Puzzles in the Charmonium Sector of QCD

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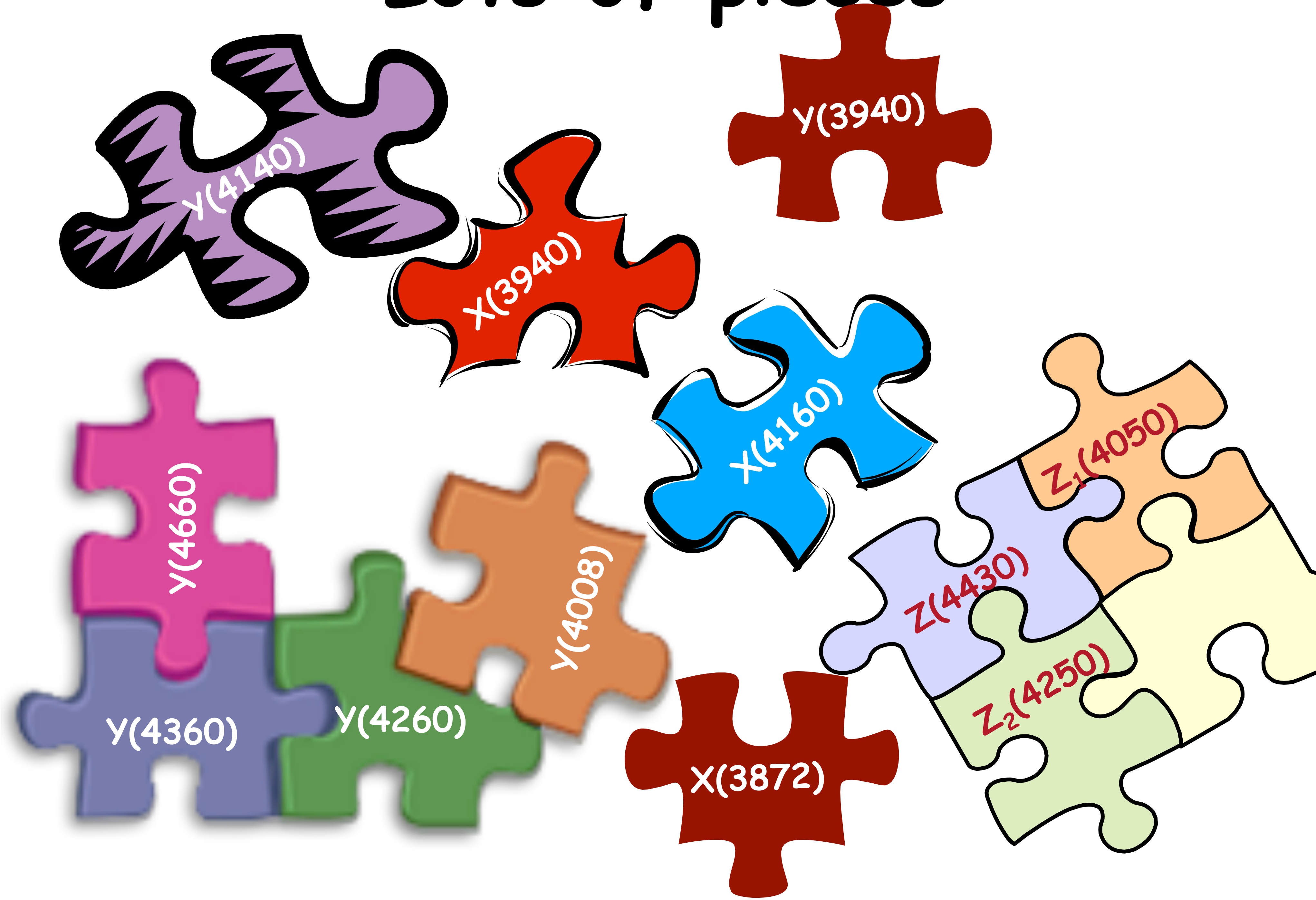
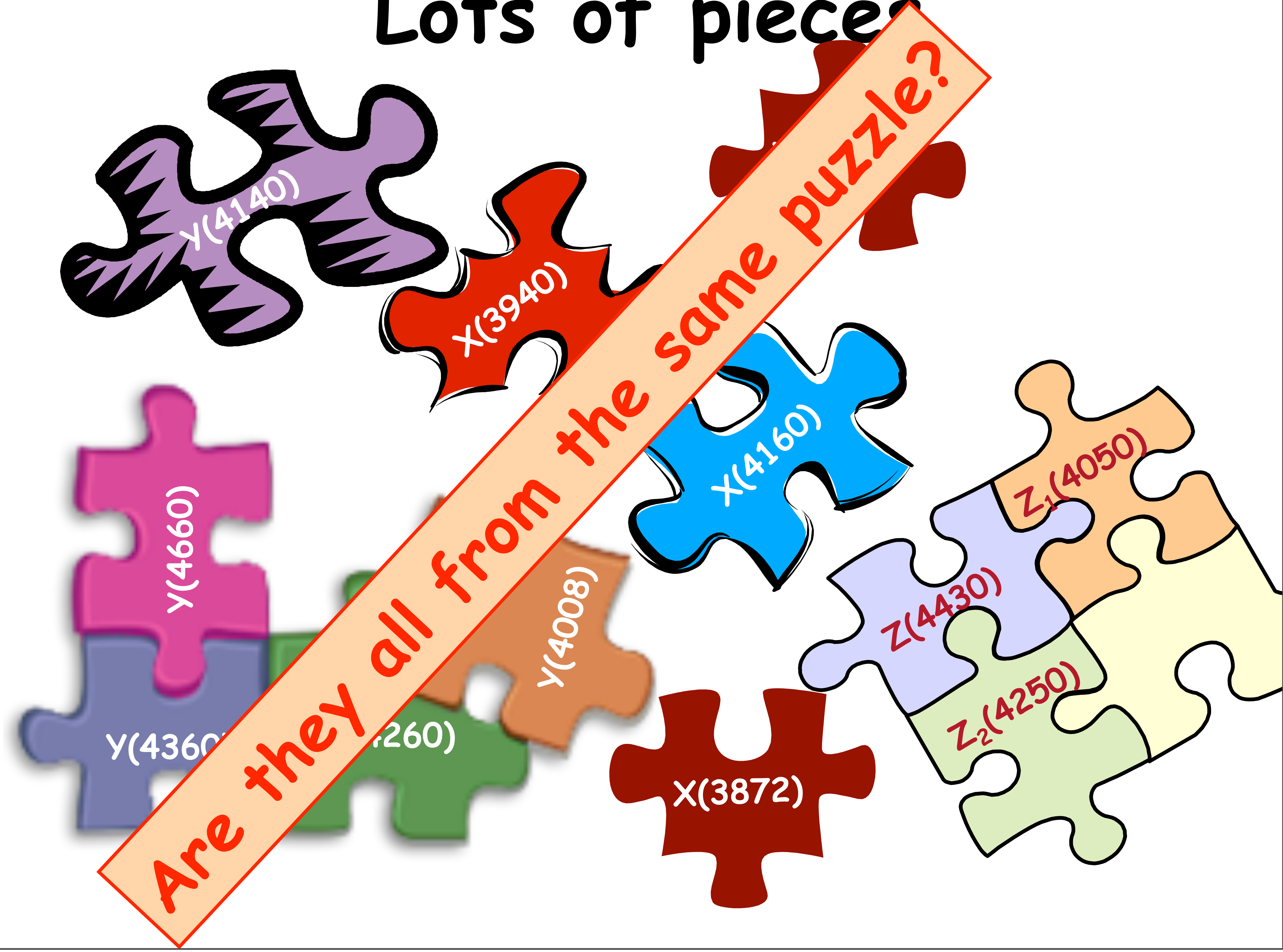
Lots of pieces



Lots of pieces



Puzzles in the Charmonium Sector of QCD

New $c\bar{c}$ mesons above $D\bar{D}$ threshold

What are they?

- charmonium?
- charmonium hybrids?
- tetraquarks?
- molecules?

X(3872)

Reviews

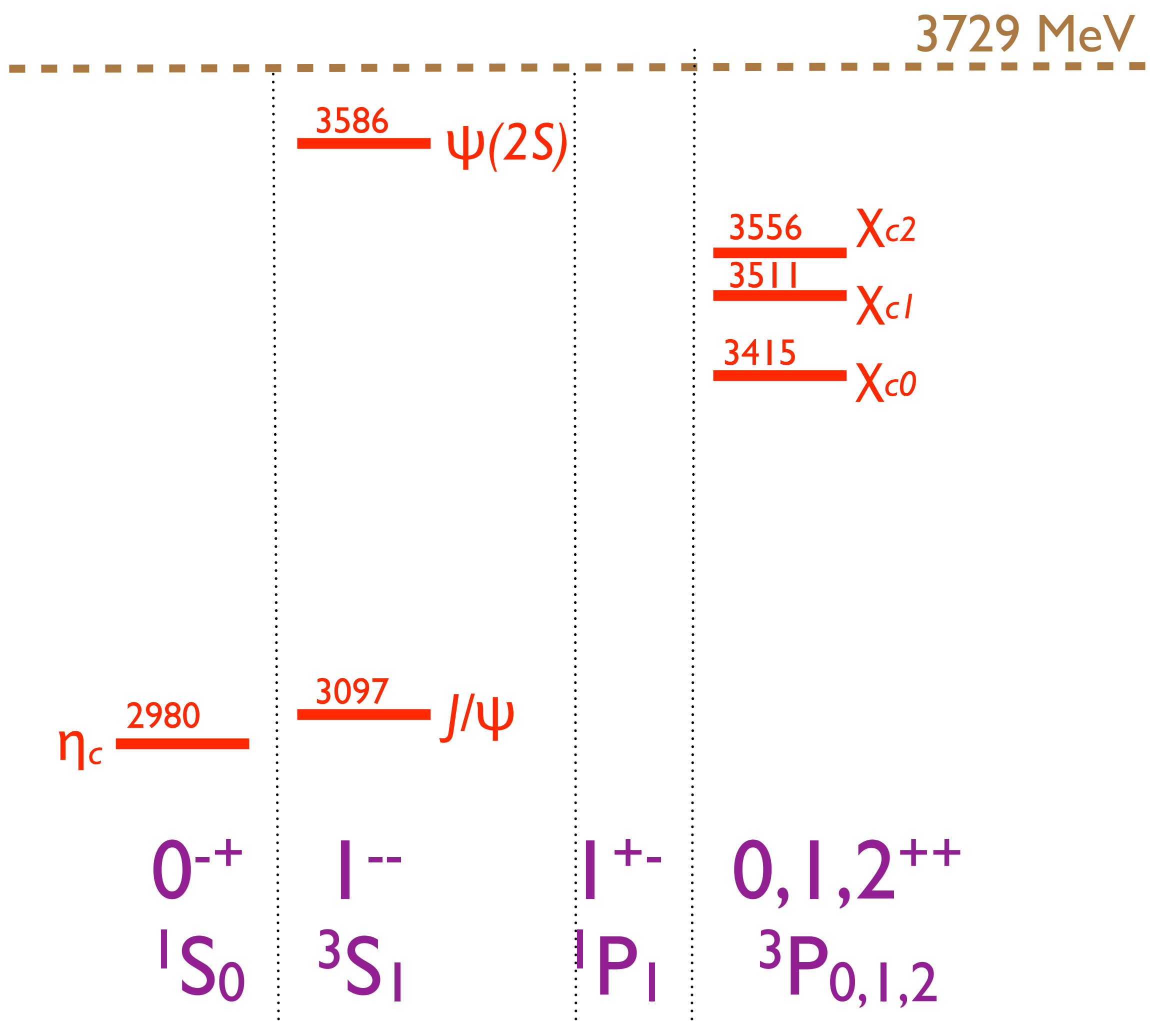
The Exotic *XYZ* Charmonium-like Mesons

Godfrey and Olsen arXiv:0801.3867

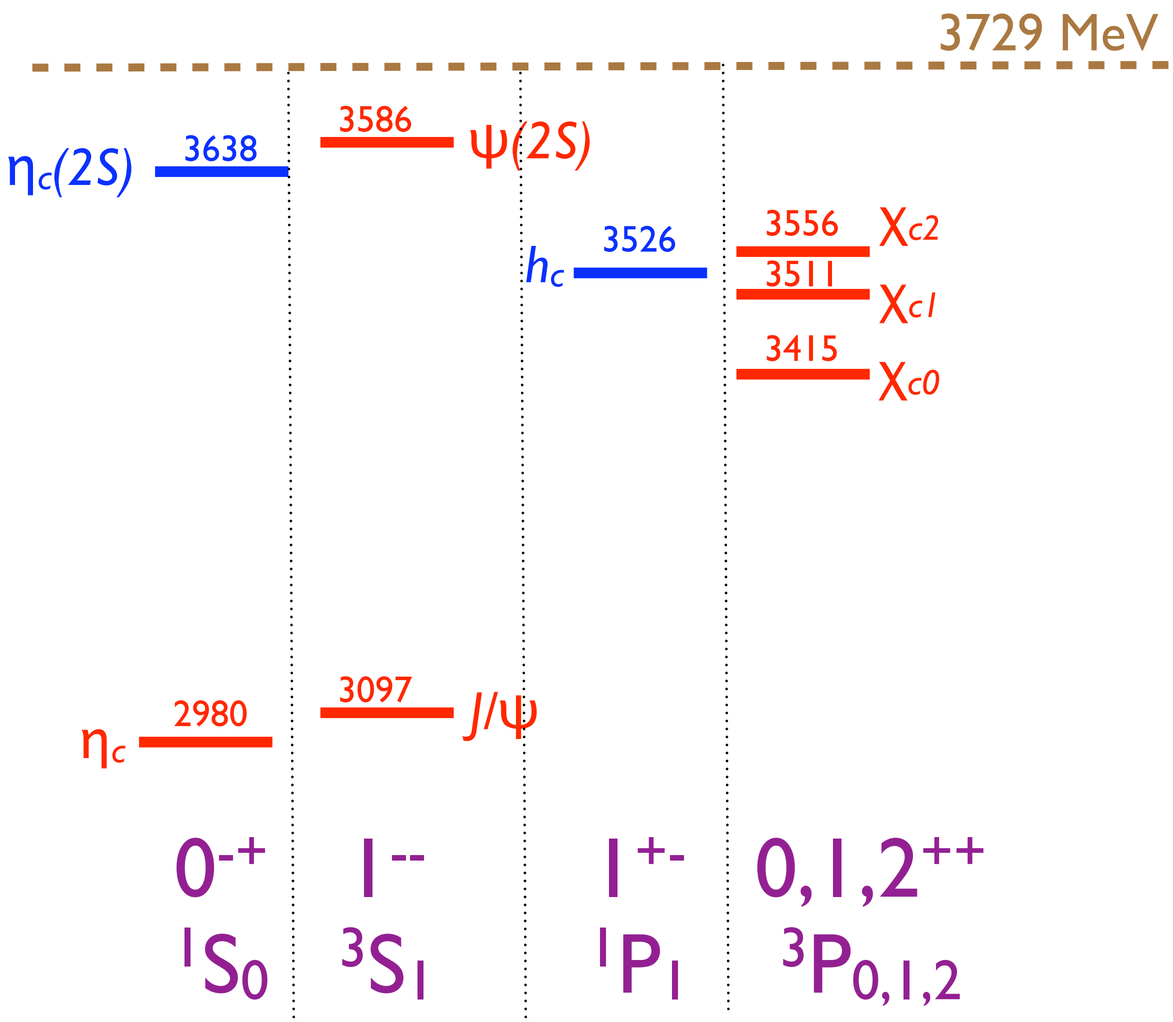
Quarkonium: puzzles and opportunities
at present and future facilities

Quarkonium Working Group (in preparation)

charmonium below the $D\bar{D}$ threshold before the B factories

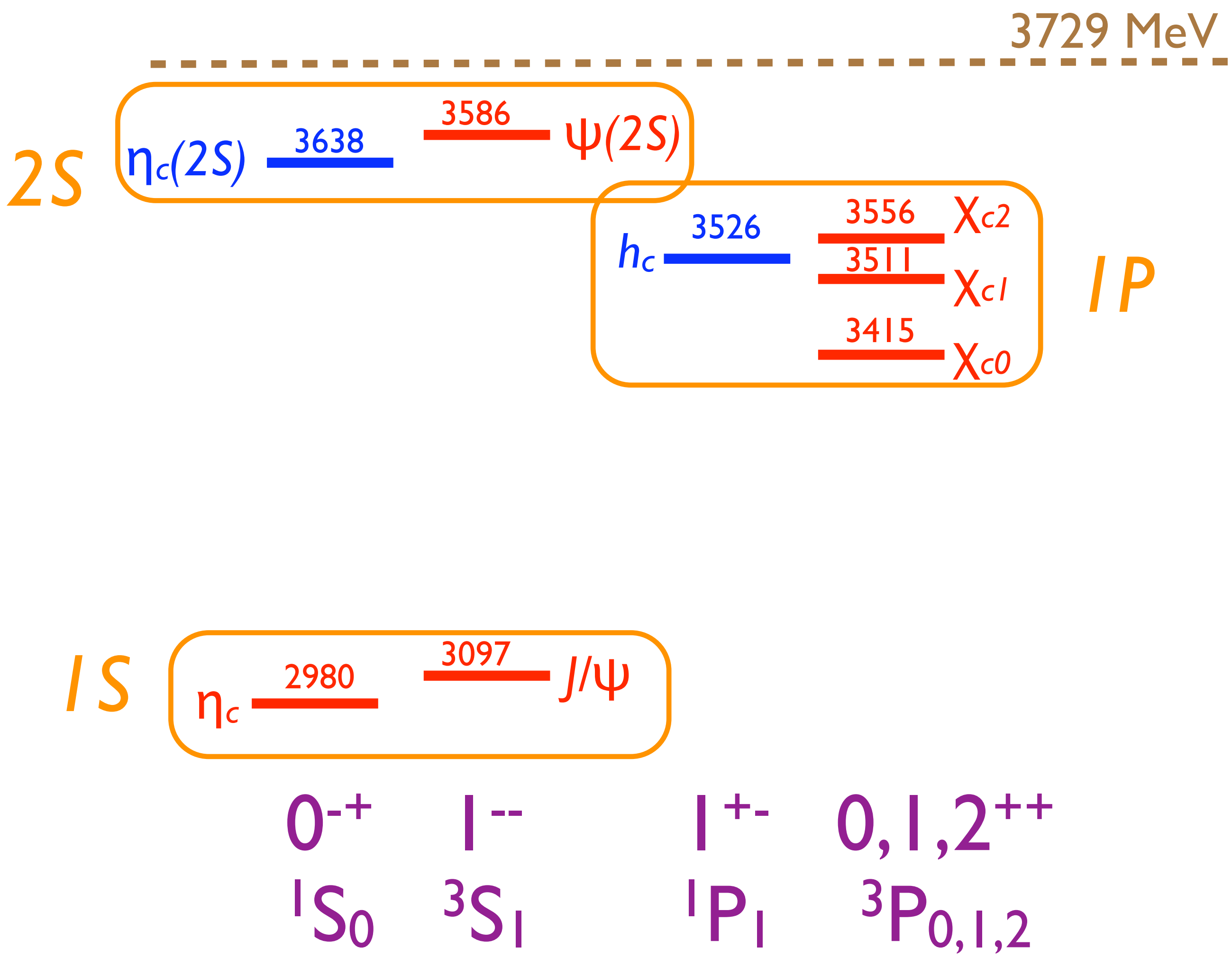


charmonium below the $D\bar{D}$ threshold after the B factories



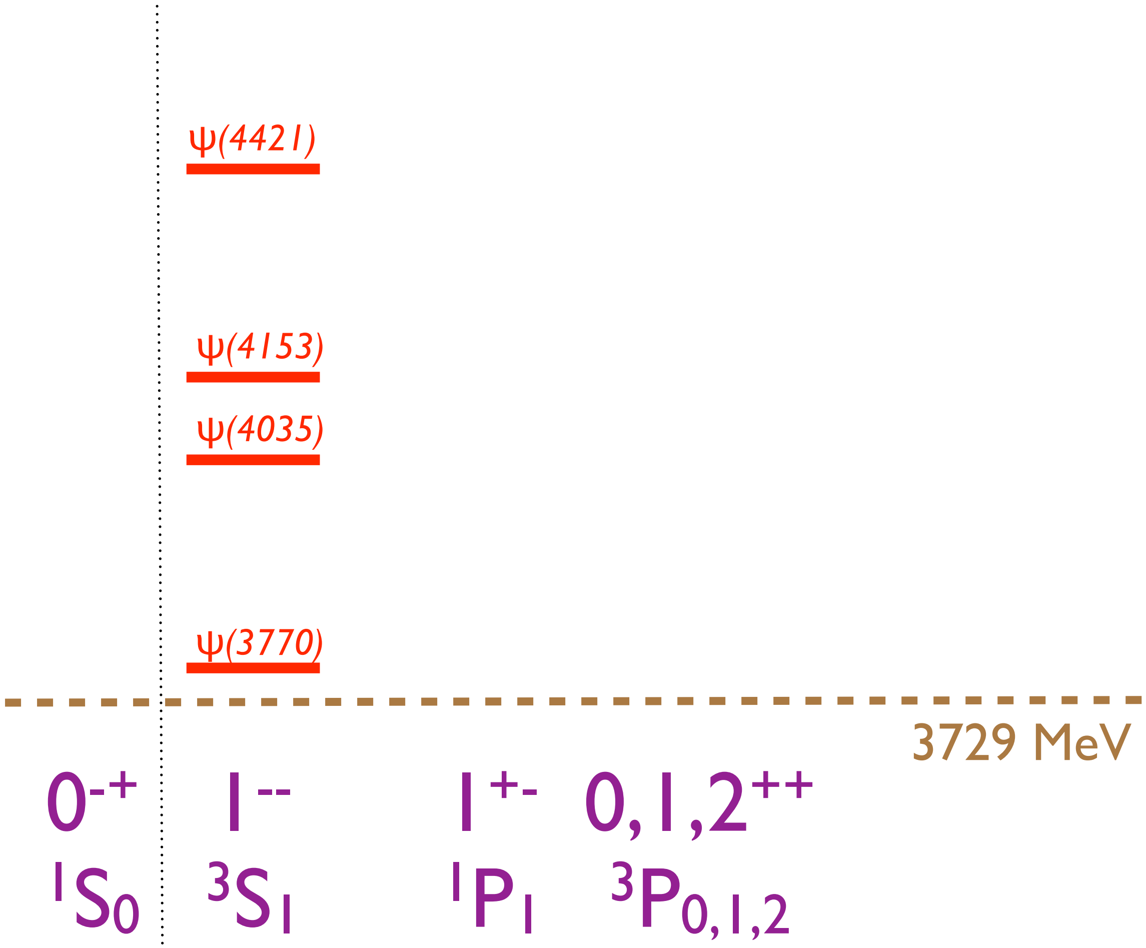
- 2 new states: $\eta_c(2S)$, $h_c(1P)$

charmonium below the $D\bar{D}$ threshold after the B factories



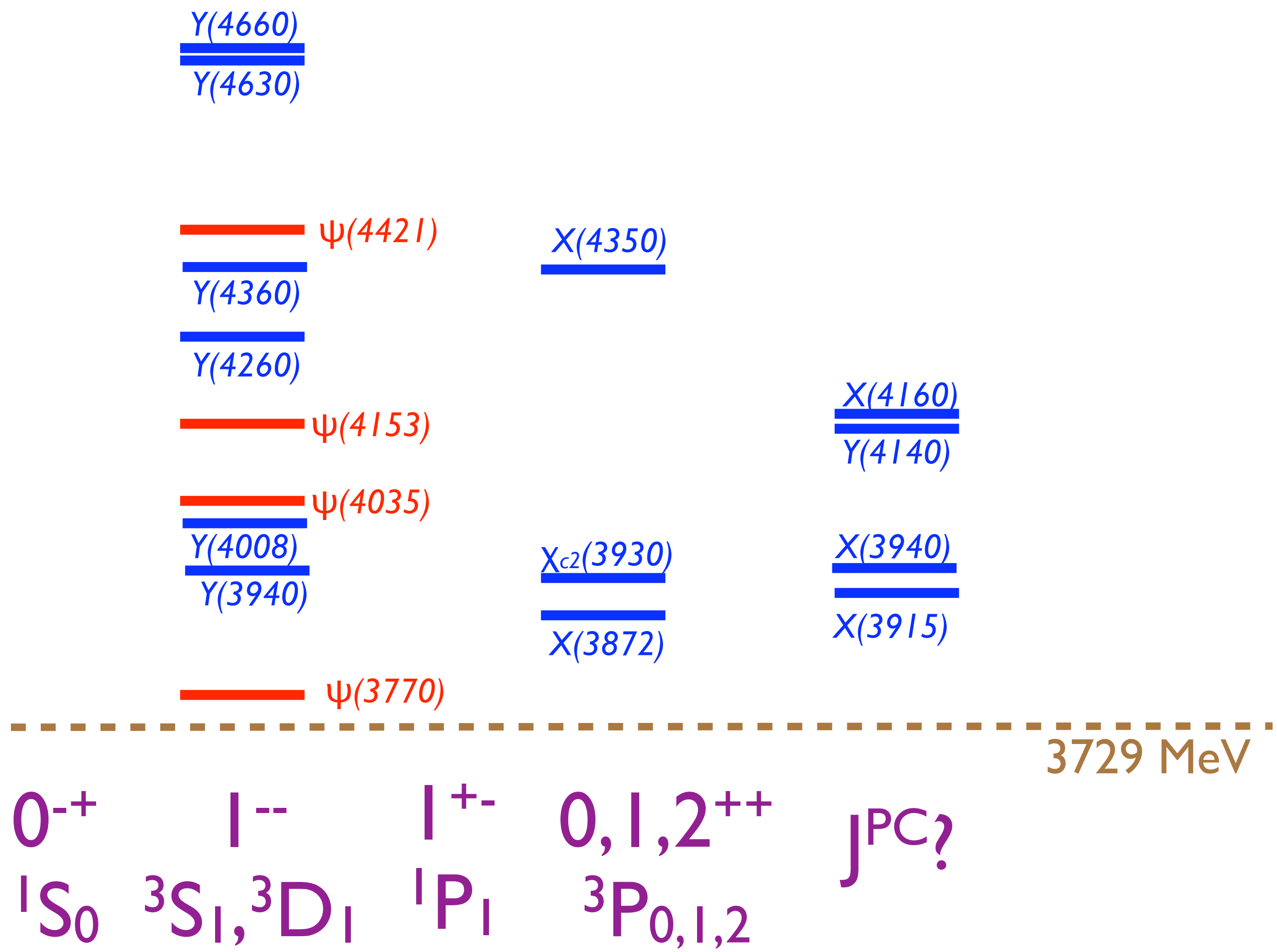
- 3 complete multiplets: *1S*, *1P*, *2S*

$c\bar{c}$ mesons above the $D\bar{D}$ threshold before the B factories



- four 1^{--} states

new $c\bar{c}$ mesons above the $D\bar{D}$ threshold after the B factories



- up to six new 1^{--} states
- up to seven additional states

new $c\bar{c}$ mesons with electric charge?

Belle 2007, 2008

$$Z(4430)^+ \rightarrow \psi(2S)\,\pi^+$$
$$Z_1(4050)^+ \rightarrow \chi_{c1}\,\pi^+$$
$$Z_2(4250)^+ \rightarrow \chi_{c1}\,\pi^+$$

- must have constituents $c\,\bar{c}\,u\,\bar{d}$
- $Z(4430)^+$ not confirmed by Babar
  (but not excluded)
- $\psi(2S)\,\pi^+$ can be observed at a hadron collider
  Tevatron, LHC

Wait and see!

13 new *neutral* $c\bar{c}$ mesons

- Discoveries

2003	2004	2005	2006	2007	2008	2009	2010
1	1	1	0	7	0	2	1

most recent: *Y(4140)* → *J*/ψ φ CDF

- Some have been confirmed

X(3872) Belle, CDF, D0, Babar
X(3915) Belle, Babar
Y(3940) Babar, Belle
Y(4260) Babar, CLEO, Belle
Y(4360) Babar, Belle

13 new *neutral* $c\bar{c}$ mesons

- *X(3872)* has been observed in 6 decay modes
  $J/\psi\ \pi^+\pi^-$, $J/\psi\ \pi^+\pi^-\pi^0$, $J/\psi\ \gamma$, $\psi(2S)\ \gamma$
  $D^0\bar{D}^0\pi^0$, $D^0\bar{D}^0\gamma$

- Most have been observed in only one decay mode
  X(3915) → $J/\psi\ \omega$
  X(3940), X(4160) → $D^*\bar{D}$
  Y(3940) → $D\bar{D}$
  Y(4008) → $J/\psi\ \pi^+\pi^-$
  Y(4140), X(4350) → $J/\psi\ \varphi$
  Y(4008), Y(4660) → $\psi(2S)\ \pi^+\pi^-$
  Y(4630) → $\Lambda_c^+\Lambda_c^-$

What are the new $c\bar{c}$ mesons above the $D\bar{D}$ threshold?

Ordinary mesons?

charmonium: $c\bar{c}$

Exotic mesons?

exotic quantum numbers?

0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, ...

exotic constituents?

charmonium hybrid: $c\bar{c}g$

tetraquark: $c\bar{c}q\bar{q}$

exotic structure: *X(3872)*!

Charmonium

Potential models

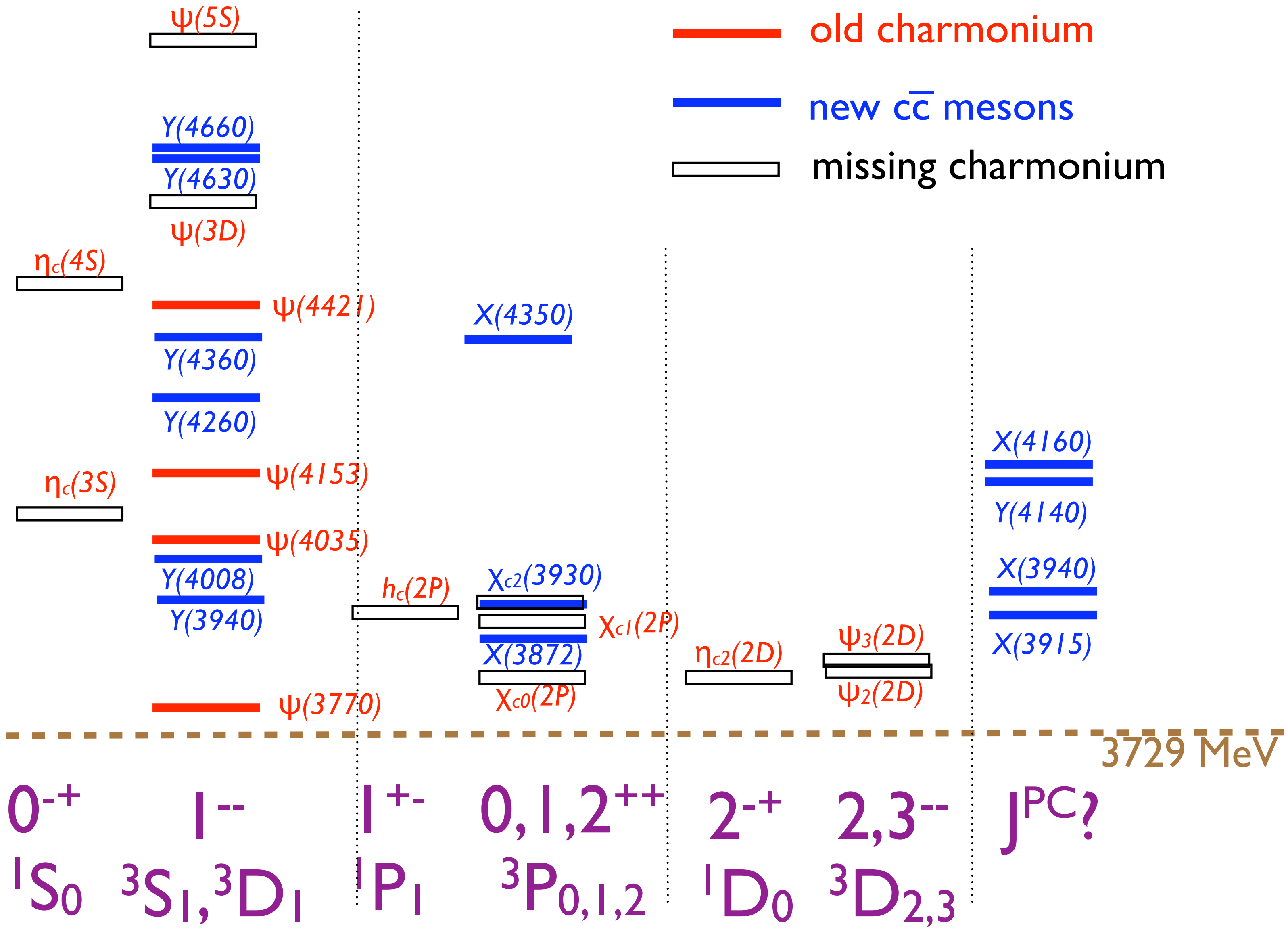
Barnes, Godfrey, & Swanson
Eichten, Lane, & Quigg
Eichten, Godfrey, Mahlke, & Rosner

well-developed phenomenology
(<u>except</u> for effects of couplings to charm meson pairs)
predictions of masses, widths
radiative transitions
hadronic transitions

Incomplete multiplets:		
	4S	~ 4400 MeV
	2D	~ 4200
	3S	~ 4000
	2P	~ 3900
	1D	~ 3800

Charmonium (cont.)

missing charmonium states



Charmonium (cont.)

- one new state identified: *Z(3930)* ≡ $\chi_{c2}(2P)$
  or is it $\chi_{c2}(1F)$?

- six new 1^{--} states: no plausible candidates

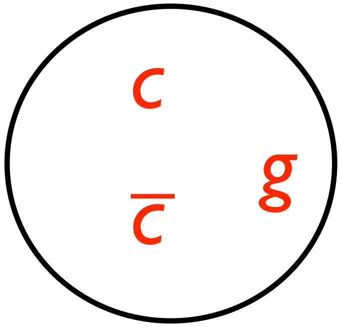
- 1^{++} state *X(3872)*: $\chi_{c1}(2P)$ is plausible candidate,
  but decay mode $J/\psi\ \pi^+\pi^- \approx J/\psi\ \rho^0$ has isospin 1

- states with unknown J^{PC}:
  plausible candidates, but decay patterns do not match

Charmonium hybrids

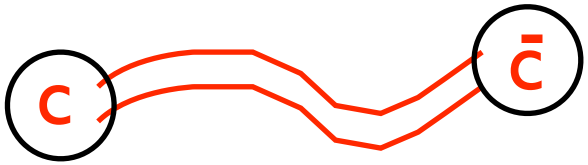
Constituent gluon model

bound state of $c\,\bar{c}\,g$



Flux-tube model

c and $\bar{c}$ connected by excited flux tube



Charmonium hybrids (cont.)

Quantum numbers

same as charmonium

plus exotic quantum numbers: 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, ...

Decays

Isgur, Kokowski, & Paton
Close & Page
Kuo & Pene

suppression of decays into $D^{(*)}\bar{D}^{(*)}$ (S-wave + S-wave)

preference for $D^{**}\bar{D}^{(*)}$ (P-wave + S-wave)

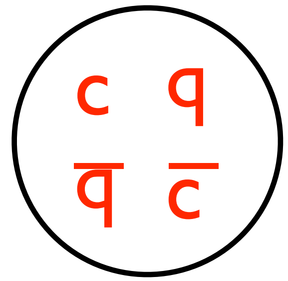
robust prediction?

Tetraquarks

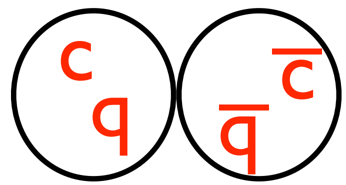
Constituent quark model: $c\bar{c}q\bar{q}$

Classify according to color structure

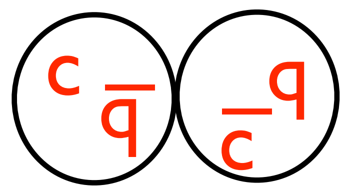
compact tetraquark: $(c\bar{c}q\bar{q})_1$



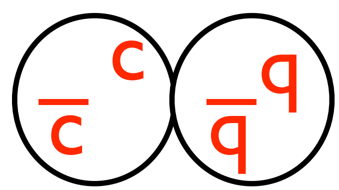
diquark-onium: $(cq)_{3^*} + (\bar{c}\bar{q})_3$
$(cq)_6 + (\bar{c}\bar{q})_{6^*}$



charm meson molecule: $(c\bar{q})_1 + (\bar{c}q)_1$



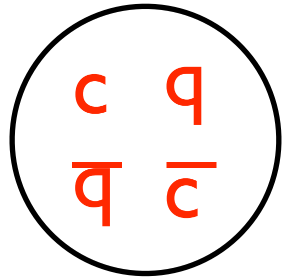
hadro-charmonium: $(c\bar{c})_1 + (q\bar{q})_1$



superposition of all the above?

Tetraquarks (cont.)

Compact tetraquarks



Constituent quark model: $c\bar{c}q\bar{q}$

exact numerical solution of the 4-body problem

Vijande, Valcarce, et al.

Hiyama, Suganama, & Kamimura

no stable $c\bar{c}q\bar{q}$ states

with only color-dependent 2-body forces

there are always lower energy two-meson states:

$$(c\bar{c})_1 + (q\bar{q})_1 \text{ or } (c\bar{q})_1 + (\bar{c}q)_1$$

metastable states above two-meson threshold?

strong correlations not describable by 2-body force?

Tetraquarks (cont.)

Diquark-onium

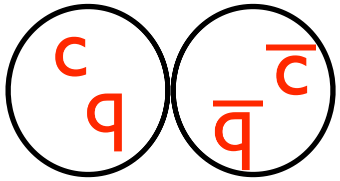
Maiani, Piccinini, Polosa, & Ricquer
Ishida, Ishida, & Maeda
Ebert, Faustov, & Galkin

constituent diquarks:
$$S = (cq)_{3^*, S=0}$$
$$A = (cq)_{3^*, S=1}$$

S-wave tetraquarks:
$$S\bar{S} : \quad 0^{++}$$
$$A\bar{S},\ S\bar{A} : \quad 1^{++},\ 1^{+-}$$
$$A\bar{A} : \quad 0^{++},\ 1^{+-},\ 2^{++}$$

flavor multiplets for each J^{PC}:
$$q = (u, d) \quad : \quad (X^-, X^0, X^+),\ X^{0\prime}$$
$$q = (u, d, s) : \quad 9 \text{ states}$$

Tetraquarks (cont.)



Diquark-onium

$(cq)_{3^*}$ diquarks

S-wave 6 x 9 = 54 states

$q=(u,d,s)$

plus orbital excitations?

radial excitations?

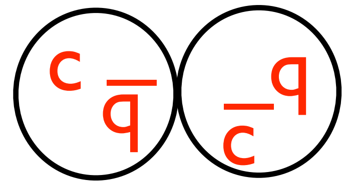
$(cq)_6$ diquarks?

proliferation of predicted states!

unknown dynamics $\Rightarrow$ few constraints

Tetraquarks (cont.)

Charm meson molecules



A. Meson potential models

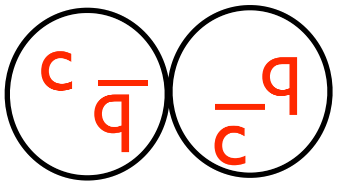
- one-pion exchange — Tornqvist 1991, 1993
  Liu, Liu, Deng, & Zhu 2008
  Thomas & Close 2008

- add quark exchange — Swanson 2003

- add heavier mesons: $\eta, \sigma, \rho, \omega$
  Ding, Liu, & Yan 2009

Tetraquarks (cont.)

Charm meson molecules



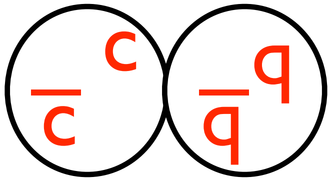
B. Meson scattering models

solve Lippman-Schwinger integral equations for scattering amplitudes

- charm mesons with contact interactions
- charm mesons with pion exchange
- more elaborate models (Oset, ...)

Tetraquarks (cont.)

Hadro-charmonium



Liu, Zeng, & Li 2005
Yuan, Wang, & Mo 2006
Guo, Hanhart, & Meissner 2008
Dubinskiy & Voloshin 2008

light hadron bound to a charmonium

$Y(4260) = \chi_{c1}\,\omega$?

$Y(4660) = \psi(2S)\,f_0$?

$Z^+(4430) = \psi(2S)\,\rho^+$?

Lattice QCD

pioneering calculations for charmonium, bottomonium
using nonrelativistic QCD
NRQCD collaboration (Davies, Lepage, Shigemitsu,...)
including dynamical light quarks
HPQCD collaboration (Davies, Lepage, Shigemitsu,...)

quantitative calculations require

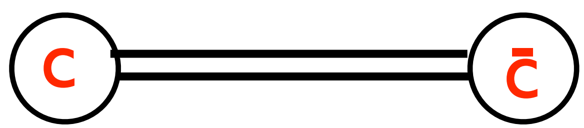
- extrapolation to zero lattice spacing ($a \to 0$)
- extrapolation to infinite volume ($V \to \infty$)
- dynamical light quarks
  (for correct running of α_s)
- extrapolation to physical pion mass

Born-Oppenheimer approximation

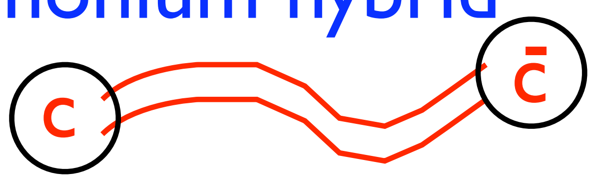
c and *c̄* move slowly in potential *V(r)*
V(r) = energy of gluon field
for static color sources separated by *r*
calculate *V(r)* using lattice QCD

c and *c̄* with gluon field ...

... in ground state: charmonium



... in excited state: charmonium hybrid



Lattice QCD (cont.)

lowest B-O potential: charmonium
potential model!

next lowest B-O potential: charmonium hybrids

9 degenerate
angular momentum multiplets:

0^{+-}	0^{-+}		
1^{-+}	1^{--}	1^{+-}	1^{++}
2^{+-}	2^{-+}		

exotic

higher B-O potentials not well-separated

with dynamical light quarks,
avoided crossings with meson-meson B-O potentials

Bali, Ehmann

Lattice QCD (cont.)

direct calculation of cc meson spectrum

charmonium hybrids (without dynamical light quarks)

	Liao & Manke 2002	Liu & Liu 2005
exotic!		
2^{+-}	4900 ± 90 MeV	
0^{+-}	4700 ± 170	4710 ± 150 MeV
1^{-+}	4430 ± 40	4410 ± 40
1^{--}		4400 ± 150
0^{-+}		4370 ± 150

Lattice QCD (cont.)

direct calculation of excited $c\bar{c}$ meson spectrum
charmonium and charmonium hybrids

one excited state (with dynamical light quarks)
Ehmann, Bali

several excited states (without dynamical light quarks)
Dudek, Edwards, Mathur, Richards
and radiative transition rates
Dudek, Edwards, Thomas

Lattice QCD is approaching the power required
to solve the $c\bar{c}$ meson puzzles!

X(3872)

discovered by Belle Collaboration in August 2003

$B^+ \rightarrow K^+ + X$ $\qquad$ $X \rightarrow J/\psi\, \pi^+ \pi^-$

confirmed by CDF Collaboration in November 2003

$p\,\bar{p} \rightarrow X$ + anything $\qquad$ $X \rightarrow J/\psi\, \pi^+ \pi^-$

other observed decay modes: $\qquad$ Belle, Babar

$J/\psi\, \pi^+ \pi^- \pi^0$ $\quad$ $J/\psi\, \gamma$ $\quad$ $D^0 \bar{D}^0 \pi^0$

$\psi(2S)\, \gamma$ (?) $\quad$ $D^0 \bar{D}^0 \gamma$

X(3872) (cont.)

1st of two crucial experimental inputs:

1. Quantum numbers: $J^{PC} = 1^{++}$

   a) decay into $J/\psi\ \gamma$

   $\Rightarrow$ $C=+$ — Belle, Babar

   b) momentum distributions for $J/\psi\ \pi^+\pi^-$

   $\Rightarrow$ $J^P = 1^+$ or 2^- — Belle, CDF

   c) decay into $D^0\bar{D}^0\pi^0$

   $\Rightarrow$ $J^P = 2^-$ disfavored — Belle, Babar

$\Rightarrow$ *X(3872)* has S-wave coupling to $D^{*0}\bar{D}^0$

X(3872) (cont.)

2nd of two crucial experimental inputs:

2. Mass: M_X = *3871.52 ± 0.20* MeV
   measured in $J/\psi\ \pi^+\pi^-$ channel CDF, Belle, Babar, D0

   Mass relative to $D^{*0}\bar{D}^0$ threshold:
   $-E_X$ = *-0.42 ± 0.39* MeV

⇒ *X(3872)* has <u>resonant</u> coupling to $D^{*0}\bar{D}^0$

X(3872) (cont.)

Two crucial experimental inputs:

1. Quantum numbers: $J^{PC} = 1^{++}$
   ⇒ *X(3872)* has <u>S-wave</u> coupling to $D^{*0}\bar{D}^0$
2. Binding energy: $E_X = 0.42 \pm 0.39$ MeV
   ⇒ *X(3872)* has <u>resonant</u> coupling to $D^{*0}\bar{D}^0$

Quantum mechanics:
S-wave threshold resonances have universal properties
determined by large scattering length

<u>Conclusion</u>: *X(3872)* is charm meson molecule

$$X = \frac{1}{\sqrt{2}}\left(D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}\right)$$

with universal properties

X(3872) (cont.)

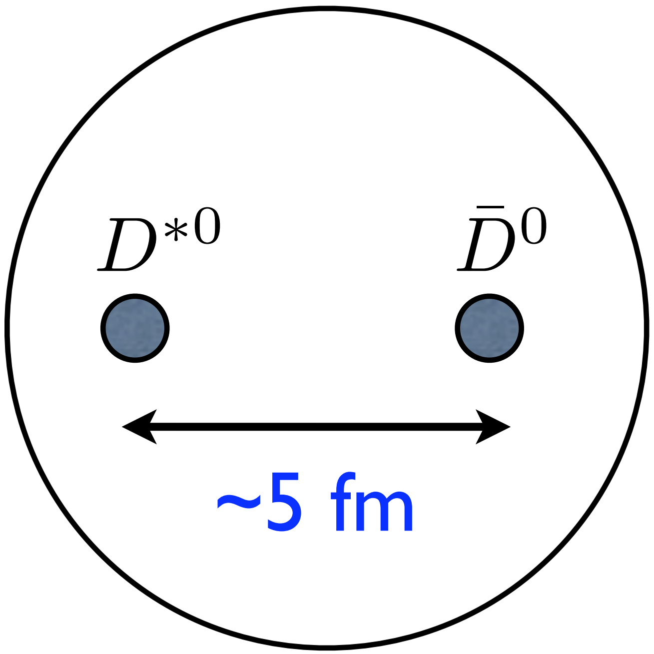
Universal properties
of an S-wave threshold resonance:
binding energy E_X and rms separation r_X

$$E_X = \hbar^2/(4\mu r_X^2)$$

Apply to *X(3872)*:

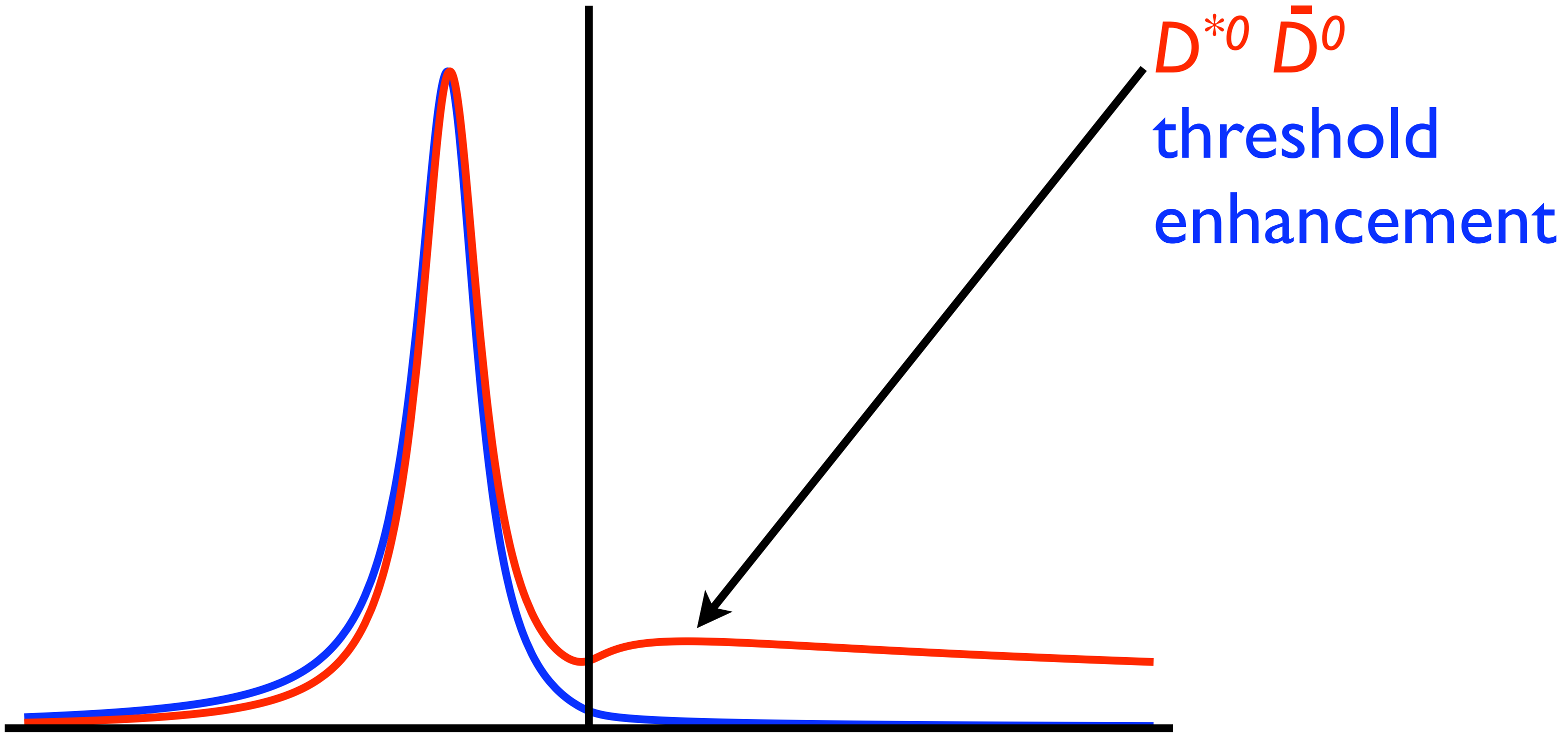
E_X = 0.42 +/- 0.39 MeV

$\Rightarrow$ r_X = $4.9^{+13.4}_{-1.4}$ fm



X(3872) (cont.)

Universal line shapes in $J/\psi\ \pi^+\pi^-$ and $\bar{D}^0 D^0 \pi^0$



Measurements in $D^0\bar{D}^0\pi^0$ channel
are <u>NOT</u> measurements of mass and width of *X(3872)*!

X(3872) (cont.)

Changes in PDG listing for *X(3872)* in 2010

PDG averages 2008, 2009

Mass: 3872.3 ± 0.8 MeV
Width: $3.4^{+2.1}_{-1.7}$ MeV
combine inconsistent measurements
from $J/\psi\ \pi^+\pi^-$ and $D^0\bar{D}^0\pi^0$ channels

PDG averages 2010

Mass: 3871.56 ± 0.22 MeV
Width: < 2.3 MeV at 90% C.L.
from measurements in $J/\psi\ \pi^+\pi^-$ channel only

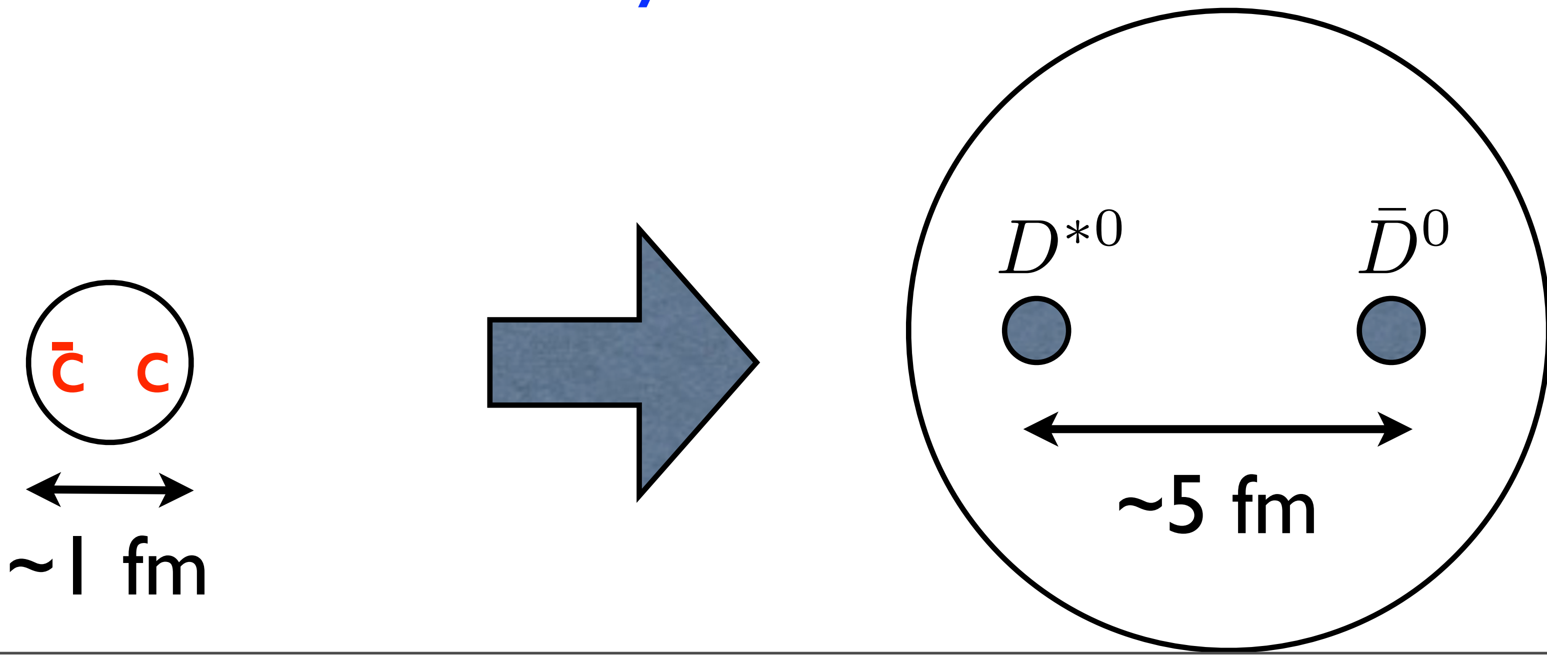
X(3872) (cont.)

How does $X(3872)$ connect to other puzzle pieces?

It depends on mechanism for $X(3872)$

- $\chi_{c1}(2P)$ with mass is accidentally near $D^{*0}\bar{D}^0$ threshold?
- $D^{*0}D^0$ potential near critical depth for bound state?

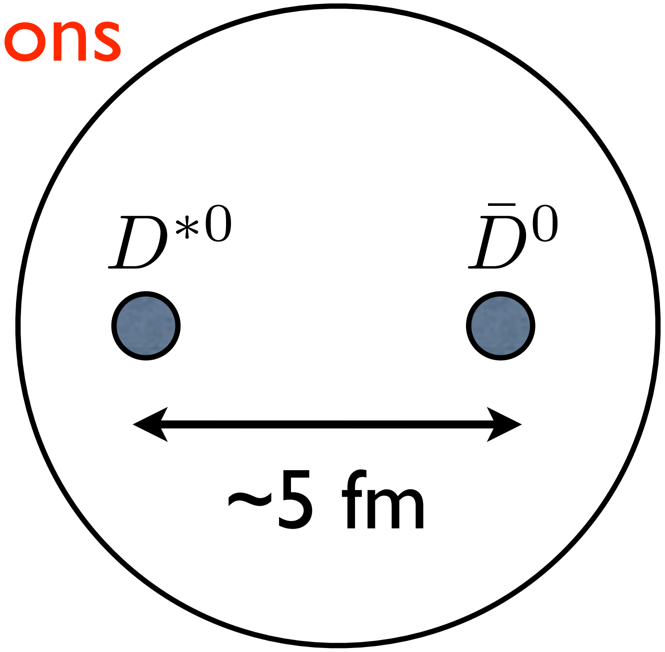
either way, resonant interactions with $D^{*0}D^0$ transform it into a loosely-bound charm meson molecule



Conclusions

One piece of the puzzle can be identified!

X(3872) is a charm meson molecule with large separation between charm mesons



But it has not been connected to any other pieces!

Does *X(3872)* exist because

- the $\chi_{c1}(2P)$ is near the $D^{*0}\bar{D}^0$ threshold?
- the $D^{*0}\bar{D}^0$ interaction is near the critical strength for bound state?

Conclusions (cont.)

Z(3930) has been identified as $\chi_{c2}(2P)$

None of the other pieces of the puzzle
has been identified!

Are they ordinary charmonium?
charmonium hybrids?
charm meson molecules?
experimental artifacts?
something else?

Conclusions (cont.)

To solve the puzzle, what is needed from theory is

definitive lattice QCD calculations of
cc meson spectrum and properties

- without dynamical quarks
  extrapolate to $a \to 0$, $V \to \infty$

- with dynamical quarks
  extrapolate to $a \to 0$, $V \to \infty$, $m_\pi \to$ physical mass

systematic theoretical treatment
of nearby charm meson thresholds

Conclusions (cont.)

To solve the puzzle,
what is needed from experiment is

- more pieces of the puzzle
- J^{PC} for existing pieces

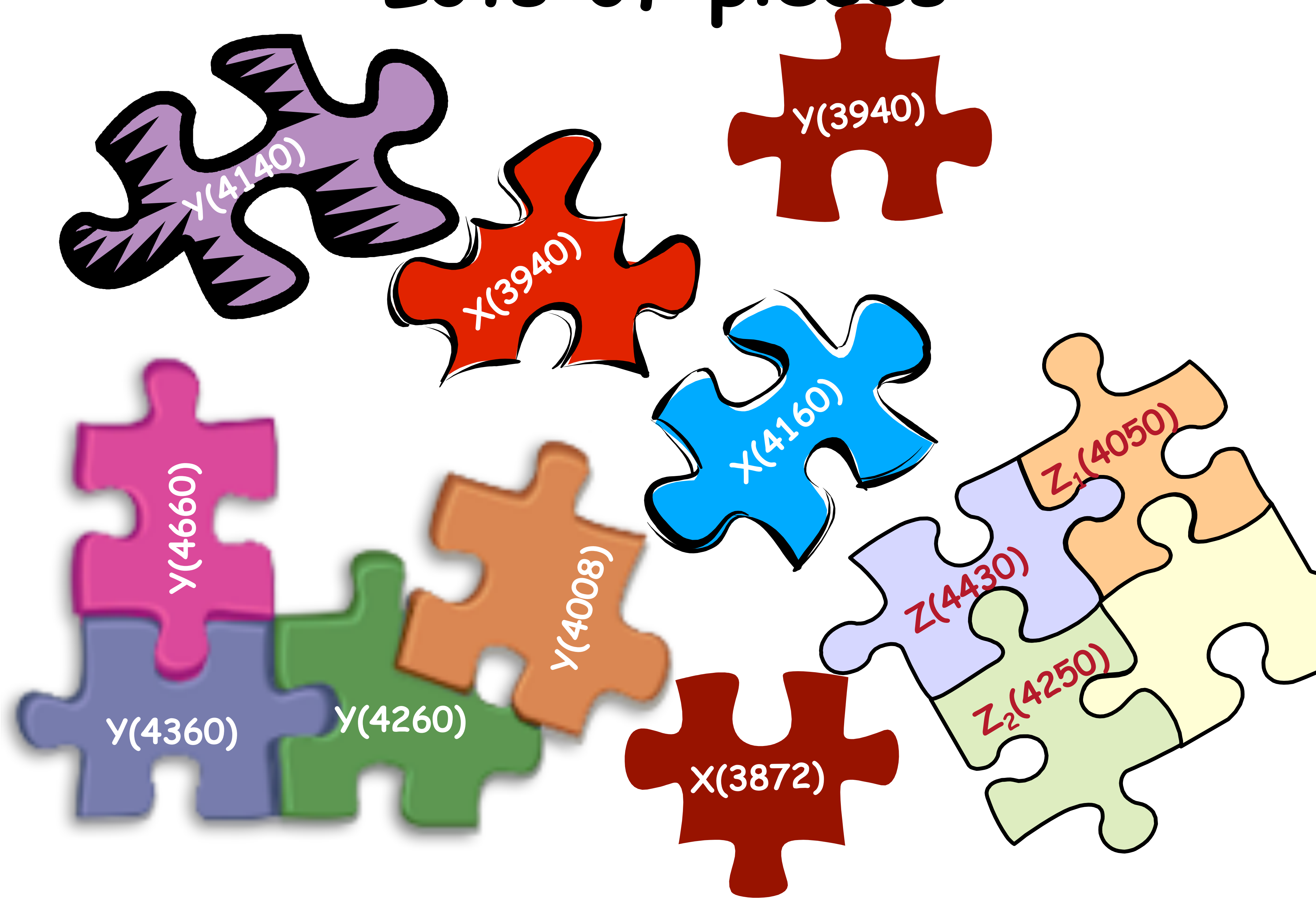
from experiments at

LHC-B
super-B factory
PANDA
Fermilab E-986?

antiproton annihilation experiment
needs collaborators: contact Dan Kaplan (IIT)
needs jazzier name: FANTASTIC?

(Fermilab ANTiproton Annihilation Spectrometer To Investigate Charmonium)

Lots of pieces



Lots of pieces