A PERSONAL JOURNEY THROUGH HADRONIC EXOTICA

Kamal K. Seth
Northwestern University
(kseth@northwestern.edu)

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EXOTICA

Exotica and **Erotica** differ only in one letter.

They are equally addictive.

Like all addictions, they have consequences.

- They consume a lot of the resources.
- They make you often do things you should not do.
- **BUT**, they are exciting, and they give you a great surge of adrenaline.

I have to confess that over the years I have fallen for exotica, and often. So, let me take you on a personal journey through exotica.

So, what is Exotic?

Exotic has to be unexpected. Exotic has to have the nature of the "forbidden fruit".

- Exotic in hadronic physics often begins with provocative suggestions by theorists, which drives experimentalists to search for it, often at **exotic cost** (think Higgs).
- At other times, it begins with an unexpected experimental observation for which theorists come up with exotic explanations (think J/ψ).

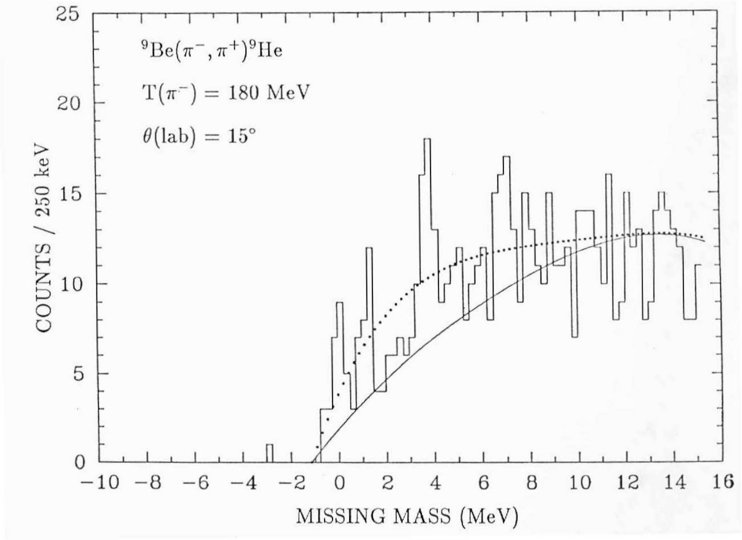
I want to tell the story of the hadronic exotica, necessarily from a personal point of view.

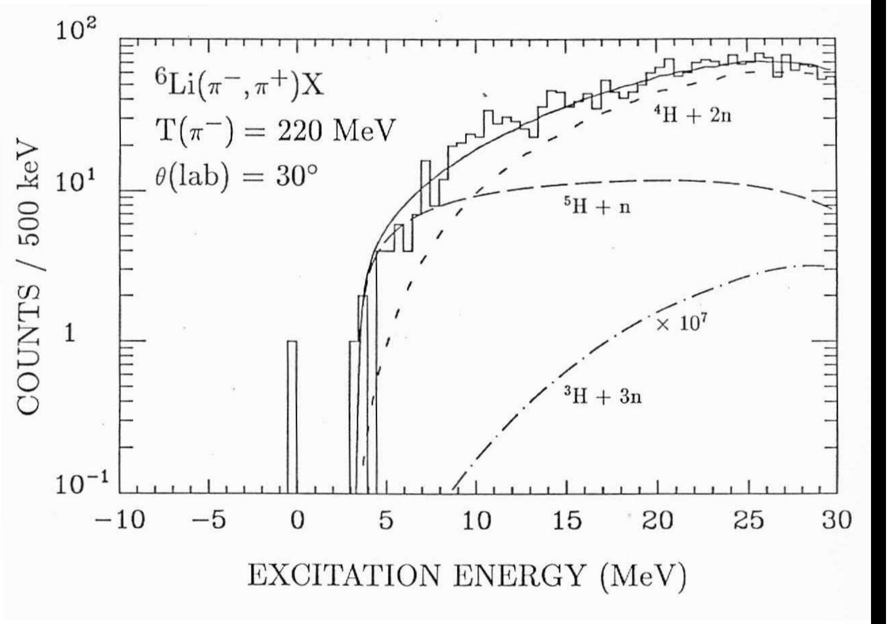
Chasing Exotica in Nuclear Physics

I began my career as a nuclear physicist. So, my first run in with exotica was in the search for **exotic nuclei**. Nuclei are exotic if they are very rich in neutrons, i.e., have an exceptionally large value of $(N - Z)/A.$, or if they are just very heavy, $A \gg 240$.

- In the 1970's, there were no easy ways of making a nucleus which was very rich in neutrons, like ^{18}C with 6 protons and 12 neutrons. And so we went for it by the very exotic pion double charge exchange (DCX) reaction (π^+, π^-).
- We discovered ^{18}C by the reaction $^{18}\mathrm{O}(\pi^-, \pi^+)^{18}\mathrm{C}$ [1]. That was exciting.
- As I said before, exotica is addictive. So, after ^{18}C we went for ^{9}He, 2 protons+7 neutrons, $(N - Z)/A = 5/9$, by means of the reaction $^{9}\mathrm{Be}(\pi^-, \pi^+)^{9}\mathrm{He}$ [2]. We found it, and Bethe called it **"a drop of neutron star"**. How much more exotic can you get?
- Well, how about ^{6}H by $^{6}\mathrm{Li}(\pi^-, \pi^+)^{6}\mathrm{H}$. We tried and failed to find it, bound or unbound [3].

  So, running after exotica can lead to disappointments.





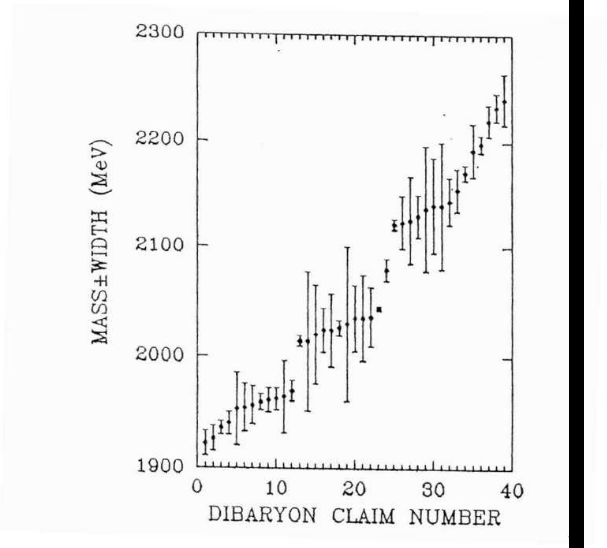
$\mathbf{^{9}Be(\pi^-,\pi^+)^{9}He}$

$\mathbf{^{6}Li(\pi^-,\pi^+)^{6}H(?)}$

- The other end of exotic nuclei is the **superheavy nuclei**. I have never worked in this field. But Berkeley, Dubna, and GSI have crossed swords in claims about who has the heaviest of the superheavy. After some embarrassing incidents, the current winner is $^{294}\mathrm{X}_{114}$ with 114 protons and 180 neutrons [4].

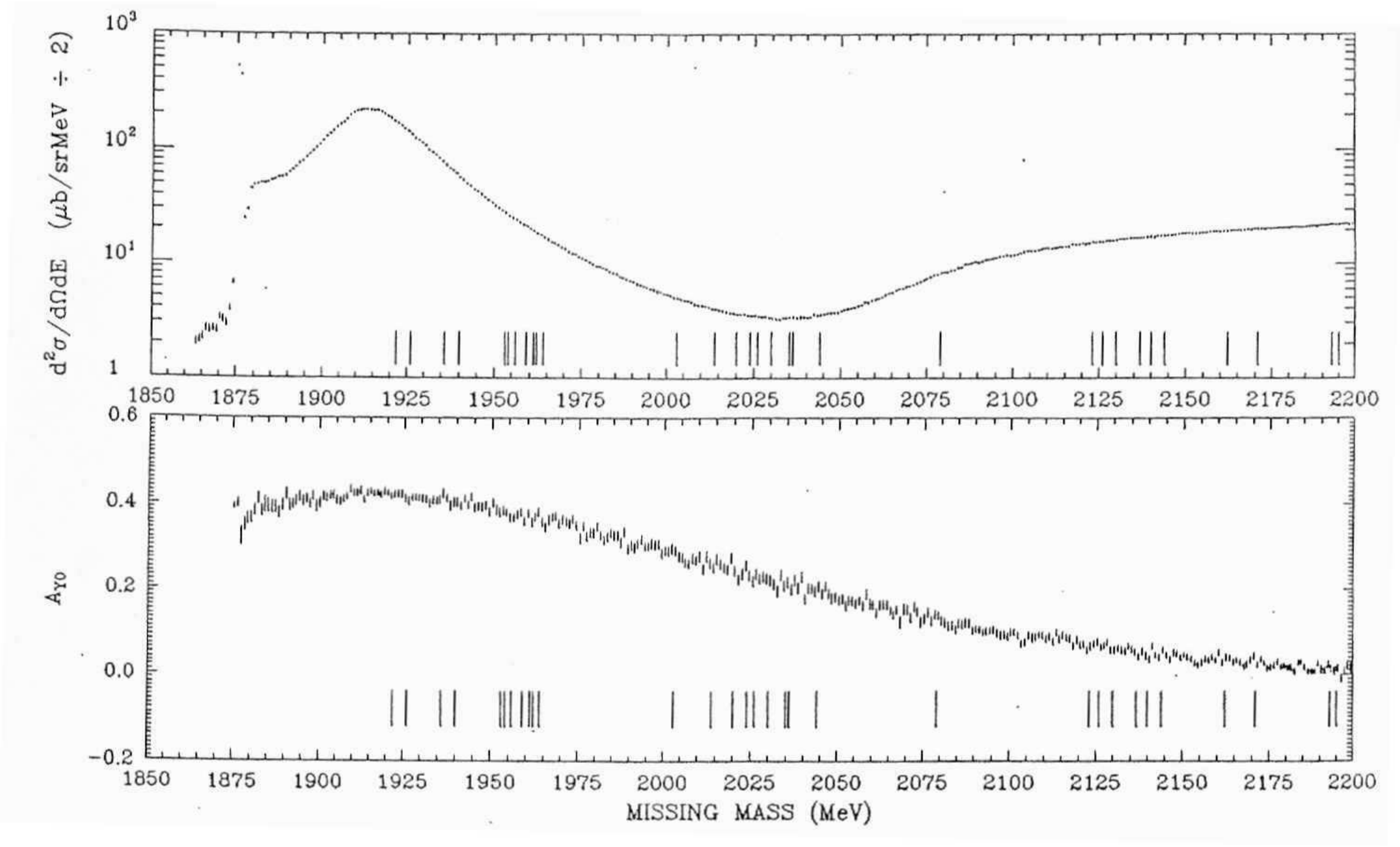
Chasing Exotica in Quark Physics

Quarks carry color, and **only color-neutral hadrons, $q\bar{q}$ mesons or qqq, baryons exist** in nature. In the quark bag model [5] hadrons with other color-neutral combinations, such as $(qqq)(qqq)$ **dibaryons**, or $qq\bar{q}\bar{q}$ **four-quark** state can exist. de Swart and colleagues calculated the masses of scores of dibaryons [6] and started a stampede for the search of dibaryons.



- Lots of people started looking for dibaryons in their old experiments, analyzing old bubble chamber pictures and claiming observation of scores of dibaryons. As many as 40 dibaryon states were claimed in the mass range $1900 - 2300$ MeV.
- We thought we could become famous by pinning these dibaryons down since we had orders of magnitude greater luminosity and energy resolution available at the Los Alamos Meson Factory. Instead of becoming **famous** for discovering dibaryons, we became **infamous** for killing all of them.

Dibaryons

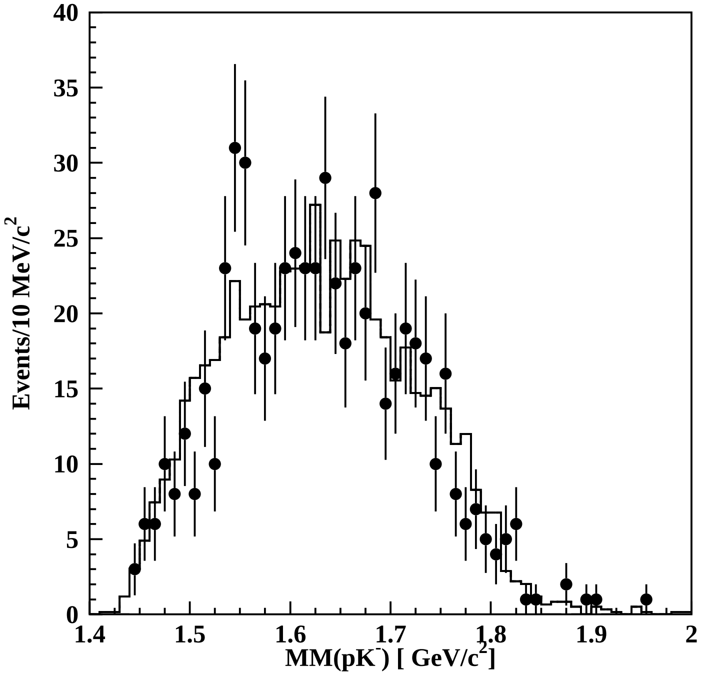


$\vec{p} + d \rightarrow p' + X$ at $T_p = 800$ MeV, $\Theta = 15°$: **No Dibaryons anywhere!**

Pentaquark

But that is not the end of this story. If not two baryons making a dibaryon, how about a baryon+a meson, or a color-neutral pentaquark? It surfaced a few years ago by the claim by Nakano et al. of a narrow peak, called Θ^+, with a mass of $M(\Theta^+) = 1540 \pm 10$ MeV, $\Gamma(\Theta^+) < 25$ MeV, in the invariant mass of K^+n in the reaction $\boldsymbol{\gamma n \longrightarrow K^-(K^+n)}$ [7]. If true, it would have strangeness $+1$ and at least five quarks/antiquarks. The object was so exotic that a stampede of **confirming** claims flooded the literature. In a little more time, an equal number of non-observations were reported. If you go to Google, you find 99,800 entries for **Pentaquark**, and it will be difficult to decide whether the pentaquark is alive or not.

In a high-statistics repeat of their own measurement, JLab found that their own earlier observation of Θ^+ was false and no evidence for the existence of the pentaquark exists [8]. However, rumor has it that Nakano et al. claim that they still see the pentaquark in a high-statistics remeasurement.



So, once claimed, an exotic is difficult to kill!

I end with a quote from PDG08 summarizing the saga of the pentaquark

> "The whole story — the discoveries themselves, the tidal wave of papers by theorists and phenomenologists that followed, and the eventual **'undiscovery'** — is a curious episode in the history of science."

The H Dibaryon

The $uuddss$ H dibaryon was predicted by Jaffe [9], but it became so exotic that it was even considered a candidate for dark matter. Stubborn searches for the H were made for years at Brookhaven and KEK. The u, d quark dibaryons died a long time ago, but the H dibaryon lived longer. By now, however, by common consensus it is also considered dead. For a detailed history see [10].

Exotica in QCD

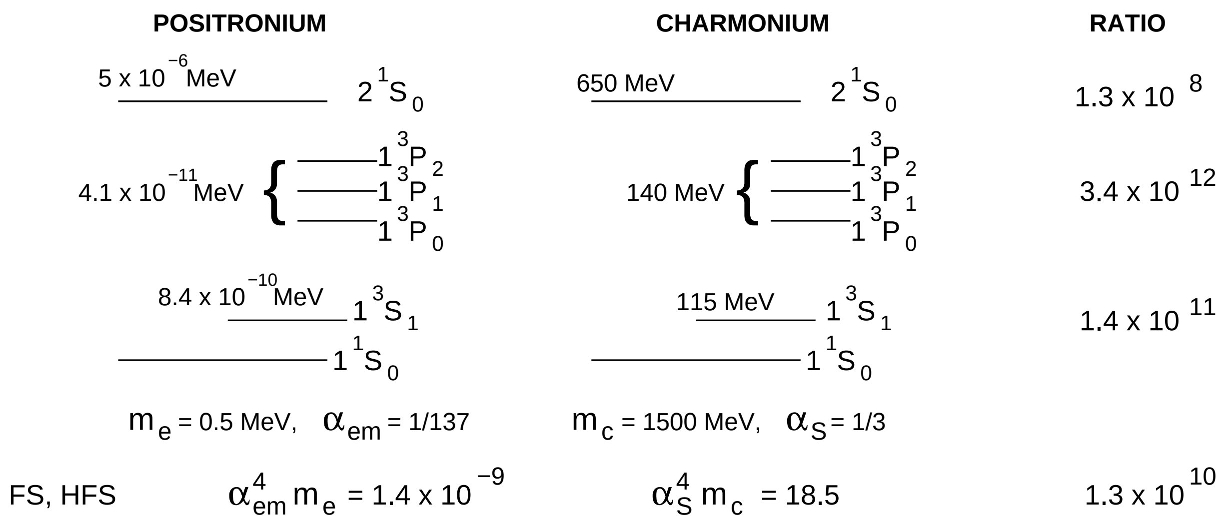
In Dec. 1974, a large narrow peak was disocvered at ~ 3.1 GeV mass at Brookhaven and SLAC [11] in e^+e^- formation and $\mu^+\mu^-$ decay. It was the $\boldsymbol{J/\psi}$ which launched the era of modern Quantum Chromodynamics (QCD).

- It is amusing to note that barely four weeks later **eight papers** by theoretical physicists (including four Nobel laureates) appeared in the Jan. 6, 1974 issue of Phys. Rev. Letters [12], offering explanations of what J/ψ might be. Several of them were truely exotic explanations, like J/ψ was a bound state of a baryon/antibaryon, or two spin–one mesons, or it was a member of a $15 \oplus 1$ dimensional representation of SU(4).
- **Tells you that nobody is immune to the lore of exotica.**
- I have been talking too much about the exotics which failed to materialize. Let me now, for awhile, focus on exciting physics which is **not exotica, but exitica** (my construct for something very exciting).

QCD versus QED

The QCD potential which arises due to the exchange of a massless vector **photon** is $V(r) \propto \alpha_{em}/r$. The QCD potential due to the exchange of a massless vector **gluon** is $V(r) \propto \alpha_{\rm strong}/r$. Because free quarks do not exist, in QCD there is an additional confinement term proportional to r.

With such close analogy to QED, it is interesting to compare the QCD spectrum of charmonium with the QCD spectrum of 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}
$1\,^3S_1$, $1\,^1S_0$	8.4×10^{-10} MeV	115 MeV	1.4×10^{11}
	$m_e = 0.5$ MeV, $\alpha_{em} = 1/137$	$m_c = 1500$ MeV, $\alpha_S = 1/3$	
FS, HFS	$\alpha_{em}^4\, m_e = 1.4 \times 10^{-9}$	$\alpha_S^4\, m_c = 18.5$	1.3×10^{10}

Hyperfine Interaction in QCD

The Coulombic ($\propto 1/r$) part of the QCD interaction gives rise to the usual spin dependence in the potential, with spin-orbit, tensor, and spin-spin components, in addition to the central part. Of these three, arguably the most important is the spin-spin interaction. For example, the ground state masses of $q\bar{q}$ mesons are:

$$M(q_1\bar{q}_2) = m_1(q_1) + m_2(q_2) + A_{hf}\left[\frac{\vec{s}_1 \cdot \vec{s}_2}{m_1 m_2}\right]$$

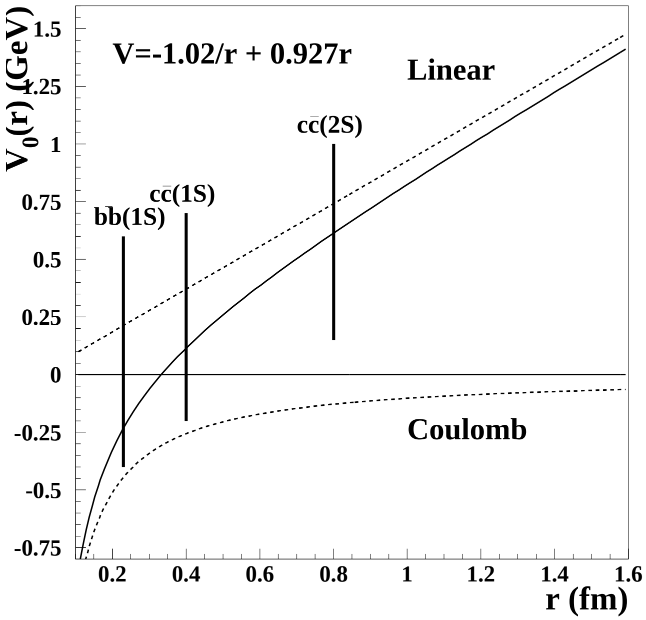
In order to determine the hyperfine interaction A_{hf} it is necessary to measure the **hyperfine splitting** between the spin–singlet and spin–triplet states it causes. This means identifying and measuring the massses of ${}^3L_J$ and ${}^1L_J$ states.

- The masses of **spin–triplet** ${}^3L_J$ states, ${}^3S_1$ and ${}^3P_J$ states are well-determined because either they are directly populated in e^+e^- annihilation ($|{}^3S_1\rangle$) or they are reached by strong E1 transitions from the $|{}^3S_1\rangle$ states ($|{}^3S_1\rangle \to \gamma_{E1}\,|{}^3P_J\rangle$).
- The **spin–singlet** states ${}^1L_{J=L}$ can not be directly formed, and radiative transitions to them from spin–triplet states are either forbidden or weak M1.
- The net result is that our knowledge of the spin–singlet states, and therefore of the hyperfine interaction, has been very poor in the past. Very recently this has changed.

Hyperfine Interaction in QCD

For heavy quark systems, $c\bar{c}$ charmonium, and $b\bar{b}$ bottomonium, we would like to know how the hyperfine interaction changes as we move from the Coulomb dominated region of the $q\bar{q}$ potential to the confinement dominated region. We would like to study the change in the hyperfine interaction

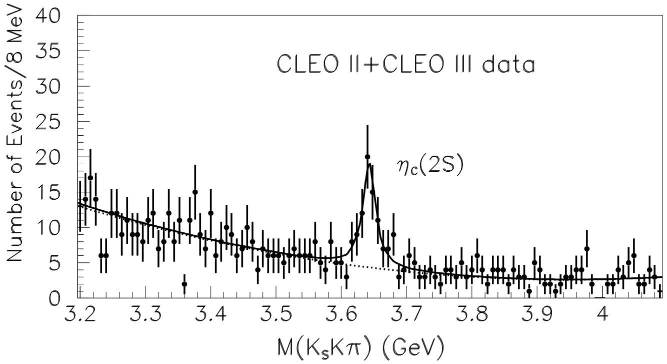
1. between $c\bar{c}(1S)$ and $c\bar{c}(2S)$
2. between $c\bar{c}(1S)$ and $b\bar{b}(1S)$
3. between $c\bar{c}(1S)$ and $c\bar{c}(1P)$

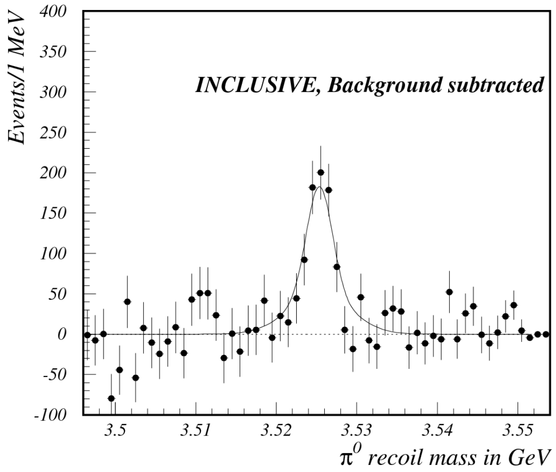


- Until recently, the only hyperfine splitting known was

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

- $\eta_c'(1^1S_0)$, $h_c(1^1P_1)$, **and** $\eta_b(1^1S_0)$were not even identified. In the last five years, all this has changed due to the measurements at Belle, BaBar, and CLEO.



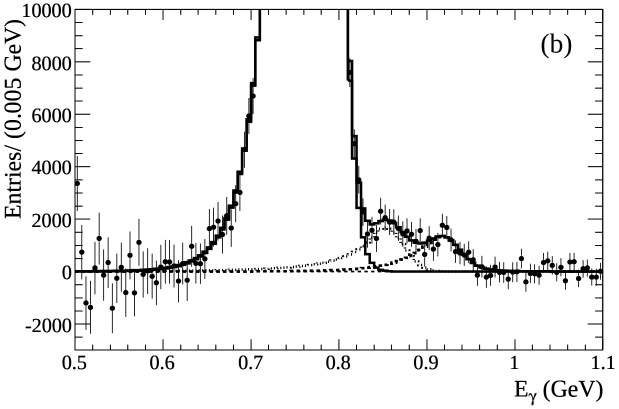


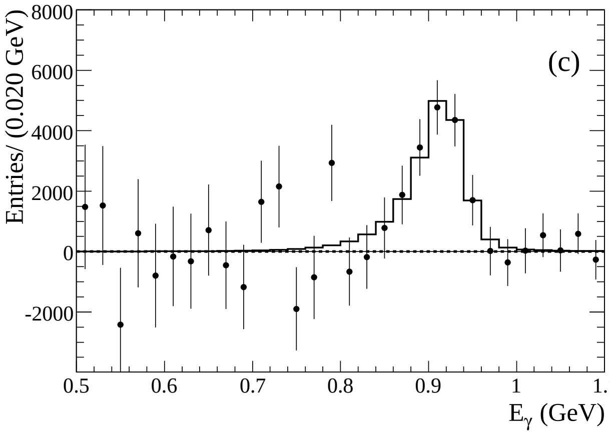
$M(\eta_c'(2^1S_0)) = 3642.9 \pm 3.4$ **MeV** (CLEO [13])

$\Delta M_{hf}(2S)_{c\bar{c}} = +43.2 \pm 3.4$ **MeV**

$M(h_c(1^1P_1)) = 3525.28 \pm 0.23$ **MeV** (CLEO [14])

$\Delta M_{hf}(1P)_{c\bar{c}} = +0.02 \pm 0.23$ **MeV**

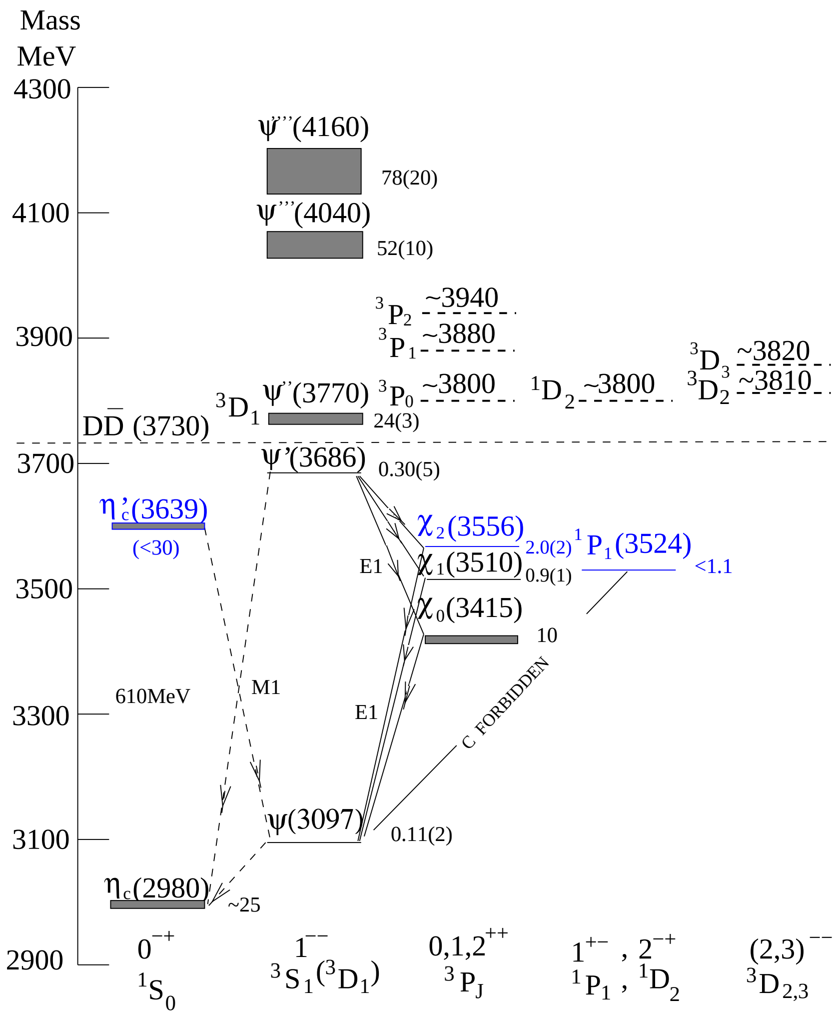




$M(\eta_b(1^1S_0)) \;=\; 9388.9^{+4.1}_{-3.5}$ **MeV** (BaBar [15])

$\Delta M_{hf}(1S)_{b\bar{b}} = +71.4^{+4.1}_{-3.5}$ **MeV**

Back to Exotica



I now return to the domain of Exotica.

Recently, a number of new states have been claimed in the mass region 3800–4700 MeV, above the $D\overline{D}$ breakup of charmonium at 3730 MeV. It is usually called the “charmonium energy region”.

CHARMONIUM EXOTICS

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

- Three years ago, all that was known above $D\overline{D}$ was 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**.

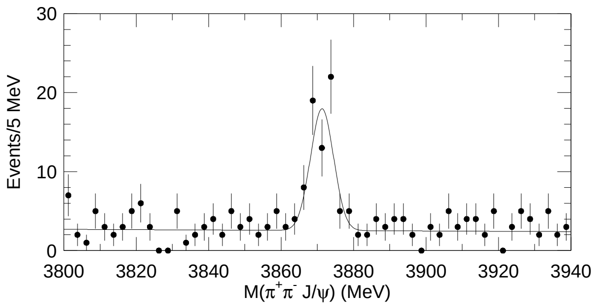
  Let me go over them one by one.

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 gives $M(D^0D^{0*}) = \mathbf{3871.81 \pm 0.36}$ MeV. This corresponds to X(3872) being **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. These two observations raise 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 higher precision $M(\mathrm{X})$ and $M(D^0)$, and $B(\mathrm{X} \to D^0D^0\pi^0)$ to throw some fresh light on the nature of X(3872).

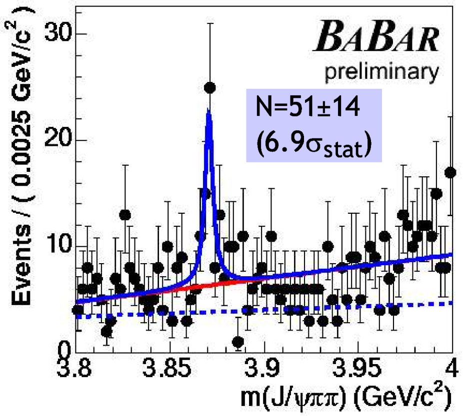
The Veteran of Suprises—X(3872)

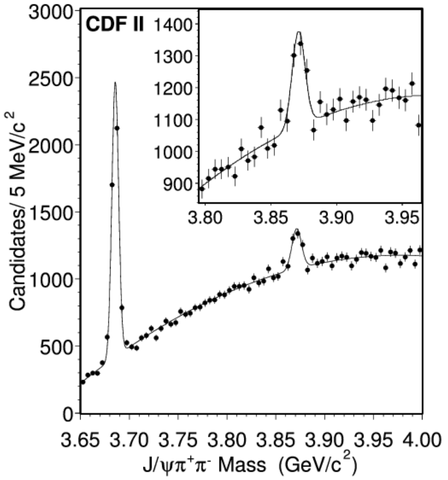
The experimental observations (2003–4):



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

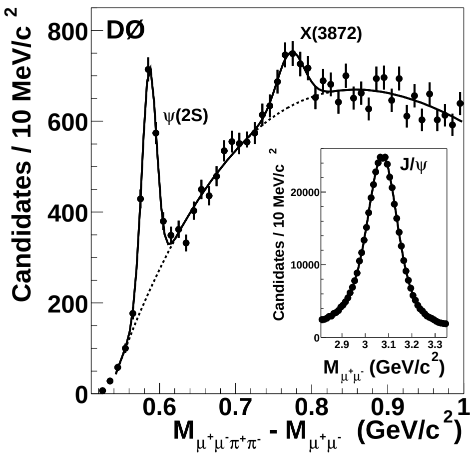
226M $B\bar{B}$ decays (BaBar)
$M = 3871.3 \pm 0.6$ MeV
(BaBar, right)
$N = 51 \pm 14$ events





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

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



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

Y(4260)

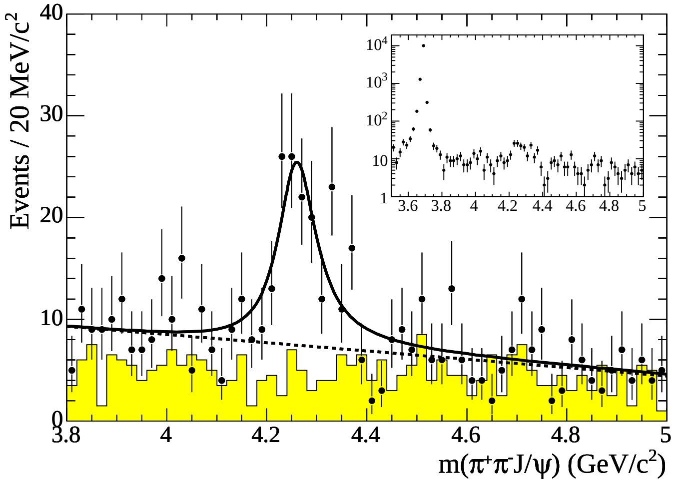
- The Y(4260) has been observed in ISR production by BaBar, CLEO and Belle, and in direct production by CLEO. Y(4260) is clearly **a vector** with $J^{PC} = 1^{--}$, but a very strange one, since it sits at a very deep minimum in R, with

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

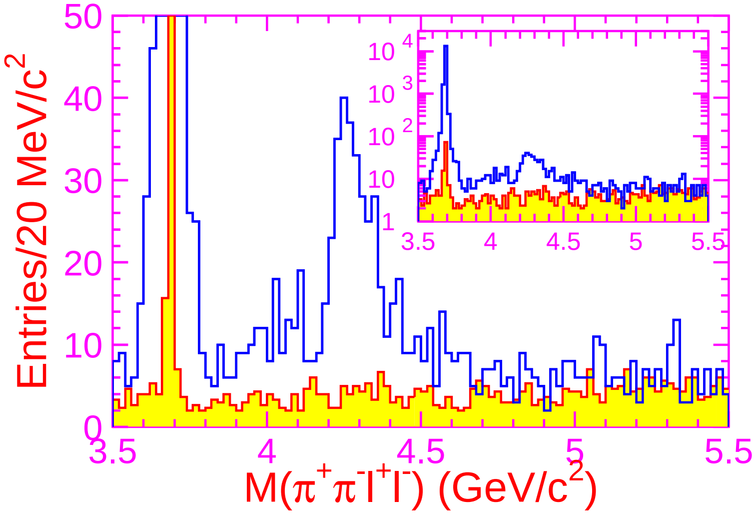
  So it is not likely to be a charmonium vector, which are all spoken for, anyway.

  So what is Y(4260)?

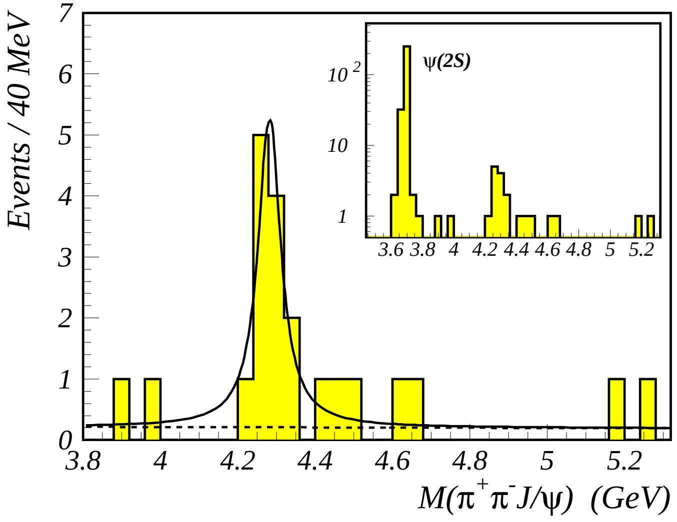
- It is suggested that Y(4260) is a ccg charmonium hybrid. If so, there ought to be 0^{-+} and 1^{-+} hybrids companions nearby. The exciting challenge for experimentalists is to find them.
- There are new problems. Belle has revived the question whether there is actually one resonance or two. Further, 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.



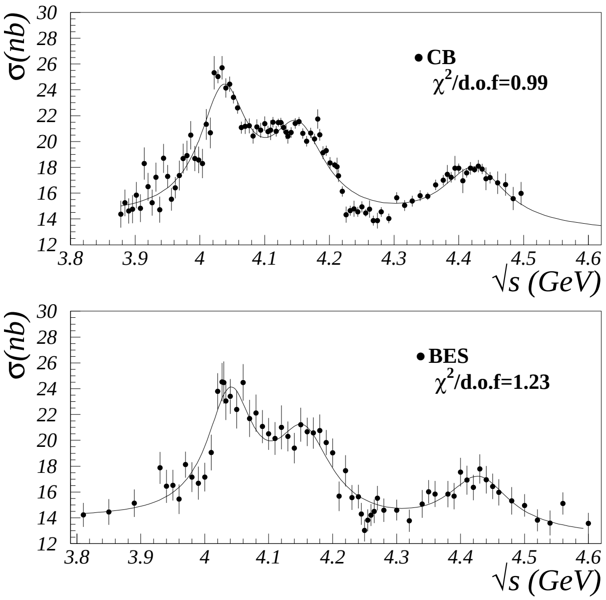
BaBar: 233 fb^{-1}



Belle: 548 fb^{-1}

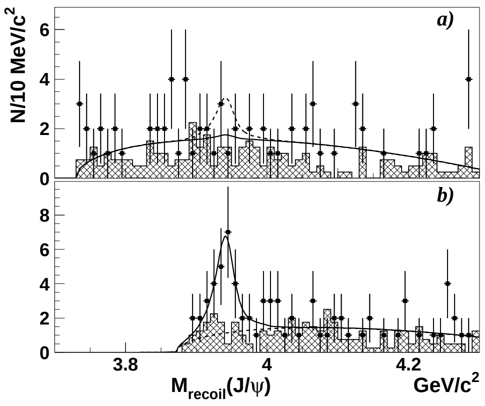


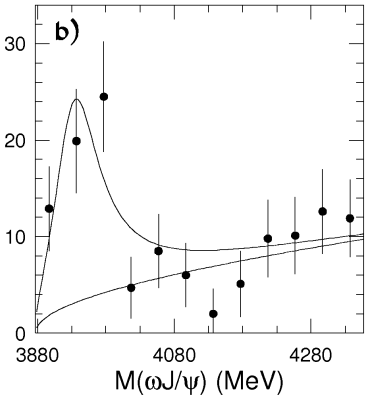
CLEO: 13.3 fb^{-1}

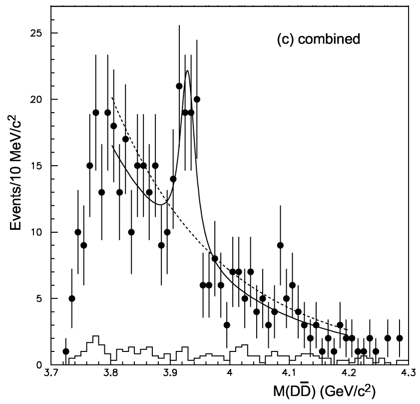


The Saga of X,Y,Z(∼3940)

- 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.





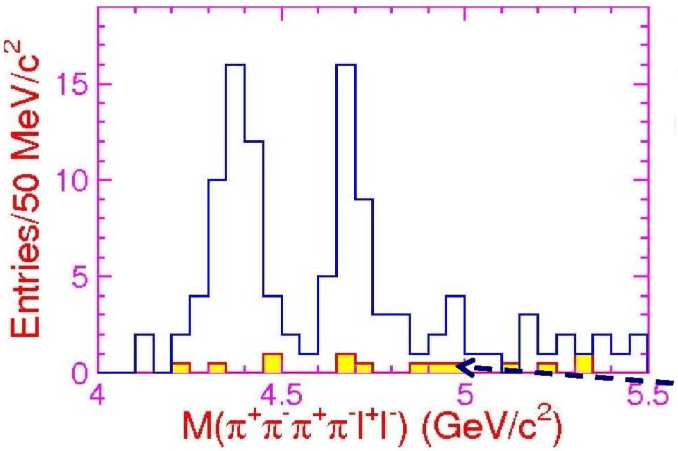


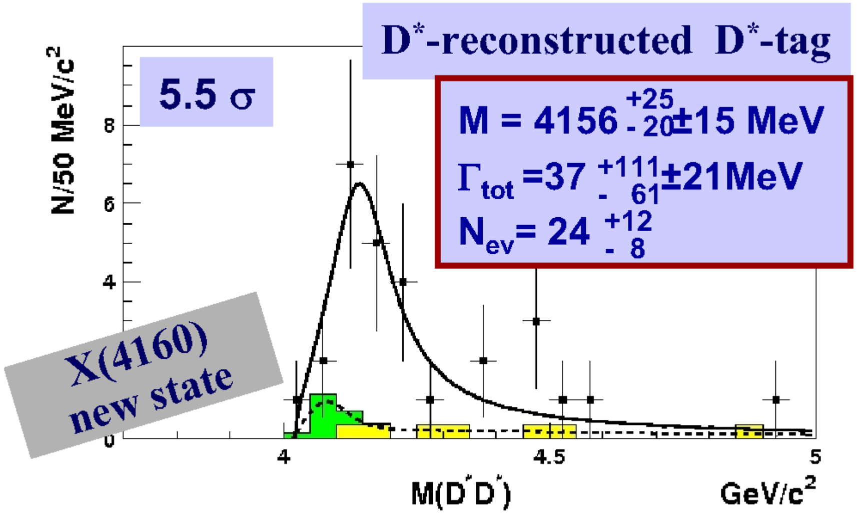
	X(3943)—Belle	**Y(3943)—Belle**	**Z(3929)—Belle**
	$N(\mathrm{X}) = 24.5 \pm 6.9$	$N(\mathrm{Y}) = 58 \pm 11$	$N(\mathrm{Z}) = 64 \pm 18$
	$M(\mathrm{X}) = 3943 \pm 10$	$M(\mathrm{Y}) = 3943 \pm 17$	$M(\mathrm{Z}) = 3929 \pm 10$
	$\Gamma(\mathrm{X}) = 15.4 \pm 10.1$	$\Gamma(\mathrm{Y}) = 87 \pm 16$	$M(\mathrm{Z}) = 20 \pm 8$
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	$e^+e^- \to \psi(2S)\pi^+\pi^-$





D*-reconstructed D*-tag

5.5 σ

$M = 4156^{+25}_{-20} \pm 15$ MeV

$\Gamma_{tot} = 37^{+111}_{-61} \pm 21$ MeV

$N_{ev} = 24^{+12}_{-8}$

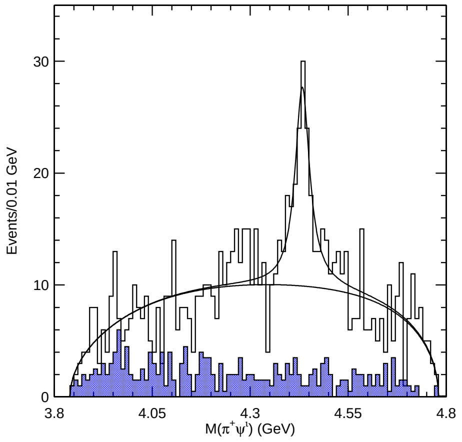
X(4160) new state

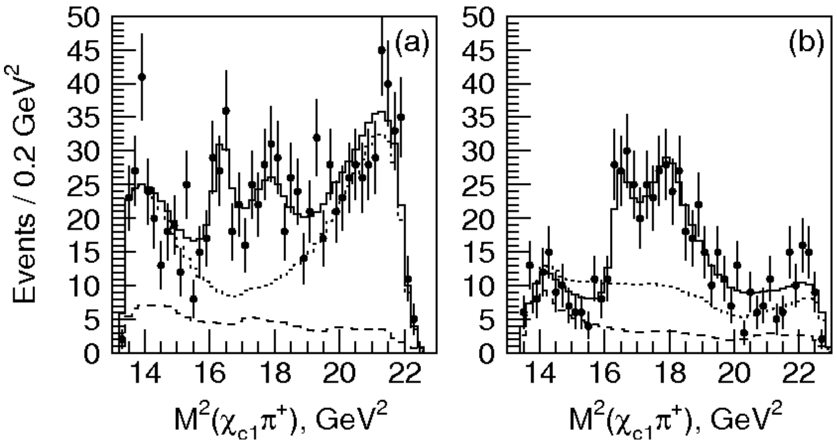
Highly Questionable. Likely $\psi(4160)$!

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)	$4248^{+44+180}_{-29-35}$	$177^{+54+316}_{-39-61}$	$\left(3.0^{+1.5+3.7}_{-0.8-1.6}\right) \times 10^{-5}$





Epilogue

The sum total of the experiences in this journey through hadronic **exotica** is that

- The journey is certainly worth it. It is unquestionably exciting.
- But the road is full of pitfalls and disappointments.

Only the brave should enter!

They should be proud of their successes, and humble enough to admit their failures.

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