The multiquark states in the b-quark sector - I/II

Christian Hambrock

TU Dortmund

July 2013

Dubna 2013

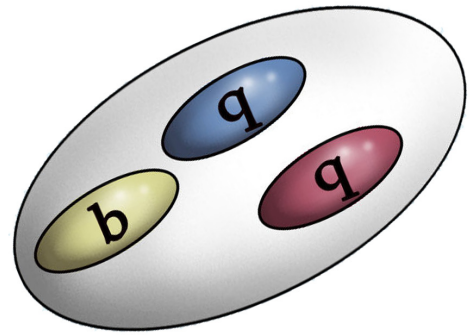

SM: familiar as your neighborhood


SM more exotic than you think?

Non-Exotica

mesons

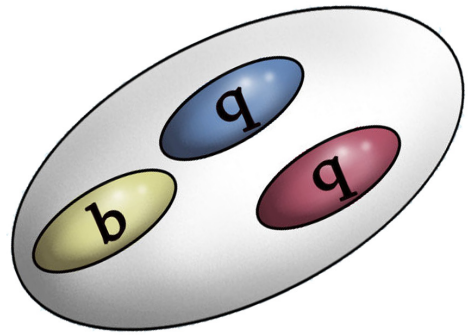
baryons



Non-Exotica

mesons

baryons



exotic types

meson-like states:

baryon number = 0

NOT $q\bar{q}$

baryon-like states:

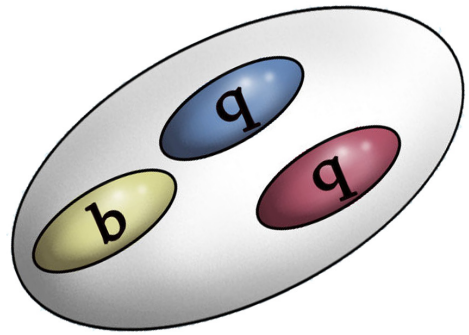
baryon number = 1,2,3,...

NOT qqq

Non-Exotica

mesons

baryons



exotic types

meson-like states:

baryon number = 0

NOT $q\bar{q}$

baryon-like states:

baryon number = 1,2,3,...

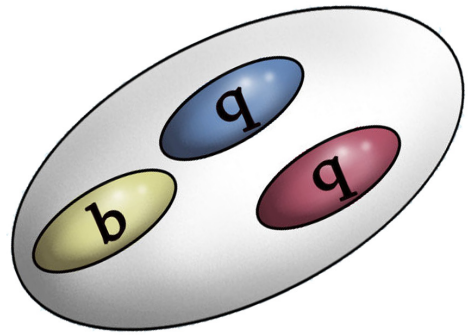
NOT qqq

candidate in 2003 observed by LEPS, DIANA & CLAS
later refuted

Non-Exotica

mesons

baryons



exotic types

meson-like states:

baryon number = 0

NOT $q\bar{q}$

several candidates since 2003 discussed here

baryon-like states:

baryon number = 1,2,3,...

NOT qqq

candidate in 2003 observed by LEPS, DIANA & CLAS later refuted

Exotica

Belle & others [Zupanc et al. 09] , [Bondar et al., PRL 12] , [Liu et al., 13] , [Ablikim et al., 13]

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes	Also observed by
					e^+e^- (ISR)	
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	$J/\psi \to \eta Y_s(2175)$	BaBar*, BESII
				$\pi^+\pi^- J/\psi$,		BaBar
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\gamma J/\psi$,$D\bar{D}^*$	$B \to KX(3872)$, $p\bar{p}$	CDF, D0
$Z(3900)$	3899 ± 6	46 ± 22	1^+	$\pi^\pm J/\psi$	$Z(4260) \to Z(3900)\pi$	BESIII*
$X(3915)$	3914 ± 4	28^{+12}_{-14}	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$	
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$	
				$D\bar{D}^*$ (not $D\bar{D}$		
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	or $\omega J/\psi$)	$e^+e^- \to J/\psi X(3940)$	
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}^*$)	$B \to KY(3940)$	BaBar
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)	
$Z(4020)$	4022 ± 3	6 ± 4	1^+	$\pi^\pm J/\psi$	$Z(4260) \to Z(4020)\pi$	BESIII* (*only*)
$Z(4025)$	4026 ± 5	25 ± 10	1^+	$\pi^\pm J/\psi$	$Z(4260) \to Z(4025)\pi$	BESIII* (*only*)
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$D^*\bar{D}^*$ (not $D\bar{D}$)	$e^+e^- \to J/\psi X(4160)$	
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)	BaBar*, CLEO
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)	BaBar*
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$	e^+e^- (ISR)	
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)	
$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4050)$	
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4250)$	
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm \psi'$	$B \to KZ^\pm(4430)$	
$Z_b(10610)$	$10,607 \pm 2$	18.4 ± 2.4	1^+	$\pi^\pm h_b(1,2P)$, $\pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10610)\pi$	
$Z_b(10650)$	$10,652 \pm 2$	11.5 ± 2.2	1^+	$\pi^\pm h_b(1,2P)$, $\pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10650)\pi$	
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^- \Upsilon(1,2,3S)$	$e^+e^- \to Y_b$	

Exotica

Belle & others [Zupanc et al. 09] , [Bondar et al., PRL 12] , [Liu et al., 13] , [Ablikim et al., 13]

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes	Also observed by
					e^+e^- (ISR)	
$Y_S(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	$J/\psi \to \eta Y_S(2175)$	BaBar*, BESII
				$\pi^+\pi^- J/\psi$,		BaBar
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\gamma J/\psi$,$D\bar{D}^*$	$B \to KX(3872)$, $p\bar{p}$	CDF, D0
$Z(3900)$	3899 ± 6	46 ± 22	1^+	$\pi^\pm J/\psi$	$Z(4260) \to Z(3900)\pi$	BESIII*
$X(3915)$	3914 ± 4	28^{+12}_{-14}	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$	
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$	
				$D\bar{D}^*$ (not $D\bar{D}$		
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	or $\omega J/\psi$)	$e^+e^- \to J/\psi X(3940)$	
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}^*$)	$B \to KY(3940)$	BaBar
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)	
$Z(4020)$	4022 ± 3	6 ± 4	1^+	$\pi^\pm J/\psi$	$Z(4260) \to Z(4020)\pi$	BESIII* (*only*)
$Z(4025)$	4026 ± 5	25 ± 10	1^+	$\pi^\pm J/\psi$	$Z(4260) \to Z(4025)\pi$	BESIII* (*only*)
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$D^*\bar{D}^*$ (not $D\bar{D}$)	$e^+e^- \to J/\psi X(4160)$	
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)	BaBar*, CLEO
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)	BaBar*
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$	e^+e^- (ISR)	
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)	
$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4050)$	
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4250)$	
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm \psi'$	$B \to KZ^\pm(4430)$	
$Z_b(10610)$	$10,607 \pm 2$	18.4 ± 2.4	1^+	$\pi^\pm h_b(1,2P), \pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10610)\pi$	
$Z_b(10650)$	$10,652 \pm 2$	11.5 ± 2.2	1^+	$\pi^\pm h_b(1,2P), \pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10650)\pi$	
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^- \Upsilon(1,2,3S)$	$e^+e^- \to Y_b$	

Light states [PDG] :

$a_0(980)$ in 1965, $\sigma(600)^{\text{now } 500}$ in 1972, $f_0(980)$ in 1979, $\kappa(980)$ in 1997
discussion reopened: ['t Hooft, Isidori, Maiani, Polosa, Riquer, PLB 08]

Exotica

Belle & others [Zupanc et al. 09] , [Bondar et al., PRL 12] , [Liu et al., 13] , [Ablikim et al., 13]

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes	Also observed by	date
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR) $J/\psi \to \eta Y_s(2175)$	BaBar*, BESII	2006
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi$,$D\bar{D}^*$	$B \to KX(3872)$, $p\bar{p}$	BaBar CDF, D0	2003
$Z(3900)$	3899 ± 6	46 ± 22	1^{+}	$\pi^\pm J/\psi$	$Z(4260) \to Z(3900)\pi$	BESIII*	2013
$X(3915)$	3914 ± 4	28^{+12}_{-14}	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$		2009
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$		2009
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	$e^+e^- \to J/\psi X(3940)$		2005
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}^*$)	$B \to KY(3940)$	BaBar	2005
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J$	e^- (ISR)		2005
$Z(4020)$	4022 ± 3	6 ± 4	1^{+}	$\pi^\pm J/\psi$		BESIII* (*only*)	2013
$Z(4025)$	4026 ± 5	25 ± 10	1^{+}	$\pi^\pm J/\psi$	$Z(4260) \to Z(4025)\pi$	BESIII* (*only*)	2013
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$D^*\bar{D}^*$ (not $D\bar{D}$)	$e^+e^- \to J/\psi X(4160)$		2008
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)	BaBar*, CLEO	2005
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	π^+	R)	BaBar*	2007
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	Λ_c	R)		2008
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^-\psi'$	e^+ (ISR)		2007
$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^\pm\chi_{c1}$	$B \to KZ^\pm$ (4050)		2008
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^\pm\chi_{c1}$	$B \to KZ^\pm(4250)$		2008
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm\psi'$	$B \to KZ^\pm(4430)$		2007
$Z_b(10610)$	$10,607 \pm 2$	18.4 ± 2.4	1^{+}	$\pi^\pm h_b(1,2P)$, $\pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10610)\pi$		2011
$Z_b(10650)$	$10,652 \pm 2$	11.5 ± 2.2	1^{+}	$\pi^\pm h_b(1,2P)$, $\pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10650)\pi$		2011
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^-\Upsilon(1,2,3S)$	$e^+e^- \to Y_b$		2008

3 weeks old

last weeks of Belle

Light states [PDG] :

$a_0(980)$ in 1965, $\sigma(600)^{\text{now } 500}$ in 1972, $f_0(980)$ in 1979, $\kappa(980)$ in 1997
discussion reopened: ['t Hooft, Isidori, Maiani, Polosa, Riquer, PLB 08]

Exotica

Belle & others [Zupanc et al. 09] , [Bondar et al., PRL 12] , [Liu et al., 13] , [Ablikim et al., 13]

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes	Also observed by	date
					e^+e^- (ISR)		
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	$J/\psi \to \eta Y_s(2175)$	BaBar*, BESII	2006
				$\pi^+\pi^- J/\psi$,		BaBar	
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\gamma J/\psi$,$D\bar{D}^*$	$B \to KX(3872)$, $p\bar{p}$	CDF, D0	2003
$Z(3900)$	3899 ± 6	46 ± 22	1^{+}	$\pi^\pm J/\psi$	$Z(4260) \to Z(3900)\pi$	BESIII*	2013
$X(3915)$	3914 ± 4	28^{+12}_{-14}	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$		2009
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$		2009
$X(3940)$	3942 ± 9	37 ± 17	0		$e^+e^- \to J/\psi X(3940)$		2005
$Y(3940)$	3943 ± 17	87 ± 34	?		$B \to KY(3940)$	BaBar	2005
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1		e^+e^- (ISR)		2005
$Z(4020)$	4022 ± 3	6 ± 4	1		$Z(4260) \to Z(4020)\pi$	BESIII* (*only*)	2013
$Z(4025)$	4026 ± 5	25 ± 10	1		$Z(4260) \to Z(4025)\pi$	BESIII* (*only*)	2013
$X(4160)$	4156 ± 29	139^{+113}_{-65}	0		$e^+e^- \to J/\psi X(4160)$		2008
$Y(4260)$	4264 ± 12	83 ± 22	1		e^+e^- (ISR)	BaBar*, CLEO	2005
$Y(4350)$	4361 ± 13	74 ± 18			e^+e^- (ISR)	BaBar*	2007
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$	e^+e^- (ISR)		2008
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^-\psi'$	e^+e^- (ISR)		2007
$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^\pm\chi_{c1}$	$B \to KZ^\pm(4050)$		2008
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^\pm\chi_{c1}$	$B \to KZ^\pm(4250)$		2008
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm\psi'$	$B \to KZ^\pm(4430)$		2007
$Z_b(10610)$	$10,607 \pm 2$	18.4 ± 2.4	1^+	$\pi^\pm h_b(1,2P)$, $\pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10610)\pi$		2011
$Z_b(10650)$	$10,652 \pm 2$	11.5 ± 2.2	1^+	$\pi^\pm h_b(1,2P)$, $\pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10650)\pi$		2011
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^-\Upsilon(1,2,3S)$	$e^+e^- \to Y_b$		2008

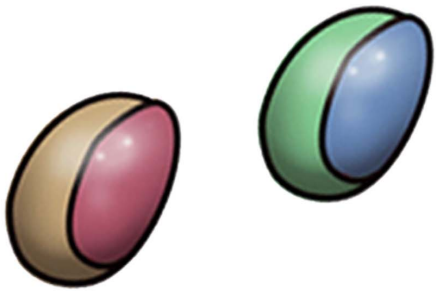
focus here:
$Z_c(3900, 402X)$
$Y_c(4260)$
$Z_b(106XX)$
$Y_b(10890)$

Light states [PDG] :

$a_0(980)$ in 1965, $\sigma(600)^{\text{now } 500}$ in 1972, $f_0(980)$ in 1979, $\kappa(980)$ in 1997
discussion reopened: ['t Hooft, Isidori, Maiani, Polosa, Riquer, PLB 08]

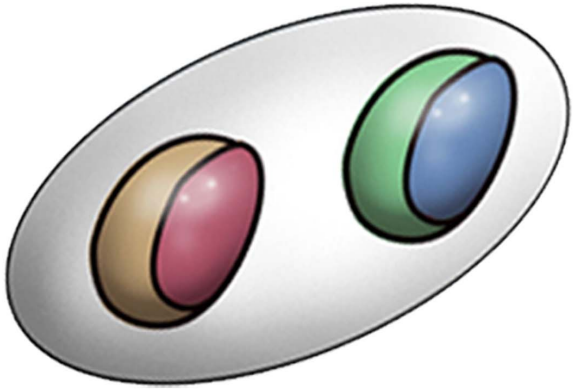
Exotic Zoo

Exotic Zoo



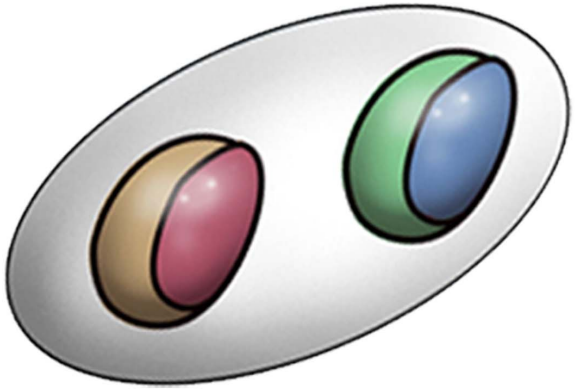
gluons

Exotic Zoo

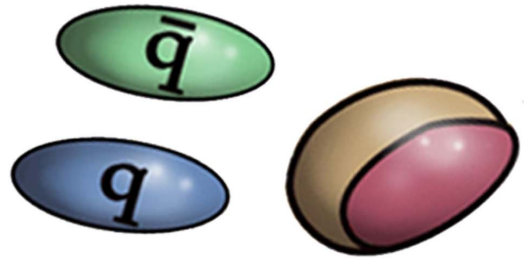


gluons --> Glueball
(lighter flavor sectors)

Exotic Zoo

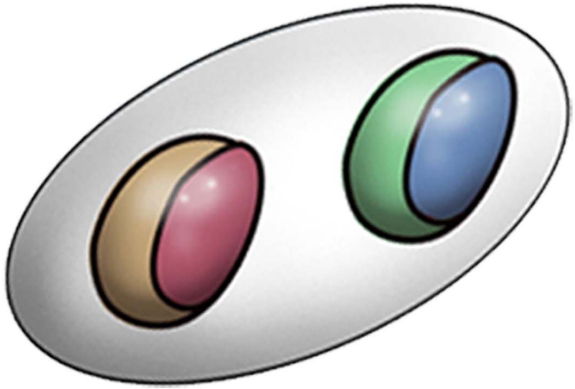


gluons --> Glueball
(lighter flavor sectors)

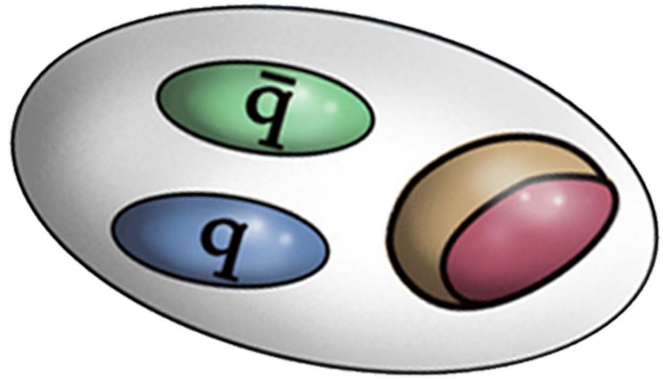


quarks + gluons

Exotic Zoo

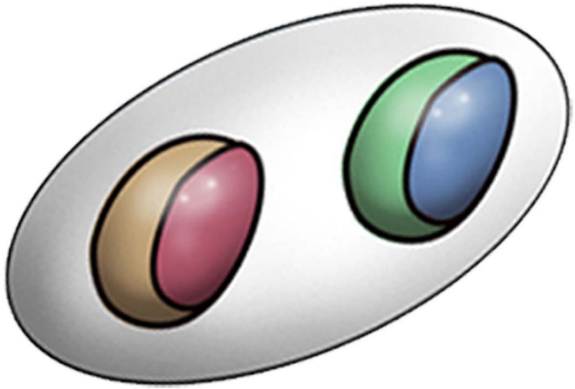


gluons --> Glueball
(lighter flavor sectors)

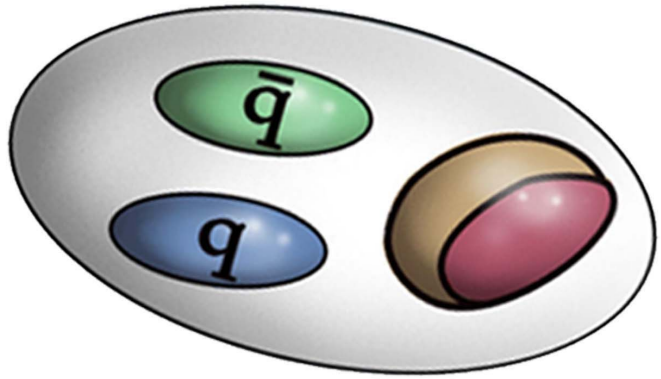


quarks + gluons --> Hybrid

Exotic Zoo



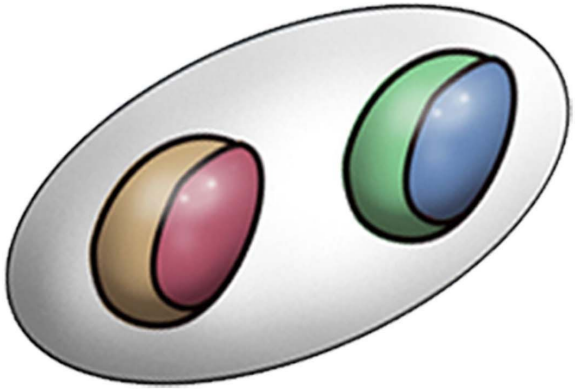
gluons --> Glueball
(lighter flavor sectors)



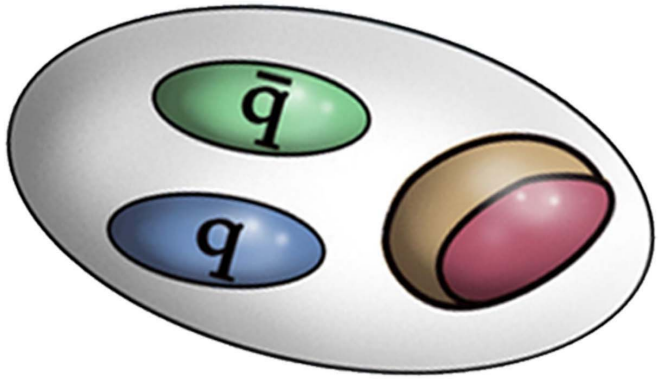
quarks + gluons --> Hybrid

quarks

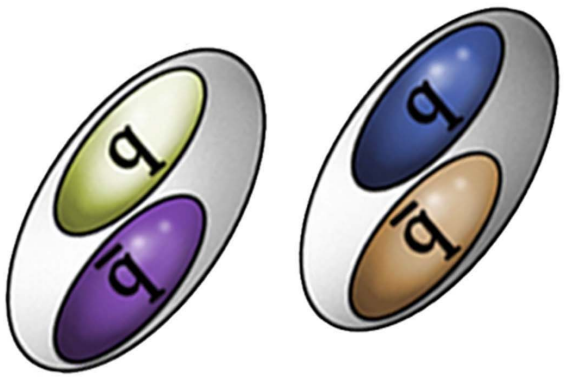
Exotic Zoo



gluons --> Glueball
(lighter flavor sectors)

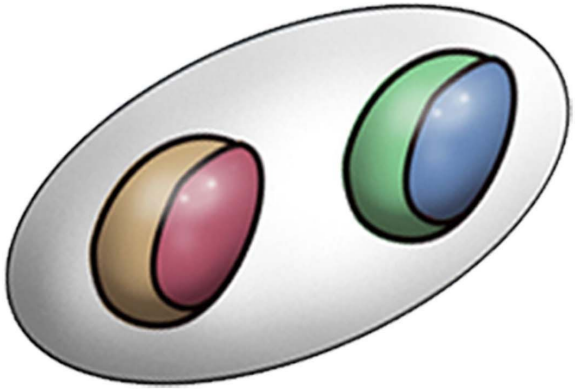


quarks + gluons --> Hybrid

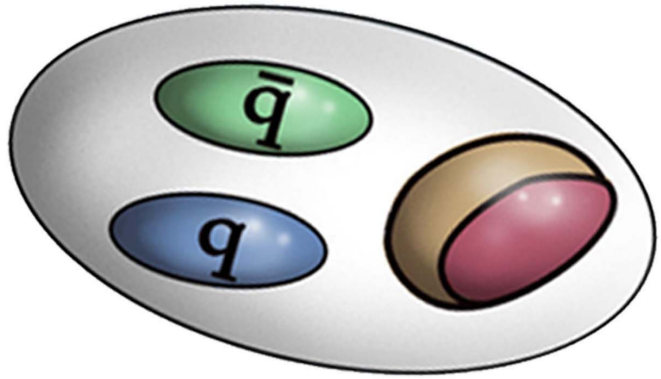


quarks --> mesons

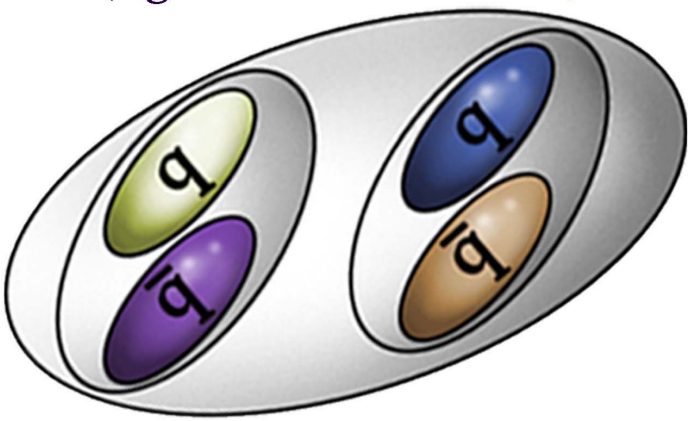
Exotic Zoo



gluons --> Glueball
(lighter flavor sectors)

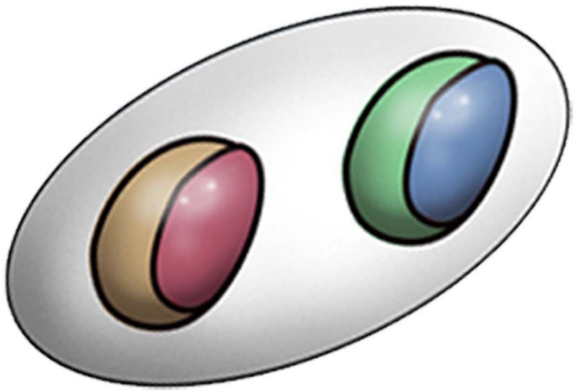


quarks + gluons --> Hybrid

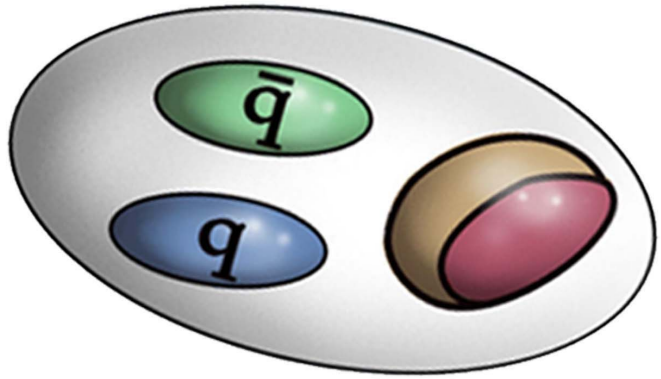


quarks --> mesons
--> Meson Molecule

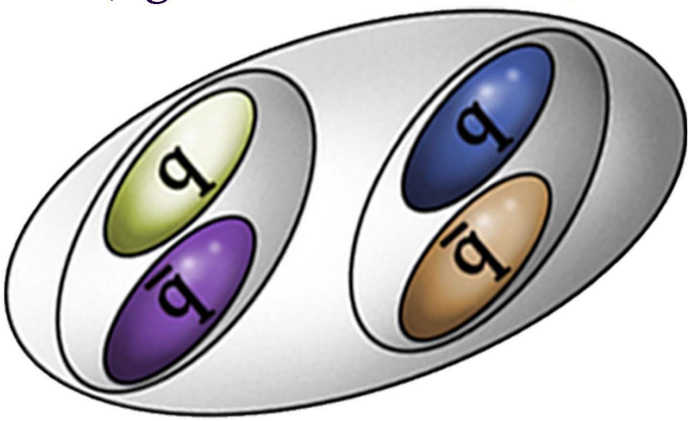
Exotic Zoo



gluons --> Glueball
(lighter flavor sectors)



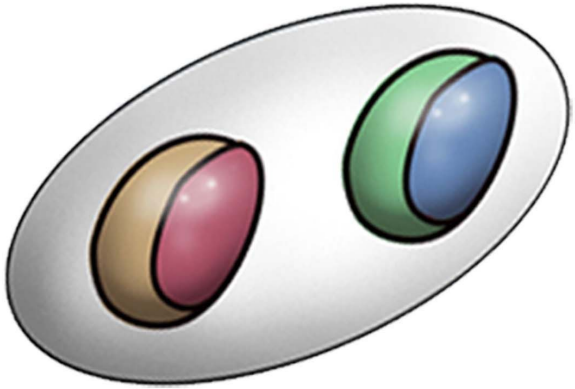
quarks + gluons --> Hybrid



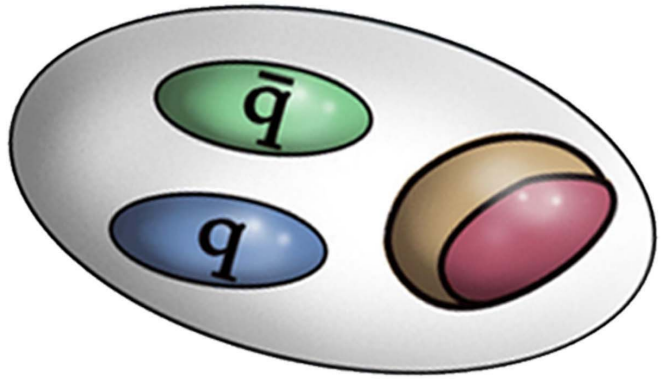
quarks --> mesons
--> Meson Molecule

quarks

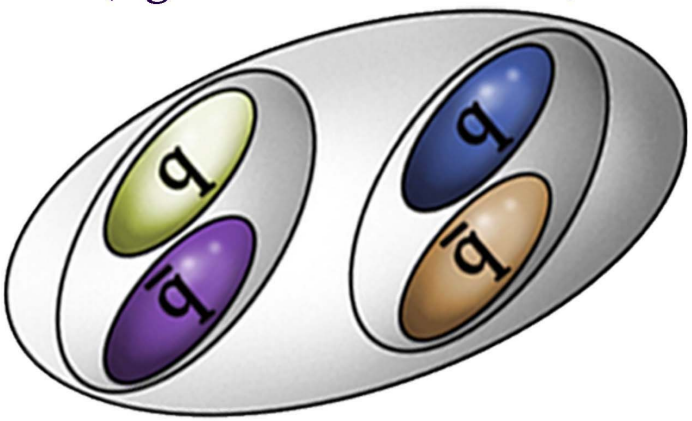
Exotic Zoo



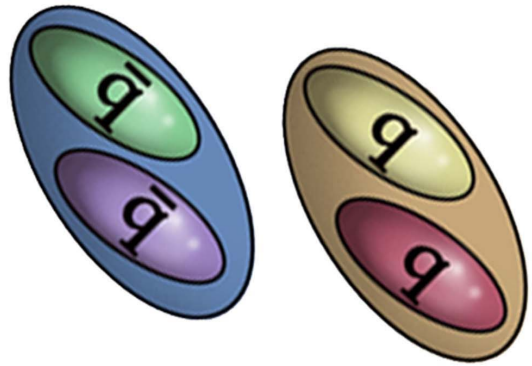
gluons --> Glueball
(lighter flavor sectors)



quarks + gluons --> Hybrid

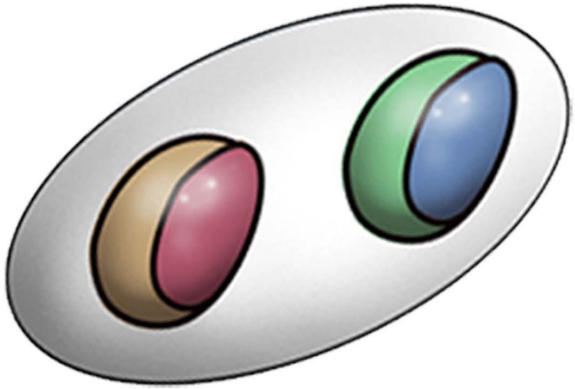


quarks --> mesons
--> Meson Molecule

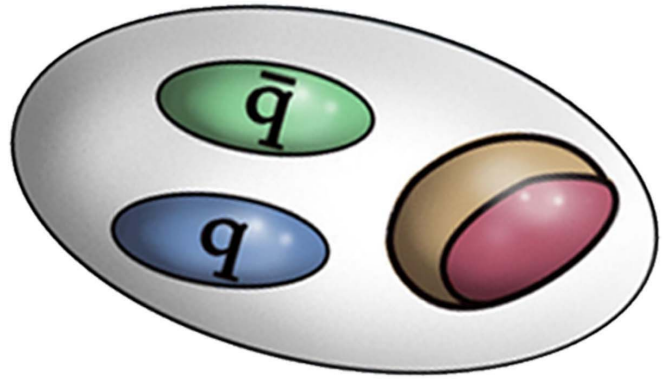


quarks --> diquarks

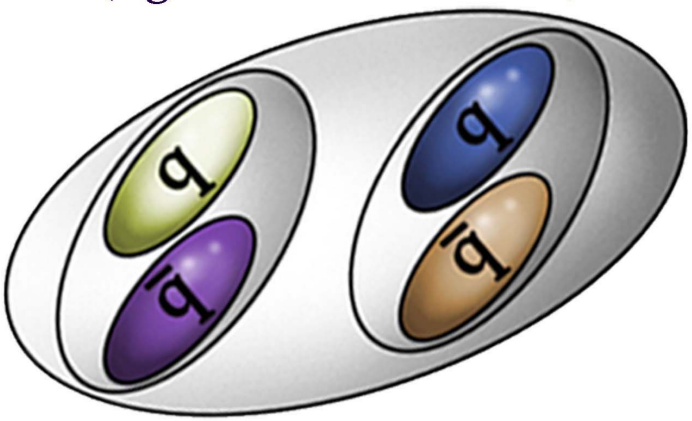
Exotic Zoo



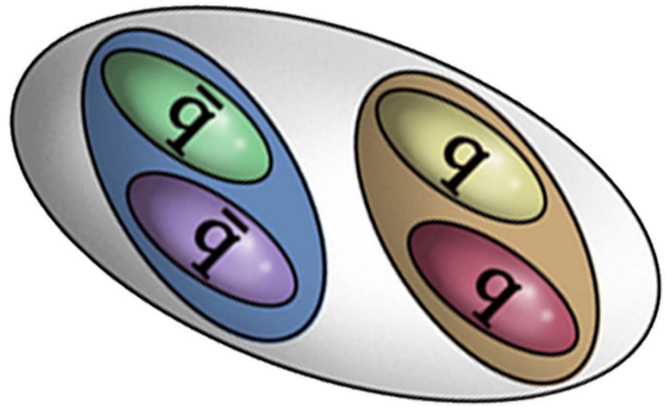
gluons --> Glueball
(lighter flavor sectors)



quarks + gluons --> Hybrid

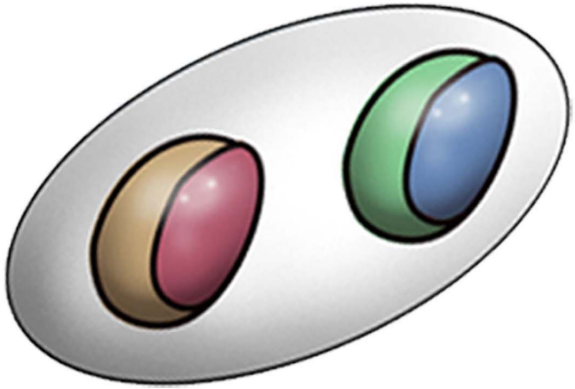


quarks --> mesons
--> Meson Molecule

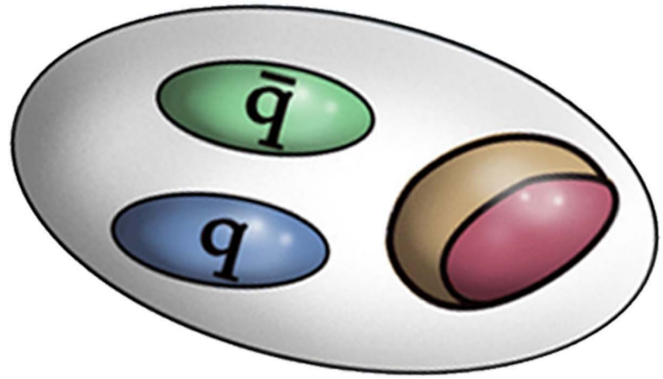


quarks --> diquarks
--> Tetraquark

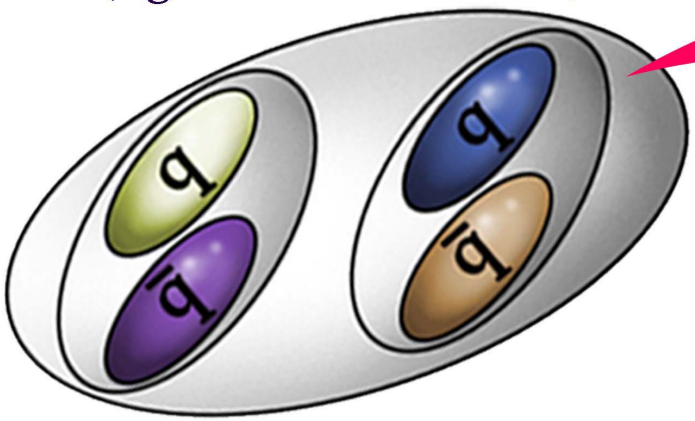
Exotic Zoo



gluons --> Glueball
(lighter flavor sectors)

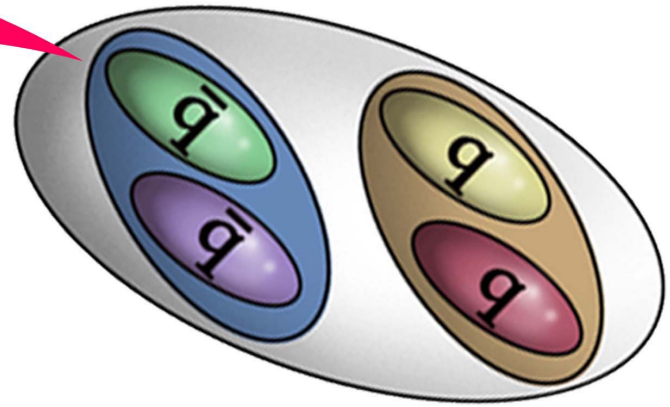


quarks + gluons --> Hybrid



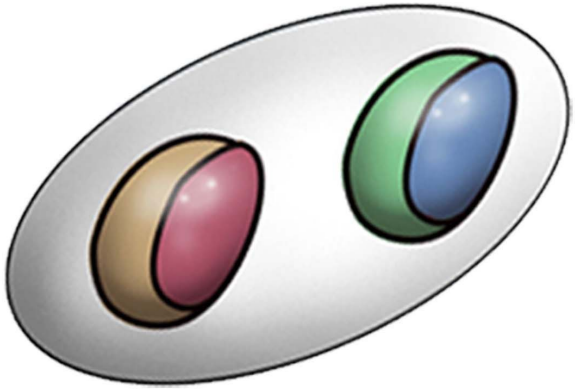
quarks --> mesons
--> Meson Molecule

seemingly similar hadrons

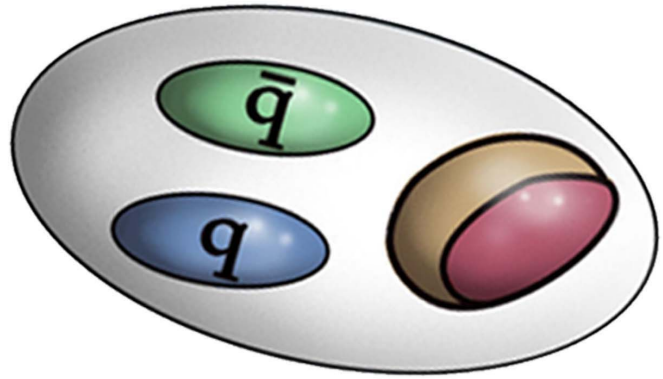


quarks --> diquarks
--> Tetraquark

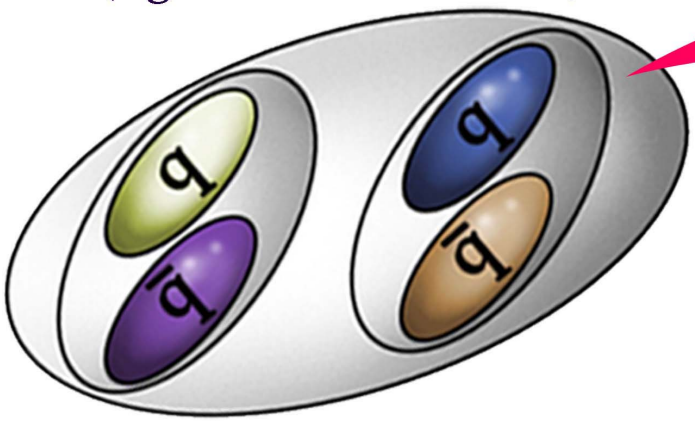
Exotic Zoo



gluons --> Glueball
(lighter flavor sectors)

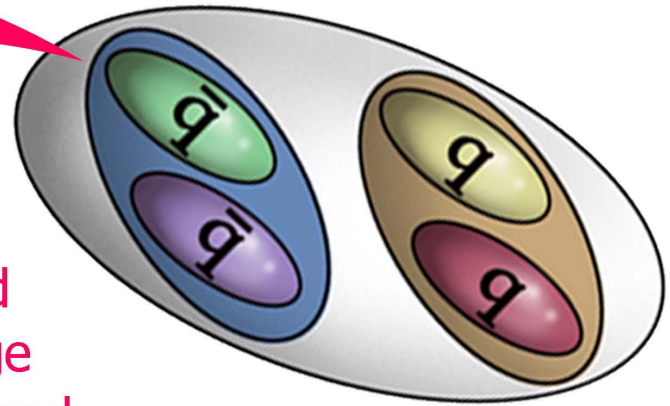


quarks + gluons --> Hybrid



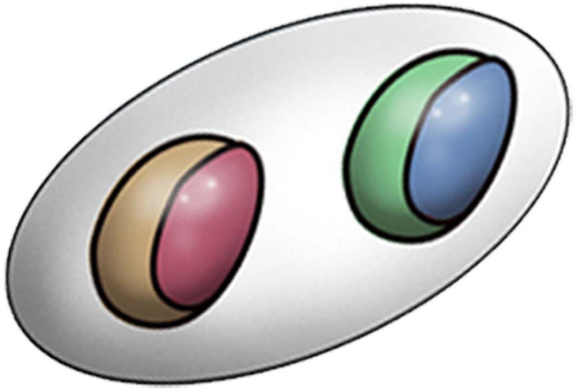
quarks --> mesons
--> Meson Molecule

seemingly similar
hadrons
But!:
Molecules bound
by Pion exchange
Tetraquarks bound
by color force!

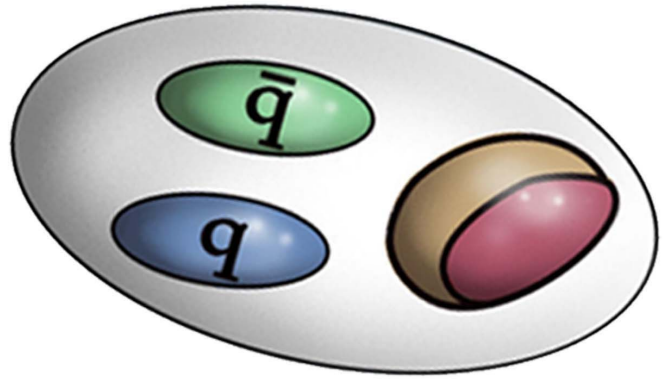


quarks --> diquarks
--> Tetraquark

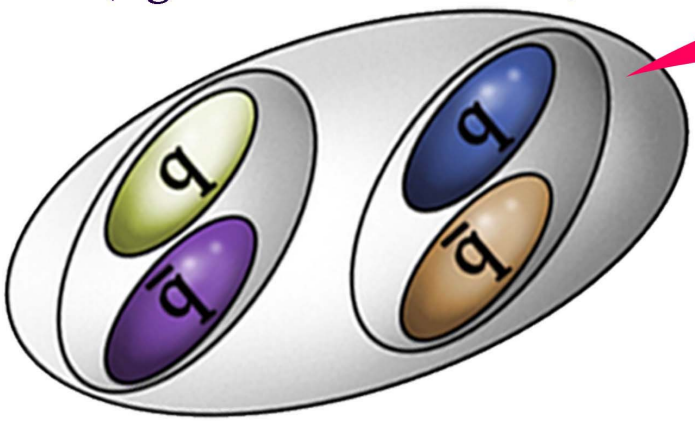
Exotic Zoo



gluons --> Glueball
(lighter flavor sectors)



quarks + gluons --> Hybrid



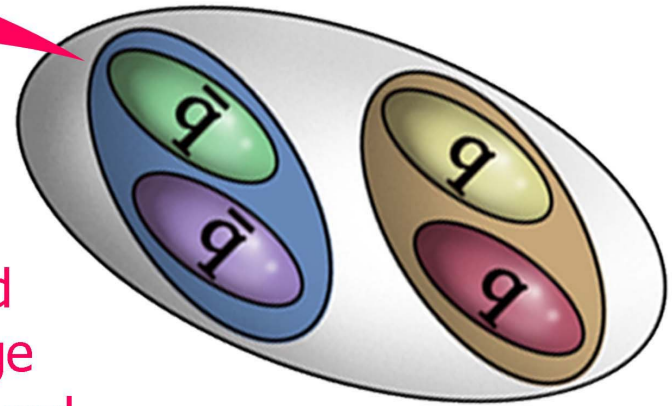
quarks --> mesons
--> Meson Molecule

seemingly similar hadrons

But!:

Molecules bound by Pion exchange

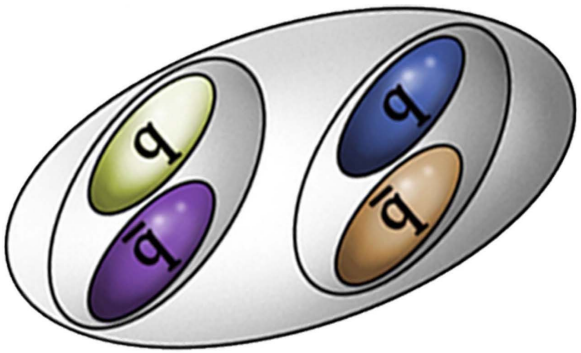
Tetraquarks bound by color force!

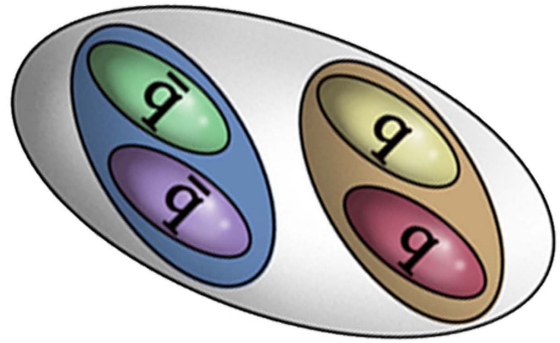


quarks --> diquarks
--> Tetraquark

➡ **different phenomenology**

Molecules & Tetraquarks





Most prominent explanations of exotica

Pion exchange ↷

- **Mass:** E_{binding} few MeV;
  Masses below corresponding 2 meson threshold
- **Width:** educated guess: size similar to constituent mesons or $\mathcal{O}(E_{\text{binding}})$ → narrow

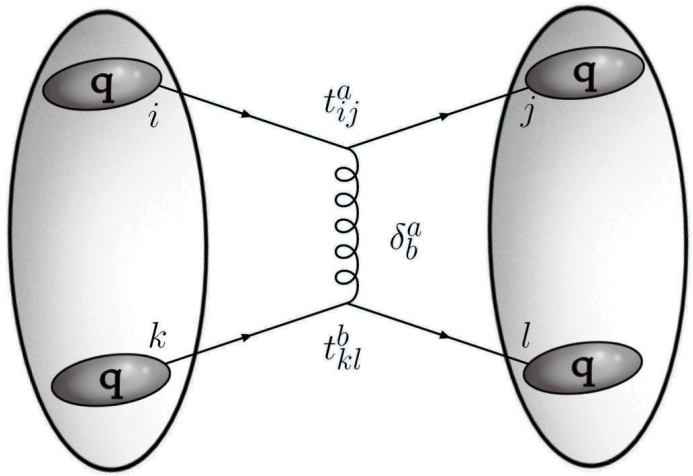
Gluon exchange ↷

- **Mass:** E_{binding} $\mathcal{O}(\Lambda_{\text{QCD}})$; Masses vary
- **Width:** typical hadronic decay width

Diquarks: Color Representation

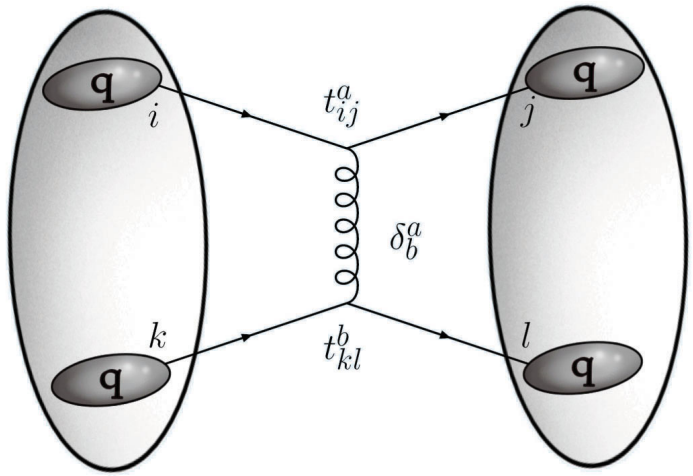
- One gluon exchange model [Jaffe,Phys.Rept.(2005)]

  ↳ Color factor determines binding:
  Negative sign → Attractive



Diquarks: Color Representation

- One gluon exchange model [Jaffe,Phys.Rept.(2005)]



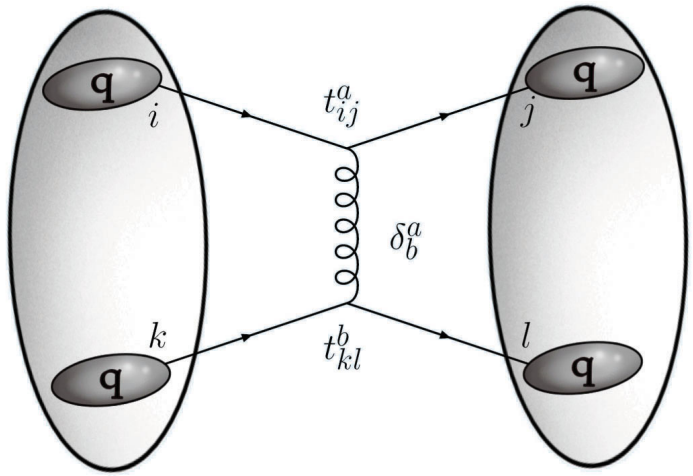
  ↳ Color factor determines binding:
  Negative sign → Attractive

- Quarks in diquark transform as:

$$\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}} \oplus \mathbf{6}$$

Diquarks: Color Representation

- One gluon exchange model [Jaffe,Phys.Rept.(2005)]



  ↳ Color factor determines binding:
  Negative sign → Attractive

- Quarks in diquark transform as:

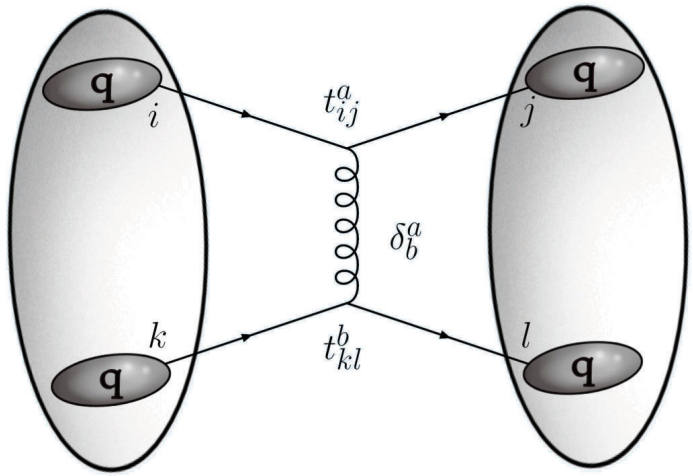
$$\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}} \oplus \mathbf{6}$$

- qq bound state color factor:

$$t^a_{ij} t^a_{kl} = -\frac{2}{3} \underbrace{(\delta_{ij}\delta_{kl} - \delta_{il}\delta_{kj})/2}_{\text{antisymmetric: projects } \bar{\mathbf{3}}} + \frac{1}{3} \underbrace{(\delta_{ij}\delta_{kl} + \delta_{il}\delta_{kj})/2}_{\text{symmetric: projects } \mathbf{6}}$$

Diquarks: Color Representation

- One gluon exchange model [Jaffe,Phys.Rept.(2005)]



  - ➥ Color factor determines binding:
    Negative sign ➞ Attractive

- Quarks in diquark transform as:

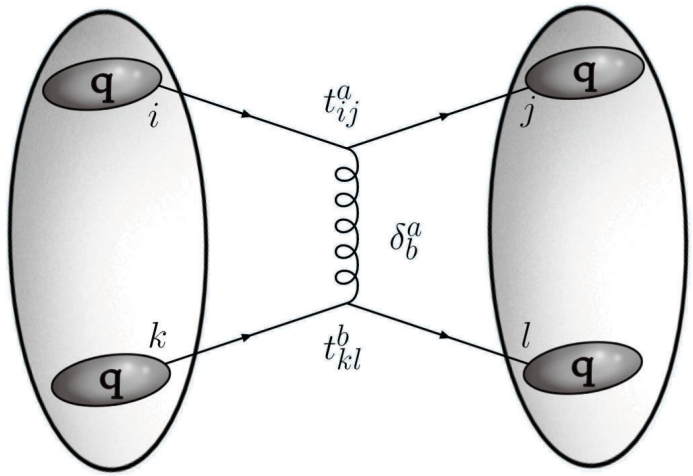
$$\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}} \oplus \mathbf{6}$$

- qq bound state color factor:

$$t^a_{ij} t^a_{kl} = \left(-\frac{2}{3}\right) \underbrace{(\delta_{ij}\delta_{kl} - \delta_{il}\delta_{kj})/2}_{\text{antisymmetric: projects } \bar{\mathbf{3}}} + \frac{1}{3} \underbrace{(\delta_{ij}\delta_{kl} + \delta_{il}\delta_{kj})/2}_{\text{symmetric: projects } \mathbf{6}}$$

Diquarks: Color Representation

- One gluon exchange model [Jaffe,Phys.Rept.(2005)]



  ↳ Color factor determines binding:
  Negative sign → Attractive

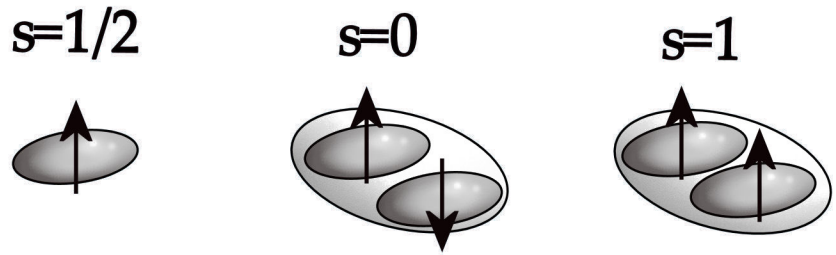
- Quarks in diquark transform as:

$$\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}} \oplus \mathbf{6}$$

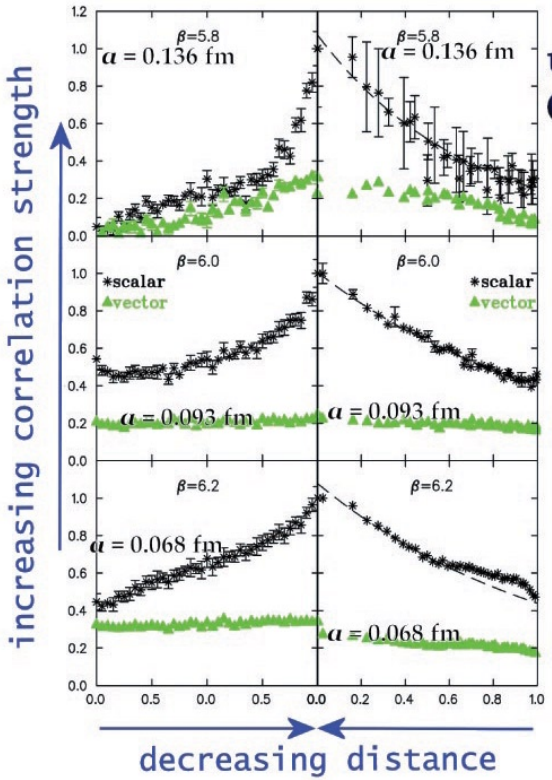
- qq bound state color factor:

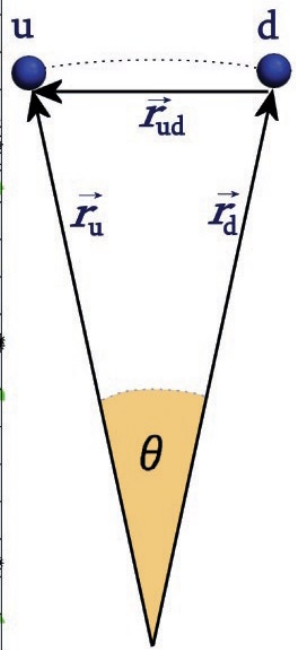
$$t^a_{ij} t^a_{kl} = \underbrace{-\frac{2}{3}}_{\text{antisymmetric: projects } \bar{\mathbf{3}}} \underbrace{(\delta_{ij}\delta_{kl} - \delta_{il}\delta_{kj})/2}_{} \underbrace{+\frac{1}{3}}_{\text{symmetric: projects } \mathbf{6}} \underbrace{(\delta_{ij}\delta_{kl} + \delta_{il}\delta_{kj})/2}_{}$$

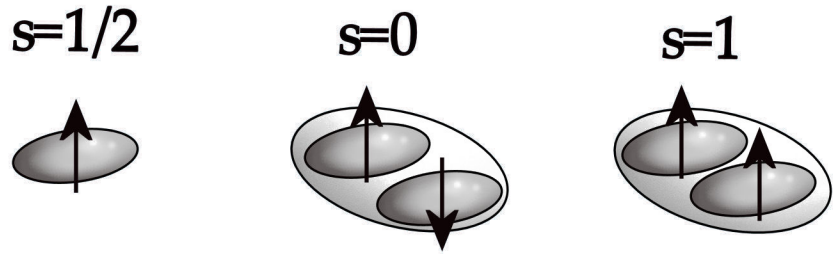
Diquarks: Spin representation



Diquarks: Spin representation



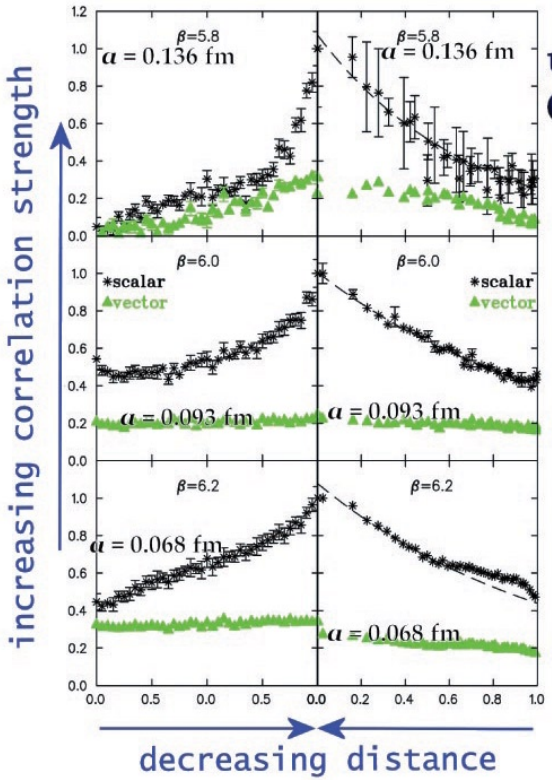


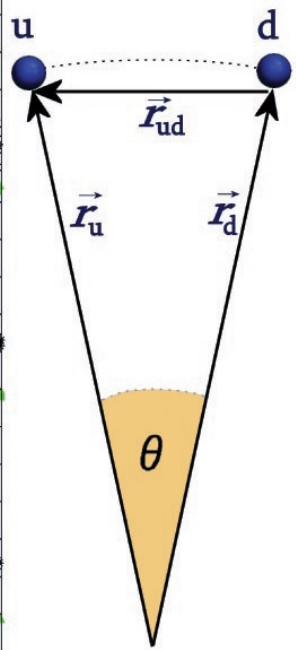


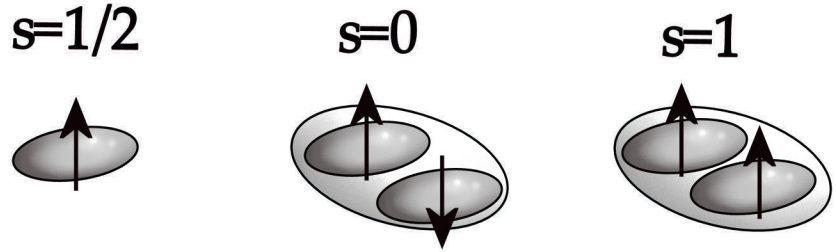
Lattice simulations for light quarks [Alexandrou, Forcrand, Lucini, PRL (2006)] :

- Calculation of 2 quark correlation strength
- Decreasing distance
  - ↪ Increasing strength for "good" diquarks
- Diquark size $\mathcal{O}(1\text{fm})$

Diquarks: Spin representation







Lattice simulations for light quarks [Alexandrou, Forcrand, Lucini, PRL (2006)] :

- Binding for "good" spin 0 diquarks
- No binding for "bad" spin 1 diquarks

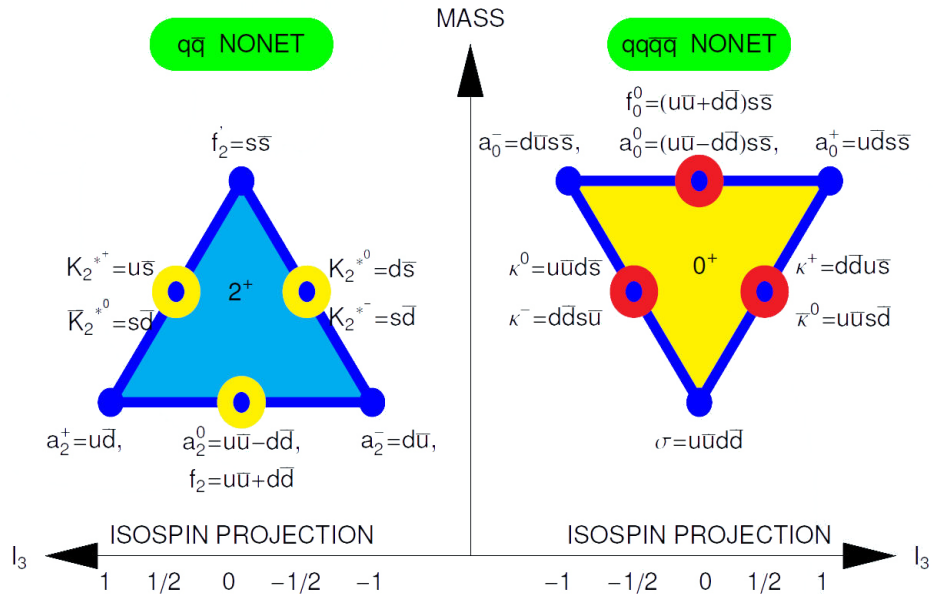
- Calculation of 2 quark correlation strength
- Decreasing distance
  - ⤷ Increasing strength for "good" diquarks
- Diquark size $\mathcal{O}(1\text{fm})$

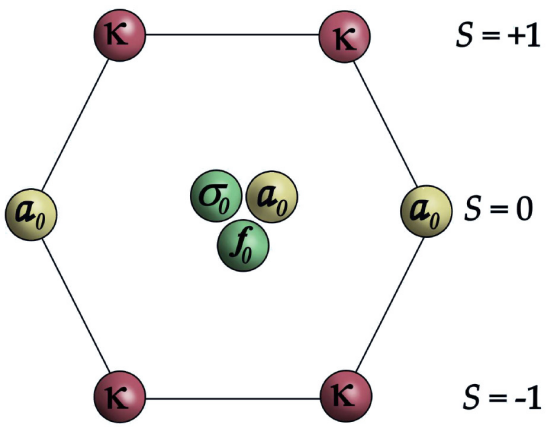
Spin decoupling in HQ-Limit

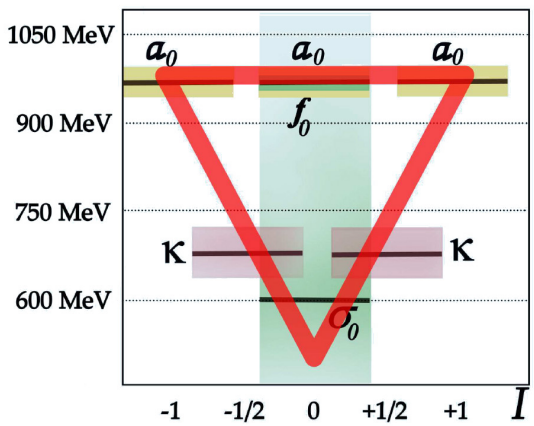
⤷ "Bad" diquarks in b-sector might bind

Constituent Quark Modell and Light States

- Masses for light resonances in constituent model
  - ⤷ Flavor nonets are arranged as triangles







- Tetraquark interpretation in agreement with experiment
  ['t Hooft, Isidori, Maiani, Polosa, Riquer, PLB (2008)]

NR States

Interpolating diquark operators ($P = -1$ larger energy):

$$\text{“good”:} \quad 0^+ \quad \mathcal{Q}_{i\alpha} = \epsilon_{\alpha\beta\gamma}(\bar{b}_c^\beta \gamma_5 q_i^\gamma - \bar{q}_{i_c}^\beta \gamma_5 b^\gamma)$$

$$\text{“bad”:} \quad 1^+ \quad \vec{\mathcal{Q}}_{i\alpha} = \epsilon_{\alpha\beta\gamma}(\bar{b}_c^\beta \vec{\gamma} q_i^\gamma + \bar{q}_{i_c}^\beta \vec{\gamma} b^\gamma)$$

α, β, γ: $SU(3)_C$ indices

NR States

Interpolating diquark operators ($P = -1$ larger energy):

$$\begin{aligned} \text{“good”:} \quad 0^+ \quad \mathcal{Q}_{i\alpha} &= \epsilon_{\alpha\beta\gamma}(\bar{b}_c^\beta \gamma_5 q_i^\gamma - \bar{q}_{i_c}^\beta \gamma_5 b^\gamma) \\ \text{“bad”:} \quad 1^+ \quad \vec{\mathcal{Q}}_{i\alpha} &= \epsilon_{\alpha\beta\gamma}(\bar{b}_c^\beta \vec{\gamma} q_i^\gamma + \bar{q}_{i_c}^\beta \vec{\gamma} b^\gamma) \end{aligned}$$

α, β, γ: $SU(3)_C$ indices

NR limit: States parametrized by Pauli matrices :

$$\begin{aligned} \text{“good”:} \quad 0^+ \quad \Gamma^0 &= \frac{\sigma_2}{\sqrt{2}} \\ \text{“bad”:} \quad 1^+ \quad \vec{\Gamma} &= \frac{\sigma_2 \vec{\sigma}}{\sqrt{2}} \end{aligned}$$

NR States

Interpolating diquark operators ($P = -1$ larger energy):

$$\begin{aligned} \text{“good”:} \quad 0^+ \quad \mathcal{Q}_{i\alpha} &= \epsilon_{\alpha\beta\gamma}(\bar{b}_c^\beta \gamma_5 q_i^\gamma - \bar{q}_{i_c}^\beta \gamma_5 b^\gamma) \\ \text{“bad”:} \quad 1^+ \quad \vec{\mathcal{Q}}_{i\alpha} &= \epsilon_{\alpha\beta\gamma}(\bar{b}_c^\beta \vec{\gamma} q_i^\gamma + \bar{q}_{i_c}^\beta \vec{\gamma} b^\gamma) \end{aligned}$$

α, β, γ: $SU(3)_C$ indices

NR limit: States parametrized by Pauli matrices :

$$\begin{aligned} \text{“good”:} \quad 0^+ \quad \Gamma^0 &= \frac{\sigma_2}{\sqrt{2}} \\ \text{“bad”:} \quad 1^+ \quad \vec{\Gamma} &= \frac{\sigma_2 \vec{\sigma}}{\sqrt{2}} \end{aligned}$$

Diquark spin $s_\mathcal{Q}$ ➞ tetraquark total angular momentum J:

$$\left|\Upsilon_{[bq]}\right\rangle = \left|s_\mathcal{Q}, s_{\bar{\mathcal{Q}}};\, J\right\rangle$$

➥ Tetraquark matrix representation:

$$\begin{aligned} \left|0_\mathcal{Q}, 0_{\bar{\mathcal{Q}}};\, 0_J\right\rangle &= \Gamma^0 \otimes \Gamma^0, \\ \left|1_\mathcal{Q}, 1_{\bar{\mathcal{Q}}};\, 0_J\right\rangle &= \frac{1}{\sqrt{3}} \Gamma^i \otimes \Gamma_i, \ldots \end{aligned}$$

NR Hamiltonian

States need to diagonalize Hamiltonian:

$$H = 2m_Q + H_{SS}^{(qq)} + H_{SS}^{(q\bar{q})} + H_{SL} + H_{LL}$$

NR Hamiltonian

States need to diagonalize Hamiltonian:

$$H = 2m_Q + H_{SS}^{(qq)} + H_{SS}^{(q\bar{q})} + H_{SL} + H_{LL}$$

with

constituent mass

NR Hamiltonian

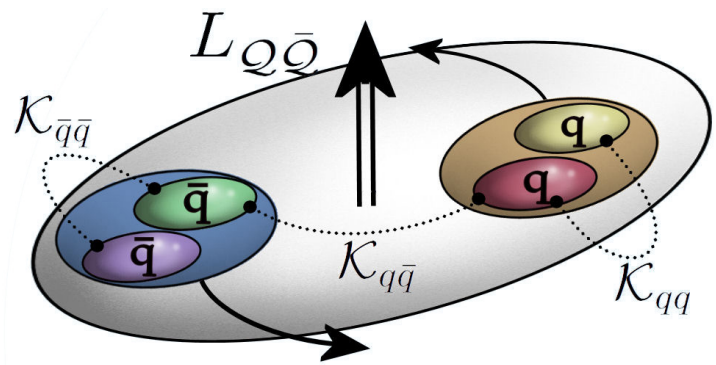
States need to diagonalize Hamiltonian:

$$H = 2m_Q + H_{SS}^{(qq)} + H_{SS}^{(q\bar{q})} + H_{SL} + H_{LL}$$

with qq spin coupling $q\bar{q}$ spin coupling

$$H_{SS}^{(qq)} = 2(\mathcal{K}_{bq})_{\bar{3}}[(\mathbf{S}_b \cdot \mathbf{S}_q) + (\mathbf{S}_{\bar{b}} \cdot \mathbf{S}_{\bar{q}})]$$

$$H_{SS}^{(q\bar{q})} = 2(\mathcal{K}_{b\bar{q}})(\mathbf{S}_b \cdot \mathbf{S}_{\bar{q}} + \mathbf{S}_{\bar{b}} \cdot \mathbf{S}_q) + 2\mathcal{K}_{b\bar{b}}(\mathbf{S}_b \cdot \mathbf{S}_{\bar{b}}) + 2\mathcal{K}_{q\bar{q}}(\mathbf{S}_q \cdot \mathbf{S}_{\bar{q}})$$



NR Hamiltonian

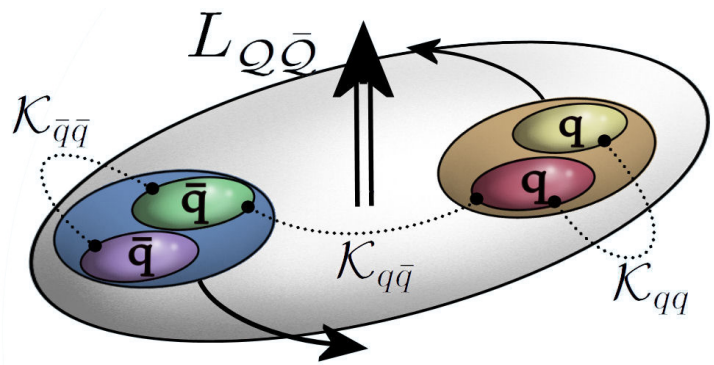
States need to diagonalize Hamiltonian:

$$H = 2m_{\mathcal{Q}} + H_{SS}^{(qq)} + H_{SS}^{(q\bar{q})} + H_{SL} + H_{LL}$$

LS coupling LL coupling

with

$$\begin{aligned}
H_{SS}^{(qq)} &= 2(\mathcal{K}_{bq})_{\bar{3}}[(\mathbf{S}_b \cdot \mathbf{S}_q) + (\mathbf{S}_{\bar{b}} \cdot \mathbf{S}_{\bar{q}})] \\
H_{SS}^{(q\bar{q})} &= 2(\mathcal{K}_{b\bar{q}})(\mathbf{S}_b \cdot \mathbf{S}_{\bar{q}} + \mathbf{S}_{\bar{b}} \cdot \mathbf{S}_q) \\
&\quad + 2\mathcal{K}_{b\bar{b}}(\mathbf{S}_b \cdot \mathbf{S}_{\bar{b}}) + 2\mathcal{K}_{q\bar{q}}(\mathbf{S}_q \cdot \mathbf{S}_{\bar{q}}) \\
H_{SL} &= 2A_{\mathcal{Q}}(\mathbf{S}_{\mathcal{Q}} \cdot \mathbf{L} + \mathbf{S}_{\bar{\mathcal{Q}}} \cdot \mathbf{L}) \\
H_{LL} &= B_{\mathcal{Q}} \frac{L_{\mathcal{Q}\bar{\mathcal{Q}}}(L_{\mathcal{Q}\bar{\mathcal{Q}}} + 1)}{2}
\end{aligned}$$



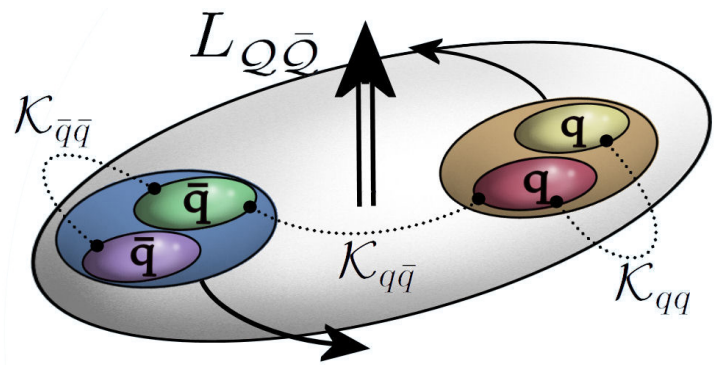
NR Hamiltonian

States need to diagonalize Hamiltonian:

$$H = 2m_{\mathcal{Q}} + H_{SS}^{(qq)} + H_{SS}^{(q\bar{q})} + H_{SL} + H_{LL}$$

with

$$\begin{aligned}
H_{SS}^{(qq)} &= 2(\mathcal{K}_{bq})_{\bar{3}}[(\mathbf{S}_b \cdot \mathbf{S}_q) + (\mathbf{S}_{\bar{b}} \cdot \mathbf{S}_{\bar{q}})] \\
H_{SS}^{(q\bar{q})} &= 2(\mathcal{K}_{b\bar{q}})(\mathbf{S}_b \cdot \mathbf{S}_{\bar{q}} + \mathbf{S}_{\bar{b}} \cdot \mathbf{S}_q) \\
&\quad + 2\mathcal{K}_{b\bar{b}}(\mathbf{S}_b \cdot \mathbf{S}_{\bar{b}}) + 2\mathcal{K}_{q\bar{q}}(\mathbf{S}_q \cdot \mathbf{S}_{\bar{q}}) \\
H_{SL} &= 2A_{\mathcal{Q}}(\mathbf{S}_{\mathcal{Q}} \cdot \mathbf{L} + \mathbf{S}_{\bar{\mathcal{Q}}} \cdot \mathbf{L}) \\
H_{LL} &= B_{\mathcal{Q}} \frac{L_{\mathcal{Q}\bar{\mathcal{Q}}}(L_{\mathcal{Q}\bar{\mathcal{Q}}} + 1)}{2}
\end{aligned}$$



fit to known hadrons ➞ coefficients

NR spin operators

spin operators via Pauli matrices $\mathbf{S}_q = \frac{1}{2}\vec{\sigma}$:

$$\begin{array}{rclrcl} \mathbf{S}_b(\Gamma \otimes \Gamma') & = & (\frac{1}{2}\vec{\sigma}^T\Gamma \otimes \Gamma') & \mathbf{S}_q(\Gamma \otimes \Gamma') & = & (\Gamma\frac{1}{2}\vec{\sigma} \otimes \Gamma') \\ \mathbf{S}_{\bar{b}}(\Gamma \otimes \Gamma') & = & (\Gamma \otimes \frac{1}{2}\vec{\sigma}^T\Gamma') & \mathbf{S}_{\bar{q}}(\Gamma \otimes \Gamma') & = & (\Gamma \otimes \Gamma'\frac{1}{2}\vec{\sigma}) \end{array}$$

$$\Gamma^{(\prime)} = \frac{\sigma_2}{\sqrt{2}}, \frac{\sigma_2\vec{\sigma}}{\sqrt{2}}$$

NR spin operators

spin operators via Pauli matrices $\mathbf{S}_q = \frac{1}{2}\vec{\sigma}$:

$$\begin{array}{rclrcl} \mathbf{S}_b(\Gamma \otimes \Gamma') & = & (\frac{1}{2}\vec{\sigma}^T\Gamma \otimes \Gamma') & \mathbf{S}_q(\Gamma \otimes \Gamma') & = & (\Gamma\frac{1}{2}\vec{\sigma} \otimes \Gamma') \\ \mathbf{S}_{\bar{b}}(\Gamma \otimes \Gamma') & = & (\Gamma \otimes \frac{1}{2}\vec{\sigma}^T\Gamma') & \mathbf{S}_{\bar{q}}(\Gamma \otimes \Gamma') & = & (\Gamma \otimes \Gamma'\frac{1}{2}\vec{\sigma}) \end{array}$$

$$\Gamma^{(\prime)} = \frac{\sigma_2}{\sqrt{2}}, \frac{\sigma_2\vec{\sigma}}{\sqrt{2}}$$

For example:

$$\mathbf{S}_q.\mathbf{S}_{\bar{q}}|1,0;1> = \frac{1}{8}(\sigma_2\sigma^j\sigma_i) \otimes (\sigma_2\sigma^i)$$

NR spin operators

spin operators via Pauli matrices $\mathbf{S}_q = \frac{1}{2}\vec{\sigma}$:

$$\begin{aligned} \mathbf{S}_b(\Gamma \otimes \Gamma') &= (\tfrac{1}{2}\vec{\sigma}^T\Gamma \otimes \Gamma') & \mathbf{S}_q(\Gamma \otimes \Gamma') &= (\Gamma\tfrac{1}{2}\vec{\sigma} \otimes \Gamma') \\ \mathbf{S}_{\bar{b}}(\Gamma \otimes \Gamma') &= (\Gamma \otimes \tfrac{1}{2}\vec{\sigma}^T\Gamma') & \mathbf{S}_{\bar{q}}(\Gamma \otimes \Gamma') &= (\Gamma \otimes \Gamma'\tfrac{1}{2}\vec{\sigma}) \end{aligned}$$

$$\Gamma^{(\prime)} = \frac{\sigma_2}{\sqrt{2}}, \frac{\sigma_2\vec{\sigma}}{\sqrt{2}}$$

For example:

$$\begin{aligned} \mathbf{S}_q.\mathbf{S}_{\bar{q}}|1,0;1> &= \frac{1}{8}(\sigma_2\sigma^j\sigma_i) \otimes (\sigma_2\sigma^i) \\ &= -\frac{i}{8}\epsilon^{jki}(\sigma_2\sigma_k) \otimes (\sigma_2\sigma_i) + \frac{1}{8}(\sigma_2) \otimes (\sigma_2\sigma^j) \end{aligned}$$

NR spin operators

spin operators via Pauli matrices $\mathbf{S}_q = \frac{1}{2}\vec{\sigma}$:

$$\begin{aligned} \mathbf{S}_b(\Gamma \otimes \Gamma') &= (\tfrac{1}{2}\vec{\sigma}^T\Gamma \otimes \Gamma') & \mathbf{S}_q(\Gamma \otimes \Gamma') &= (\Gamma\tfrac{1}{2}\vec{\sigma} \otimes \Gamma') \\ \mathbf{S}_{\bar{b}}(\Gamma \otimes \Gamma') &= (\Gamma \otimes \tfrac{1}{2}\vec{\sigma}^T\Gamma') & \mathbf{S}_{\bar{q}}(\Gamma \otimes \Gamma') &= (\Gamma \otimes \Gamma'\tfrac{1}{2}\vec{\sigma}) \end{aligned}$$

$$\Gamma^{(\prime)} = \frac{\sigma_2}{\sqrt{2}}, \frac{\sigma_2\vec{\sigma}}{\sqrt{2}}$$

For example:

$$\begin{aligned} \mathbf{S}_q.\mathbf{S}_{\bar{q}}|1,0;1> &= \frac{1}{8}(\sigma_2\sigma^j\sigma_i) \otimes (\sigma_2\sigma^i) \\ &= -\frac{i}{8}\epsilon^{jki}(\sigma_2\sigma_k) \otimes (\sigma_2\sigma_i) + \frac{1}{8}(\sigma_2) \otimes (\sigma_2\sigma^j) \\ &= -\frac{i\sqrt{2}}{4}|1,1;1> + \frac{1}{4}|0,1;1> \end{aligned}$$

Example 1^{++} state

$[\bar{b}\bar{q}][bq]$state:

$$\left|1^{++}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|0_{\mathcal{Q}}, 1_{\bar{\mathcal{Q}}};\, 1_J\right\rangle + \left|1_{\mathcal{Q}}, 0_{\bar{\mathcal{Q}}};\, 1_J\right\rangle\right)$$

Example 1^{++} state

$[\bar{b}\bar{q}][bq]$state:

$$\left|1^{++}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|0_{\mathcal{Q}}, 1_{\bar{\mathcal{Q}}};\, 1_J\right\rangle + \left|1_{\mathcal{Q}}, 0_{\bar{\mathcal{Q}}};\, 1_J\right\rangle\right)$$

Mass $M\left(1^{++}\right) = \left\langle 1^{++}\right| H \left|1^{++}\right\rangle$:

Example 1^{++} state

$[\bar{b}\bar{q}][bq]$state:

$$\left|1^{++}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|0_{\mathcal{Q}}, 1_{\bar{\mathcal{Q}}};\, 1_J\right\rangle + \left|1_{\mathcal{Q}}, 0_{\bar{\mathcal{Q}}};\, 1_J\right\rangle\right)$$

Mass $M\left(1^{++}\right) = \left\langle 1^{++}\right| H \left|1^{++}\right\rangle$:

$$M\left(1^{++}\right) = 2m_{[bq]} - (\mathcal{K}_{bq})_{\bar{3}} + \frac{1}{2}\mathcal{K}_{q\bar{q}} - \mathcal{K}_{b\bar{q}} + \frac{1}{2}\mathcal{K}_{b\bar{b}}$$

Example 1^{++} state

$[\bar{b}\bar{q}][bq]$state:

$$\left|1^{++}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|0_{\mathcal{Q}}, 1_{\bar{\mathcal{Q}}};\, 1_J\right\rangle + \left|1_{\mathcal{Q}}, 0_{\bar{\mathcal{Q}}};\, 1_J\right\rangle\right)$$

Mass $M\left(1^{++}\right) = \left\langle 1^{++}\right| H \left|1^{++}\right\rangle$:

$$M\left(1^{++}\right) = 2m_{[bq]} - \left(\mathcal{K}_{bq}\right)_{\bar{3}} + \frac{1}{2}\mathcal{K}_{q\bar{q}} - \mathcal{K}_{b\bar{q}} + \frac{1}{2}\mathcal{K}_{b\bar{b}}$$

Example parameters from known hadron spectrum:

$m_{[bq]}$	$\left(\mathcal{K}_{bq}\right)_{\bar{3}}$	$\mathcal{K}_{b\bar{q}}$	$\mathcal{K}_{q\bar{q}}$	$\mathcal{K}_{b\bar{b}}$
5250 MeV	6 MeV	6 MeV	80 MeV	9 MeV

Example 1^{++} state

$[\bar{b}\bar{q}][bq]$state:

$$\left|1^{++}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|0_{\mathcal{Q}}, 1_{\bar{\mathcal{Q}}};\, 1_J\right\rangle + \left|1_{\mathcal{Q}}, 0_{\bar{\mathcal{Q}}};\, 1_J\right\rangle\right)$$

Mass $M\left(1^{++}\right) = \left\langle 1^{++}\right| H \left|1^{++}\right\rangle$:

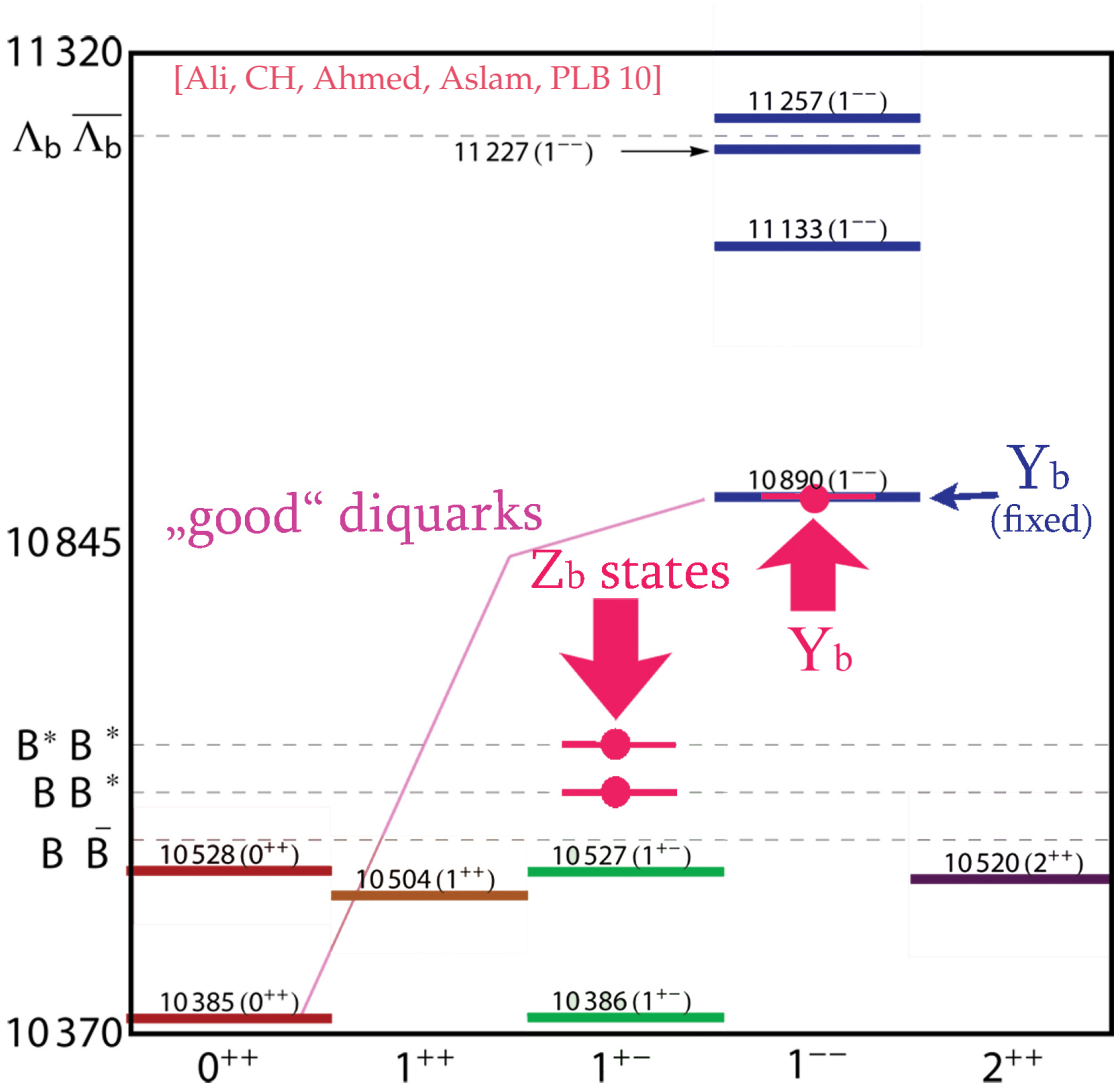
$$M\left(1^{++}\right) = 2m_{[bq]} - \left(\mathcal{K}_{bq}\right)_{\bar{3}} + \frac{1}{2}\mathcal{K}_{q\bar{q}} - \mathcal{K}_{b\bar{q}} + \frac{1}{2}\mathcal{K}_{b\bar{b}}$$

Example parameters from known hadron spectrum:

$m_{[bq]}$	$\left(\mathcal{K}_{bq}\right)_{\bar{3}}$	$\mathcal{K}_{b\bar{q}}$	$\mathcal{K}_{q\bar{q}}$	$\mathcal{K}_{b\bar{b}}$
5250 MeV	6 MeV	6 MeV	80 MeV	9 MeV

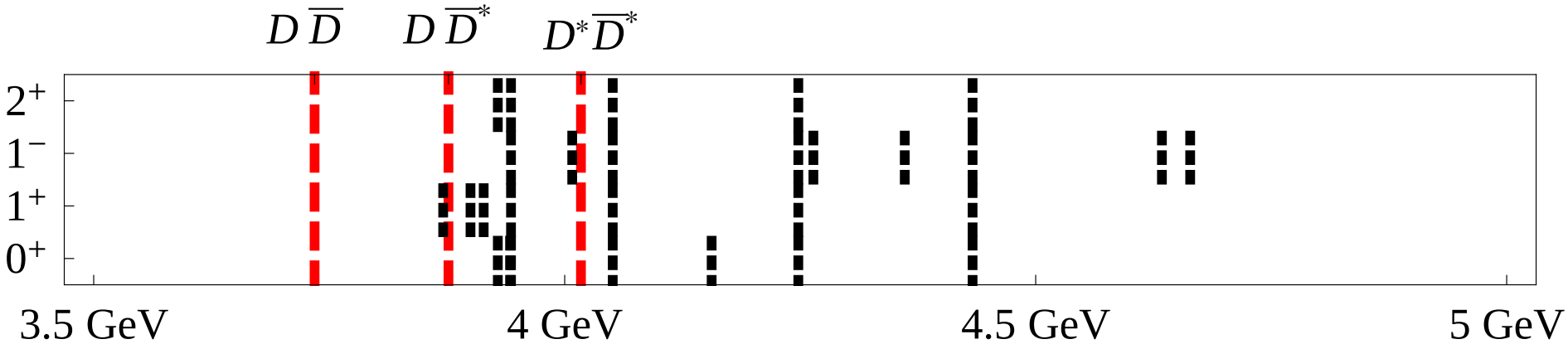
$\hookrightarrow$ $M(1^{++}) = 10533$ MeV ...repeat...

$[bq][\bar{b}\bar{q}]$ Constituent Model Spectrum



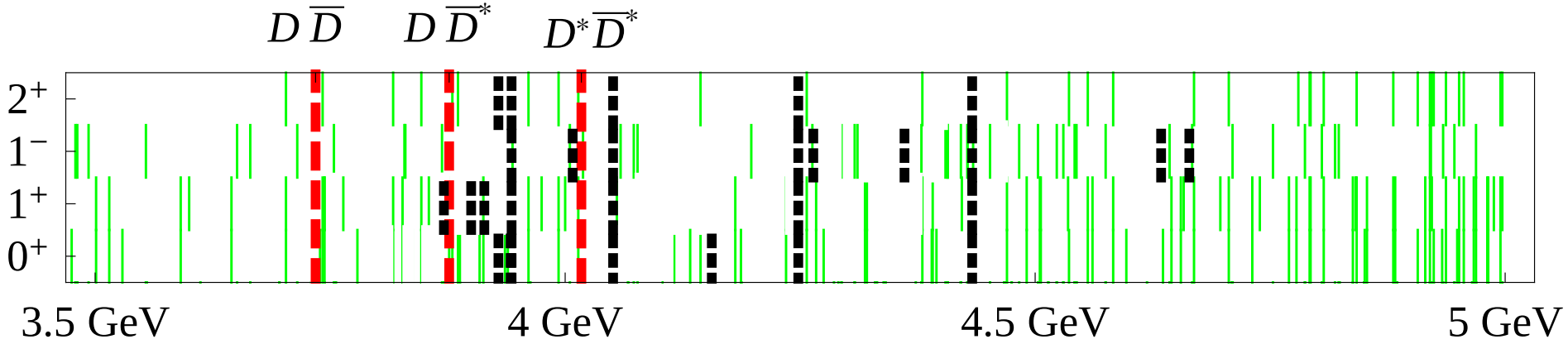
- HQ symmetry motivates fixing (diquark mass estimate from charm 30 MeV off)
- states are iso-doublets $q = u, d$
- tetraquark $Z_b$masses do not agree with Belle
- However tetraquarks with mixing & self energy corrections in principle allowed in parts of parameter space [Ali, CH, Wang, PRD 11]

$c\bar{c}$ Masses Theory vs Experiment



- - - measured exotica

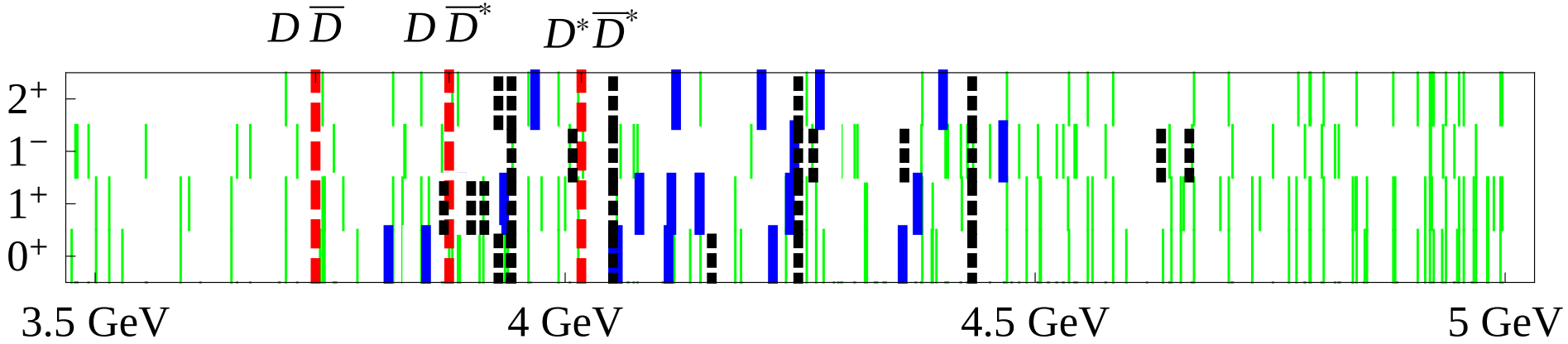
$c\bar{c}$ Masses Theory vs Experiment



- - - measured exotica

—— molecule masses (illustrative combination from [PDG])

$c\bar{c}$ Masses Theory vs Experiment

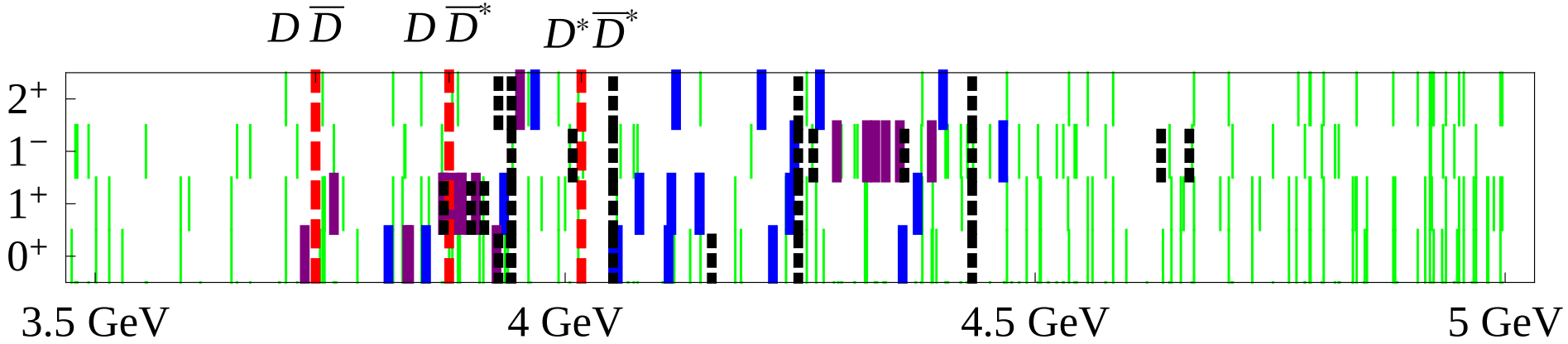


- - - measured exotica

—— molecule masses (illustrative combination from [PDG])

—— relativistic quark model tetraquark estimates (coulomb + conf. potential fixed from mesons) (but $m_{\Upsilon_b} = 10807$ MeV not far away)
[Ebert, Faustov, Galkin, PLB 06], [Ebert, Faustov, Galkin, Lucha, PRD 07]

$c\bar{c}$ Masses Theory vs Experiment



- - - measured exotica

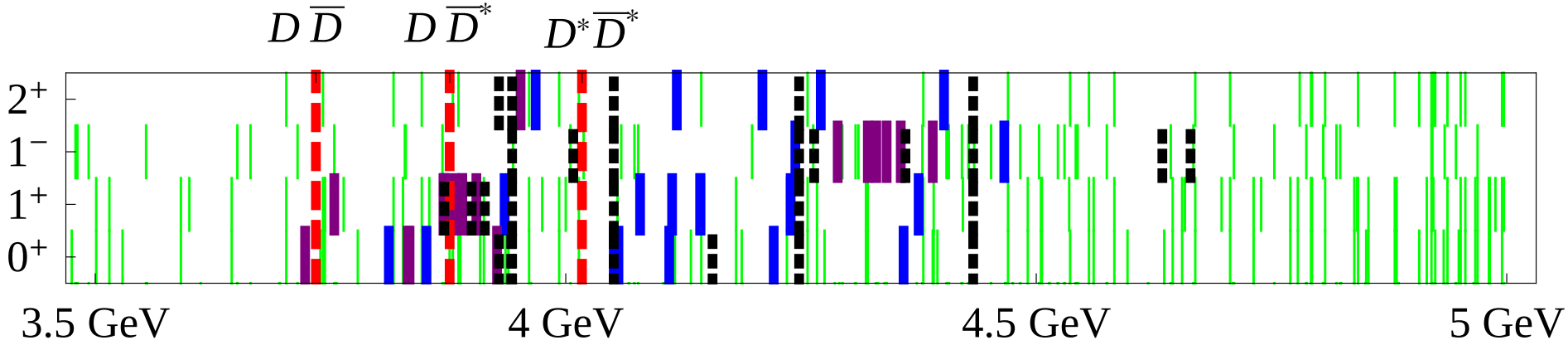
—— molecule masses (illustrative combination from [PDG])

—— relativistic quark model tetraquark estimates (coulomb + conf. potential fixed from mesons) (but $m_{\Upsilon_b} = 10807$ MeV not far away)
[Ebert, Faustov, Galkin, PLB 06], [Ebert, Faustov, Galkin, Lucha, PRD 07]

—— constituent quark model (effective hamiltonian fixed from common hadrons)
[Maiani, Piccinini, Polosa, Riquer, PRD 05], [Drenska, Faccini, Polosa, PRD 09]

…(QCDSR tetraquark estimates (not shown) also not consistent)

$c\bar{c}$ Masses Theory vs Experiment



- - - measured exotica

—— molecule masses (illustrative combination from [PDG])

—— relativistic quark model tetraquark estimates (coulomb + conf. potential fixed from mesons) (but $m_{\Upsilon_b} = 10807$ MeV not far away)
[Ebert, Faustov, Galkin, PLB 06], [Ebert, Faustov, Galkin, Lucha, PRD 07]

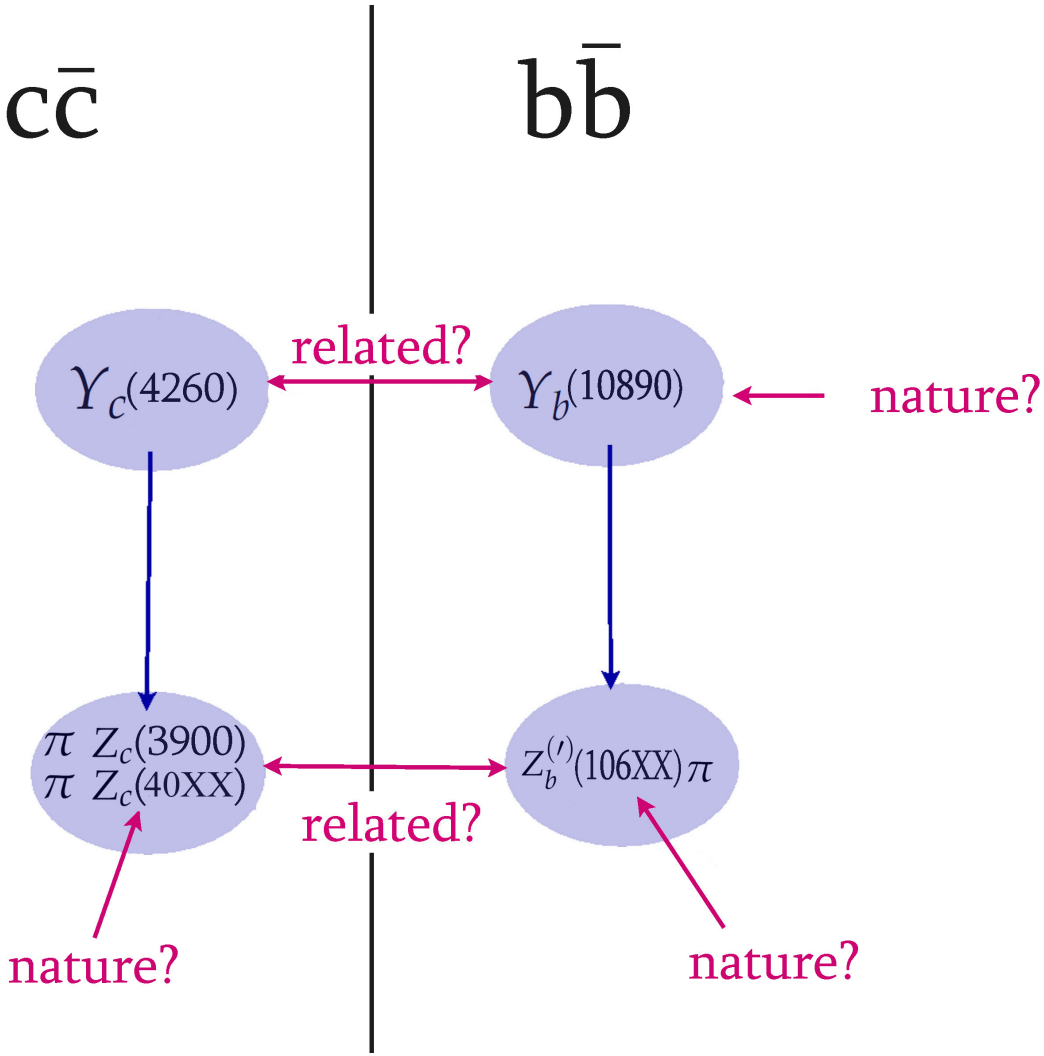
—— constituent quark model (effective hamiltonian fixed from common hadrons)
[Maiani, Piccinini, Polosa, Riquer, PRD 05], [Drenska, Faccini, Polosa, PRD 09]

…(QCDSR tetraquark estimates (not shown) also not consistent)

→ messy! - no model independent studies

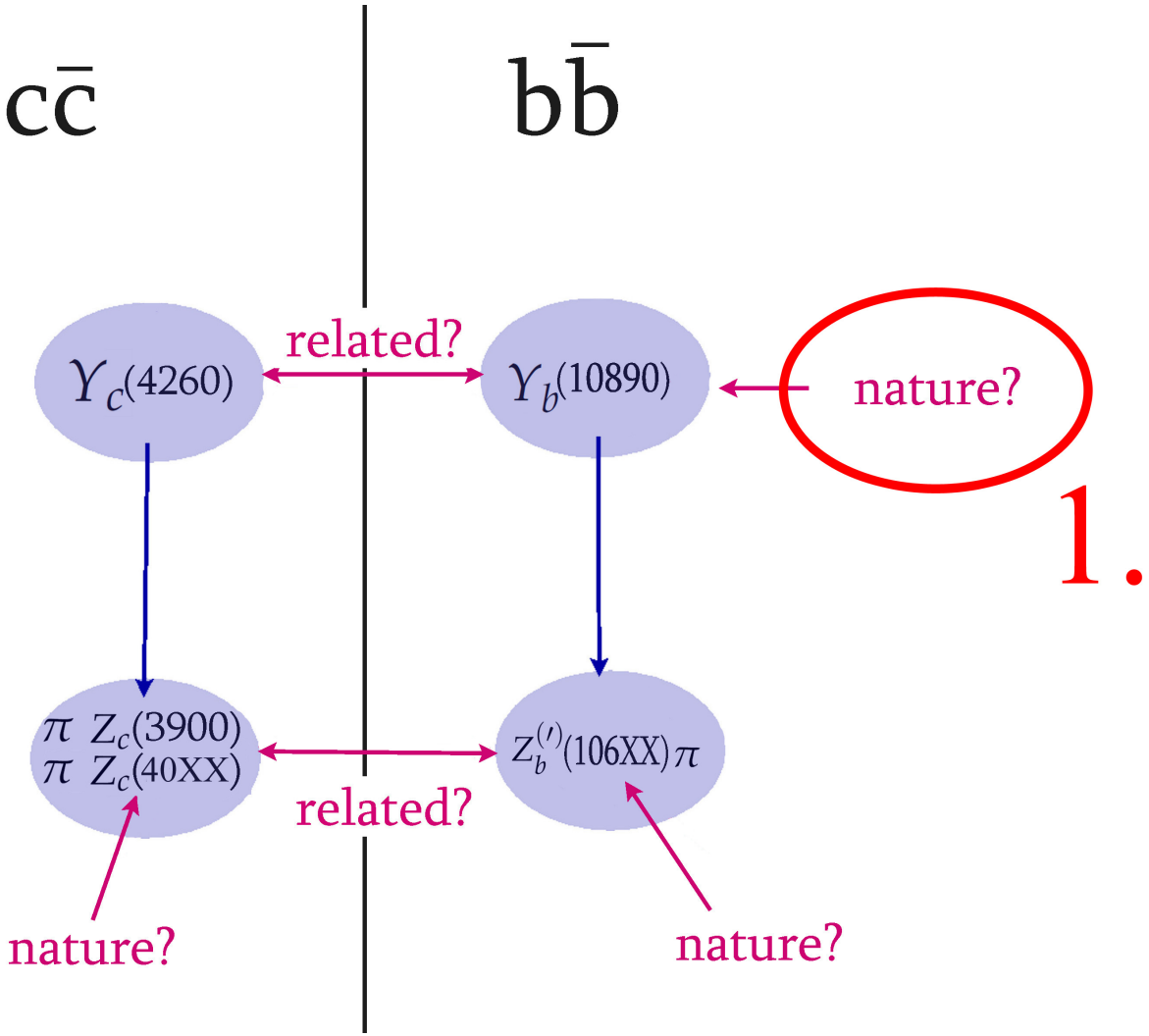
↪ find relations & look at decays

Relation $c\bar{c}$ & $b\bar{b}$



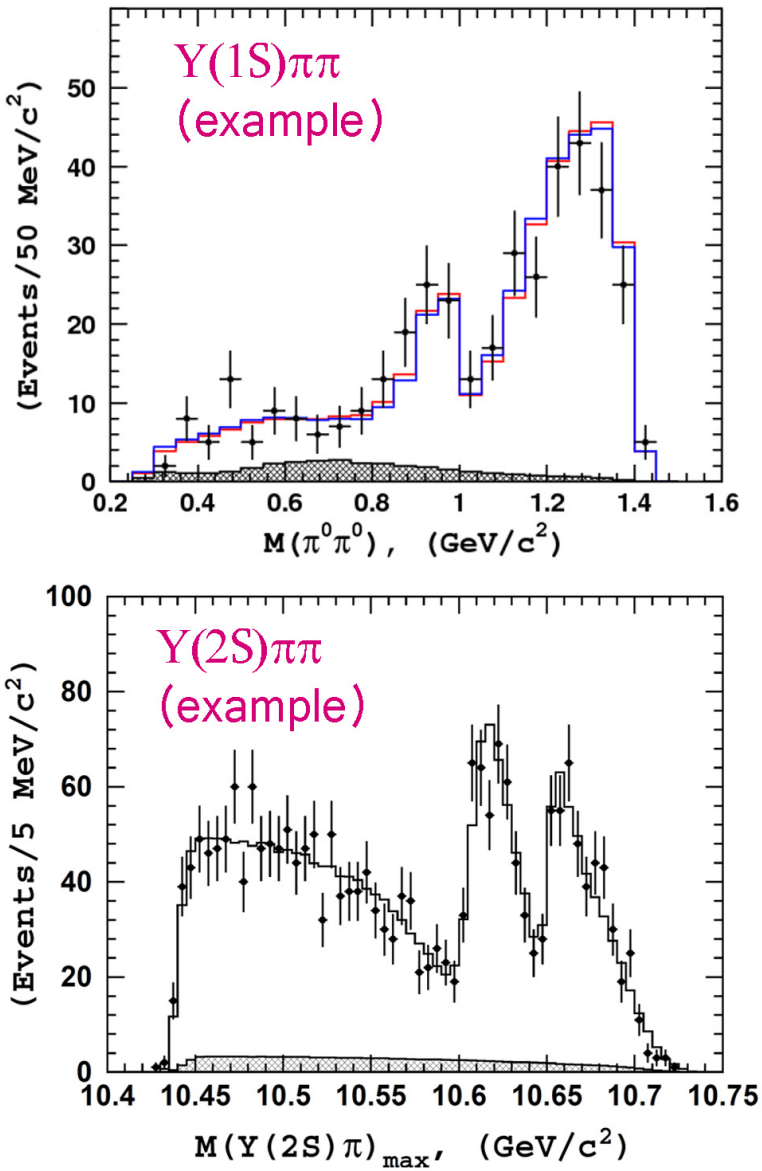
- Understanding heavy exotica means to understand both sectors!
- Only 3 candidates in $b\bar{b}$ → this is a key puzzle!

Relation $c\bar{c}$ & $b\bar{b}$

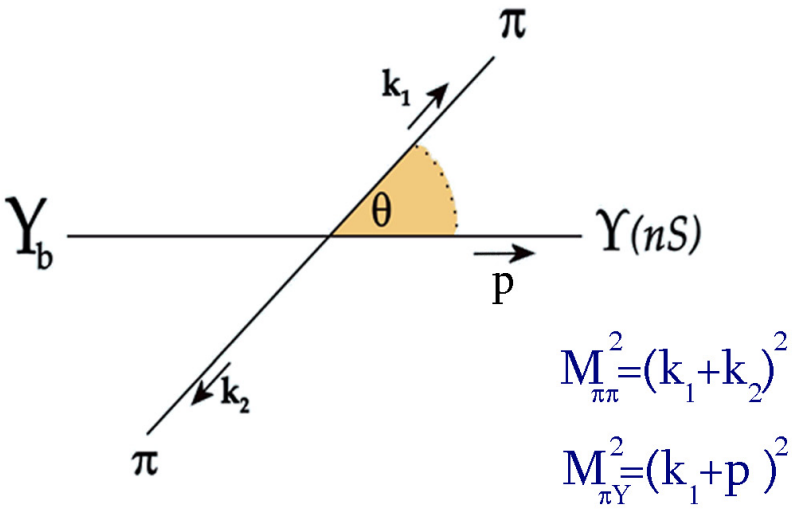


- Understanding heavy exotica means to understand both sectors!
- Only 3 candidates in $b\bar{b}$ → this is a key puzzle!

Why is the data @Y(5S) anomalous?



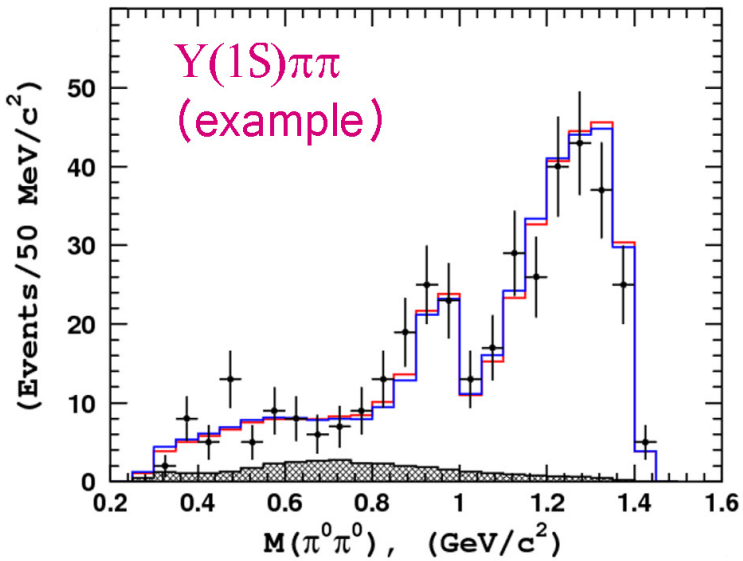
[Belle Collaboration (2012)]

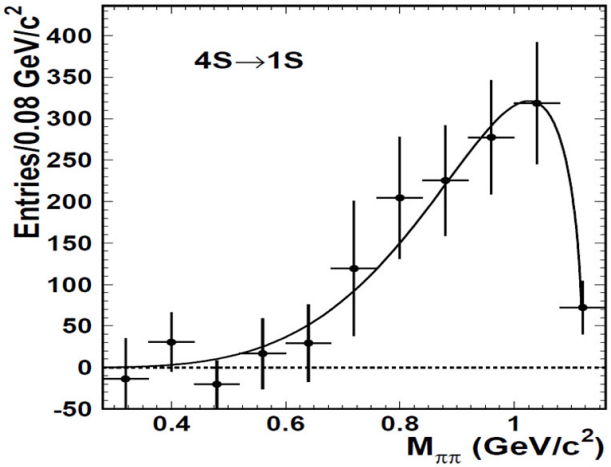


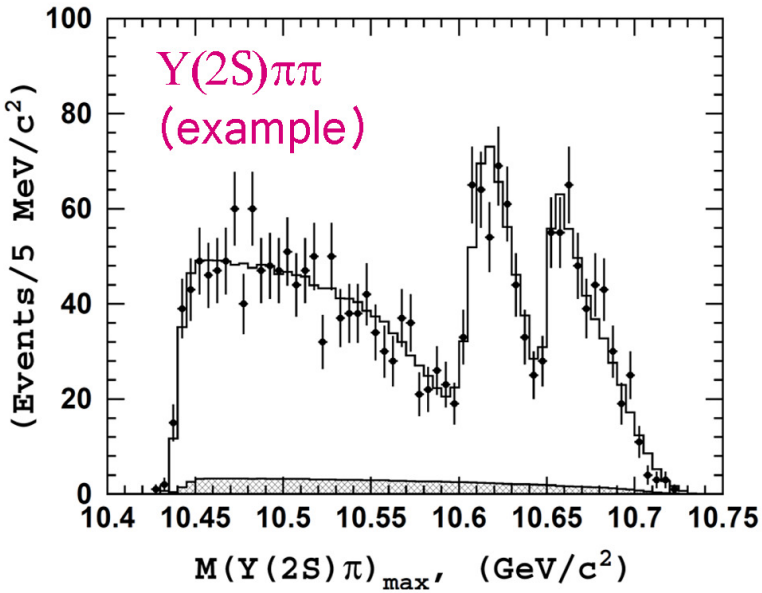
$$M^2_{\pi\pi}=(k_1+k_2)^2$$

$$M^2_{\pi\Upsilon}=(k_1+p)^2$$

Why is the data @Y(5S) anomalous?



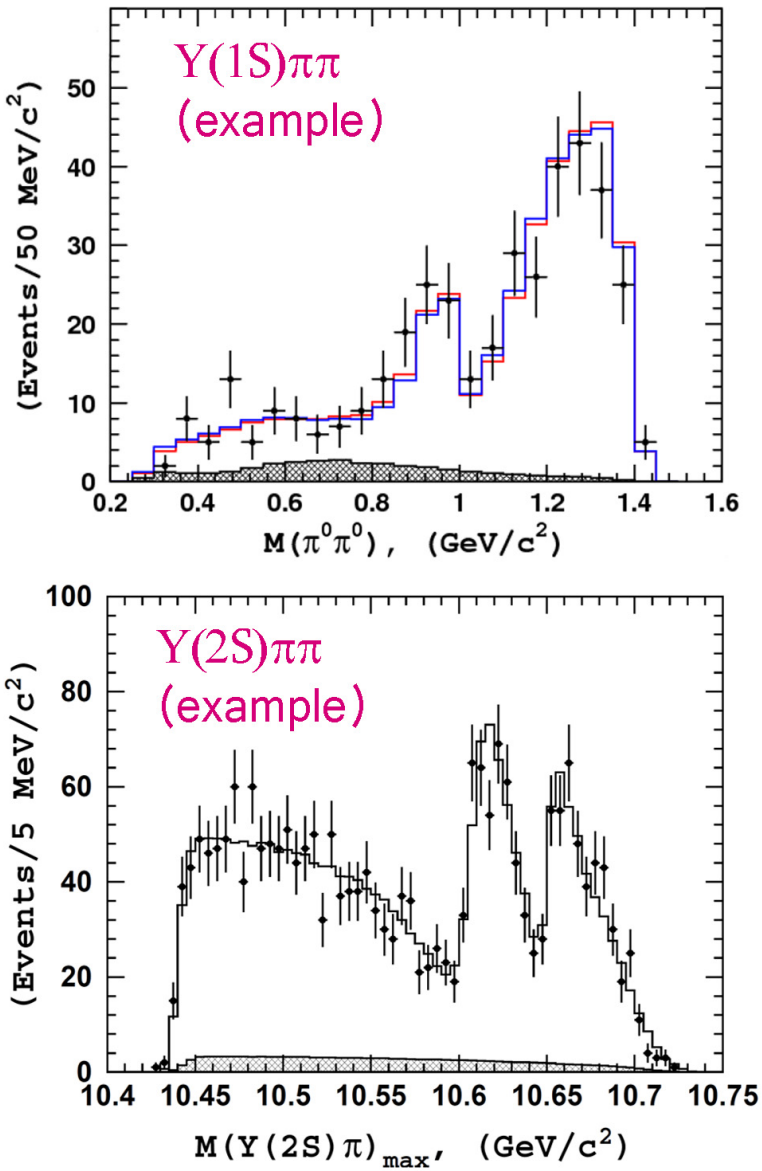


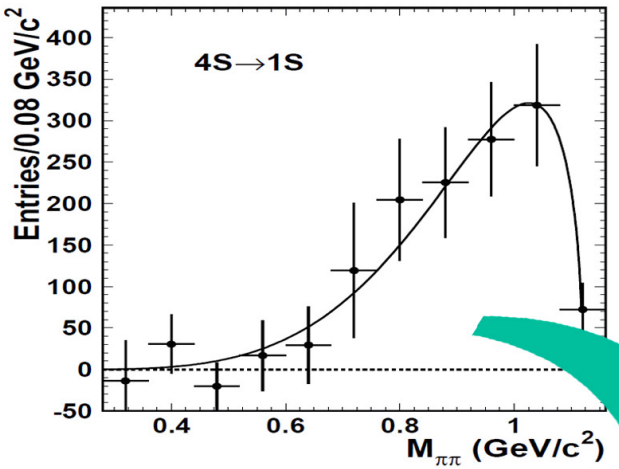


[Belle Collaboration (2012)]

Why is the data @Υ(5S) anomalous?

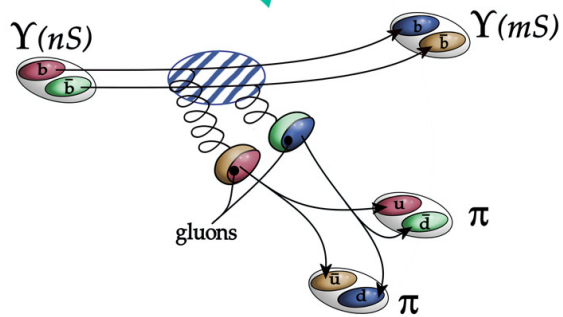
[Belle Collaboration (2012)]





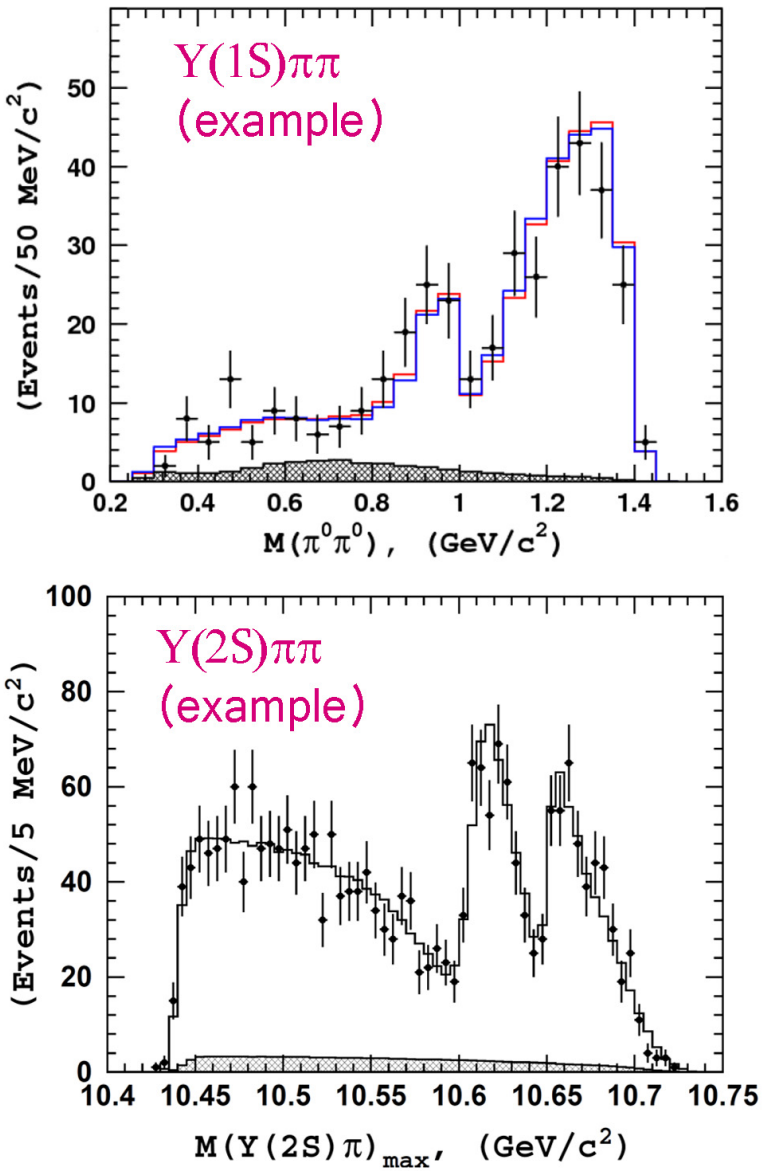
theory works well (multipole exp.) [Brown, Cahn PRL 75] [Voloshin, JETP 75]

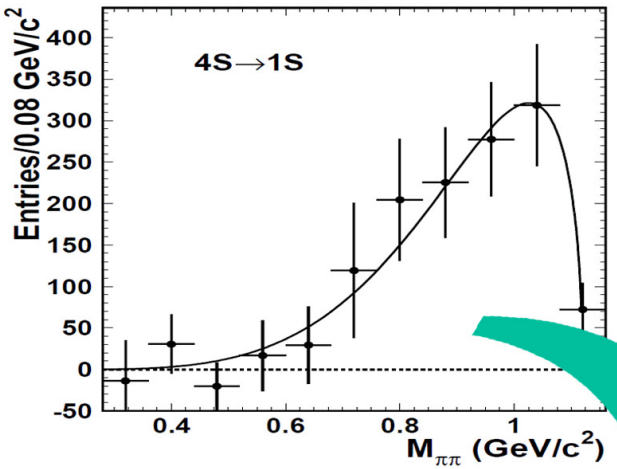
Process:



Why is the data @Υ(5S) anomalous?

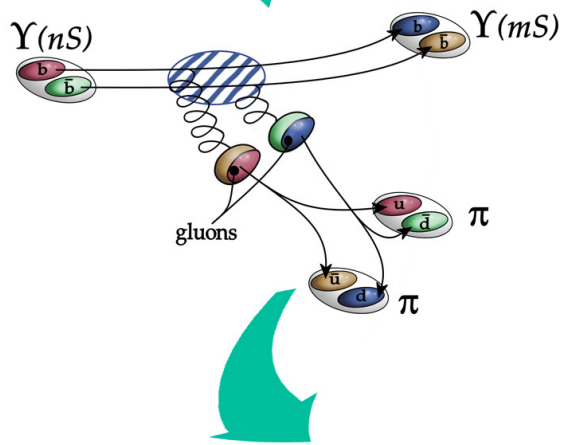
[Belle Collaboration (2012)]





theory works well (multipole exp.) [Brown, Cahn PRL 75] [Voloshin, JETP 75]

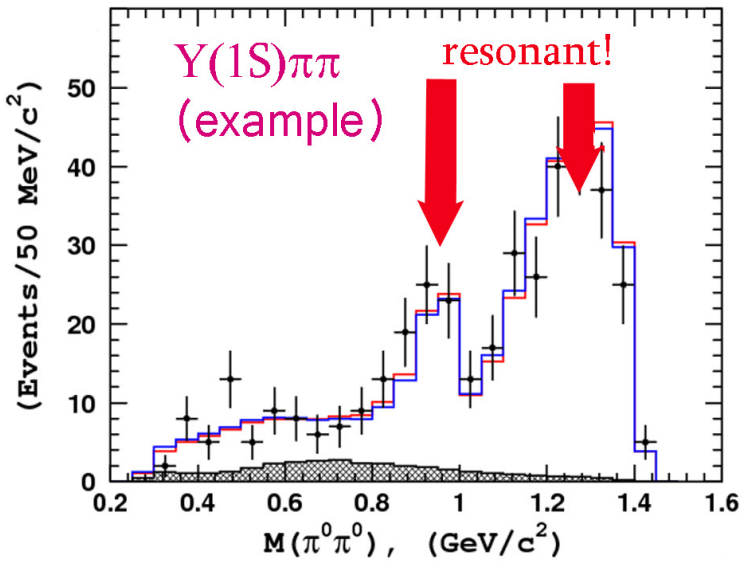
Process:

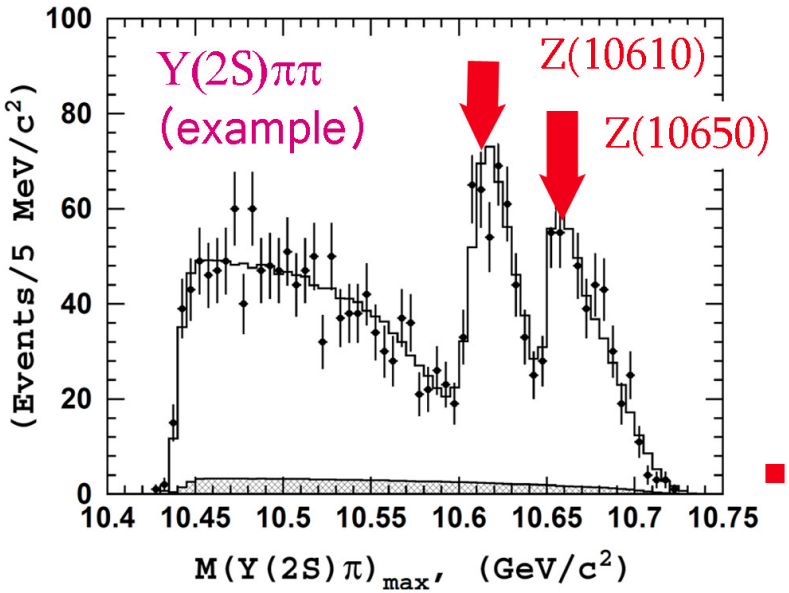


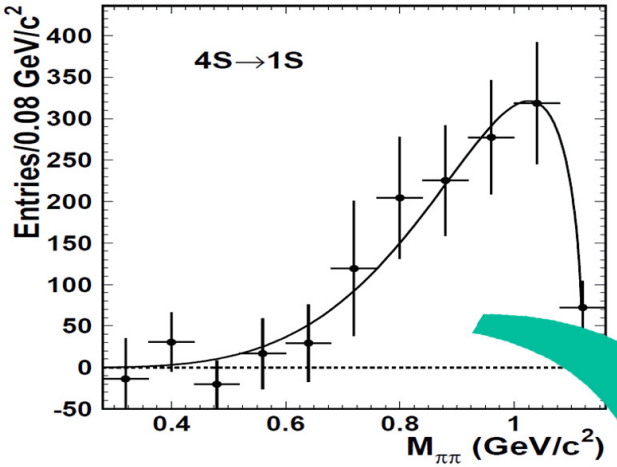
- NO resonant structure
- Zweig forbidden

Why is the data @Υ(5S) anomalous?

[Belle Collaboration (2012)]

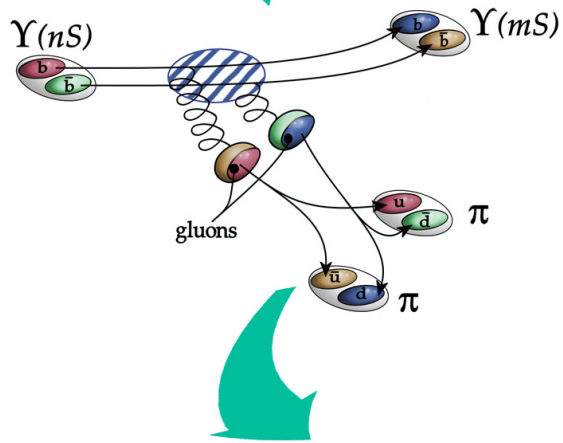






theory works well (multipole exp.)
[Brown, Cahn PRL 75]
[Voloshin, JETP 75]

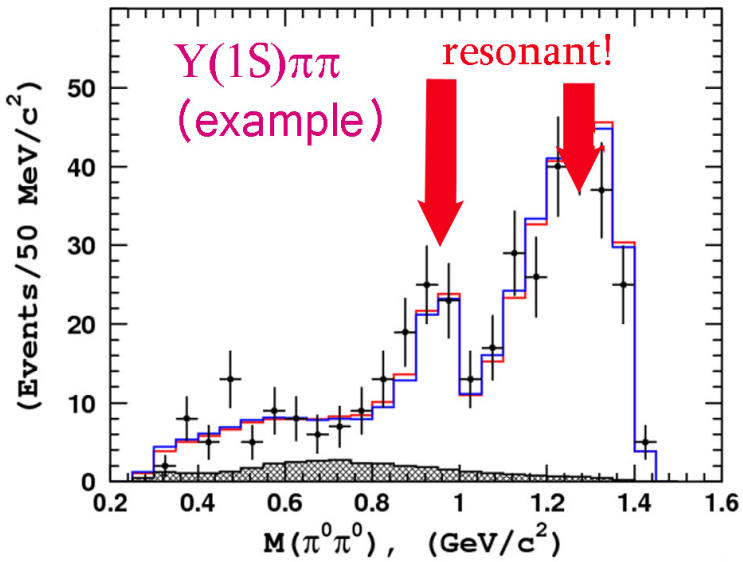
Process:

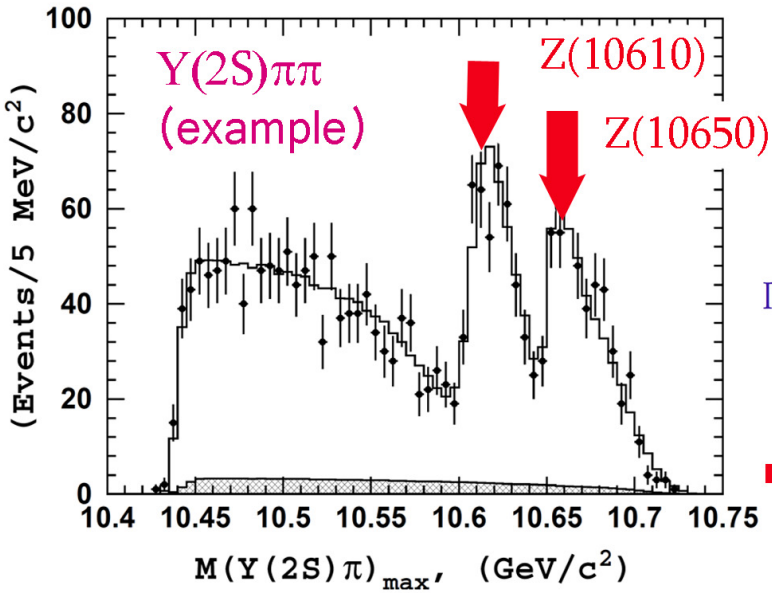


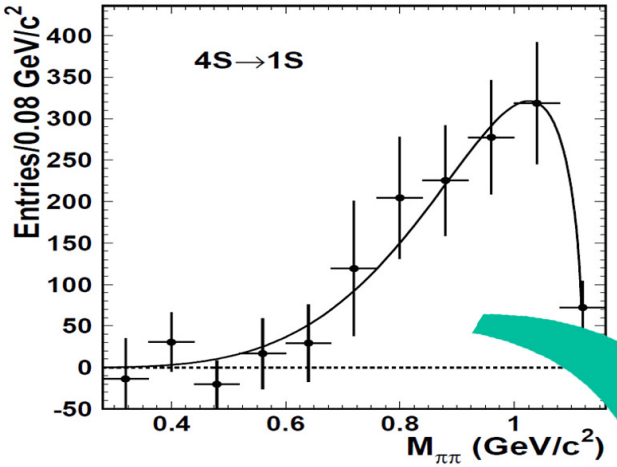
- distinct resonant structure ↯
- NO resonant structure
- Zweig forbidden

Why is the data @Υ(5S) anomalous?

[Belle Collaboration (2012)]

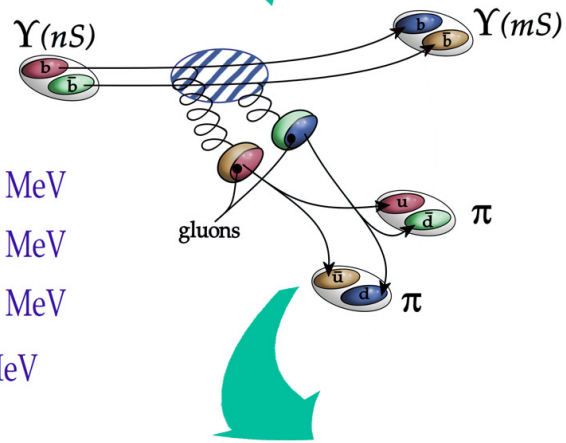






theory works well (multipole exp.) [Brown, Cahn PRL 75] [Voloshin, JETP 75]

Process:



$\Gamma(\Upsilon(2S) \to \Upsilon(1S)\pi\pi) \approx 0.0060$ MeV

$\Gamma(\Upsilon(3S) \to \Upsilon(1S)\pi\pi) \approx 0.0009$ MeV

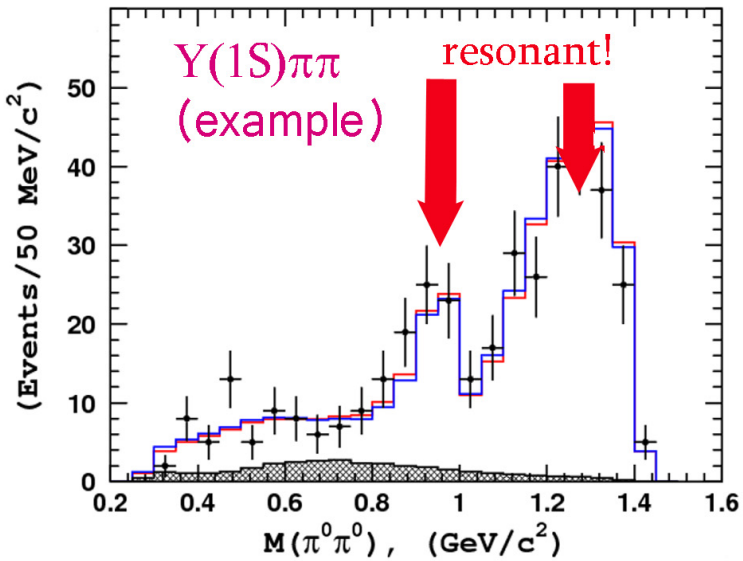
$\Gamma(\Upsilon(4S) \to \Upsilon(1S)\pi\pi) \approx 0.0019$ MeV

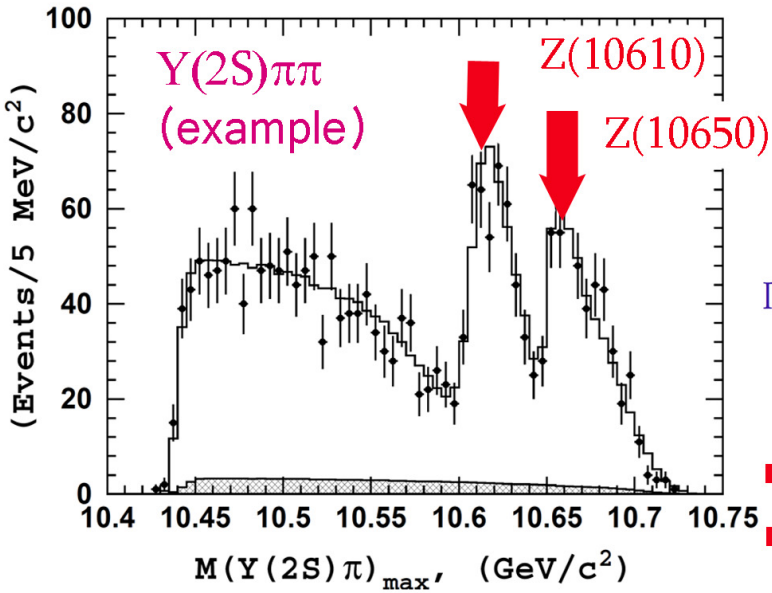
$\Gamma(\text{“}\Upsilon(5S)\text{“} \to \Upsilon(1S)\pi^+\pi^-) \approx 0.59$ MeV

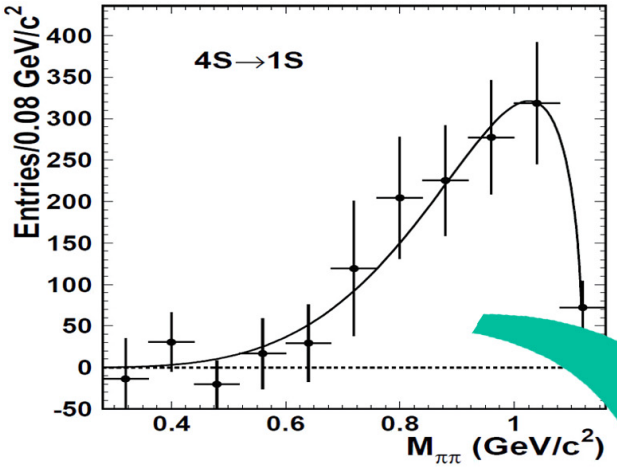
- distinct resonant structure ↯ NO resonant structure
- Zweig forbidden

Why is the data @Υ(5S) anomalous?

[Belle Collaboration (2012)]

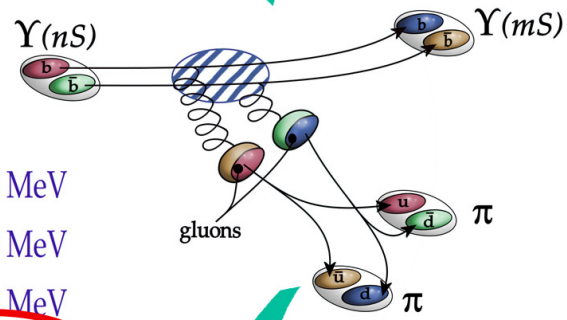






theory works well (multipole exp.) [Brown, Cahn PRL 75] [Voloshin, JETP 75]

Process:



$\Gamma(\Upsilon(2S) \to \Upsilon(1S)\pi\pi) \approx 0.0060$ MeV

$\Gamma(\Upsilon(3S) \to \Upsilon(1S)\pi\pi) \approx 0.0009$ MeV

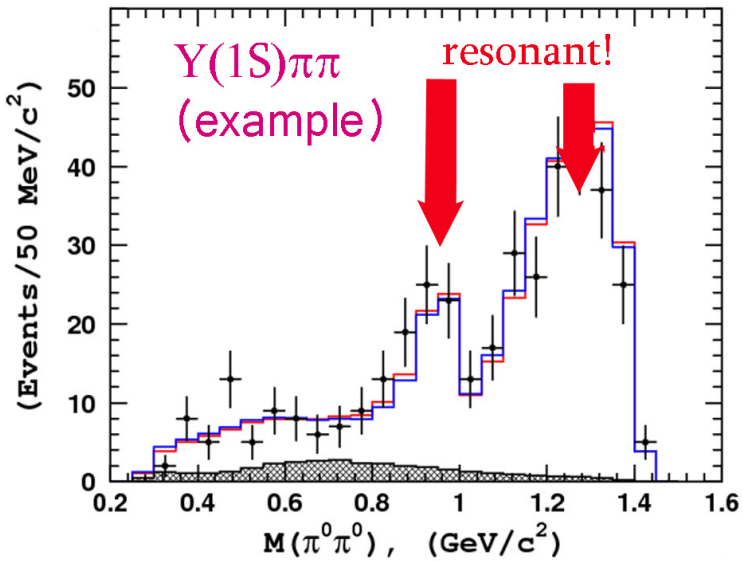
$\Gamma(\Upsilon(4S) \to \Upsilon(1S)\pi\pi) \approx 0.0019$ MeV

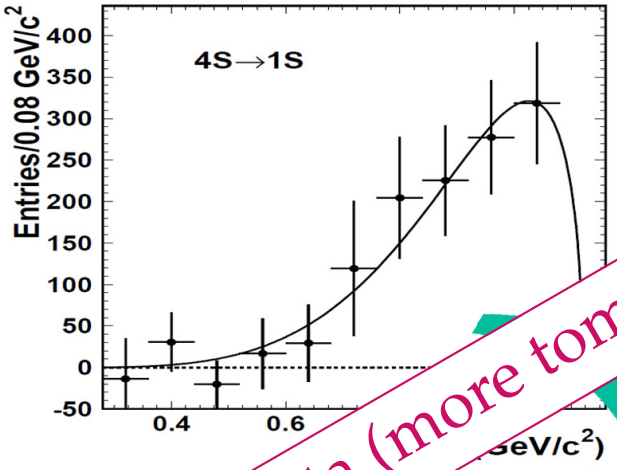
$\Gamma(\text{“}\Upsilon(5S)\text{“} \to \Upsilon(1S)\pi^+\pi^-) \approx 0.59$ MeV

- distinct resonant structure
- differs by two orders of Magnitude!

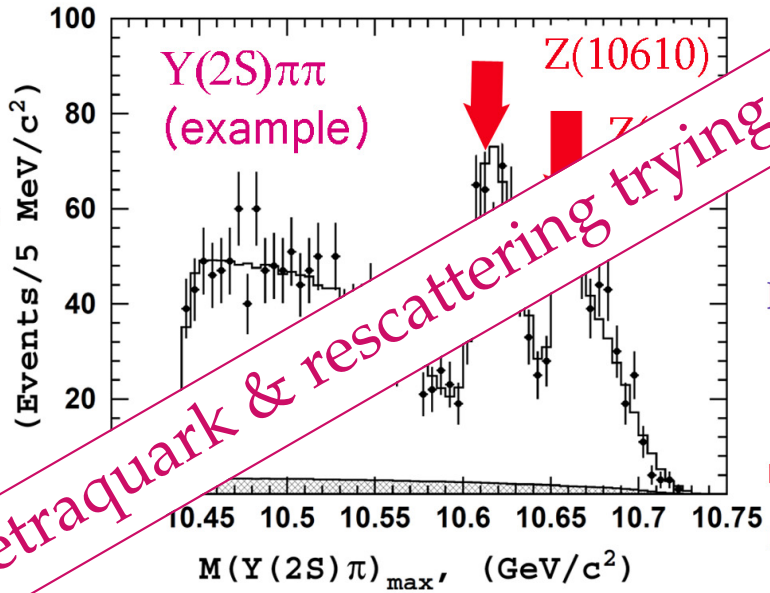
- NO resonant structure
- Zweig forbidden

Why is the data @Υ(5S) anomalous?





[Belle Collaboration (2012)]



theory works well (...pole exp.) [Brov... hn PRL 75] [Vo... JETP 75]

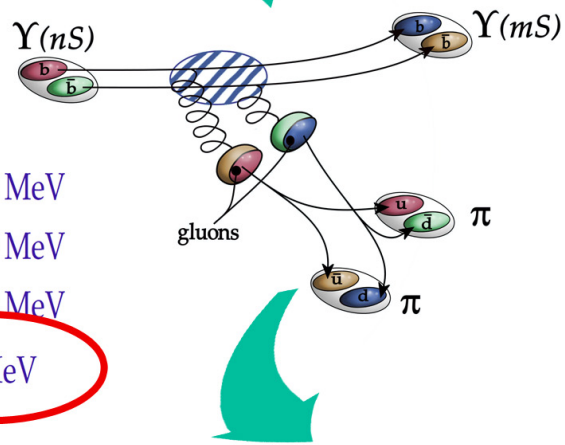
cess:

$\Gamma(\Upsilon(2S) \to \Upsilon(1S)\pi\pi) \approx 0.0060$ MeV

$\Gamma(\Upsilon(3S) \to \Upsilon(1S)\pi\pi) \approx 0.0009$ MeV

$\Gamma(\Upsilon(4S) \to \Upsilon(1S)\pi\pi) \approx 0.0019$ MeV

$\Gamma(\text{“}\Upsilon(5S)\text{“} \to \Upsilon(1S)\pi^+\pi^-) \approx 0.59$ MeV

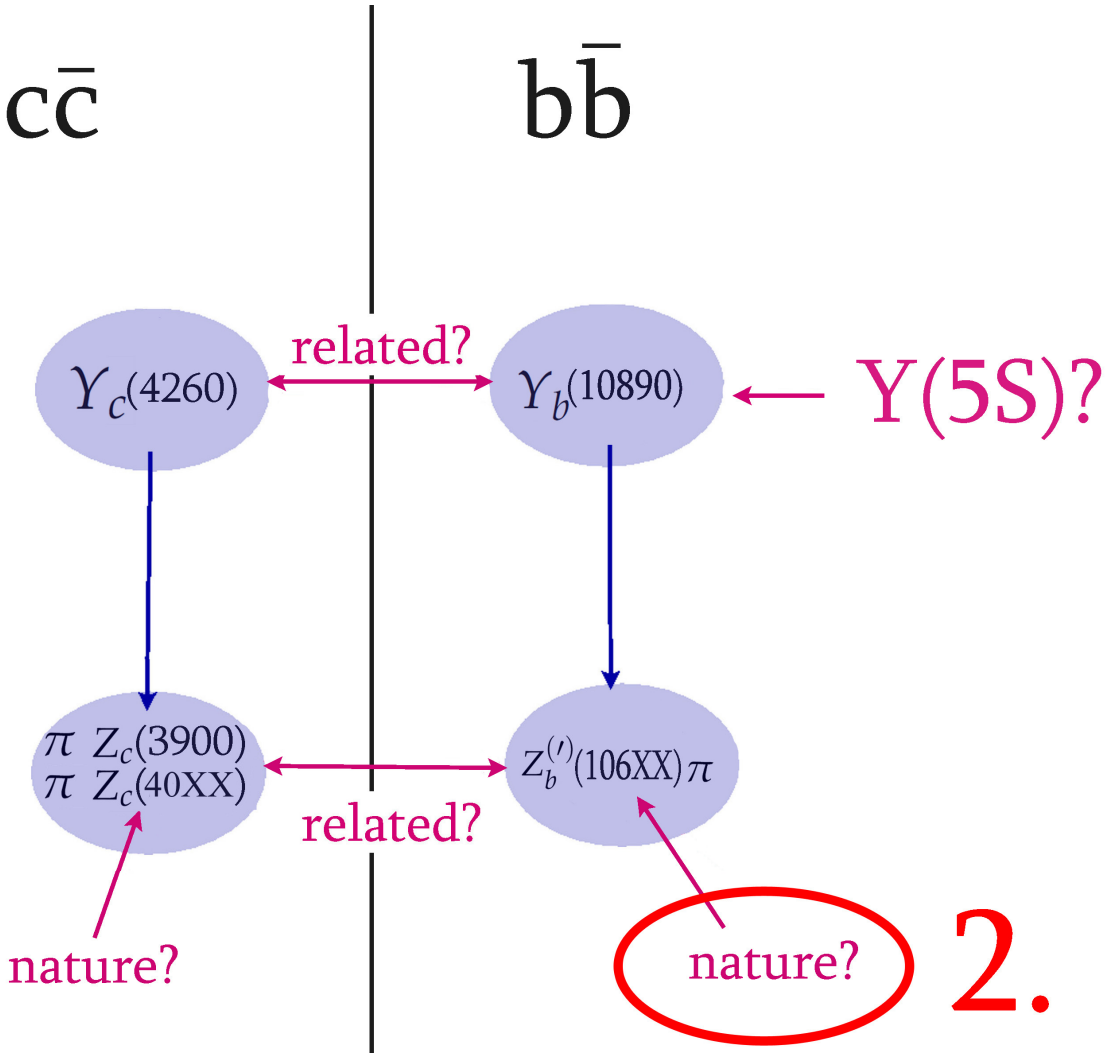


tetraquark & rescattering trying to explain data (more tomorrow)

- distinct resonant structure
- differs by two orders of Magnitude!

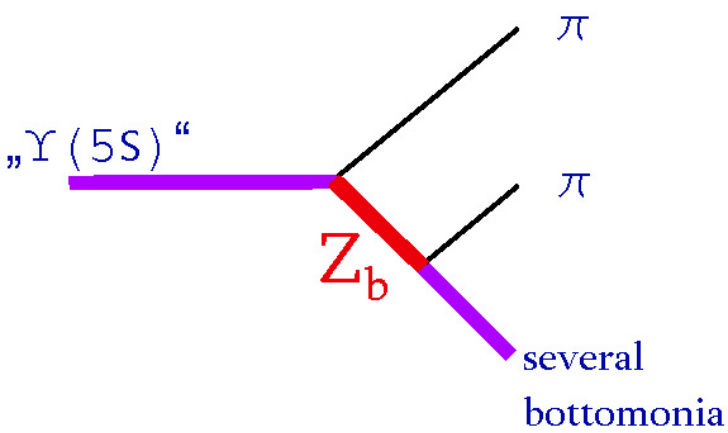
- NO resonant structure
- Zweig forbidden

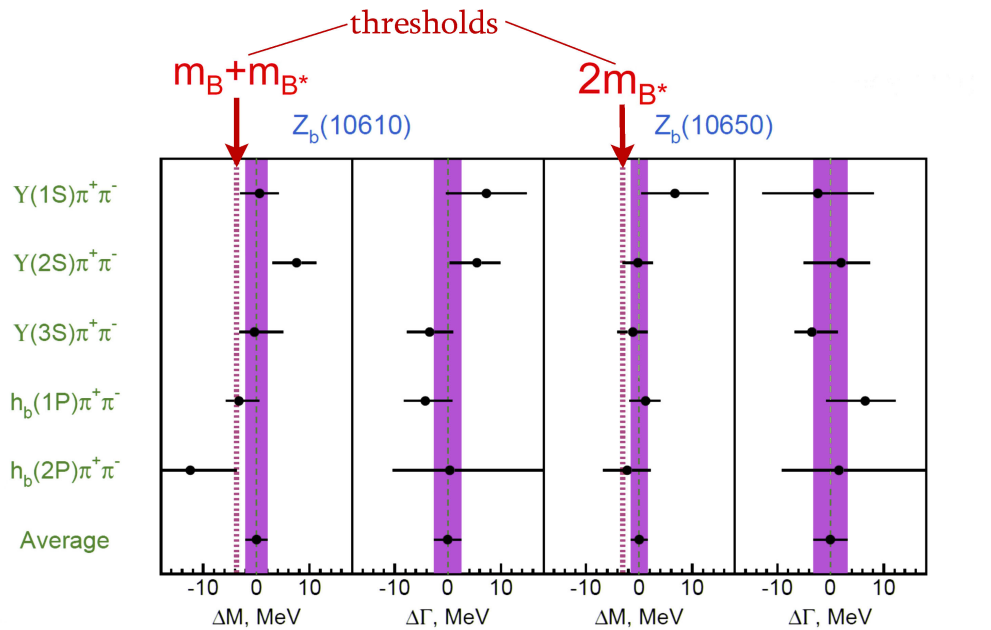
Relation $c\bar{c}$ & $b\bar{b}$



Z_b Masses by Belle

[Belle Collaboration, PRL (2012)]
measured in:





$Z_b(10610)$ M=10607.2±2.0 MeV $Z_b(10650)$ M=10652.2±1.5 MeV

- Masses close to threshold:

No need for tetraquark scenario

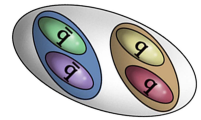
Z_b States: Molecule or Tetraquark?

Molecule

[Bondar, Garmash, Milstein, Mizuk, Voloshin, PRD 11] , [Zhang, Zhong, Huang, PLB 11] , [Voloshin, PRD 11] , [Yang,Ping, Deng, Zong, JPG 11] , [Sun, He, Liu, Luo, Zhu, PRD 11] , ...

$$|Z_{b(10610)}\rangle = \left(0_{b\bar{q}} \otimes 1_{\bar{b}q} + 1_{b\bar{q}} \otimes 0_{\bar{b}q}\right)/\sqrt{2}$$

$$|Z_{b(10650)}\rangle = 1_{b\bar{q}} \otimes 1_{\bar{b}q}$$



Tetraquark

[Yang, Ping, Deng, Zong, JPG 11] , [Guo, Cao, Zhou, Chen, 11] , [Ali, CH, Wang, PRD 11] , ...

$$|Z_{b(10610)}\rangle = \left(0_{[bq]} \otimes 1_{[\bar{b}\bar{q}]} - 1_{[bq]} \otimes 0_{[\bar{b}\bar{q}]}\right)/\sqrt{2}$$

$$|Z_{b(10650)}\rangle = 1_{[bq]} \otimes 1_{[\bar{b}\bar{q}]}$$

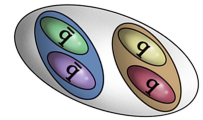
Z_b States: Molecule or Tetraquark?

Molecule

[Bondar, Garmash, Milstein, Mizuk, Voloshin, PRD 11] , [Zhang, Zhong, Huang, PLB 11] , [Voloshin, PRD 11] , [Yang,Ping, Deng, Zong, JPG 11] , [Sun, He, Liu, Luo, Zhu, PRD 11] , ...

$$|Z_{b(10610)}\rangle = \left(0_{b\bar{q}} \otimes 1_{\bar{b}q} + 1_{b\bar{q}} \otimes 0_{\bar{b}q}\right)/\sqrt{2}$$

$$|Z_{b(10650)}\rangle = 1_{b\bar{q}} \otimes 1_{\bar{b}q}$$



Tetraquark

[Yang, Ping, Deng, Zong, JPG 11] , [Guo, Cao, Zhou, Chen, 11] , [Ali, CH, Wang, PRD 11] , ...

$$|Z_{b(10610)}\rangle = \left(0_{[bq]} \otimes 1_{[\bar{b}\bar{q}]} - 1_{[bq]} \otimes 0_{[\bar{b}\bar{q}]}\right)/\sqrt{2}$$

$$|Z_{b(10650)}\rangle = 1_{[bq]} \otimes 1_{[\bar{b}\bar{q}]}$$

$$\downarrow \text{ Fierz } \downarrow$$

$$|Z_{b(10610)}\rangle = 1^{-}_{b\bar{q}} \otimes 1^{-}_{q\bar{b}}$$

$$|Z_{b(10650)}\rangle = \left(1^{-}_{b\bar{q}} \otimes 0^{-}_{q\bar{b}} + 0^{-}_{b\bar{q}} \otimes 1^{-}_{q\bar{b}}\right)/\sqrt{2}$$

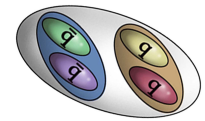
Z_b States: Molecule or Tetraquark?

Molecule

[Bondar, Garmash, Milstein, Mizuk, Voloshin, PRD 11] , [Zhang, Zhong, Huang, PLB 11] , [Voloshin, PRD 11] , [Yang,Ping, Deng, Zong, JPG 11] , [Sun, He, Liu, Luo, Zhu, PRD 11] ,...

$$|Z_{b(10610)}\rangle = \left(0_{b\bar{q}} \otimes 1_{\bar{b}q} + 1_{b\bar{q}} \otimes 0_{\bar{b}q}\right)/\sqrt{2}$$

$$|Z_{b(10650)}\rangle = 1_{b\bar{q}} \otimes 1_{\bar{b}q}$$



Tetraquark

[Yang, Ping, Deng, Zong, JPG 11] , [Guo, Cao, Zhou, Chen, 11] , [Ali, CH, Wang, PRD 11] , ...

$$|Z_{b(10610)}\rangle = \left(0_{[bq]} \otimes 1_{[\bar{b}\bar{q}]} - 1_{[bq]} \otimes 0_{[\bar{b}\bar{q}]}\right)/\sqrt{2}$$

$$|Z_{b(10650)}\rangle = 1_{[bq]} \otimes 1_{[\bar{b}\bar{q}]}$$

$$\downarrow \text{ Fierz } \downarrow$$

$$|Z_{b(10610)}\rangle = 1^-_{b\bar{q}} \otimes 1^-_{q\bar{b}}$$

$$|Z_{b(10650)}\rangle = \left(1^-_{b\bar{q}} \otimes 0^-_{q\bar{b}} + 0^-_{b\bar{q}} \otimes 1^-_{q\bar{b}}\right)/\sqrt{2}$$

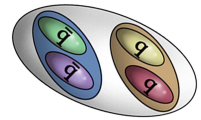
$Z_{b(10610)} \to B\bar{B}^* + B^*\bar{B}$

$Z_{b(10650)} \to B^*\bar{B}^*$

$Z_{b(10610)} \to B^*\bar{B}^*$

$Z_{b(10650)} \to B\bar{B}^* + B^*\bar{B}$

Z_b States: Molecule or Tetraquark?



Molecule

[Bondar, Garmash, Milstein, Mizuk, Volos-hin, PRD 1 11] , [Volos Zong, JPG 11] ,...

$|Z_{b(10610)}\rangle =$

$|Z_{b(10650)}\rangle =$

Tetraquark

[Yang, Ping, Deng, Zong, JPG 11] , [Guo, Cao, ng, PRD 11] ,

$\otimes 0_{[\bar{b}\bar{q}]}) / \sqrt{2}$

[Belle Collaboration (2012)]

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

$|Z_{b(10650)}\rangle = (1^-_{b\bar{q}} \otimes 0^-_{q\bar{b}} + 0^-_{b\bar{q}} \otimes 1^-_{q\bar{b}}) / \sqrt{2}$

$Z_{b(10610)} \to B\bar{B}^* + B^*\bar{B}$

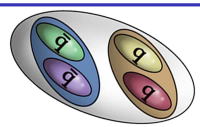
$Z_{b(10650)} \to B^*\bar{B}^*$

$Z_{b(10610)} \to B^*\bar{B}^*$

$Z_{b(10650)} \to B\bar{B}^* + B^*\bar{B}$

Z_b Concluding Remarks

Tetraquark

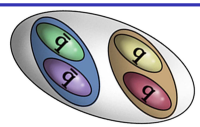


PRO:
nothing special yet

Molecule

PRO:
Close to thresholds (but above)
Explains $B^{(*)}\bar{B}^{(*)}$ decay pattern

Z_b Concluding Remarks



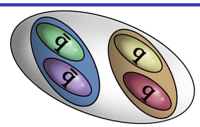
Tetraquark

PRO:
nothing special yet

Molecule

PRO:
Close to thresholds (but above)
Explains $B^{(*)}\bar{B}^{(*)}$ decay pattern

Z_b Concluding Remarks



Tetraquark

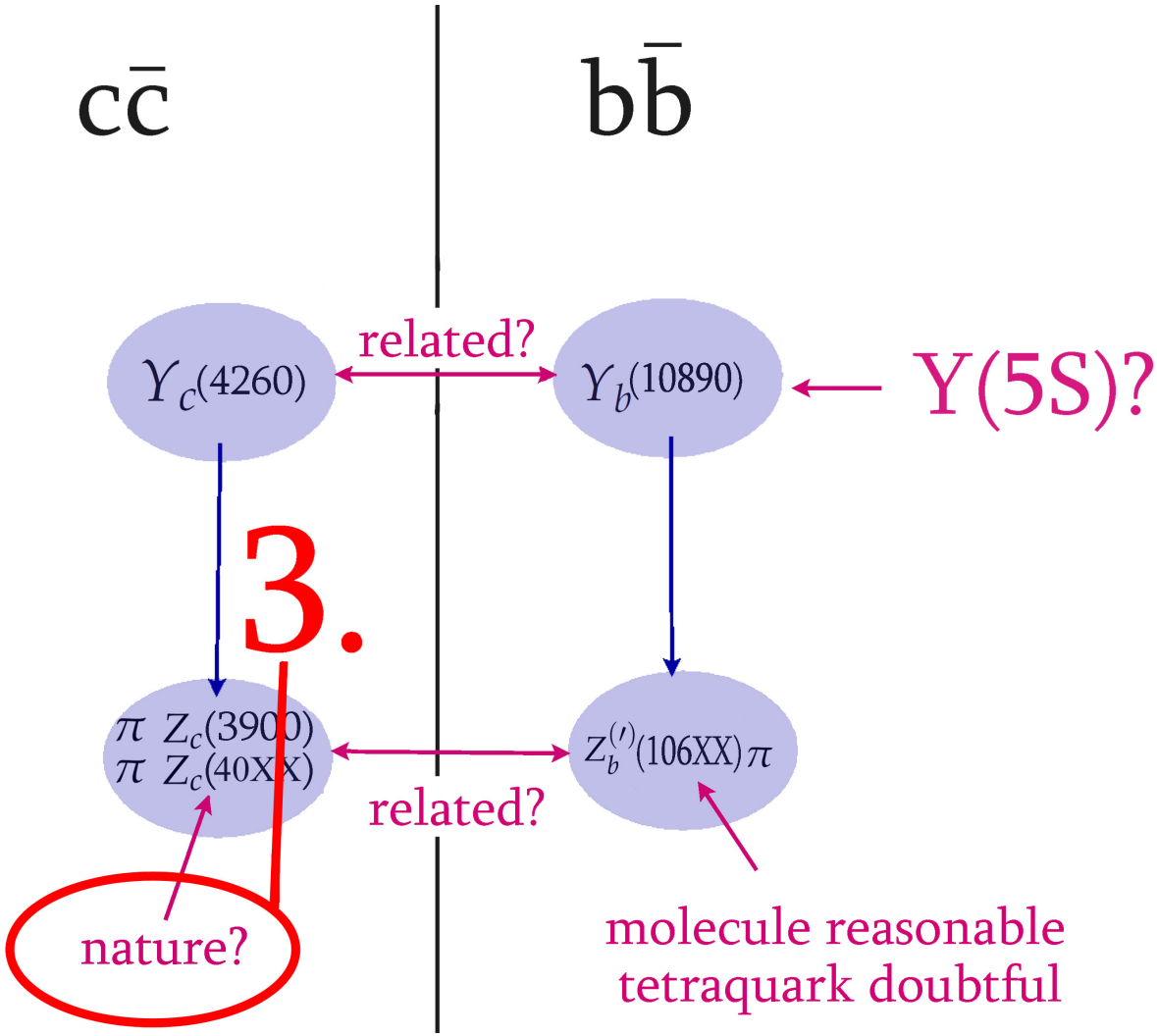
PRO:
nothing special yet

Molecule

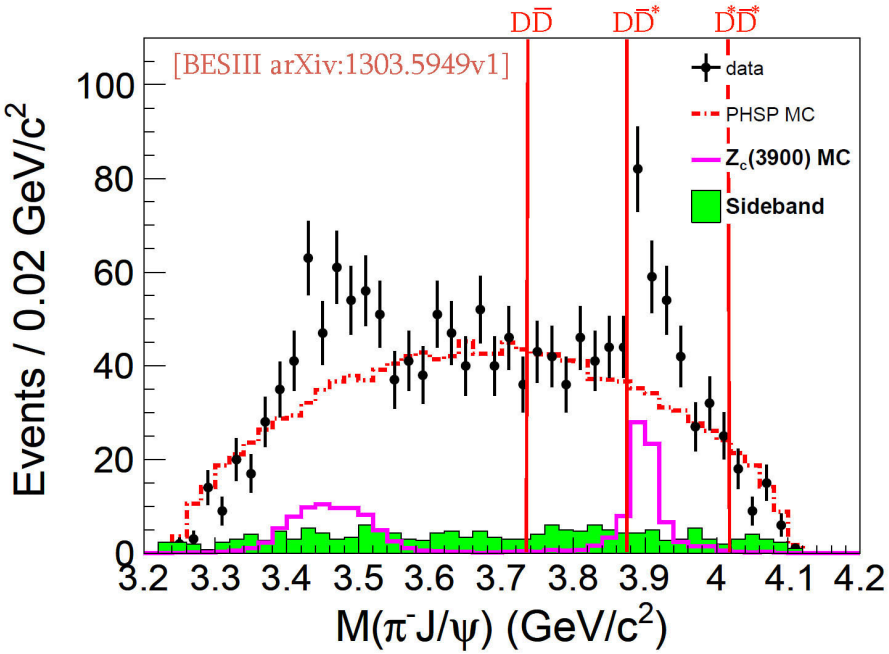
PRO:
Close to thresholds (but above)
Explains $B^{(*)}\bar{B}^{(*)}$ decay pattern

. . . but then, something unexpected happened in 2013: $Z_c(3900)$ & $Z_c(40XX)$
. . .

Relation $c\bar{c}$ & $b\bar{b}$

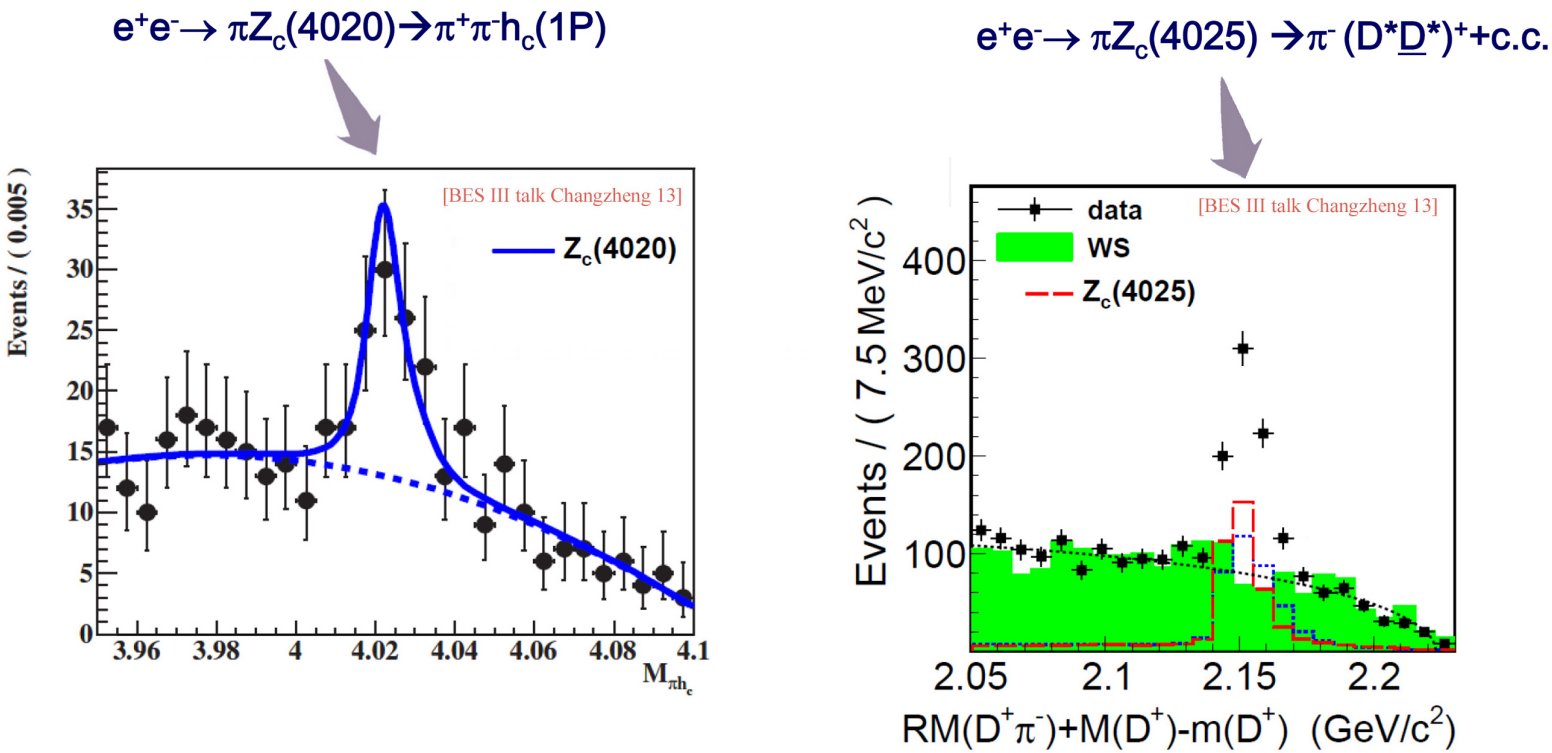


Surprise Nº 1 from BESIII (4 months ago)



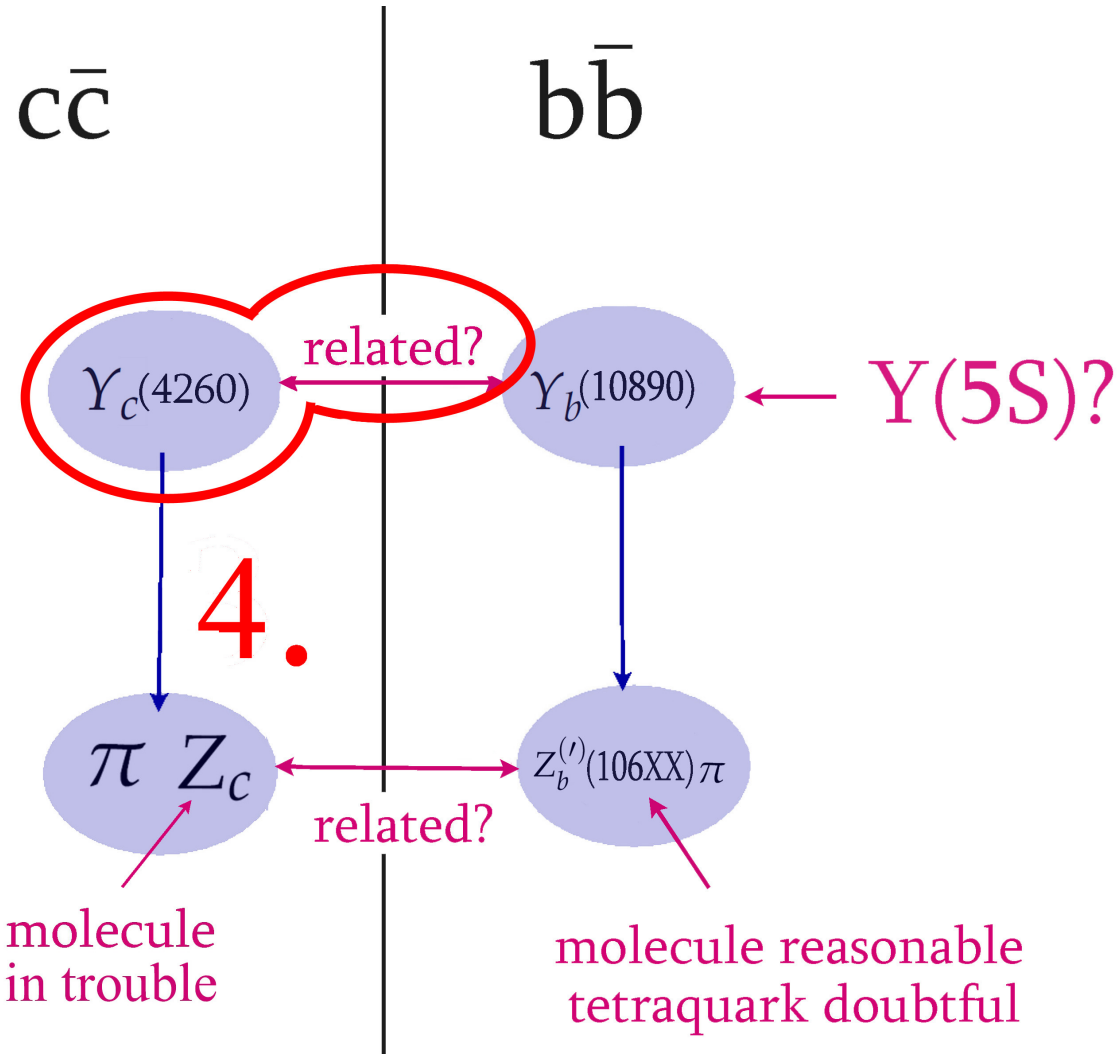
- $Y_c(4260) \to J/\psi\pi\pi$ (similar to $Y_b(10890) \to \Upsilon(1S)\pi\pi$)
  - $m_{Z_c(3900)} = 3899 \pm 6$ MeV, $\Gamma_{Z_c(3900)} = 46 \pm 22$ MeV
  - ($\approx 4\sigma$ above $D\bar{D}^*$ threshold)
- important question: $Z_c(3900) \to D\bar{D}^*$ mode dominant?

Surprise Nº 2 from BESIII (3 weeks ago)

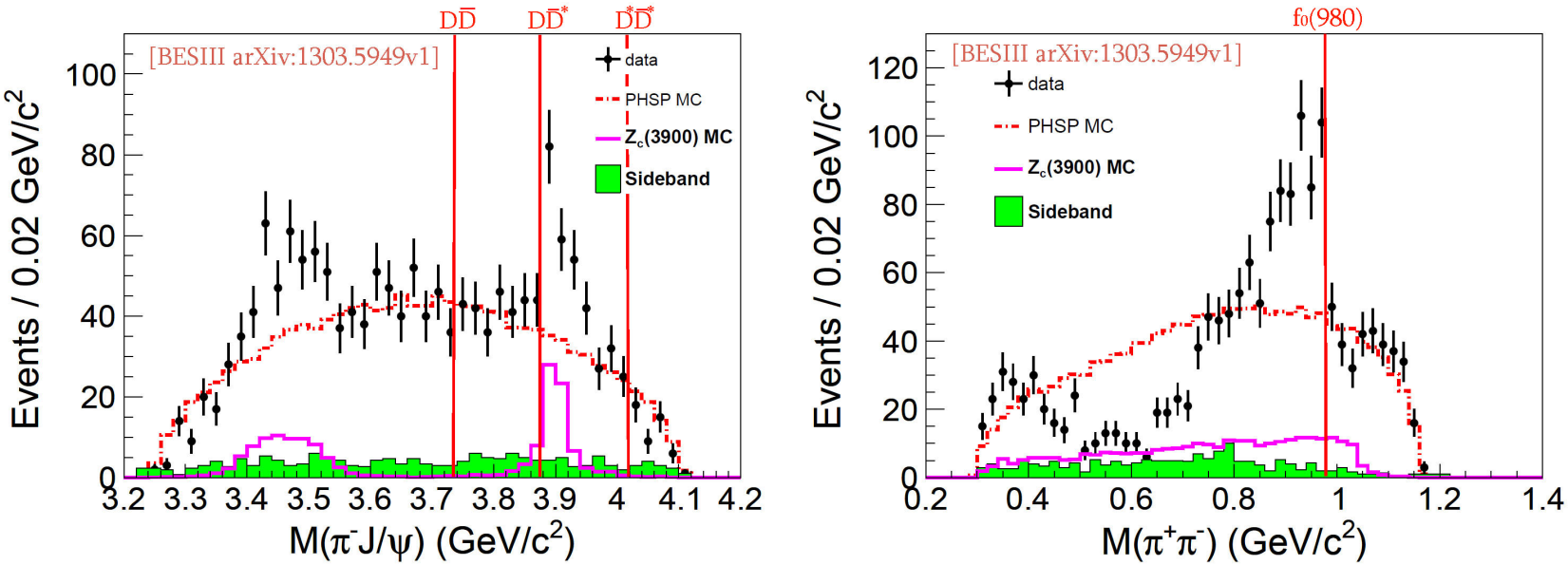


- NOT seen in $J/\psi\pi\pi$
- seen in $h_c(1P)\pi\pi$ and $\pi D^*\bar{D}^*$
  - $Z_c(4020)$ $J^P = 1^+$ $m = 4022 \pm 3$ $\Gamma = 6 \pm 4$
  - $Z_c(4025)$ $J^P = 1^+$ $m = 4026 \pm 5$ $\Gamma = 25 \pm 10$
- consistent with 1 state, but maybe 2 states?
- $(2m_{D^*})^+ = 2017$ MeV → $\approx 2\sigma$ above $D^*\bar{D}^*$ threshold

Relation $c\bar{c}$ & $b\bar{b}$



$Y_c(4260), J^{PC} = 1^{--}$



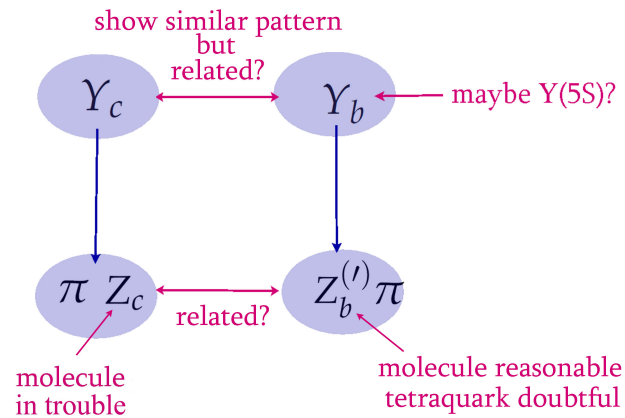
- discovered in $J/\psi\pi\pi$ by BaBar, confirmed by CLEO Belle and BESIII
- no open charm seen
- [BaBar, PRL 05] : $m = 4252 \pm 73$ MeV, $\Gamma = 105 \pm 20$ MeV
  $B(J/\psi\pi\pi)\Gamma_{e+e-} = 7.5 \pm 1.2$ eV
  ↪ $\Gamma(Y_c(4260) \to J/\psi\pi\pi) > 0.5$ MeV (limit on Γ_{e+e-})
  (at least $\mathcal{O}(10)$ enhanced vs charmonia)
- candidates: hybrids, tetraquarks, $D_1\bar{D}$ molecule, ...
- related to other 1^{--} states in $c\bar{c}$, $Y_c(4360, 4660, 4008)$?
- $Y_c(4008)$ with significance $> 5\sigma$ from Belle but not seen by BaBar

Similarities between $\Upsilon_b(10890)$ and $\Upsilon_c(4260)$

Similarities between $\Upsilon_b(10890)$ and $\Upsilon_c(4260)$:

- both 1^{--}
- constituent model: $m_b - m_c \approx 3333$ MeV
  - $\hookrightarrow$ $m_{\Upsilon_b(10890)} \approx m_{\Upsilon_c(4260)} + 2(m_b - m_c)$ (naive estimate 30 MeV off)
- seen & enhancement in decay $V\pi\pi$ (V is J/ψ or Υ)
- similar resonant structure $f_0(500, 980)$ in $m_{\pi\pi}$ and $Z_{b,c}$ in $m_{V\pi}$

  But: molecule interpretation for Z_c in trouble (states above thresholds)

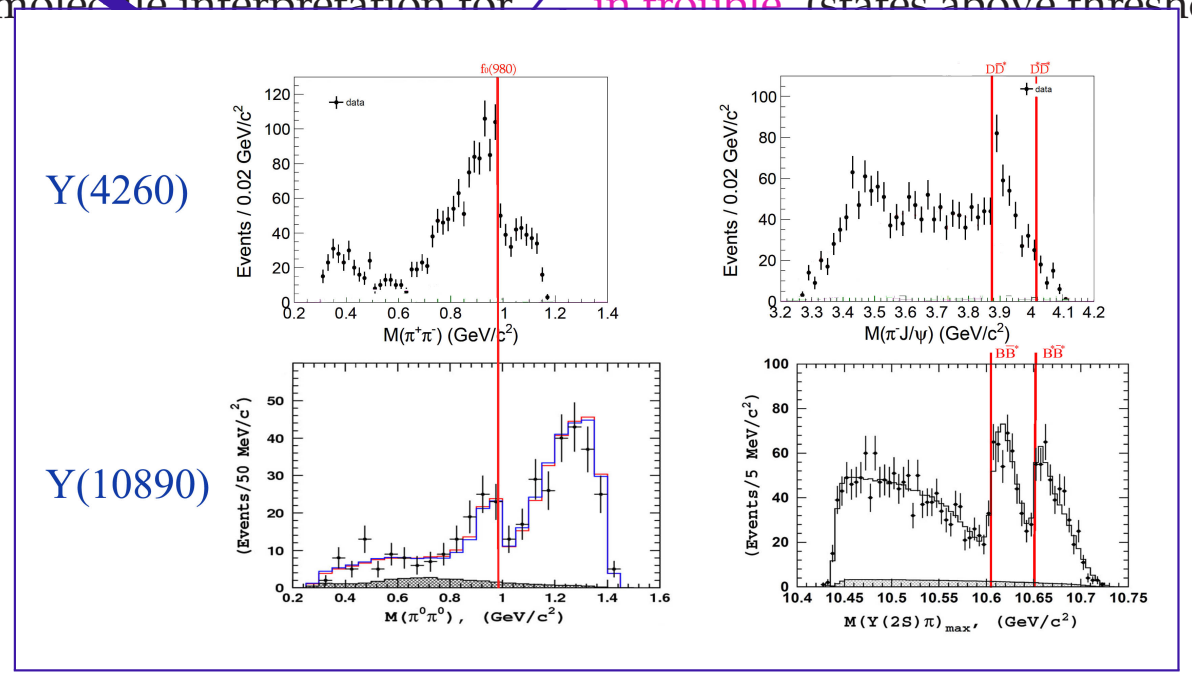


Similarities between $\Upsilon_b(10890)$ and $\Upsilon_c(4260)$

Similarities between $\Upsilon_b(10890)$ and $\Upsilon_c(4260)$:

- both 1^{--}
- constituent model: $m_b - m_c \approx 3333$ MeV
  - $m_{\Upsilon_b(10890)} \approx m_{\Upsilon_c(4260)} + 2(m_b - m_c)$ (naive estimate 30 MeV off)
- seen & enhancement in decay $V\pi\pi$ (V is J/ψ or Υ)
- similar resonant structure $f_0(500, 980)$ in $m_{\pi\pi}$ and $Z_{b,c}$ in $m_{V\pi}$

But: molecule interpretation for $Z_{b,c}$ in trouble (states above thresholds)



Similarities between $\Upsilon_b(10890)$ and $\Upsilon_c(4260)$

Similarities between $\Upsilon_b(10890)$ and $\Upsilon_c(4260)$:

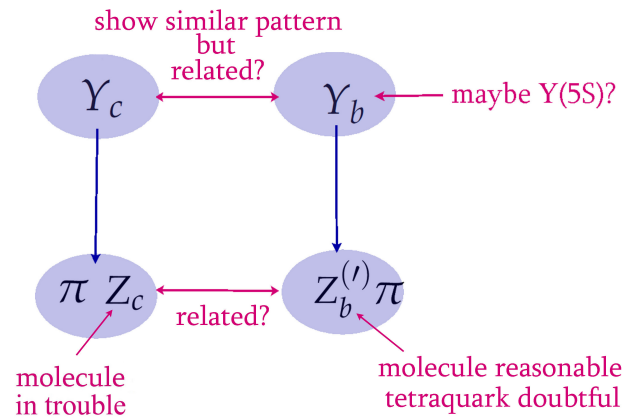
- both 1^{--}
- constituent model: $m_b - m_c \approx 3333$ MeV
  - ↳ $m_{\Upsilon_b(10890)} \approx m_{\Upsilon_c(4260)} + 2(m_b - m_c)$ (naive estimate 30 MeV off)
- seen & enhancement in decay $V\pi\pi$ (V is J/ψ or Υ)
- similar resonant structure $f_0(500, 980)$ in $m_{\pi\pi}$ and $Z_{b,c}$ in $m_{V\pi}$

  But: molecule interpretation for Z_c in trouble (states above thresholds)

$\Upsilon_b(10890)$ is a cornerstone!

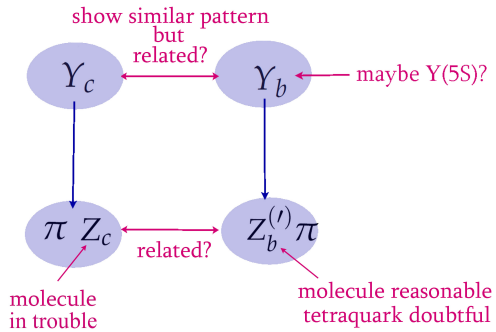
↳ knowing its nature is important!

(e.g. $m_{B_1\bar{B}} \approx 11$ GeV would hint at conflict with molecule $D_1\bar{D}$ interpretation,...)



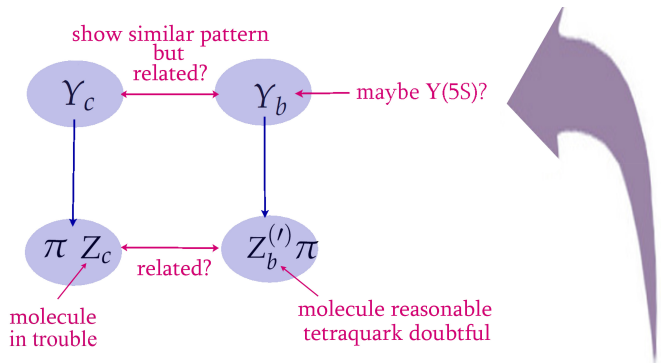
Today

- Mass estimates strongly model dependent - market is messy
- Important puzzle:



Today

- Mass estimates strongly model dependent - market is messy
- Important puzzle:

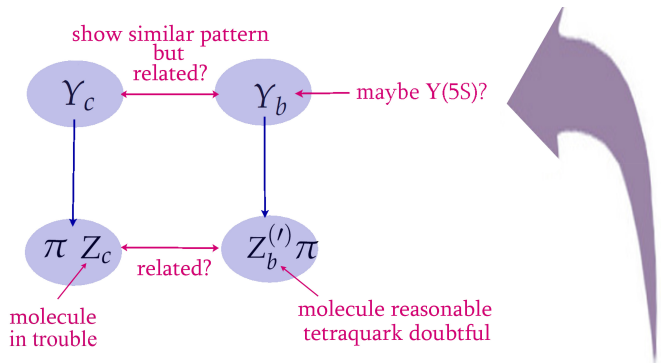


Tomorrow

- $\Upsilon_b(10890)$ what can we do about it?

Today

- Mass estimates strongly model dependent - market is messy
- Important puzzle:



Tomorrow

- $\Upsilon_b(10890)$ what can we do about it?

thank you & stay tuned for tomorrow!