THE EXCITING NEW DEVELOPMENTS IN THE SPECTROSCOPY OF THE CHARMONIUM REGION

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In Praise of Hadron Spectroscopy

In focussing on **"Beyond the Standard Model"**, we often seem to loose sight of what we still do not know about **"Within the Standard Model"**.

Searching for the promised (?) land of Higgs, supersymmetrics, and extra dimensions is fine, but a whole lot remains to be done in understanding the third leg of the Standard Model, QCD, **the** theory of strong interactions. And the tool for understanding the strong interaction is **hadron spectroscopy**, just as for the electromagnetic interaction it was atomic spectroscopy.

So, with no apologies, and some pride, in this talk I will confine myself to the **new and exciting developments in hadron spectroscopy**.

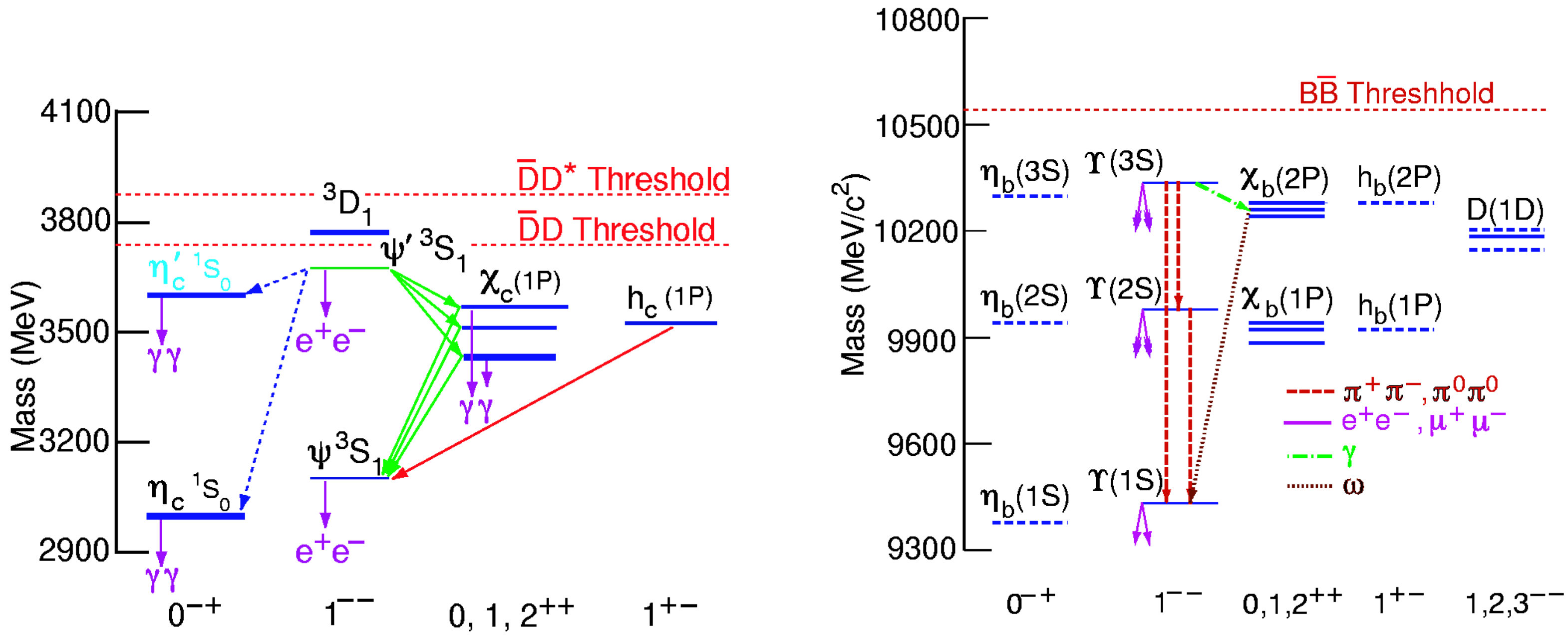
The Contrast Between Light & Heavy Quark Spectroscopy

Light Quarkonia ($n\bar{n}$, $n = u, d, s$)

- $(v/c)^2 \gtrsim 0.7$
  - non–relativistic predictions unreliable
- $\alpha_S \geq 0.6$
  - perturbative calculations unreliable
- $M(u, d, s)$ similar
  - states are mixtures of three flavors
- Broad overlapping states
  $\langle$level spacing$\rangle \approx 14$ MeV
  $\langle$level widths$\rangle \approx 150$ MeV
- Large σ (mb, μb)

Heavy Quarkonia ($c\bar{c}$, $b\bar{b}$)

- $(v/c)^2 \approx 0.2$ $(c\bar{c})$, 0.1 $(b\bar{b})$
  - non–relativistic predictions manageable
- $\alpha_S \approx 0.3$ $(c\bar{c})$, 0.2 $(b\bar{b})$
  - pQCD useful with cautious optimism
- unmixed states of single flavor
- Narrow non-overlapping states
  $\langle$level spacing$\rangle \approx 100$ MeV
  $\langle$level widths$\rangle < 10$ MeV
- Small σ (nb, pb, fb)



CHARMONIUM ($c\bar{c}$) BOTTOMONIUM ($b\bar{b}$)

Heavy Quark (c, b) Spectroscopy

During the last three years there has been a renaissance in hadron spectroscopy. States which have been missing for 30 years have been identified, and a number of new and unexpected states have appeared.

This is all due to the huge e^+e^- luminosities which have become available at Belle (KEK), BaBar (SLAC), and CLEO (Cornell).

To exploit the huge luminosities, state-of-the-art detectors have been deployed, and not only are new, perhaps exotic, states being discovered, great strides are being made in the precision of measurements.

Let me begin with a few examples of precision measurements.

Precision (and what it buys for you)

At Novosibirsk (Pride!) $M(J/\psi) = 3096.917 \pm 0.012$ MeV, ~ 1 part in 3 million [1].

At CLEO (2005) in single measurements (symmetry tests) [2,3]

$\frac{\mathcal{B}(J/\psi \to e^+e^-)}{\mathcal{B}(J/\psi \to \mu^+\mu^-)}$	$\frac{\mathcal{B}(\psi' \to \pi^+\pi^- J/\psi)}{\mathcal{B}(\psi' \to \pi^0\pi^0 J/\psi)}$	$\frac{\mathcal{B}(\psi' \to \pi^0 J/\psi)}{\mathcal{B}(\psi' \to \eta J/\psi)}$
0.997 ± 0.013	2.03 ± 0.04	$(0.40 \pm 0.04)\%$
Lepton Univerisality	Isospin Conservation	Isospin Violation

At CLEO (2006), major gains in precision have been made in measuring **leptonic** and **radiative** decays in $|c\bar{c}>$ charmonium and $|b\bar{b}>$ bottomonium. Numerous controversies and conflicts in $|c\bar{c}>$ and $|b\bar{b}>$ spectroscopy have been settled as a result. An example from Charmonium: A new precision measurement of $\mathcal{B}(\chi_{c2} \to \gamma J/\psi)$ leads to [4]

Measurement	$\Gamma_{\gamma\gamma}(\chi_{c2})$ (eV) (as published)	$\Gamma_{\gamma\gamma}(\chi_{c2})$ (eV) (as corrected)
CLEO (2005)		559 ± 81
Belle (2002)	850 ± 127	570 ± 81
E835 (2002)	270 ± 59	384 ± 83

Precision (and what it buys for you)

An example from $|b\bar{b}>$ bottomonium leptonic decays: [5,6,7]

	$\mathcal{B}_{\mu\mu}$ (%)		Γ_{tot} (keV)		$\mathcal{B}(\Upsilon(nS) \to \gamma\chi_{b2}((n-1)P))$	
	PDG	CLEO	PDG	CLEO	PDG	CLEO
$\Upsilon(1S)$	2.48(6)	2.49(2)	53.0(15)	54.4(18)	—	—
$\Upsilon(2S)$	1.31(21)	2.03(3)	43.0(60)	30.5(14)	6.8(7)	7.2(4)
$\Upsilon(3S)$	1.81(17)	2.39(7)	26.3(34)	18.6(10)	11.4(8)	15.8(7)

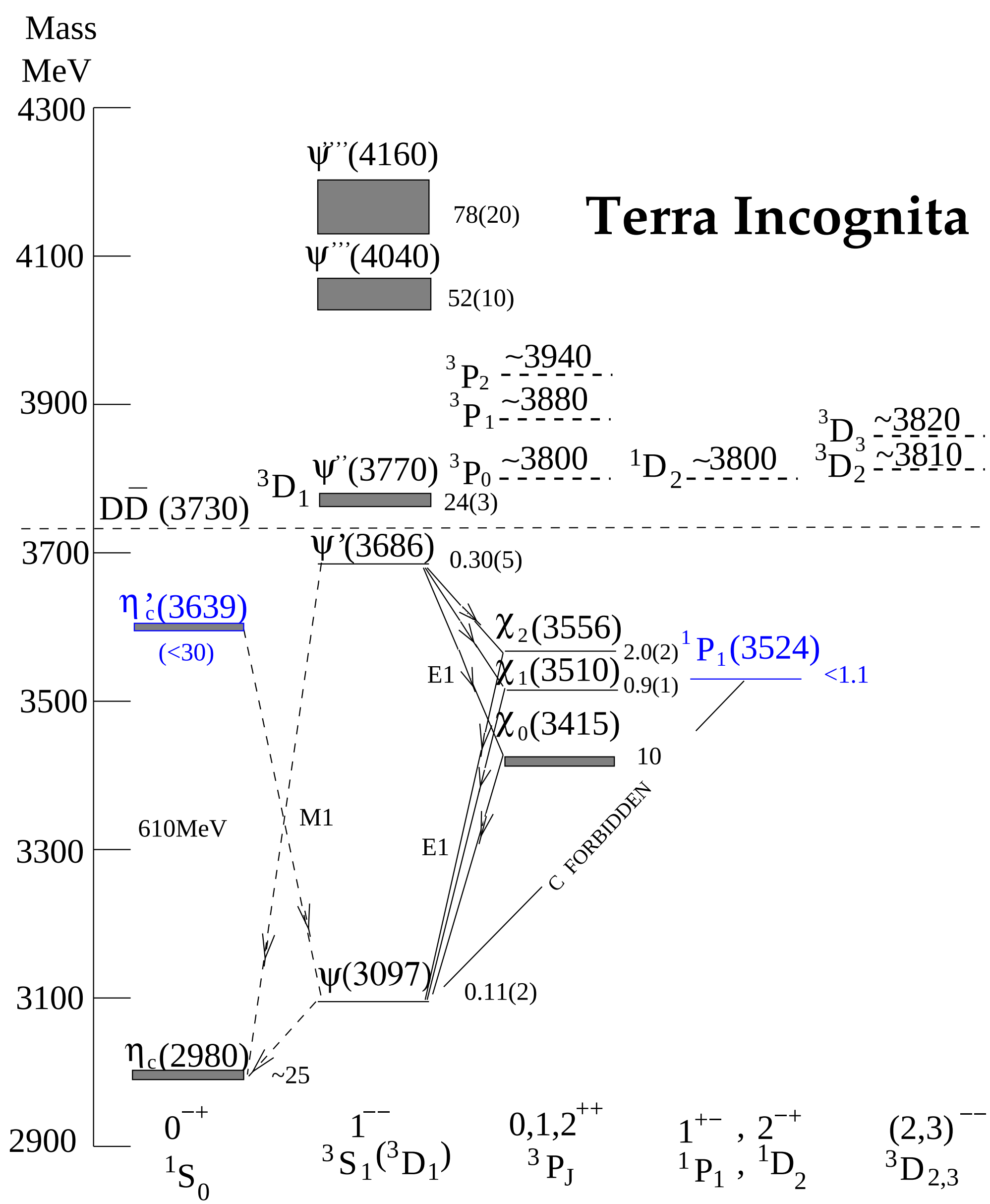
What this precision buys you is confidence in **Lattice QCD!**

For example, the latest unquenched lattice results give:

LATTICE(2005) $\Gamma_{ee}(\Upsilon(2S))/\Gamma_{ee}(\Upsilon(1S)) = 1.28(1)/0.67(3) = 1.91(5)$

CLEO(2006) [6] $\Gamma_{ee}(\Upsilon(2S))/\Gamma_{ee}(\Upsilon(1S)) = 1.35(2)/0.62(1) = 2.18(6)$

Lattice is getting there! Today $|b\bar{b}>$, tomorrow $|c\bar{c}>$?


Terra Incognita
Mass
MeV
4300
4100
3900
3700
3500
3300
3100
2900
ψ'''(4160)
78(20)
ψ'''(4040)
52(10)
3P2 ~3940
3P1 ~3880
3P0 ~3800
1D2 ~3800
3D3 ~3820
3D2 ~3810
3D1
ψ''(3770)
24(3)
DD̄ (3730)
ψ'(3686)
0.30(5)
η'c(3639)
(<30)
χ2(3556)
2.0(2)
1P1(3524)
<1.1
χ1(3510)
0.9(1)
E1
χ0(3415)
10
C FORBIDDEN
610MeV
M1
E1
ψ(3097)
0.11(2)
ηc(2980)
~25
0−+
1S0
1−−
3S1(3D1)
0,1,2++
3PJ
1+− , 2−+
1P1 , 1D2
(2,3)−−
3D2,3

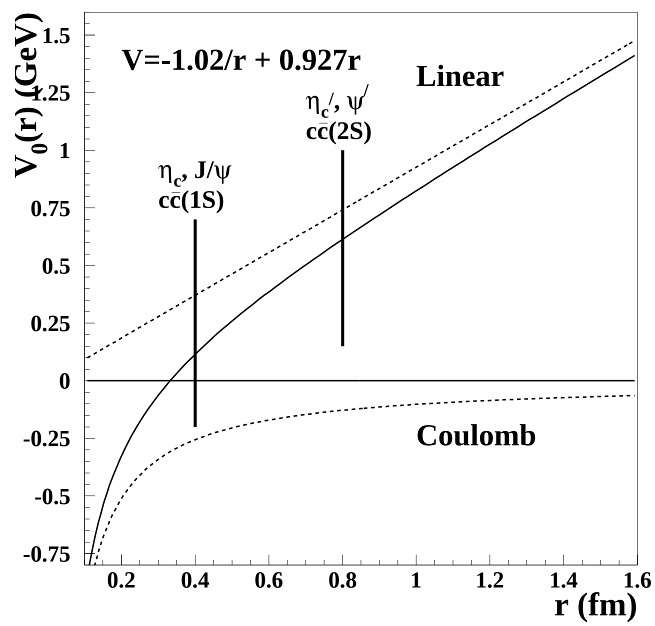
The Long Lost Singlet States of Charmonium

There are 8 bound states of charmonium below the $D\bar{D}$ breakup threshold. These are

spin triplets: $J/\psi(1^3S_1)$, $\psi'(2^3S_1)$, and $\chi_{0,1,2}(1^3P_{0,1,2})$, lots is known

spin singlets: $\eta_c(1^1S_0)$, $\eta_c'(2^1S_0)$, and $h_c(1^1P_1)$, very little is known

- Why? Because spin-singlets can not be directly produced in e^+e^- annihilation, and their population via radiative transitions from the vector states is either very weak (M1 for η_c, η_c') or C-forbidden ($h_c(1^{+-})$).
- It is important to identify the singlets in order to determine the hyperfine or spin–spin interaction, which is responsible for singlet–triplet splitting of $q\bar{q}$ states.
- It is important to know the possible variation of spin–spin interaction from Coulombic ($J/\psi,\ \eta_c$) to Confinement ($\psi',\ \eta_c'$) regions of the $q\bar{q}$ interaction.



Discovery of $\eta_c(2^1S_0)$ — The radial excitation of the singlet $|c\bar{c}>_{g.s.}$

We begin with η_c', because $\eta_c(2982)$ is well known.

- The $\eta_c(2^1S_0)$ or η_c' is known to be bound, somewhere below the triplet state $\psi(2^3S_1)$ or ψ' which has a mass of 3686.11 ± 0.03 MeV.

- In 1982 the Crystal Ball reported observation of a weak, 91 ± 5 MeV transition in the inclusive photon spectrum from the decay of $\psi(2S)$, and claimed [8] $M(\eta_c') = 3594 \pm 5$ MeV.

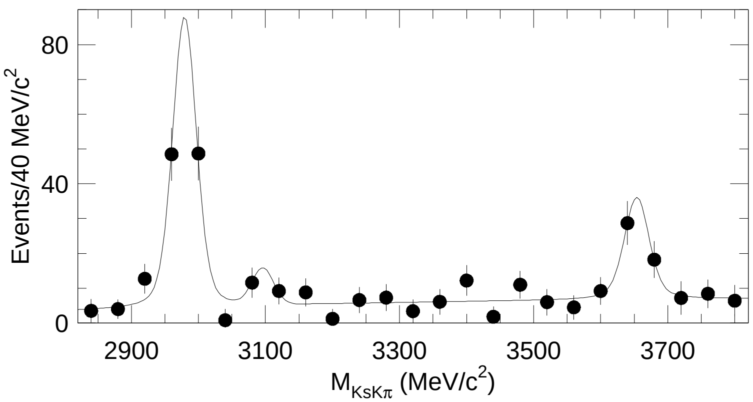
- Several subsequent attempts, $p\bar{p}$ (E760[9]/E835[10]), $\gamma\gamma$ fusion, (DELPHI[11], L3[12]), inclusive photon (CLEO[13]), to find η_c' were unsuccessful.

  Prior to 2002 all editions of PDG dropped η_c' from their meson summary.

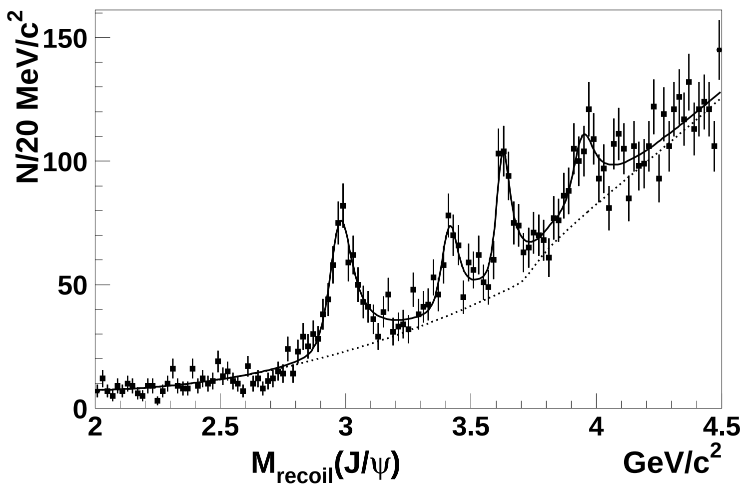
- Most potential model calculations predicted $M(\eta_c') = 3594 - 3626$ MeV.

  We do not need more theory. We need to find η_c' experimentally. So, where is η_c'?

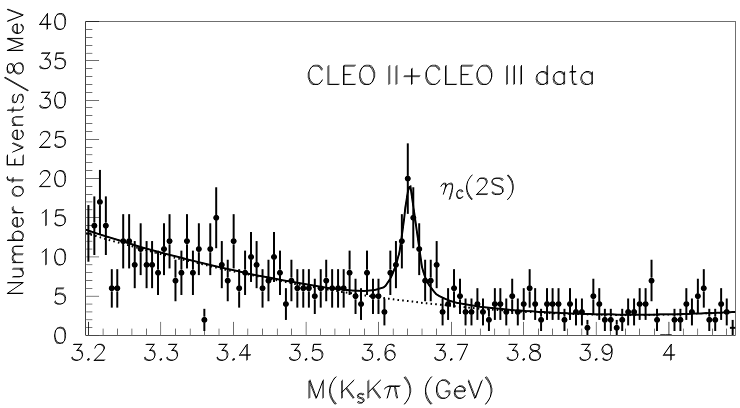
- The breakthrough for η_c' came from the observation of η_c' in B decays by Belle [14]. It was followed by its observation in $\gamma\gamma$ fusion at CLEO [15] and BaBar [16].



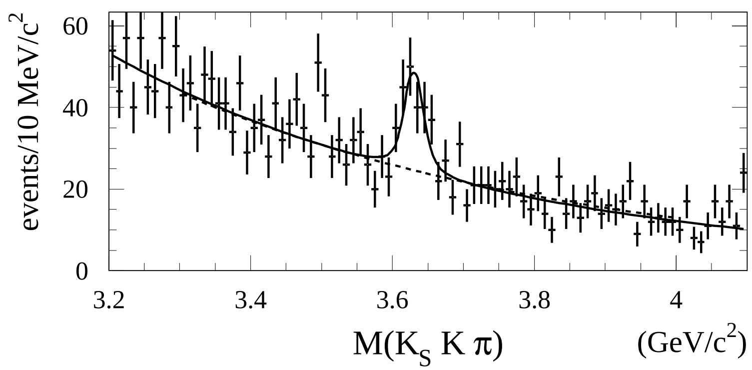
Belle: 42 fb^{-1} $(B \to K(K_S K\pi))$



Belle: 350 fb^{-1} $(e^+e^- \to J/\psi + c\bar{c})$



CLEO II+III: 27 fb^{-1} $(\gamma\gamma \to K_S K\pi)$



BaBar: 86 fb^{-1} $(\gamma\gamma \to K_S K\pi)$

The Discovery of $\eta_c'(2^1S_0)$

(in MeV)	$M(\eta_c'(2S))$	$\Gamma(\eta_c'(2S))$	events (reaction)
Belle(2002) [14]	3654 ± 10	< 55	39 ± 11 $(B \to K(K_S K\pi))$
CLEO(2004) [15]	$\mathbf{3642.9 \pm 3.4}$	$\mathbf{< 31}$	$\mathbf{61 \pm 15}$ $(\gamma\gamma \to K_S K\pi)$
BaBar(2004) [16]	3630.8 ± 3.5	17.0 ± 8.7	112 ± 24 $(\gamma\gamma \to K_S K\pi)$
BaBar(2005) [17]	3645.0 ± 5.5	22 ± 14	121 ± 27 $(e^+e^- \to J/\psi(c\bar{c}))$
Belle(2005)* [18]	3636 ± 9		311 ± 42 $(e^+e^- \to J/\psi(c\bar{c}))$

*I have increased $M(\eta_c')$ of Belle by 10 MeV, to be consistent $M(\eta_c')$ and $M(\chi_{c0})$ measured by them.

- The weighted average is $M(\eta_c') = 3638.7 \pm 2.0$ MeV.
- This leads to the hyperfine splitting

  $\boldsymbol{\Delta M_{hf}(2S) = 3686.1 - 3638.7 = 47.4 \pm 2.0}$ **MeV.**

  Recall that, $\boldsymbol{\Delta M_{hf}(1S) = 3097 - 2980 = 117 \pm 1}$ **MeV.**
- Explaining this large difference is a challenge for the theorists.
- Finding the width of η_c' is a challenge to the experimentalists.
- **LOTS REMAINS TO BE DONE ABOUT** $\boldsymbol{\eta_c'(2^1S_0)}$.

The Discovery of $h_c(1^1P_1)$

If the confinement potential is Lorentz scalar, there is no long–range spin–spin interaction in $q\bar{q}$. It follows that the hyperfine splitting is zero for $l \neq 0$, or

$$\Delta M_{hf}(1P) = M(\langle {}^3P_J \rangle) - M({}^1P_1)$$

To test this prediction it is necessary to identify $h_c(1^1P_1)$ and measure $M(h_c)$ with precision.

- In 1982 Crystal Ball [19] failed in the search for h_c in the reaction $\psi(2S) \to \pi^0 h_c,\ h_c \to \gamma\eta_c$.
- In 1992 Fermilab E760 [20] studied the reaction $p\bar{p} \to h_c \to \pi^0 J/\psi$ and claimed the observation of a signal for h_c. However, higher luminosity runs in 1996 and 2000 have failed to confirm this observation.
- Fermilab E835 [21] has searched for h_c in their 1996/2000 data in the reaction $p\bar{p} \to h_c \to \gamma\eta_c$.
  They report, $\Delta M_{hf}(1P) = -0.4 \pm 0.2 \pm 0.2$ MeV with a significance of the h_c signal at **$\sim 3\sigma$ level**.
- Now CLEO [22] has firmly identified h_c, at a significance level **$> 6\sigma$**.

CLEO Observation of $h_c(1^1P_1)$

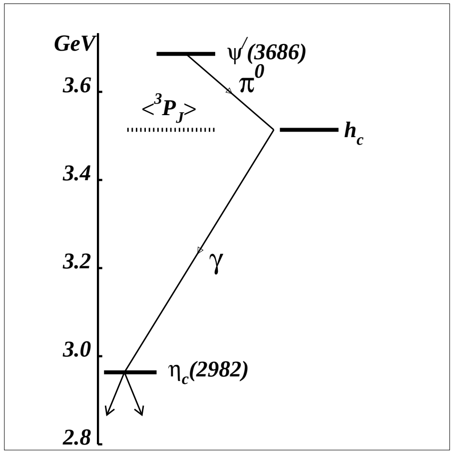
At CLEO-c data were taken at $\psi(2S)$, with 3.08 million $\psi(2S)$. These data have been analyzed for [22]

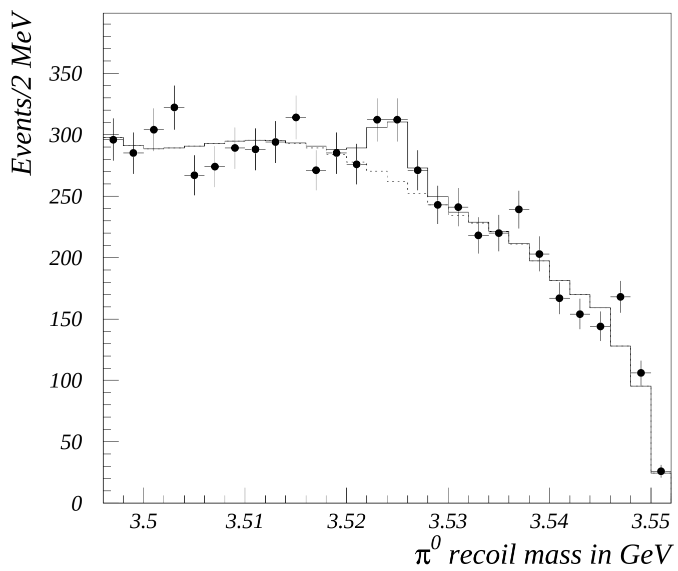
$$\psi(2S) \to \pi^0 h_c \ , \ h_c \to \gamma\eta_c$$

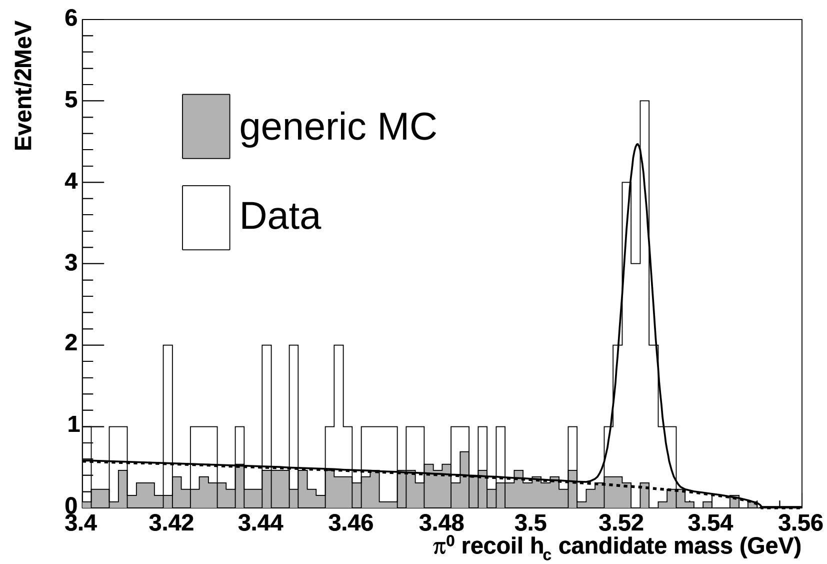
Both inclusive and exclusive analyses were done, and an accurate determination of h_c mass was made in recoils against π^0's whose energy could be measured with precision.

Inclusive Analyses: Two independent analyses, different in details of event selection and resonance analysis, were made. One constrained the photon energy, and the other constrained the η_c mass. Completely consistent results were obtained.

Exclusive Analysis: In this analysis, instead of constraining E_γ or $M(\eta_c)$, seven known decay channels with a total branching fraction of $\sim 10\%$ were measured. Once again, consistent results were obtained.







INCLUSIVE

significance $= 3.8\sigma$

EXCLUSIVE

significance $= 6.1\sigma$

The overall result is

$$\boldsymbol{M(h_c) = 3524.4 \pm 0.6 \pm 0.4 \text{ MeV}, \text{ or}}$$

$$\boldsymbol{\Delta M_{hf}(1P) = \langle M(\chi_{cJ})\rangle - M(h_c) = +1.0 \pm 0.6 \pm 0.4 \text{ MeV}}$$

Two conclusions follow:

- Simple pQCD expectation, $\Delta M_{hf}(1P) = 0$, is not strongly violated.
- The magnitude and sign of ΔM_{hf} is not yet well determined.

The Unanticipated Discoveries

Let me now move on to the discoveries of exciting new states which motivated the title of my talk. These were largely unanticipated, and seem to have properties which are difficult to understand, **at least at present**.

Chronologically, these consist of

- Pentaquark — (Jan. 2003)
- D_{sJ} — BaBar (Mar. 2003)
- X(3872) — Belle (Mar. 2003)
- X, Y, Z(3940) — Belle (May 2005)
- Y or V(4260) — BaBar (May 2005)

Let me describe these in the same order

The Pentaquark

- As is probably well known to most of the audience, when the Pentaquark was born in 2003, it caused great–great interest.

  Google tells me that there are 123,000 entries for it. (March 28, 2006)*

- There were many reported sightings of pentaquarks of all kinds, and even a greater number of reported failures to find the expected signals.
- Finally, there is the recent JLab report of the absence of the pentaquark signal in a large statistics repeat of their earlier measurement.
- My personal, perhaps biased, conclusion is that

the pentaquark is now on life–support.

May it rest in peace!

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* Looks like they will not let the pentaquark rest in peace. Google tells me that the number of entries has increased to 135,000 in two weeks. (April 10, 2006)

The New D_s^* $(c\bar{s})$ Mesons

Properly speaking, these are not "unanticipated". They were anticipated, but not where they showed up. As is well known, for heavy–heavy $Q\bar{Q}$ mesons we use $\vec{J} = \vec{L} + \vec{S}$ classification.

For heavy–light $Q\bar{q}$ mesons we use $\vec{J} = \vec{j}_q + \vec{s}_Q$, with $\vec{q} = \vec{L} + \vec{s}_q$.

Thus, the P–wave D mesons fall in two classes, $j_q = \frac{1}{2}$ and $j_q = \frac{3}{2}$.

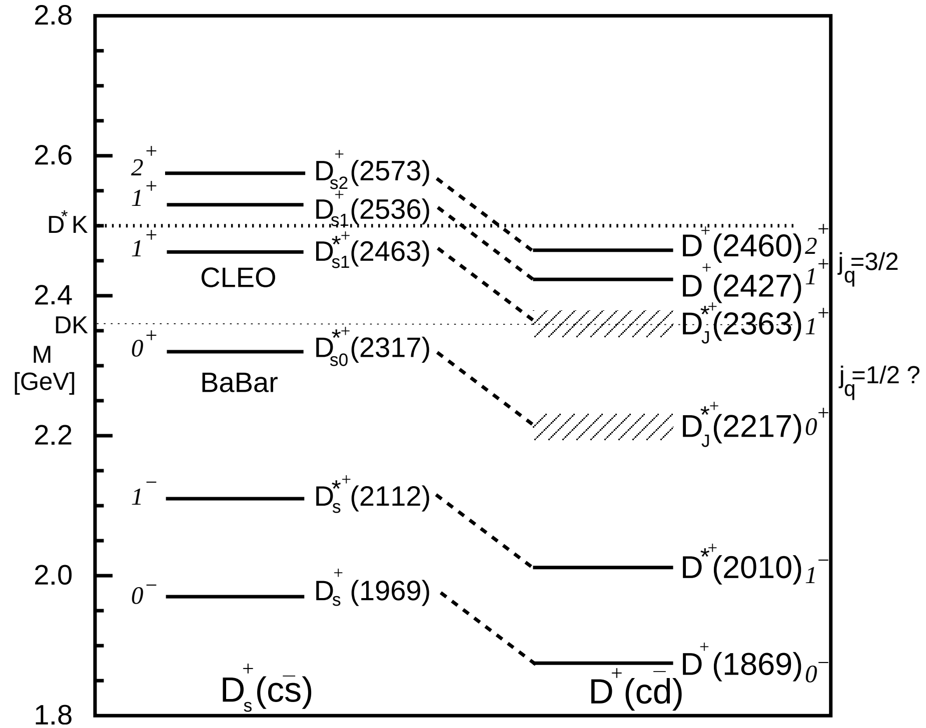
The $j_q = \frac{1}{2}$ $D_{sJ}(J^\pi = 0^+,\ 1^+)$, and $j_q = \frac{3}{2}$ $D_{sJ}(J^\pi = 1^+,\ 2^+)$, were all expected to be above DK thresholds, and therefore decay into isospin–allowed DK and D^*K. Indeed the $j_q = \frac{3}{2}$ $D_{s1}(2536)$ and $D_{s2}(2573)$ do so. **The surprise came with the $\boldsymbol{j_q = \frac{1}{2}}$ mesons.**

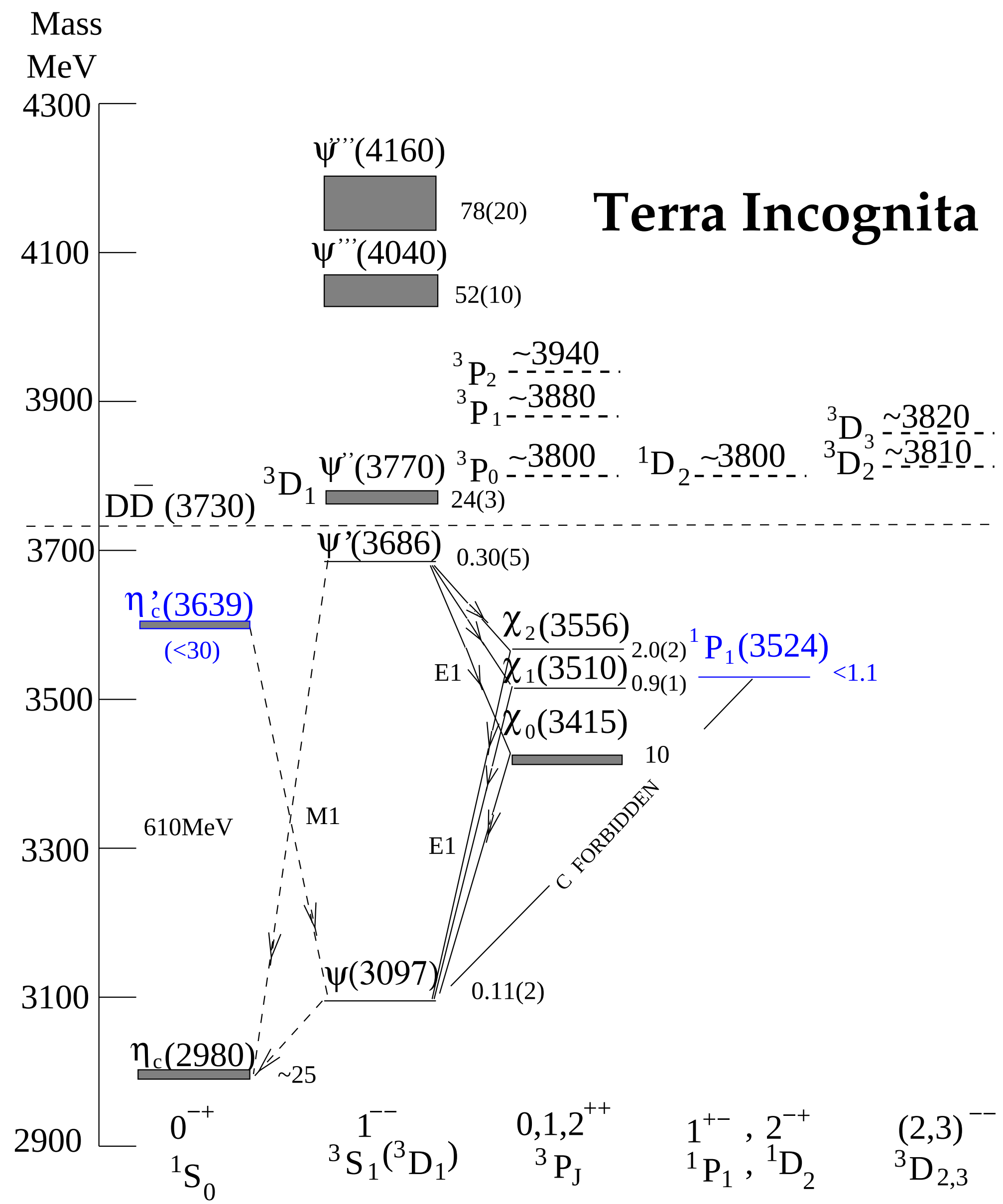
The New D_s^* $(c\bar{s})$ Mesons

- BaBar [23] announced the discovery of $D_{s0}^{*+}(J^P = 0^+)$ with a mass of 2317 MeV, well below the DK threshold at 2367 MeV, and with $\Gamma < 5$ MeV, in the isospin–forbidden decay mode $D_{s0}^{*+} \to D_s^+ + \pi^0$.

- CLEO [24] followed with finding the 1^+ partner $D_{s1}^*(J^P = 1^+)$ with a mass of 2463 MeV, with narrow width, $\Gamma < 7$ MeV, and still decay into isospin–forbidden $D_{s1}^{*+} \to D_s^{*+} + \pi^0$

- Of course, each discovery poses new questions. The systematics obvious in the figure raises the question: **Where are the $j_q = \frac{1}{2}$ partners of $D(c\bar{d})$?**




Mass
MeV
4300
4100
3900
3700
3500
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2900
ψ'''(4160)
78(20)
Terra Incognita
ψ'''(4040)
52(10)
³P₂ ~3940
³P₁ ~3880
³D₃ ~3820
³D₂ ~3810
³D₁ ψ''(3770)
³P₀ ~3800
¹D₂ ~3800
DD̄ (3730)
24(3)
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ηc(2980)
~25
0⁻⁺
¹S₀
1⁻⁻
³S₁(³D₁)
0,1,2⁺⁺
³P_J
1⁺⁻ , 2⁻⁺
¹P₁ , ¹D₂
(2,3)⁻⁻
³D₂,₃

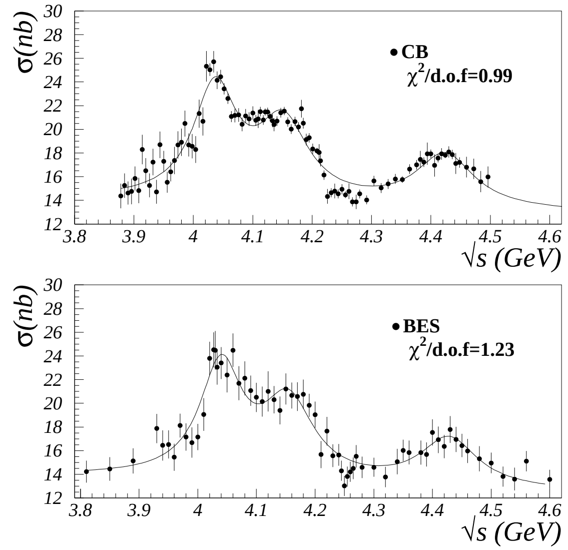
What We Know About Terra Incognita

1. This is the region in which all the radial excitations of the bound charmonium states, $\eta(3S, 4S)$, $\psi(3S, 4S)$, $\chi(2P, 3P)$, should exist.

2. Until three years ago, the only experimental measurements which existed in this mass region were the measurements of $R \equiv \sigma(e^+e^- \to h^+h^-)/\sigma(e^+e^- \to \mu^+\mu^-)$.

In a reanalysis of the two most consistent measurements of R, it is found [25] that the three prominent enhancements have larger widths than accepted before.

	M (MeV)	Γ (MeV) PDG04	Γ (MeV) [25]
3^3S_1	4039(1)	52(10)	88(5)
2^3D_1	4153(3)	78(20)	107(8)
4^3S_1	4426(5)	43(15)	119(15)

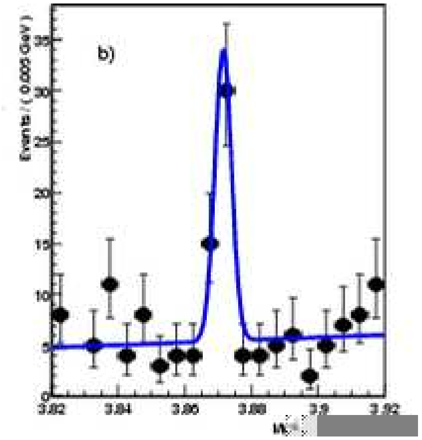


Notice the absence of any fine structure in the R. Notice, in particular, the deep minimum around $\sqrt{s} = 4250$ MeV.

It is just this region of $\sqrt{s} = 3800 - 4500$ which has become the hotbed of discovery!

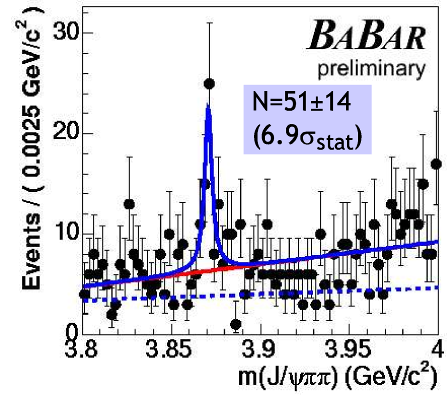
The Veteran, X(3872)

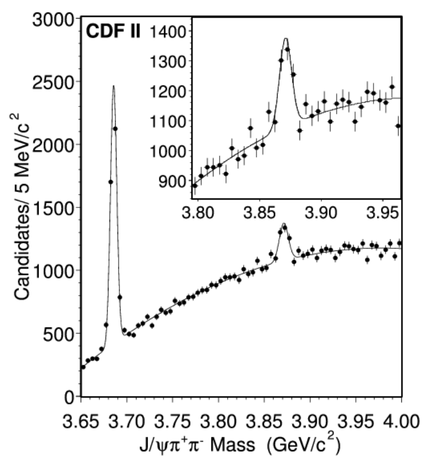
In 2003 Belle [26] announced the discovery of an unexpected state, X(3872). It was quickly confirmed by CDF [27], DØ [28] and BaBar [29].



152M $B\bar{B}$ decays
$M = 3872.0 \pm 0.8$ MeV
(Belle [26], left)

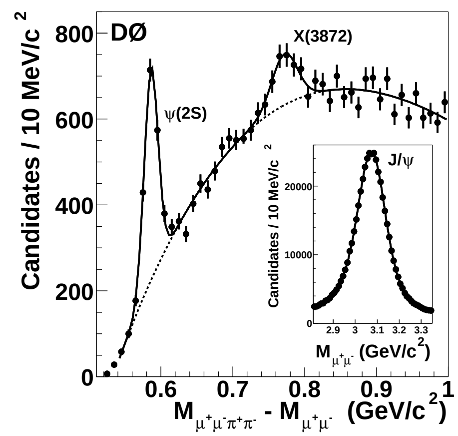
226M $B\bar{B}$ decays (BaBar)
$M = 3871.3 \pm 0.6$ MeV
(BaBar [29], right)





$M = 3871.3 \pm 0.8$ MeV
(CDF [27], left)

$M = 3873.4 \pm 1.4$ MeV
(DØ [28], right)



What is X(3872)?

Unusual Properties

1. $M(\mathrm{X}) = 3871.1 \pm 0.4$ MeV (latest average)

   Notice: $M(D) + M(D^*) = (3870.3 \pm 2.0)$ MeV

   $M(\rho) + M(J/\psi) = (3872.7 \pm 0.5)$ MeV
2. $\Gamma(\mathrm{X}) \leq 2.3$ MeV @ 90% C.L.
3. Prominent decay: $\mathrm{X}(3872) \to \pi^+\pi^- J/\psi$
4. Absent decays: $\mathrm{X} \to \pi^0\pi^0 J/\psi$, $\mathrm{X} \to \eta J/\psi$, $\mathrm{X} \to \gamma\chi_c$

   No charged partner found, $I = 0$

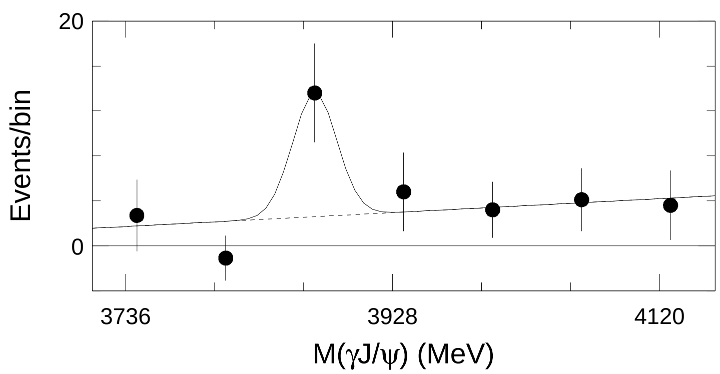
Field Day for Theorists

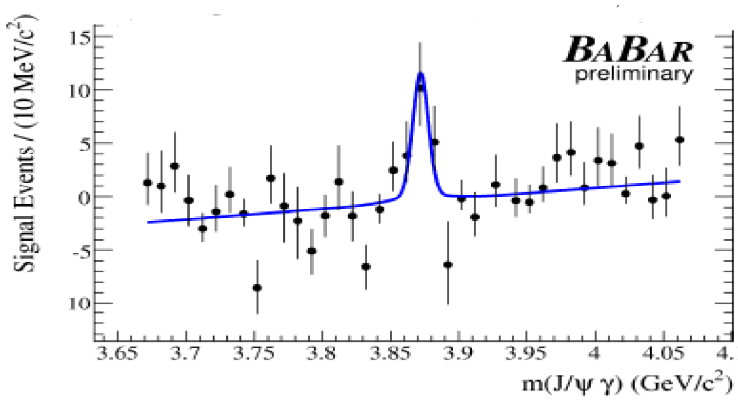
1. X as a Charmonium State: $C = (+)$: $1^3D_{2,3}$, 2^1P_1; $C = (+)$: 1^1D_2, 2^3P_1
2. DD^* Molecule: $C = (+)$: 0^{-+}, 1^{++}
3. Charmonium Hybrid: $C = (+)$
4. Vector Charmonium + Glueball: $J^{PC} = 1^{--}$

Obviously, what is needed to confirm one or the other interpretation is $J^{PC}(\mathrm{X}(3872))$. This only experiments can do.

X(3872) — New Observations

- From CLEO [30]:
  $\gamma\gamma$ fusion, $(C=+)$: $(2J+1)\Gamma(\mathrm{X}\to\gamma\gamma) < 0.65$ keV, (90% CL)
- From CLEO, BaBar [30,31]:
  ISR production, $(J^{PC}=1^{--})$: $\mathcal{B}(\mathrm{X}\to\pi^+\pi^- J/\psi)\times\Gamma(\mathrm{X}\to e^+e^-) < 6.2$ eV, (90% CL)
- From Belle [32] and BaBar [33]: From $B-$decay, $\boldsymbol{X\to\gamma J/\psi}$, $(C=+)$, but notice
  N(events)$=13.6\pm4.4$, sig $=4.0\sigma$ (Belle: 275 M $B\bar{B}$)
  N(events)$=19.4\pm5.7$, sig $=3.4\sigma$ (BaBar: 287 M $B\bar{B}$)

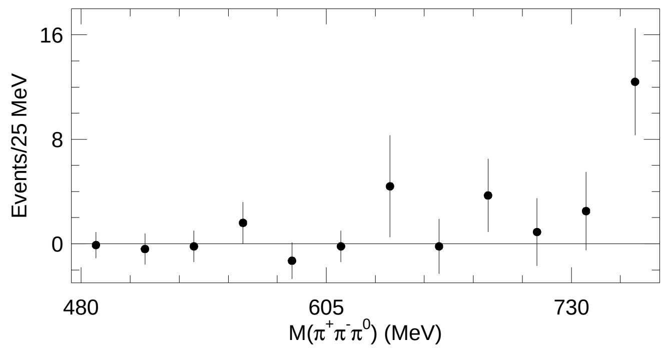




X(3872) — New Observations

From Belle [32], from $B-$decay: $\mathbf{X \to \pi^+\pi^-\pi^0 J/\psi}$, or $\to$ virtual $\omega + J/\psi$,

$(m_\omega + m_{J/\psi} = 3879.5 \text{ MeV})$



N(events)$=12.4 \pm 4.1$

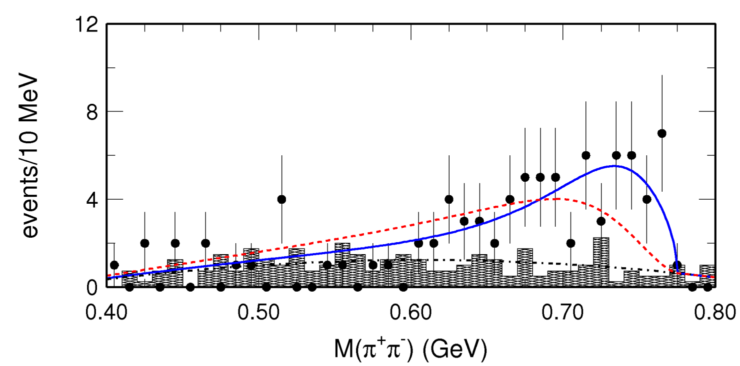
$\mathcal{B}(\text{X}\to\pi^+\pi^-\pi^0 J/\psi)/\mathcal{B}(\text{X}\to\pi^+\pi^- J/\psi) = 1.0 \pm 0.5$

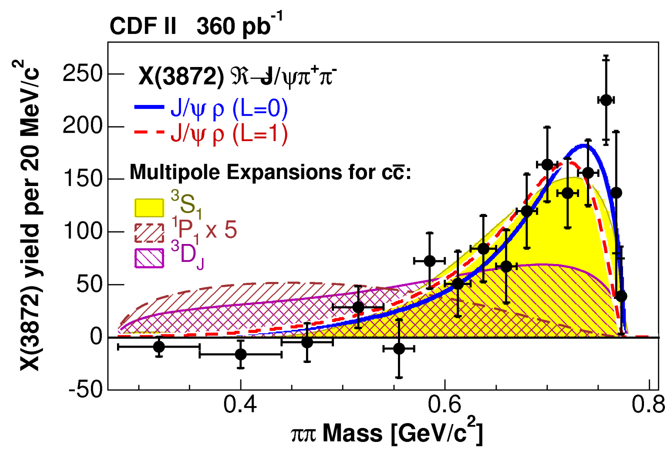
C(X(3872))=(+)

From Belle [34] and CDF [35]: L between $(\pi^+\pi^-)$ and J/ψ.

Belle: s–wave, **strongly disfavors** 2^{-+}

CDF: s–wave, p–wave, **allows** 1^{++} and 2^{-+}





X(3872) — New Observations

From Belle [33]: $\mathbf{X \rightarrow D^0 D^0 \pi^0}$ (or $\overline{D^0} D^{0*}$)

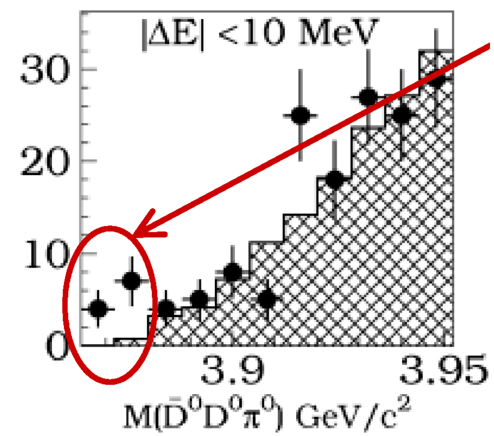
$2M(D^0) + M(\pi^0) = 3864$ MeV

N(events)$= 12.5 \pm 3.9$, sig.$> 5\sigma$

$\mathcal{B}(\mathrm{X} \rightarrow \overline{D^0} D^0 \pi^0)/\mathcal{B}(\mathrm{X} \rightarrow \pi^+\pi^- J/\psi) =$

13.8 ± 4.9

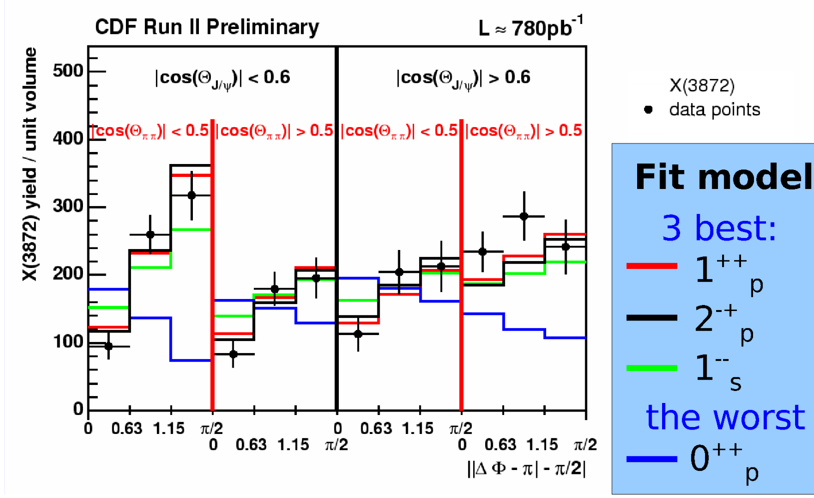
Allows only $J^{PC} = 1^{++}$



Angular Distributions from CDF [33]

3000 X(3872) events from 780 pb^{-1} of CDFII data. Simultaneous analysis of 3 angular distributions excludes 1^{--}.

Allows 1^{++} (prob $= 28\%$), 2^{-+} (prob $= 26\%$)



Angular Distributions from Belle [34]

58 events of X(3872) with 275M $B\bar{B}$

Excludes $J^{PC} = 0^{-+}, 0^{++}$

Allows $J^{PC} = 1^{++}, 2^{++}$

X(3872) — Conclusion

- There are contradictory experimental observations which exclude and allow different J^{PC} assignments.
- $J^{PC} = 1^{++}$ is the only assignment allowed by all.
- Little consolation, because 1^{++} charmonium, hybrid, and molecule all remain alive.

The Unexpected States From Belle and BaBar

- During the last four years Belle and BaBar at the KEK and SLAC B–factories have produced surprise after surprise, with announcements of discoveries of unexpected resonances.
- These observations owe their origin to unprecedented integrated luminosities for e^+e^- collisions at $\Upsilon(4S)$, which have become available at Belle (563 fb^{-1}) and BaBar (331 fb^{-1}).
- The new resonances reported are:
  X(3943) — Belle
  Y(3943) — Belle
  Z(3931) — Belle
  Y(4260) — BaBar, CLEO
- Although the experimental data is still sparse, and not completely 'shaken down', the excitement caused by these is unavoidable.
- On the theoretical side, these discoveries have caused mostly confusion!

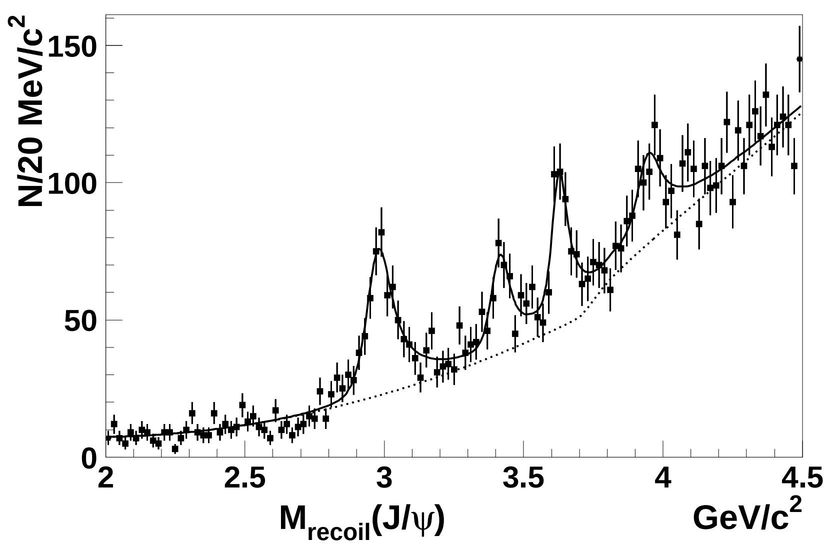
X(3940) in Charmonium Pair Production)

In 2002, Belle [14] presented their first report on double charmonium production with 42 fb^{-1} of e^+e^- data at $\Upsilon(4S)$

$$e^+e^- \to J/\psi + (c\bar{c}).$$

The results showed the excitation of three spin zero states of charmonium, $\eta_c(1S)$, $\chi_0(1P)$, and $\eta_c'(2S)$. Now Belle [36] has analyzed data for 357 fb^{-1}. The inclusive spectrum shows clear excitation of a fourth state for which they fit

N=266 $\pm$ 63, M(X)=3936 $\pm$ 14 MeV, Γ(X)=39 $\pm$ 36 MeV, sig.=5.0σ



X(3940) in Charmonium Pair Production)

A fit to the recoil spectrum for exclusive $J/\psi D^*\overline{D}$ yields:

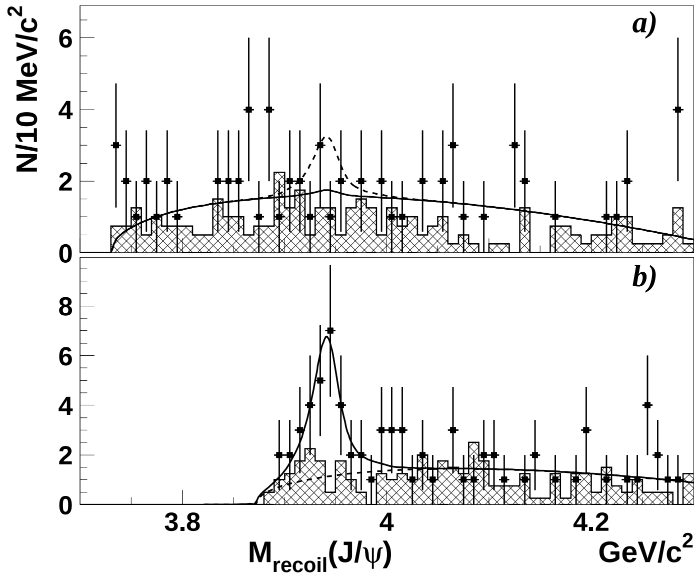
N=24.5 $\pm$ 6.9, M(X)=3943 $\pm$ 6 MeV, Γ(X)=15.4 $\pm$ 10.1 MeV, sig.=5.0σ

They establish upper limits (90% CL)

$\mathcal{B}(\mathrm{X} \to D^*\overline{D}) > 45\%$

$\mathcal{B}(\mathrm{X} \to D\overline{D}) < 41\%$

$\mathcal{B}(\mathrm{X} \to \omega J/\psi) < 26\%$



- The observation of $D^*\overline{D}$ decay and the non-observation of $D\overline{D}$ decay suggests unnatural parity, and make its **most plausible** assignment as $\eta_c''(3^1S_0)$, particularly because all other states (η_c, χ_{c0}, η_c') in the inclusive spectrum have $J = 0$.
- **Problem:** With $\psi(4040)$ being generally accepted as (3^3S_1), this would give **the implausible** hyperfine splitting $\Delta M_{hf}(3S) \approx 100$ MeV.

Recall that $\Delta M_{hf}(2S) \approx 46$ MeV.

Y(3940) in B Decay

Belle [37] has reported what they call "a near threshold" enhancement in exclusive $B \to K(\omega J/\psi)$ decays from their 253 fb^{-1} data sample. They obtain

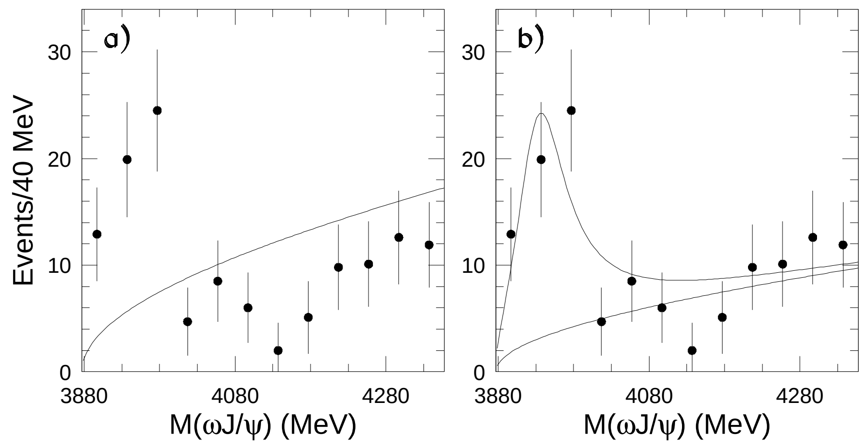
N(events)=58 ± 11, M(Y)=3943 ± 17 MeV, Γ(Y)=87 ± 26 MeV, sig. $> 8\sigma$

$\mathcal{B}(B \to KY) \times \mathcal{B}(Y \to \omega J/\psi) = (7.1 \pm 1.3 \pm 3.1) \times 10^{-5}$.

Not seen: $\mathrm{Y} \to D\overline{D}$, $\mathrm{Y} \to D^*\overline{D}$

Being above the $D\overline{D}$ threshold, the absence of these decays suggests a non-charmonium nature. The authors therefore suggest that it could be a $|c\bar{c}g>$ hybrid, but note that such hybrids are expected at much higher masses, $\sim 4300 - 4500$ MeV.

A more sensitive search for $D^*\overline{D}$ decay is needed to ensure that Y(3940) is not identical to X(3940).



Phase space only Phase space + Y(3943)

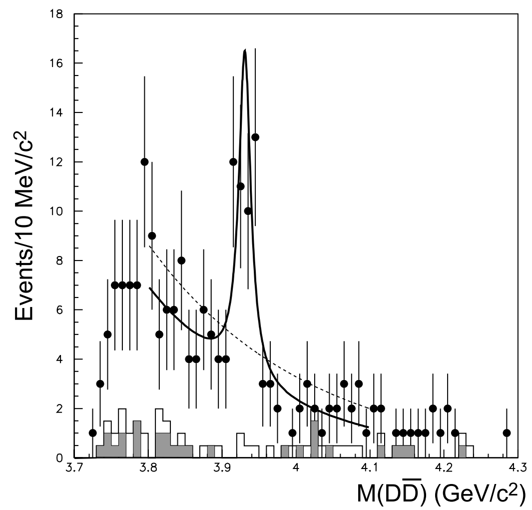
Z(3931) in Two Photon Fusion

Belle [38] continues to present surprises. We already had X(3940) and Y(3943).

Now comes Z(3931) observed in two photon fusion with 395 fb^{-1}

$e^+e^- \to e^+e^-(\gamma\gamma)$, $\gamma\gamma \to D\bar{D}$

M(Z)=$3929 \pm 5 \pm 2$ MeV, N(events)= 64 ± 18
Γ(Z)=$20 \pm 8 \pm 3$ MeV, sig.=5.3σ
$\Gamma_{\gamma\gamma} \times \mathcal{B}(\to D\bar{D}) = 0.18 \pm 0.05 \pm 0.03$ keV



- Helicity angular distribution agrees with $J = 2$, and excludes $J = 0$.
- The logical assignment is $\chi'_{c2}(2^3P_2)$.

To summarize, the X, Y, Z are claimed to be distinct, but can they be?

	M(MeV)	Γ(MeV)	Formed in	Decays in	not in	suggests
X	$3943 \pm 6 \pm 6$	15 ± 10	$e^+e^- \to J/\psi(c\bar{c})$	$D^*\overline{D}$	$D\overline{D}$, $\omega J/\psi$	$\eta_c(3^1S_0)$
Y	$3943 \pm 11 \pm 13$	87 ± 22	$B \to K(\omega J/\psi)$	$\omega J/\psi$	$D^*\overline{D}$(?)	$c\bar{c}$ hybrid?
Z	$3931 \pm 4 \pm 2$	$20 \pm 8 \pm 3$	$\gamma\gamma$ fusion	$D\overline{D}$		$\chi'_{c2}(2^3P_2)$

One More Surprise, V(4260) From BaBar

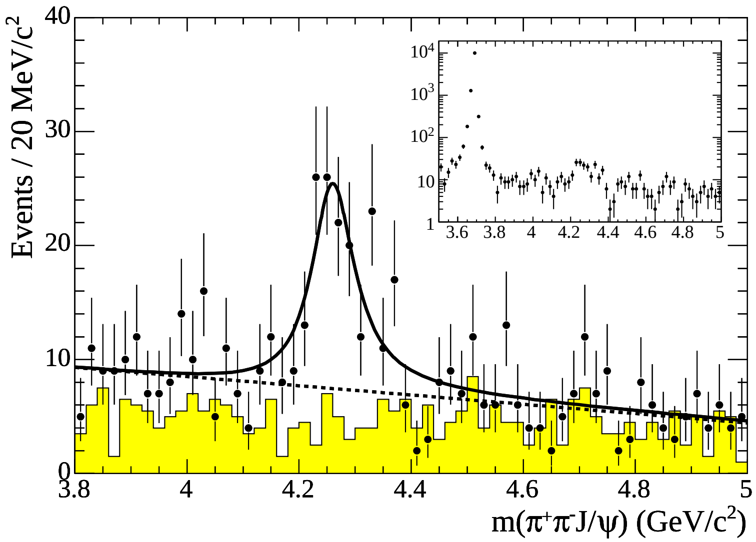
Belle has been running away with too many new resonances. Now comes BaBar.

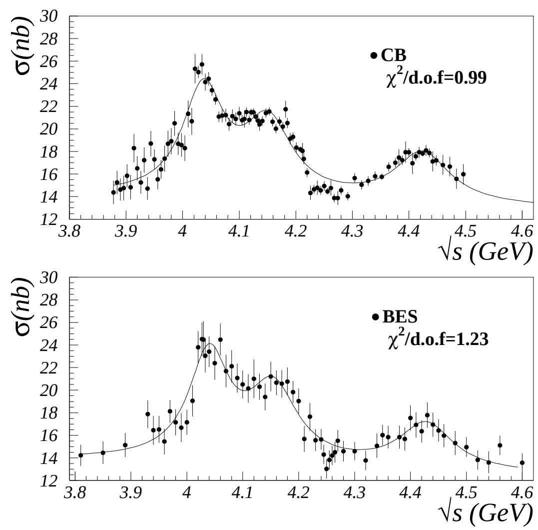
BaBar [39] has analyzed ISR events from 233 fb^{-1} of data, and reported a convincing (significance 8σ), broad enhancement in the invariant mass M($\pi^+\pi^- J/\psi$) spectrum.

M(V)=$4259 \pm 8^{+2}_{-6}$ MeV, Γ(V)=$88 \pm 23^{+6}_{-4}$ MeV, $N = 125 \pm 23$ events

$\Gamma(e^+e^- \to V) \times \mathcal{B}(V \to \pi^+\pi^- J/\psi) = (5.5 \pm 1.0^{+0.8}_{-0.7})$ eV.

They suggest that it might be a previously unobserved 1^{--} resonance. This is quite surprising because no vector around this mass is predicted, and the R measurements actually show a dip in this mass region [25].





V(4260) Confirmation by CLEO

- Since V(4260) of BaBar is so unexpected, it is necessary to have independent confirmation.
- Like BaBar, we at CLEO, studied the reaction

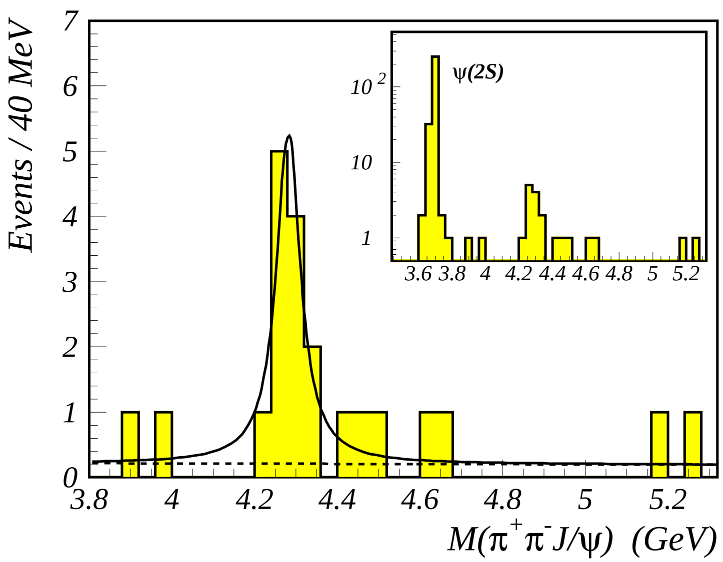
$$e^+e^- \to \gamma_{ISR}(\pi^+\pi^- J/\psi)$$

Although we have much smaller luminosity, we find a clear signal for V(4260) in the $\pi^+\pi^- J/\psi$ invariant mass, and obtain

$$M(4260) = 4283 \pm 17 \pm 17 \text{ MeV}, \text{ and } \Gamma(4260) = 70^{+40}_{-25} \pm 11 \text{ MeV}.$$

- **So the vector V(4260) definitely exists!** But what is it?

- The charmonium vectors through $\psi(4S)$ are all accounted for. Somewhat reluctantly, we have to look for an exotic explanation for it. It has been suggested that V(4260) is a $|c\bar{c}g>$ hybrid. But remember that the lightest $|c\bar{c}g>$ hybrid is expected at about 4400 MeV!



Postscript

It is undeniable that the new states X(3872), X, Y, Z(3940), and V(4260) have thrown a big monkey–wrench in our clean understanding of spectroscopy in the charmonium region, based on bound $|c\bar{c}>$ states.

The theorists are running in all different directions. But this is not unusual.

I remind you that the J/ψ discovery was followed by 8 theoretical papers in just one issue of Phys. Rev. Letters proposing some of the most bizarre explanations for it (and the authors included five Nobel laureates). It took a while to settle down to $|c\bar{c}>$!

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