERE IS THE POTENTIAL FOR MANY NEW MEASUREMENTS (BABAR, BELLE). **PANDA AT FAIR PROMISE TO PRODUCE EXCITING NEW PHYSICS IN THE LONGER TERM.**

- STUDY OF CHARMONIUM SPECTROSCOPY SEEMS TO BE PERSPECTIVE IN THE EXPERIMENTS USING LOW ENERGY ANTIPROTON BEAMS WITH THE MOMENTUM RANGING FROM 1 GeV/c TO 15 GeV/c. THEREFORE THE **PANDA EXPERIMENT** WITH ITS HIGH QUALITY ANTIPROTON BEAM (HIGH LUMINOSITY, MINIMAL BEAM MOMENTUM SPREAD, SMALL LATERAL BEAM DIMENSIONS) IS SURE TO BE AN EXCELLENT TOOL TO STUDY THE CHARMONIUM SPECTROSCOPY