Unusual Peaks around the Open Charm Threshold

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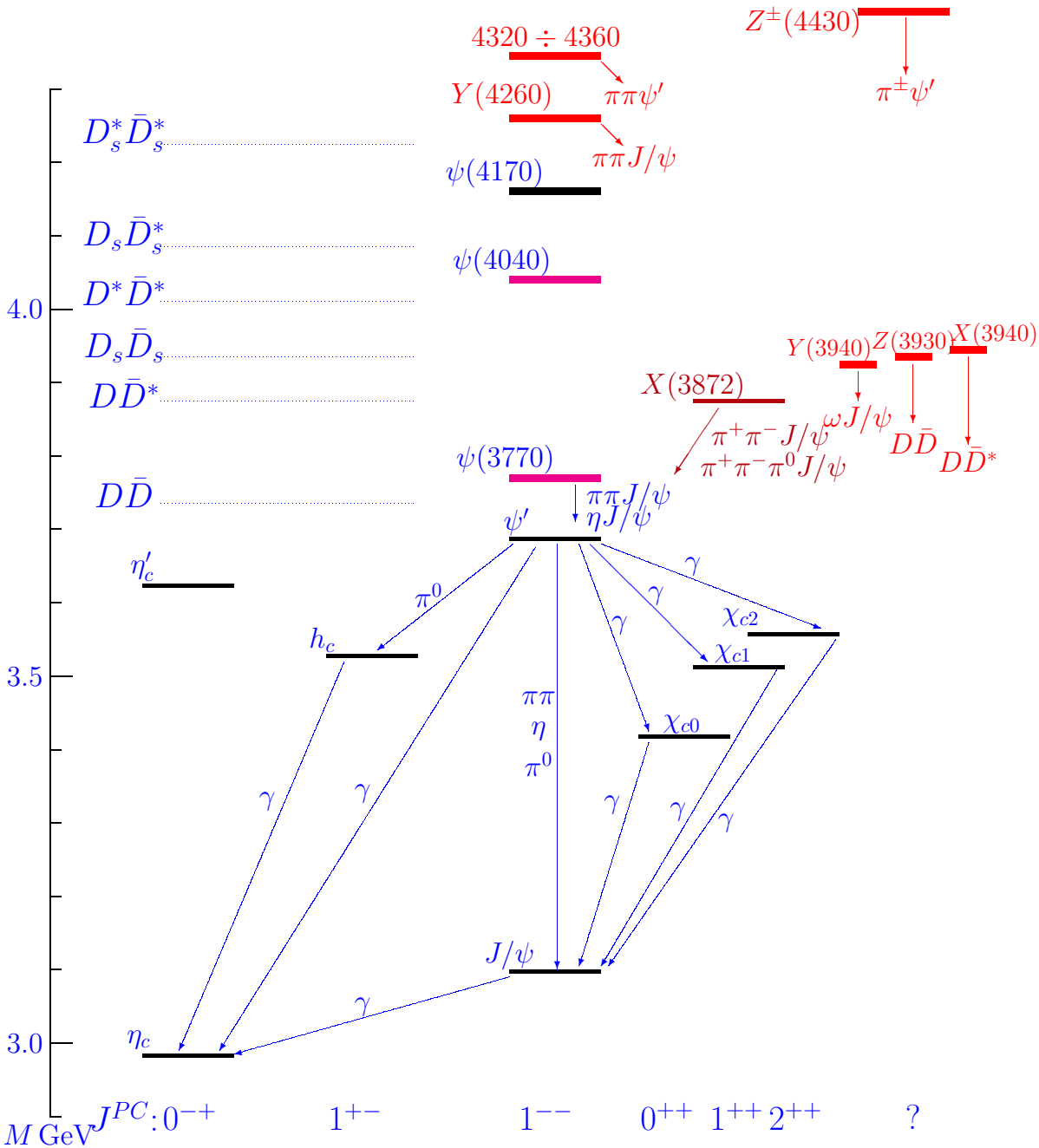
Charmonium '08



$X(3872)$. The peak that started it all

'03-'05. Belle, BaBaR: $B \to K\, J/\psi\, \pi^+\pi^-$,
CDF, $D\emptyset$: $p\bar{p} \to J/\psi\, \pi^+\pi^- + X$.
Resonance $X(3872)$ in the $J/\psi\, \pi^+\pi^-$ channel.
Belle, CDF: 10 - 11 σ. Listed as "established" in PDG06.

Mass $3871.2 \pm 0.5\, MeV$ is within less than 1 MeV from the $D^0\bar{D}^{0*}$ threshold:
$M_X - M(D^0\bar{D}^{*0}) = -0.6 \pm 0.6\,\text{MeV}$. Width unresolved ($\Gamma < 2.3\,\text{MeV}$).
Crucial observations:

- (Belle '04): $X(3872) \to J/\psi\, \pi^+\pi^-\pi^0$ (4.5σ)

$$\frac{\Gamma(X(3872) \to J/\psi\, \pi^+\pi^-\pi^0)}{\Gamma(X(3872) \to J/\psi\, \pi^+\pi^-)} = 1.1 \pm 0.4 \pm 0.3$$

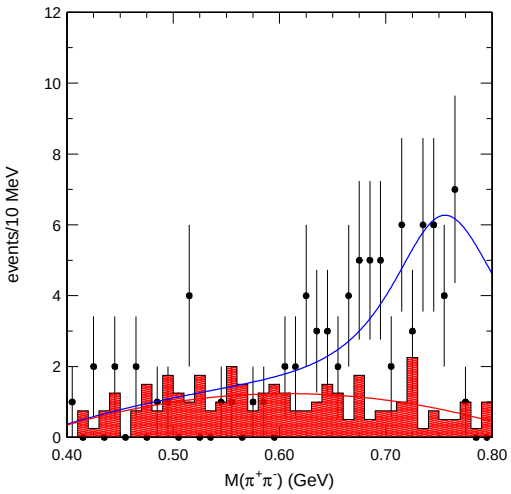
- (Belle '05): $X(3872) \to J/\psi\, \gamma \Rightarrow C = +1$
- (Belle '05): Angular analysis of $X(3872) \to J/\psi\, \pi^+\pi^-$ strongly favors $J^{PC} = 1^{++}$

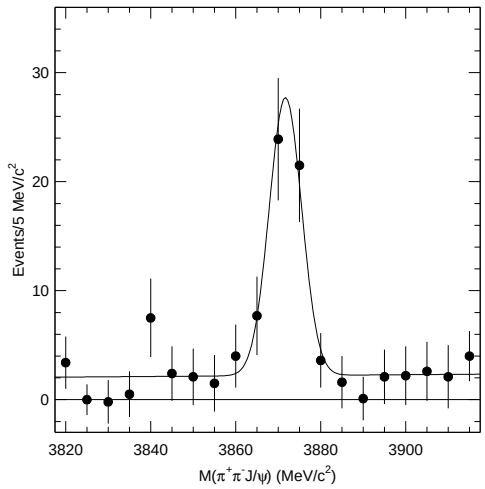
Isospin (G parity) is necessarily broken: $G(J/\psi\, \pi^+\pi^-) = -1$, $G(J/\psi\, \pi^+\pi^-\pi^0) = +1$. $\Rightarrow$ Cannot be a pure $c\bar{c}$.
The pion-system invariant mass distributions hint at $X(3872) \to J/\psi\rho \to J/\psi\, \pi^+\pi^-$ and $X(3872) \to J/\psi\omega \to J/\psi\, \pi^+\pi^-\pi^0$.
• It is highly likely that X(3872) is a $D^0\bar{D}^{0*} + D^{0*}\bar{D}^0$ molecule, $J^{PC} = 1^{++}$. The isospin is badly broken, since the D^+D^{*-} pair is 8 MeV heavier.

Belle '04

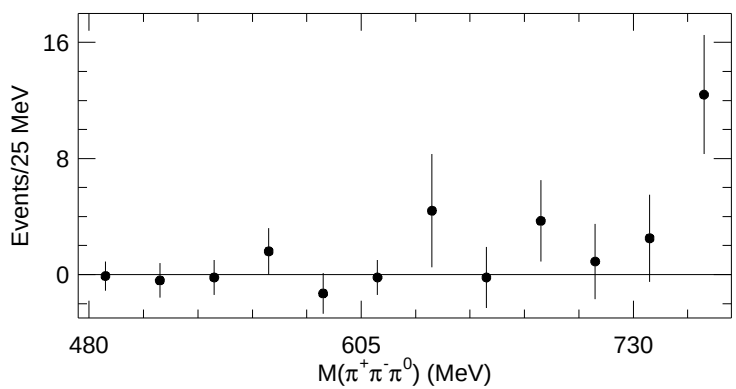
hep-ex/0412068

$X(3872) \to J/\psi\rho \to J/\psi\,\pi^+\pi^-$





$X(3872) \to J/\psi\omega \to J/\psi\,\pi^+\pi^-\pi^0$

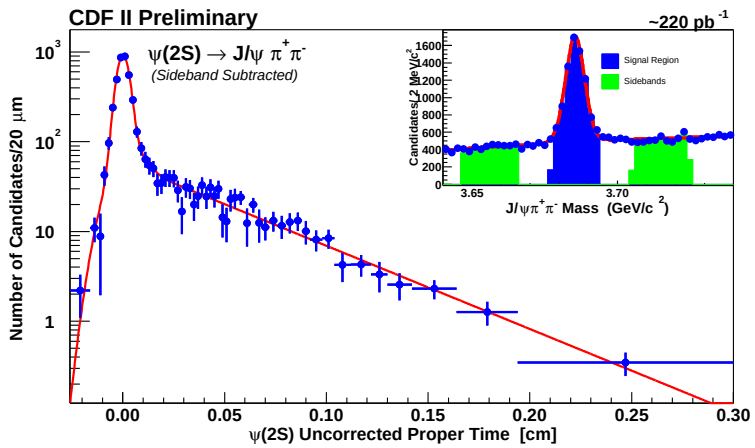


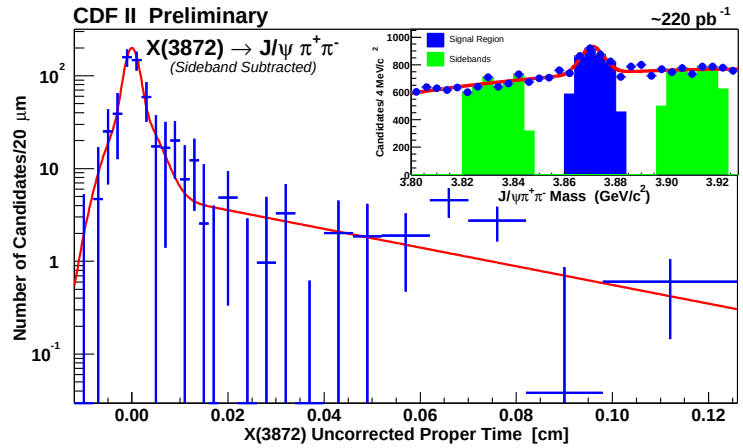
All events are at $m_{3\pi} > 750\,MeV$

CDF '04

http://www-cdf.fnal.gov/physics/new/bottom/040624.blessed-xlonglived/

$\psi(2S)$ vs $X(3872)$ production in $p\bar{p}$ (Tevatron)





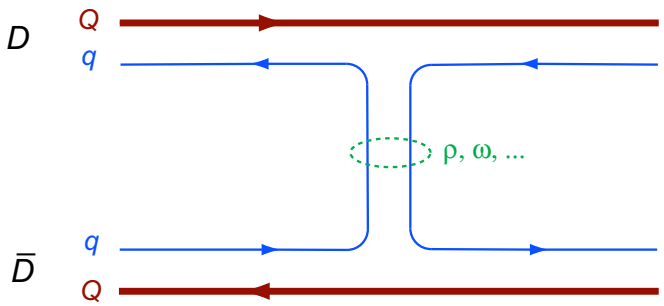
$\psi(2S)$: $28.3 \pm 1.0 \pm 0.7\,\%$ from b decays

$X(3872)$: $16.1 \pm 4.9 \pm 2.0\,\%$ from b decays

Pretty similar.

• X(3872) as a 'molecule'

Existence of bound heavy meson states was expected



A normal "nuclear" force. The strength and the radius r_0 do not depend on m_Q.

$$E = \frac{p_D^2}{m_D} + U(r)$$

At sufficiently large m_Q ($m_D = m_Q + \bar{\Lambda} + \ldots$) the $U(r)$ wins.

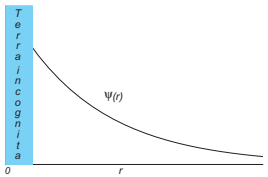
Heavy-meson bound states, "molecules" should exist. L.B. Okun & MV '76

Structure of the X(3872)

$$\psi_X = a_0\,\psi_0 + \sum_i a_i\,\psi_i$$

ψ_0: state of $(D^0\bar{D}^{*0} + \bar{D}^0 D^{*0})/\sqrt{2}$ ("molecular component"); $\sum_i a_i\,\psi_i$: short-distance "core".

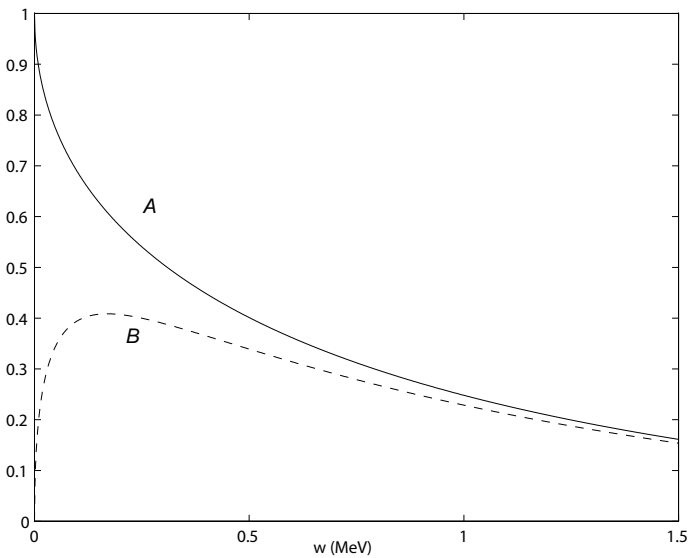
Similarly to deutron $= \alpha\, pn + \beta$"*core*", where "core" $= N\,\Delta$, six-quark state, etc. The "core" is localized at short distances ($\sim \Lambda_{QCD}^{-1}$). $|\beta|^2 \sim$ few percent.



"Molecular": $|a_0|^2$ is a large fraction of the total normalization. $\psi_0(r) \propto \exp(-\kappa r)/r$, free motion at distances $\sim \kappa^{-1}$, $\kappa \approx \sqrt{m_D w} \approx 40 MeV \sqrt{w/1\,MeV}$. w =binding energy.

Can be probed by the decays $X(3872) \to D^0 \bar{D}^0 \pi^0$ and $X(3872) \to D^0 \bar{D}^0 \gamma$. Interference between $D^{0*} \to D^0 \pi^0(\gamma)$ and $\bar{D}^{0*} \to \bar{D}^0 \pi^0(\gamma)$.

$$\Gamma(X(3872) \to D^0 \bar{D}^0 \pi^0) = |a_0|^2 \Gamma(D^{*0} \to D^0 \pi^0)\,[A(w) + B(w)]$$



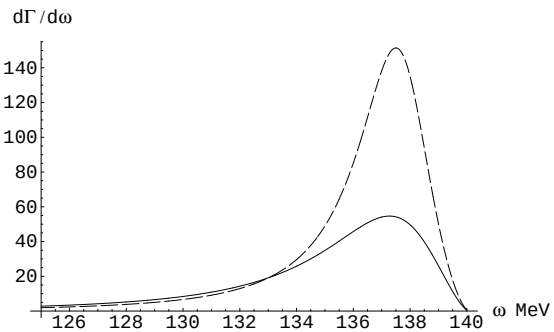
$\Gamma(D^{*0} \to D^0 \pi^0) = 43 \pm 10\,\mathrm{keV}$.

$X \to D^0 \bar{D}^0 \gamma$:

$$\Gamma(X \to D^0 \bar{D}^0 \gamma) = |a_0|^2 \, \Gamma_\gamma \left(1 - \frac{2\,\kappa}{k_\gamma} \arctan \frac{k_\gamma}{2\,\kappa}\right)$$

$k_\gamma \approx 137\,\mathrm{MeV}$, $\Gamma_\gamma = \Gamma(D^{*0} \to D^0 \gamma) = 26 \pm 6\,\mathrm{KeV}$.

Interference term: 0.32 at $w = 0.1\,MeV$, and 0.71 at $w = 0.5\,MeV$.



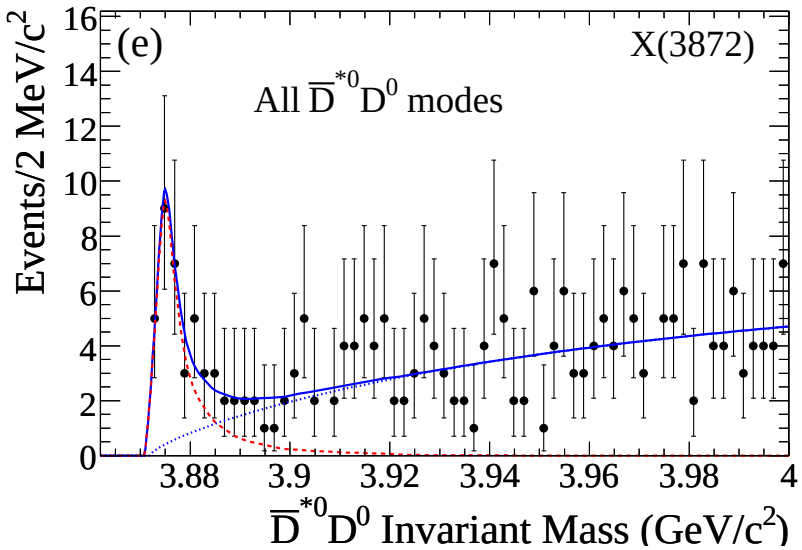
A small $X(3872) \to D^+ D^- \gamma$ is possible due to the charmonium "core" component:
$X(3872) \to \psi(3770)\,\gamma \to D^+ D^- \gamma$.

Production in hard processes ($B \to XK$, $p\bar{p} \to X + \ldots$) due to the charmonium "core".

$$\frac{\mathcal{B}(B^0 \to X(3872) K^0)}{\mathcal{B}(B^\pm \to X(3872) K^\pm)} = 0.94 \pm 0.24 \pm 0.10$$

Combined BaBar & Belle '07.

Decays $X(3872) \to D\bar{D}\pi^0(\gamma)$ were sought for through $B \to D\bar{D}\pi^0(\gamma) + K$.
A peak was found (Belle '06, BaBar '07). But $M_X = 3875\,\mathrm{MeV}$.
BaBar:



If the peak interpreted as X(3872): $\mathcal{B}(X \to DD^*)/\mathcal{B}(X \to \pi^+\pi^- J/\psi) \gtrsim 10$.

X = virtual state (?) (D.V.Bugg, C.Hanhart *et.al.*).
'Virtual state' = 'almost bound' (Well known in low-energy pp scattering.)
Scattering length a. ($\sigma = 4\pi a^2$). Large and positive a — shallow bound state. Large and negative a— virtual state. In either case the cross section is large.

Useful: $\kappa = 1/a$. Small κ: $\kappa\, r_0 \ll 1$ with $r_0 \sim 1\,\mathrm{fm}$ being the radius of strong interaction. $\chi(r)$ - radial wave function, $\kappa = -\chi'(r_0)/\chi(r_0) \to -\chi'(0)/\chi(0)$.

• Two channels: $n = D^0\bar{D}^{*0} + \bar{D}^0 D^{*0}$, $c = D^+D^{*-} + D^-D^{*+}$. S wave.
Consider energy $E = W_{tot} - M(D^0D^{*0})$ between the thresholds, i.e. $0 < E < \Delta$.
$\Delta = M(D^+D^{*-}) - M(D^0D^{*0}) \approx 8\,\mathrm{MeV}$. At $r > r_0$ free S wave motion:

$$\chi_n(r) = \sin(k_n r + \delta), \qquad \chi_c(r) = \xi\, \exp(-\kappa_c r)$$

$k_n = \sqrt{2m^*E}$, $\kappa_c = \sqrt{2m^*(\Delta - E)}$. The constants ξ and δ are to be determined by boundary conditions at $r = r_0$. These BC are for the isospin states: $\chi_0 = \chi_n + \chi_c$ and $\chi_1 = \chi_n - \chi_c$. Shift r_0 to $r = 0$:

$$\chi_0'(0)/\chi_0(0) = -\kappa_0\,, \qquad \chi_1'(0)/\chi_1(0) = -\kappa_1$$

κ_0 and κ_1 are determined by the strong interaction in $I = 0$ and $I = 1$ channels (at $r < r_0$).
Simplified picture: strong attraction for $I = 0$, weak attraction or repulsion for $I = 1 \Rightarrow |\kappa_0|$ small, $|\kappa_1|$ large. Then the scattering amplitude for the n channel

$$f_n = -\frac{1}{2\kappa_0 - \kappa_c + i\,k_n}$$

Scattering length in the 'n' channel: $a_n = 1/(2\kappa_0 - \sqrt{2m^*\Delta})$. Negative a
$\Rightarrow \kappa_0 < \sqrt{m^*\Delta/2} \approx 63\,\mathrm{MeV}$.
Inelastic channels (relatively weak) shift the pole: $f_n = -\frac{1}{2\kappa_0 - \kappa_c + i\,k_n + i\,\gamma}$.
Hanhart *et.al.* estimate $a_n = -(4 + 0.5\,i)\,\mathrm{fm} \Rightarrow \kappa_0 \approx 38\,\mathrm{MeV}$, $\gamma \approx 6\,\mathrm{MeV}$.

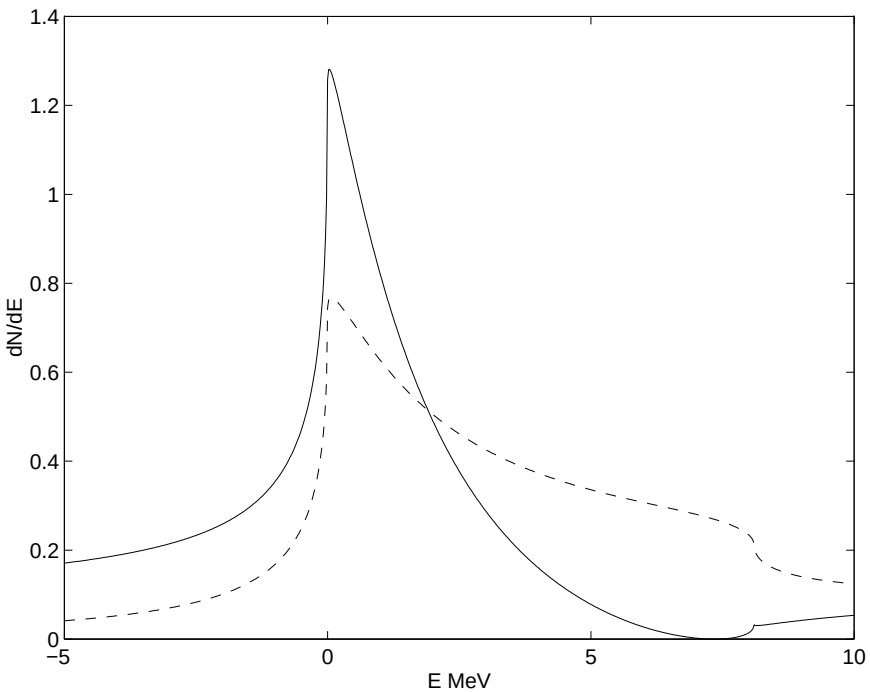
$$\mathcal{B}[B \to (D^0\bar{D}^{*0} + \bar{D}D^{*0})\,K] \,:\, \mathcal{B}(B \to \omega J/\psi\, K) \,:\, \mathcal{B}(B \to \rho J/\psi\, K) = \; k_n\,|f|^2 \,:\, \gamma_\omega\,|f|^2 \,:\, \gamma_\rho\,|f|^2$$

Agrees with $\mathcal{B}[B \to (D^0\bar{D}^{*0} + \bar{D}D^{*0})\,K] \gg \mathcal{B}(B \to \rho J/\psi\, K)$.

• The virtual state picture can be tested by the shapes of the peaks in $\pi^+\pi^- J/\psi$ ($\rho J/\psi$) and $\pi^+\pi^-\pi^0 J/\psi$ ($\omega J/\psi$): The ratio of the $I = 1$ and $I = 0$ short-distance production amplitudes is given in this picture as

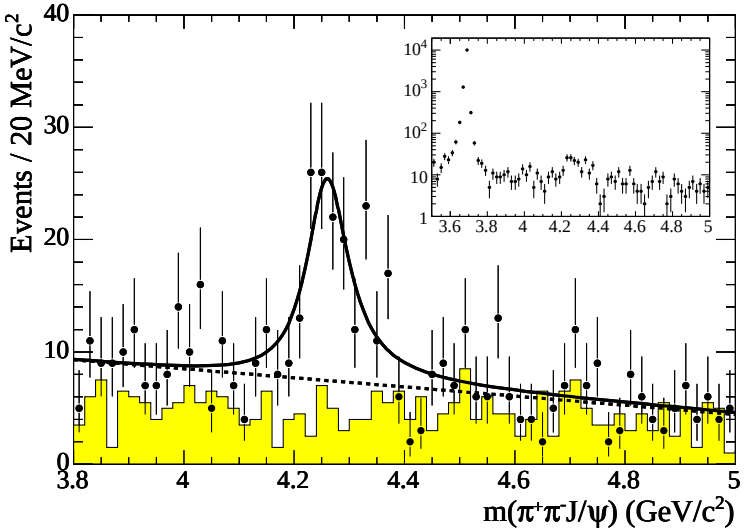
$$\frac{A_\rho}{A_\omega} \propto \frac{\kappa_0 - \kappa_c}{\kappa_1 - \kappa_c}$$

$\kappa_0 - \kappa_c$ necessarily changes sign between the thresholds.

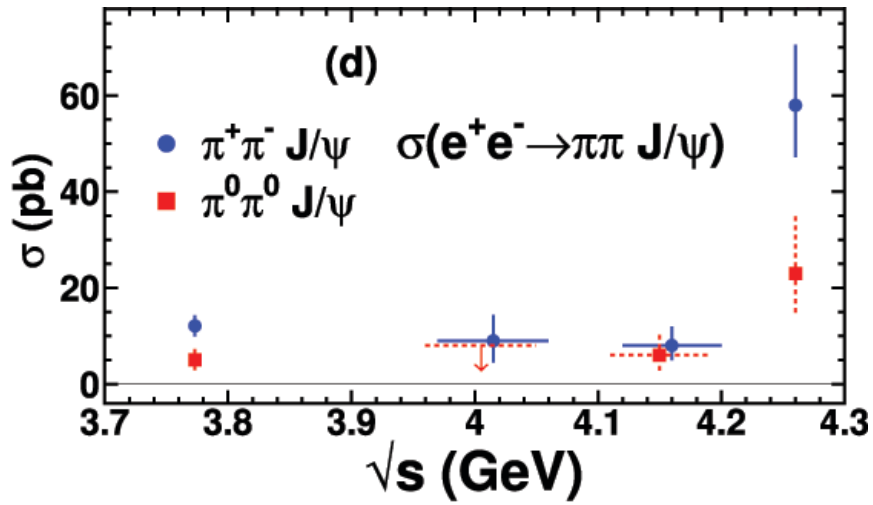


Yield of $\pi^+\pi^- J/\psi$ (solid) and $\pi^+\pi^-\pi^0 J/\psi$ (dashed) channels

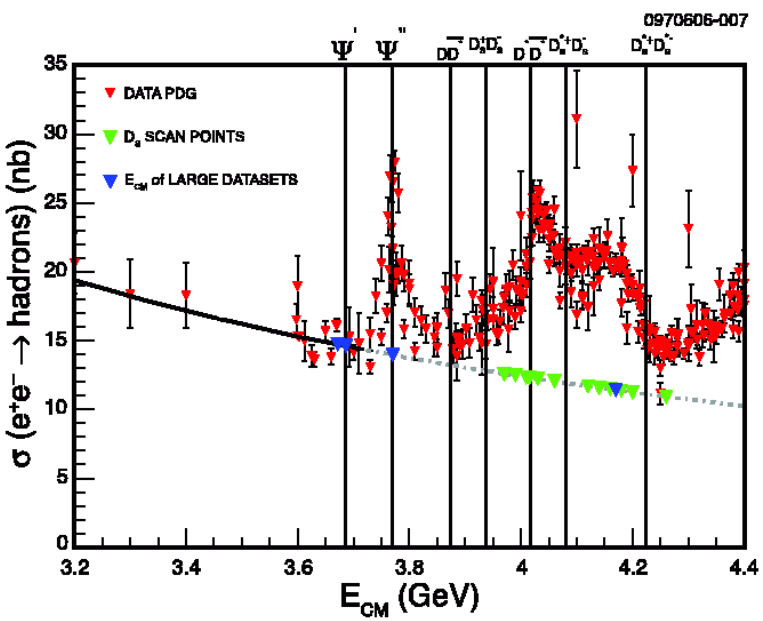
$Y(4.26)$, $Y(4.32-4.36)$, $Y(4.66)$



BaBar '05 (ISR, $e^+e^- \to \gamma + X$)



CLEO '06 (direct scan in e^+e^-)



• $Y(4260)$: Confirmed by Belle, CLEO, CLEO-c. Also seen in $B \to \pi^+\pi^- J/\psi K$.

$Y(4260) \to \pi^+\pi^- J/\psi$: $M = 4264^{+10}_{-12}$ MeV, $\Gamma = 83^{+20}_{-17}$ MeV

Other decay modes seen: $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$. $\frac{\Gamma(Y \to K^+K^- J/\psi)}{\Gamma(Y \to \pi^+\pi^- J/\psi)} \approx 0.15$

No decays with $D\bar{D}$ in the final state were seen. In particular:

$\Gamma(Y \to D\bar{D})/\Gamma(Y \to \pi^+\pi^- J/\psi) < 1.0$

Impossible to explain if $Y(4260)$ is a pure charmonium state!

Compare e.g. with $\Gamma(\psi(3770) \to D\bar{D})/\Gamma(\psi(3770) \to \pi^+\pi^- J/\psi) \approx 400$

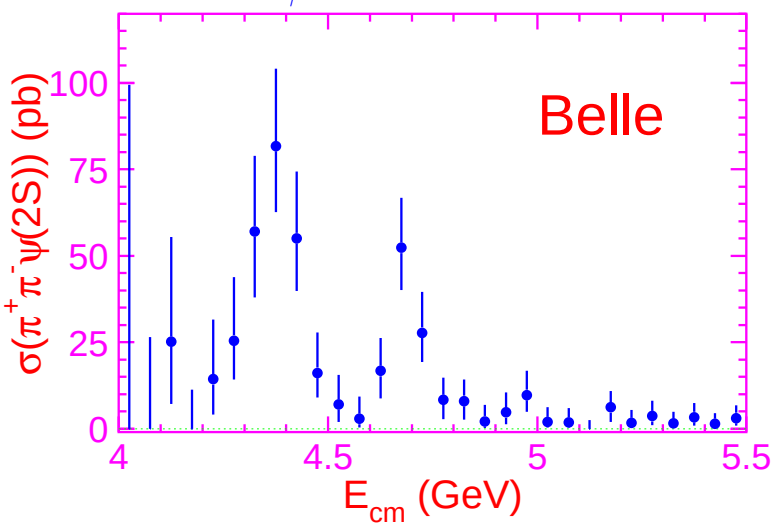
• $Y(4.32 - 4.36)$:

"Broad structure" in (ISR) $e^+e^- \to \pi^+\pi^-\psi'$ (not J/ψ!)

BaBar: $M = 4324 \pm 24$ MeV, $\Gamma = 172 \pm 33$ MeV Belle: $M = 4361 \pm 9 \pm 9$ MeV, $\Gamma = 74 \pm 15 \pm 10$ MeV and additionally:

• $Y(4.66)$

Peak in $\pi^+\pi^-\psi'$ at $M = 4664 \pm 11 \pm 5$ MeV, $\Gamma = 48 \pm 15 \pm 3$ MeV.



• Suggested explanations for Y's:

Hybrids: $c\bar{c} + glue$ F.Close and P.Page, E.Kou and O.Pene

Di-diquarks: $[cs][\bar{c}\bar{s}]$ L.Miani *et.al.*

Enhanced strangeness not likely in view of $\frac{\Gamma(Y \to K^+K^- J/\psi)}{\Gamma(Y \to \pi^+\pi^- J/\psi)} \approx 0.15$

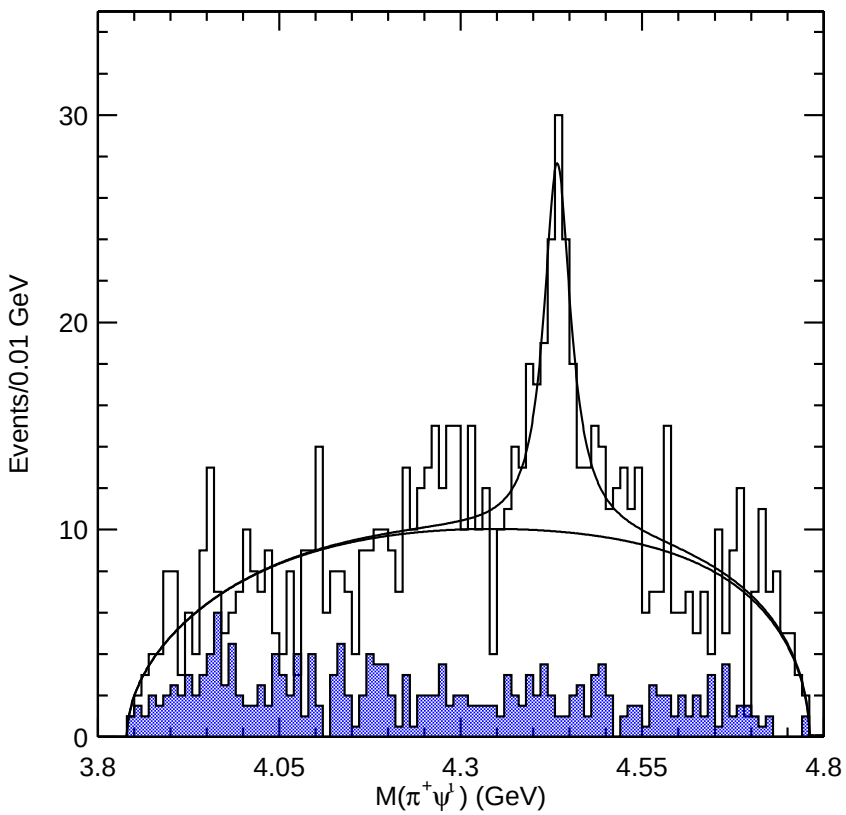
Why a hybrid would chose to go into a particular charmonium state J/ψ or ψ'? Why no very strong $D\bar{D}$ decays?

$Z(4430)$ Manifestly Exotic

Belle '07: Peak in $\pi^+\psi'$ inv. mass in the decays $B \to \pi^+\psi' K$. ($6.5\,\sigma$ significance).

Z(4430): $M = 4333 \pm 4 \pm 2\,\mathrm{MeV}$, $\Gamma = 45^{+18}_{-15}\,{}^{+30}_{-13}\,\mathrm{MeV}$.

$\mathcal{B}(B^0 \to K Z^\pm)\,\mathcal{B}(Z^\pm \to \pi^\pm\psi') \approx 4 \times 10^{-5}$ (similar to $B \to K X(3872)$ followed by $X \to \pi^+\pi^- J/\psi$)



- Explanations on the market:
  - Molecule/threshold cusp $D_1^+ \bar{D}^{*0} + \xi\, D^{*+} \bar{D}_1^0$. Rosner, Meng & Chao, Bugg, X.Liu et.al., Y.Li et.al., Ding

    D_1: 1^+, $M(D_1^0) = 2422.3 \pm 1.3\,\mathrm{MeV}$, $\Gamma = 20.4 \pm 1.7\,\mathrm{MeV}$.

    $M(D^{*+} D_1^0) \approx 4430\,\mathrm{MeV}$. For S-wave $1^+ \otimes 1^-$ possible J^P are 0^-, 1^-, and 2^-. Rosner argues $J^P = 0^-$ (small energy release in $B \to ZK$).

    $Z \to D^* \bar{D}^* \pi$ should be much stronger than $Z \to \pi\psi'$.

    Other charmonium+pions modes? Why $\pi\psi'$, rather than $\pi J/\psi$?

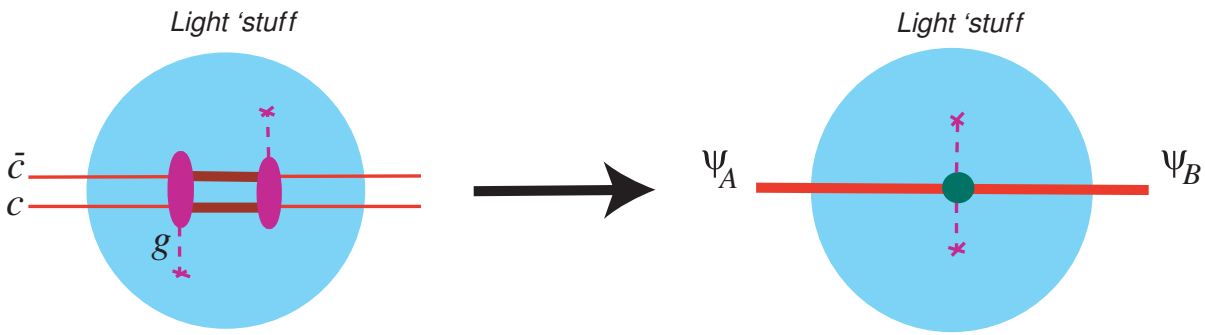
    I have hard time understanding a resonance with the width $20\,\mathrm{MeV}$ having a binding energy $\sim 3\,\mathrm{MeV}$ (decays faster than binds).
  - Tetraquark: $[cu] + [\bar{c}\bar{d}]$ Miani et.al., Gershtein et.al.

    Not many new predictions. Same questions as for the molecule.
  - Baryon-antibaryon (baryonium)... C.F.Qiao

• If you ask me...

To me $Y(4260)$, $Y(4.32-4.36)$, $Y(4.66)$, $Z(4430)$ all look like 'a charmonium stuck in a light hadron'. At least this can explain why a specific charmonium state e.g. J/ψ or ψ' appears in the decay.

Here's what I mean:



$$\langle B|H_{eff}|A\rangle = -\frac{1}{2}\,\alpha_{AB}\,\vec{E}^a\cdot\vec{E}^a \qquad \text{Chromo}-\text{polarizability}: \alpha_{AB}$$

$|\alpha_{\psi' J/\psi}| \approx 2\,GeV^{-3}$ is known from $\psi' \to \pi\pi\, J/\psi$. Schwartz inequality $\alpha_{J/\psi}\alpha_{\psi'} \geq \alpha^2_{\psi' J/\psi}$.

$$\langle X|\vec{E}^a\cdot\vec{E}^a\,|X\rangle \geq \langle X|\vec{E}^a\cdot\vec{E}^a - \vec{B}^a\cdot\vec{B}^a|X\rangle = -\frac{1}{2}\langle X|(F^a_{\mu\nu})^2|X\rangle = \frac{32\pi^2}{9}\,M_X^2$$

X=(Light hadron) $\Rightarrow$ strong interaction with heavier hadronic states made of light quarks and gluons.

E.g. J/ψ binding potential in heavy nuclei $V < -27\,\text{MeV}$.

If such interpretation of Y's and Z has anything to do with reality, there should be bound states of J/ψ and/or ψ' with light nuclei, or even a proton and/or a deuteron.

• New Exotics in 'Old' Resonances

ψ':

$$\frac{\Gamma(\psi' \to \pi^0\, J/\psi)}{\Gamma(\psi' \to \eta\, J/\psi)} = 3\left(\frac{m_d - m_u}{m_d + m_u}\right)^2 \frac{F_\pi^2}{F_\eta^2}\,\frac{m_\pi^4}{m_\eta^4}\,\frac{p_\pi^3}{p_\eta^3} < 0.023$$

$\frac{m_d - m_u}{m_d + m_u} < 0.35$ (Gasser, Leutwyler '82 - present). Central value: 0.285.

CLEO-c: $\Gamma(\psi' \to \pi^0\, J/\psi)/\Gamma(\psi' \to \eta\, J/\psi) = 0.041 \pm 0.004 \pm 0.001$.

$\Rightarrow I = 1$ admixture in ψ'. Can arise e.g. thorugh $\psi' - \psi(3770)$ $({}^3S_1 - {}^3D_1)$ mixing ($\theta \sim 0.1$) and a larger 4-quark component with isospin violation in $\psi(3770)$ due to $M(D^+D^-) - M(D^0\bar{D}^0) \approx 9\,\mathrm{MeV}$.

If such picture is correct then (predicted) enhanced decay $\psi(3770) \to \eta J/\psi$. (Specifically, expected $\mathcal{B}[\psi(3770) \to \eta J/\psi] \sim 0.14\%$.) Measured:

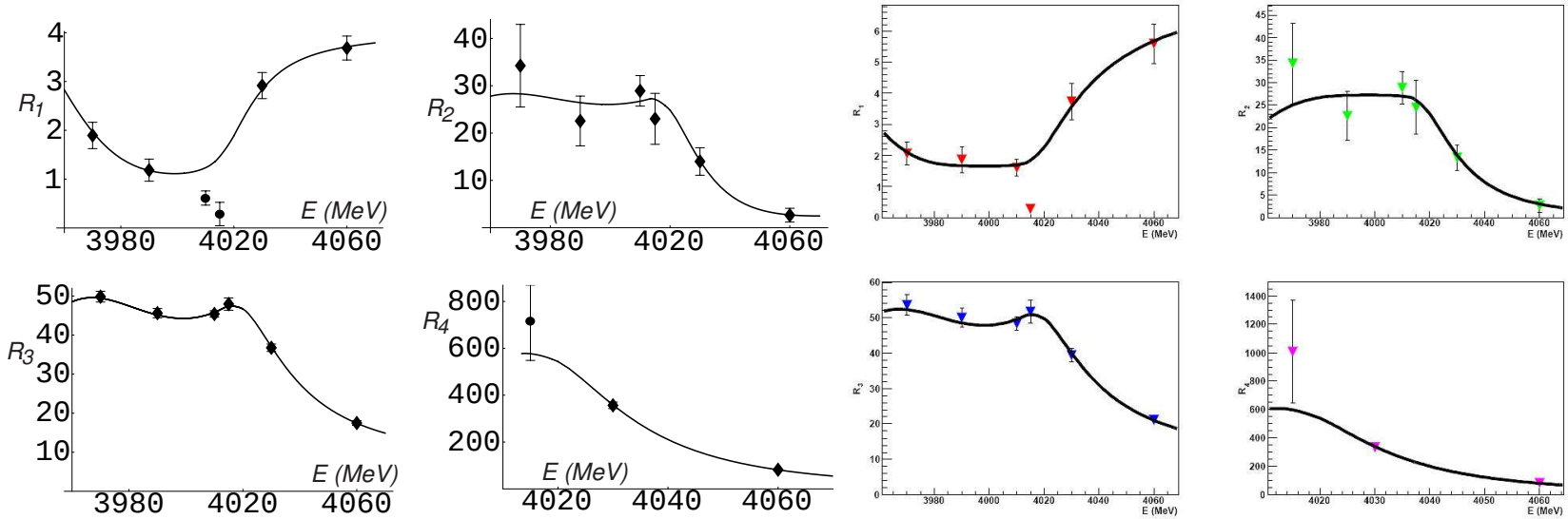
$$\mathcal{B}[\psi(3770) \to \pi^+\pi^- J/\psi] = (0.189 \pm 0.020 \pm 0.020)\%\,, \quad \mathcal{B}[\psi(3770) \to \eta J/\psi] = (0.087 \pm 0.033 \pm 0.022)\%$$

$$\Rightarrow \frac{\mathcal{B}[\psi(3770) \to \eta J/\psi]}{\mathcal{B}[\psi(3770) \to \pi^+\pi^- J/\psi]} \sim 0.5$$

Compare with $\mathcal{B}(\psi' \to \eta J/\psi)/\mathcal{B}(\psi' \to \pi^+\pi^- J/\psi) \sim 0.1$.

- $D^*\bar{D}^*$ threshold, $\psi(4040)$

Fit to the data at $\sqrt{s} = 3970 - 4060\,\mathrm{MeV}$, background+resonance with channel coupling.



R_1: DD, R_2: D_sD_s, R_3: DD^*, R_4: D^*D^*.

Left: S.Dubynskiy and MBV '06 (used preliminary data), points at 4010 and 4015 for DD and D^*D^* excluded from fit.

$M = 4019\,\mathrm{MeV}$, $\Gamma(non - D^*D*) = 65\,\mathrm{MeV}$, $\Gamma_{ee} \approx 1.7\,\mathrm{KeV}$; $\chi^2/NDF = 3.0/5$.

Right: B.Lang [CLEO] thesis (26 Oct. 06) with updated data. The data at 4015 for DD and D^*D^* excluded from fit.

$M = 4013 \pm 0.4\,\mathrm{MeV}$, $\Gamma(non - D^*D*) = 66 \pm 8\,\mathrm{MeV}$, $\Gamma_{ee} = 1.9 \pm 0.7\,\mathrm{KeV}$; $\chi^2/NDF = 3.8/6$.

No fit is possible if all points are included ($\chi^2/NDF = 17.6/8$ for DV, $\chi^2/NDF = 36.3/8$ for BL). Narrow structure at 4015 MeV?

Summary

- It looks like that the presence of heavy charmed quarks and the fixed range/strength strong force give rise to exotic near-threshold states.
- The peaks X, Y, Z very likely provide us with the much expected exotica: molecules and/or hybrids and/or multiquark hadrons and/or 'charmonium stuck in glue'.
- For the X and Y a pure charmonium interpretation is logically possible, but physically unlikely.
- The charged Z(4430) is manifestly exotic
- The rate of appearance of new surprising peaks exceeds the theory's ability of making sense of them. (Exciting time!)
- There are possible 'Easter eggs' in the long-known resonances.
- B physics is likely to be even more rich with exotics. However a study of it would require a dedicated effort.