STRONG INTERACTIONS

through the eyes of

HEAVY QUARK SPECTROSCOPY

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Preamble

Particle physics is the **reductionist** approach to understanding **Nature**. We believe that once one understands Nature's interactions at a **microscopic** level, the rest will follow.

- Nature has given us four interactions, the **Strong**, **Electromagnetic**, **Weak**, and **Gravitation**, and we believe that despite their apparent diversity, at some ultimate level they must unite.
- The **"Standard Model"** of particle physics takes us 3/4 of the way there. It unites the Electromagnetic, Weak and Strong interactions.
- The common cast of players of the Standard Model are three families each of **leptons** and **quarks** (all spin $1/2$ fermions), and four spin 1 force carrier bosons (photons, W, Z, and gluons).

	Leptons (s=1/2)	**Quarks (s=1/2)**	**Bosons (s=1)**
I	$e^+,\ e^-,\ \nu_e$	$d(-1/3),\ u(+2/3)$	Photons
II	$\mu^+,\ \mu^-,\ \nu_\mu$	$s(-1/3),\ c(+2/3)$	$W^\pm,\ Z^0$
III	$\tau^+,\ \tau^-,\ \nu_\tau$	$b(-1/3),\ t(+2/3)$	Gluons

The Standard Model

The SM itself can be divided into two well-defined parts. The **Electroweak** part of the SM unifies the electromagnetic and weak interactions, and is now extremely well-established, with its precision rivaling QED (predictions confirmed to parts in billions).

The **Strong** interaction part of the **SM** is modeled after QED. It is **Quantum Chromodynamics**, or **QCD**. It has been quite successful at very high energies, but has aspects, like **confinement**, which are not well understood. It is not so well tested, and not confirmed at lower energies.

- I am going to talk about the smaller, but to me more interesting part of the **SM**, the strong interaction part, or **QCD**.
- Those among us who are high-flyers have migrated to the hunt for the **Higgs** and **"Beyond the SM"**. And then there are those who like to keep their feet on the ground and try to better understand what is undeniably here. I am one of those, and this talk is meant to be at the ground level!

Quantum Chromodynamics, QCD

To study any **interaction**, one has to study what it produces, and the properties of what it produces, i.e., one has to study its **spectroscopy**. Strong interactions produce hadrons — mesons and baryons — composites of quarks and gluons, and **hadron spectroscopy** is devoted to their study.

In principle, the non–Abelian gauge theory of QCD is all contained in the QCD

Lagrangian

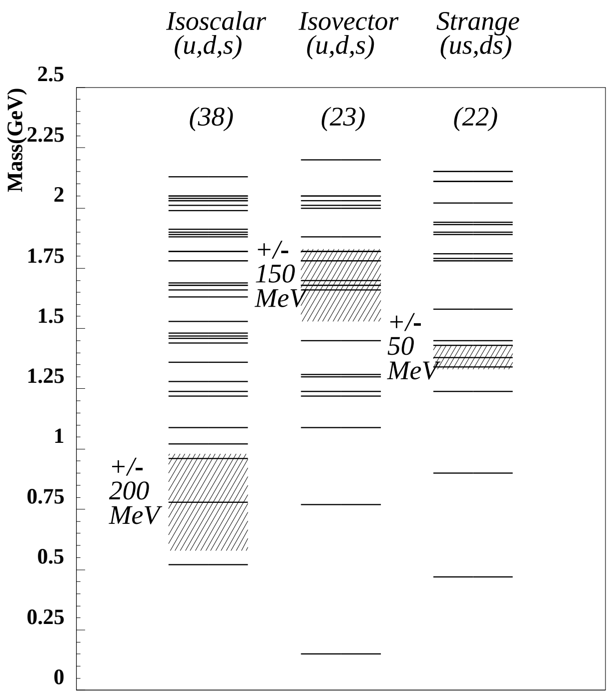
$$\mathcal{L} = -\frac{1}{4} F^{(a)}_{\mu\nu} F^{(a)\mu\nu} + i \sum_q \overline{\psi}^i_q \gamma^\mu (D_\mu)_{ij} \psi^j_q - \sum_q \overline{\psi}^i_q \psi_{qi}$$

It contains all there is to know, but that is an exaggeration , because it needs input of experimental parameters (like quark masses), and even then it can not be analytically solved. So, we have to rely on experimentation, just as all physics must.

Hadron Spectrum

In principle, the **QCD interaction is independent of quark masses**, and can therefore be studied in light quark (u, d, s) hadrons as well as heavy quark (c, b) hadrons. In practice, this is not so.

Because the **light quarks**, u, d, s, have very similar effective masses $(300 - 500$ MeV), light-quark hadrons are always mixtures of all three types. This leads to a **large density of states** and **large widths**, i.e., states which overlap greatly and are difficult to identify and characterize. Add to it the theoretical problems of a **large coupling constant** $(\alpha_S \gtrsim 0.6)$, and the **extremely relativistic** nature of quarks in these hadrons $(\beta > 0.8)$, and **spectroscopy of light-quark hadrons is not the way to go**.

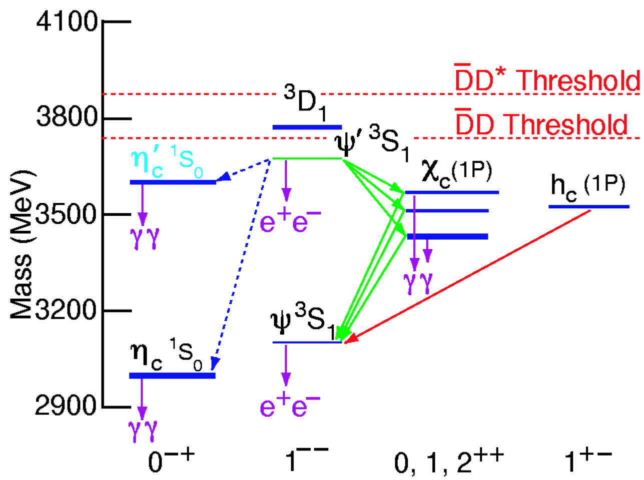


Average spacing ≈ 14 MeV

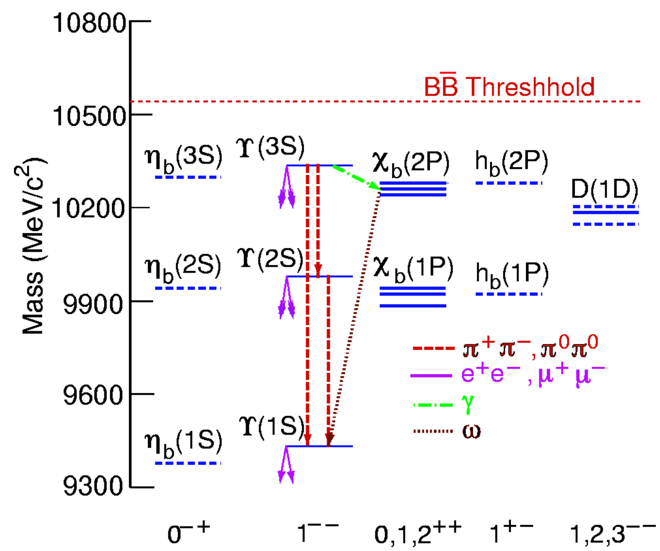
Average width ≈ 150 MeV

Quarkonium Spectra

In order to study strong interactions, it is **better** to study the simplest hadronic systems, $q\bar{q}$ mesons instead of qqq baryons, and it is **best** to study mesons with only one kind of quarks, e.g., $c\bar{c}$, $b\bar{b}$. In contrast to light quarks, the heavy quarks have nothing in their neighborhood to mix with, and the spectra of charmonium and bottomonium are sparse and easier to characterize and study. Further, the coupling constant ($\alpha_S \lesssim 0.3$) and relativistic problems ($\beta < 0.2$) are far more tractable.



CHARMONIUM ($c\bar{c}$)



BOTTOMONIUM ($b\bar{b}$)

QCD Potentials

While it is true that one does not *a priori* expect that the non-Abelian gauge theory of the QCD interactions can be replaced by a potential, it is a fact that a relatively simple potential model of the $q\bar{q}$ interaction **works**, and rather beautifully.

The potential model proposition is that the major part of the strong interaction arises from the **one-gluon exchange** between quarks, much like the Coulomb interaction due to the **one-photon exchange** between charges. It is **proportional to $\mathbf{1/r}$**. However, since free quarks are not observed, a confining part, **proportional to $\mathbf{r}$** is added to it. The most commonly used Cornell potential is then

$$V(r) = -\frac{4}{3}\frac{\alpha_{\mathrm{strong}}}{r} + \sigma r$$

The spin-dependence of the potential follows from the assumed vector nature of the $1/r$ part of the potential, and results in the classical **spin-orbit**, **tensor**, and **spin-spin** components. The confinement potential is assumed to be Lorentz scalar and no spin-dependence (other than the Thomas term) is assumed to arise from it.

With the close analogy between QED and QCD, it is interesting to compare the spectra of charmonium and positronium with masses and interactions miles apart. It is nothing short of fantastic that **Nature repeats herself!** with energy scales different by a factor $\sim \mathbf{10^{10}}$.

	POSITRONIUM	CHARMONIUM	RATIO
$2\,^1S_0$	5×10^{-6} MeV	650 MeV	1.3×10^{8}
$1\,^3P_2$, $1\,^3P_1$, $1\,^3P_0$	4.1×10^{-11} MeV	140 MeV	3.4×10^{12}
$1\,^3S_1$	8.4×10^{-10} MeV	115 MeV	1.4×10^{11}
$1\,^1S_0$			
	$m_e = 0.5$ MeV, $\alpha_{em} = 1/137$	$m_c = 1500$ MeV, $\alpha_S = 1/3$	
Fine structure proportionality	$\alpha_{em}^4 m_e = 1.4 \times 10^{-9}$	$\alpha_S^4 m_c = 18.5$	1.3×10^{10}

Heavy Quark Spectroscopy

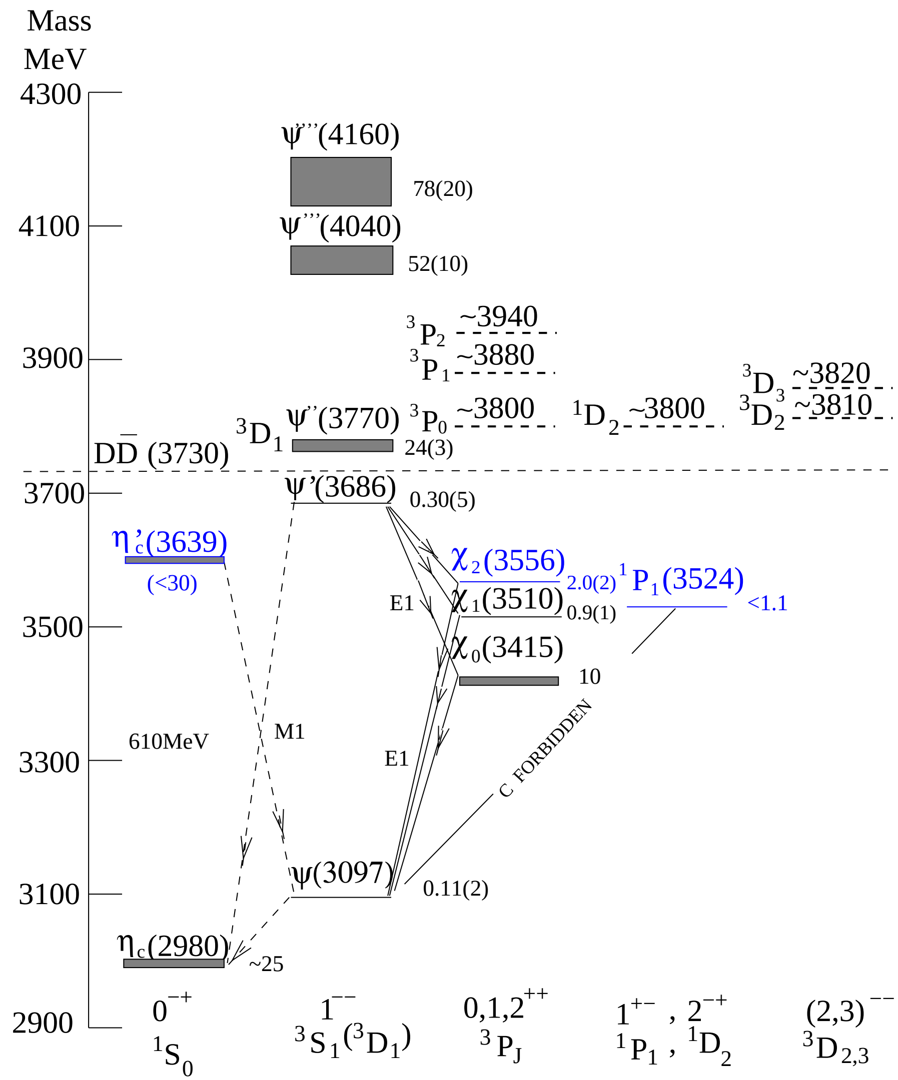
I have already pointed out that heavy-quark spectroscopy is the best place to study strong interactions. The two families available are $c\bar{c}$ **charmonium** and $b\bar{b}$ **bottomonium**. From a strictly theoretical point of view, bottomonium is definitely better, with smaller α_S and smaller relativistic problems. However, the experimental situation for bottomonium is worse, primarily because formation cross sections are smaller, level spacings are smaller, and transitions are weaker. So, the spectroscopic data available for bottomonium are far fewer. A crude measure is provided by the pages devoted to each in the Particle Data Book: 44 pages for charmonium, 14 pages for bottomonium.

- So, most of my talk is devoted to the spectroscopy of the charmonium region.

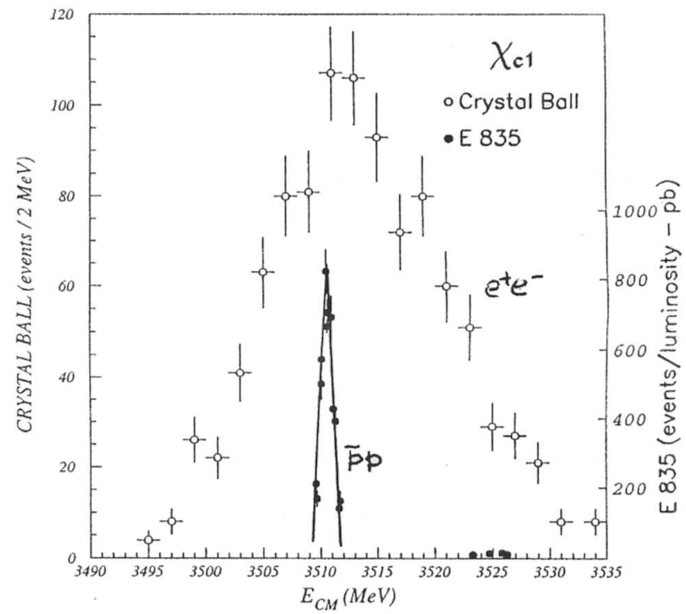
Charmonium — Historical

In 1974 J/ψ, the $^3S_1$ state of charmonium was identified.

- In the following 20 years the SLAC group primarily studied the **triplet** states $^3S_1(J/\psi, \psi')$ and $^3P_J(\chi_{c0,1,2})$.
- Of the **three singlet states**, η_c, $\eta_c'(^1S_0)$ and $h_c(^1P_1)$, only the η_c was identified.
- Almost nothing was done above the $D\overline{D}$ breakup at 3,730 MeV.



At Fermilab a program for the study of charmonium via $p\bar{p}$ annihilation was started in 1990. Unlike e^+e^- annihilations in which only vector (1^{--}) states, J/ψ and ψ', could be directly produced via a virtual photon, $p\bar{p}$ annihilations can proceed by two or three gluons and can directly populate states of any J^{PC}.



Further, unlike e^+e^- beams, antiproton beams could be stochastically cooled which, together with a gas target, provided more than an order of magnitude improvement in mass resolution. The most significant contributions of the Fermilab experiments E760/E835, were the precision determination of the **masses and width** of J/ψ, ψ', and χ_{cJ} states.

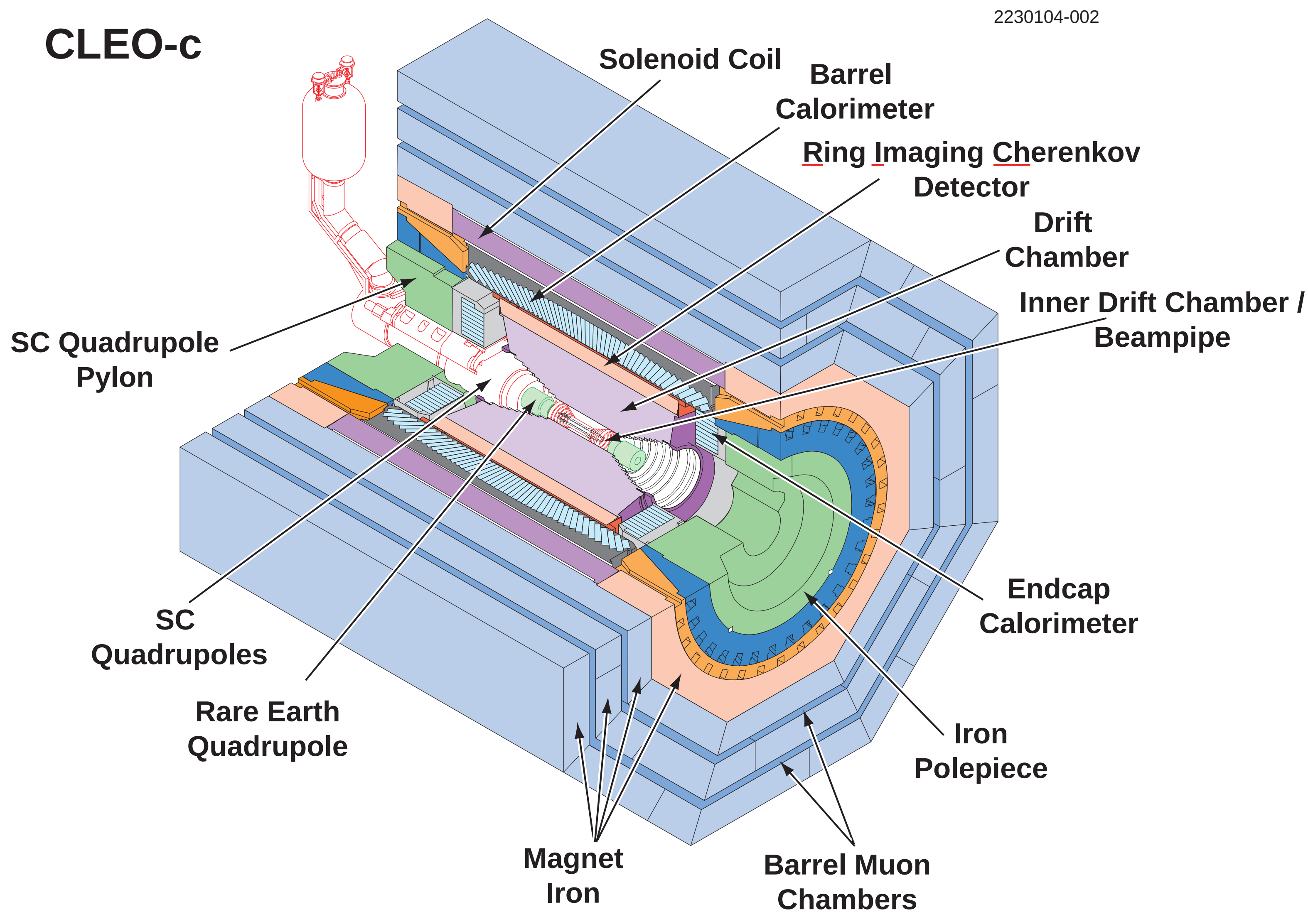
- For example, the width of the χ_{c1} state was improved from the SLAC result of $\Gamma(\chi_{c1}) < 3.8$ MeV to the Fermilab result of $\Gamma(\chi_{c1}) = 0.87 \pm 0.14$ MeV.

At the **Beijing Electron–Positron Collider** (BEPC), with the BES detector, a vigorous program of charmonium spectroscopy was started in 1990 and continued through 2005. With large data sets of J/ψ (58 million) and ψ' (14 million), it has provided substantial updates on a large number of J/ψ and ψ' decays.

BEPC and BES are now entering phase–2, with large improvement in luminosity and detector. They are becoming **operational just now**.

The **CLEO program** in charmonium spectroscopy started essentially in 2002, with the lowering of the CESR energy from $\sqrt{s} \approx 10$ GeV to $\sqrt{s} < 5$ GeV. The great advantage of the CLEO-c program, which has just ended, is in its superb, state-of-the-art detector, which is very much better than BES in photon detection and particle identification. Even in its relatively short lifetime, and with only 60 pb^{-1} of luminosity devoted to charmonium spectroscopy,the CLEO program has made major achievements, and I will describe some of them in detail.

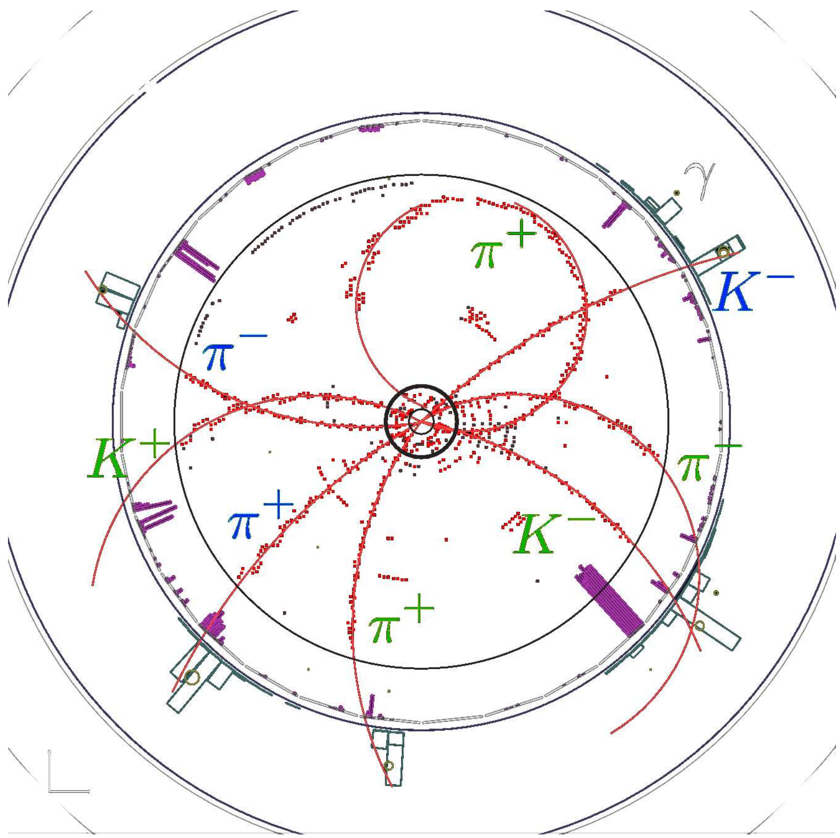
The **GSI program**, with its PANDA detector, is a serious extension of the Fermilab $p\bar{p}$ program. It expects to be **operational in $\sim \mathbf{2015}$**.


CLEO-c
2230104-002
Solenoid Coil
Barrel Calorimeter
Ring Imaging Cherenkov Detector
Drift Chamber
Inner Drift Chamber / Beampipe
SC Quadrupole Pylon
SC Quadrupoles
Rare Earth Quadrupole
Endcap Calorimeter
Iron Polepiece
Magnet Iron
Barrel Muon Chambers

A DRAMATIC EVENT IN THE CLEO-c DETECTOR

$$e^+e^-\ (4.17\ \text{GeV}) \rightarrow D_S^{*+} + D_S^- \rightarrow K_S + K^-$$

$$D_S^{*+} \downarrow D_S^+ + \gamma, \quad D_S^+ \downarrow K^+K^- + \pi^+\pi^- + \pi^+, \quad K_S \downarrow \pi^+\pi^-$$



Bottomonium

- The **bottom quark** was discovered at Fermilab in 1977 with the observation of Upsilons, $\Upsilon(1S, 2S)$, in $p+$Nucleus collisions at 400 GeV.
- For the next 25 years the spectroscopy of bottomonium $(b\bar{b})$ was vigorously pursued primarily at the ~ 10 GeV e^+e^- collider (CESR) at Cornell with the CLEO and CUSB detectors. Contributions were also made by the e^+e^- colliders, Doris at DESY (with ARGUS and CB detectors), and VEPP–4.
- The smaller cross sections for Υ production, and the generally smaller level spacing of bottomonium states have had the effect that far **less spectroscopic information** is available for bottomonium states.
- For the $\Upsilon(2S, 3S)$ bound states only the leptonic decays, radiative decays to $\chi_b(^3P_J)$ and two pion decay to lower Υ's are known.
- Only radiative decays of χ_b to lower Υ's have been measured (until now).
- The ground state $\eta_b(1^1S_0)$ has not been identified until now.
- Recently, the situation for bottomonium spectroscopy has changed because of the entry into the game by the $B-$factories at SLAC and KEK with their monstrous luminosities.

Developments in Spectroscopy

Developments in spectroscopy are of two kinds: improved precision and new discoveries.

PRECISION: Some improvements in precision can lead to significant results of physics, and some are just beautiful measurements. Let me give you two examples.

MASSES: from Novosibirsk: $M(J/\psi) = 3096.916$ MeV± 11 keV. Great!

from Cornell: $M(D^0) = 1864.85 \pm 0.18$ MeV

The $M(D^0)$ measurement has important physics impact because it establishes the very small binding energy of the exotic state, X(3872), and may be able to settle the argument about the DD^* molecular nature of X(3872).

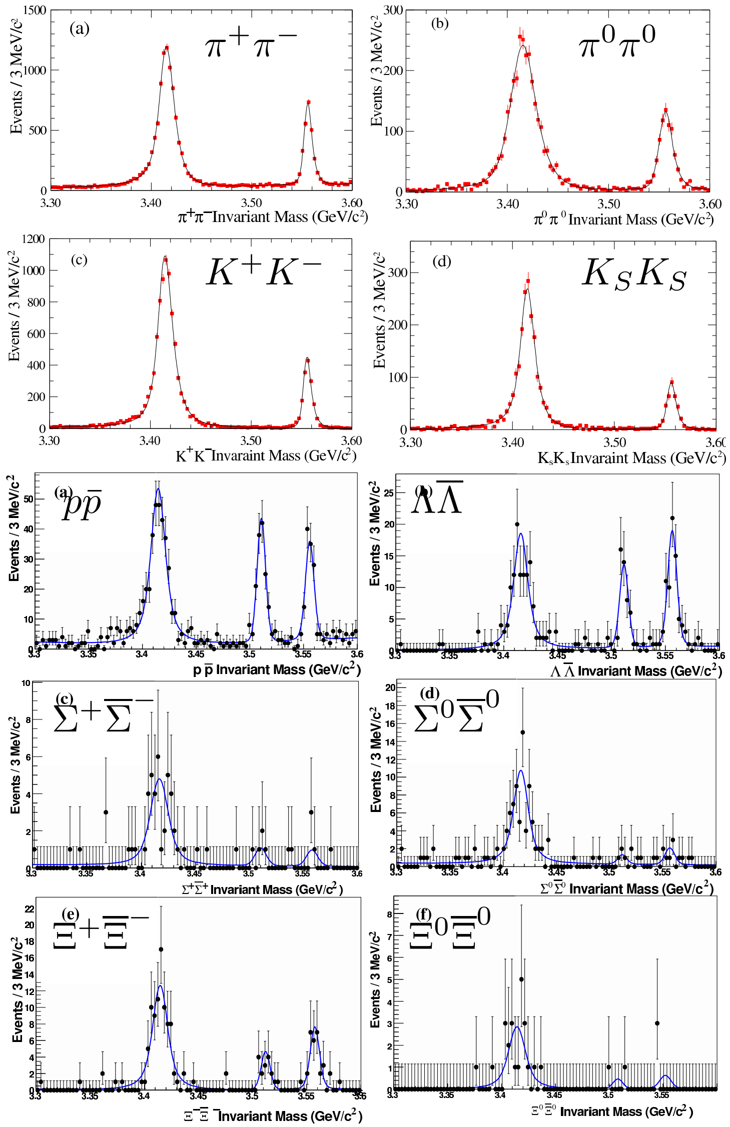
BRANCHING FRACTIONS:

These constitue the bulk of spectroscopic information. They are not just "bread and butter" physics. They are the essential physics, often difficult to interpret, but this is the challenge that theories must meet. I can not discuss the roughly 500 charmonium branching fractions that have been measured, but only give you an idea of the progress, and some of the interesting questions they pose for theory.

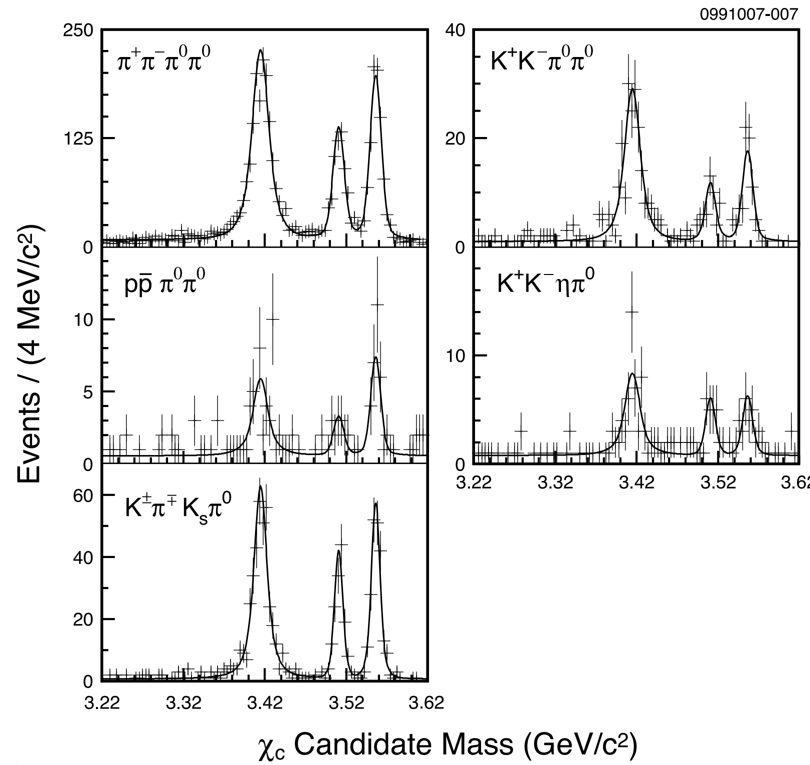
- To illustrate the continuing progress in measuring more and more decays of charmonium states, let me quote the number of hadronic decays listed by PDG06→PDG08: $\eta_c(15 \to 19)$, $J/\psi(98 \to 116)$, $\chi_{c0}(30 \to 50)$, $\chi_{c1}(18 \to 33)$, $\chi_{c2}(23 \to 36)$, $\psi(2S)(86 \to 95)$, $\psi(3770)(35 \to 59)$. The **notable exception** is η_c' for which only one hadronic decay, $K_S K \pi$, has ever been observed.
- Some of the interesting theoretical problems that the branching fractions pose:
  - $J/\psi \to \rho\pi$ is the **strongest** two–body decay of J/ψ. $\mathcal{B} = 1.7\%$
  - $J/\psi \to \pi^+\pi^-$ is the **weakest** two–body decay of J/ψ. $\mathcal{B} = 0.01\%$
  - $\psi' \to \rho\pi$ is **500 times weaker** than $J/\psi \to \rho\pi$.
  - $\psi' \to$**baryon pairs**, ranging from $p\bar{p}$ to $\Xi\overline{\Xi}$, have almost the same strength even as phase space decreases by a factor three.
  - The ratios of the decays of χ_{c0} and χ_{c2} disagree with pQCD expectations.

Experiment	pQCD	+ rad. correction
$\mathcal{B}(\chi_{c0} \to \pi^+\pi^-)/\mathcal{B}(\chi_{c2} \to \pi^+\pi^-) = 22 \pm 2$	15/4=3.8	9.5
$\mathcal{B}(\chi_{c0} \to \gamma\gamma)/\mathcal{B}(\chi_{c2} \to \gamma\gamma) = 4.8 \pm 0.4$	15/4=3.8	7.6

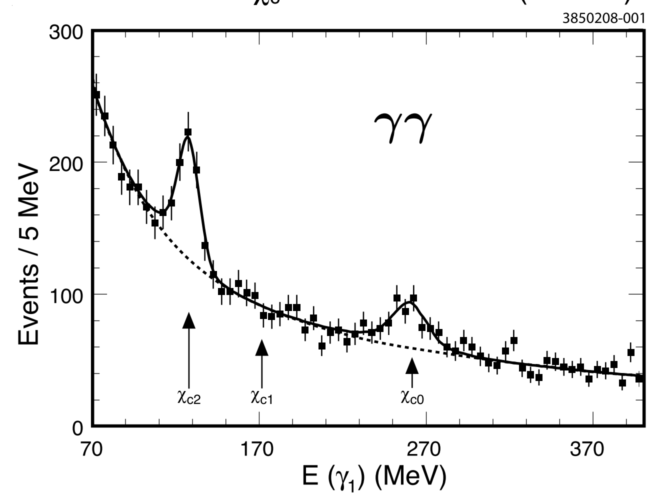
These raise serious questions about the validity of 1st order rad. corrections. Many other observations like the above await theoretical understanding.



(a) $\pi^+\pi^-$
$\pi^+\pi^-$ Invariant Mass (GeV/c²)
(b) $\pi^0\pi^0$
$\pi^0\pi^0$ Invariant Mass (GeV/c²)
(c) K^+K^-
K^+K^- Invariant Mass (GeV/c²)
(d) K_SK_S
K_sK_s Invariant Mass (GeV/c²)
Events / 3 MeV/c²
(a) $p\bar{p}$
$p\bar{p}$ Invariant Mass (GeV/c²)
(b) $\Lambda\bar{\Lambda}$
$\Lambda\bar{\Lambda}$ Invariant Mass (GeV/c²)
(c) $\Sigma^+\bar{\Sigma}^-$
$\Sigma^+\bar{\Sigma}^-$ Invariant Mass (GeV/c²)
(d) $\Sigma^0\bar{\Sigma}^0$
$\Sigma^0\bar{\Sigma}^0$ Invariant Mass (GeV/c²)
(e) $\Xi^+\bar{\Xi}^-$
$\Xi^-\bar{\Xi}^-$ Invariant Mass (GeV/c²)
(f) $\Xi^0\bar{\Xi}^0$
$\Xi^0\bar{\Xi}^0$ Invariant Mass (GeV/c²)



0991007-007
$\pi^+\pi^-\pi^0\pi^0$
$K^+K^-\pi^0\pi^0$
$p\bar{p}\,\pi^0\pi^0$
$K^+K^-\eta\pi^0$
$K^\pm\pi^\mp K_s\pi^0$
Events / (4 MeV/c²)
χ_c Candidate Mass (GeV/c²)



3850208-001
$\gamma\gamma$
χ_{c2}
χ_{c1}
χ_{c0}
Events / 5 MeV
E (γ_1) (MeV)

$\chi_{bJ}(3P_J)$ States of Bottomonium

As mentioned earlier, until now no hadronic decays of $\chi_{bJ}(^3P_J)$ states were ever measured. Using the existing CLEO data for 9.3 million $\Upsilon(2S)$ and 5.9 million $\Upsilon(3S)$ CLEO has now measured the product branching fractions
$\mathcal{B}(\Upsilon(2S) \to \gamma\chi_{bJ}(1P)) \times \mathcal{B}(\chi_{bJ}(1P) \to X_i)$ and
$\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{bJ}(2P)) \times \mathcal{B}(\chi_{bJ}(2P) \to X_i)$
for 14 different hadronic decays X_i. These are the first ever measured, and their impact on models of fragmentation of heavy quark states should be important. In the meanwhile we make three empirical observations:

1. The corresponding branching ratios for $\chi_{bJ}(1P) \to X_i$ and $\chi_{bJ}(2P) \to X_i$ are equal within errors. This is also true for the sums over all 14 decays.
2. The ratio of branching fractions $\mathcal{B}(\chi_b \to n\pi^{\pm}2\pi^0)/\mathcal{B}(\chi_b \to (n+2)\pi^{\pm})$ is ~ 5 for $n = 4$ and ~ 7 for $n = 6$. This is in good agreement with the old combinatoric predictions of Pais.
3. The ratio $\mathcal{B}(\chi_b(J=1) \to \Sigma X_i)/\mathcal{B}(\chi_b(J=2) \to \Sigma X_i) \approx 5/3$. This is almost inverse of what is expected.

Hadronic Decays of $\chi_{bJ}(1P, 2P)$

Branching fractions in 10^{-4}

X_i	J=0		J=1		J=2	
	$1P$	$2P$	$1P$	$2P$	$1P$	$2P$
$2\pi 2K 1\pi^0$	< 1.6	< 0.3	$2.0 \pm 0.5 \pm 0.5$	$3.0 \pm 0.6 \pm 0.8$	$0.9 \pm 0.4 \pm 0.2$	< 1.1
$3\pi 1K 1K_S^0$	< 0.5	< 0.5	$1.3 \pm 0.4 \pm 0.3$	$1.1 \pm 0.4 \pm 0.3$	< 1.2	< 0.9
$3\pi 1K 1K_S^0 2\pi^0$	< 4.7	< 2.3	< 6.1	$7.7 \pm 2.3 \pm 2.2$	$5.3 \pm 1.9 \pm 1.5$	< 6.7
$\boldsymbol{4\pi 2\pi^0}$	< 2.1	< 2.5	$7.9 \pm 1.4 \pm 2.1$	$5.9 \pm 1.2 \pm 1.6$	$3.5 \pm 1.1 \pm 0.9$	$3.9 \pm 1.2 \pm 1.1$
$\boldsymbol{6\pi}$	< 0.8	< 0.7	$1.8 \pm 0.4 \pm 0.4$	$1.2 \pm 0.3 \pm 0.3$	$0.7 \pm 0.3 \pm 0.2$	$0.9 \pm 0.3 \pm 0.2$
$4\pi 2K$	$1.2 \pm 0.5 \pm 0.3$	< 1.5	$1.5 \pm 0.4 \pm 0.4$	$0.9 \pm 0.3 \pm 0.2$	$1.2 \pm 0.3 \pm 0.3$	$0.9 \pm 0.3 \pm 0.2$
$4\pi 2K 1\pi^0$	< 2.7	< 2.2	$3.4 \pm 0.8 \pm 0.9$	$5.5 \pm 1.0 \pm 1.5$	$2.1 \pm 0.7 \pm 0.5$	$2.4 \pm 0.8 \pm 0.7$
$4\pi 2K 2\pi^0$	< 5.4	< 10.8	$8.6 \pm 2.0 \pm 2.4$	$9.6 \pm 2.3 \pm 2.8$	$3.9 \pm 1.6 \pm 1.1$	$4.7 \pm 1.8 \pm 1.4$
$5\pi 1K 1K_S^0 1\pi^0$	< 1.7	< 6.7	$9.2 \pm 2.3 \pm 2.5$	$6.7 \pm 1.9 \pm 1.9$	< 5.0	< 4.5
$\boldsymbol{6\pi 2\pi^0}$	< 5.9	< 12.3	$17.2 \pm 2.7 \pm 4.8$	$11.9 \pm 2.4 \pm 3.4$	$10.2 \pm 2.2 \pm 2.8$	$12.1 \pm 2.5 \pm 3.6$
$\boldsymbol{8\pi}$	< 0.7	< 1.7	$2.7 \pm 0.6 \pm 0.7$	$1.7 \pm 0.5 \pm 0.5$	$0.8 \pm 0.4 \pm 0.2$	$0.9 \pm 0.4 \pm 0.3$
$6\pi 2K$	$2.4 \pm 0.9 \pm 0.7$	< 1.5	$2.6 \pm 0.6 \pm 0.7$	$2.0 \pm 0.6 \pm 0.5$	< 0.8	$1.4 \pm 0.5 \pm 0.4$
$6\pi 2K 1\pi^0$	< 9.9	< 7.3	$7.5 \pm 1.6 \pm 2.1$	$6.1 \pm 1.4 \pm 1.8$	$3.7 \pm 1.2 \pm 1.0$	$4.2 \pm 1.2 \pm 1.2$
$8\pi 2\pi^0$	< 20.5	< 6.5	$14.0 \pm 3.5 \pm 4.3$	$19.2 \pm 3.7 \pm 6.0$	$18.5 \pm 4.4 \pm 5.6$	$12.6 \pm 3.5 \pm 4.1$

The greater fun in spectroscopy comes from new discoveries. In quarkonia, they have recently come from the study of

Spin–Dependent Interactions

In the potential model formulation of the $q\bar{q}$ interaction, spin dependence is generally assumed to come as the Breit-Fermi interaction arising from the Coulombic or $1/r$ dependent part of the potential. The confinement part of the potential is generally assumed to be Lorentz scalar and except for the Thomas–term, no spin dependence arises from it.

The richness of quarkonium spectra lies in their spin structure. The Coulombic part gives rise to the familiar **spin–orbit**, **tensor**, and **spin–spin** potentials. Because the $\chi_{cJ}(1P)$ and $\chi_{bJ}(1P, 2P)$ states are well–established this spin–orbit and tensor potentials are empirically well determined.

Unfortunately, the **hyperfine interaction**, which leads to the splitting between the spin–singlet and spin–triplet states, is not well determined. The reason lies in the experimental difficulty in accessing the spin–singlet states in e^+e^- annihilation experiments. Recently these difficulties have been largely overcome, and I want to talk about the discoveries of $\eta_c'(2^1S_0)$, $h_c(1^1P_1)$, and $\eta_b(1^1S_0)$ spin–singlets, and their impact on our understanding of the hyperfine interaction.

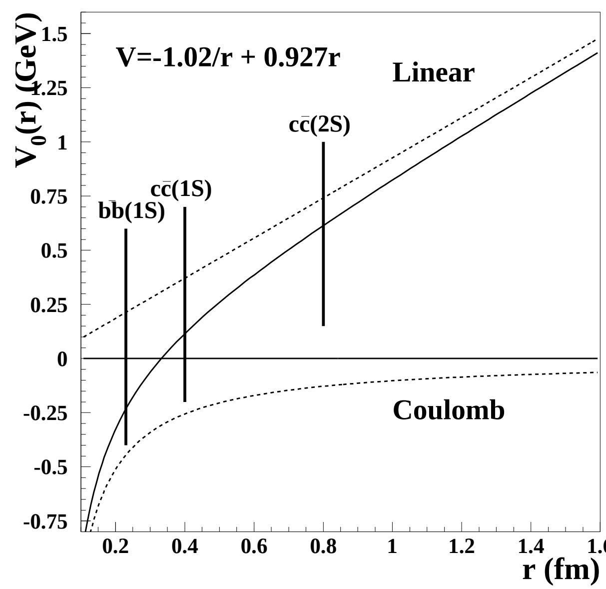
The Hyperfine Interaction

The hyperfine interaction determines the **ground-state masses** of all hadrons. The textbook statement of the quark-model is that the mass of a pseudoscalar or vector $q\bar{q}$ meson is

$$M(q_1\bar{q}_2) = m_1(q_1) + m_2(q_2) + A\,[\vec{s}_1 \cdot \vec{s}_2/m_1 m_2]$$

If you fit the known masses of all the light-quark vectors and pseudoscalars, you obtain the measure of the hyperfine interaction, $A \approx 640\ \mathrm{MeV} \times m_n^2$, ($n \equiv u, d$ quark), which nicely gives the $\rho - \pi$ splitting as ≈ 640 MeV, as well as the $D^* - D$ splitting of 141 MeV.

- The interesting questions for us are **how the hyperfine interaction evolves** in the heavy "onia", the $c\bar{c}$ charmonium and the $b\bar{b}$ bottomonium.
- How does it change with principle and orbital quantum numbers?
- How does it change with quark mass?



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

Until very recently, in all of onium spectroscopy, the only hyperfine splitting known was that for the charmonium $1S$ state

$$\boldsymbol{\Delta M_{hf}(1S) \equiv M(J/\psi,^3S_1) - M(\eta_c,^1S_0) = 116.7 \pm 1.2}\ \text{MeV}$$

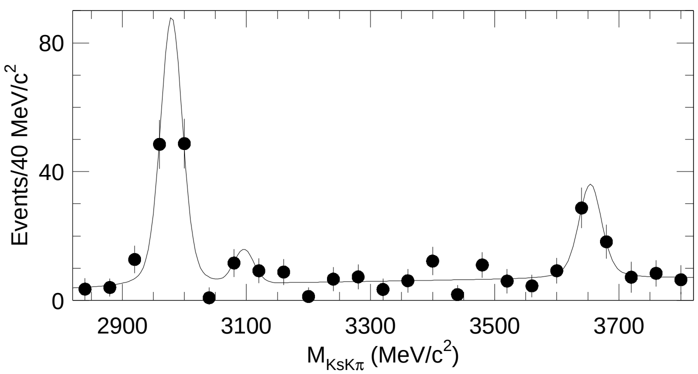
A model-independent prediction is that (with the radial wave function at origin $R(0)$)

$$\frac{\Delta M_{hf}(2S)}{\Delta M_{hf}(1S)} = \frac{[R(0)]^2_{2S}}{[R(0)]^2_{1S}} = \frac{\Gamma(\psi'(2S) \to e^+e^-) \times M^2(\psi'(2S))}{\Gamma(J/\psi(1S) \to e^+e^-) \times M^2(J/\psi(1S))},$$

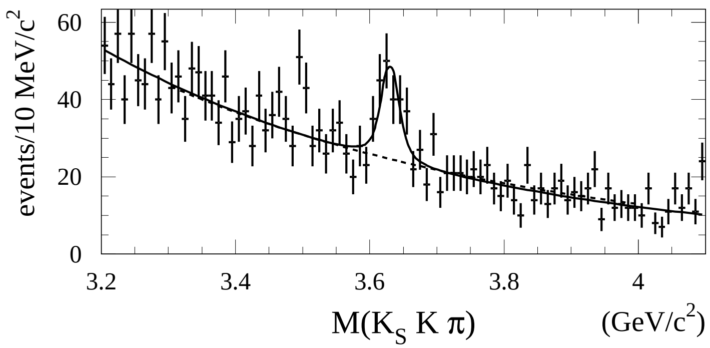
so that $\boldsymbol{\Delta M_{hf}(2S) \equiv M(\psi',^3S_1) - M(\eta_c',^1S_0) \quad = 62 \pm 5\ \text{MeV}}$.

- Despite an early claim by Crystal Ball at SLAC and several subsequent attempts by Fermilab, DELPHI, L3, and CLEO **η_c' remained undiscovered for 30 years!**.
- The surprising annoucement of the discovery of η_c' came in 2003 from a rather unexpected source—Belle. In the decays $B \to K(K_SK\pi)$, Belle observed an enhancement in the invariant mass of $K_SK\pi$ at $M = 3654 \pm 10$ MeV. If it is attributed to η_c', it leads to $\boldsymbol{\Delta M_{hf}(2S) = 32 \pm 10}$ **MeV**.

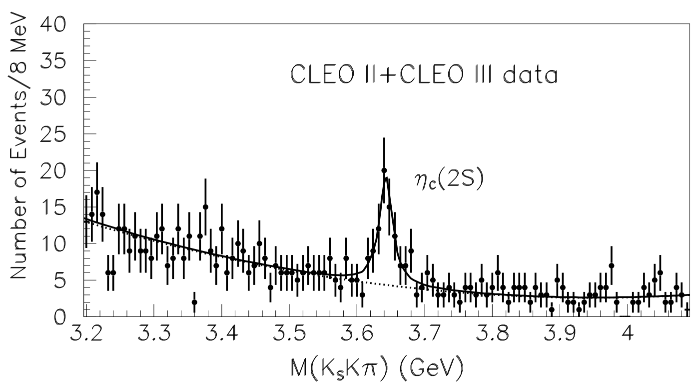
This was a true surprise, because it implied that the $2S$ hyperfine splitting was a **factor 4 smaller** than the $1S$ splitting!! It needed to be confirmed. It was soon confirmed by CLEO and BaBar by η_c' formation in two–photon fusion.



Belle
42 fb^{-1}
PRL 91, 262001 (2003)



BaBar
86 fb^{-1}
PRL 92, 142002 (2004)



CLEO
27 fb^{-1}
PRL 92, 142001 (2004)

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

(in MeV)	$M(\eta_c'(2S))$	$\Gamma(\eta_c'(2S))$	events (reaction)
Belle(2002)	3654 ± 10	< 55	$39 \pm 11\ (B \to K(K_S K\pi))$
CLEO(2004)	$\mathbf{3642.9 \pm 3.4}$	$\mathbf{< 31}$	$\mathbf{61 \pm 15\ (\gamma\gamma \to K_S K\pi)}$
BaBar(2004)	3630.8 ± 3.5	17.0 ± 8.7	$112 \pm 24\ (\gamma\gamma \to K_S K\pi)$
BaBar(2005)	3645.0 ± 5.5	22 ± 14	$121 \pm 27\ (e^+e^- \to J/\psi(c\bar{c}))$
Belle(2005)	3626 ± 9		$311 \pm 42\ (e^+e^- \to J/\psi(c\bar{c}))$

- Notice that the reported masses of η_c' range from 3626 to 3654 MeV, and the width of η_c' is essentially unmeasured so far. The PDG08 average is $\mathbf{M(\eta_c') = 3637 \pm 4}$ **MeV.**
- The hyperfine splitting is $\mathbf{\Delta M_{hf}(2S) = 49 \pm 4}$ **MeV.**

  Recall that, $\mathbf{\Delta M_{hf}(1S) = 117 \pm 1}$ **MeV.**
- Explaining this large difference between $1S$ and $2S$ hyperfine splitting is a challenge for theorists. Lattice is not much help so far. $\Delta M_{hf}(2S) = 75(44)$ MeV—(Columbia), $26(17)$ MeV—(CP–PACS)
- **LOTS REMAINS TO BE DONE ABOUT $\eta_c'(2^1S_0)$.**

Hyperfine Interaction in P–wave

In the lowest order the **spin–spin interaction** resulting from the $1/r$ vector potential is a **contact interaction**, i.e., it needs a finite $R(0)$, the radial wave function at the origin. The confinement potential is generally assumed to be Lorentz scalar and it makes no spin-dependent contribution. As a result the hyperfine splitting is finite for $l = 0$, $S-$states, and zero for all $l \neq 0$ states. In particular, it means that for $P-$states the singlet–triplet hyperfine splitting should be zero, i.e.,

$$\Delta M_{hf}(1P) \equiv M(^3P) - M(^1P) = 0$$

It is important to experimentally determine if this **simple, but extreme,** prediction is true. It bears on the possible vector component in the confinement potential as well as the **higher order** corrections in the conventional reduction of the Breit–Fermi Hamiltonian. Theoretical predictions for $\Delta M_{hf}(1P)$ range from +20 to –20 MeV

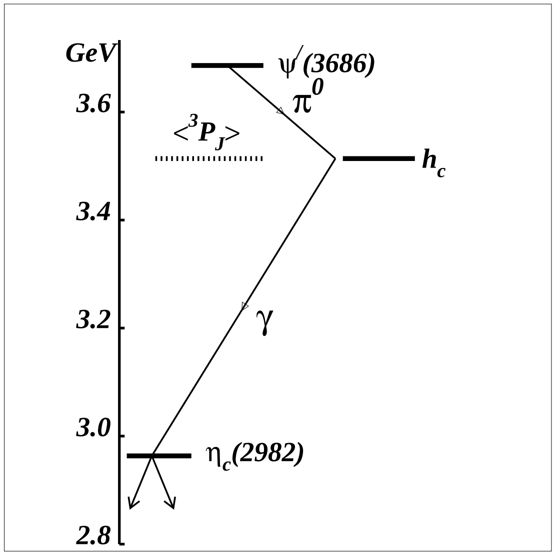
- In 2004, Fermilab E835 determined that the previous E760 claim of observing h_c in the reaction $p\bar{p} \to h_c \to \pi^0 J/\psi$ could not be confirmed. It searched for h_c by combining their data sets for the 1996 and 2000 runs for the reaction $p\bar{p} \to h_c \to \gamma\eta_c$, and reported

  $$\boldsymbol{N(h_c) = 13\,\mathrm{cts}, \quad \Delta M_{hf}(1P) = -0.4 \pm 0.2 \pm 0.2\ \mathrm{MeV}, \quad \mathrm{significance} \approx 3\sigma.}$$

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

As mentioned earlier, $h_c(^1P_1)$ can not be reached by a radiative transition from the $\psi'(2^3S_1)$ state produced in e^+e^- annihilation. The transition is $C-$forbidden. The only way to reach it from ψ' is via the isospin forbidden transition

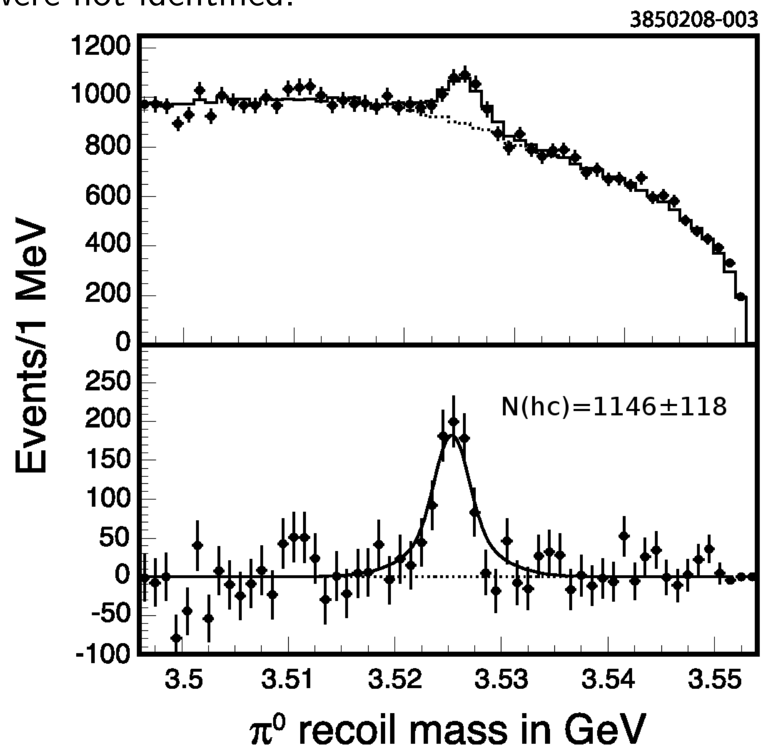
$$\psi' \to \pi^0 h_c, \quad h_c \to \gamma\eta_c,$$



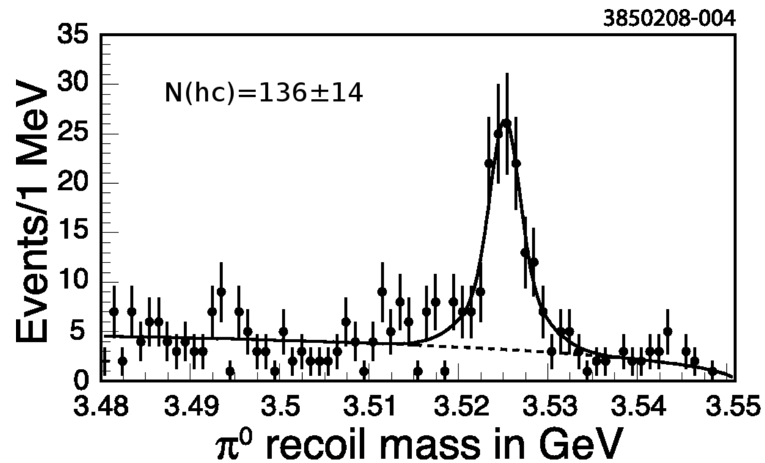
- In 2004, CLEO studied this reaction with 3 million ψ', and reported a firm identification of h_c, at a significance level $> 6\sigma$. Now, we have the precision results from the CLEO data with 24 million ψ', and more than a thousand h_c events.

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

Inclusive Analysis: The E1 photon energy E_γ was loosely constrained, but the decay products of η_c were not identified.



Exclusive Analysis: Instead of constraining E_γ fifteen hadronic decay channels of η_c' with a total branching fraction of $\sim 40\%$ were measured.



$$M(h_c) = 3525.28 \pm 0.19 \pm 0.12 \text{ MeV}$$
$$\Delta M_{hf}(1P) = +0.02 \pm 0.19 \pm 0.13 \text{ MeV}$$

(PRL 101, 182003 (2008))

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

But the $1P$ hyperfine splitting $\boldsymbol{\Delta M_{hf}(1P) = +0.02 \pm 0.19 \pm 0.13}$ **MeV** is obtained by defining $M(^3P) = \langle M(^3P_J)\rangle = [5M(\chi_{c2}) + 3M(\chi_{c1}) + M(\chi_{c0})]/9$.

- However, certainly the centroid $\langle M(^3P_J)\rangle \neq M(^3P)$. The equality is only true if the overall spin–orbit splitting is perturbatively small. With $M(\chi_2) - M(\chi_0) = 140$ MeV, this is hardly true here. In fact, the perturbative result $M(^3P_1) - M(^3P_0) = (5/2)[M(^3P_2) - M(^3P_1)] = \mathbf{114}$ **MeV** disagrees from the experimental result, $\mathbf{95.9 \pm 0.4}$ **MeV**, by 18 MeV.
- So, **why** does the $\Delta M_{hf}(1P)$ experimental results, obtained with the wrong $M(^3P)$, agree so well with the naive prediction of $\Delta M_{hf}(1P) = 0$??
- With both η_c' and h_c identified, the spectrum of the bound states of **charmonium** is complete. But we are far from understanding the true nature of the $q\bar{q}$ hyperfine interaction. We do not really know if there is an intrinsic long range hyperfine interaction. And if it is there, what is its origin? Is there a vector component in the confinement part of the potential?
- We do not know how to improve on the lowest order Breit–Fermi reduction of the spin dependent interaction which makes the spin-spin a contact interaction.

η_b — The Spin–Singlet g.s. of Bottomonium

It has been more or less of a disgrace that the g.s. of bottomonium $\eta_b(1^1S_0)$ had not been observed for the ~ 30 years since the discovery of spin–triplet $\Upsilon(1^3S_1)$.

- It is not for the lack of efforts. CLEO and CUSB tried, DELPHI tried, CDF tried, and none succeeded. All anybody could do was to establish upper limits.
- Using our existing 1.2 fb^{-1} of data at $\Upsilon(1S)$ with 21 million $\Upsilon(1S)$, at CLEO **we began** a new effort to identify η_b in the exclusive reaction

$$\Upsilon(1S) \to \gamma\eta_b(1S), \quad \eta_b(1S) \to X_i.$$

  with 26 different all–charged hadronic decay channels, X_i. We were making good progress, but—
- On July 7, 2008, the bomb exploded. BaBar announced (PRL 101, 071801 (2008)) that it had discovered η_b in the inclusive radiative decay

$$\Upsilon(3S) \to \gamma\eta_b$$

  in their 28 fb^{-1} sample of $\Upsilon(3S)$.

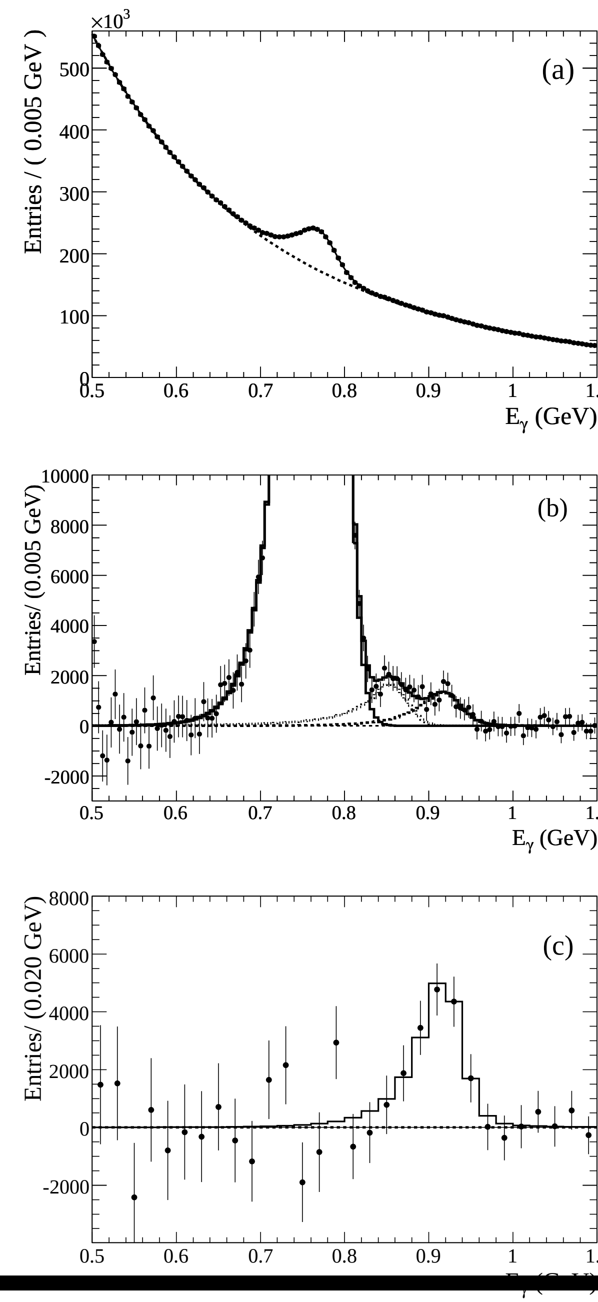
This is undoubtedly **the news** of heavy quark spectroscopy, and at CLEO we are trying to see if we can confirm it in our 1.5 fb^{-1} of data at $\Upsilon(3S)$.

BaBar's Discovery of $\eta_b(1^1S_0)$

It is a tour-de-force discovery:

$$e^+e^-(28\ \text{fb}^{-1}) \to \Upsilon(3S) \to \gamma\eta_b$$

- The inclusive photon spectrum is dominated by the $\chi_{bJ}(2P)$ peak from $\Upsilon(3S) \to \gamma\chi_{bJ}(2P)$, with $\chi_{b0,1,2}(2P) \to \gamma\Upsilon(1S)$ unresolved.
- On the high energy tail of χ_{bJ} there are two enhancements, $\gamma_{ISR}\Upsilon(1S)$ and $\gamma\eta_b$.
  - $\boldsymbol{E_\gamma(\eta_b) = 921.2^{+2.1}_{-2.9} \pm 2.4}$ **MeV**
  - $\boldsymbol{M(\eta_b) = 9388.9^{+3.1}_{-2.3} \pm 2.7}$ **MeV**
  - $\boldsymbol{\Delta M_{hf}(1S)_b = 71.4^{+2.3}_{-3.1} \pm 2.7}$ **MeV**
- The above $\Delta M_{hf}(1S)_b$ agrees with model independent prediction relating it to $\Delta M_{hf}(1S)_c = 116.8$ MeV, and also the Lattice prediction of 60 ± 14 MeV.



CHARMONIUM EXOTICS

The Unexpected States Above the $D\overline{D}$ Threshold

- Three years ago, all that was known above $D\overline{D}$ was the four vector states $\psi(3770,\ 4040,\ 4160,\ \text{and}\ 4415)$ observed as enhancements in the ratio, $R = \sigma(hh)/\sigma(\mu^+\mu^-)$.
- There has been a great amount of work by CLEO, Belle and BaBar about the properties of D and D_s mesons produced at these resonances.
- However, the great excitement, often called the **renaissance** in hadron spectroscopy, has come from the discovery of a whole host of unexpected states by the meson factory detectors, Belle and BaBar.

  The new states are called **"charmonium-like states"**, not because they naturally fit into the spectrum of charmonium states, but because they seem to always decay into **final states containing a charm quark and an anti-charm quark**. There are at least six of them around. The alphabet soup is getting thick with **X(3872), X,Y,Z(∼3940), Y(4260)**, and more recently **X′, X″ X‴**, and **Z**.

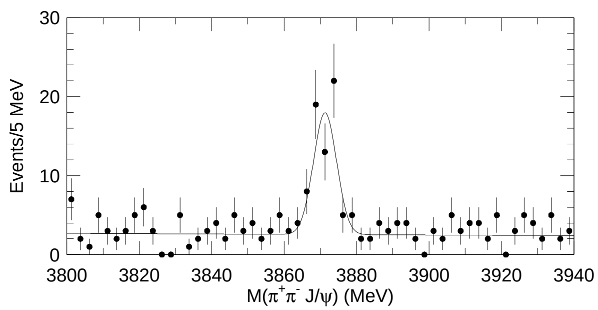
  Let me go over them in some detail.

X(3872)

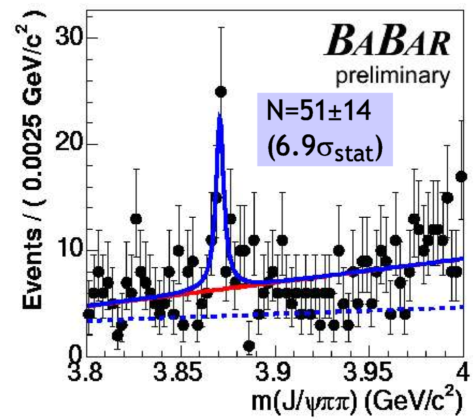
- This narrow state with $M(\mathrm{X}) = \mathbf{3872.2 \pm 0.8}$ MeV, and $\Gamma(\mathrm{X}) = 3.0^{+1.9}_{-1.4} \pm 0.9$ MeV, has been observed by Belle, BaBar, CDF, DØ, and it definitely exists. [PDG08]
- CDF angular correlation studies show that its $J^{PC} = 1^{++}$ or 2^{-+}.
- X(3872) does not easily fit in the charmonium spectrum. Since its mass is very close to $M(D) + M(D^*)$, the most popular conjecture is that it is a weakly **bound molecule** of D and D^*. If so, our recent precision measurement of D^0 mass at CLEO implies X(3872) is **unbound** by 0.4 ± 0.8 MeV.
- If X(3872) were bound by ~ 0.4 MeV, the branching fraction for the molecule's breakup into $D\overline{D}\pi$ is predicted to be factor 400 smaller than observed. This raises serious doubts about the molecular model for X(3872).
- To avoid the $D\overline{D}\pi$ problem it is speculated that there is another resonance nearby. There are no convincing observations of it so far. **So what is X(3872) ?**
- We need even higher precision mass measurements of $M(\mathrm{X})$ and $M(D^0)$, and $B(\mathrm{X} \to D^0 D^0 \pi^0)$ to throw some fresh light on the nature of X(3872).

The Veteran of Suprises—X(3872)

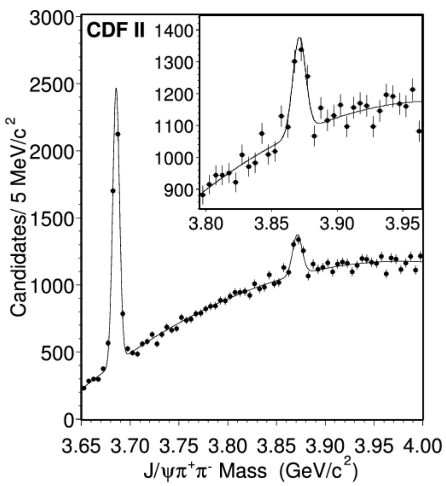
The experimental observations (2003–4):



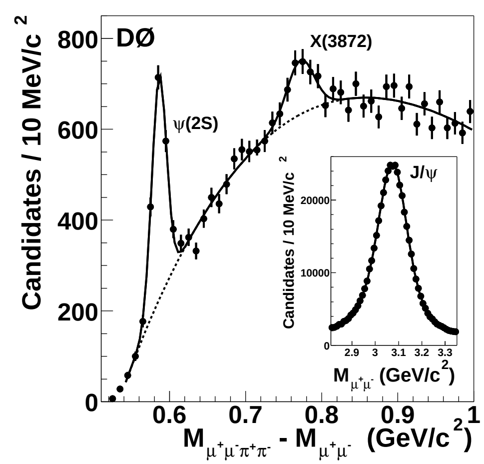
275M $B\bar{B}$ decays
$M = 3872.0 \pm 0.8$ MeV
(Belle, left)
$N = 49.1 \pm 8.4$ events



226M $B\bar{B}$ decays (BaBar)
$M = 3871.3 \pm 0.6$ MeV
(BaBar, right)
$N = 51 \pm 14$ events



$M = 3871.3 \pm 0.8$ MeV
(CDF, left)
$N = 730 \pm 30$ events



$M = 3873.4 \pm 1.4$ MeV
(DØ, right)
$N = 522 \pm 100$ events

$$\langle M \rangle = 3872.2 \pm 0.8 \text{ MeV}, \quad \langle \Gamma \rangle = 3.0^{+1.9}_{-1.4} \pm 0.9 \text{ MeV}$$

Y(4260)

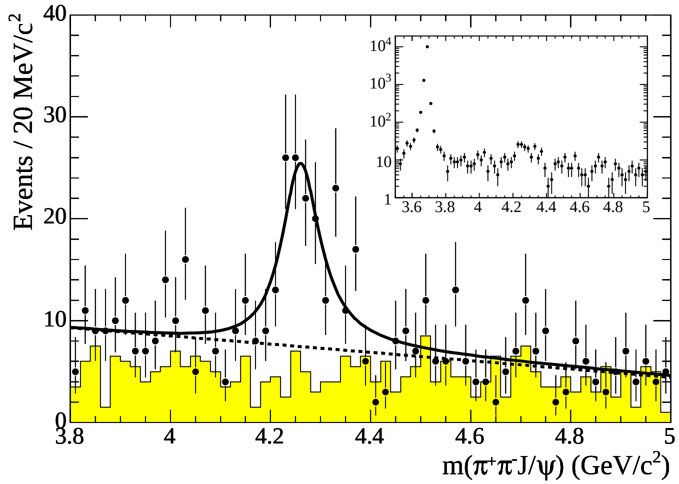
- The Y(4260) has been observed in ISR production by BaBar, CLEO and Belle, and in direct production by CLEO. Y(4260) is clearly **a vector** with $J^{PC} = 1^{--}$, but a very strange one, since it sits at a very deep minimum in R, with

$$M(\mathrm{Y}(4260)) = 4263^{+8}_{-9}\ \mathrm{MeV}, \quad \Gamma(\mathrm{Y}(4260)) = 95 \pm 14\ \mathrm{MeV} \qquad (\mathrm{PDG08})$$

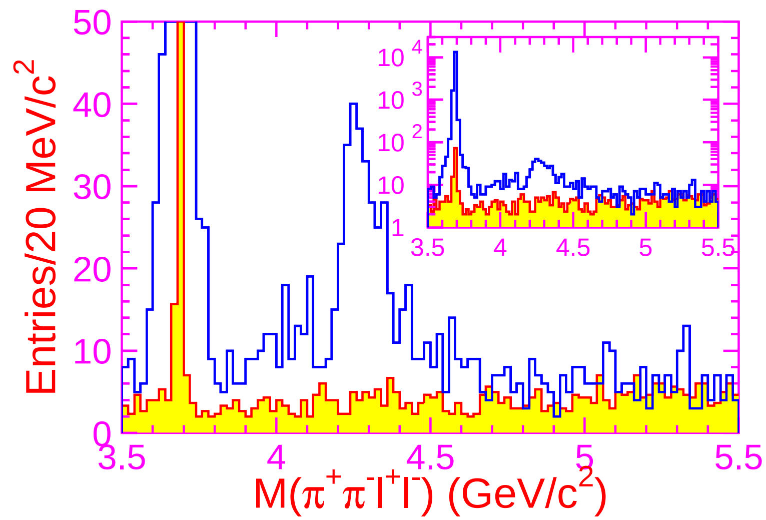
So it is not likely to be a charmonium vector, which are all spoken for, anyway.

So what is Y(4260)?

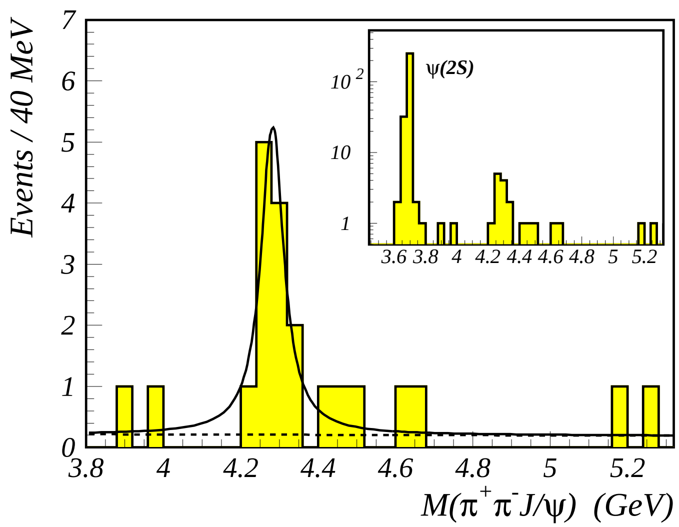
- It is suggested that Y(4260) is a $c\bar{c}g$ charmonium **hybrid**. If so, there ought to be 0^{-+} and 1^{-+} hybrids companions nearby. The exciting challenge for experimentalists is to find them.
- There are new problems. Belle has revived the question whether there is actually one resonance or two. Further, Belle reports that $M(\mathrm{Y})$ in $Y \to J/\psi\pi\pi$ and $Y \to \psi'\pi\pi$ is different by almost 120 MeV.
- It is a real experimental challenge to clarify this situation before taking any theoretical conjecture seriously.



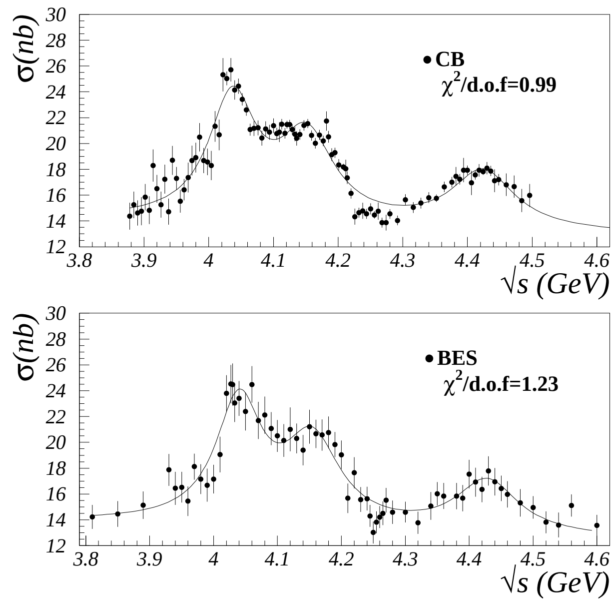
BaBar: 233 fb^{-1}



Belle: 548 fb^{-1}

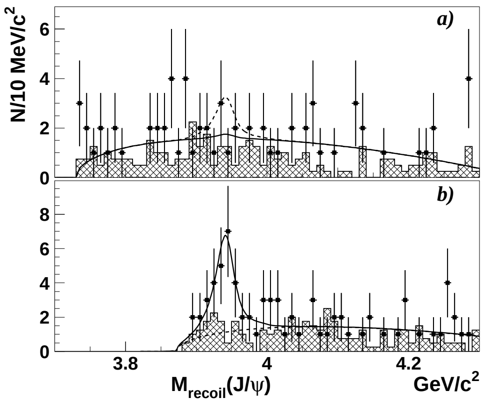


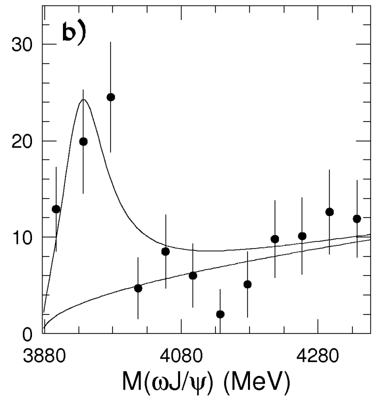
CLEO: 13.3 fb^{-1}

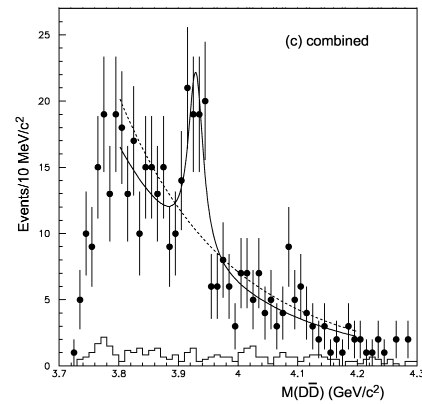


The Saga of X,Y,Z(∼3940)

- These three states, reported so far by Belle only, all have same masses within ± 7 MeV. All decay into states which contain a c and a $\bar{c}$ quark; hence the designation charmonium-like. **Each is produced in a different formation channel and each decays into a different decay channel.** Even with e^+e^- luminosities of up to ~ 700 fb^{-1} thrown at them **none has more than 75 counts** in their favorite decay. If all that makes you slightly skeptical you are not alone. I summarize them in a table.
- The X(3943) is produced in $e^+e^- \rightarrow$double charmonium, and since only $J = 0$ states, η_c, χ_{c0}, and η_c' appear to be produced in the same spectrum, it is conjectured that its spin is also $J = 0$, and it is most likely $\eta_c''(3^1S_0)$.
- The Z(3929) is produced in $\gamma\gamma$ fusion and decays to $D\overline{D}$. Its angular distribution suggests $J = 2$, and it is conjectured to be $\chi_{c2}'(2^3P_2)$.
- The Y(3943) is produced in $B \rightarrow KY$ and decays to $\omega J/\psi$. It is speculated that it might be a hybrid. It appears least convincing of the three.





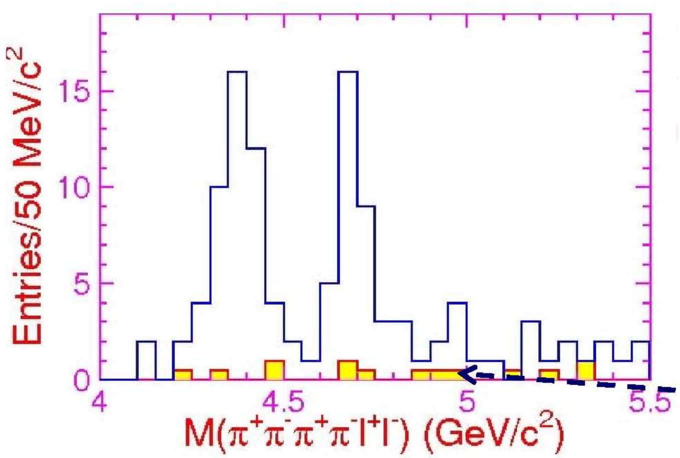


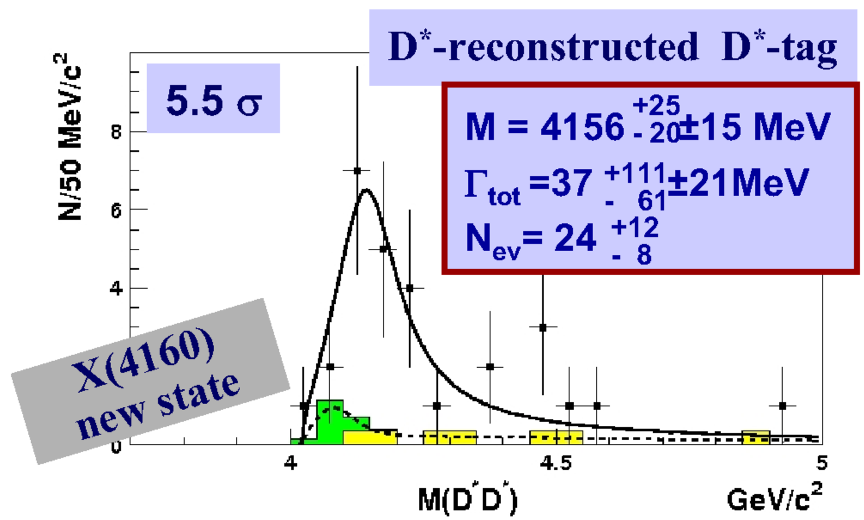
	X(3943)—Belle	**Y(3943)—Belle**	**Z(3929)—Belle**
	$N(\mathrm{X}) = 24.5 \pm 6.9$	$N(\mathrm{Y}) = 58 \pm 11$	$N(\mathrm{Z}) = 64 \pm 18$
	$M(\mathrm{X}) = 3943 \pm 10$	$M(\mathrm{Y}) = 3943 \pm 17$	$M(\mathrm{Z}) = 3929 \pm 10$
	$\Gamma(\mathrm{X}) = 15.4 \pm 10.1$	$\Gamma(\mathrm{Y}) = 87 \pm 16$	$M(\mathrm{Z}) = 20 \pm 8$
Production:	Double Charmonium	$B \to KY$	$\gamma\gamma$ fusion $(J = 2)$
Decay:	X$\to D * \overline{D} > 45\%$	Y$\to \omega J/\psi$	Z$\to D\overline{D}$
	X$\nrightarrow D * \overline{D} < 41\%$	Y$\nrightarrow D\overline{D}$	
	X$\nrightarrow \omega J/\psi < 26\%$		
Best Guess:	$\eta_c''(3^1S_0)$	Hybrid??	$\chi_{c2}'(2^3P_2)$
Challenge:	Search for X in $\gamma\gamma$ fusion	Search for Y$\to D\overline{D},\ D^*\overline{D},$	Search for Z$\to D^*\overline{D}$

Bigger Challenge: Find some way other than e^+e^- to excite these states.

Three Newer States from Belle

	Source	Mass (MeV)	Width (MeV)	Events	Reaction
X′	Belle	4160	$139(^{113}_{65})$	$24(^{12}_{8})$	$e^+e^- \to J/\psi + D^*D^*$
X″	BaBar	4324	172(33)	65(10)	$e^+e^- \to \psi(2S)\pi^+\pi^-$
	Belle	4360	74(18)	~ 50	$e^+e^- \to \psi(2S)\pi^+\pi^-$
X‴	Belle	4660	48(15)	~ 36	$e^+e^- \to \psi(2S)\pi^+\pi^-$





Highly Questionable. Likely $\psi(4160)$!

More From Belle

At this point you probably wish that these "discoveries" of exotic states by Belle would stop. But it is not to be. In the last six months, Belle has produced at least three more, and they are more exotic than all the previous ones. Because they are charged. They are:

		M(Z) (MeV)	**Γ(Z) (MeV)**	$\boldsymbol{\mathcal{B}(Z^{\pm}(4430) \to \pi^{\pm}\psi(2S))}$
$B \to K(\pi^{\pm}\psi(2S))$		$4433 \pm 4 \pm 2$	45^{+18+30}_{-13-12}	$(4.1 \pm 0.1 \pm 0.1) \times 10^{-5}$
				$\boldsymbol{\mathcal{B}(\overline{B^0} \to K^- Z_n^+) \times \mathcal{B}(Z_n^+ \to \pi^+\chi_{c1})}$
$\overline{B^0} \to K^-(\pi^+\chi_{c1})$	(Z_1)	$4051 \pm 14^{+20}_{-41}$	82^{+21+47}_{-17-22}	$\left(4.0^{+2.3+19.7}_{-0.9-0.5}\right) \times 10^{-5}$
	(Z_2)	$4248^{+44+180}_{-29-35}$	$177^{+54+316}_{-39-61}$	$\left(3.0^{+1.5+3.7}_{-0.8-1.6}\right) \times 10^{-5}$