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

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WITH THE CONSTRACTION OF **HESR** A NEW ERA IN CHARM-PHYSICS WOULD START:

● search for the bound states with gluonic degrees of freedom: glueballs and hybrids of the type *gg, ggg,* $\overline{Q}Qg$, Q^3g in mass range from 1.3 to 5.0 GeV. Especially pay attention at the states $\overline{s}sg$, $\overline{c}cg$ in mass range from 1.8 – 5.0 GeV.

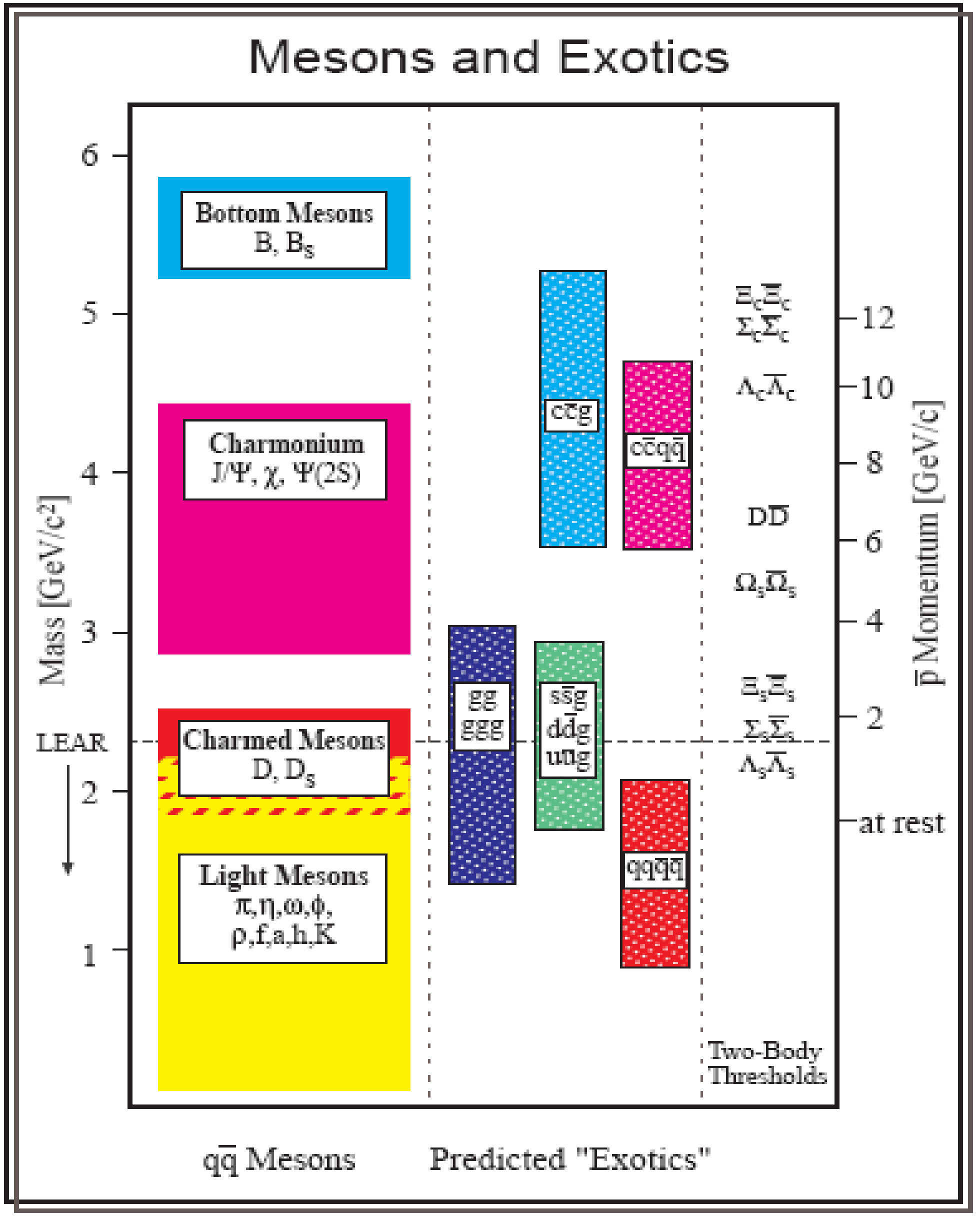
● charmonium spectroscopy $\overline{c}c$ (measuring of mass, width and branch ratios of different charmonium decays in mass range from 2.9 GeV to 5.0 GeV).

● baryons and nuclei with strangeness and charm: $\overline{\Lambda}\Lambda$, $\overline{\Sigma}\Sigma$, $\overline{\Xi}\Xi$, $\overline{\Omega}\,\Omega$ up to $\Omega^0{}_c$, $\Xi^+{}_{cc}$.

● *D*-meson spectroscopy and *D*-meson interactions: *D*-meson in pairs and *D*-meson decays.

● *CP*-violation in strange and charmed sector (*D*-meson, *Λ*-hyperon decays).

● production and study of hypernuclei, double,… hypernuclei to get information about their structure and nucleon-hyperon and hyperon-hyperon interaction.



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

PREAMBLE

1. STUDY OF THE MAIN CHARACTERISTICS OF CHARMONIUM 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 MAINLY ABOVE $D\bar{D}$-THRESHOLD. ESPECIALLY PAY ATTENTION AT THE NEW RECENTLY DISCOVERED STATES WITH HIDDEN CHARM (***XYZ***-PARTICLES). 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 ABOVE $D\bar{D}$-THRESHOLD.

4. A BRIEF REVIEW OF THE NEW ***XYZ*** CHARMONIUMLIKE MESON STATES AND ATTEMPTS OF THEIR POSSIBLE INTERPRETATION.

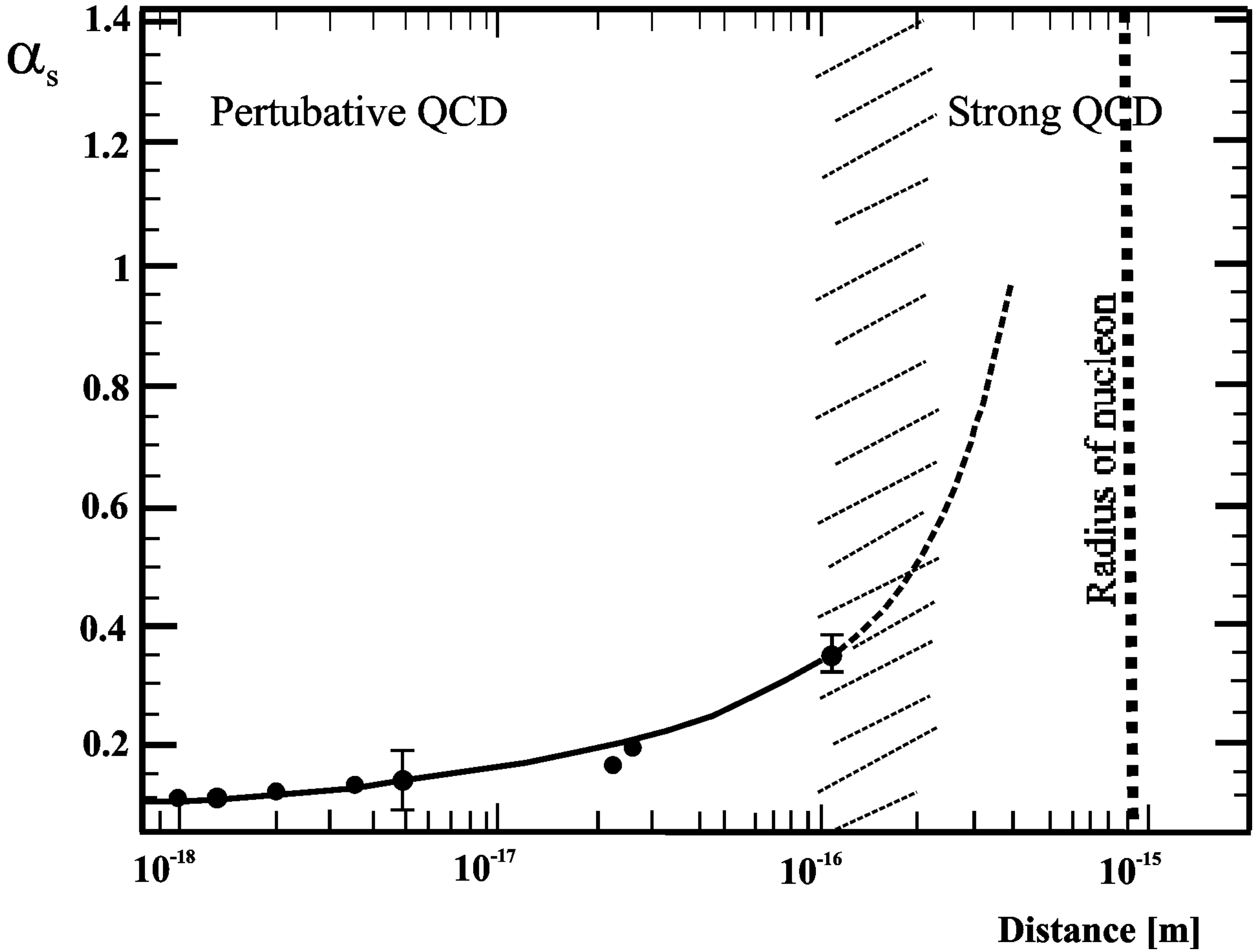
5. APPLICATION OF THE INTEGRAL FORMALISM FOR DECAY OF HADRON RESONANCES TO CALCULATE THE WIDTHS OF RADIAL EXCITED STATES OF CHARMONIUM. ANALYSIS OF THE RESULTS OF CALCULATION FOR THE WIDTHS OF ***SCALAR*** AND ***VECTOR*** CHARMONIUM STATES (MAINLY ABOVE $D\bar{D}$-THRESHOLD) IN THE FRAMEWORK OF INTEGRAL 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;

Therefore:

- 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 $<v^2/c^2> \approx 0.2$.

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: $\begin{cases} V(r)|_{r\to 0} \sim 1/r \text{ or } \dfrac{1}{r\ln(1/r\Lambda)} \\ V(r)|_{r\to\infty} \sim kr \end{cases}$

The Cornel potential: $\boldsymbol{V(r) = -a/r + kr;}\ a = 0.52$ 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 $C = (-1)^{L+S}$.

According to the non-relativistic potential model of quarkonium the spectrum and wave functions defines from the Schrodinger-type 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 charmonium (quarkonium). One of the QCD features consists of the fact that well developed method of calculation in the field theory - perturbation theory can be applied only at small distances or large transfer momentum. From this follows that for heavy quarkonium with small radius of bound state in qaurk-antiquark potential will dominate the term deals with one-gluon exchange : $V(\vec{q}^2)\sim\frac{\alpha_s(q^2)}{q^2}$ or $V(r)\sim\frac{\alpha_s(r)}{r}$.

The coupling constant $\alpha_s = g^2/4\pi$; g – the constant of colour interaction; $\vec{q}$ - three-dimensional momentum transferred between quark and antiquark.

At small distances interaction reduces and manifests via the dependence:

$$\alpha_s\sim\frac{1}{\ln(q^2/\Lambda^2)} \quad (\text{when } q^2\to\infty) \text{ or } \quad \alpha_s\sim\frac{1}{\ln(1/r^2\Lambda^2)} \quad (\text{when } r\to 0)$$

where Λ – is QCD parameter. This dependence defines the phenomenon of asymptotic freedom and emerges from renormgroup approach: (A.A. Bykov et al. Physics – Uspekhi, V.143, N1, 1 (1984)).
QCD doesn't applicable at large distances.
From LQCD we have: $V(q^2) \sim \frac{1}{q^4}(q^2 \to 0)$ or $V(r) \sim r\,(r \to \infty)$

corresponding to interaction between quarks with the strength: $F = -dV\frac{r}{dr} = const.$

When $R\to\infty$ quantum fluctuations of the string are present: $V(r)|_{r\to\infty} = kr - \frac{\gamma}{r}.$
These properties underlie the choice most of potentials:

$$\begin{cases} V(r)|_{r\to 0} \sim 1/r \ \text{ or } \ \dfrac{1}{r\ln(1/r\Lambda)} \\ V(r)|_{r\to\infty} \sim kr \end{cases}$$

Cornell Potential: $V(r) = -a/r + kr$; a = 0.52 GeV; k = 0.18 GeV.
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:

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

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

When cotangent argument in $V_3(r)$ is small: $r^2/a^2 \ll \pi^2$, 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 $\longrightarrow$ $\vec{M} = [\vec{r} \times \vec{p}];\ \vec{N} = r_4 \vec{p} - \vec{r} p_4$

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 $\longrightarrow$ $\vec{N} = R\vec{p} + \vec{r}(\vec{r}, \vec{p}) / R$

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

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:

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

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

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

the Hamiltonian tends to the Pauli operator for the free particle motion:

$$H = \frac{1}{2mR^2}\{2\hbar + (\vec{\mu}_{\pm}, \vec{\sigma})\}\{2\hbar + (\vec{\mu}_{\pm}, \vec{\sigma})\} \to \frac{1}{2m}(\vec{p}, \vec{\sigma})^2.$$

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 $\longrightarrow$ $\vec{J}^2 = ((\vec{\mu}_{\pm} + \vec{\sigma})/2)^2$ of the top.

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

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:

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

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 $p\bar{p}$-annihilation (the experiments R704 at CERN and E760/E835 at Fermilab).

The number of unsolved questions related to charmonium has remained:

- radial excited scalar states of charmonium $^1S_0$ (except $\eta_c(2S)$) are not found yet, radial excitations of $^1P_1$ - state and $^1D_2$ - state are also not established;

- properties of radial excited vector states of charmonium $^3S_1$ and ^3P_J are badly investigated;

- only few partial widths of ^3P_J - vector states are known (some of the measured decay widths don't fit into 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);

- ^3D_J - vector states and their radial excitations are not established yet;

AS RESULT:

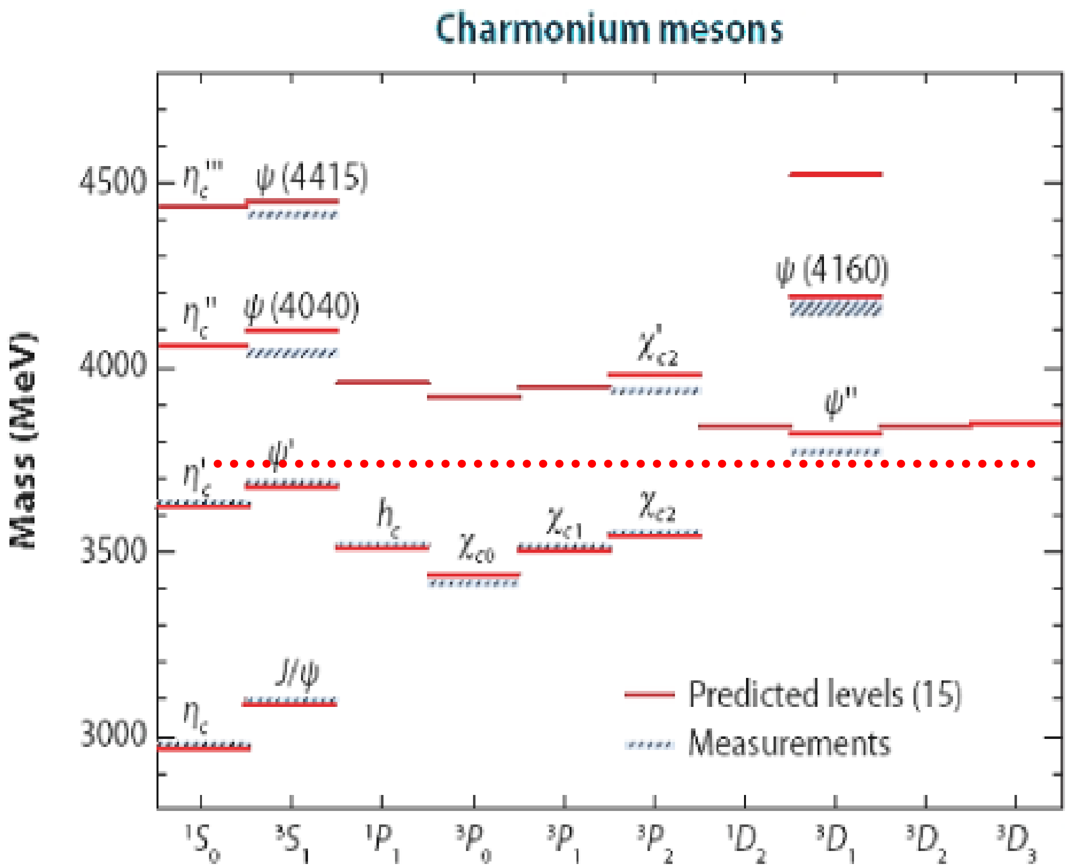
● little is known on charmonium states above the the $D\bar{D}$ – threshold (*S, P, D,….*);

● many recently discovered states above $D\bar{D}$ - threshold (*XYZ*-states) expect their verification and explanation (their interpretation nowadays is far from being obvious).

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

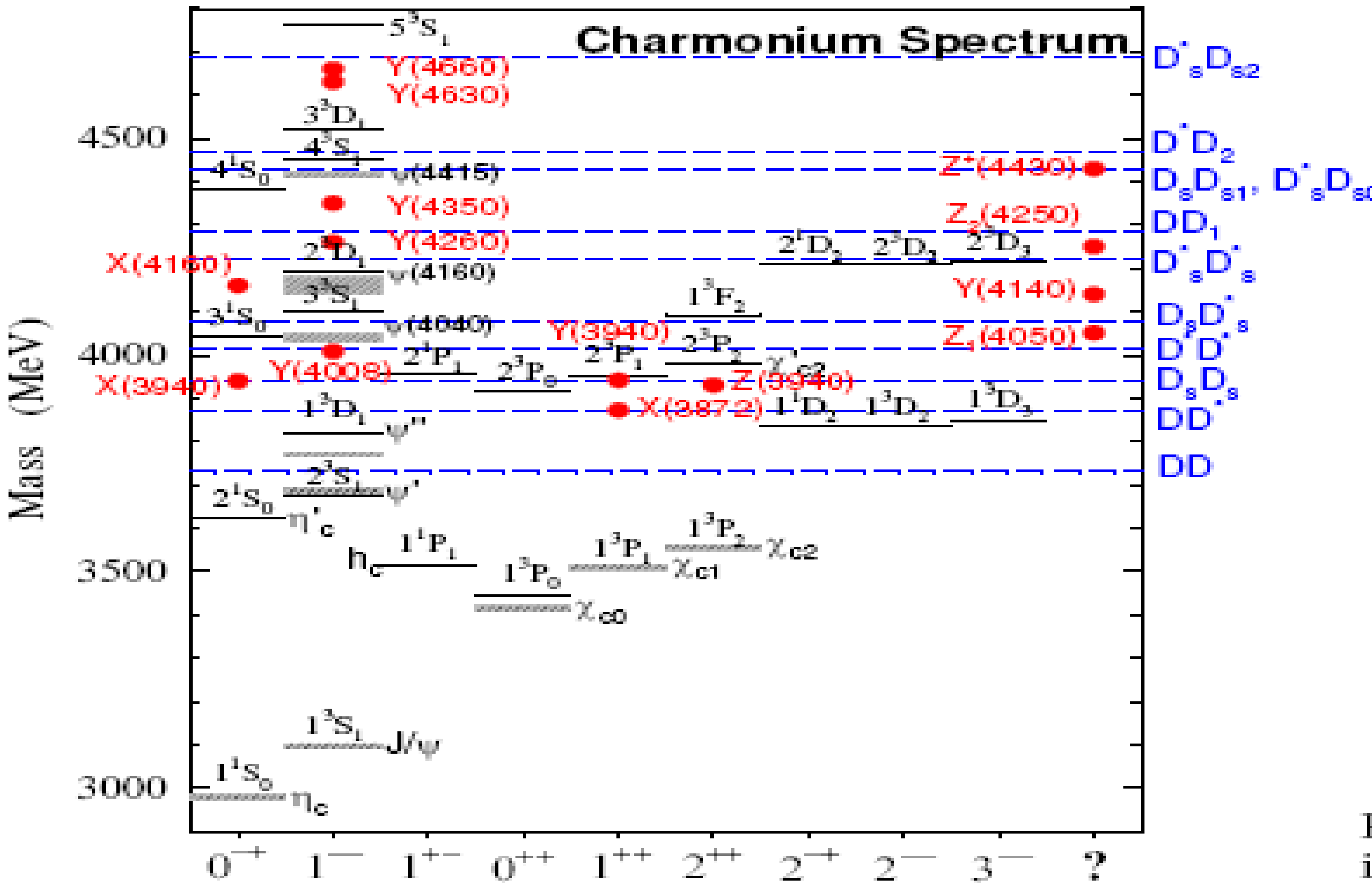
- decays into particle-antiparticle or $D\bar{D}$-pair: $p\bar{p} \rightarrow (\Psi, \eta_c, \chi_{cJ}) \rightarrow$ barion-antibaryon or $D^{(*)}\bar{D}^{(*)}$
- decays into light hadrons: $p\bar{p} \rightarrow (\Psi, \eta_c) \rightarrow \rho\pi$; $p\bar{p} \rightarrow \Psi \rightarrow \pi^+\pi^-$,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

$c\bar{c}$ meson spectrum



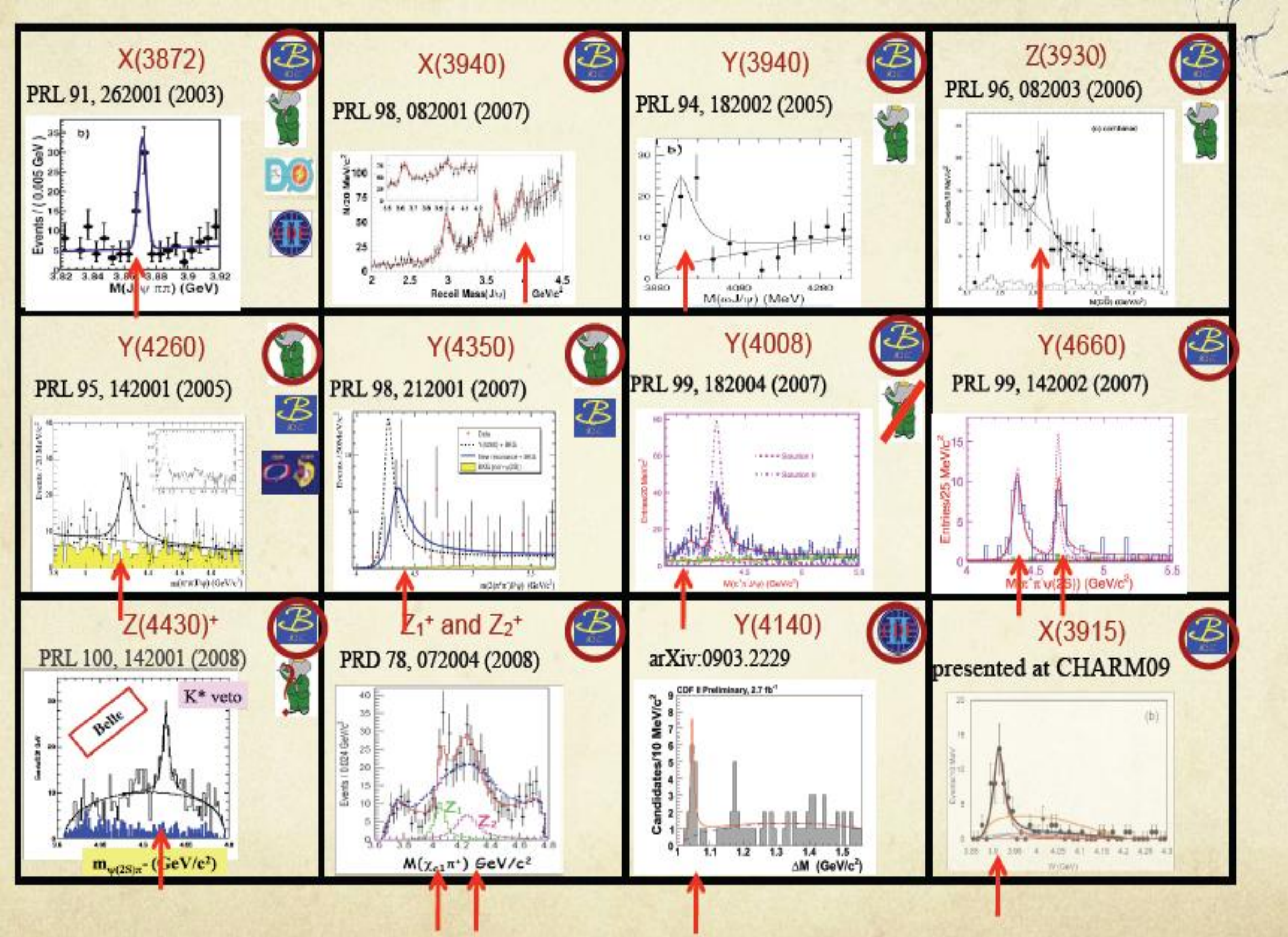
- mass spectrum predicted by potential models and lattice calculations
- good agreement with data below $D\bar{D}$ threshold
- missing states above threshold
- defined basis to study meson structure

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 $D_S^{(*)}\bar{D}_S^{(*)}$ 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.



Many new states: above $D\overline{D}$ – 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

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}	?	$B \to KZ_1^{\pm}(4050) \to \pi^{\pm}\chi_{c1}$	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	

Unusual strong decay into hidden charm

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

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

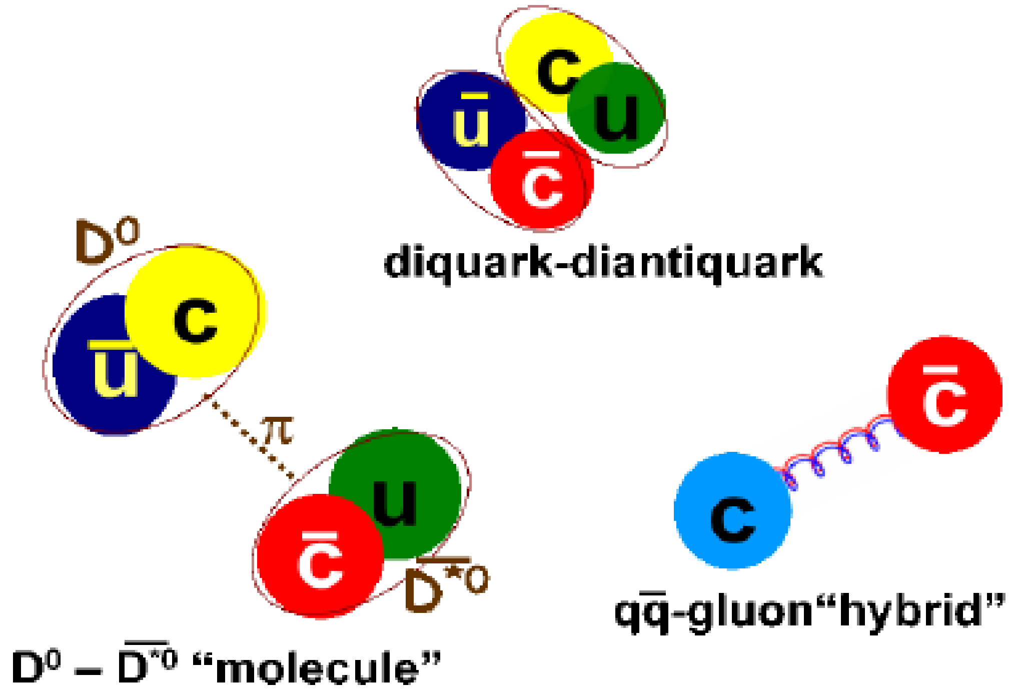
***B*-decays to final states containing $c\overline{c}$ mesons.** At the quark level, the dominant decay mechanism is the weak interaction transition of a *b* quark to *c* quark accompanied by the emission of a virtual W^- boson, the mediator of the weak interaction. Approximately half of the time, the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

■ **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 => $e^+e^- \to J/\Psi + (c\overline{c}) \Rightarrow J/\Psi + \eta_c$ 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 [$cu\bar{c}\bar{d}$], strangeness [$cd\bar{c}\bar{s}$], or both [$cu\bar{c}\bar{s}$] (Z^+ - particles). * *Maiani, et al., Phys. Rev.,* ***D*** *71:014028.*

$C\bar{C}g$ – charmed hybrid

Charmed hybrids are the states with excited gluonic degree of freedom. These states are described by many different models and calculational schemes (LQCD, flux tube model).

$J^{PC}=0^{+-}, 1^{-+}, 2^{+-}$ - exotic quantum numbers (0^{--} - is exotic quantum number).

$J^{PC}=0^{-+}, 1^{+-}, 2^{-+}, 1^{++}, 1^{--}$ - non-exotic quantum numbers.

$C\bar{C}g$ – decay modes

$c\bar{c}g \to$ decay via electromagnetic and hadronic transitions & open charm final states.

Two important decay modes are:

- $c\bar{c}g \to D^{(*,**)}\bar{D}^{(*,**)}$ (P-wave +S-wave mesons). Thus D (L=0) + $\bar{D}^{**}$ (L=1) final states should dominate over decays to $D\bar{D}$ and the partial width of $D\bar{D}^{**}$ should be very small.
- $c\bar{c}g \to c\bar{c}$ (Ψ, χ_{cJ}) + light mesons (η, η', ω, φ). These modes supply small widths and significant branch fractions.

$C\bar{C}g$ – masses

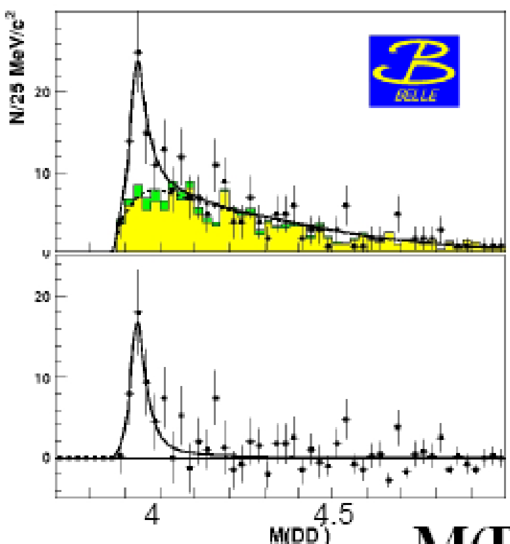
$c\bar{c}g \to$ is expected a multiplet consisting of eight states with masses in the 4000 MeV/c^2 to 4500 MeV/c^2 mass range (flux tube model).

The X,Y,Z near 3940 MeV

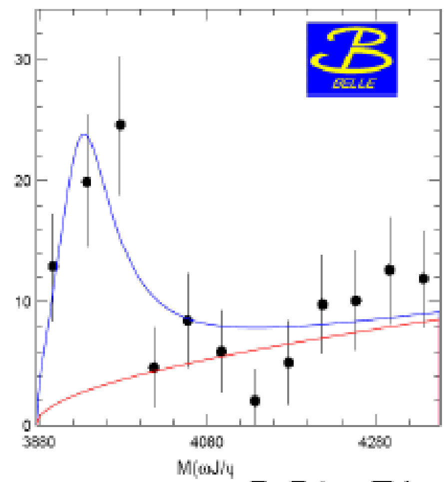
not seen in $\omega J/\psi$	probably different	not seen in DD^*	Probably the χ_{c2}'

X(3940) — **Y(3940)** — **Z(3930)**

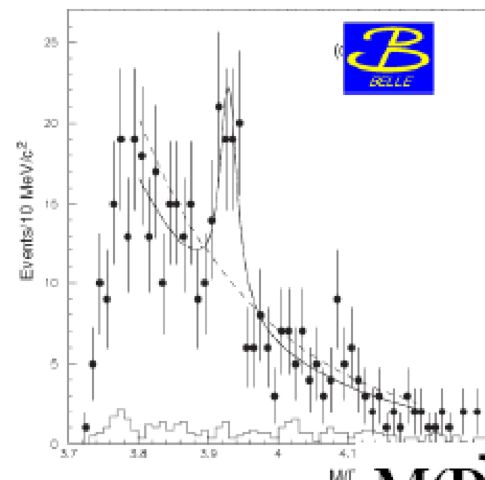
$e^+e^- \to J/\psi\ D\bar{D}^*$ | $B \to K\ \omega J/\psi$ | $\gamma\gamma \to D\bar{D}$



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



$M(\omega J/\psi)$



$M(D\bar{D})$

$M = 3942\ ^{+7}_{-6} \pm 6$ MeV

$\Gamma_{tot} = 37\ ^{+26}_{-15} \pm 12$ MeV

Nsig $= 52\ ^{+24}_{-16} \pm 11$ evts

PRL 100, 202001 (2008)

$M \approx 3940 \pm 11$ MeV

$\Gamma \approx 92 \pm 24$ MeV

PRL94, 182002 (2005)

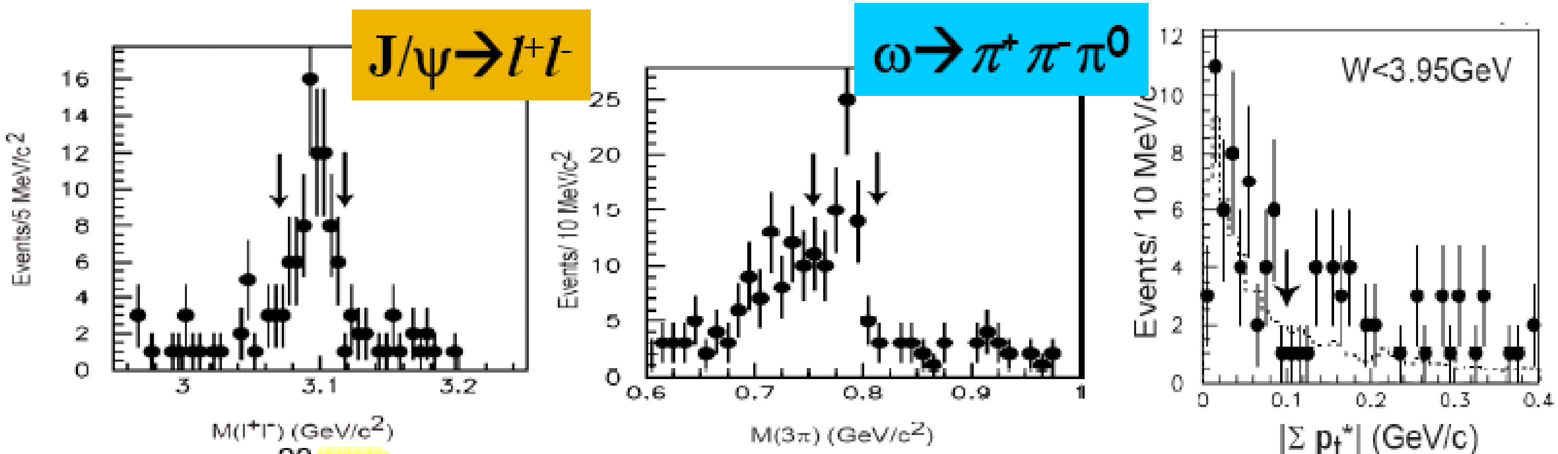
$M = 3929 \pm 5 \pm 2$ MeV

$\Gamma_{tot} = 29 \pm 10 \pm 2$ MeV

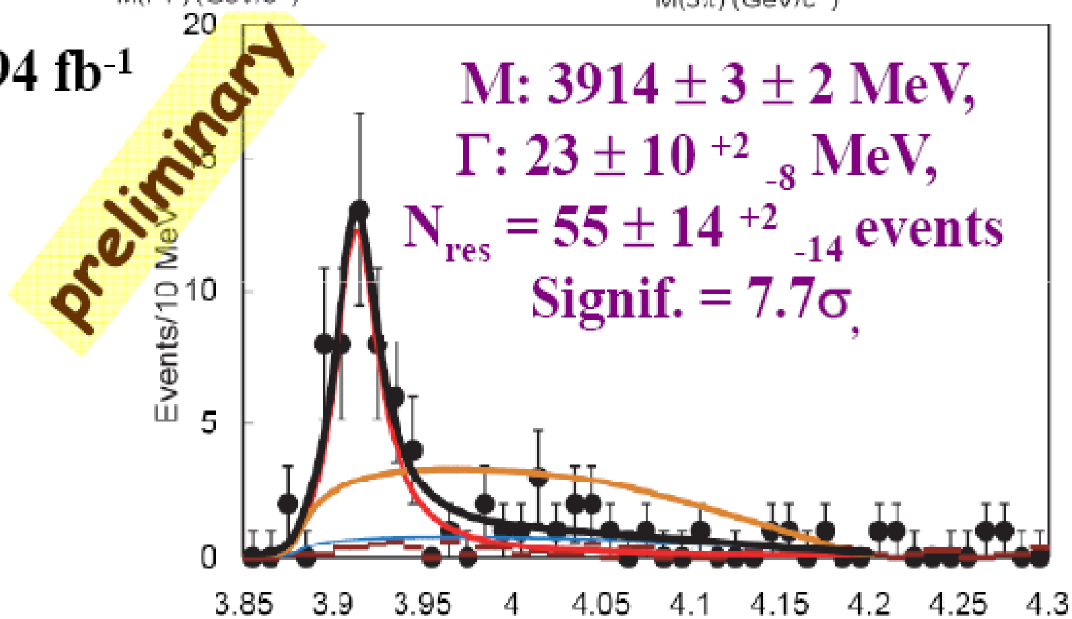
Nsig $= 64 \pm 18$ evts

PRL 96, 082003 (2006)

New peak in γγ→ωJ/ψ from Belle



694 fb^{-1}



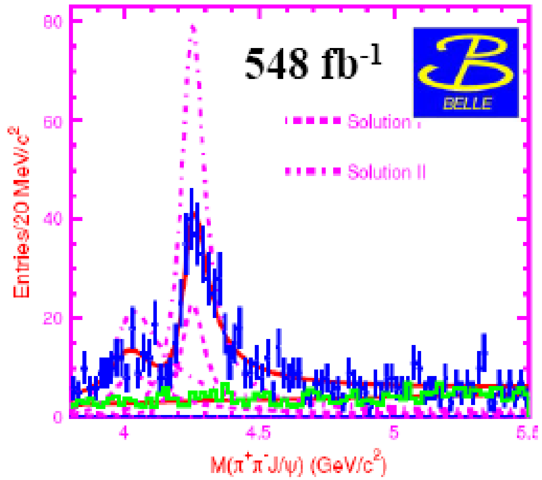
Two-photon production of Y(3940)?

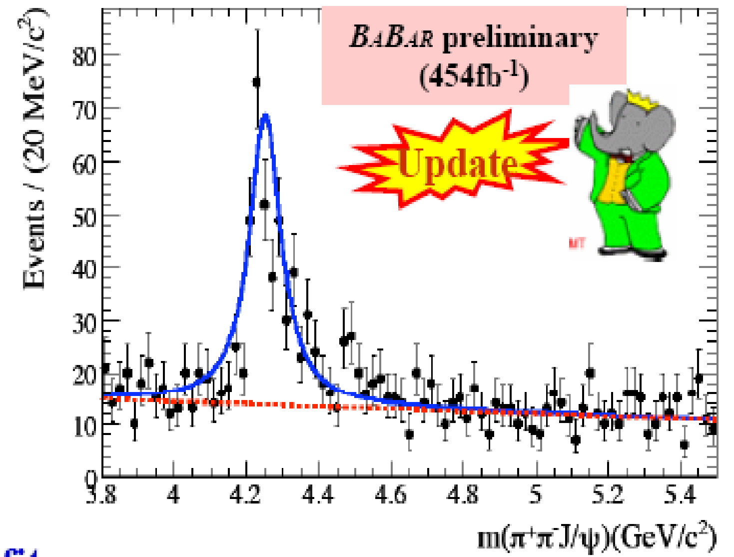
or New decay mode of Z(3930)?

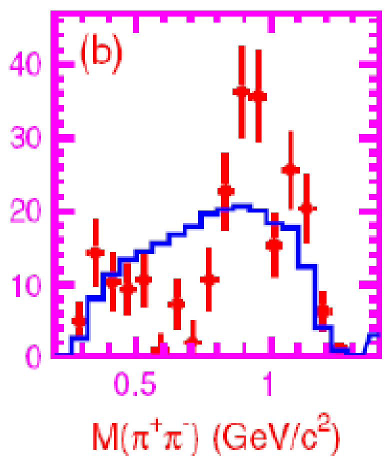
Updates of Y(4260)

Belle, PRL 99, 182004 (2007)

BaBar, arXiv:0808.1543(2008)







Belle's Two-peak fit

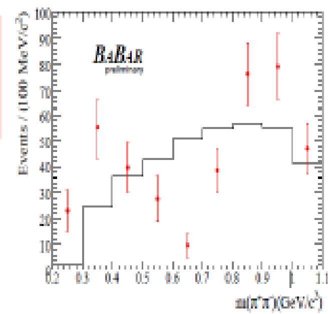
M=4008 ±40 $^{+114}_{-28}$ MeV
Γ=226 ± 44 ± 87 MeV

M=4247 ± 12 $^{+17}_{-32}$ MeV
Γ=108 ± 19 ± 10 MeV

BaBar's single-peak fit

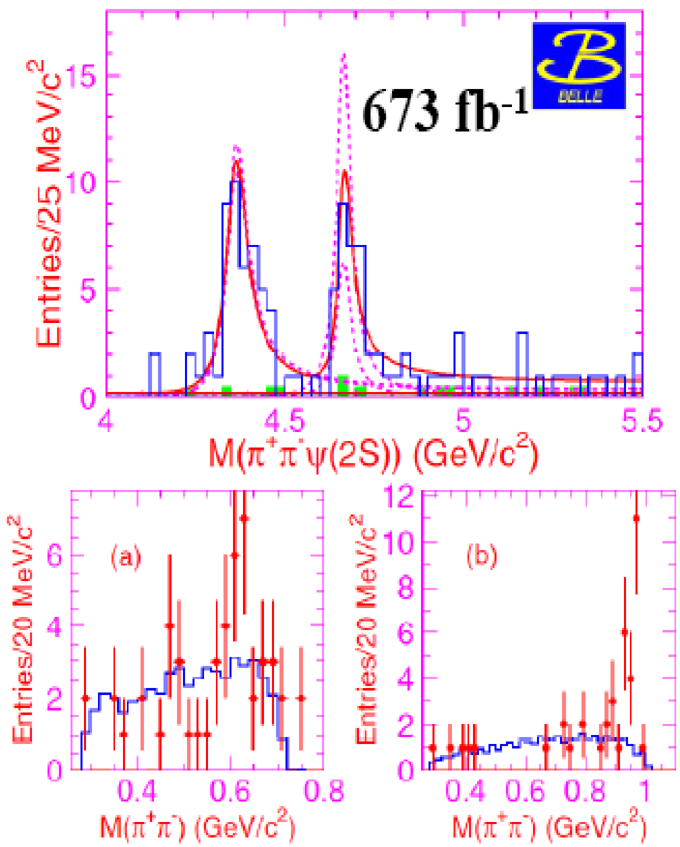
M=4252 ± 6 $^{+2}_{-3}$ MeV
Γ=105 ± 18 $^{+4}_{-6}$MeV

Y(4008) is not evident.

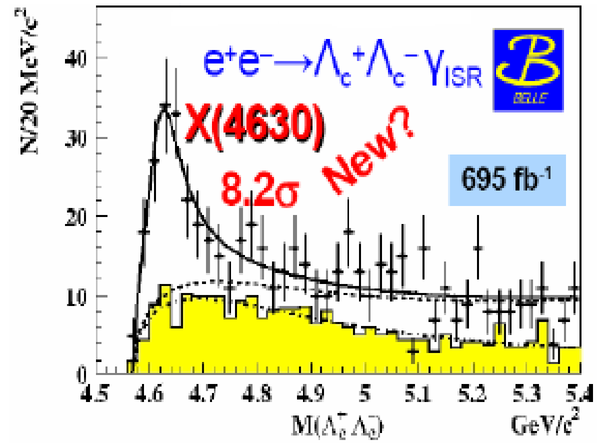


Y(4320) and Y(4664), and X(4630) in $\Lambda c^+ \Lambda c^-$

Belle, PRL 99, 142002 (2007)



Belle. PRL 101, 172001(2008)



State	M, MeV/c^2	Γ_{tot}, MeV
X(4630)	4634^{+8+5}_{-7-8}	92^{+40+10}_{-24-21}
Y(4660)	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$

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

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

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$\overline{\text{D}}$** (only J^{PC} = 0^{++} and J^{PC} = 2^{++})
- **Y(3940) – B → KωJ/ψ (**J^{PC} = 1^{++}**) =>** $\frac{\mathcal{B}(Y(3940) \to \omega J/\psi)}{\mathcal{B}(Y(3940) \to D^{*0}\bar{D}^0)} > 0.75$
- **X(3940) – e$^+$e$^-$ → J/ψ D$\overline{\text{D}}$*** **(**J^{PC} = 0^{-+}, not 0^{++}) => $\frac{\mathcal{B}(X(3940) \to \omega J/\psi)}{\mathcal{B}(X(3940) \to D^{*0}\bar{D}^0)} < 0.60$

New state

- **Y(4140) – B → KφJ/ ψ** (B → KωJ/ ψ)

double charm production

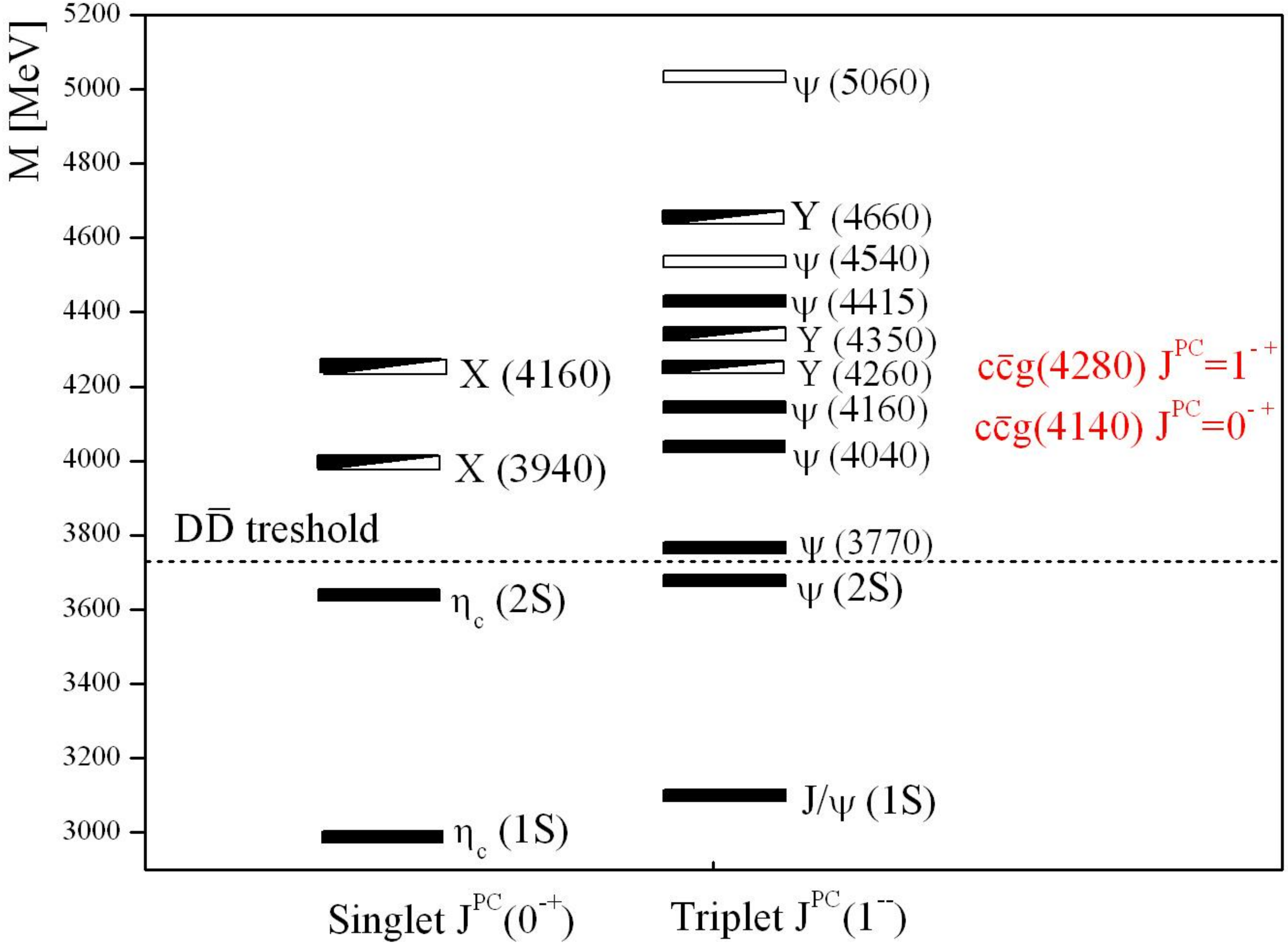
- **X(4160) – e$^+$e- → J/ ψ D*$\overline{\text{D}}$* (**J^{PC} = 0^{-+}, not 0^{++})
- **Y(4260) – e$^+$e$^-$ → γ π$^+$π$^-$J/ψ (**appears a dip in the measured total cross section**)**
- **Y(4350) – e$^+$e$^-$ → γ π$^+$π$^-$ψ(2*S*)** (no evidence for open charm decay D$\overline{\text{D}}$, …, D*$\overline{\text{D}}$*)
- **Y(4660) – e$^+$e$^-$ → γ π$^+$ π$^-$ ψ(2S)(**no evidence for open charm decay D$\overline{\text{D}}$, …, D*$\overline{\text{D}}$*)
- **Z$^\pm$(4430) – B → Kπ$^\pm$ ψ(2*S*); Z$^\pm$(4050) – B → K π$^\pm\chi_{c1}$; Z$^\pm$(4250) – B → K π$^\pm\chi_{c1}$**
- ISR 1^{--} states => higher laying conventional c$\bar{\text{c}}$ states : Y(4350) <=> 3^{3}D$_1$ and Y (4660) <=> 5^{3}S$_1$ 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) – not charmonium; some authors interpret this as $D^0\overline{D}^{*0}$ molecule or tetraquark $[(cq)\,(\overline{cq})]_{\text{S-wave}}$ $(q = u, d)$ [1),2)]
  - X(3915) – $\chi_{c0}(2P)$
  - Y(3940) – $\chi_{c1}(2P)$
  - Z(3930) – $\chi_{c2}(2P)$
  - X(3940) – $\eta_c(3S)$
  - Y(4140) – $c\overline{c}g$
  - X(4160) – $\eta_c(4S)$
  - Y(4260) – Ψ''; some authors interpret as charmed hybrid $(c\overline{c}g)$ or tetraquark $[(cs)\,(\overline{cs})]_{\text{P-wave}}$, or baryonium $\Lambda^+_c\Lambda^-_c$ [1),2)]
  - Y(4350) – Ψ'''…
  - Y(4660) – Ψ''''…
  - $Z^{\pm}$(4430) – not charmonium; some authors interpret this as charged tetraquark state $[(cu)][(\overline{cd})]$ or baryonium $\Lambda^{\pm}_c\overline{\Sigma}^0_c$ [1),2)], or $D^*\overline{D}_1(2420)$ molecule
  - Y(4630) – baryonium $(\Lambda^+_c\Lambda^-_c)$, threshold effect or what??

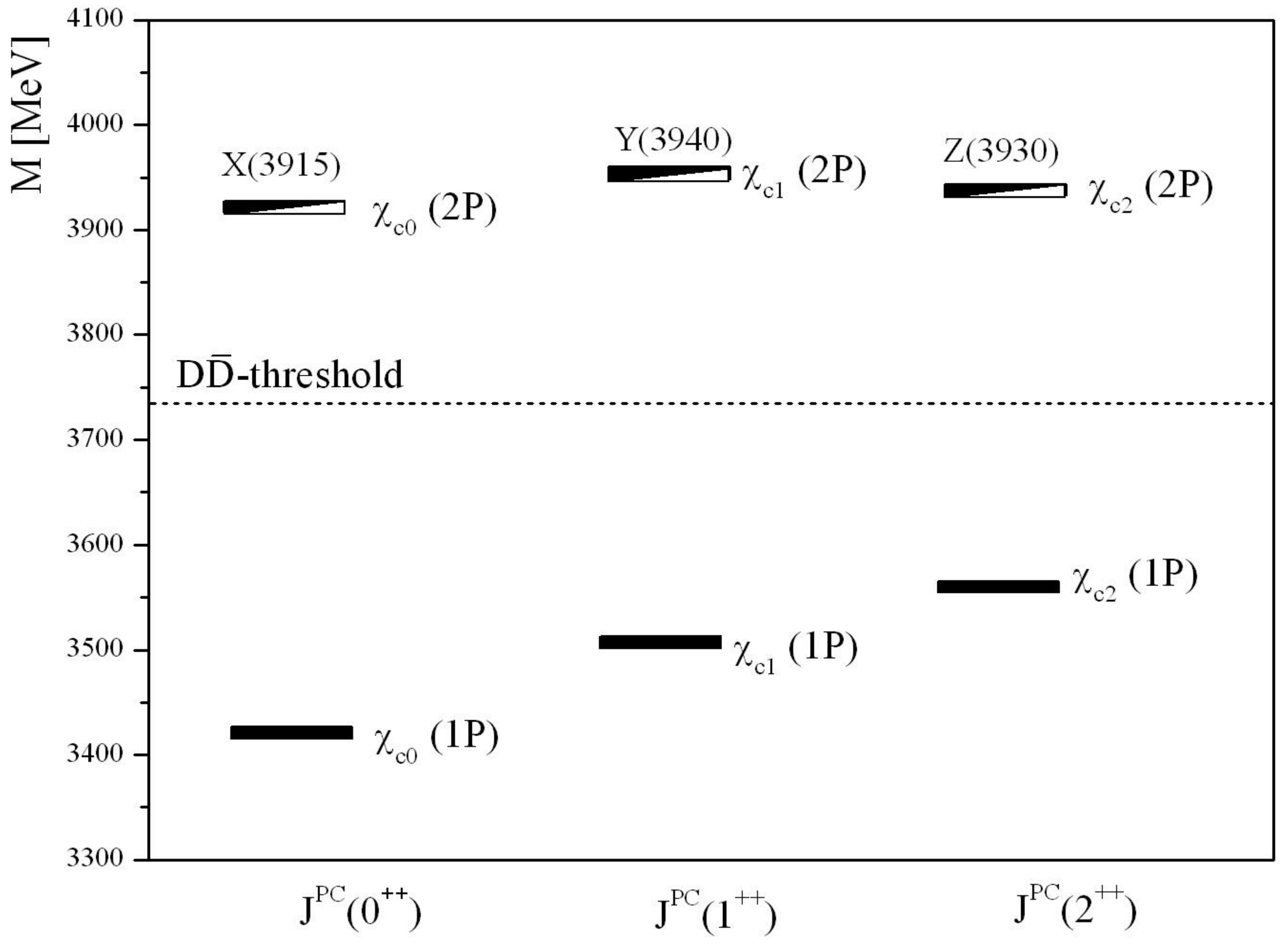
1) **presented by Prof. Luciano Maiani, INFN, XII Conference on Hadron Spectroscopy, Frascati, Italy, 2007**

2) **presented by Prof. Roberto Mussa, INFN, XII Conference on Hadron Spectroscopy, Frascati, Italy, 2007**

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):

$$\Gamma = 2\pi \left| \int_0^{\infty} \phi_L(r) V(r) F_L(r) dr \right|^2$$

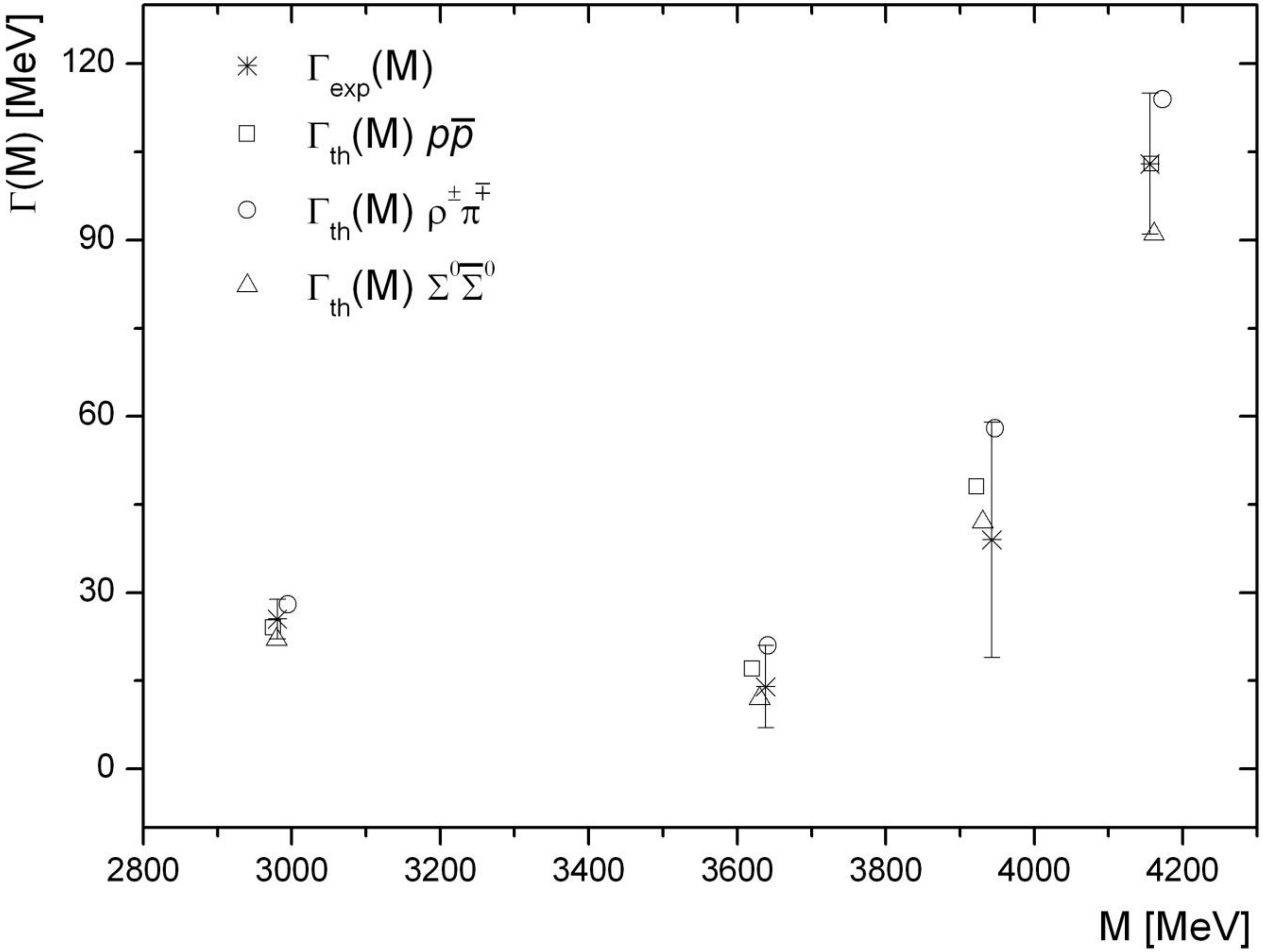
where

$$(r < R): \int_0^{R} |\phi_L(r)|^2 dr = 1$$

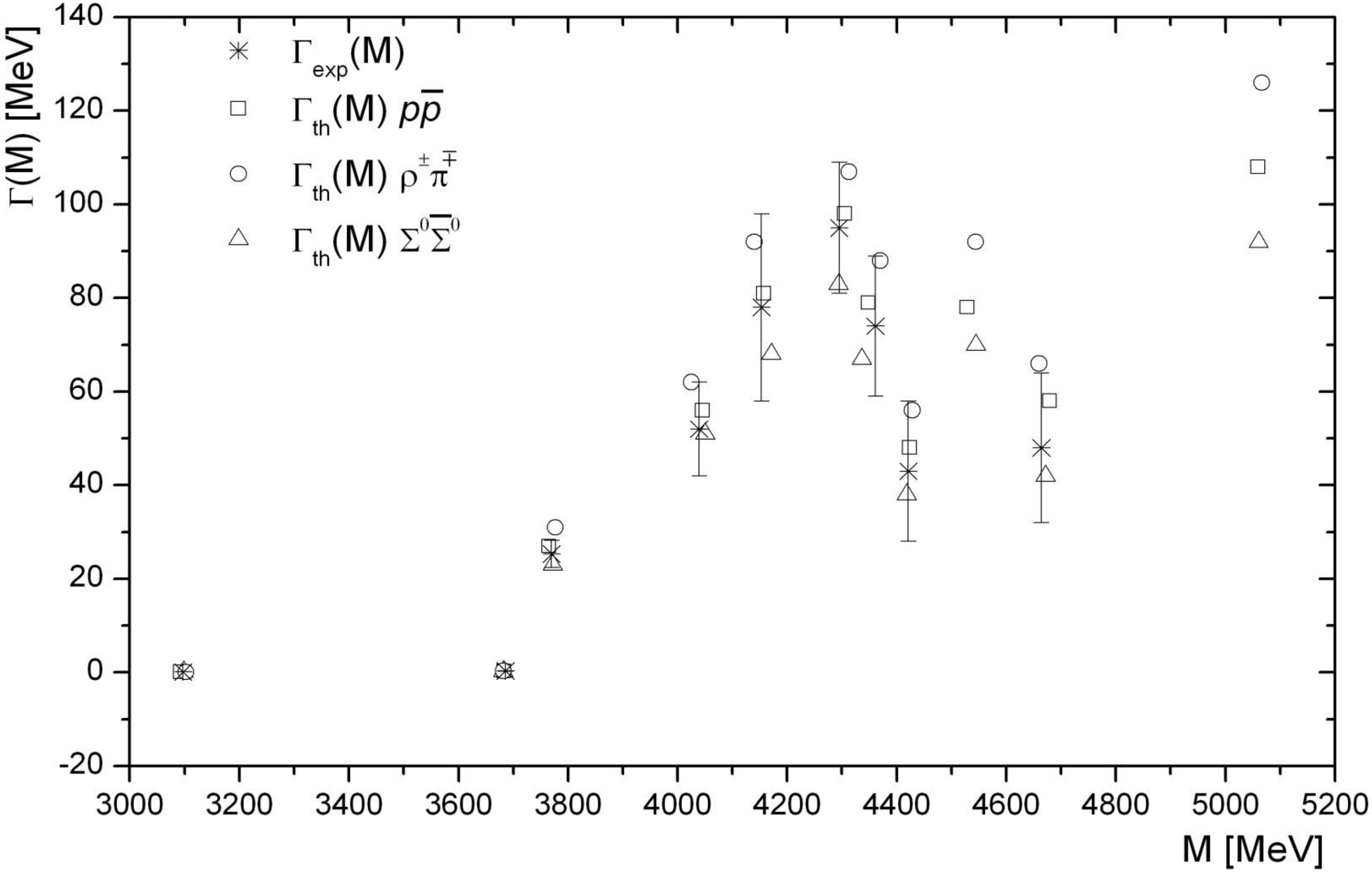
where $F_L(r)$ – is the regular decision in the $V_2(r)$ potential, normalized on the energy delta-function; $\phi_{L(}r)$ – normalized wave function of the resonance state. This wave function transforms into irregular decision in the $V_2(r)$ potential far away from the internal turning point.

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

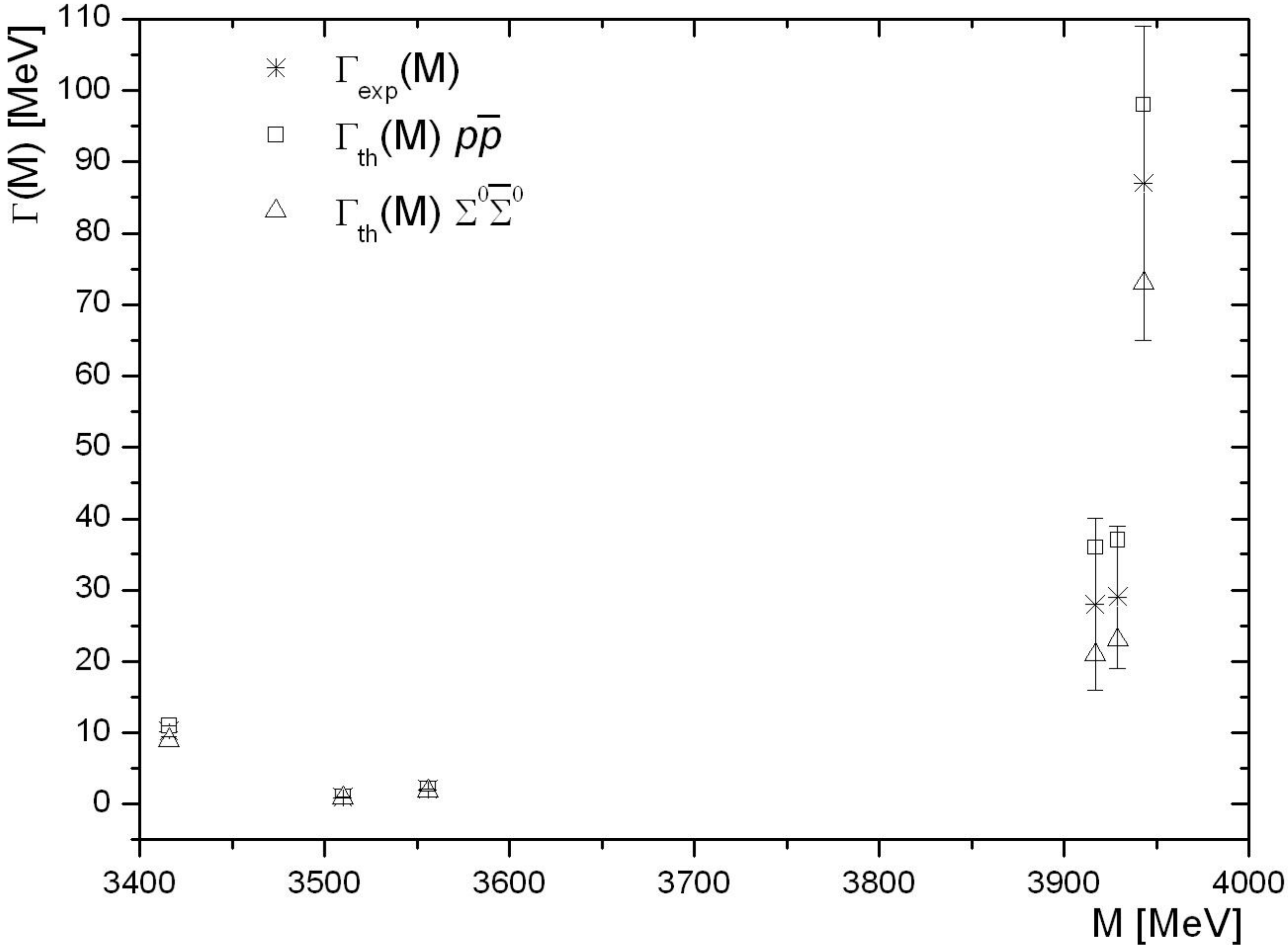
THE WIDTHS OF THE SCALAR $^1S_0$ CHARMONIUM STATES



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



THE WIDTHS OF THE ^3P_J CHARMONIUM STATES



CONCLUSION

The progress of the future charmonium and charmed hybrids ($c\overline{c}g$) researches at FAIR is related to the results obtained below:

■ A combined approach has been considered to study the charmonium and charmed hybrids on the basis of quarkonium potential model and relativistic top model for decay products.

■ Several promising decay channels of charmonium like $p\overline{p} \rightarrow c\overline{c} \rightarrow \rho\pi$, $p\overline{p} \rightarrow c\overline{c} \rightarrow \Sigma^0\overline{\Sigma^0}$, decays into $D\overline{D}$ - pair and decays with J/ψ in the final state $p\overline{p} \rightarrow J/\psi + X$ were, in particular, investigated.

■ Ten radial excited states of charmonium (two scalar and eight vector states) above $D\overline{D}$ - threshold are anticipated to exist in the framework of the combined approach.

■ The recently discovered states above $D\overline{D}$ - threshold 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.

■ Using the integral approach, the widths of the expected radial excited (and also well-established) charmonium states were calculated. It has been demonstrated that their widths are also narrow and don’t have anomalous large values.

■ Simulation of the appropriate physical processes of charmonium formation and its decay through the considered above channels is in progress nowadays. This information is rather useful for the PANDA detector simulation.

AFTERWORD

- DURING THE PAST SEVERAL YEARS (ESPECIALLY 2009 YEAR) 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