A RENAISSANCE IN STRONG INTERACTION PHYSICS

Hadrons and Exotics

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Symposium on Strong Interactions in the 21st Century
Bhabha Centenary Celebration, TIFR, Mumbai
Feb. 10–12, 2010

A Reminiscence of H. J. Bhabha

Since this is part of the celebration of the birth centenary of Homi J. Bhabha, it is perhaps not inappropriate for me to recall the times I saw him.

In 1954, I obtained my M.S. in physics from the Lucknow University and received a fellowship to study for Ph.D. at the University of Pittsburgh in the U.S. Not having enough money for air travel to the U.S., I booked passage to the U.S. on a cargo ship (S.S. Steel Voyager). That brought me to Bombay in September 1954. Since I was in Bombay, I just had to see the famous **H.J. Bhabha**. I came to the TIFR and tried to get an appointment to see him. Unfortunately, he was busy, and I only got to meet his deputy(?) K.S. Singwi. Later that afternoon, I did get to see **Bhabha** in a fire drill on the lawn where he was valiantly and clumsily demonstrating how to use a fire extinguisher.

Fast forward three years to September 1957. I had just obtained my Ph.D. for research in neutron physics done at the graphite reactor at the Brookhaven National Laboratory. That year Columbia University organized an International Conference on neutron physics. Some 240 practitioners of Nuclear Physics, including the greats, and that included **Bhabha**, were there, and so was I.

Proceedings

International Conference on the Neutron Interactions with the Nucleus

Held at

Columbia University

New York

September 9 -13, 1957

UNITED STATES ATOMIC ENERGY COMMISSION
Technical Information Service Extension
Oak Ridge, Tennessee

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The session in which I gave my talk on confirmation of a prediction of the recently proposed Optical Model of Nuclear Reactions was chaired by **Bhabha**, who appeared to be rather pleasantly surprised as he introduced my talk. After the session he came to me, complimented me on my talk, and asked me to consider coming back to India and joining TIFR. He said that he had asked Ramanna, who was also at the conference, to talk to me and work out the details. Unfortunately, the details did not work out, and I stayed in the U.S.

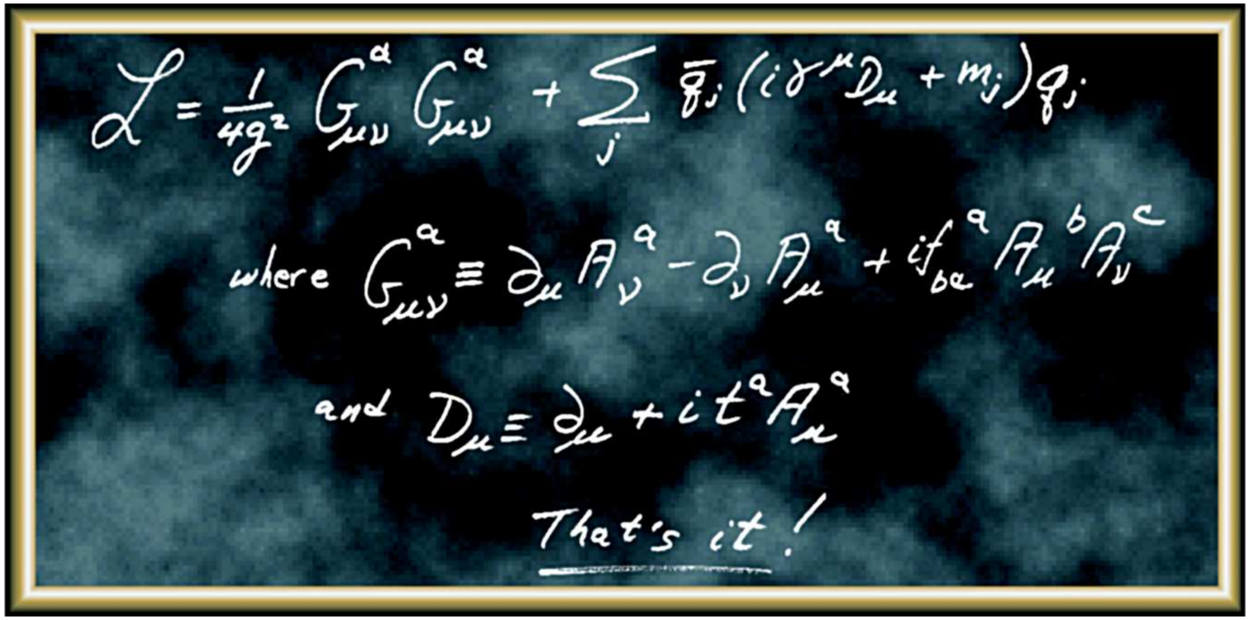
That was my second and last meeting with Bhabha. I did not meet Bhabha after 1957. However, in my present life as a researcher in hadron spectroscopy via e^+e^- annihilation, **not a single day passes** in our research group when we do not talk about the **Bhabhas** (plural), since the luminosity of e^+e^- electron–positron annihilations is measured in terms of the Bhabhas produced.

The Strong Interaction

Historical: As we all know, the first manifestation of the strong interaction was in nuclei. The binding energy/nucleon in nuclei is $\sim$8 MeV, as compared to the electromagnetic binding energy of electrons in an atom, which is of the order of 10 eV, i.e., a million times smaller. Hence, **the strong interaction**.

At the beginning of the 20th century the only knowledge we had about the strong interaction was empirical, obtained from the experimental measurements of the properties of nuclei. Then Yukawa gave us the **pion**, and we tried to understand the nuclear strong interaction by the exchange of a pion between two nucleons, giving rise to **OPEP**, or the One Pion Exchange Potentials, and subsequently to **MPEP** and **OBEP**. However, two problems remained. The success of the potentials was limited to energies below particle production threshold, i.e., $\sim$300 MeV. Further, the entire edifice was based on phenomenology. No fundamental understanding of the strong interaction was achieved.

The situation changed with the discovery of quarks, the quark model of hadrons, including, of course, the nucleons, and then of the theory of Quantum Chromodynamics, or QCD. We now believe that **QCD** is **the** theory of strong interactions. To quote Wilczek, it is all contained in the QCD Lagrangian:



As true as this statement may be, life is not simple for several reasons.

1. The QCD Lagrangian can not be solved analytically. It must be solved numerically by what has come to be called Lattice Gauge calculations.
2. Several constants of QCD, the masses of the six quarks (u, d, s, c, b, t) and the scale parameter Λ(QCD) must be supplied from outside.
3. Since the exact calculations must be made by numerical methods, the Lattice Gauge Calculations require larger and larger computing efforts, and unfortunately **transparency** to the underlying physics **is lost**.

- The Lagrangian formulation of an interaction is doubtlessly more powerful, but the potential model description of the interaction is more transparent and physical.
- In Dec. 1974 a narrow resonance with mass $\approx$ 3.1 GeV, the J/ψ, was discovered. The next issue of PRL had eight papers by very good physicists including several Nobel laureates. Six of the eight were completely wrong, but two recognized that J/ψ was a particle-antiparticle hadron, and the particle was a new quark, the charm quark.
- The only particle-antiparticle system known at that time was **positronium**, the electron-positron system bound by the $1/r$ Coulomb interaction which is mediated by the exchange of the vector photon. The natural suggestion was that $c\bar{c}$ were similarly bound (or glued together) by a **Coulombic interaction** mediated by the exchange of a vector (1^{--}) particle, appropriately named the **gluon**. However, since free quarks are not seen, it was suggested that the quarks are confined inside charmonium by an additional term in the potential called the **confinement potential**, proportional to a positive power of r. Thus the simplest representation of the strong $q\bar{q}$ interaction was born as the central **Cornell Potential**:

$$\mathbf{V}(\mathbf{r}) = -\frac{\mathbf{c}}{\mathbf{r}} + \sigma\mathbf{r}$$

This replacement of the non-Abelian gauge-invariant field theory contained in Wilczek's QCD Lagrangian by a potential may appear far-fetched and presumptuous, but the fact is that the Potential Model predictions are unexpectedly successful.

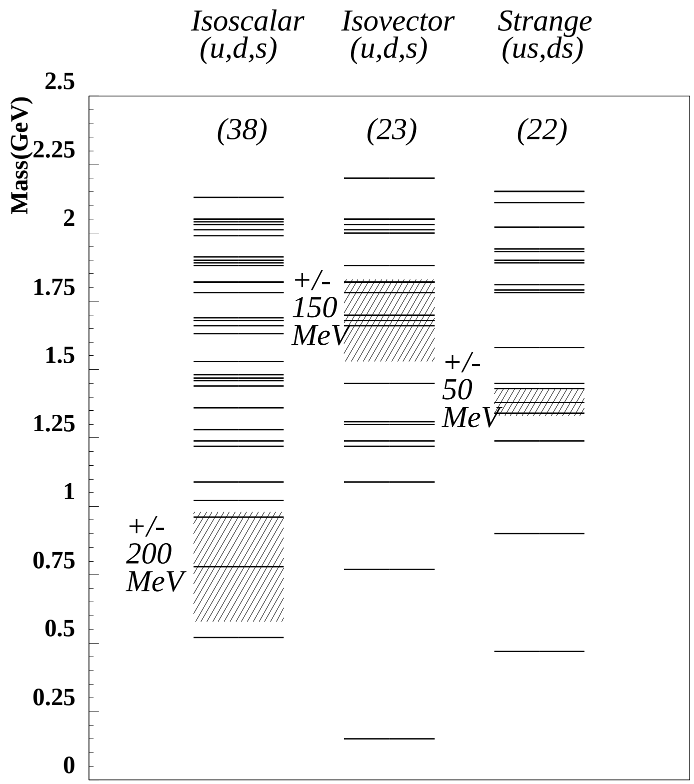
And what works should not be sneezed at.

In the following I will present a sampling of the latest experimental results in quarkonium spectroscopy, compare them with potential model predictions, and also with lattice predictions when they are available.

Let me first explain why I confine myself to heavy quark spectroscopy. There are both experimental and theoretical reasons.

1. The constituent quark masses of the light quarks, u, d, and s are similar (300–500 MeV), so that the light quark hadrons almost always contain admixtures of all three in their wave functions. The result is that their states are very numerous, and have **large overlapping widths**. For example, in the mass region 1–2 GeV, the average level spacing of meson states is $\sim$15 MeV and the average width is 150 MeV. This makes experimental spectroscopy very difficult.
2. There are important theoretical problems also. Although the $q\bar{q}$ interaction is flavor-independent, the quarks in light-quark hadrons are very **relativistic** ($\boldsymbol{v/c \sim 0.8}$) and the strong coupling constant is too large ($\boldsymbol{\alpha_S \geq 0.6}$) to make **perturbative treatment** feasible for light quark hadrons.
3. In contrast, in heavy quark hadrons both above problems are minimized.

Light Quark Mesons

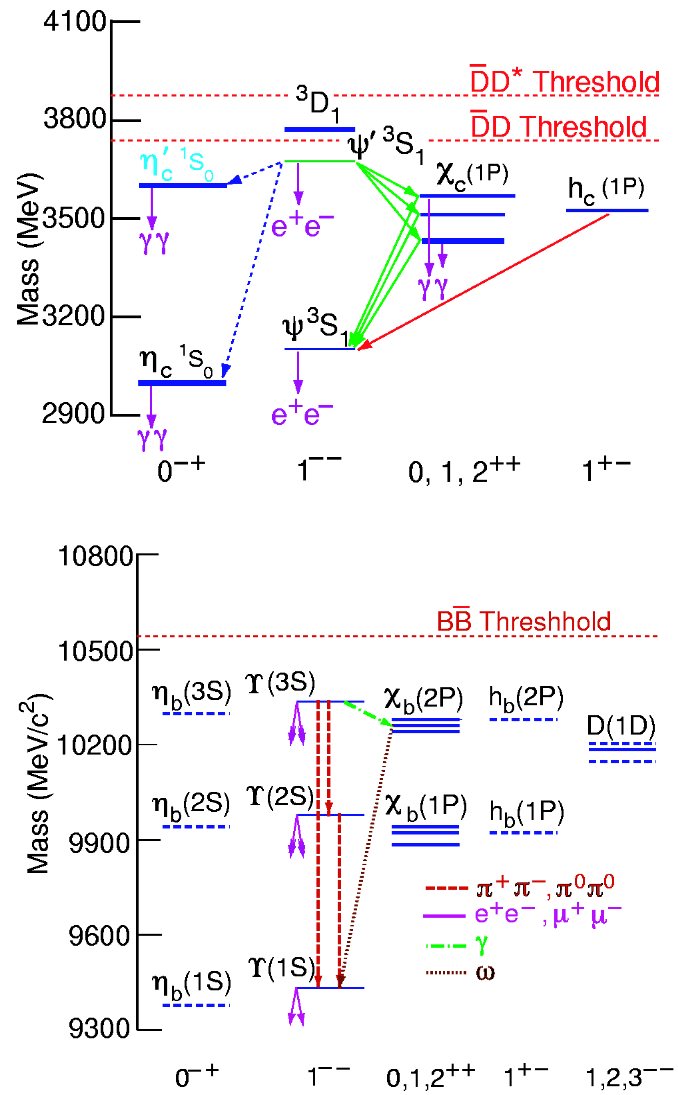


For $M > 1$ GeV

Average Spacing ≈ 15 MeV

Average Width ≈ 150 MeV

Charmonium and Bottomonium



Strong Interactions in the QCD Era

It is often stated that given "enough" computing resources and manpower and time, all strong interaction problems can be solved by Lattice calculations of QCD, and we, experimentalists will become obsolete. Fortunately, the statement is about as true as colonising Mars and mounting a mining industry there to solve the problem of the limited resources on Earth, and we are not in danger of losing our jobs. Besides, there are problems that Lattice can not handle, for example hadron form-factors for timelike momentum transfers, or making heavy nuclei out of quarks and gluons.

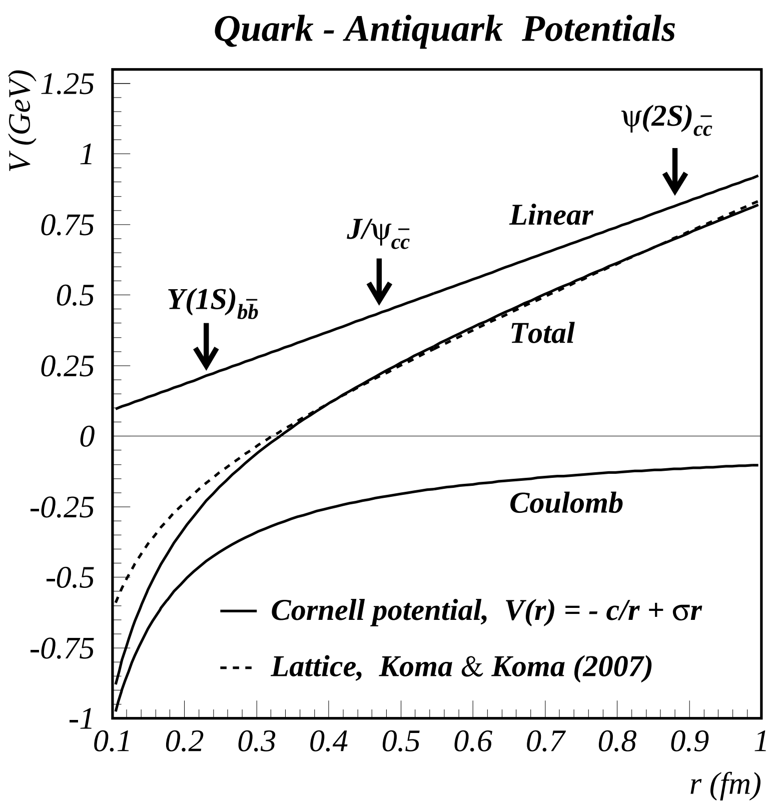
The Quark–Antiquark Static Potential

In the potential model calculations the parameters of the potentials are determined by fitting the masses of some of the well measured states, usually the S–wave singlet and triplet states of $c\bar{c}$ charmonium and $b\bar{b}$ bottomonium. This requires one to input quark masses, and therefore to a certain extent the potential parameters depend on the choice of the quark masses. Nevertheless, the general features of various potentials which have been used remain the same.

- It is important to examine **how consistent** the physically motivated, but nevertheless ad-hoc potentials, with their parameters fitted to few data, are with the predictions based on the QCD lattice calculations.

  The figure illustrates a comparison of the **Cornell potential** with the **lattice prediction** of the static potential from a recent calculation by Koma and Koma[1] (henceforth KK).

- It is gratifying to see that the the lattice potential has the general features of the Cornell potential, with both Coulombic and confinement parts. However, the lattice potential is **less singular** in the extreme Coulombic region, for $r < 0.2$ fermi, where there are no experimental data to constrain the potentials. This could be important, but we have to also keep in mind that the KK lattice calculation is only in the **quenched approximation**.



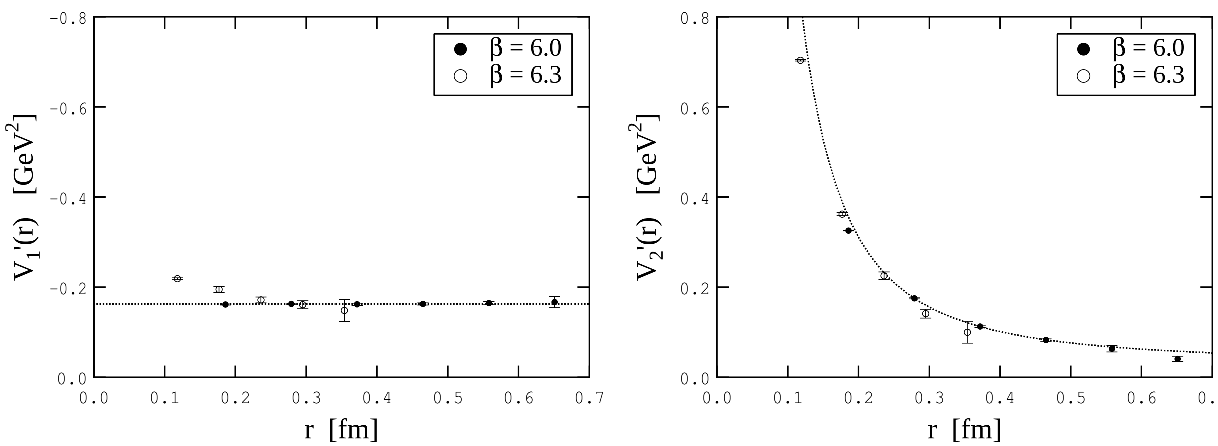
Spin-Dependent Potentials

- The richness of hadron spectroscopy resides in its the spin-dependent features, and it is even more important to see how well the commonly used spin-dependent potentials compare with the predictions of lattice calculations.
- As in atomic physics, the non-relativistic reduction of the Bethe–Salpeter equation results into the familiar Breit–Fermi spin-dependent interaction which has **spin-orbit**, **tensor**, and **spin–spin** parts. Their contribution to the potential depends on the Lorentz structure of the kernel in the B–S integral.
- Both vector and scalar kernels give rise to spin-orbit potentials, but the tensor and spin-spin potentials arise only from the vector kernel. Further, the spin–spin potential for the vector kernel is a contact potential, finite only for S–waves. The potential models **assume** the one gluon vector exchange Coulombic potential, and an essentially ad-hoc linear confinement potential which is generally **assumed** to be scalar.
- **Questions:** To what extent are these assumptions of the potential model calculations supported by experimental data, and to what extent do lattice calculations support these assumptions? The answers to these questions are important for our understanding of the strong interaction in the QCD era.

Let us first compare the potential model spin–dependent potentials with those from the lattice.

The Spin-Orbit Potential (Theoretical): The spin-orbit potential can be written in terms of the sum of three sub-potentials, $V_0'(r)$, $V_1'(r)$, and $V_2'(r)$. For the vector kernel, V_0' and V_2' are finite and V_1' is zero. A scalar component in the B–S kernel can add a finite value for V_1'. The figure below shows what KK find in their Lattice calculation. Lattice results for V_2' are fitted well with the $1/r^2$ dependence expected for a vector, one-gluon exchange kernel, but $\boldsymbol{V_1'}$ **is clearly non-zero.**

- This implies that **something other than vector exchange is needed** in the B–S kernel, a scalar exchange, or even a rather strange pseudoscalar exchange as KK suggest. This is an important finding, which, if confirmed in unquenched lattice calculations, can have significant effect on potential model calculations currently in vogue.



The Spin-Orbit Potential (Experimental):

A simple measure of spin-orbit splitting is

$$\rho = \left[M(^3P_2) - M(^3P_1)\right] / \left[M(^3P_2) - M(^3P_1)\right].$$

The perturbative prediction is that ρ should be equal to $\mathbf{2/5 = 0.4}$.

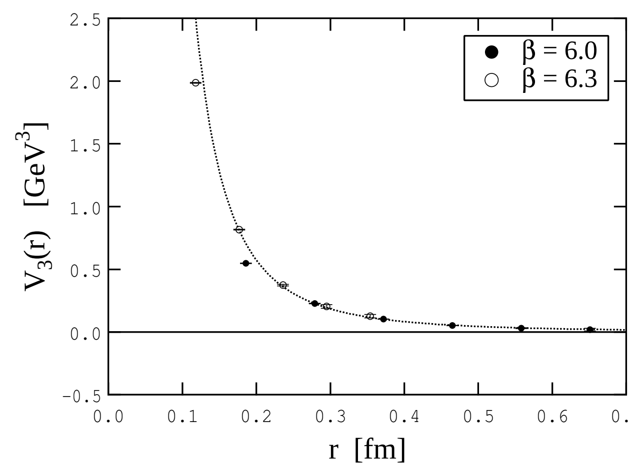
The experimental values for charmonium $\rho_{c\bar{c}} = \mathbf{0.475 \pm 0.002}$, and for bottomonium $\rho_{b\bar{b}} = \mathbf{0.583 \pm 0.020}$, strongly differ from this.

Potential model predictions for ρ vary, but are generally not in good agreement with the experimental values for $\rho_{c\bar{c}}$ or $\rho_{b\bar{b}}$.

Unfortunately, we do not have predictions of spin-orbit splittings based on the KK lattice potentials for either charmonium or bottomonium. The unquenched lattice prediction $\boldsymbol{\rho_{b\bar{b}} = 0.32 \pm 0.29 \pm 0.08}$ has admittedly too large errors to be of value.

So, we have open questions at this time.

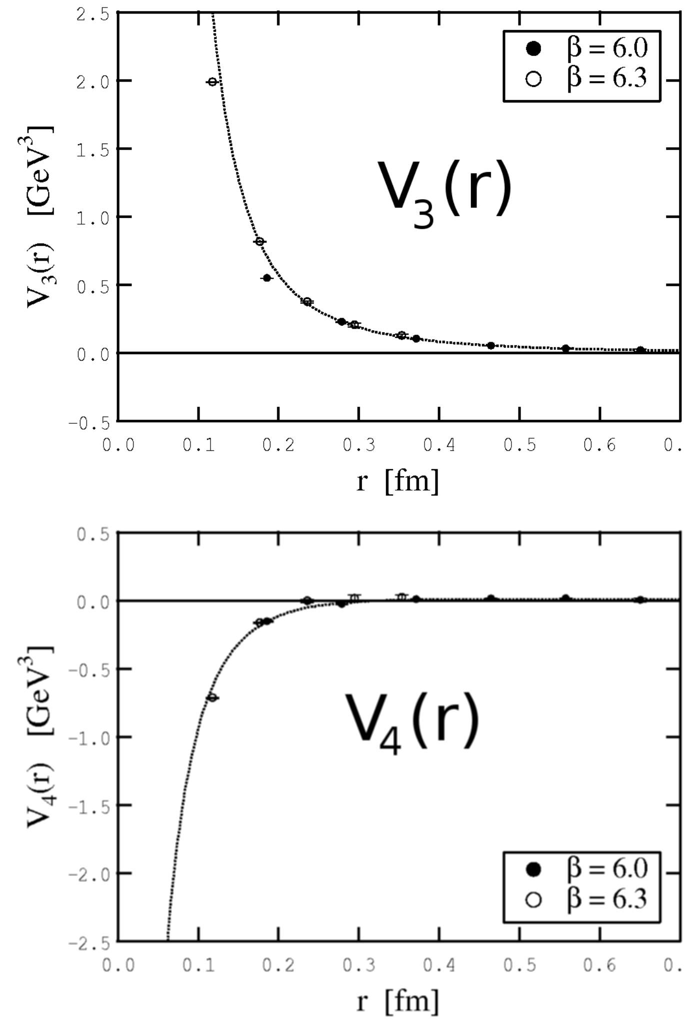
The Tensor Potential: The vector kernel leads to a potential $V_3(r)$ proportional to $1/r^3$ and, the lattice result essentially confirms it, as shown in the figure.



The Spin-Spin Potential (Theoretical):
The vector kernel leads to a delta function spin-spin potential, $V_4(r)$, and once again a scalar component makes no contribution. The figure shows that the lattice data confirm that the $V_4(r)$ spin-spin potential is **essentially zero beyond 0.2 fermi**. The deviation for $r < 0.2$ fermi appears to be connected to the deviation observed in the same region in $V_3(r)$, which also contributes to the spin-spin interaction.

- There appears to be almost no evidence for a long-range spin-spin potential in these quenched lattice calculations.

  If true, this would justify the assumption that the confiement potential is Lorentz scalar.



The Quark–Antiquark Hyperfine Interaction

The spin-spin, or hyperfine interaction is of singular importance in the quark model. It determines the ground state masses of all hadrons. For $q\bar{q}$ mesons, for example, the masses of the pseudoscalar ground states ($J^{PC} = 0^{-+}$) and the vector ($J^{PC} = 1^{--}$) states are given by

$$M(q_1\bar{q}_2, J) = m(q_1) + m(q_2) + \frac{32\pi}{9}\alpha_S\left(\frac{|\psi(0)|^2}{m_1 m_2}\right)(\vec{s_1}\cdot\vec{s_2}), \quad s_1 + s_2 = S = J.$$

The hyperfine spin triplet-singlet splitting is

$$\Delta M_{hf} = M(n^3S_1) - M(n^1S_0) = (32\pi\alpha_S/9)\,|\psi(0)|^2/m_1m_2.$$

The importance of the S–wave triplet–singlet splitting can not be overemphasized. In QED it is responsible for the **21 cm** line which is the workhorse of microwave astronomy. In QCD it is always used for calibration of potential model parameters.

- The spin–dependent potentials we have been discussing are those which arise from the one gluon vector interaction in B–S kernel, and that is also what is assumed in potential model calculations. But that begs the question: **“What about the confinement potential?”** The confinement potential obviously does not arise from one gluon exchange. So, assuming it to be scalar is simply an ad-hoc assumption. Could it have a different origin and different spin–dependent character? We do not know. Only the experimental measurements of hyperfine splittings can tell us.

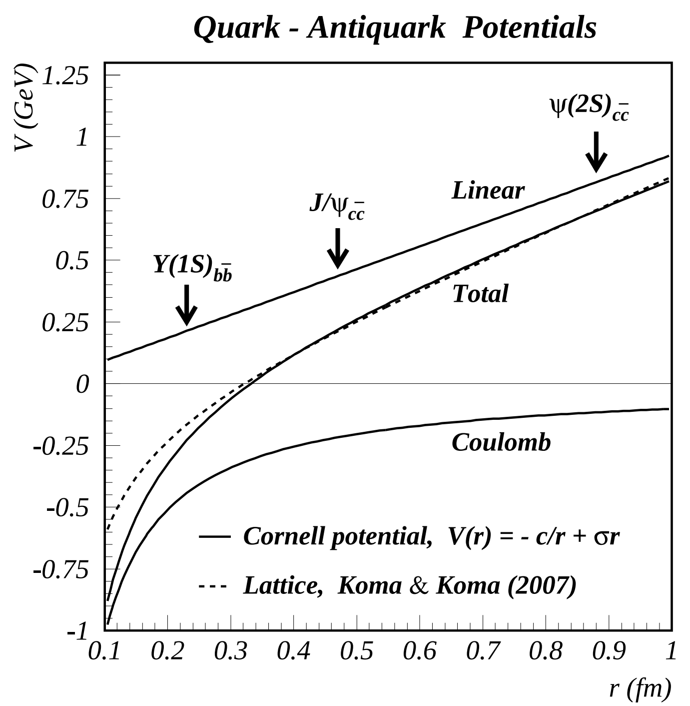
The Spin–Spin Potential

To put the question about the role of the confiement potential in the nature of the $q\bar{q}$ spin–spin potential in perspective, we note again that different $q\bar{q}$ states sample different regions of the $q\bar{q}$ potential with quite different levels of contribution from the Coulombic and confinement potentials. It ranges from being dominantly Coulombic for the bottomonium 1S states to dominantly confinement for the 2S charmonium states. This raises the following questions. How does the hyperfine interaction change

(a) with principal quantum number n, for example between 1S and 2S states,

(b) between S–wave and P–wave states, e.g., between 1S and 1P states,

(c) with quark masses, e.g., between c–quark states and b–quark states?



Experimental Measures of the Hyperfine Interaction

The answers to the questions posed can be provided only by experimental data about hyperfine splittings. Unfortunately, there is a generic problem in measuring hyperfine splittings,

$$\Delta M_{hf}(nL) \equiv M(n^3L) - M(n^1L).$$

The problem is that while the triplet states are conveniently excited in e^+e^- annihilation, either directly (e.g., $^3S_1$) or via **strong E1** radiative transitions (e.g., ^3P_J), the radiative excitation of singlet states is either forbidden, or possible only with **weak M1** allowed $(n \to n)$ and forbidden $(n \to n')$ transitions.

As a consequence of these difficulties, while the spin triplet S– and P–wave states were identified early in the spectroscopy of charmonium and bottomonium, the identification of the singlet states has taken a torturously long time.

- The identification of the first singlet state, $\eta_c(1^1S_0)_{c\bar{c}}$ took 6 years and many false steps after the discovery of $J/\psi(1^3S_1)$, the identification of $\eta_c'(2^1S_0)_{c\bar{c}}$ state took 26 years, the identification of $h_c(1^1P_1)_{c\bar{c}}$ took 29 years, and the identification of the first singlet state in bottomonium, $\eta_b(1^1S_0)_{b\bar{b}}$ took 32 years.

  But great progress has been made in the last five years.
- Many attempts and many laboratories have been involved. I do not have time to describe the details of these marathon efforts, but I do want to give you the important results.

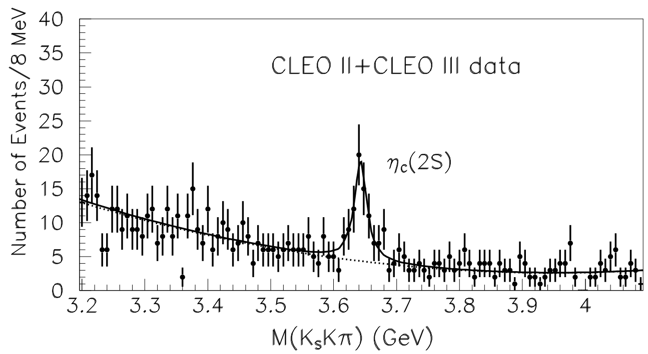
The Experimental Results

Hyperfine Splitting of Ground State

- $\boldsymbol{\Delta M_{hf}(1S)_{c\bar{c}} = M(J/\psi, 1^3S_1) - M(\eta_c, 1^1S_0) = 116.6 \pm 1.0}$ **MeV**.
  This remains the best measured hyperfine splitting in a heavy quark hadron.

Hyperfine Splitting of a Radial Excitation

- $\boldsymbol{\Delta M_{hf}(2S)_{c\bar{c}} = M(\psi', 2^3S_1) - M(\eta_c', 2^1S_0) = 49 \pm 4}$ **MeV**.
  η_c' was first identified in 2002 by Belle[2] in B–decay, and confirmed by its formation in two-photon fusion, and decay into $K_S K\pi$, by CLEO[3] and BaBar[4] in 2004.
  The figure shows the CLEO spectrum.



- This is the first measurement of hyperfine splitting in the radial excitations. The result of this measurement, namely the fact that this hyperfine splitting of the 2S state is a factor 2.5 smaller than that of the 1S state, poses serious problems for theoretical understanding.

- There are numerous pQCD–based predictions for $\Delta M_{hf}(2S)_{c\bar{c}}$, and they range all over the map (and occasionally even hit 50 MeV). However, it is fair to say that nobody expected the 2S hyperfine splitting to be ~ 2.5 times smaller than the 1S hyperfine splitting. A **model–independent** prediction, relating 2S to 1S splitting using $J/\psi(1S)$ and $\psi'(2S)$ masses, and e^+e^- decay widths, gives $\Delta M_{hf}(2S)_{c\bar{c}} = 68 \pm 7$ MeV, which is 40% larger than the measured value of 49 ± 4 MeV.

- So far lattice calculations are not of much help. The two predictions based on unquenched lattice calculations are

$$\begin{aligned} \mathrm{Columbia:} \quad & \Delta M_{hf}(2S)_{c\bar{c}} = 75 \pm 44 \ \mathrm{MeV} \\ \mathrm{CP-PACS:} \quad & \Delta M_{hf}(2S)_{c\bar{c}} = 25 - 43 \ \mathrm{MeV} \end{aligned}$$

- It has been suggested that the smaller than expected 2S hyperfine splitting is a consequence of $\psi(2S)$ being very close to the $|c\bar{c}\rangle$ break-up threshold, and continuum mixing lowers its mass, resulting in a reduced value of $\Delta M_{hf}(2S)_{c\bar{c}}$. However, no definitive numerical predictions are available so far.

Hyperfine Splitting in P–waves

- $\boldsymbol{\Delta M_{hf}(1P)_{c\bar{c}} = M(1^3P) - M(h_c, 1^1P_1) =?}$

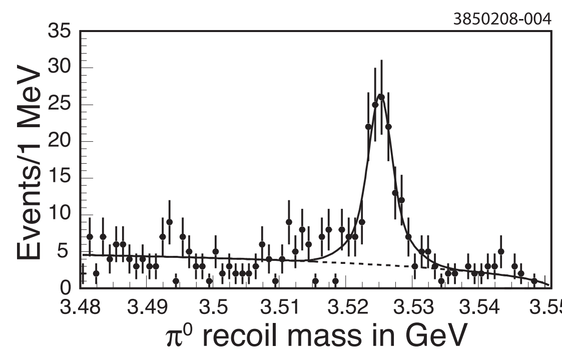
  The masses of the spin–orbit split P–triplet states of charmonium, $\chi_J(1^3P_J)$ were measured with precision by the Fermilab $p\bar{p}$ annihilation experiments E760/E835 nearly twenty years ago, and their centroid,

  $\boldsymbol{\langle M(^3P_J)\rangle = [5M(^3P_2) + 3M(^3P_1) + M(^3P_0)]/\,9 = 3525.30{\pm}0.04\,\text{MeV}.}$

- The identification of $h_c(^1P_1)_{c\bar{c}}$ was, however, extremely challenging because both its formation by radiative decay of ψ', and its decay to J/ψ are forbidden by charge conjugation invariance. Further, its formation by π^0 decay of ψ' is isospin violating and has very little phase space. Nevertheless, in 2005 CLEO[5] succeeded in identifying it in the latter reaction,

$$e^+e^- \to \psi'(2^3S_1)_{c\bar{c}} \to \pi^0 h_c(1^1P_1)_{c\bar{c}},\ h_c(^1P_1) \to \gamma\eta_c(^1S_0)$$

and made a precision determination of its mass to be $\boldsymbol{M(h_c,{}^1P_1) = 3525.28 \pm 0.22}$ **MeV**. The figure illustrates the spectrum from the exclusive analysis of the CLEO data. If we identify the triplet centroid mass $\langle M(^3P_J)\rangle = 3525.30 \pm 0.04$ MeV with the true triplet mass $M(^3P)$, we get



$$\boldsymbol{\Delta M_{hf}(1P)_{c\bar{c}} = 0.02 \pm 0.22\ \text{MeV}.}$$

- The theoretical expectation for a delta function spin–spin hyperfine interaction is indeed $\boldsymbol{\Delta M_{hf}(1P)_{c\bar{c}} = 0}$. It is therefore very tempting to assume that $\langle M(^3P_J)\rangle = M(^3P)$, and that $\Delta M_{hf}(1P)_{c\bar{c}} = 0.02 \pm 0.22$ MeV.
- But this identification can not be right because the centroid determination of $M(^3P)$ is only valid if the spin-orbit splitting is perturbatively small, and we have already noted that the perturbative prediction

$$\rho = \left[M(^3P_2) - M(^3P_1)\right] / \left[M(^3P_2) - M(^3P_1)\right] = 2/5 = \mathbf{0.4}$$

is in large disagreement with the experimental result, $\rho_{c\bar{c}} = \mathbf{0.475 \pm 0.002}$.
- This leads to serious questions.
  - What mysterious cancellations are responsible for the wrong estimate of $M(^3P)$ giving the expected answer that

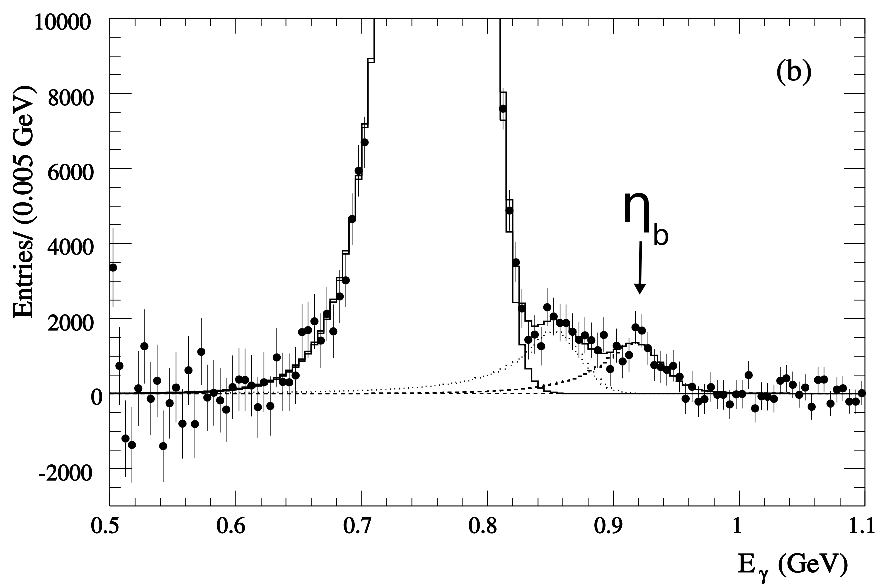
$$\Delta M_{hf}(1P) = 0$$

  - Or, is it possible that the expectation is wrong? Is it possible that the hyperfine interaction is not entirely a **contact interaction**?
  - Potential model calculations are not of much help because they smear the potential at the origin in order to be able to do a Schrödinger equation calculation.
  - Can Lattice help? Not so far.

Hyperfine Splitting with b–Quarks

- $\boldsymbol{\Delta M_{hf}(1S)_{b\bar{b}} = M(\Upsilon(1^3S_1)) - M(\eta_b(1^1S_0)) = 70.6 \pm 3.5}$ **MeV**.

  Upsilon $\Upsilon(1^3S_1)$ was discovered in 1977, but it took 31 years to identify $\eta_b(1^1S_0)_{b\bar{b}}$. In 2008 BaBar[6] announced its discovery by identifying it in the inclusive photon spectrum for the radiative decay of $\Upsilon(1^3S_1)_{b\bar{b}}$. It was a tour-de-force analysis of the data for the radiative decay, $\Upsilon(3S) \to \gamma\eta_b$ of 109 million $\Upsilon(3S)$. Their spectrum is shown in below. The BaBar result has been recently confirmed in an independent measurement by CLEO[7]. The experimental result is in good agreement with the **unquenched** lattice prediction of $\Delta M_{hf}(1S)_{b\bar{b}} = 61 \pm 14$ MeV.

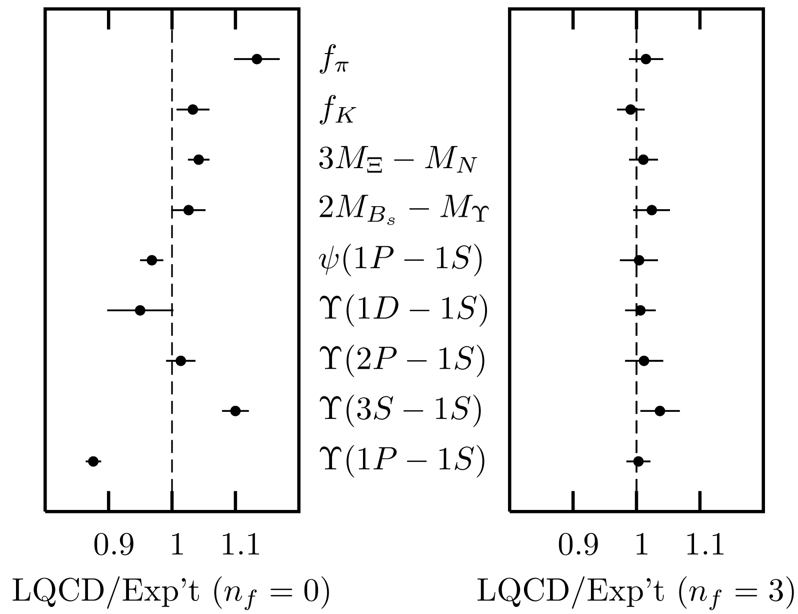


Present Limitations of Lattice and Potential Model Calculations

Let me summarize where we stand at this point with Lattice and potential model calculations.

Lattice calculations are getting to be more and more sophisticated, but few **unquenched** lattice calculations are so far available.

- The results of one unquenched calculation for the **bottomonium** system mass differences is presented in the figure. It illustrates the improvement achieved by the unquenched calculations over the quenched calculations.



In the same calculations good agreement with experimental e^+e^- decay widths is obtained for $\Upsilon(1S)$ and $\Upsilon(2S)$. Lattice calculations for transition widths to hadronic final states of lighter quarks are more difficult, and none are presently available even for the bottomonium system.

Similar calculations for the **charmonium** system are not yet available.

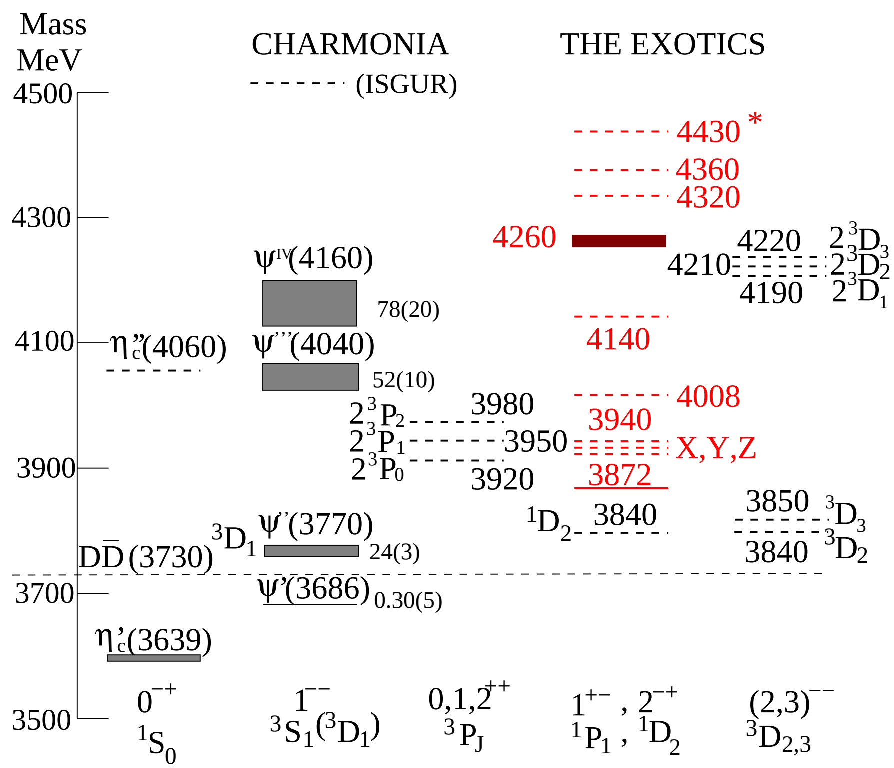
- **In Potential Model** calculations experimental masses of 1S states are generally used to determine potential parameters. For the predictions of radial excitations and P– and D–wave states, only broad agreement with the experiments is found. Detailed features like spin-orbit or spin-spin splittings are not well predicted. For unbound states the predictions become more uncertain; more about this later.
- The one advantage potential model calculations have in principle over the present lattice calculations is in their ability to predict **decay widths**, following the corresponding radiative decays in positronium. However, while the first order radiative corrections work quite well for positronium, the **first-order strong radiative corrections** do not work well for charmonium or bottomonium.
- Because of the large values of the strong coupling constant the first-order strong corrections are often very large and produce absurd answers. For example, the correction factor for the decay $\chi_{c0}(^3P_0)_{c\bar{c}} \rightarrow \mathrm{glue}$ is $[1 + 9.5\alpha_S/\pi] = 1.91$ for $\alpha_S = 0.3$. A 91% correction in the first order is essentially meaningless and unacceptable. Unfortunately, higher order corrections are not available. I am told that it is now possible to make them, and it would be my strong request to the strong interaction community to make them.

To summarize the summary, there is lots of work to do in the spectroscopy of strong interactions in the 21st century.

The Renaissance in Hadron Spectroscopy: The Exotics

Let me now turn to the "Renaissance" in the title of my talk. This refers to the unexpected, and therefore "exotic" states recently discovered above the charmonium break-up threshold at 3.73 GeV by Belle and BaBar, and later by CDF, DØ, and CLEO. (I am skipping over the hybrids and glueballs about which you already heard from Matt Shephard.)

- These states do not generally fit in the charmonium spectrum, but are often called "charmonium-like", because they seem to always decay into final states containing a charm and an anticharm quark.
- There are by now more than half a dozen of them, and they go by X,Y,Z,X′,X″,X‴,Z′.
  The alphabet soup is getting thicker by the day.



The Veteran of Exotics—X(3872)

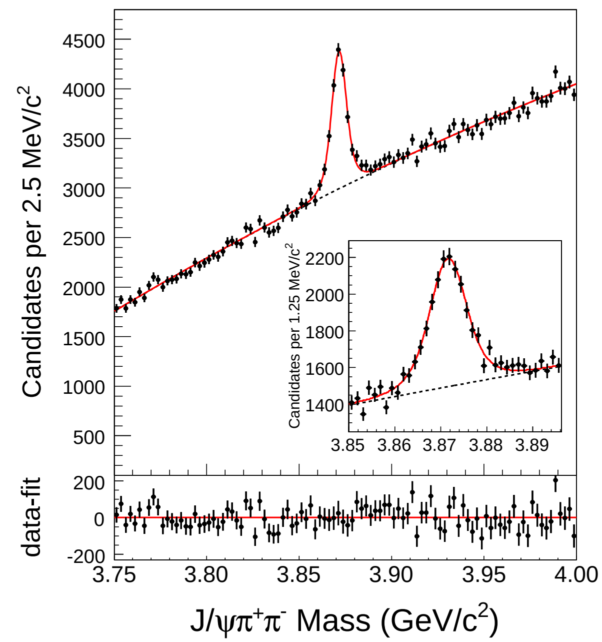
- In 2003, Belle[8] reported a very narrow peak with 37 counts in the decay, $B^- \to \mathrm{X}K^-$, $\mathrm{X} \to \pi^+\pi^- J/\psi$. X(3872) was born. Very soon it was confirmed by BaBar[9], CDF[10] (6000 counts), and DØ[11], and by now it has been observed in many decay modes. Its measured parameters are:

  Mass$= \mathbf{3871.56 \pm 0.21}$ **MeV**, **Width**$= \mathbf{1.34 \pm 0.64}$ **MeV**, $\boldsymbol{J^{PC} = 1^{++}}$

- X(3872) decays a factor 10 more strongly to $\overline{D}^{*0}D^0$ than to its discovery mode $J/\psi\pi^+\pi^-$, and its mass is very close to $M(D^0) + M(D^{*0})$. This has given rise to its interpretation as a $\boldsymbol{\overline{D}^{*0}D^0}$ **molecule**.

- CLEO[12] has recently made a precision measurement of $M(D^0)$. It leads to the very small binding energy,
  $\mathbf{BE(X(3872)) = 0.14 \pm 0.28\ MeV}$.

- If the picture of X(3872) as a very weakly bound $\overline{D}^{*0}D^0$ molecule is correct, a very exciting new chapter of **hadronic molecules** has been opened. However, we should keep open its interpretation as the 2^3P_1 state of charmonium as a possibility.



The Strange Vector, Y(4260)

The Y(4260) has been observed in ISR production

$$e^+e^- \to \gamma_{\rm ISR} e^+e^- \to \gamma_{\rm ISR} \mathrm{Y}(4260), \qquad \mathrm{Y}(4260) \to \pi^+\pi^- J/\psi$$

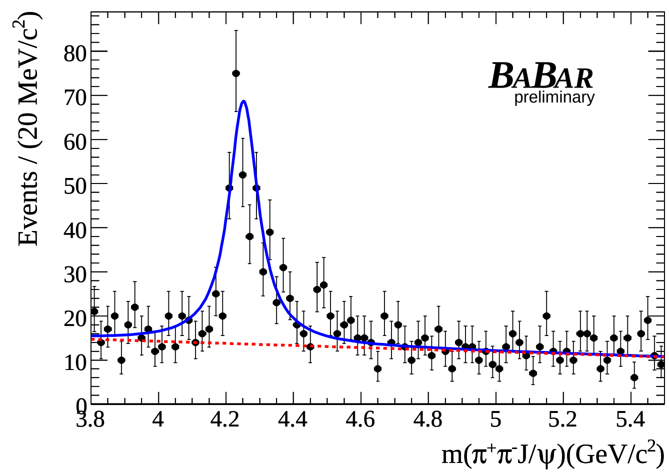
by BaBar[13], CLEO[14] and Belle[15], and in direct production by CLEO[16].

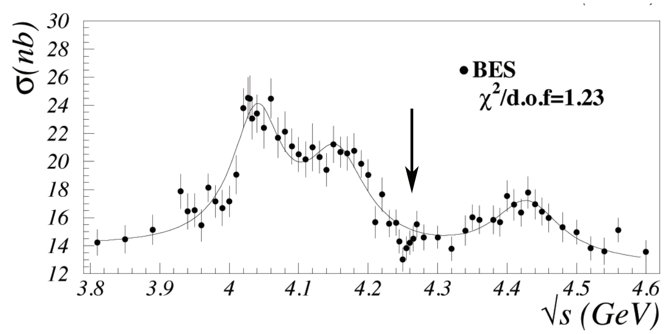
- Y(4260) is clearly **a vector** with $J^{PC} = 1^{--}$, but a very **strange** one, since it sits at a very deep minimum in $R \equiv \sigma(h)/\sigma(\mu^+\mu^-)$, with

  $$\boldsymbol{M(\mathrm{Y}(4260)) = 4252 \pm 7\ \mathrm{MeV},}$$
  $$\boldsymbol{\Gamma(\mathrm{Y}(4260)) = 105 \pm 19\ \mathrm{MeV}}$$

  Is Y(4260) a charmonium vector, perhaps 2^3D_1? If not, **what is it?**

- It is suggested that Y(4260) is a $c\bar{c}g$ charmonium **hybrid**.
  If so, where are the 0^{-+} and 1^{-+} hybrids companions?





The Saga of X,Y,Z($\sim$3940)

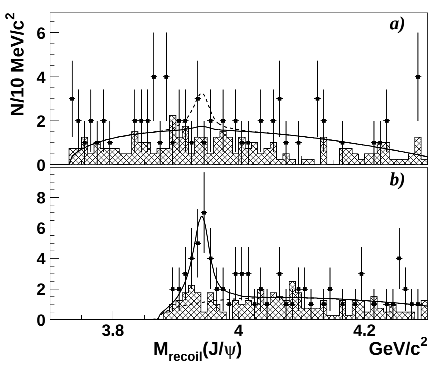
Between 2004 and 2006, Belle reported three new states with very similar masses, ~ 3940 MeV. Besides nearly identical masses, they had other unusual properties.

- The three were formed in different reactions
- The three decayed in different final states, but all containing a c and a $\bar{c}$ quark.
- Unfortunately, all three were observed as peaks with poor statistics.

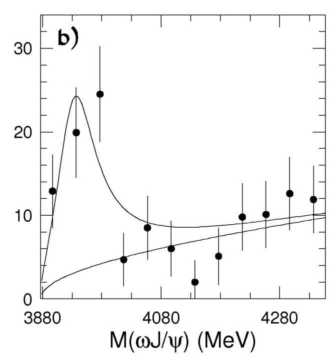
While these gave rise to great excitement, they also made many of us skeptical about their separate reality.

- It has been more than five years since the claims of X,Y,Z.

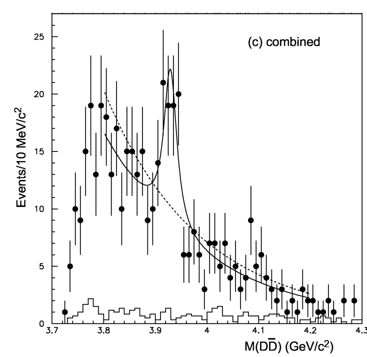
  Where do we stand now? Are they real? If real, what are they?



X(3940)



Y(3940)



Z(3940)

About X(3940)

X(3940) was observed[17] in $e^+e^-(10.6\ \mathrm{GeV}) \to J/\psi + X$ (double charmonium)

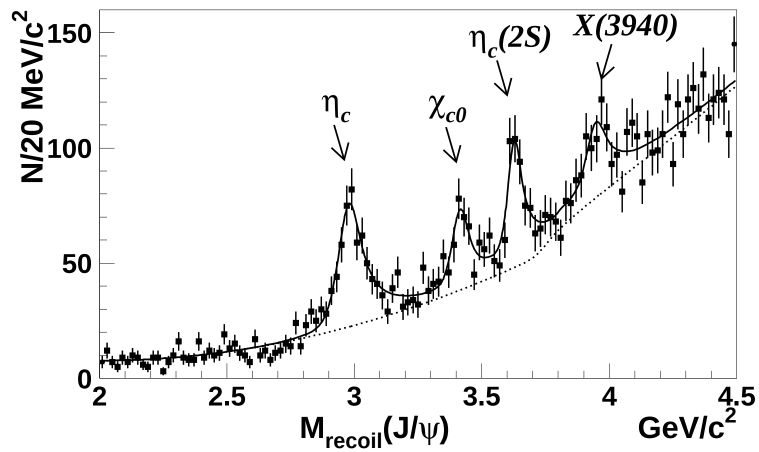
It was found to decay in $D\overline{D^*}$.

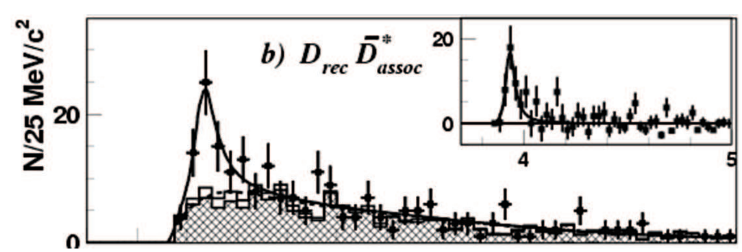
$\boldsymbol{M(\mathrm{X}(3940)) = 3943 \pm 9}$ **MeV,** $\boldsymbol{\Gamma < 52}$ **MeV**

- Its spin was not specified, but is conjectured to be $J = 0$ because only $J = 0$ states, η_c, χ_{c0}, η_c' seem to be excited in double-charmonium production.

  This resonance remains unconfirmed by BaBar.

  So, it is meaningless to speculate whether X(3940) is η_c'' which is predicted to have a mass 100–130 MeV higher.





About Y(3940)

- This resonance was reported by **Belle**[18] in the reaction

$$B \to KY, \quad Y \to \omega J/\psi, \qquad \text{with } 58 \pm 11 \text{ counts}$$

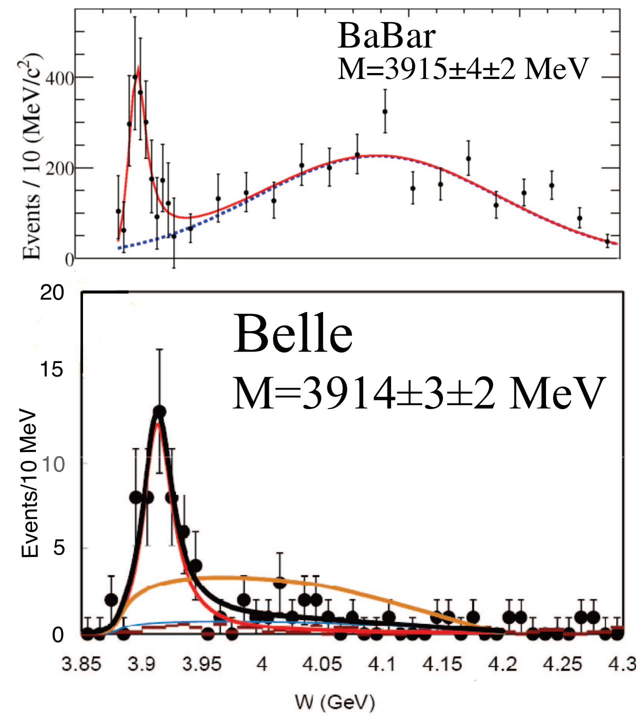
$$\boldsymbol{M(\mathrm{Y}) = 3943 \pm 11 \pm 13} \textbf{ MeV,} \quad \boldsymbol{\Gamma(\mathrm{Y}) = 87 \pm 22 \pm 26} \textbf{ MeV.}$$

- Recently, **BaBar**[19] has reported it in the same reaction with 1980^{+396}_{-379} counts.
  $\boldsymbol{M(\mathrm{Y}) = 3914.6^{+3.8}_{-3.4} \pm 2.0}$ **MeV,** $\boldsymbol{\Gamma(\mathrm{Y}) = 34^{+12}_{-8} \pm 5}$ **MeV.**
  The mass and width are different but statistically consistent with Belle's.

- A further confirmation of this resonance has been now reported by Belle[20] in the reaction

$$\gamma\gamma \to \omega J/\psi, \quad \text{with } 55 \pm 14^{+2}_{-14} \text{ counts}$$

$$\boldsymbol{M(\mathrm{Y}) = 3914 \pm 4} \textbf{ MeV, } \boldsymbol{\Gamma(\mathrm{Y}) = 23 \pm 11} \textbf{ MeV.}$$



- So, this resonance appears to be real, and not degenerate with X(3940) and Z(3940), and $J^{PC} = J^{++}$. It would appear to be a good candidate for the charmonium 2^3P_0 state!

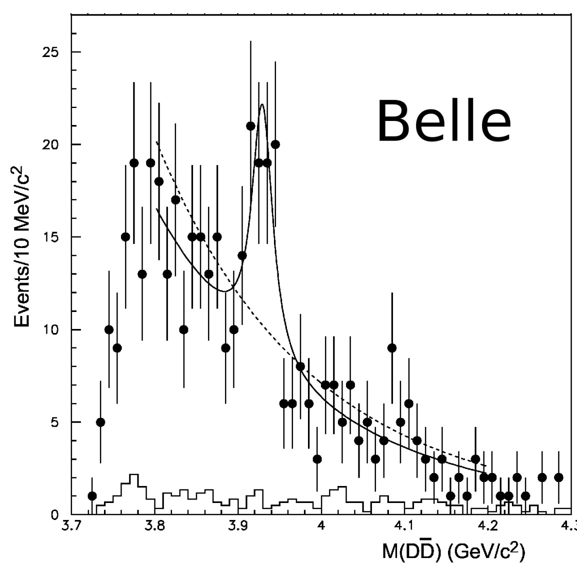
- Or is it an exotic? A $|c\bar{c}g\rangle$ **hybrid**?

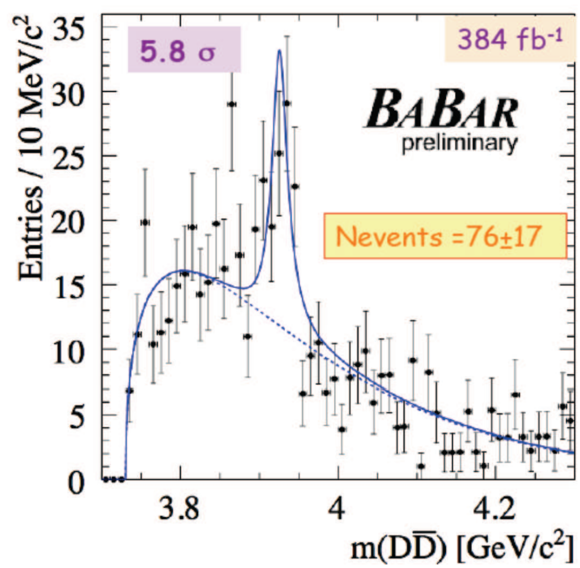
About Z(3930)

This resonance was reported by Belle[21] with formation in $\gamma\gamma$ fusion and decay in $D\overline{D}$, $\gamma\gamma \rightarrow \mathrm{Z}(3940) \rightarrow D\overline{D}$. It was recently confirmed by BaBar[22] in the same reaction.

$$\begin{array}{lll} \boldsymbol{M(\mathrm{Z})} & = \mathbf{3929 \pm 5 \pm 2 \ \textbf{MeV (Belle)},} & \mathbf{3926.7 \pm 2.9 \pm 1.1 \ \textbf{MeV (BaBar)}} \\ \boldsymbol{\Gamma(\mathrm{Z})} & = \mathbf{29 \pm 10 \pm 2 \ \textbf{MeV (Belle)},} & \mathbf{21.3 \pm 6.8 \pm 3.6 \ \textbf{MeV (BaBar)}} \\ \boldsymbol{N(\mathrm{Z})} & = \mathbf{64 \pm 18 \ \ \textbf{(Belle 395 fb}^{-1}\textbf{)},} & \mathbf{76 \pm 17 \ \ \textbf{(BaBar 384 fb}^{-1}\textbf{)}} \end{array}$$

- This is now the best confirmed of the three X,Y,Z resonances.
- Both Belle and BaBar find that its spin $J = 2$.
- Z(3940) is a candidate for 2^3P_2 state of charmonium, but this is difficult if Y(3914) is 2^3P_0.





Exotics? — Unconfirmed & Rare

CDF(2009)[23] $B^+ \to K^+\mathrm{X},\ \mathrm{X} \to J/\psi\phi$

$\boldsymbol{M(4140)} = 4143.0 \pm 3.1$ MeV $\quad \Gamma = 11.7^{+9.1}_{-6.2}$ MeV, $\quad N = 14 \pm 5$

not seen by Belle in the same reaction, or in $\gamma\gamma$

Belle(2009)[20] $\gamma\gamma \to J/\psi\phi$

$\boldsymbol{M(4350)} = 4350.6 \pm 5.1$ MeV $\quad \Gamma = 13.3^{+18.4}_{-10.0}$ MeV, $\quad N = 8.8^{+4.2}_{-3.2}$

Babar(2009)[24] $e^+e^- \to \gamma_{\mathrm{ISR}}\mathrm{X},\ \mathrm{X} \to \pi^+\pi^- J/\psi$

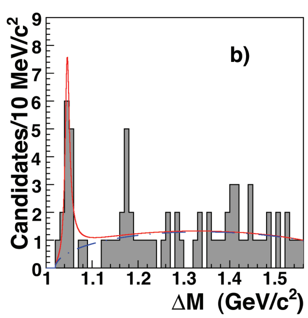
$\boldsymbol{M(4320)} = 4324 \pm 24$ MeV $\quad \Gamma = 172 \pm 33$ MeV, $\quad N \approx 68$

X(4260)?

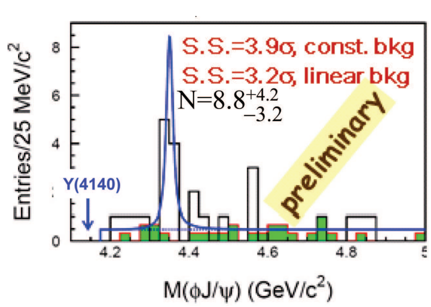
Belle(2007)[25] $e^+e^- \to \gamma_{\mathrm{ISR}}\mathrm{X},\ \mathrm{X} \to \pi^+\pi^- J/\psi$

$\boldsymbol{M(4360)} = 4361 \pm 13$ MeV $\quad \Gamma = 74 \pm 18$ MeV, $\quad N =\sim 45$

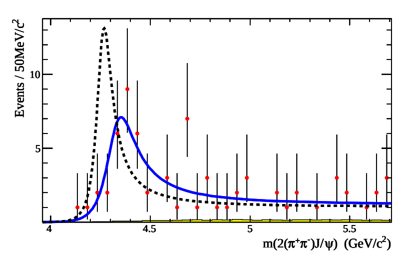
$\boldsymbol{M(4660)} = 4664 \pm 12$ MeV $\quad \Gamma = 48 \pm 15$ MeV, $\quad N =\sim 35$



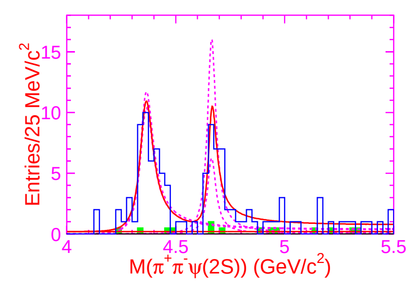
CDF–$M(4140)$



Belle–$M(4350)$



BaBar–$M(4320)$



Belle–$M(4360, 4660)$

The Super Exotics

All the exotic states I have so far talked about are uncharged. Below 5 GeV the only charged mesons which are known are either entirely made of the (u, d, s) light quarks or a light quark and a charm quark (the $D-$mesons).

So a charged exotic with mass between 3 GeV and 5 GeV would indeed by a **super exotic**.

- Two years ago, **Belle**(2007)[26] dropped a bombshell of a claim of observing a charged exotic, the $Z^+(4430)$

$$B^0 \to K^\mp Z^\pm, \quad Z^\pm \to \pi^\pm \psi(2S)$$

$$\boldsymbol{M(Z^+) = 4433 \pm 4 \pm 2 \text{ MeV}, \ \ \Gamma(Z^+) = 45^{+18+30}_{-13-13} \text{ MeV}, \ \ N = 121 \pm 30 \text{ evts}}$$

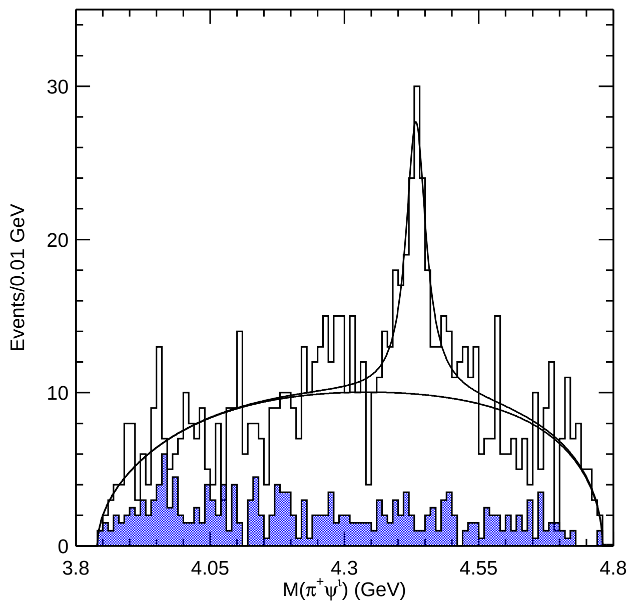
  If true, this would be a fantastic discovery, opening a new chapter in hadron spectroscopy.

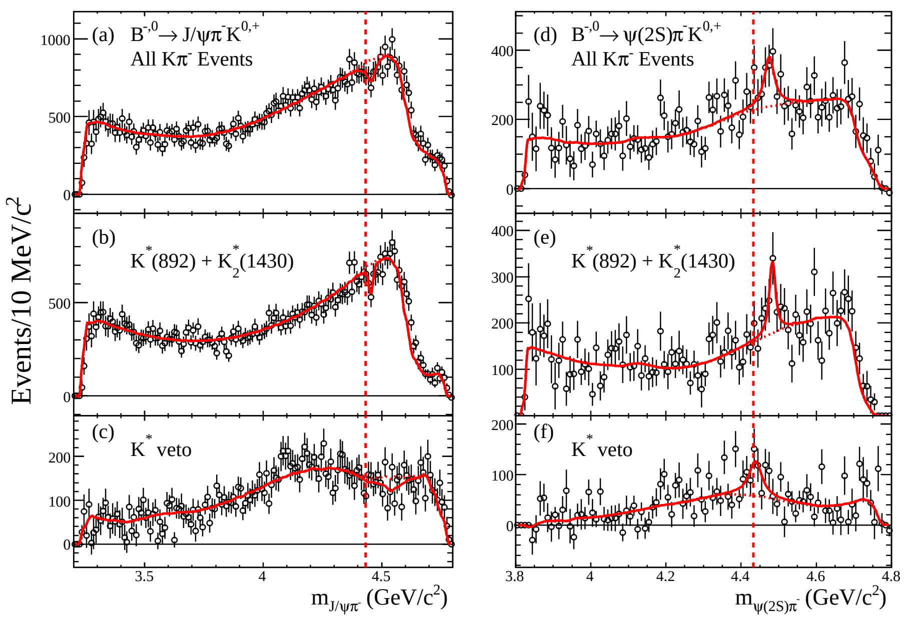
- BaBar(2009)[27] has searched for the Z^- decaying to $\pi^- J/\psi$ and $\pi^-\psi(2S)$, done very detailed Dalitz plot analyses, and finds **no statistically significant evidence** for the charged Z.

- Belle[28] has also announced two more charged exotics with masses of 4051 and 4248 MeV observed in the reaction

$$B^0 \to K^- Z^+, \qquad Z^+ \to \pi^+ \chi_{c1}$$

  but it does not make sense to dwell on these until the dust about $Z^+(4433)$ settles.





$Z^{\pm} \to \pi^{\pm}\psi(2S)$ $\quad$ $Z^- \to \pi^- J/\psi$ $\quad$ $Z^- \to \pi^-\psi(2S)$

Belle, $M(Z) = 4433 \pm 5$ MeV $\quad$ BaBar, no evidence for $Z(4433)$

Summarizing the Exotics

As many as a dozen new states have been reported in the 1 GeV mass region, 3.8 GeV to 4.8 GeV.

- The evidence for some of them is shaky, and not all of them may eventually survive. But many are firmly established.
- The states are variously populated in $B-$decays, two–photon fusion, and ISR e^+e^- annihilation.
- They all decay in final states containing a charm and anticharm quark, as J/ψ, $\psi(2S)$, or $D\overline{D}$.
- Their masses and widths do not fit **easily** in the predicted spectrum of chamrmonium states, hence the label **exotic**, and the proposals to identify them as **hadronic molecules**, $q\bar{q}g$ **hybrids**, **four quark states**, etc.
- There are no firm proofs of the exotic explanations, but some are more likely than others.
- Even if only a few of these survive as true exotics, they will open new chapters in hadron spectroscopy. A true Renaissance indeed!

[1] Y. Koma and M. Koma, NPB 769, 79 (2007)
[2] Belle, PRL 91, 262001 (2003)
[3] CLEO, PRL 92, 142001 (2004)
[4] BaBar, PRL 92, 142001 (2004)
[5] CLEO, PRL 95, 102003 (2005); PRL 101, 182003 (2008)
[6] BaBar, PRL 101, 071801 (2008)
[7] CLEO, arXiv:0909.5474
[8] Belle, arXiv:hep-ex/0505038; arxiv:0809.1224
[9] BaBar, PRL 71, 071103 (2005); PRD 77, 111101(R) (2008)
[10] CDF, PRL 93, 072001 (2004); PRL 103, 152001 (2009)
[11] DØ, PRL 93, 162002 (2004)
[12] CLEO, PRL 98, 092002 (2007)
[13] BaBar, PRL 95, 142001 (2005); arXiv:0808.1543
[14] CLEO, PRD 74, 091104(R) (2006)
[15] Belle, PRL 98, 212001 (2007); PRL 99, 182004 (2007)
[16] CLEO, PRL 96, 162003 (2006)
[17] Belle, PRD 70, 071102 (2004); PRL 98, 082001 (2007)
[18] Belle, PRL 94, 182002 (2005)
[19] BaBar, PRL 101, 082001 (2008)
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[22] BaBar, V. Santoro, HADRON2009
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[26] Belle, PRL 100, 142001 (2008)
[27] BaBar, PRD 79, 112001 (2009)
[28] Belle, PRD 78, 072004 (2008)