Multiquark Hadrons - A New Facet of QCD

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DESY, Hamburg

18-30 July, 2016

Helmholtz International Summer Schoo, JINR, Dubna

- Experimental Evidence for Multiquark states X, Y, Z
- Models for X, Y, Z Mesons
- Phenomenology of the diquark model of Tetraquarks
- The LHCb Pentaquarks $\mathbb{P}^{\pm}(4380)$ and $\mathbb{P}^{\pm}(4450)$
- Theoretical interpretations of the Pentaquarks
- Summary

$X(3872)$ - the poster Child of the X, Y, Z Mesons

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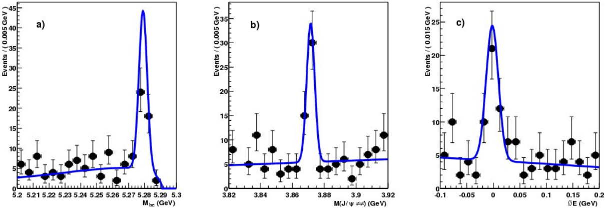
Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays

S.-K. Choi,[5] S. L. Olsen,[6] K. Abe,[7] T. Abe,[7] I. Adachi,[7] Byoung Sup Ahn,[14] H. Aihara,[43] K. Akai,[7] M. Akatsu,[20] M. Akemoto,[7] Y. Asano,[48] T. Aso,[47] V. Aulchenko,[1] T. Aushev,[11] A. M. Bakich,[38] Y. Ban,[31] S. Banerjee,[39] A. Bondar,[1] A. Bozek,[25] M. Bračko,[18,12] J. Brodzicka,[25] T. E. Browder,[6] P. Chang,[24] Y. Chao,[24] K.-F. Chen,[24] B. G. Cheon,[37] R. Chistov,[11] Y. Choi,[37] Y. K. Choi,[37] M. Danilov,[11] L. Y. Dong,[9] A. Drutskoy,[11] S. Eidelman,[1] V. Eiges,[11] J. Flanagan,[7] C. Fukunaga,[45] K. Furukawa,[7] N. Gabyshev,[7] T. Gershon,[7] B. Golob,[17,12] H. Guler,[6] R. Guo,[22] C. Hagner,[50] F. Handa,[42] T. Hara,[29] N. C. Hastings,[7] H. Hayashii,[21] M. Hazumi,[7] L. Hinz,[16] Y. Hoshi,[41] W.-S. Hou,[24] Y. B. Hsiung,[24,*] H.-C. Huang,[24] T. Iijima,[20] K. Inami,[20] A. Ishikawa,[20] R. Itoh,[7] M. Iwasaki,[43] Y. Iwasaki,[7] J. H. Kang,[52] S. U. Kataoka,[21] N. Katayama,[7] H. Kawai,[2] T. Kawasaki,[27] H. Kichimi,[7] E. Kikutani,[7] H. J. Kim,[52] Hyunwoo Kim,[14] J. H. Kim,[37] S. K. Kim,[36] K. Kinoshita,[3] H. Koiso,[7] P. Koppenburg,[7] S. Korpar,[18,12] P. Križan,[17,12] P. Krokovny,[1] S. Kumar,[30] A. Kuzmin,[1] J. S. Lange,[4,33] G. Leder,[10] S. H. Lee,[36] T. Lesiak,[25] S.-W. Lin,[24] D. Liventsev,[11] J. MacNaughton,[10] G. Majumder,[39] F. Mandl,[10] D. Marlow,[32] T. Matsumoto,[45] S. Michizono,[7] T. Mimashi,[7] W. Mitaroff,[10] K. Miyabayashi,[21] H. Miyake,[29] D. Mohapatra,[50] G. R. Moloney,[19] T. Nagamine,[42] Y. Nagasaka,[8] T. Nakadaira,[43] T. T. Nakamura,[7] M. Nakao,[7] Z. Natkaniec,[25] S. Nishida,[7] O. Nitoh,[46] T. Nozaki,[7] S. Ogawa,[40] Y. Ogawa,[7] K. Ohmi,[7] Y. Ohnishi,[7] T. Ohshima,[20] N. Ohuchi,[7] K. Oide,[7] T. Okabe,[20] S. Okuno,[13] W. Ostrowicz,[25] H. Ozaki,[7] H. Palka,[25] H. Park,[15] N. Parslow,[38] L. E. Piilonen,[50] H. Sagawa,[7] S. Saitoh,[7] Y. Sakai,[7] T. R. Sarangi,[49] M. Satapathy,[49] A. Satpathy,[7,3] O. Schneider,[16] A. J. Schwartz,[3] S. Semenov,[11] K. Senyo,[20] R. Seuster,[6] M. E. Sevior,[19] H. Shibuya,[40] T. Shidara,[7] B. Shwartz,[1] V. Sidorov,[1] N. Soni,[30] S. Stanič,[48,†] M. Starič,[12] A. Sugiyama,[34] T. Sumiyoshi,[45] S. Suzuki,[51] F. Takasaki,[7] K. Tamai,[7] N. Tamura,[27] M. Tanaka,[7] M. Tawada,[7] G. N. Taylor,[19] Y. Teramoto,[28] T. Tomura,[43] K. Trabelsi,[6] T. Tsukamoto,[7] S. Uehara,[7] K. Ueno,[24] Y. Unno,[2] S. Uno,[7] G. Varner,[6] K. E. Varvell,[38] C. C. Wang,[24] C. H. Wang,[23] J. G. Wang,[50] Y. Watanabe,[44] E. Won,[14] B. D. Yabsley,[50] Y. Yamada,[7] A. Yamaguchi,[42] Y. Yamashita,[26] H. Yanai,[27] Heyoung Yang,[36] J. Ying,[31] M. Yoshida,[7] C. C. Zhang,[9] Z. P. Zhang,[35] and D. Žontar[17,12]

(Belle Collaboration)

- Discovery Mode : $B \to J/\psi\pi^+\pi^- K$
- $M = 3872.0 \pm 0.6 \pm 0.5$ MeV
- $\Gamma < 2.3$ MeV
- $J^{PC} = 1^{++}$ [LHCb] [PRL110, 22201(2013)]



Tetraquark Candidates

Belle & others [Liu et al., 13] , [Ablikim et al., 13] , [Brambilla et al., 14]

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes	Also observed by
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR) $J/\psi \to \eta Y_s(2175)$	BaBar*, BESII
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi$, $D\bar{D}^*$	$B \to KX(3872)$, $p\bar{p}$	BaBar CDF, D0, BaBar, LHCb
$Z(3900)$	3891.2 ± 3.3	40 ± 8	1^+	$\pi^\pm J/\psi$	$Y(4260) \to Z(3900)\pi$	BESIII*, CLEO
$X(3915)$	3914 ± 4	28^{+12}_{-14}	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$	
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$	
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	$e^+e^- \to J/\psi X(3940)$	
$Y(3940)$	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	8 ± 4	1^+	$\pi^\pm J/\psi$	$Y(4260) \to Z(4020)\pi$	BESIII* (*only*)
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$X(4160)$	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
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$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4050)$	
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4250)$	
$Z(4430)$	4475 ± 7	$172 \pm 13^{+37}_{-34}$	1^+	$\pi^\pm \psi'$	$B \to KZ^\pm(4430)$	LHCb
$Z_b(10610)$	$10,607 \pm 2$	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^{--}	$\pi^+\pi^- \Upsilon(1,2,3S)$	$e^+e^- \to Y_b$	

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$a_0(980)$ in 1965, $\sigma(600)^{\text{now } 500}$ in 1972, $f_0(980)$ in 1979, $\kappa(980)$ in 1997

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

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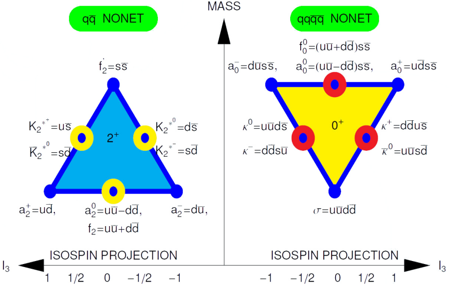
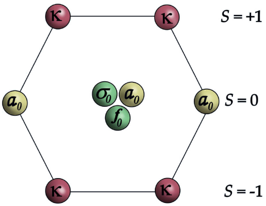
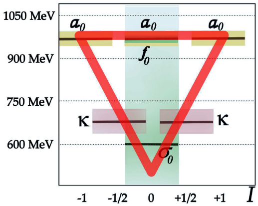
Constituent Quark Model and Light States

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





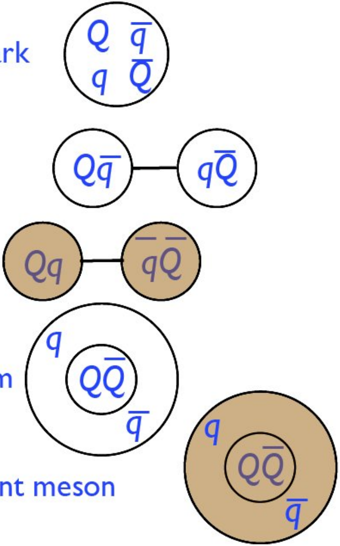


- Tetraquark interpretation in agreement with experiment ['t Hooft, Isidori, Maiani, Polosa, Riquer, PLB (2008)]

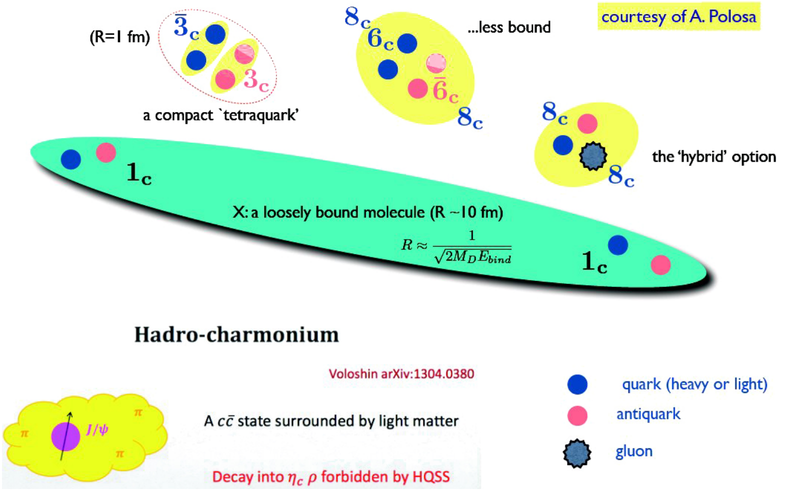
Models for *XYZ* Mesons

Quarkonium Tetraquarks

- compact tetraquark
- meson molecule
- diquark-onium
- hadro-quarkonium
- quarkonium adjoint meson



X, Y, Z Exotics

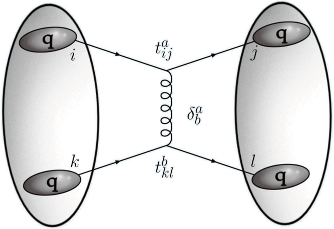


courtesy of A. Polosa
(R=1 fm)
$\bar{3}_c$
3_c
a compact `tetraquark'
8_c
6_c
$\bar{6}_c$
8_c
...less bound
8_c
8_c
the 'hybrid' option
1_c
X: a loosely bound molecule (R ~10 fm)
$R \approx \frac{1}{\sqrt{2M_D E_{bind}}}$
1_c
Hadro-charmonium
Voloshin arXiv:1304.0380
J/ψ
π
π
π
A $c\bar{c}$ state surrounded by light matter
Decay into $\eta_c\, \rho$ forbidden by HQSS
quark (heavy or light)
antiquark
gluon

Diquarks: Color Representation

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

  ➥ Color factor determines binding:
  Negative sign ⟶ Attractive



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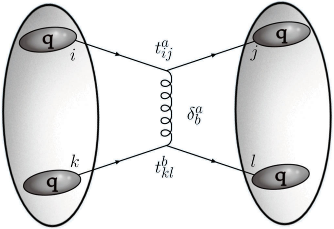

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- Quarks in diquark transform as:

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

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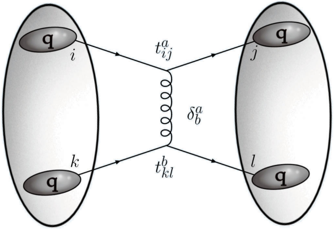

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- qq bound state color factor:

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

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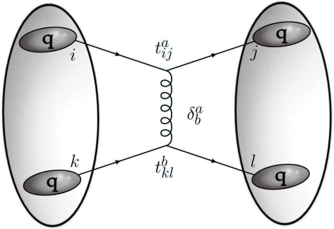

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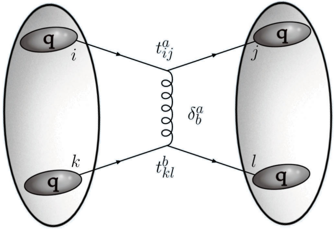

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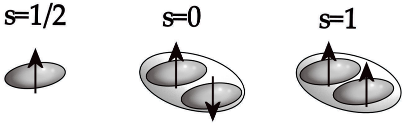

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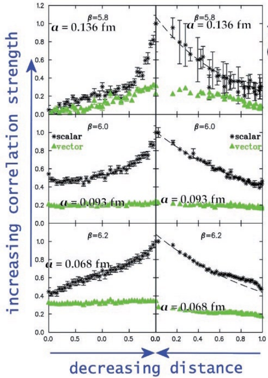
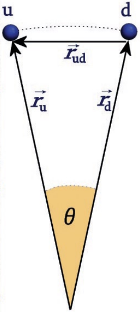
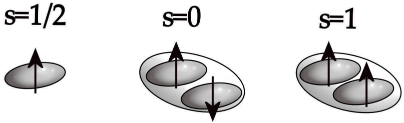


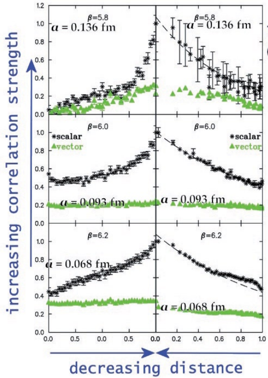


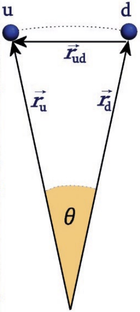


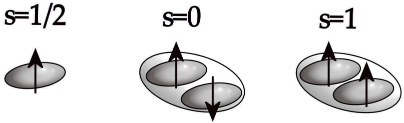
Lattice simulations for light quarks [Alexandrou, Forcrand, Lucini, PRL (2006)] :

- 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 $\mathcal{O}$(1fm)

Spin decoupling in HQ-Limit

↪ "Bad" diquarks in b-sector might bind

Diquark Model of Tetra- and Pentaquarks

Diquarks and Anti-diquarks are the building blocks of Tetraquarks
Color representation: $3 \otimes 3 = \bar{3} \oplus 6$; only $\bar{3}$ is attractive; $C_{\bar{3}} = 1/2\, C_3$

Interpolating diquark operators for the two spin-states of diquarks

$$\begin{array}{rccl} \text{Scalar:} & 0^+ & \mathcal{Q}_{i\alpha} & = & \epsilon_{\alpha\beta\gamma}(\bar{c}_c^{\beta}\gamma_5 q_i^{\gamma} - \bar{q}_{i_c}^{\beta}\gamma_5 c^{\gamma}) \\ \text{Axial-Vector:} & 1^+ & \vec{\mathcal{Q}}_{i\alpha} & = & \epsilon_{\alpha\beta\gamma}(\bar{c}_c^{\beta}\vec{\gamma} q_i^{\gamma} + \bar{q}_{i_c}^{\beta}\vec{\gamma} c^{\gamma}) \end{array}$$

α, β, γ: $SU(3)_C$ indices

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NR limit: States parametrized by Pauli matrices :

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

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

➥ Tetraquarks:

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

NR Hamiltonian for Tetraquarks with hidden charm

States need to diagonalize Hamiltonian:

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

$$\begin{aligned} H_{\rm eff}(X,Y,Z) &= 2m_{\mathcal{Q}} + \frac{B_Q}{2}\langle L^2\rangle - 2a\langle L\cdot S\rangle + 2\kappa_{qQ}\left[\langle s_q\cdot s_Q\rangle + \langle s_{\bar{q}}\cdot s_{\bar{Q}}\rangle\right] \\ &= 2m_{\mathcal{Q}} - aJ(J+1) + \left(\frac{B_Q}{2}+a\right)L(L+1) + aS(S+1) - 3\kappa_{qQ} \\ &+ \kappa_{qQ}\left[s_{qQ}(s_{qQ}+1) + s_{\bar{q}\bar{Q}}(s_{\bar{q}\bar{Q}}+1)\right] \end{aligned}$$

NR Hamiltonian for Tetraquarks with hidden charm

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constituent mass

with

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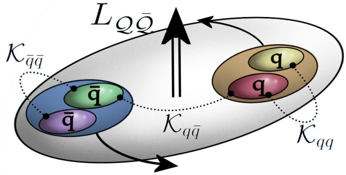
qq spin coupling $\quad$ $q\bar{q}$ spin coupling

with

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

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



$$H_{\text{eff}}(X,Y,Z) = 2m_Q + \frac{B_Q}{2}\langle L^2\rangle - 2a\langle L\cdot S\rangle + 2\kappa_{qQ}[\langle s_q \cdot s_Q\rangle + \langle s_{\bar{q}} \cdot s_{\bar{Q}}\rangle]$$

$$= 2m_Q - aJ(J+1) + \left(\frac{B_Q}{2} + a\right)L(L+1) + aS(S+1) - 3\kappa_{qQ}$$

$$+ \kappa_{qQ}[s_{qQ}(s_{qQ}+1) + s_{\bar{q}\bar{Q}}(s_{\bar{q}\bar{Q}}+1)]$$

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

LS coupling   *LL* coupling

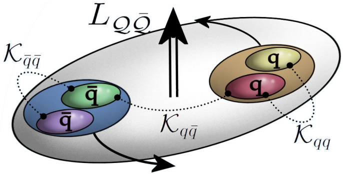
with

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

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

$$H_{SL} = 2A_{\mathcal{Q}}(\mathbf{S}_{\mathcal{Q}} \cdot \mathbf{L} + \mathbf{S}_{\bar{\mathcal{Q}}} \cdot \mathbf{L})$$

$$H_{LL} = B_{\mathcal{Q}} \frac{L_{\mathcal{Q}\bar{\mathcal{Q}}}(L_{\mathcal{Q}\bar{\mathcal{Q}}} + 1)}{2}$$



$$H_{\text{eff}}(X,Y,Z) = 2m_{\mathcal{Q}} + \frac{B_{\mathcal{Q}}}{2}\langle L^2 \rangle - 2a\langle L \cdot S \rangle + 2\kappa_{q\mathcal{Q}}\left[\langle s_q \cdot s_{\mathcal{Q}} \rangle + \langle s_{\bar{q}} \cdot s_{\bar{\mathcal{Q}}} \rangle\right]$$

$$= 2m_{\mathcal{Q}} - aJ(J+1) + \left(\frac{B_{\mathcal{Q}}}{2} + a\right)L(L+1) + aS(S+1) - 3\kappa_{q\mathcal{Q}} + \kappa_{q\mathcal{Q}}\left[s_{q\mathcal{Q}}(s_{q\mathcal{Q}}+1) + s_{\bar{q}\bar{\mathcal{Q}}}(s_{\bar{q}\bar{\mathcal{Q}}}+1)\right]$$

S-wave states

- In the $|s_{qQ}, s_{\bar{q}\bar{Q}}; S, L\rangle_J$ and $|s_{q\bar{q}}, s_{Q\bar{Q}}; S', L'\rangle_J$ bases, the positive parity S-wave tetraquarks are given in terms of the six states listed below (charge conjugation is defined for neutral states)

Label	J^{PC}	$\|s_{qQ}, s_{\bar{q}\bar{Q}}; S, L\rangle_J$	$\|s_{q\bar{q}}, s_{Q\bar{Q}}; S', L'\rangle_J$	Mass
X_0	0^{++}	$\|0,0;0,0\rangle_0$	$\left(\|0,0;0,0\rangle_0 + \sqrt{3}\|1,1;0,0\rangle_0\right)/2$	$M_{00} - 3\kappa_{qQ}$
X_0'	0^{++}	$\|1,1;0,0\rangle_0$	$\left(\sqrt{3}\|0,0;0,0\rangle_0 - \|1,1;0,0\rangle_0\right)/2$	$M_{00} + \kappa_{qQ}$
X_1	1^{++}	$\left(\|1,0;1,0\rangle_1 + \|0,1;1,0\rangle_1\right)/\sqrt{2}$	$\|1,1;1,L'\rangle_1$	$M_{00} - \kappa_{qQ}$
Z	1^{+-}	$\left(\|1,0;1,0\rangle_1 - \|0,1;1,0\rangle_1\right)/\sqrt{2}$	$\left(\|1,0;1,L'\rangle_1 - \|0,1;1,L'\rangle_1\right)/\sqrt{2}$	$M_{00} - \kappa_{qQ}$
Z'	1^{+-}	$\|1,1;1,0\rangle_1$	$\left(\|1,0;1,L'\rangle_1 + \|0,1;1,L'\rangle_1\right)/\sqrt{2}$	$M_{00} + \kappa_{qQ}$
X_2	2^{++}	$\|1,1;2,0\rangle_2$	$\|1,1;2,L'\rangle_2$	$M_{00} + \kappa_{qQ}$

P-wave ($J^{PC} = 1^{--}$) states

Label	J^{PC}	$\|s_{qQ}, s_{\bar{q}\bar{Q}}; S, L\rangle_J$	$\|s_{q\bar{q}}, s_{Q\bar{Q}}; S', L'\rangle_J$	Mass
Y_1	1^{--}	$\|0,0;0,1\rangle_1$	$\left(\|0,0;0,1\rangle_1 + \sqrt{3}\|1,1;0,1\rangle_1\right)/2$	$M_{00} - 3\kappa_{qQ} + B_Q$
Y_2	1^{--}	$\left(\|1,0;1,1\rangle_1 + \|0,1;1,1\rangle_1\right)/\sqrt{2}$	$\|1,1;1,L'\rangle_1$	$M_{00} - \kappa_{qQ} + 2a + B_Q$
Y_3	1^{--}	$\|1,1;0,1\rangle_1$	$\left(\sqrt{3}\|0,0;0,1\rangle_1 - \|1,1;0,1\rangle_1\right)/2$	$M_{00} + \kappa_{qQ} + B_Q$
Y_4	1^{--}	$\|1,1;2,1\rangle_1$	$\|1,1;2,L'\rangle_1$	$M_{00} + \kappa_{qQ} + 6a + B_Q$
Y_5	1^{--}	$\|1,1;2,3\rangle_1$	$\|1,1;2,L'\rangle_1$	$M_{00} + \kappa_{qQ} + 16a + 6B_Q$

Charmonium-like and Bottomonium-like Tetraquark Spectrum

(with Satoshi Mishima)

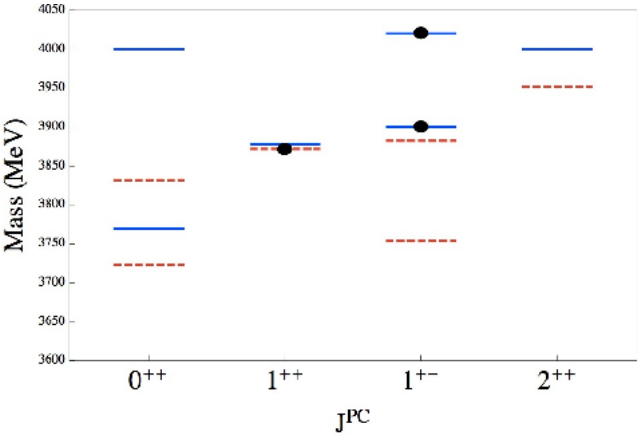
Parameters in the Mass Formula

	charmonium-like	bottomonium-like
M_{00} [MeV]	3957	10630
κ_{qQ} [MeV]	67	22.5
B_Q [MeV]	268	329
a [MeV]	52.5	26

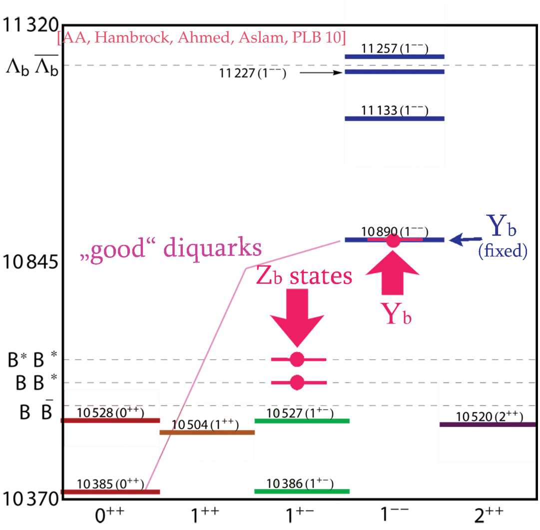
Label	J^{PC}	charmonium-like State	charmonium-like Mass [MeV]	bottomonium-like State	bottomonium-like Mass [MeV]
X_0	0^{++}	—	3756	—	10562.2
X_0'	0^{++}	—	4024	—	10652
X_1	1^{++}	$X(3872)$	3890	—	10607
Z	1^{+-}	$Z_c^+(3900)$	3890	$Z_b^{+,0}(10610)$	10607
Z'	1^{+-}	$Z_c^+(4020)$	4024	$Z_b^+(10650)$	10652
X_2	2^{++}	—	4024	—	10652
Y_1	1^{--}	$Y(4008)$	4024	$Y_b(10891)$	10891
Y_2	1^{--}	$Y(4260)$	4263	$Y_b(10987)$	**10987**
Y_3	1^{--}	$Y(4290)$ (or $Y(4220)$)	4292	—	**10981**
Y_4	1^{--}	$Y(4630)$	4607	—	11135
Y_5	1^{--}	—	6472	—	13036

Comparison with current data in the Charmonium-like sector

- Better agreement with data achieved with more tightly-bound quarks inside a diquark than is the case for diquarks in baryons [Maiani et al. (2014)]
- – – – – – New;   - - - - - Old



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



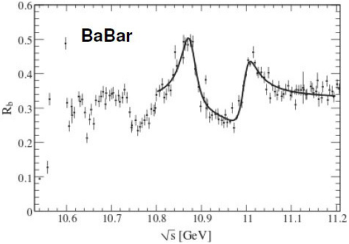
- states are iso-doublets $q = u, d$
- With the old Maiani *et al.* Paradigm, tetraquark $Z_b$masses do not agree with Belle
- However tetraquarks with mixing & self energy corrections in principle allowed in parts of parameter space [AA, Hambrock, Wang, PRD 11] ,
- but with the new Maiani *et al.* paradigm, $M(Z_b) - M(Z_b')$ fixes $2\kappa_{qb} = 45$MeV ,
- in agreement with the heavy quark symmetry: $\kappa_{qb}/\kappa_{qc} \simeq m_c/m_b$

Enigmatic $\Upsilon(5S)$ Decays!

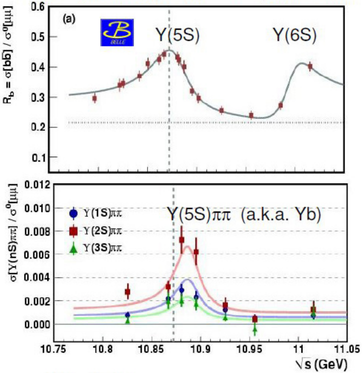
PRL 100, 112001 **(2008)**
21.7 fb^{-1} at 10.580 GeV

$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

PRL 102, 012001 **(2009)**



PRD 89, 091106 **(2010)** ~1 fb^{-1}/point SCAN



Belle 2010

M(5S)$b\bar{b}$ = **10869 ± 2 MeV**
M(5S)ππ = **10888.4 ± 2.7 ± 1.2 MeV**
M(5S) - M(5S)ππ = -9 ± 4 MeV

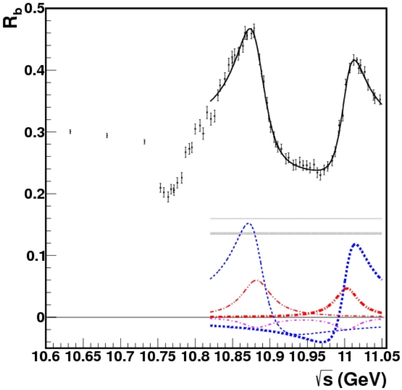
- Is there a $Y_b(10890)$ close to $\Upsilon(5S)$? If yes, what is it??

[AA, Hambrock, Ishtiaq Ahmed, Jamil Aslam, PLB 684 (2010) 28]

$\sigma(e^+e^- \to b\bar{b})$ in the $\Upsilon(10860)$ and $\Upsilon(11020)$ resonance region [Belle]

R_b' data and fit

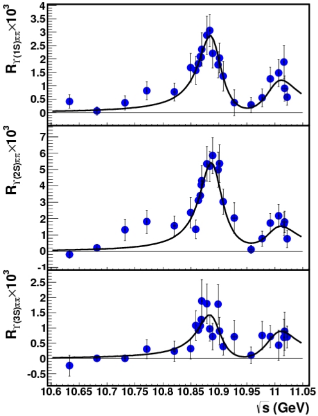
- $F_{b\bar{b}} = |A_{nr}|^2 + |A_r + A_{5S}e^{i\phi_{5S}}f_{5S} + A_{6S}e^{i\phi_{6S}}f_{6S}|^2$
- $f_{nS} = M_{ns}\Gamma_{nS}/[(s - M_{ns}^2) + iM_{nS}\Gamma_{nS}]$ [BW]; A_r and A_{nr}[Continuum]
- No peaking structure seen at 10.9 GeV, hinted by the BaBar data; $\Gamma(e^+e^-) < 9$ eV (@ 90% C.L.)



$\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)$ in the $\Upsilon(10860)$ and $\Upsilon(11020)$ resonance region

[D. Santel et al. (Belle), arxiv:1501.01137 (2015)]

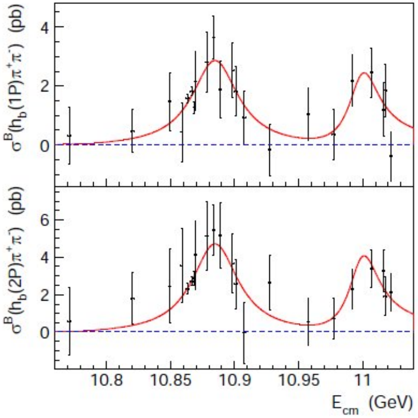
- Fit Values (MeV): $M_{10860} = 10891.1 \pm 3.2^{+0.6}_{-1.5}$; $\Gamma_{10860} = 53.7^{+7.1}_{-5.6}{}^{+0.9}_{-5.4}$
- $M_{5S}(\Upsilon(nS)\pi\pi) - M_{5S}(b\bar{b}) = 9.2 \pm 3.4 \pm 1.9$ MeV ?
- Fit Values (MeV): $M_{11020} = 10987.5^{+6.4}_{-2.5}{}^{+9.0}_{-2.1}$; $\Gamma_{11020} = 61^{+9}_{-19}{}^{+2}_{-20}$



$\sigma(e^+e^- \to h_b(1P,2P)\pi^+\pi^-)$ in the $\Upsilon(10860)$ and $\Upsilon(11020)$ resonance region

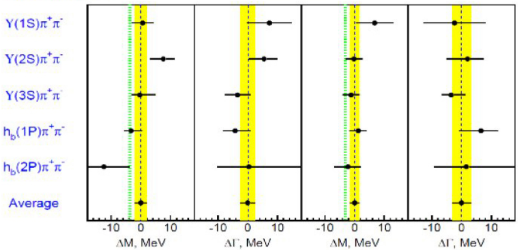
[A. Abdesselam et al. (Belle), arxiv:1508.06562 (2015)]

- Fit Values (MeV): $M_{10860} = 10884.7^{+3.2}_{-2.9}{}^{+8.6}_{-0.6}$; $\Gamma_{10860} = 44.2^{+1.9}_{-7.8}{}^{+2.2}_{-15.8}$
- Fit Values (MeV): $M_{11020} = 10998.6 \pm 6.1^{+16.1}_{-1.1}$; $\Gamma_{11020} = 29^{+20}_{-11}{}^{+2}_{-7}$



Evidence for $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$ (Belle)

PRL108,122001



Mass and Γ measured in 5 different final states agree

Angular analysis suggests $J^P = 1^+$

Z_b(10610)
M = 10608 pm 2.0 MeV
Γ = 15.6 pm 2.5 MeV
Z_b(10650)
M = 10653 pm 1.5 MeV
Γ = 14.4 pm 3.2 MeV

The Di Pion transitions from the Υ(5S) proceed via the intermediate charged state Z_b

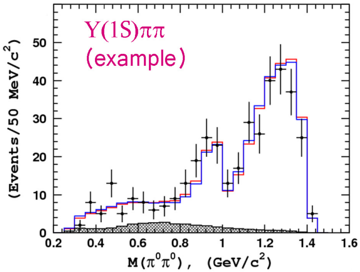
The transition does not imply spin flip

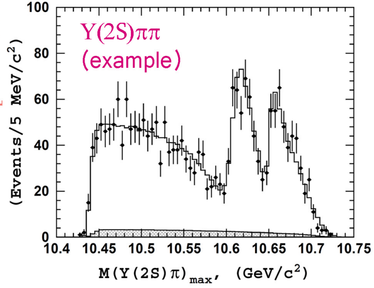
Masses are close to B*B and B*B* theresholds
Molecules?

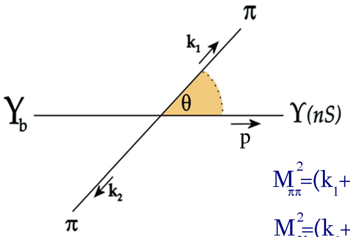
The Υ(5S) is an unexpected source of h_b

Dipion mass distributions in $\Upsilon(5S) \to \Upsilon(nS)\pi\pi$ decays?

[Belle Collaboration (2012)]







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

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

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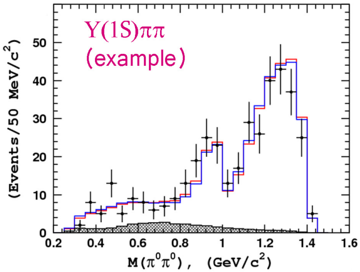
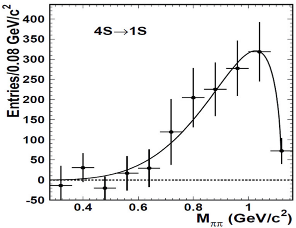
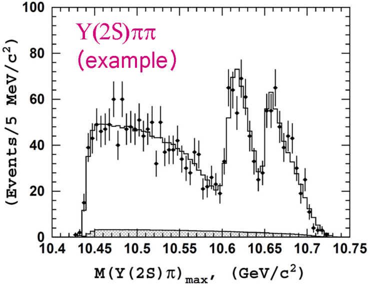
[Belle Collaboration (2012)]

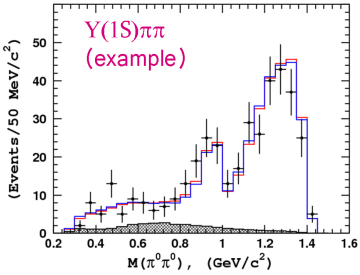


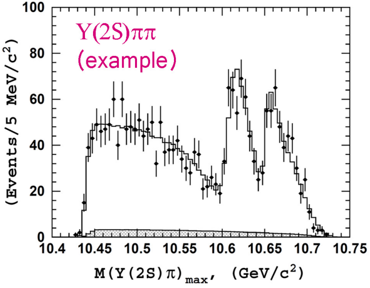


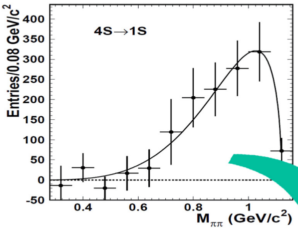


Dipion mass distributions in $\Upsilon(5S) \to \Upsilon(nS)\pi\pi$ decays?

[Belle Collaboration (2012)]







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

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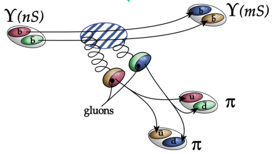

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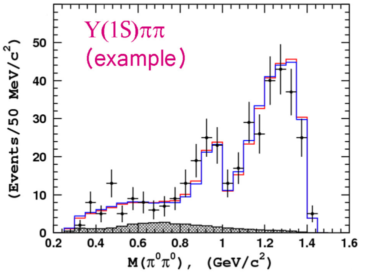

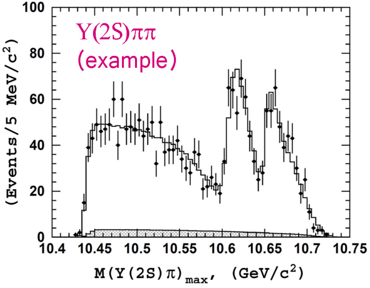

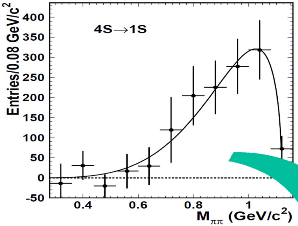

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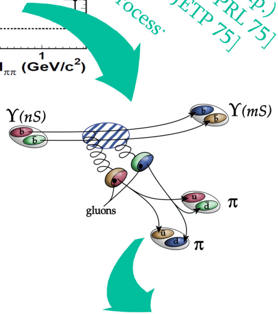

- NO resonant structure
- Zweig forbidden

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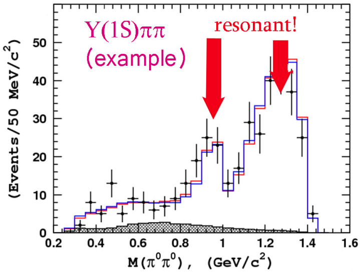

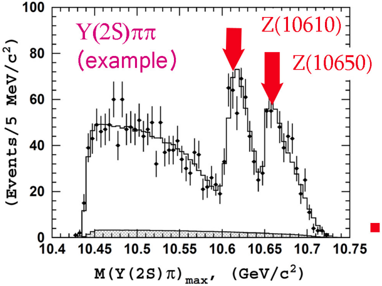

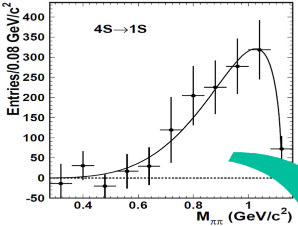

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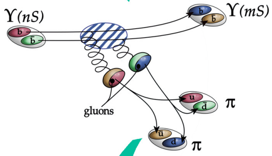

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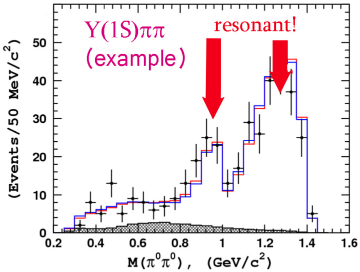

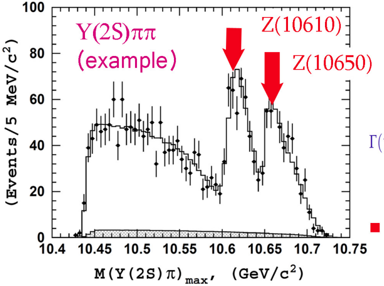

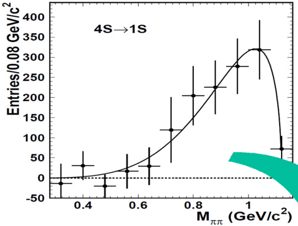

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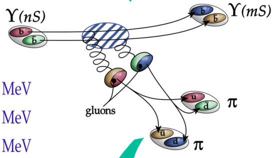

$\Gamma(\Upsilon(2S) \to \Upsilon(1S)\pi\pi) \approx 0.0060$ MeV

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

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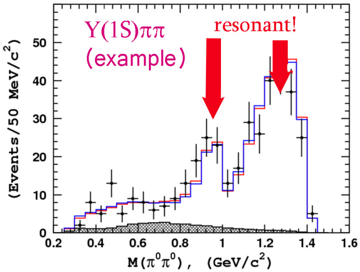

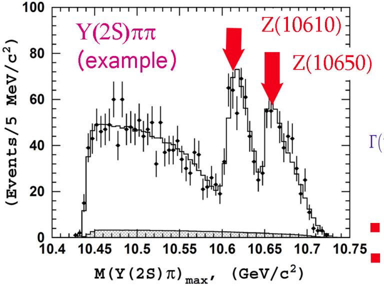

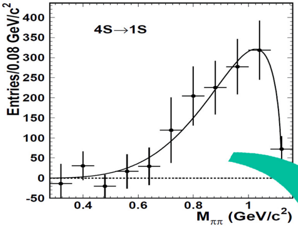

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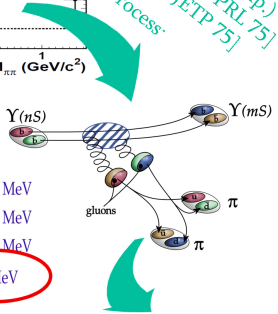

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- distinct resonant structure ↯
- differs by two orders of Magnitude! ↯

- NO resonant structure
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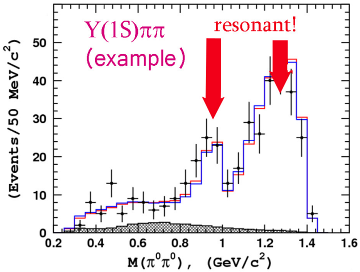

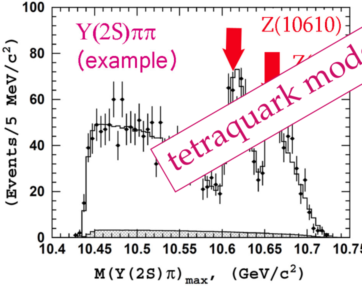

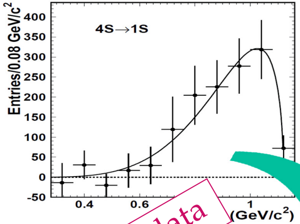

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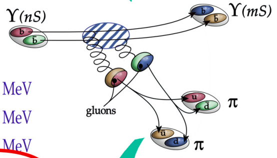

tetraquark model can explain data

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

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- distinct resonant structure ↯ — NO resonant structure
- differs by two orders of Magnitude! ↯ — Zweig forbidden

Heavy-Quark-Spin Flip in $\Upsilon(10890) \to Z_b/Z_b' + \pi \to h_b(1P,2P)\pi\pi$

A.A., L. Maiani, A.D. Polosa, V. Riquer; PR D91, 017502 (2015)

Relative normalizations and phases for $s_{b\bar{b}}$: $1 \to 1$ and $1 \to 0$ transitions

Final State	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
Rel. Norm.	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. Phase	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

- In $\Upsilon(10890)$, $S_{b\bar{b}} = 1$. In $h_b(nP)$, $S_{b\bar{b}} = 0$, transitions above involve heavy-quark spin-flip, yet rates not suppressed, violating heavy-quark-spin conservation
- This contradiction is only apparent. Expressing the states Z_b and Z_b' in the basis of definite $b\bar{b}$ and light quark $q\bar{q}$ spins

$$|Z_b\rangle = \frac{\alpha|1_{q\bar{q}}, 0_{b\bar{b}}\rangle - \beta|0_{q\bar{q}}, 1_{b\bar{b}}\rangle}{\sqrt{2}}, \quad |Z_b'\rangle = \frac{\beta|1_{q\bar{q}}, 0_{b\bar{b}}\rangle + \alpha|0_{q\bar{q}}, 1_{b\bar{b}}\rangle}{\sqrt{2}}$$

- and defining (g are the effective couplings at the vertices $\Upsilon\, Z_b\, \pi$ and $Z_b\, h_b\, \pi$)

$$g_Z \equiv g(\Upsilon \to Z_b\pi)g(Z_b \to h_b\pi) \propto -\alpha\beta\langle h_b|Z_b\rangle\langle Z_b|\Upsilon\rangle$$

$$g_{Z'} \equiv g(\Upsilon \to Z_b'\pi)g(Z_b' \to h_b\pi) \propto \alpha\beta\langle h_b|Z_b'\rangle\langle Z_b'|\Upsilon\rangle$$

Heavy-Quark-Spin Flip in $\Upsilon(10890) \to Z_b/Z_b' + \pi \to h_b(1P,2P)\pi\pi$

- Within errors, Belle data is consistent with heavy quark spin conservation, which requires $g_Z = -g_{Z'}$
- To determine the coefficients α and β, one has to resort to $s_{b\bar{b}}$: $1 \to 1$ transitions

$$\Upsilon(10890) \to Z_b/Z_b' + \pi \to \Upsilon(nS)\pi\pi \ (n = 1,2,3)$$

- The analogous effective couplings are

$$f_Z = f(\Upsilon \to Z_b\pi)f(Z_b \to \Upsilon(nS)\pi) \propto |\beta|^2 \langle \Upsilon(nS)|0_{q\bar{q}}, 1_{b\bar{b}}\rangle \langle 0_{q\bar{q}}, 1_{b\bar{b}}|\Upsilon\rangle$$
$$f_{Z'} = f(\Upsilon \to Z_b'\pi)f(Z_b' \to \Upsilon(nS)\pi) \propto |\alpha|^2 \langle \Upsilon(nS)|0_{q\bar{q}}, 1_{b\bar{b}}\rangle \langle 0_{q\bar{q}}, 1_{b\bar{b}}|\Upsilon\rangle$$

- Dalitz analysis indicates:
  $\Upsilon(10890) \to Z_b/Z_b' + \pi \to \Upsilon(nS)\pi\pi \ (n = 1,2,3)$ proceed mainly through the resonances Z_b and Z_b', though $\Upsilon(10890) \to \Upsilon(1S)\pi\pi$ has a significant direct component, expected in tetraquark interpretation of $\Upsilon(10890)$
  [A.A., S. Mishima, C. Hambrock, PRL 106, 092002 (2011)]

Determination of α/β from $\Upsilon(10890) \to Z_b/Z_b' + \pi \to \Upsilon(nS)\pi\pi \ (n = 1,2,3)$

- A comprehensive analysis of the Belle data including the direct and resonant components is required to test the underlying dynamics, yet to be carried out
- Parametrizing the amplitudes in terms of two Breit-Wigners, one can determine the ratio α/β

$$s_{b\bar{b}} : 1 \to 1 \text{ transition :}$$
$$\overline{\text{Rel.Norm.}} = 0.85 \pm 0.08 = |\alpha|^2/|\beta|^2$$
$$\overline{\text{Rel.Phase}} = (-8 \pm 10)^\circ$$

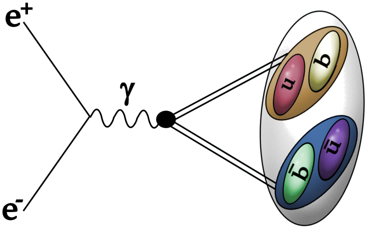
$$s_{b\bar{b}} : 1 \to 0 \text{ transition :}$$
$$\overline{\text{Rel.Norm.}} = 1.4 \pm 0.3$$
$$\overline{\text{Rel.Phase}} = (185 \pm 42)^\circ$$

- Within errors, the tetraquark assignment with $\alpha = \beta = 1$ is supported, i.e.,

$$|Z_b\rangle = \frac{|1_{bq}, 0_{\bar{b}\bar{q}}\rangle - |0_{bq}, 1_{\bar{b}\bar{q}}\rangle}{\sqrt{2}}, \quad |Z_b'\rangle = |1_{bq}, 1_{\bar{b}\bar{q}}\rangle_{J=1}$$

$$|Z_b\rangle = \frac{|1_{q\bar{q}}, 0_{b\bar{b}}\rangle - |0_{q\bar{q}}, 1_{b\bar{b}}\rangle}{\sqrt{2}}, \quad |Z_b'\rangle = \frac{|1_{q\bar{q}}, 0_{b\bar{b}}\rangle + |0_{q\bar{q}}, 1_{b\bar{b}}\rangle}{\sqrt{2}}$$

Tetraquark model for Y_b production and decays



- Van Royen-Weisskopf formula
  $\Rightarrow \Gamma(1^{--} \rightarrow e^+ e^-)$

Assumption: Point-like diquarks

[AA, Hambrock, Mishima, PRL 106 (2011), 092002]

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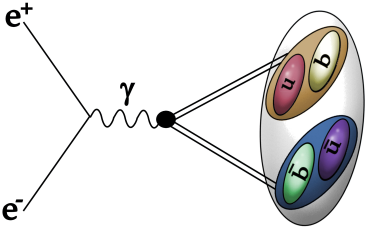

$$\Gamma_{ee}(Y_{[b,l/h]}) = \frac{24\alpha^2 Q^2_{[b,l/h]}}{M^4_{Y_{[b,l/h]}}} \kappa^2 \left| R^{(1)}_{11}(0) \right|^2$$

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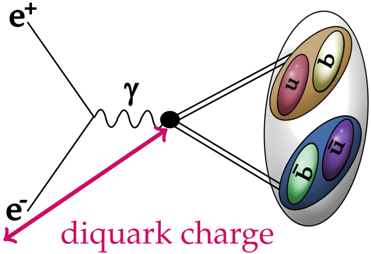

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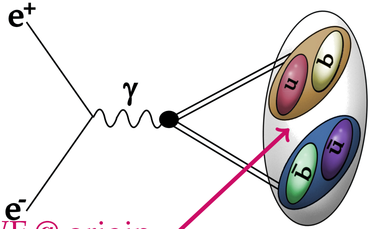

radial tetraquark WF @ origin

$$\Gamma_{ee}(Y_{[b,l/h]}) = \frac{24\alpha^2 Q^2_{[b,l/h]}}{M^4_{Y_{[b,l/h]}}} \kappa^2 \left| R^{(1)}_{11}(0) \right|^2$$

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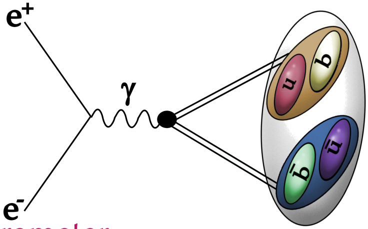

Assumption: Point-like diquarks

[AA, Hambrock, Mishima, PRL 106 (2011), 092002]

hadronic size parameter

$$\Gamma_{ee}(Y_{[b,l/h]}) = \frac{24\alpha^2 Q^2_{[b,l/h]}}{M^4_{Y_{[b,l/h]}}} \kappa^2 \left| R^{(1)}_{11}(0) \right|^2$$

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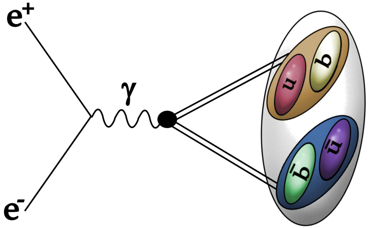


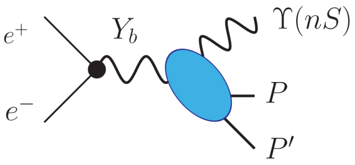
$$\Gamma_{ee}(Y_{[b,l/h]}) = \frac{24\alpha^2 Q^2_{[b,l/h]}}{M^4_{Y_{[b,l/h]}}} \kappa^2 \left| R^{(1)}_{11}(0) \right|^2$$

- Suppressed $\mathcal{O}(10)$ vs $\Upsilon(5S)$
- Production ratio: $\Gamma_{Y_{[b,l]}} / \Gamma_{Y_{[b,h]}} = \left(\frac{1-2\tan\theta}{2+\tan\theta}\right)^2$
- Isospin breaking through production

e.g. $\frac{\sigma_{\Upsilon(1S)K^+K^-}}{\sigma_{\Upsilon(1S)K^0\bar{K}^0}} = \frac{Q^2_{[bu]}}{Q^2_{[bd]}} = \frac{1}{4}$

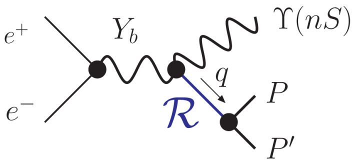
Y_b decay

Continuum



+

Resonance



- Breit-Wigner shape for resonance:

$$\frac{1}{(q^2 - M^2) + iM\Gamma}$$

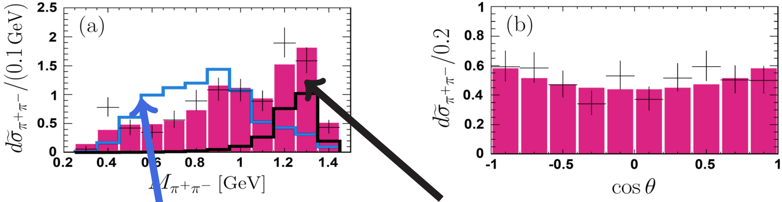
$q^2 \equiv M^2_{PP'}$ ➡ Resonances show in $M_{PP'}$ spectrum

Not in $M_{\Upsilon P}$ spectrum since Z_b negligible

Fit to $\sigma(e^+e^- \to Y_b \to \Upsilon(1S)\pi^+\pi^-)$

[AA, Hambrock, Jamil Aslam; PRL 104 (2010) 162001

AA, Hambrock, Mishima, PRL 106 (2011), 092002]



2^{++} meson $f_2(1270)$

0^{++} tetraquarks $\sigma(500)\ +\ f_0(980)$

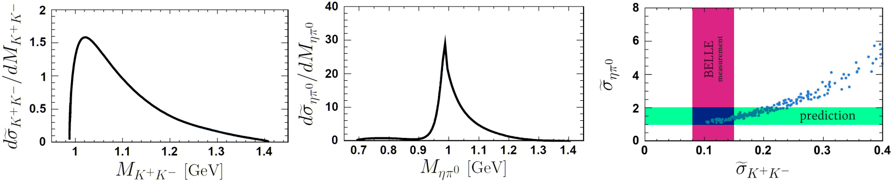
- Fit results, data from [Belle, PRL 08]
- $\chi^2/\text{d.o.f.} = 21.5/15$ → Good agreement with data
- Clear resonance dominance!

Predictions for $\Upsilon(1S)(K^+K^-, \eta\pi^0)$

[AA, Hambrock, Mishima, PRL 106 (2011), 092002]

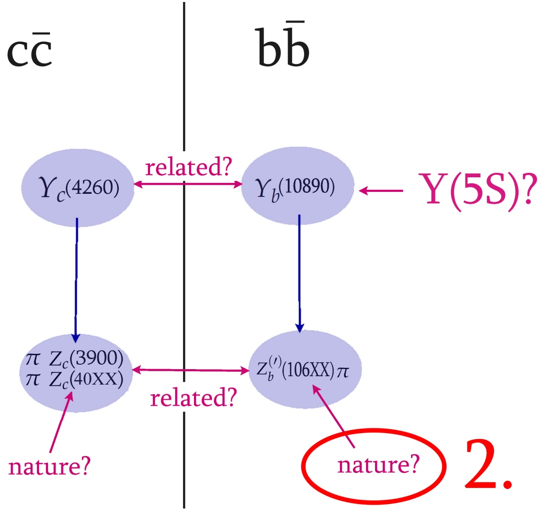
Fit determines couplings (assume $SU(3)$ flavor symmetry for couplings $(\sigma(500), f_0(980), a_0(980)) \to PP'$, ['t Hooft, Isidori, Maiani, Polosa, Riquer, PLB 08])

➥ predictions for spectra:

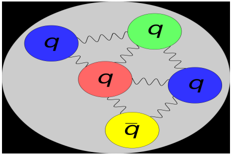


- Agreement with $\tilde{\sigma}_{K^+K^-} = 0.11^{+0.04}_{-0.03}$ (BELLE)
  - ➥ $1.0 \lesssim \tilde{\sigma}_{\eta\pi^0} \lesssim 2.0$ predicted
- Resonance dominance
  - ➥ Characteristic shape
    - ➥ **Good tests (relying on Y_b has 2 flavor states)**

Are Y_c, Z_cs, Y_b and Z_bs related?



Pentaquarks



- Pentaquarks remained cursed under the shadow of the botched discoveries of $\Theta(1540)$, $\Phi(1860)$, $\Theta_c(3100)$!

- Review on Pentaquarks [C.G. Wohl in PDG (2014)]:

  There are two or three recent experiments that find weak evidence for signals near the nominal masses, but there is simply no point in tabulating them in view of the overwhelming evidence that the claimed pentaquarks do not exist. The only advance in particle physics thought worthy of mention in the American Institute of Physics "Physics News in 2003" was a false alarm. The whole story — is a curious episode in the history of science.

Elusive Pentaquark Comes into View! (R. Aaij et al., PRL 115, 072001 (2015)

CERN-PH-EP-2015-153
LHCb-PAPER-2015-029
July 13, 2015

Observation of $J/\psi\, p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays

The LHCb collaboration[1]

Abstract

Observations of exotic structures in the $J/\psi p$ channel, which we refer to as charmonium-pentaquark states, in $\Lambda_b^0 \to J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb^{-1} acquired with the LHCb detector from 7 and 8 TeV pp collisions. An amplitude analysis of the three-body final-state reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments are of opposite parity, with one state having spin 3/2 and the other 5/2.

The Pentaquarks $P_c^+(4380)$ and $P_c^+(4450)$ as resonant $J/\psi p$ states

- Discovery Channel (LHC; $\sqrt{s} = 7$ & 8 TeV; $\int L dt = 3$ fb^{-1})

$$pp \to b\bar{b} \to \Lambda_b X; \quad \Lambda_b \to K^- J/\psi p$$

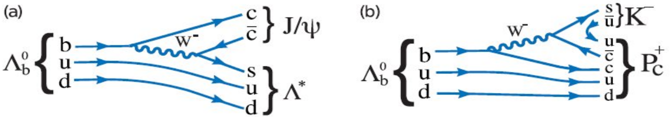


Figure 1: Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

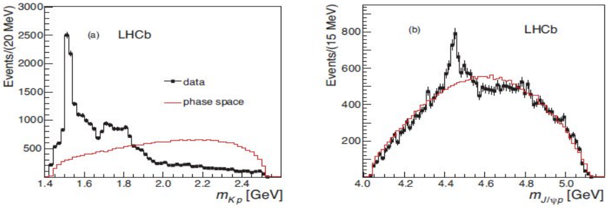
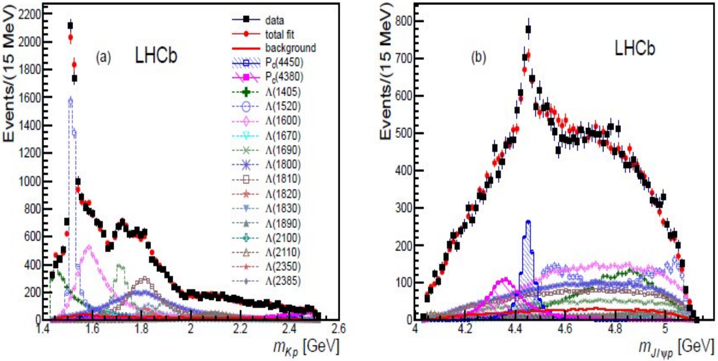


Figure 2: Invariant mass of (a) $K^- p$ and (b) $J/\psi p$ combinations from $\Lambda_b^0 \to J/\psi K^- p$ decays. The solid (red) curve is the expectation from phase space. The background has been subtracted.

Model fits with two [$P_c^+(4380)$ and $P_c^+(4450)$] states

- Fits with two P_c^+ states. Acceptable fits found for several J^P combinations
- The best fit yields $J^P = (3/2^-, 5/2^+)$ for $[P_c^+(4380), P_c^+(4450)]$ states. Both the m_{Kp} and $m_{J/\psi p}$ projections are well described



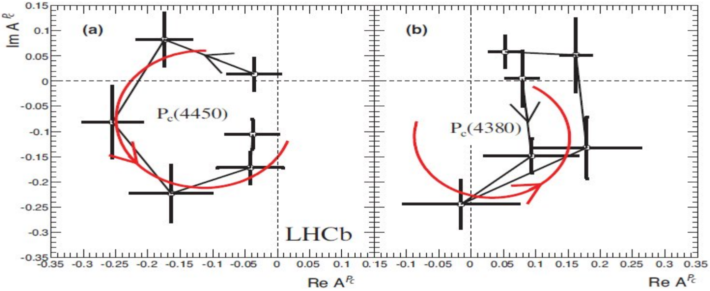
- Higher mass state (statistical significance 12σ)

$$M = 4449.8 \pm 1.7 \pm 2.5 \;\text{MeV};\;\; \Gamma = 39 \pm 5 \pm 19 \;\text{MeV}$$

- Lower mass state (statistical significance 9σ)

$$M = 4380 \pm 8 \pm 29 \;\text{MeV};\;\; \Gamma = 205 \pm 18 \pm 86 \;\text{MeV}$$

- Fitted Values of the real and imaginary parts of the amplitudes



- For $P_c^+(4450)$, fit shows a phase change in amplitudes consistent with a resonance

Summary of the LHCb Pentaquark Measurements (Contd.)

Possible J^P assignments and the energies of the nearby thresholds

	$P_c(4380)^+$	$P_c(4450)^+$
Mass	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width	$205 \pm 18 \pm 86$	$35 \pm 5 \pm 19$
Assignment 1	$3/2^-$	$5/2^+$
Assignment 2	$3/2^+$	$5/2^-$
Assignment 3	$5/2^+$	$3/2^-$
$\Sigma_c^{*+}\bar{D}^0$	4382.3 ± 2.4	
$\chi_{c1}p$		4448.93 ± 0.07
$\Lambda_c^{*+}\bar{D}^0$		4457.09 ± 0.35
$\Sigma_c^+\bar{D}^{*0}$		4459.9 ± 0.5
$\Sigma_c^+\bar{D}^0\pi^0$		4452.7 ± 0.5

Theoretical Interpretations of the LHCb Pentaquarks

Rescattering-induced kinematic effects

- Feng-Kun Guo, Ulf-G.Meißner, Wei Wang, Zhi Yang, arxiv:1507.04950
- Xiao-Hai Liu, Qian Wang, Qiang Zhao, arxiv:1507.05359
- M. Mikhasenko, arxiv:1507.06552
- Ulf-G.Meißner, Jose A. Oller, arxiv:1507.07478

Open-charm-baryon and -meson bound states

- Hua-Xing Chen, Wei Chen, Xiang Liu, T.G. Steele, Shi-Lin Zhu, arxiv:1507.03717
- Jun He, arxiv:1507.05200
- L. Roca, J. Nieves, E. Oset, arxiv:1507.04249
- Rui Chen, Xiang-Liu, arxiv:1507.03704
- C. W. Xiao and Ulf-G.Meißner, arxiv:1508.00924

Pentaquarks as Baryocharmonia

- Formation of hidden-charm pentaquarks in photon-nucleon collisions
  V. Kubarovsky and M.B. Voloshin, arxiv:1508.00888

Theoretical Interpretations of the LHCb Pentaquarks (Contd.)

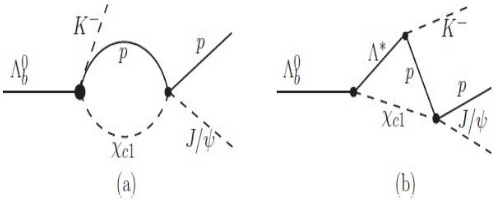
Compact Pentaquarks

- L. Maiani, A.D. Polosa, V. Riquer, arxiv: 1507.04980
- Richard F. Lebed, arxiv:1507.05867
- Guan-Nan Li, Xiao-Gang He, Min He, arxiv:1507.08252
- A. Mironov, A. Morozov, arxiv:1507.04694
- A.V. Anisovich et al., arxiv:1507.07652
- R. Ghosh, A. Bhattacharya, B. Chakrabarti, arxiv:1508.00356
- Zhi-Gang Wang, arxiv:1508.01468
- Zhi-Gang Wang, Tao Huang, arxiv:1508.04189
- H.Y. Cheng, C.K. Chua, arxiv:1509.03708
- G.N. Li, X.G. he, M. He, arxiv:1507.08252
- A. Ali, I. Ahmed, A. Rehman, M.J. Aslam, arxiv:1607.00987

Pentaquarks as rescattering-induced kinematic effects

[Feng-Kun Guo et al.; arxiv:1507.04950]

- Hypothesis: Kinematic effects can result in a narrow structure around the $\chi_{c1}\,p$ threshold in the $J/\psi\,p$ invariant mass of the decay $\Lambda_b^0 \to K^-\,J/\psi\,p$
  $M_{P_c(4450)} - M_{\chi_{c1}} - M_p = (0.9 \pm 3.1)$ MeV
- Two possible mechanisms:
  a) 2-point loop with a 3-body production $\Lambda_b^0 \to K^-\,\chi_{c1}\,p$ followed by the rescattering process $\chi_{c1}\,p \to J/\psi\,p$
  b) The $K^-\,p$ is produced from an intermediate Λ^* and the proton rescatters with the χ_{c1} into a $J/\psi\,p$



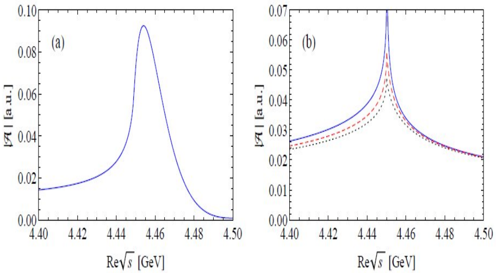
Pentaquarks as rescattering-induced kinematic effects (Contd.)

[Feng-Kun Guo et al.; arxiv:1507.04950]

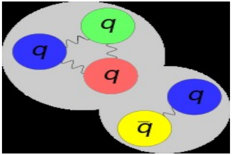
- Amplitude for Fig. (a) (μ = reduced mass and $f_\Lambda(\vec{q}^2) = \exp(-2\vec{q}^2/\Lambda^2)$)

$$G_\Lambda(E) = \int \frac{d^3q}{(2\pi)^3} \frac{\vec{q}^2 f_\Lambda(\vec{q}^2)}{E - m_p - m_{\chi_{c1}} - \vec{q}^2/(2\mu)}$$

- Fitting the Argand diagram for $P_c(4450)$ with $\mathcal{A}_{(a)} = N(b + G_\Lambda(E))$ determines the normalization N, the constant background b and Λ
- Amplitude for Fig. (b) is assumed dominated by $\Lambda^*(1890)$-exchange, and its width is varied from 10 MeV to 100 MeV, leading to sharp peaks at $\mathrm{Re}\sqrt{s} = 4450$ MeV



Pentaquarks as hadronic molecular states [Rui Chen et al., arxiv:1507.03704]



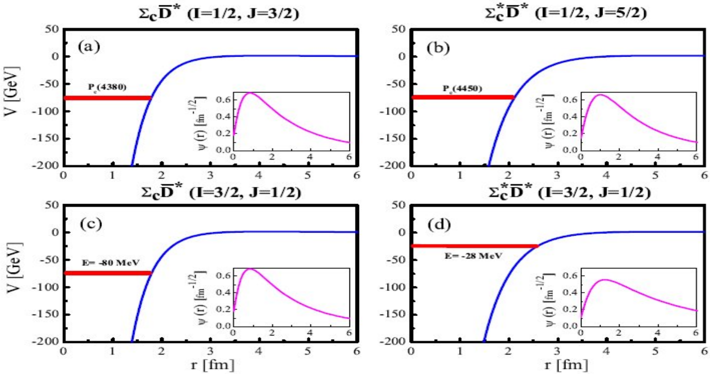
- Identify $\mathbb{P}_c^+(4380)$ with $\Sigma_c(2455)\bar{D}^*$ and $\mathbb{P}_c^+(4450)$ with $\Sigma_c(2520)\bar{D}^*$ bound by a pion exchange
- Effective Lagrangians:

$$\mathcal{L}_{\mathcal{P}} = ig\mathrm{Tr}\left[\bar{H}_a^{(\bar{Q})}\,\gamma^\mu\,A^\mu_{ab}\,\gamma_5 H_b^{(\bar{Q})}\right]$$

$$\mathcal{L}_{\mathcal{S}} = -\frac{3}{2}g_1\epsilon^{\mu\lambda\nu\kappa}v_\kappa\mathrm{Tr}\left[\bar{\mathcal{S}}_\mu\,A_\nu\,\mathcal{S}_\lambda\right]$$

- $H_a^{(\bar{Q})} = [P_a^{*(\bar{Q})\,\mu}\gamma_\mu - P_a^{(\bar{Q})}\gamma_5](1-\not{v})/2$; $v = (0,\vec{1})$ is a pseudoscalar and vector charmed meson multiplet (D, D^*);
  $\mathcal{S}_\mu = \sqrt{1/3}(\gamma_\mu + v_\mu)\gamma^5\mathcal{B}_6 + \mathcal{B}^*_{6\mu}$ stands for the charmed baryon multiplet, with $\mathcal{B}_6$ and $\mathcal{B}^*_{6\mu}$ corresponding to the $J^P = 1/2^+$ and $J^P = 3/2^+$ in 6_F flavor representation;
  A_μ is an axial-vector current, containing a pion chiral multiplet

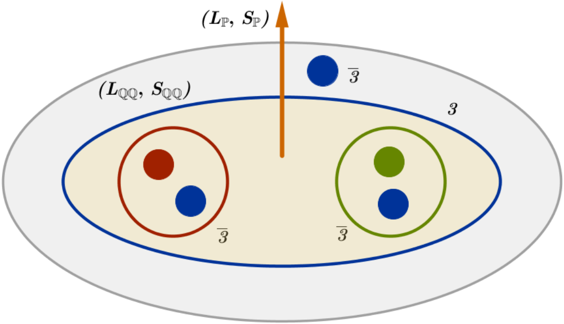
Eff. potentials, energy levels & wave-functions of the $\Sigma_c^{(*)}\bar{D}^*$ systems



- $\mathbb{P}_c(4380)$is a $\Sigma_c\bar{D}^*$ $(I=1/2, J=3/2)$ molecule
  $\mathbb{P}_c(4450)$is a $\Sigma_c^*\bar{D}^*$ $(I=1/2, J=5/2)$ molecule
- Predict two additional hidden-charm molecular pentaquark states, $\Sigma_c\bar{D}^*$ $(I=3/2, J=1/2)$ and $\Sigma_c^*\bar{D}^*$ $(I=3/2, J=1/2)$, which are isospin partners of $\mathbb{P}_c(4380)$ and $\mathbb{P}_c(4450)$, decaying into $\Delta(1232)J/\psi$ and $\Delta(1232)\eta_c$
- A rich pentaquark spectrum of states for the hidden-bottom $(\Sigma_b B^*, \Sigma_b^* B^*)$, B_c-like $(\Sigma_c B^*, \Sigma_c^* B^*)$ and $(\Sigma_b\bar{D}^*, \Sigma_b^*\bar{D}^*)$with well-defined (I,J) are predicted

Effective Hamiltonian for Pentaquarks

[Ahmed,Rehman,Aslam,AA, arxiv:1607.00987]



Diquark – Diquark – Antiquark Model of Pentaquarks

$$H_{\text{eff}}(\mathbb{P}) = H_{\text{eff}}([\mathcal{Q}\mathcal{Q}]) + m_{\bar{c}} + \kappa_{\bar{c}[\mathcal{Q}\mathcal{Q}]}(s_{\bar{c}} \cdot S_{[\mathcal{Q}\mathcal{Q}]}) - 2a_{\mathbb{P}}(L_{\mathbb{P}} \cdot S_{\mathbb{P}}) + \frac{B_{\mathbb{P}}}{2}\langle L_{\mathbb{P}}{}^2\rangle$$

- $S_{[\mathcal{Q}\mathcal{Q}]}$ is the spin of the tetraquark; $s_{\bar{c}}$ is the spin of the $\bar{c}$
  $L_{\mathbb{P}}$ and $S_{\mathbb{P}}$ are the orbital angular momentum and spin of the pentaquark, respectively

Pentaquarks in the diquark model [Maiani et al., arxiv:1507.04980]

- $\Lambda_b(bud) \to \mathbb{P}^+ K^-$ decaying according to $\mathbb{P}^+ \to J/\Psi + p$
- $\mathbb{P}^+$carry a unit of baryonic number and have the valence quarks

$$\mathbb{P}^+ = \bar{c}cuud$$

- Assume the assignments

$$\mathbb{P}^+(3/2^-) = \{\bar{c}\,[cq]_{s=1}[q'q'']_{s=1}, L=0\}$$
$$\mathbb{P}^+(5/2^+) = \{\bar{c}\,[cq]_{s=1}[q'q'']_{s=0}, L=1\}$$

- Mass difference:

  • Level spacing for $\Delta L = 1$ in light baryons; $\Lambda(1405) - \Lambda(1116) \sim 290$ MeV

  • Light-light diquark mass difference for $\Delta S = 1$:
  $[qq']_{s=1} - [qq']_{s=0} = \Sigma_c(2455) - \Lambda_c(2286) \simeq 170$ MeV

- Orbital gap $\mathbb{P}^+(3/2^-) - \mathbb{P}^+(5/2^+)$ is thereby reduced to 120 MeV, more or less in agreement with data, 70 MeV

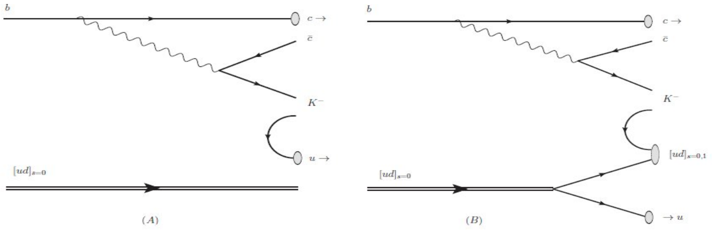
Pentaquark production mechanisms in $\Lambda_b^0 \to K^- J/\psi p$

- Two possible mechanisms are proposed by Maiani et al.

  • In the first, b -quark spin is shared between the K^- ,and the $\bar{c}$ and $[cu]$ components, the final $[ud]$ diquark has spin-0 , Fig. A

  • In the second, the $[ud]$ diquark is formed from the original d quark, and the u quark from the vacuum $u\bar{u}$; angular momentum is shared among all components, and the diquark $[ud]$ may have both spins, $s = 0, 1$, Fig. B

- Which of the two diagrams dominate is a dynamical question; semileptonic decays of Λ_b hint that the mechanism in Fig. B is dynamically suppressed



Flavor $SU(3)$ structure of Pentaquarks

- Pentaquarks are of two types:

$$\mathbb{P}_u = \epsilon^{\alpha\beta\gamma}\bar{c}_\alpha\,[cu]_{\beta,s=0,1}\,[ud]_{\gamma,s=0,1}$$
$$\mathbb{P}_d = \epsilon^{\alpha\beta\gamma}\bar{c}_\alpha\,[cd]_{\beta,s=0,1}\,[uu]_{\gamma,s=1}$$

- This leads to two distinct $SU(3)$ series of Pentaquarks

$$\mathbb{P}_A = \epsilon^{\alpha\beta\gamma}\left\{\bar{c}_\alpha\,[cq]_{\beta,s=0,1}\,[q'q'']_{\gamma,s=0}, L\right\} = \mathbf{3}\otimes\bar{\mathbf{3}} = \mathbf{1}\oplus\mathbf{8}$$
$$\mathbb{P}_S = \epsilon^{\alpha\beta\gamma}\left\{\bar{c}_\alpha\,[cq]_{\beta,s=0,1}\,[q'q'']_{\gamma,s=1}, L\right\} = \mathbf{3}\otimes\mathbf{6} = \mathbf{8}\oplus\mathbf{10}$$

- For S waves, the first and the second series have the angular momenta (multipicity)

$$\mathbb{P}_A(L=0):\quad J = 1/2(2),\ 3/2(1)$$
$$\mathbb{P}_S(L=0):\quad J = 1/2(3),\ 3/2(3),\ 5/2(1)$$

- Maiani et al. propose to assign $\mathbb{P}(3/2^-)$ to the $\mathbb{P}_A$ and $\mathbb{P}(5/2^+)$ to the $\mathbb{P}_S$ series of Pentaquarks

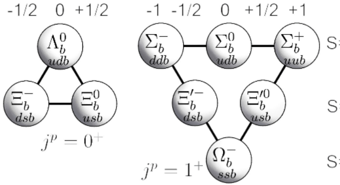
Closer look at the data on Λ_b^0 decays

K. A. Olive *et al.* **(PDG), Chin. Phys. C, 38, 090001 (2014)**

$$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}_\ell) = (\mathbf{6.2}^{+1.4}_{-1.2})\% \quad j^P: 0^+ \to 0^+$$

$$\mathcal{B}(\Lambda_b^0 \to \Sigma_c^+ \ell^- \bar{\nu}_\ell) = \text{ non-existent } j^P: 0^+ \to 1^+$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^0(2455)\pi^+\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)} \simeq 0.1 \quad j^P: 0^+ \to 1^+$$



$$\frac{\frac{1}{2}\Gamma(\Lambda_b^0 \to \Sigma^0\pi^+\ell^-\bar{\nu}_\ell) + \frac{1}{2}\Gamma(\Lambda_b^0 \to \Sigma^{++}\pi^-\ell^-\bar{\nu}_\ell)}{\Gamma(\Lambda_b^0 \to \Lambda_c^+\ell^-\bar{\nu}_\ell)} = \mathbf{0.054 \pm 0.022^{+0.021}_{-0.018}}$$

The $\Lambda_b^0 \to \Sigma^0\pi^+\ell^-\bar{\nu}_\ell$ and $\Lambda_b^0 \to \Sigma^{++}\pi^-\ell^-\bar{\nu}_\ell$, facilitating an $\mathbf{0^+ \to 1^+}$ transition are suppressed.

In heavy quark limit, the spin of the light diquark in heavy baryons has consequences for the b-baryon decays i.e., constraining the states which can otherwise be produced in b-baryon decays.

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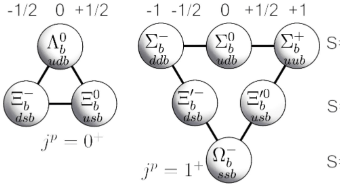

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Does the HQS hold in b-baryon decays to pentaquarks? We currently lack data to test it, but it is worthwhile to work out its implications for the interpretation of the LHCb data and the pentaquark phenomenology.

Heavy quark symmetry and observed pentaquarks

[Ahmed,Rehman,Aslam,AA, arxiv:1607.00987]

Selection rules from the the data on $b \to c$ baryonic decays and HQS

$$P_c^+(4450) = \{\bar{c}[cu]_{s=1}[ud]_{s=0}; L_{\mathcal{P}} = 1, J^{\rm P} = \frac{5}{2}^+\} \quad \textbf{Favored}$$

$$P_c^+(4380) = \{\bar{c}[cu]_{s=1}[ud]_{s=1}; L_{\mathcal{P}} = 0, J^{\rm P} = \frac{3}{2}^-\} \quad \textbf{Disfavored}$$

$\Longrightarrow$ $\frac{3}{2}^-$ **state may require a different interpretation**.

$m[\Lambda_c^+(2625); J^P = \frac{3}{2}^-] - m[\Lambda_c^+(2286); J^P = \frac{1}{2}^+] \simeq 341$ MeV $\Longrightarrow$ the mass of $J^P = 3/2^-$ state to be about 4110 MeV.

In **diquark-diquark-antiquark** spectrum, $\frac{3}{2}^-$ state is favored by HQS,

$$\{\bar{c}[cu]_{s=1}[ud]_{s=0}; L_{\mathcal{P}} = 0, J^{\rm P} = \frac{3}{2}^-\},$$

Third state anticipated in 4110-4130 MeV range. A renewed fit of the LHCb data by allowing a third resonance is called for.

Weak decays of the b-baryons into pentaquark states

$$\mathcal{A} = \left\langle \mathcal{P}\mathcal{M} \left| H_{\text{eff}}^{W} \right| \mathcal{B} \right\rangle, \text{ with } H_{\text{eff}}^{W} = \frac{4G_F}{\sqrt{2}} \left[V_{cb} V_{cq}^{*} (c_1 O_1^{(q)} + c_2 O_2^{(q)}) \right]$$

H_{eff}^{W} inducing the Cabibbo-allowed $\Delta I = 0, \Delta S = -1$ transition $b \to c\bar{c}s$, and the Cabibbo-suppressed $\Delta S = 0$ transition $b \to c\bar{c}d$.

$$O_1^{(q)} = (\bar{q}_\alpha c_\beta)_{V-A} (\bar{c}_\alpha b_\beta)_{V-A} \text{ and } O_2^{(q)} = (\bar{q}_\alpha c_\alpha)_{V-A} (\bar{c}_\beta b_\beta)_{V-A}$$

$\mathcal{B}_{ij}\ (\bar{\mathbf{3}}) = \Lambda_b^0(udb),\ \Xi_b^0(usb),\ \Xi_b^-(dsb)$, $\quad \mathcal{C}_{ij}\ (\mathbf{6}) = \Sigma_b^-(ddb),\ \Sigma_b^0(udb),\ \Sigma_b^+(uub)),\ \Xi_b'(dsb),\ \Xi_b'^0(usb),\ \Omega_b^-(ssb)$

$$\mathcal{M}_i^j = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta_8}{\sqrt{6}} \end{pmatrix}, \quad \mathcal{P}_i^j\left(J^P\right) = \begin{pmatrix} \frac{P_{\Sigma^0}}{\sqrt{2}} + \frac{P_\Lambda}{\sqrt{6}} & P_{\Sigma^+} & P_p \\ P_{\Sigma^-} & -\frac{P_{\Sigma^0}}{\sqrt{2}} + \frac{P_\Lambda}{\sqrt{6}} & P_n \\ P_{\Xi^-} & P_{\Xi^0} & -\frac{P_\Lambda}{\sqrt{6}} \end{pmatrix}.$$

A decuplet $\mathcal{P}_{ijk}$: $\mathcal{P}_{111} = P_{\Delta_{10}^{++}}$, $\mathcal{P}_{112} = P_{\Delta_{10}^{+}}/\sqrt{3}$, $\mathcal{P}_{122} = P_{\Delta_{10}^{0}}/\sqrt{3}$, $\mathcal{P}_{222} = P_{\Delta_{10}^{-}}$, $\mathcal{P}_{113} = P_{\Sigma_{10}^{+}}/\sqrt{3}$, $\mathcal{P}_{123} = P_{\Sigma_{10}^{0}}/\sqrt{6}$, $\mathcal{P}_{223} = P_{\Sigma_{10}^{-}}/\sqrt{3}$, $\mathcal{P}_{133} = P_{\Xi_{10}^{0}}/\sqrt{3}$, $\mathcal{P}_{233} = P_{\Xi_{10}^{-}}/\sqrt{3}$ and $\mathcal{P}_{333} = P_{\Omega_{10}^{-}}$.

◇ **Calculating the decay amplitudes is a formidable challenge.**
◇ **$SU(3)_F$ symmetry relations provided useful guide for pentaquark searches,** Li *et al.* [arXiv:1507.08252]

◇ **Only those states obeying the flavor constraints following from the weak Hamiltonian and having the internal spin quantum numbers compatible with the HQS will actually be produced in b-baryon decays.**

$SU(3)$ based analysis of $\Lambda_b \to \mathbb{P}^+ K^- \to (J/\psi\, p) K^-$

- With respect to flavor $SU(3)$, $\Lambda_b(bud) \sim \bar{3}$, and is isosinglet $I = 0$
- The weak non-leptonic Hamiltonian for $b \to c\bar{c}s$ decays is:

$$H_W^{(3)}(\Delta I = 0, \Delta S = -1)$$

- With M a nonet of $SU(3)$ light mesons, $\langle \mathbb{P}, M | H_W | \Lambda_b \rangle$ requires $\mathbb{P} + M$ to be in $8 \oplus 1$ representation
- Recalling the $SU(3)$ group multiplication rule

$$8 \otimes 8 = 1 \oplus 8 \oplus 8 \oplus 10 \oplus \bar{10} \oplus 27$$
$$8 \otimes 10 = 8 \oplus 10 \oplus 27 \oplus 35$$

the decay $\langle \mathbb{P}, M | H_W | \Lambda_b \rangle$ can be realized with $\mathbb{P}$ in either an octet (8) or a decuplet (10)

- The discovery channel $\Lambda_b \to \mathbb{P}^+ K^- \to J/\psi p K^-$ corresponds to $\mathbb{P}$ in an octet (8)

Weak decays with $\mathbb{P}$ in Decuplet representation

- Decays involving the decuplet (10) pentaquarks may also occur, if the light diquark pair having spin-0 $[ud]_{s=0}$ in Λ_b gets broken to produce a spin-1 light diquark $[ud]_{s=1}$

$$\Lambda_b \to \pi \mathbb{P}_{10}^{(S=-1)} \to \pi(J/\psi \Sigma(1385))$$
$$\Lambda_b \to K^+ \mathbb{P}_{10}^{(S=-2)} \to K^+(J/\psi \Xi^-(1530))$$

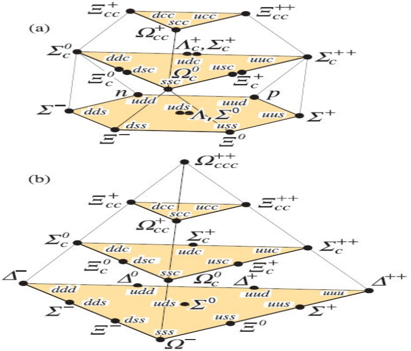
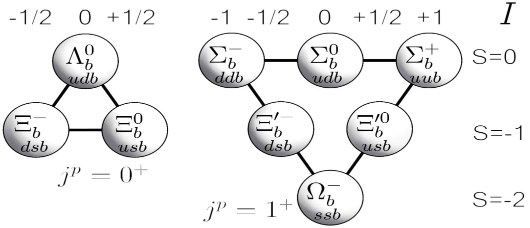


Figure 15.4: SU(4) multiplets of baryons made of u, d, s, and c quarks. (a) The 20-plet with an SU(3) octet. (b) The 20-plet with an SU(3) decuplet.

Weak decays with $\mathbb{P}$ in Decuplet representation - Contd.

- Apart from $\Lambda_b(bud)$, several b-baryons, such as $\Xi_b^0(usb)$, $\Xi_b^-(dsb)$ and $\Omega_b^-(ssb)$ undergo weak decays



- Examples of bottom-strange b-baryon in various charge combinations, respecting $\Delta I = 0$, $\Delta S = -1$ are:

$$\Xi_b^0(5794) \to K(J/\psi\Sigma(1385))$$

which corresponds to the formation of the pentaquarks with the spin configuration $(q, q' = u, d)$

$$\mathbb{P}_{10}(\bar{c}\,[cq]_{s=0,1}\,[q's]_{s=0,1})$$

Weak decays with $\mathbb{P}$ in Decuplet representation - Contd.

- The $s\bar{s}$ pair in Ω_b is in the symmetric (6) representation of flavor $SU(3)$ with spin 1; expected to produce decuplet Pentaquarks in association with a ϕ or a Kaon

$$\Omega_b(6049) \to \phi(J/\psi\,\Omega^-(1672))$$
$$\Omega_b(6049) \to K(J/\psi\,\Xi(1387))$$

- These correspond, respectively, to the formation of the following pentaquarks ($q = u, d$)

$$\mathbb{P}^-_{10}(\bar{c}\,[cs]_{s=0,1}\,[ss]_{s=1})$$
$$\mathbb{P}_{10}(\bar{c}\,[cq]_{s=0,1}\,[ss]_{s=1})$$

- These transitions are on firmer theoretical footings, as the initial $[ss]$ diquark in Ω_b is left unbroken; more transitions can be found relaxing this condition

Estimates of the ratio of decay widths for $J^P = \frac{5}{2}^+$

[Ahmed,Rehman,Aslam,AA, arxiv:1607.00987]

Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{5/2} K^-)$	Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{5/2} K^-)$
$\Lambda_b \to P_p^{\{Y_2\}c_1} K^-$	1	$\Xi_b^- \to P_{\Sigma^-}^{\{Y_2\}c_2} \bar{K}^0$	2.07
$\Lambda_b \to P_n^{\{(Y_2\}c_1} \bar{K}^0$	1	$\Xi_b^0 \to P_{\Sigma^+}^{\{Y_2\}c_2} K^-$	2.07
$\Lambda_b \to P_{\Lambda^0}^{\{Y_2\}c_3} \eta'$	0.03	$\Lambda_b \to P_{\Lambda^0}^{\{Y_2\}c_3} \eta$	0.19
$\Xi_b^- \to P_{\Sigma^0}^{\{Y_2\}c_2} K^-$	1.04	$\Xi_b^- \to P_{\Lambda^0}^{\{Y_2\}c_2} K^-$	0.34
$\Omega_b^- \to P_{\Xi^-_{10}}^{\{Y_3\}c_5} \bar{K}^0$	0.14	$\Omega_b^- \to P_{\Xi^0_{10}}^{\{Y_3\}c_5} K^-$	0.14

Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{5/2} K^-)$	Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{5/2} K^-)$
$\boldsymbol{\Lambda_b \to P_p^{\{Y_2\}c_1} \pi^-}$	**0.08**	$\Lambda_b \to P_n^{\{Y_2\}c_1} \pi^0$	0.04
$\Lambda_b \to P_n^{\{Y_2\}c_1} \eta$	0.01	$\Lambda_b \to P_n^{\{Y_2\}c_1} \eta'$	0
$\Xi_b^- \to P_{\Xi^-}^{\{Y_2\}c_4} K^0$	0.02	$\Xi_b^- \to P_{\Sigma^0}^{\{Y_2\}c_2} \pi^-$	0.08
$\Xi_b^- \to P_{\Sigma^-}^{\{Y_2\}c_2} \eta$	0.02	$\Xi_b^- \to P_{\Sigma^-}^{\{Y_2\}c_2} \eta'$	0.01
$\Xi_b^- \to P_{\Sigma^-}^{\{Y_2\}c_2} \pi^0$	0.08	$\Xi_b^0 \to P_{\Sigma^0}^{\{Y_2\}c_2} \pi^0$	0.04
$\Xi_b^0 \to P_{\Lambda^0}^{\{X_2\ (Y_2)\}c_2} \eta$	0.01	$\Xi_b^0 \to P_{\Lambda^0}^{\{Y_2\}c_2} \eta'$	0.01
$\Xi_b^0 \to P_{\Lambda^0}^{\{Y_2\}c_2} \pi^0$	0.01	$\Omega_b^- \to P_{\Xi^-_{10}}^{\{Y_3\}c_5} \pi^0$	0.01
$\Omega_b^- \to P_{\Xi^0_{10}}^{\{Y_3\}c_5} \pi^-$	0.02		

- **We have used the pentaquark masses estimated in this work.**
- **$\Delta S = 0$ are suppressed by $|V_{cd}^*/V_{cs}^*|^2$ compared to $\Delta S = 1$.**

Estimates of the ratio of decay widths for $J^P = \frac{3}{2}^-$

[Ahmed,Rehman,Aslam,AA, arxiv:1607.00987]

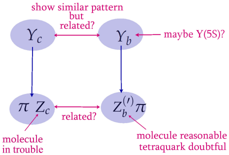
Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{X_2\}_{c_1}} K^-)$	Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{X_2\}_{c_1}} K^-)$
$\Lambda_b \to P_p^{\{X_2\}_{c_1}} K^-$	1	$\Xi_b^- \to P_{\Sigma^-}^{\{X_2\}_{c_2}} \bar{K}^0$	1.38
$\Lambda_b \to P_n^{\{X_2\}_{c_1}} \bar{K}^0$	1	$\Xi_b^0 \to P_{\Sigma^+}^{\{X_2\}_{c_2}} K^-$	1.38
$\Lambda_b \to P_{\Lambda^0}^{\{X_2\}_{c_3}} \eta'$	0.17	$\Lambda_b \to P_{\Lambda^0}^{\{X_2\}_{c_3}} \eta$	0.22
$\Xi_b^- \to P_{\Sigma^0}^{\{X_2\}_{c_2}} K^-$	0.69	$\Xi_b^- \to P_{\Lambda^0}^{\{X_2\}_{c_2}} K^-$	0.23
$\Omega_b^- \to P_{\Xi_{10}^-}^{\{X_3\}_{c_5}} \bar{K}^0$	0.24	$\Omega_b^- \to P_{\Xi_{10}^0}^{\{X_3\}_{c_5}} K^-$	0.24

Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{X_2\}_{c_1}} K^-)$	Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{X_2\}_{c_1}} K^-)$
$\boldsymbol{\Lambda_b \to P_p^{\{X_2\}_{c_1}} \pi^-}$ 1	**0.06**	$\Lambda_b \to P_n^{\{X_2\}_{c_1}} \pi^0$	0.03
$\Lambda_b \to P_n^{\{X_2\}_{c_1}} \eta$	0.01	$\Lambda_b \to P_n^{\{X_2\}_{c_1}} \eta'$	0.01
$\Xi_b^- \to P_{\Xi^-}^{\{X_2\}_{c_4}} K^0$	0.02	$\Xi_b^- \to P_{\Sigma^0}^{\{X_2\}_{c_2}} \pi^-$	0.03
$\Xi_b^- \to P_{\Sigma^-}^{\{X_2\}_{c_2}} \eta$	0.02	$\Xi_b^- \to P_{\Sigma^-}^{\{X_2\}_{c_2}} \eta'$	0.01
$\Xi_b^- \to P_{\Sigma^-}^{\{X_2\}_{c_2}} \pi^0$	0.04	$\Xi_b^0 \to P_{\Sigma^0}^{\{X_2\}_{c_2}} \pi^0$	0.02
$\Xi_b^0 \to P_{\Lambda^0}^{\{X_2\}_{c_2}} \eta$	0	$\Xi_b^0 \to P_{\Lambda^0}^{\{X_2\}_{c_2}} \eta'$	0
$\Xi_b^0 \to P_{\Lambda^0}^{\{X_2\}_{c_2}} \pi^0$	0.01	$\Omega_b^- \to P_{\Xi_{10}^-}^{\{X_3\}_{c_5}} \pi^0$	0.01
$\Omega_b^- \to P_{\Xi_{10}^0}^{\{X_3\}_{c_5}} \pi^-$	0.02		

- Neutron, η and η', and possibly π^0: only decays with K^-, or K^0, or π^-.

Summary

- A new facet of QCD is opened by the discovery of the exotic X, Y, Z, and the pentaquark states $\mathbb{P}(4380)$ and $\mathbb{P}(4450)$
- Heavy quark symmetry allows only $\mathbb{P}(4450)$ to be produced in Λ_b decays; we predict a lower-mass $J^P = 3/2^-$ state at 4110 MeV!
- A very rich spectrum of tetraquark and pentaquark states is anticipated
- Dedicated studies required to establish the nature of exotics in experiments and QCD
- Important puzzles remain in the complex:



- What is the nature of $Y_c(4260)$? A tetraquark? or a $c\bar{c}g$ hybrid?
- What exactly is $\Upsilon(10888)$? Is it just $\Upsilon(5S)$? Does $Y_b(10890)$ still exist?
- We look forward to decisive experimental results from Belle-II, LHC and $\overline{\mathrm{P}}ANDA$