How the $Z_c(3900)$ Reveals the Spectra of Quarkonium Hybrid and Tetraquark Mesons

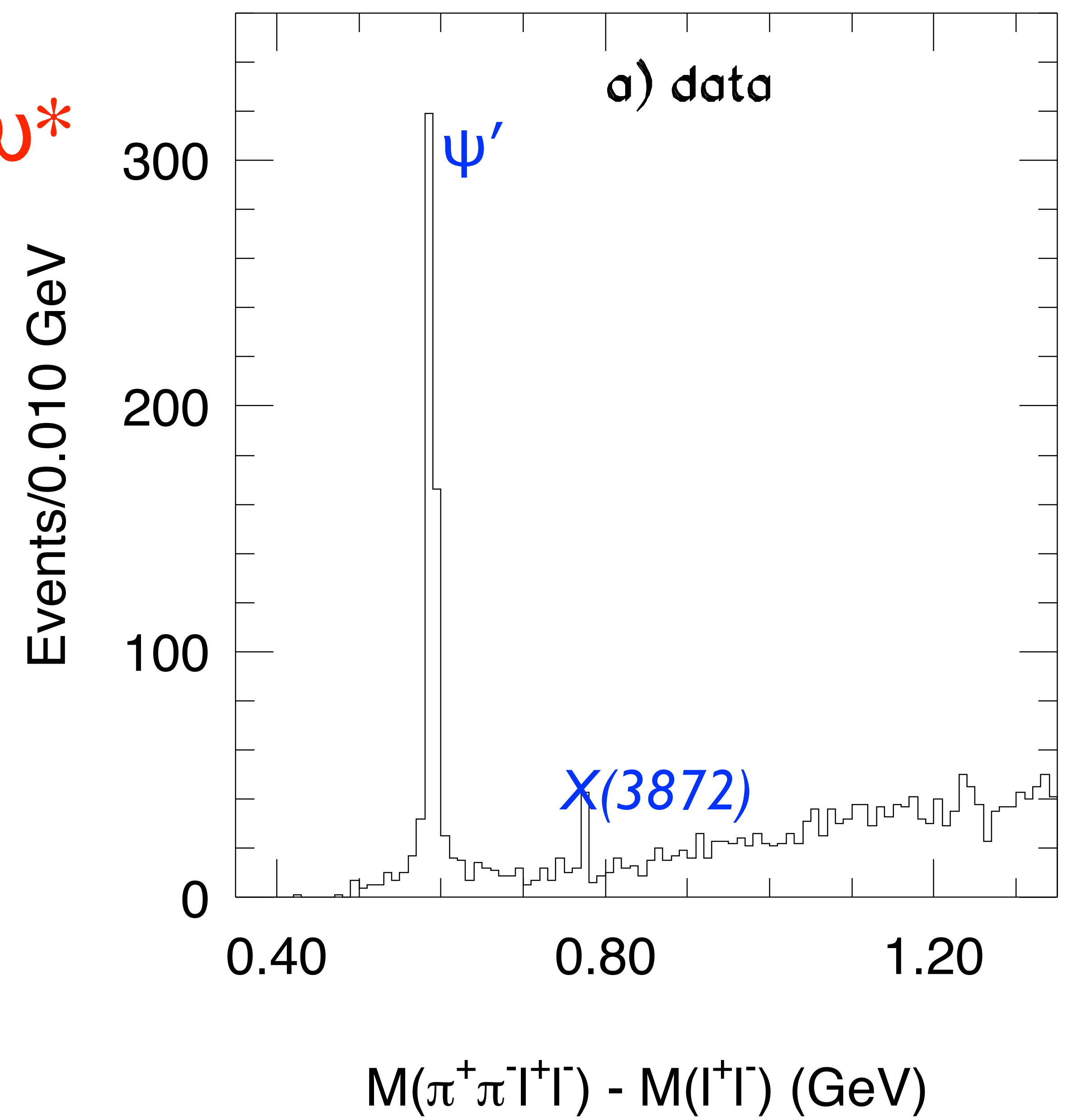
arXiv:1305.6905

Eric Braaten
Ohio State University

Unexpected $c\bar{c}$ Mesons!

X(3872) Belle 2003

- isospin-violating decays
  into $J/\psi\ \rho^*$ and $J/\psi\ \omega^*$
- extremely close to
  $D^{*0}\bar{D}^0$ threshold

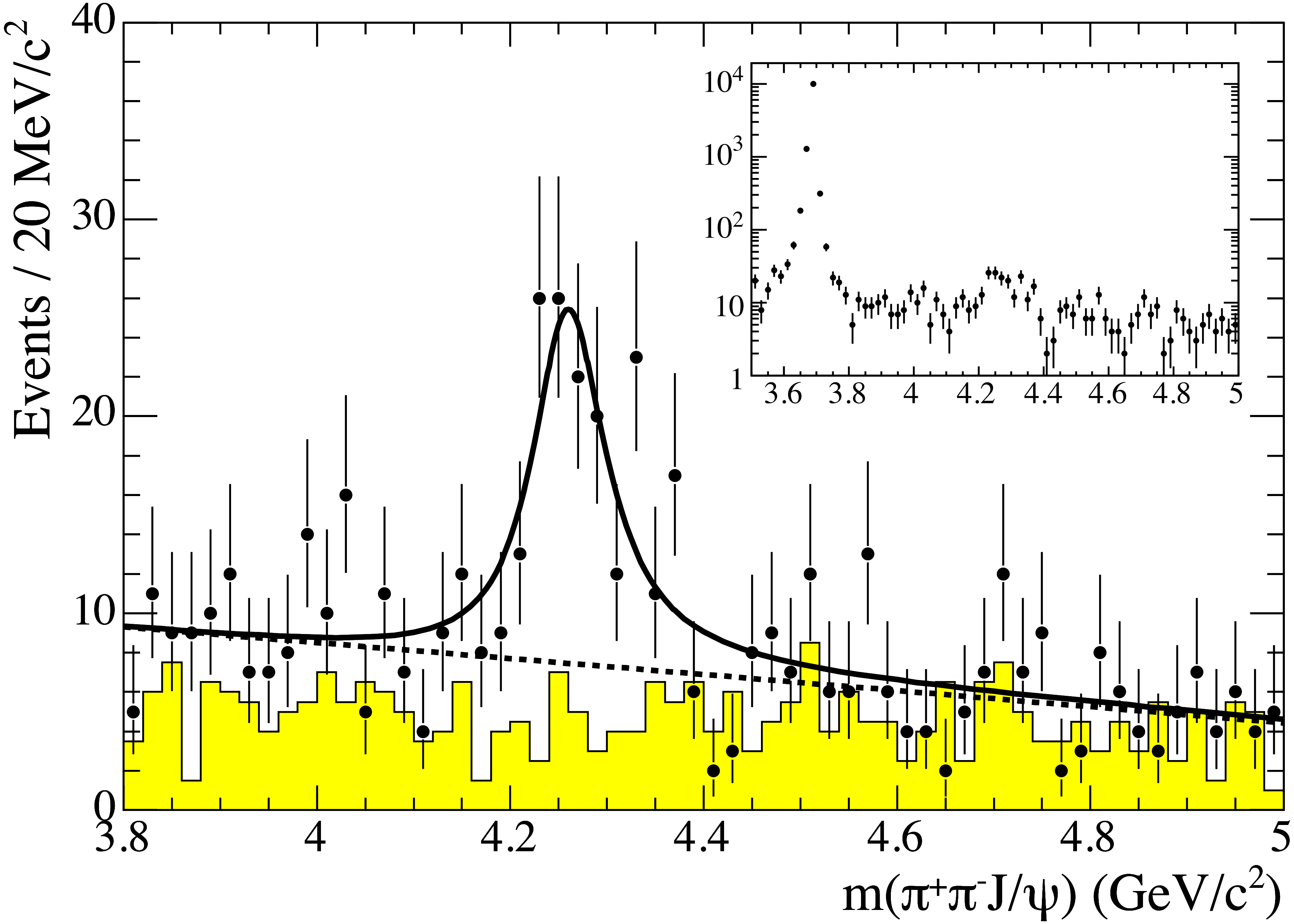


Unexpected $c\bar{c}$ Mesons!

Y(4260)

Babar 2005

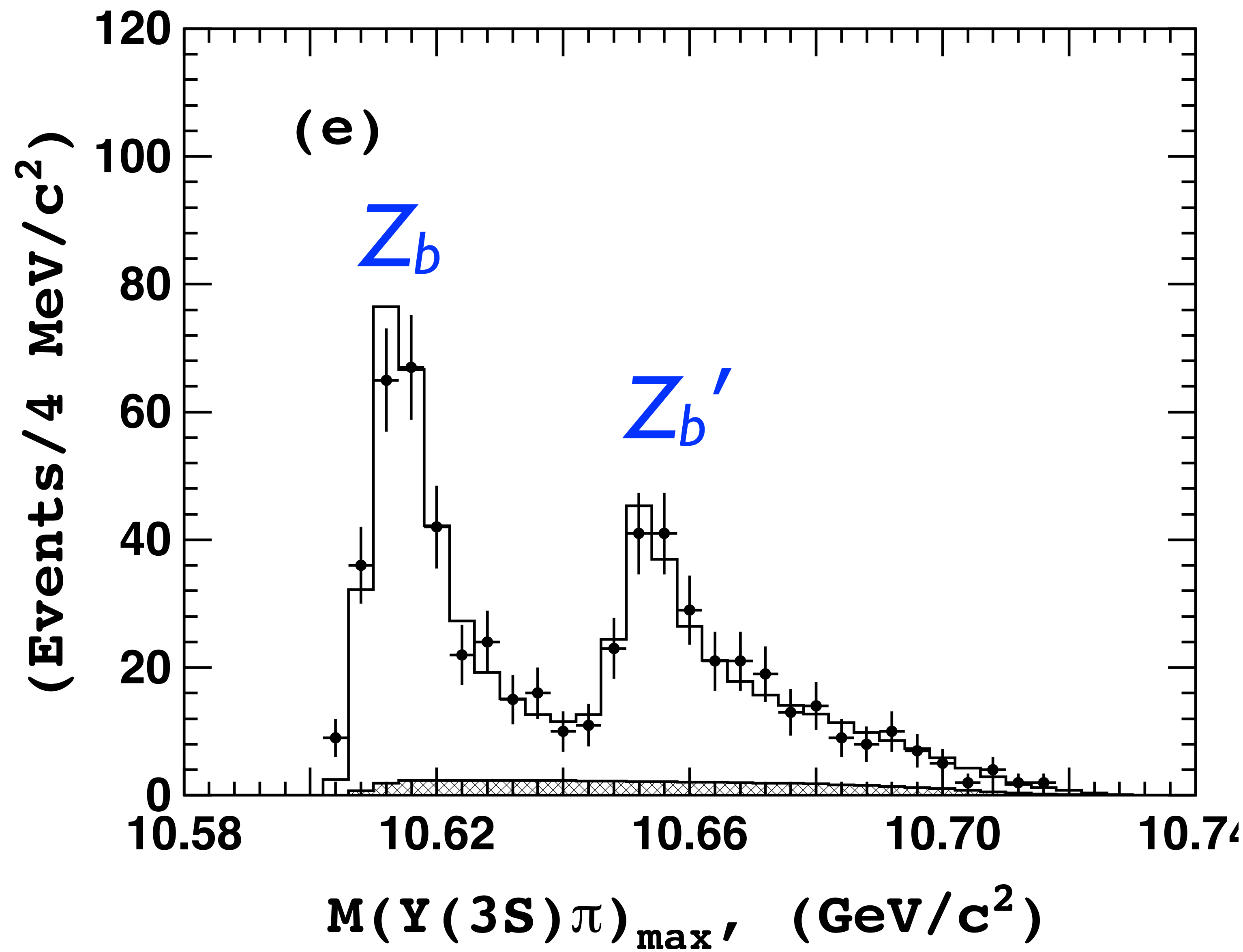
1^{--} but produced very weakly in e^+e^- annihilation



First Tetraquark $b\bar{b}$ Mesons!

$Z_b^+(10610)$, $Z_b^+(10650)$ Belle 2010

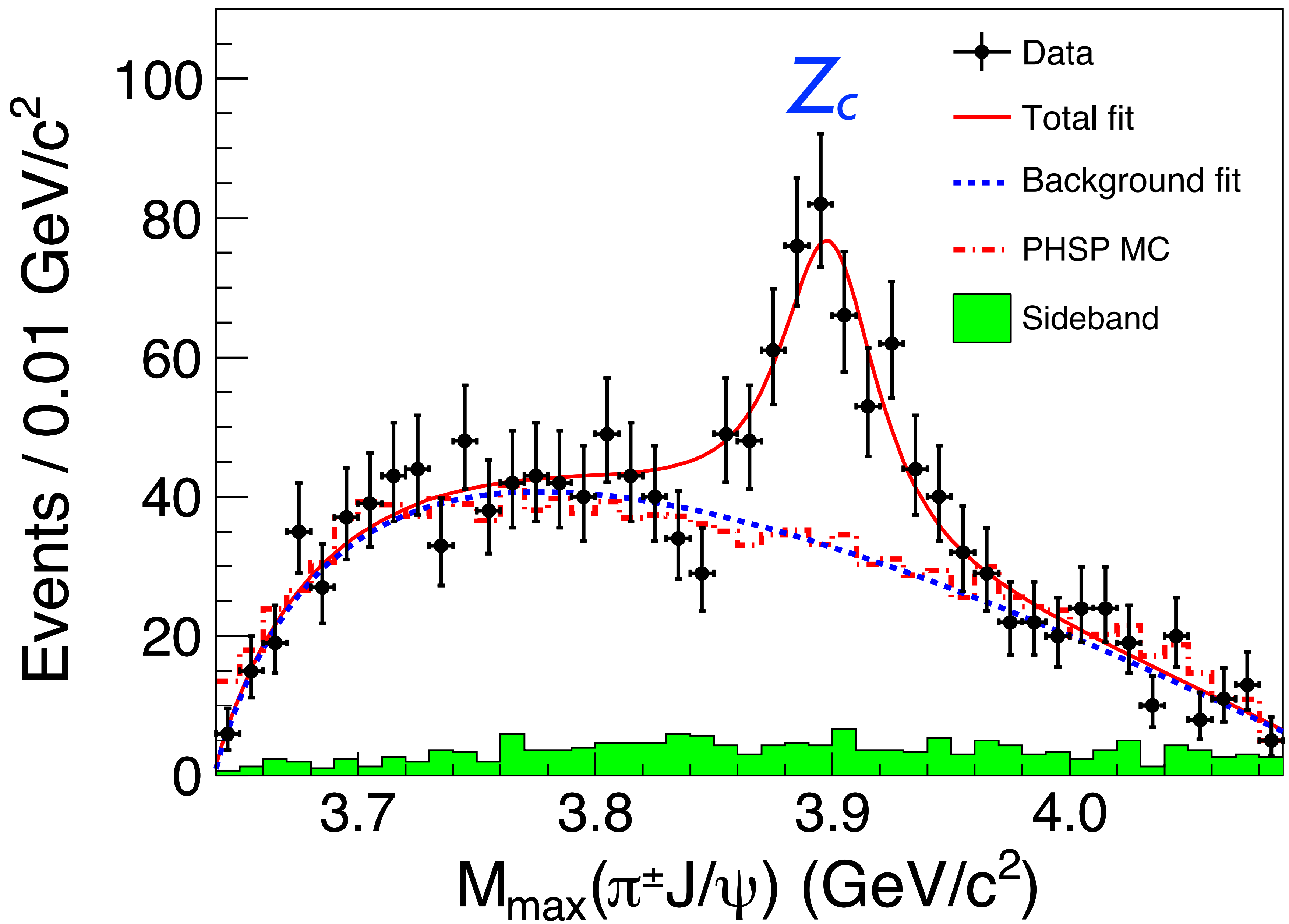
decays into $\Upsilon\pi^+$ reveal constituents: $b\,\bar{b}\,u\,\bar{d}$



First Tetraquark $c\bar{c}$ Mesons!

$Z_c^+(3900)$ BESIII 2013

decays into $J/\psi\ \pi^+$ reveal constituents: $c\ \bar{c}\ u\ \bar{d}$



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

TABLE I:

State	M (MeV)	Γ (MeV)	J^{PC}	Decay modes	1st observation
neutral $c\bar{c}$ mesons					
$X(3823)$	3823.1 ± 1.9	< 24	$?^{?-}$	$\chi_{c1}\gamma$	Belle 2013
$\boldsymbol{X(3872)}$	3871.68 ± 0.17	< 1.2	1^{++}	$J/\psi\,\pi^+\pi^-$, $J/\psi\,\pi^+\pi^-\pi^0$ $D^0\bar{D}^0\pi^0$, $D^0\bar{D}^0\gamma$ $J/\psi\,\gamma$, $\psi(2S)\,\gamma$	Belle 2003
$\boldsymbol{X(3915)}$	3917.5 ± 1.9	20 ± 5	0^{++}	$J/\psi\,\omega$	Belle 2004
$\boldsymbol{\chi_{c2}(2P)}$	3927.2 ± 2.6	24 ± 6	2^{++}	$D\bar{D}$	Belle 2005
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$D^*\bar{D}$	Belle 2007
$\boldsymbol{G(3900)}$	3943 ± 21	52 ± 11	1^{--}	$D\bar{D}$	*BABAR* 2007
$Y(4008)$	$4008^{+121}_{-\ 49}$	226 ± 97	1^{--}	$J/\psi\,\pi^+\pi^-$	Belle 2007
$\boldsymbol{Y(4140)}$	4144.5 ± 2.6	$15^{+11}_{-\ 7}$	$?^{?+}$	$J/\psi\,\phi$	CDF 2009
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$D^*\bar{D}^*$	Belle 2007
$\boldsymbol{Y(4260)}$	4263^{+8}_{-9}	95 ± 14	1^{--}	$J/\psi\,\pi^+\pi^-$, $J/\psi\,\pi^0\pi^0$ $Z_c(3900)\,\pi$	*BABAR* 2005
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$J/\psi\,\phi$	CDF 2010
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$J/\psi\,\phi$	Belle 2009
$\boldsymbol{Y(4360)}$	4361 ± 13	74 ± 18	1^{--}	$\psi(2S)\,\pi^+\pi^-$	*BABAR* 2007
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$	Belle 2007
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\psi(2S)\,\pi^+\pi^-$	Belle 2007
charged $c\bar{c}$ mesons					
$\boldsymbol{Z_c^+(3900)}$	3898 ± 5	51 ± 19	$1^{?-}$	$J/\psi\,\pi^+$	BESIII 2013
$Z_c^+(4020)$	4021.8 ± 2.7	5.7 ± 3.6	?	$h_c(1P)\,\pi^+$, $D^*\bar{D}^*$	BESIII 2013
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$\chi_{c1}(1P)\,\pi^+$	Belle 2008
$Z_2^+(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$\chi_{c1}(1P)\,\pi^+$	Belle 2008
$Z^+(4430)$	4443^{+24}_{-18}	$107^{+113}_{-\ 71}$	?	$\psi(2S)\,\pi^+$	Belle 2007

New $b\bar{b}$ Mesons above $B\bar{B}$ threshold

TABLE I:

State	M (MeV)	Γ (MeV)	J^{PC}	Decay modes	1st observation
neutral $b\bar{b}$ mesons					
$Y_b(10888)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$\Upsilon(nS)\,\pi^+\pi^-$ $Z_b^+(10610)\,\pi,\ Z_b^+(10610)\,\pi$	Belle 2010
charged $b\bar{b}$ mesons					
$Z_b^+(10610)$	10607.2±2.0	18.4±2.4	1^{+-}	$\Upsilon(nS)\,\pi^+,\ h_b(nP)\,\pi^+$	Belle 2011
$Z_b^+(10650)$	10652.2±1.5	11.5±2.2	1^{+-}	$\Upsilon(nS)\,\pi^+,\ h_b(nP)\,\pi^+$	Belle 2011

many unexpected neutral $Q\bar{Q}$ mesons
several charged tetraquark $Q\bar{Q}$ mesons
many of them are narrow

a major challenge to our understanding
of the QCD spectrum!

Possibilities for new $Q\bar{Q}$ Mesons

- quarkonium $(Q\bar{Q})$
- quarkonium hybrid $(Q\,\bar{Q}\,g)$
- meson molecule $(Q\bar{q}) = (q\bar{Q})$
- compact tetraquark $(Q\,\bar{q}\,q\,\bar{Q})$
- diquark-onium $(Qq) = (\bar{q}\bar{Q})$
- hadro-quarkonium $(q\,(Q\bar{Q})\,\bar{q})$

New suggestion: Born-Oppenheimer tetraquark!

QCD Theory Approaches

- Lattice QCD for charmonium
- Lattice NRQCD for bottomonium
- Born-Oppenheimer approximation for charmonium and bottomonium

Lattice QCD for charmonium

Dudek, Edwards, Mathur, Richards 2007
Hadron Spectrum Collaboration 2012

- anisotropic lattice: $24^3 \times 128$
- lattice spacing: $a = 0.12$ fm
- light quark masses: $m_\pi = 400$ MeV

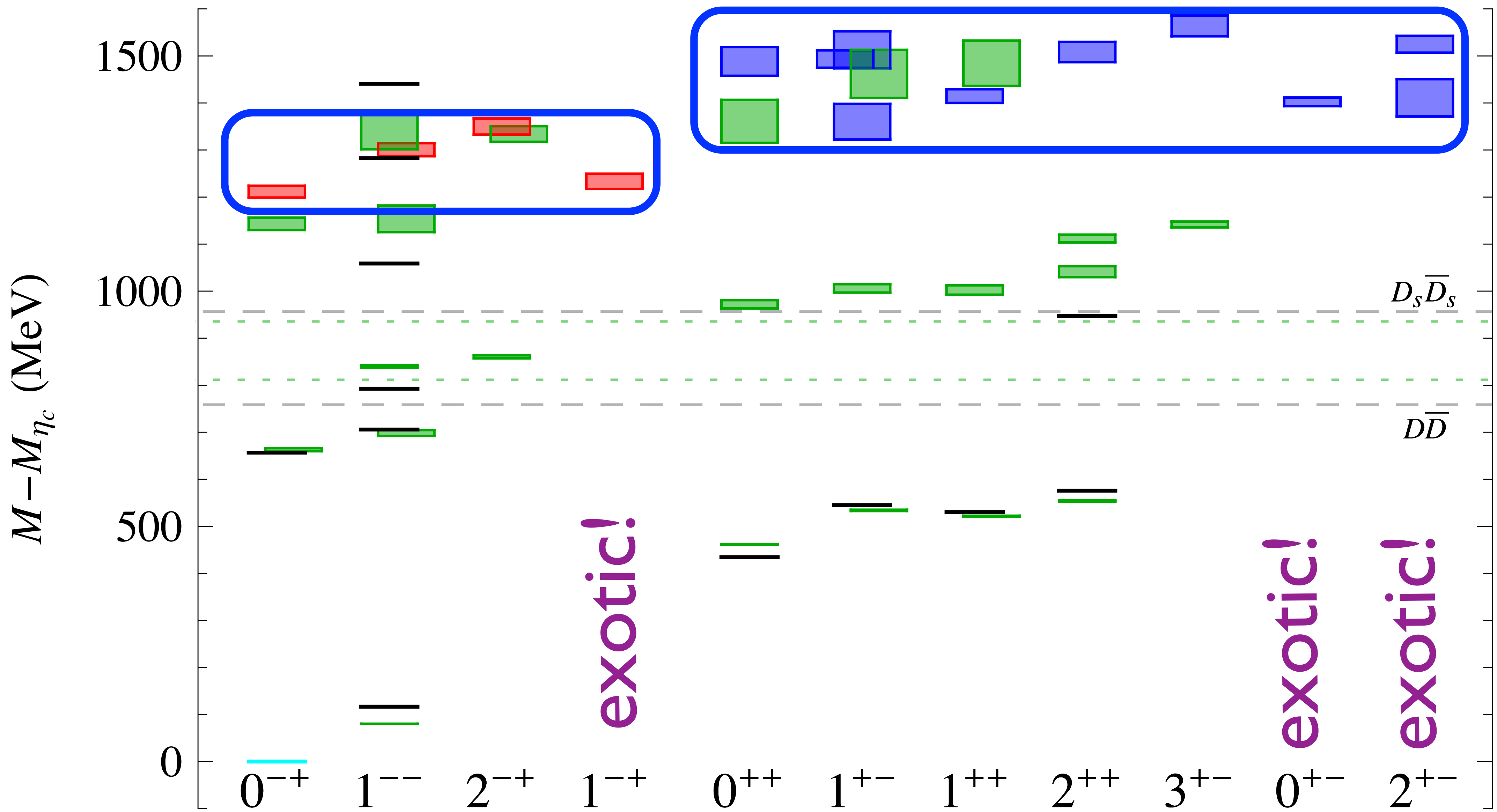
caveat: no extrapolation to physical m_π
no extrapolation to $a = 0$

- determine masses of charmonium and charmonium hybrids
from cross-correlators of many operators

- identify 46 states with various J^{PC}:
J up to 4, M up to 4.6 GeV

Lattice QCD for charmonium

Hadron Spectrum Collaboration 2012



charmonium hybrid candidates

$\{1^{--}, (0,1,2)^{-+}\}$

$\{2^{++}, (1,2,3)^{+-}\}$
$\{0^{++}, 1^{+-}\}$
$\{1^{++}, (0,1,2)^{+-}\}$

Charmonium Hybrids

- Lattice QCD predicts one 1^{--} charmonium hybrid
- identify that state as *Y(4260)*
- assume extrapolations to $a = 0$ and to physical m_π have small effects on mass splittings
- predict spectrum of charmonium hybrids

ground-state multiplet

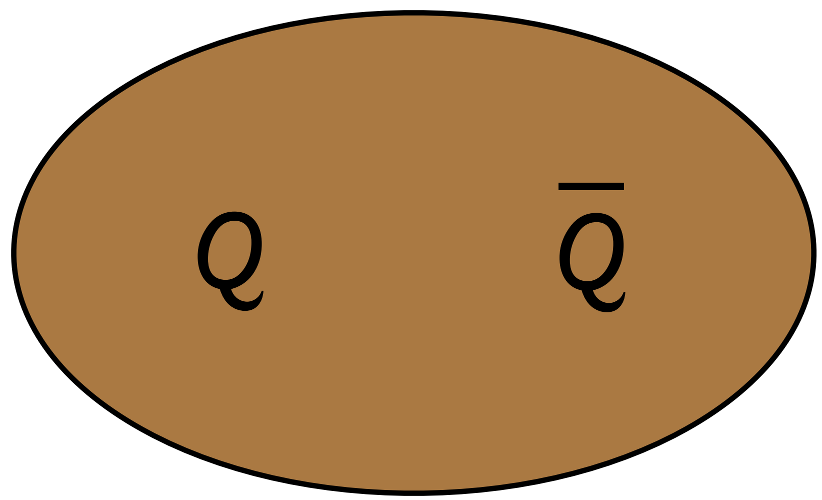
	2^{-+}	4312±24 MeV	*Y(4274)?*	$?^{?+}$
input	1^{--}	4263	*Y(4260)!*	1^{--}
	1^{-+}	4195±23		
	0^{-+}	4173±21	*Y(4140)?*	$?^{?+}$

excited multiplets

$\{1^{++}, (0,1,2)^{+-}\}$	4280-4420 MeV
$\{0^{++}, 1^{+-}\}$	4410-4490
$\{2^{++}, (1,2,3)^{+-}\}$	4430-4550

Born-Oppenheimer approximation

- Born-Oppenheimer potentials are defined by energy levels of gluons and light quarks in presence of static Q and $\bar{Q}$ sources



- Q and $\bar{Q}$ move adiabatically in B-O potential

- gluons and light quarks respond instantaneously to the motion of the Q and $\bar{Q}$

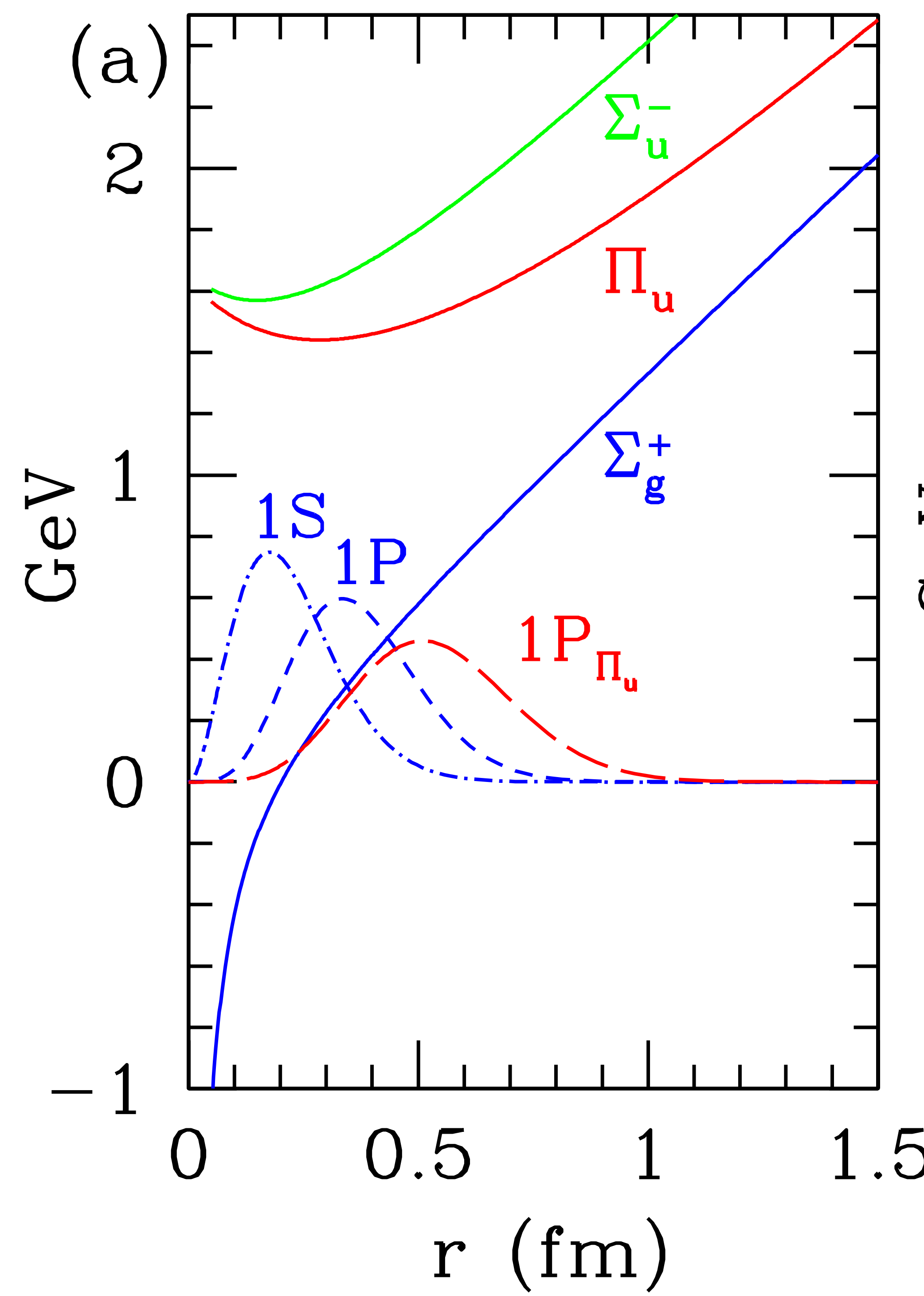
Born-Oppenheimer approximation

Juge, Kuti, Morningstar 1999

Born-Oppenheimer potentials
labelled by component of J_{light}
charge conjugation
or by Σ_g^+, Π_u, Σ_u^-, ...
(no dynamical light quarks)

Σ_g^+: quarkonium potential

Π_u, Σ_u^-, ... :
quarkonium hybrid potentials



Born-Oppenheimer approximation

Juge, Kuti, Morningstar 1999

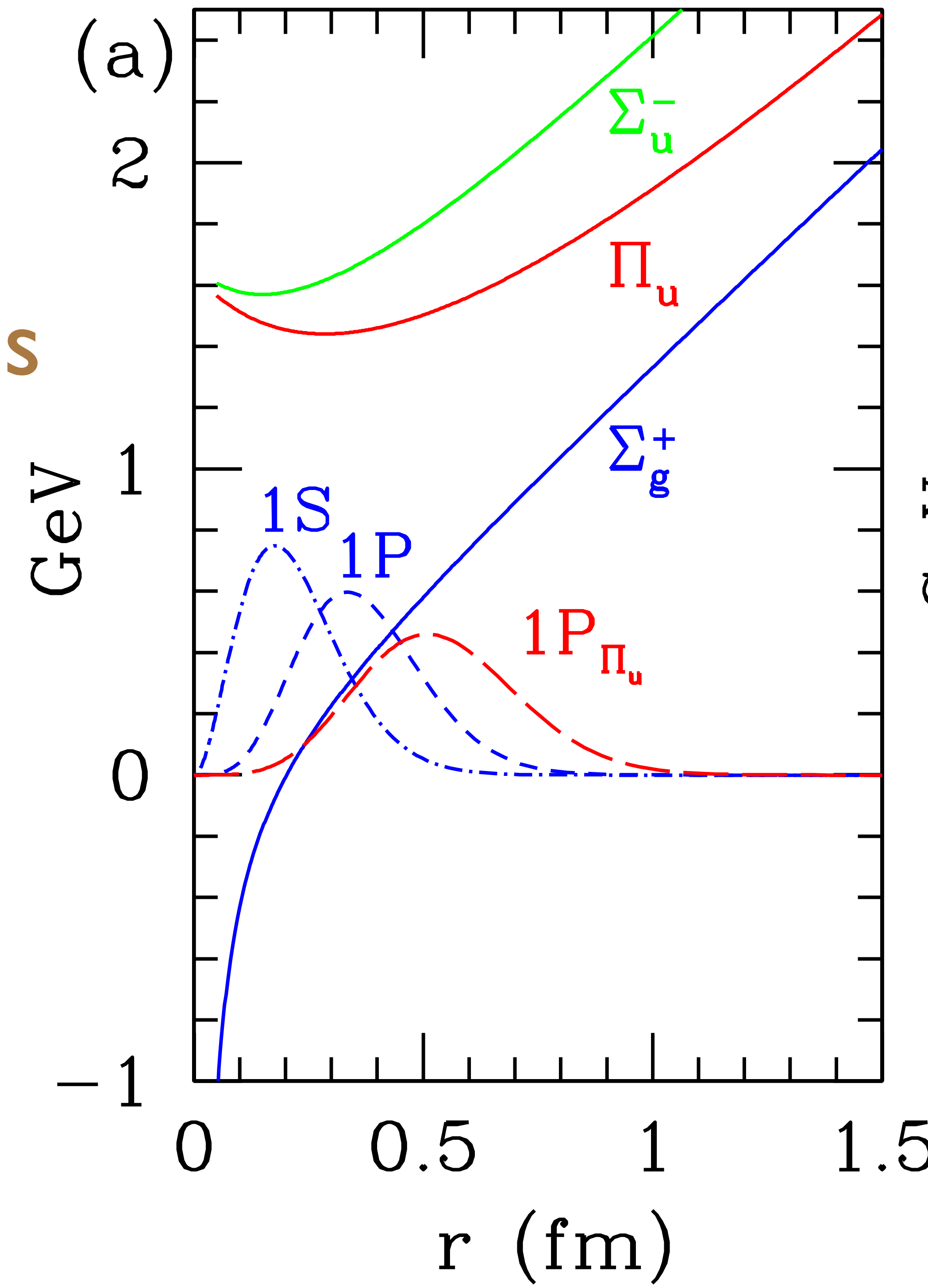
solve Schroedinger equation
for Q and $\bar{Q}$ in B-O potentials

quarkonium multiplets
$\Sigma_g^+(1S, 2S, 3S, \ldots, 1P, 2P, \ldots, 1D, \ldots)$

quarkonium hybrid multiplets
$\Pi_u(1P), \Sigma_u^-(1S), \Pi_u(2P), \ldots$

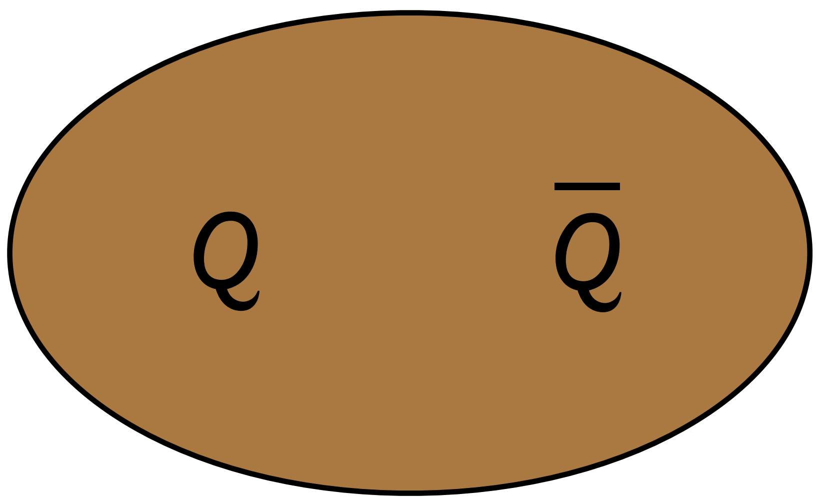
$\Pi_u(1P) \rightarrow \{1^{--}, (0,1,2)^{-+}\}$, $\{1^{++}, (0,1,2)^{+-}\}$

$\Sigma_u^-(1S) \rightarrow \{0^{++}, 1^{+-}\}$



Born-Oppenheimer Tetraquarks

- quarkonium tetraquarks
  are similar to quarkonium hybrids
  in the Born-Oppenheimer approximation
  except that the gluons and light quarks
  are in a flavor-nonsinglet state



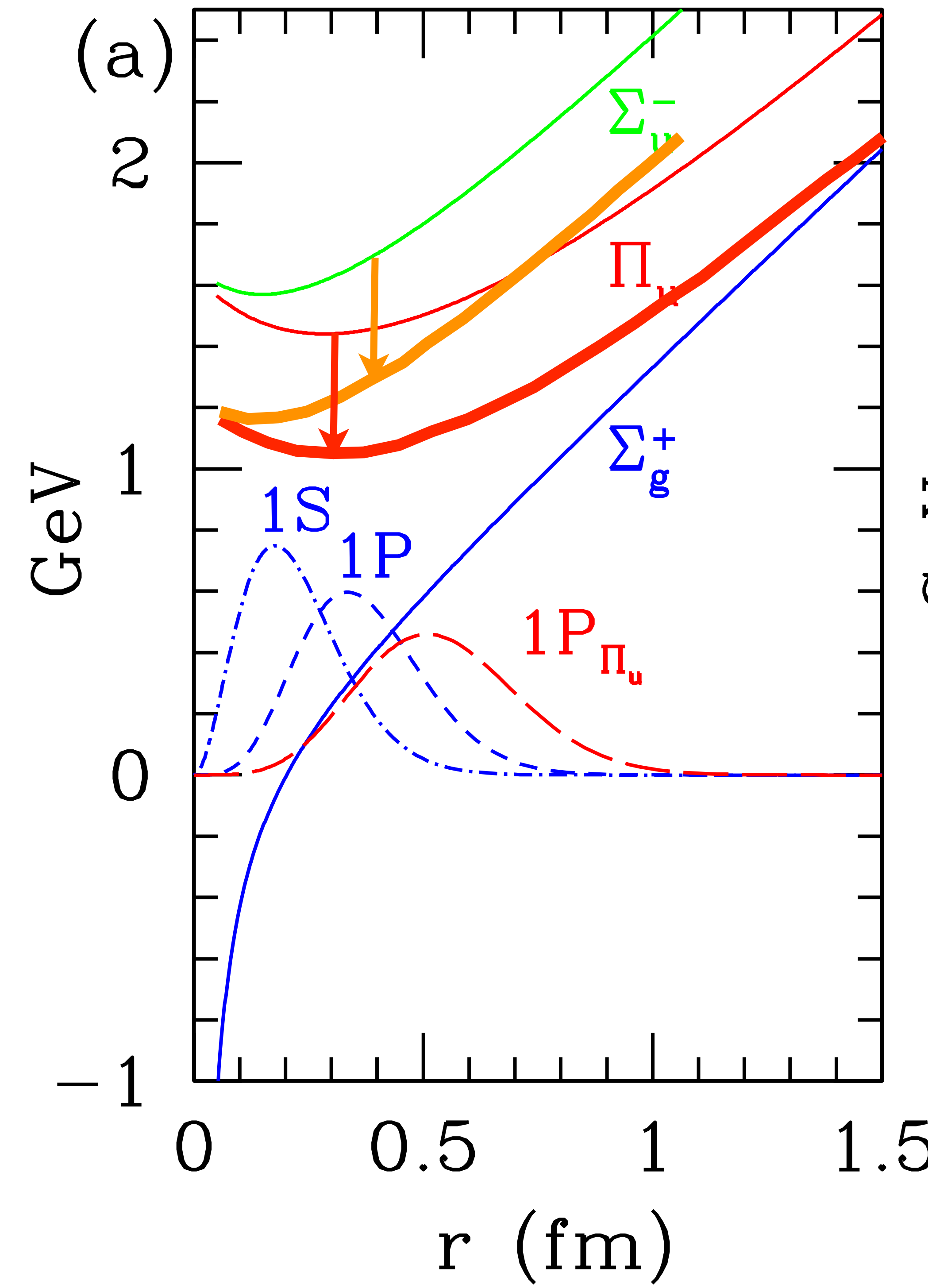
- Q and $\bar{Q}$ move adiabatically in B-O potentials
  defined by energy levels of gluons and light quarks
  with isospin 1

Born-Oppenheimer Tetraquarks

isospin-1 B-O potentials

simple assumptions:

- same qualitative behavior as flavor-singlet B-O potentials
- shifted lower in energy



$\Longrightarrow$ lowest multiplets same as for quarkonium hybrids

$\{1^{--}, (0,1,2)^{-+}\}$, $\{1^{++}, (0,1,2)^{+-}\}$, $\{0^{++}, 1^{+-}\}$, ...

Born-Oppenheimer Tetraquarks

lowest B-O tetraquark multiplets:

$\{1^{--}, (0,1,2)^{-+}\}, \ \{1^{++}, (0,1,2)^{+-}\}, \ \{0^{++}, 1^{+-}\}, \ \ldots$

bottomonium tetraquarks: $Z_b^+(10610)$, $Z_b^+(10650)$

quantum numbers 1^{+-}

$\Longrightarrow$ multiplets: $\{1^{++}, (0,1,2)^{+-}\}, \ \{0^{++}, 1^{+-}\}$

charmonium tetraquark: $Z_c^+(3900)$

quantum numbers 1^{P-}, $P = +$ or $-$:

$P = + \ \Longrightarrow \ \{1^{++}, (0,1,2)^{+-}\}$ or $\{0^{++}, 1^{+-}\}$

$P = - \ \Longrightarrow \ \{1^{--}, (0,1,2)^{-+}\}$

Born-Oppenheimer Tetraquarks

charmonium tetraquark: $Z_c^+(3900)$

$P = -$ $\Longrightarrow$ 1^{--} member of $\{1^{--}, (0,1,2)^{-+}\}$ multiplet

- predict spectrum of charmonium tetraquarks

ground-state multiplet

	2^{-+}	3946±24 MeV	
input	1^{--}	3897	$Z_c(3900)!$
	1^{-+}	3829±23	
	0^{-+}	3807±21	

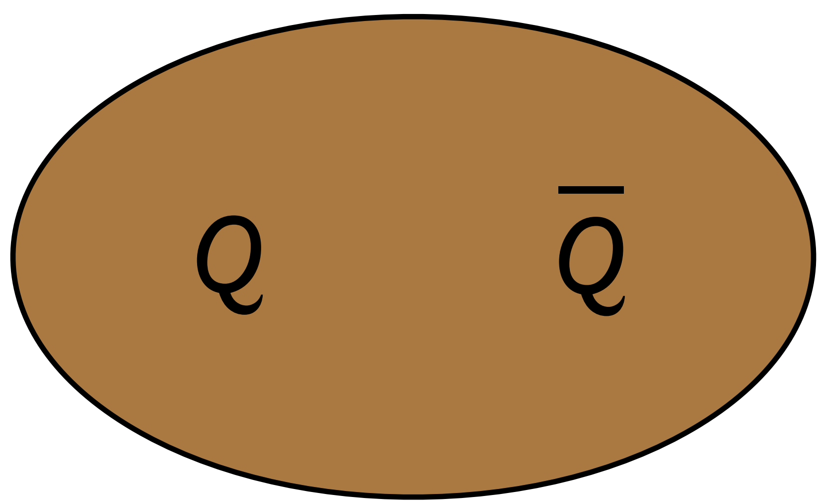
excited multiplets

$\{1^{++}, (0,1,2)^{+-}\}$	3910-4060 MeV
$\{0^{++}, 1^{+-}\}$	4040-4130
$\{2^{++}, (1,2,3)^{+-}\}$	4060-4190

Conclusions

discoveries of bottomonium tetraquarks $Z_b^+, Z_b^{+\prime}$
charmonium tetraquark Z_c^+
have revealed a serious gap in our understanding of the QCD spectrum

new proposal: Born-Oppenheimer tetraquarks

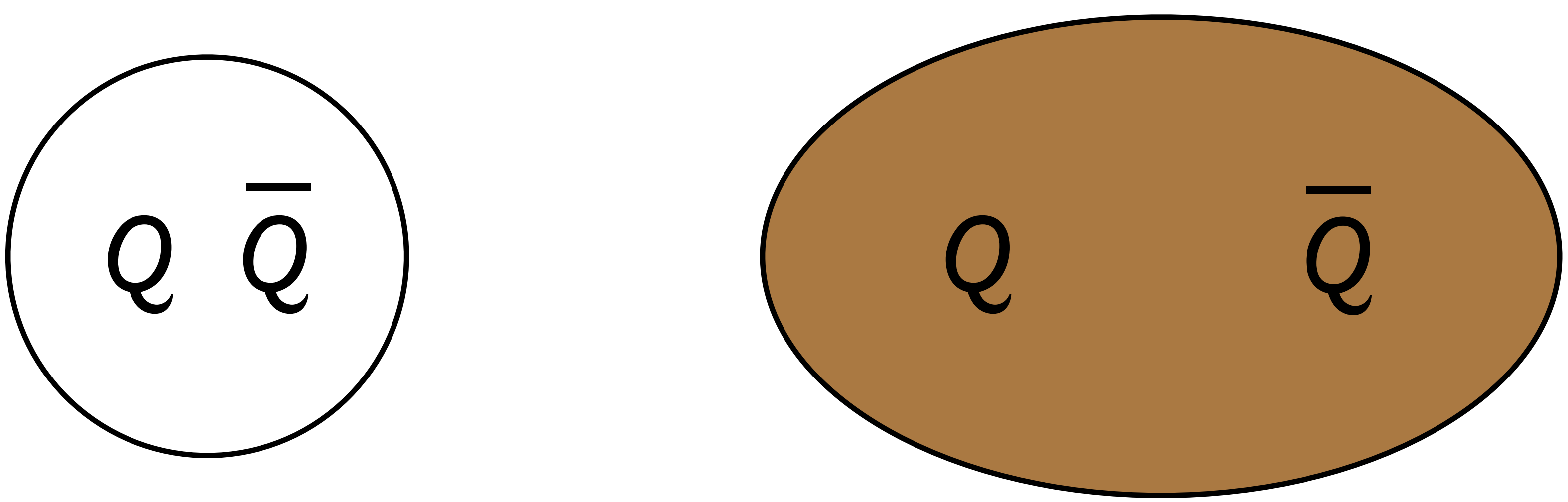


Q and $\bar{Q}$ move adiabatically in B-O potentials
defined by energy levels of gluons and light quarks
with isospin I

Conclusions

What is needed from theory:

- definitive calculations of spectrum of $c\bar{c}$ mesons using Lattice QCD
- definitive calculations of spectrum of $b\bar{b}$ mesons using Lattice NRQCD
- calculation of B-O potentials using Lattice QCD for flavor-singlet and for isospin I
- development of phenomenological models for transitions between quarkonium, quarkonium hybrids, quarkonium tetraquarks



Conclusions

Additional hints can be expected from experiment

- intensity frontier
  charm factory BEPCII
  bottom factory Super KEK-B
  PANDA: $p\bar{p}$ annihilation into charmonium

- energy frontier
  ATLAS and CMS
  LHCb

"Quarkonium at the Frontiers of High Energy Physics:
A Snowmass White Paper"
Bodwin, Braaten, Eichten, Olsen, Pedlar, and Russ
arXiv:1307.7425