Physics of the Multiquark States

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DESY, Hamburg

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Corfu Summer School & Workshop

- Prologue
- Experimental Evidence for Multiquark states X, Y, Z
- Models for X, Y, Z Mesons
- The diquark model of Tetraquarks
- Charmonium-like and bottomonium-like Tetraquark Spectrum
- The LHCb Pentaquarks $\mathbb{P}^{\pm}(4380)$ and $\mathbb{P}^{\pm}(4450)$
- Pentaquarks as Baryon-Meson molecules
- Pentaquarks as Diquark-Diquark-Antiquark baryons
- Summary

Prologue

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

- It took some 40 years before Gell-Mann's prophecy of multiquark hadrons $(q\,q\,\bar{q}\,\bar{q})$ and $(q\,q\,q\,q\,\bar{q})$ could be experimentally verified!

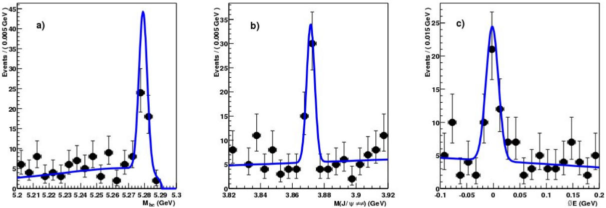
$X(3872)$ - the poster Child of the X, Y, Z Mesons

VOLUME 91, NUMBER 26 PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2003

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)



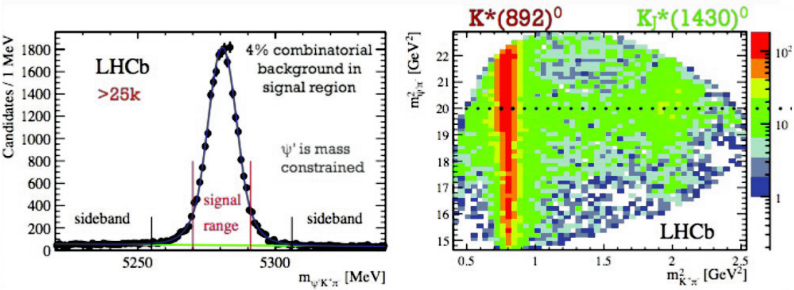
- Discovery Mode : $B \to J/\psi\pi^{+}\pi^{-}K$
- $M = 3872.0 \pm 0.6 \pm 0.5$ MeV
- $\Gamma < 2.3$ MeV
- $J^{PC} = 1^{++}$ [LHCb] [PRL110, 22201(2013)]

The charged four-quark state $Z(4430)^+$

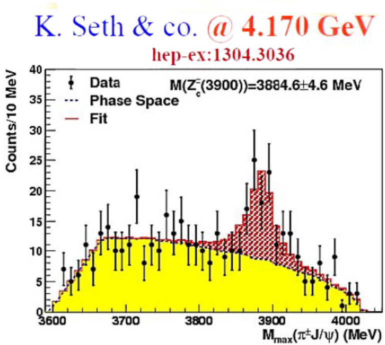
- First observed by Belle in $B^{0(+)} \to \psi(2S)\pi^+K^{-(0)}$ [PRL100, 142001, (2008)]
- Confirmed by LHCb in 2014

[PRL 112, 222002 (2014)]

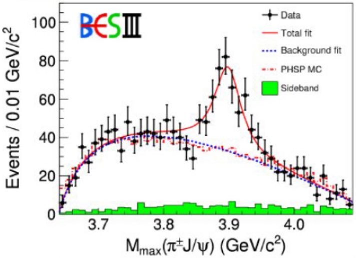
- Integrated luminosity of 3.0 fb^{-1}
- Sample of > 25k $B^0 \to \psi(2S)K^+\pi^-$ candidates (x10 Belle/BaBar)
- Backgrounds from mis-ID physics decay is small
- Sidebands are used to build 4D model of the combinatorial background

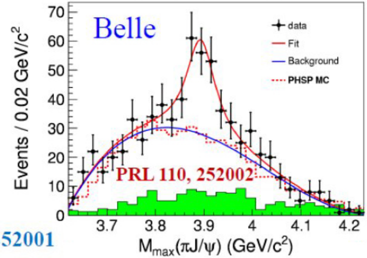


Observation of $Z_c(3900)^\pm$ in the decay $Y(4260) \to \pi Z_c(3900)$



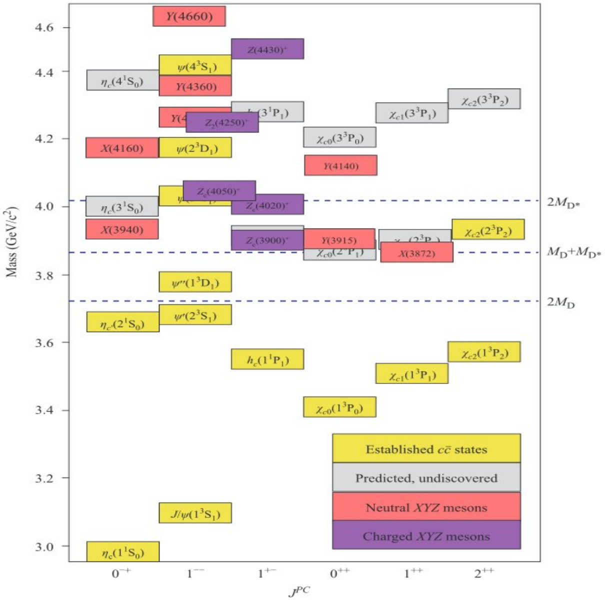
M = (3885±5±1) MeV/c²
Γ = (34±12±4) MeV/c²
81±20 events
6.1σ





PRL 110, 252001

Summary of Charmonia and Charmonium-like Hadrons (Olsen, 1411.7738)



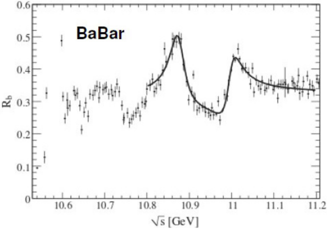
Exotic states in the hidden bottom sector

- Enigmatic $\Upsilon(5S)$ Decays and a $Y_b(10890)$ close to $\Upsilon(5S)$

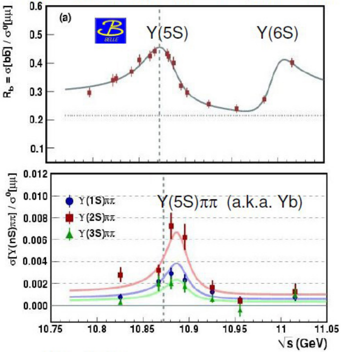
PRL 100, 112001 **(2008)**
21.7 fb^{-1} at 10.580 GeV

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

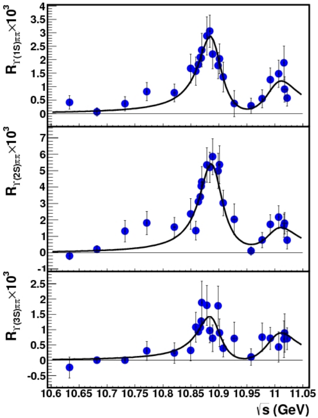
$M(5S)b\bar{b}$ = **10869 ± 2 MeV**

$M(5S)\pi\pi$ = **10888.4 ± 2.7 ± 1.2 MeV**

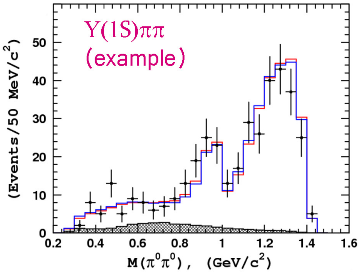
$M(5S) - M(5S)\pi\pi$ = -9 ± 4 MeV

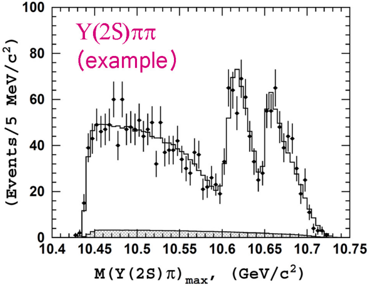
$\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)$ in the $\Upsilon(10860)$ and $\Upsilon(11020)$ resonance region [Belle]

- $F_{\Upsilon(nS)\pi\pi} = |A_{5S,n}f_{5S}|^2 + |A_{6S,n}f_{6S}|^2 + 2K_n A_{5S,n}A_{6S,n}\mathcal{R}[e^{i\delta_n}f_{5S}f_{6S}^*]$
- K_n and δ_n allowed to float
- Fit Values (MeV): $M_{5S} = 10891.1 \pm 3.2^{+0.6}_{-1.5}$; $\Gamma_{5S} = 53.7^{+7.1}_{-5.6}{}^{+0.9}_{-5.4}$
- $M_{5S}(\Upsilon(nS)\pi\pi) - M_{5S}(b\bar{b}) = 9.2 \pm 3.4 \pm 1.9$ MeV

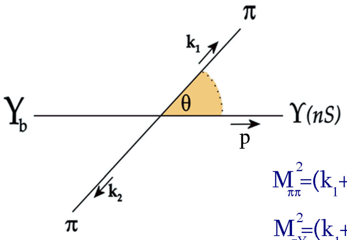


Dipion mass distributions in $\Upsilon(5S) \to \Upsilon(nS)\pi\pi$ decays?





[Belle Collaboration (2012)]



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

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

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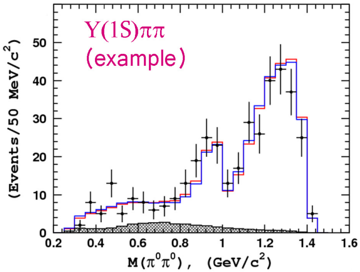

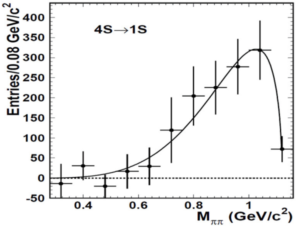

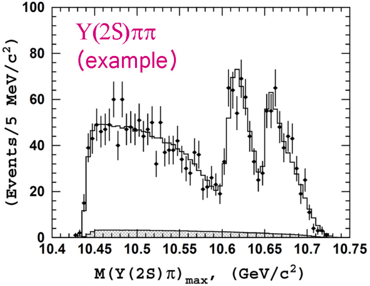

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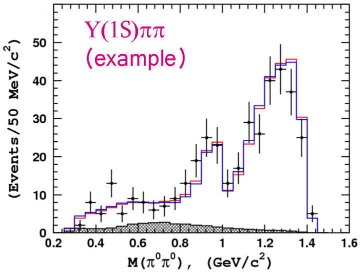
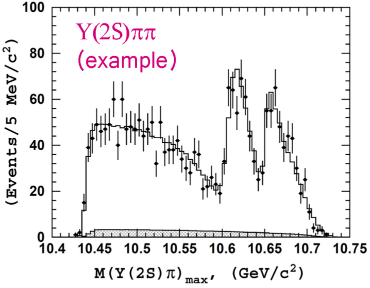
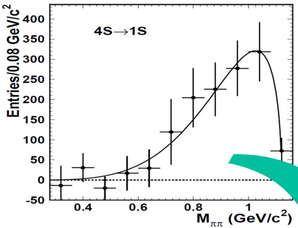
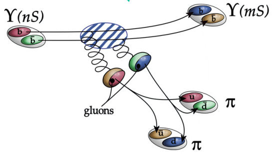






theory works well (multipole exp.)
[Brown, Cahn PRL 75]
[Voloshin, JETP 75]
Process:



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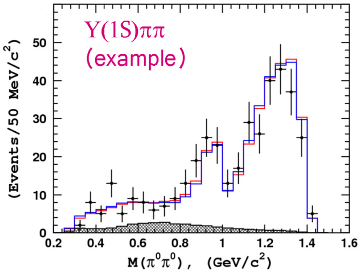

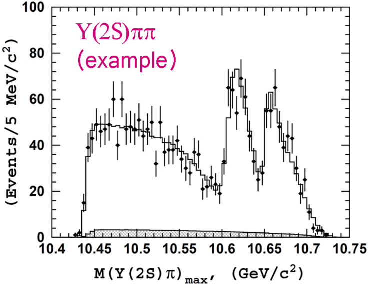

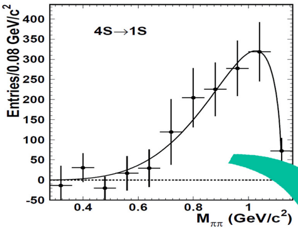

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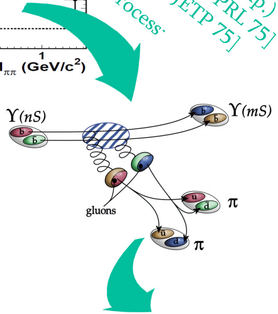

- NO resonant structure
- Zweig forbidden

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

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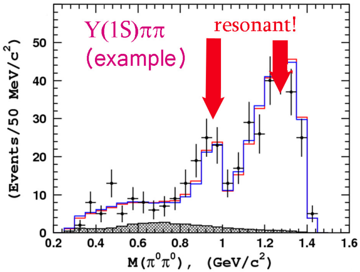

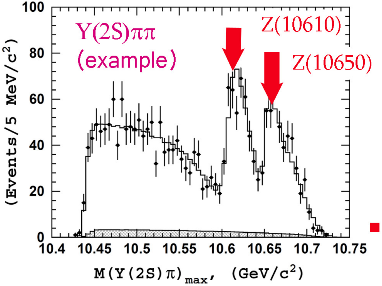

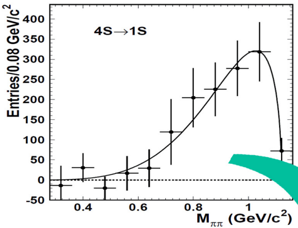

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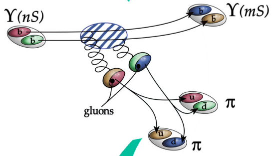

- distinct resonant structure ϟ
- NO resonant structure
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Dipion mass distributions in $\Upsilon(5S) \to \Upsilon(nS)\pi\pi$ decays?

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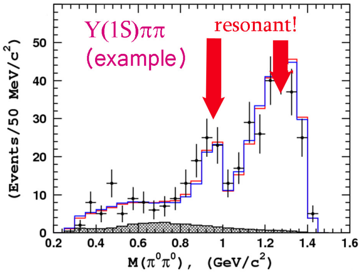

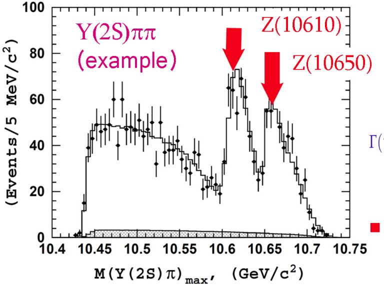

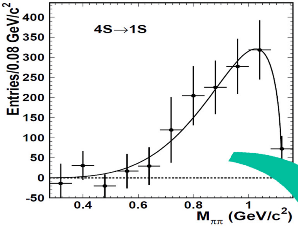

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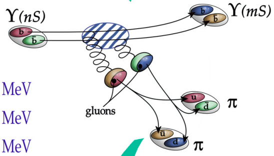

$\Gamma(\Upsilon(2S) \to \Upsilon(1S)\pi\pi) \approx 0.0060$ MeV

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

- distinct resonant structure ↯
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Dipion mass distributions in $\Upsilon(5S) \to \Upsilon(nS)\pi\pi$ decays?

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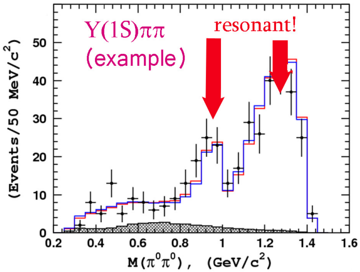

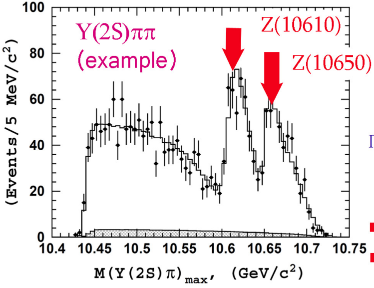

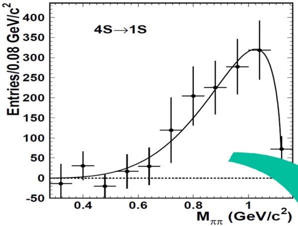

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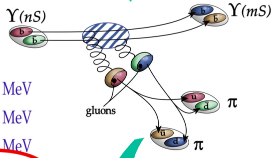

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- distinct resonant structure ↯
- differs by two orders of Magnitude! ↯

- NO resonant structure
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Dipion mass distributions in $\Upsilon(5S) \to \Upsilon(nS)\pi\pi$ decays?

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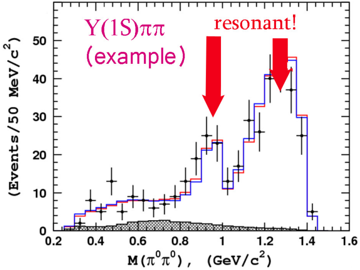
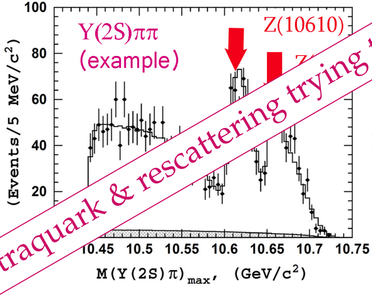
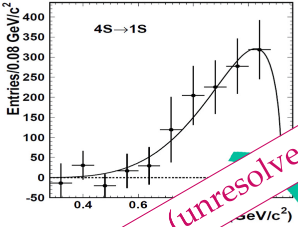
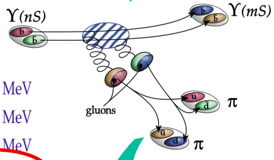






theory works well (whole exp.) [Brown, Cahn PRL 75] [Voloshin, JETP 75] ... cess.



tetraquark & rescattering trying to explain data (unresolved so far)

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- distinct resonant structure ↯ NO resonant structure
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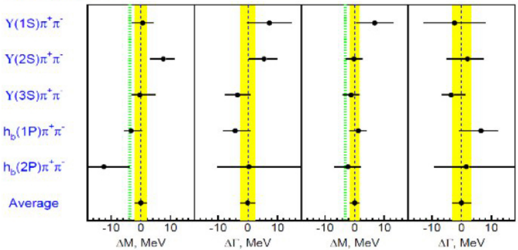
Evidence for $Z_b(10610)^{\pm}$ and $Z_b(10650)^{\pm}$ (Belle)

PRL108,122001



Mass and Γ measured in 5 different final states agree

Angular analysis suggests $\mathbf{J^P = 1^+}$

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

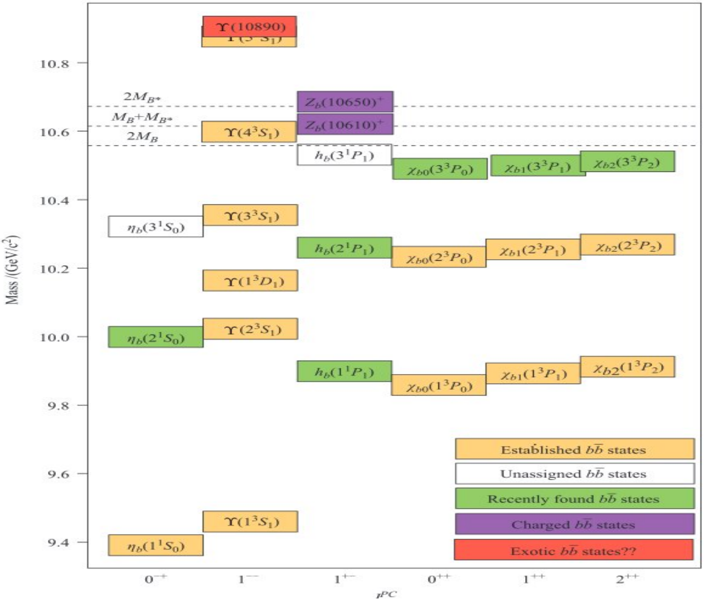
The Di Pion transitions from the Υ(5S) proceed via the intermediate charged state Z_b

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

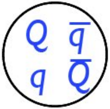
Summary of Bottomonia and Bottomonium-like Hadrons (Olsen, 1411.7738)



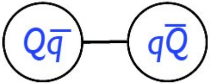
Models for *XYZ* Mesons

Quarkonium Tetraquarks

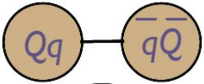
- compact tetraquark



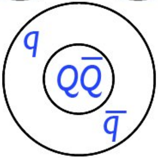
- meson molecule



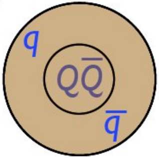
- diquark-onium



- hadro-quarkonium



- quarkonium adjoint meson



Diquark Model of Tetraquarks

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

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

α, β, γ: $SU(3)_C$ indices

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NR limit: States parametrized by Pauli matrices :

$$\text{“good”}: \quad 0^+ \quad \Gamma^0 = \frac{\sigma_2}{\sqrt{2}}$$

$$\text{“bad”}: \quad 1^+ \quad \vec{\Gamma} = \frac{\sigma_2 \vec{\sigma}}{\sqrt{2}}$$

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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:

$$\left|0_{\mathcal{Q}}, 0_{\bar{\mathcal{Q}}};\, 0_J\right\rangle = \Gamma^0 \otimes \Gamma^0$$

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

$$\left|0_{\mathcal{Q}}, 1_{\bar{\mathcal{Q}}};\, 1_J\right\rangle = \Gamma^0 \otimes \Gamma^i$$

NR Hamiltonian for Tetraquarks with hidden charm

States need to diagonalize Hamiltonian:

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

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

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constituent mass

with

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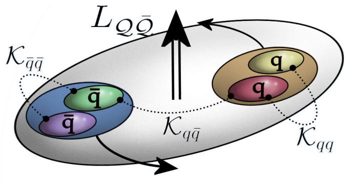
qq spin coupling $q\bar{q}$ spin coupling

with

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

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



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

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

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

NR Hamiltonian for Tetraquarks with hidden charm

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

LS coupling *LL* coupling

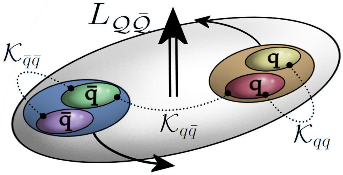
with

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

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

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

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



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

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

$$+ \kappa_{q\mathcal{Q}}\left[s_{q\mathcal{Q}}(s_{q\mathcal{Q}} + 1) + s_{\bar{q}\bar{\mathcal{Q}}}(s_{\bar{q}\bar{\mathcal{Q}}} + 1)\right]$$

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^{--}	$\|1,1;2,3\rangle_1$	$\|1,1;2,L'\rangle_1$	$M_{00} + \kappa_{qQ} + 16a + 6B_Q$

(with Satoshi Mishima)

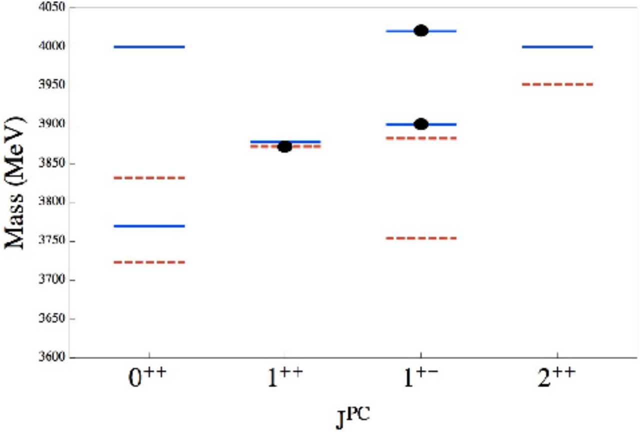
Parameters in the Mass Formula

	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

		charmonium-like		bottomonium-like	
Label	J^{PC}	State	Mass [MeV]	State	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

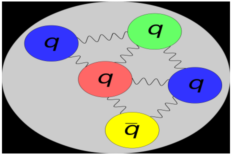
Comparison with current data in the Charmonium-like sector

- Our determination of the parameters M_{00}, κ_{qc}, B_C and a in the Charmonium-like sector close to the one by Maiani et al. (2014). Their results are shown below
- – – – – – New; - - - - - Old



- Quarks inside a Diquark are much more tightly bound than Diquarks in Baryons

Pentaquarks



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

- For example, the one-page review on Pentaquarks in PDG (2014) by C.G. Wohl states the following:

  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.

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; $\int Ldt = 3$ fb^{-1})

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

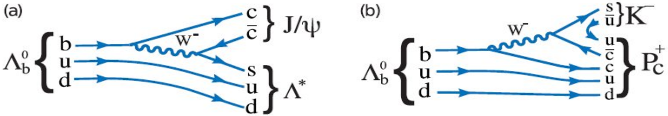


Figure 1: Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

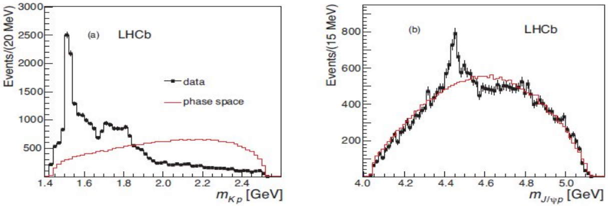
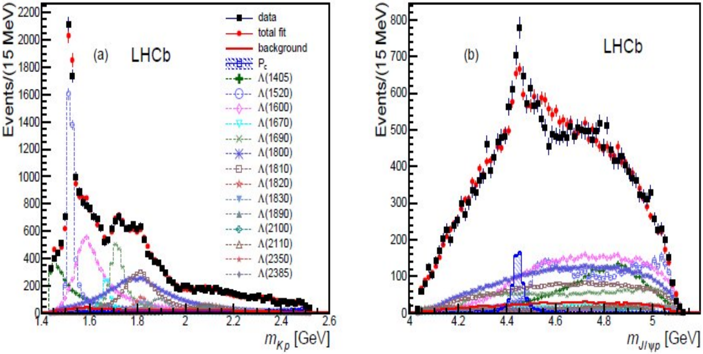


Figure 2: Invariant mass of (a) K^-p and (b) $J/\psi p$ combinations from $\Lambda_b^0 \to J/\psi K^- p$ decays. The solid (red) curve is the expectation from phase space. The background has been subtracted.

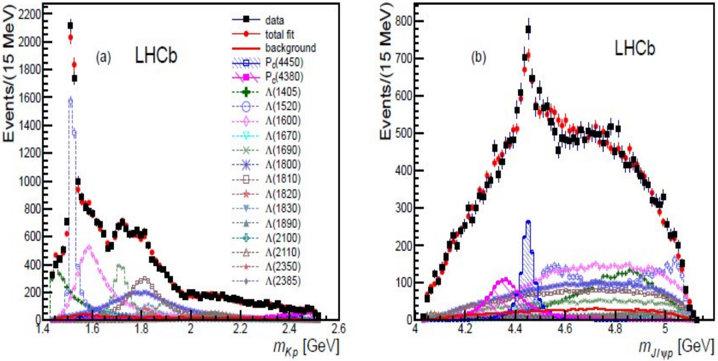
Model fits with one $P_c^+(4450)$ state with $J^P = 5/2^+$

- Results of the fit with one $J^P = 5/2^+$ P_c state. The m_{Kp} projection is well described, but discrepencies remain in the $m_{J/\psi p}$ projection



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



Summary of the LHCb Pentaquark Measurements

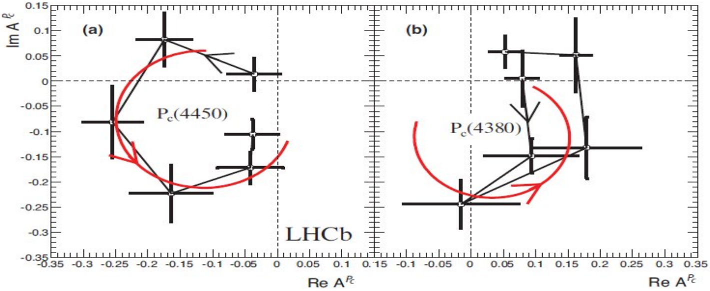
- Higher mass state (statistical significance 12σ)

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

- 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

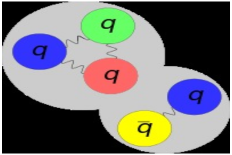


- For $P_c^+(4450)$, fit shows a phase change in amplitudes consistent with a resonance

Theoretical Interpretations of the LHCb Pentaquarks

- The new pentaquarks in the diquark model
  L. Maiani, A.D. Polosa, V. Riquer, arxiv: 1507.04980 $\rightarrow$ PLB
- The pentaquark candidates in the dynamical diquark picture
  Richard F. Lebed, arxiv:1507.05867
- Some predictions of diquark model for hidden charm pentaquark discovered at the LHCb; Guan-Nan Li, Xiao-Gang He, Min He, arxiv:1507.08252
- The LHCb pentaquark as a $\bar{D}^* \Sigma_c^*$ molecular state
  L. Roca, J. Nieves, E. Oset, arxiv:1507.04249
- Is pentaquark doublet a hadronic molecule?
  A. Mironov, A. Morozov, arxiv:1507.04694
- The $\bar{D} \Sigma_c^*$ and $\bar{D}^* \Sigma_c$ interactions and the LHCb hidden-charmed pentaquarks
  Jun He, arxiv:1507.05200
- How to reveal the exotic nature of the $\mathbb{P}_c(4450)$
  Feng-Kun Guo, Ulf-G.Meißner, Wei Wang, Zhi Yang, arxiv:1507.04950
- Testing the $\chi_{c1}\, p$ composite nature of the $\mathbb{P}_c(4450)$
  Ulf-G. Meißner, Jose A. Oliver, arxiv:1507.07478
- Towards exotic hidden-charm pentaquarks in QCD
  Hua-Xing Chen, Wei Chen, Xiang Liu, T.G. Steele, Shi-Lin Zhu, arxiv:1507.03717
- Identifying exotic hidden-charm pentaquarks
  Rui Chen, Xiang-Liu, arxiv:1507.03704 $\rightarrow$ PRL
- Understanding the newly observed heavy pentaquark candidates
  Xiao-Hai Liu, Qian Wang, Qiang Zhao, arxiv:1507.05359

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:

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

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

- $H_a^{(\bar{Q})} = [P_a^{*(\bar{Q})\,\mu}\gamma_\mu - P_a^{(\bar{Q})}\gamma_5](1-\not{v})/2$; $v = (0, \vec{1})$ 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

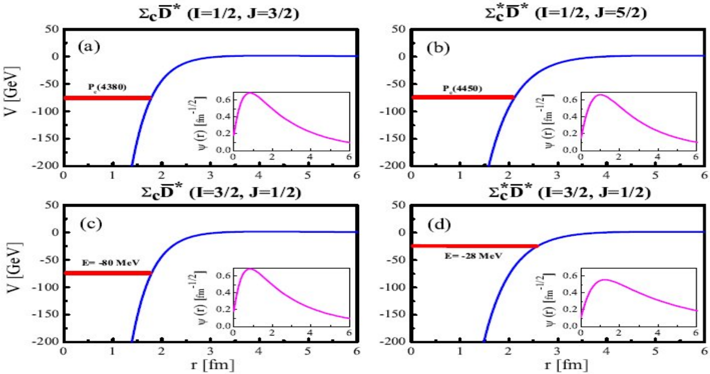
Effective potentials for the $\Sigma_c \bar{D}^*$ and $\Sigma_c^* \bar{D}^*$ systems

$$V_{\Sigma_c \bar{D}^*} = \frac{1}{3}\frac{g g_1}{f_\pi^2} \nabla^2 Y(\Lambda, m_\pi, r) \mathcal{I}_0 \, \mathcal{G}_0$$
$$V_{\Sigma_c^* \bar{D}^*} = \frac{1}{2}\frac{g g_1}{f_\pi^2} \nabla^2 Y(\Lambda, m_\pi, r) \mathcal{I}_1 \, \mathcal{G}_1$$

where $Y(\Lambda, m, r) = \frac{1}{4\pi r}(\exp^{-mr} - \exp^{-\Lambda r}) - \frac{\Lambda^2 - m^2}{8\pi\Lambda} \exp^{-\Lambda r}$

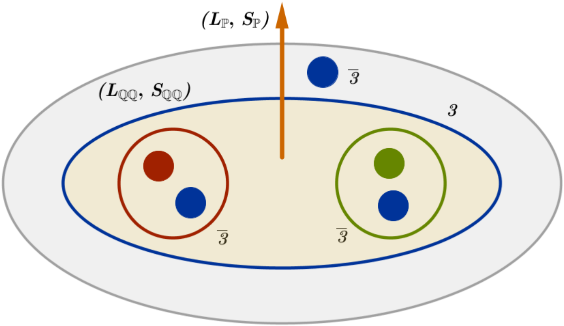
- Λ is a phenomenological parameter; the coeffs. $\mathcal{I}_i$ and $\mathcal{G}_i$ are related to the isospin and ${}^{2S+1}L_J$ quantum numbers, respectively
- Solving the Schrödinger equation, one reproduces the masses of the pentaquarks $\mathbb{P}_c(4380)$ and $\mathbb{P}_c(4450)$ as hidden-charm molecular states $\Sigma_c \bar{D}^*$ with $(I = 1/2, J = 3/2)$ and $\Sigma_c^* \bar{D}^*$ with $(I = 1/2, J = 5/2)$, respectively, for two different values of Λ

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 $\Delta(1232)\eta_c$

Effective Hamiltonian for Pentaquarks



Diquark – Diquark – Antiquark Model of Pentaquarks

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

- $S_{[\mathcal{Q}\mathcal{Q}]}$ 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

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

- Mass difference:

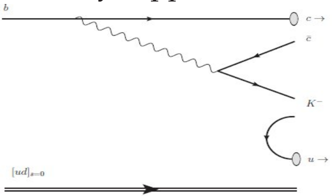
  $\Lambda(1405) - \Lambda(1116) \sim 290$ MeV, level spacing for $\Delta L = 1$ in light baryons; light-light diquark mass difference for $\Delta S = 1$: $[qq']_{s=1} - [qq']_{s=0} = \Sigma_c(2455) - \Lambda_c(2286) \simeq 170$ MeV, the orbital gap $\mathbb{P}^+(3/2^-) - \mathbb{P}^+(5/2^+)$ is reduced to about 100 MeV, in agreement with data, 70 MeV

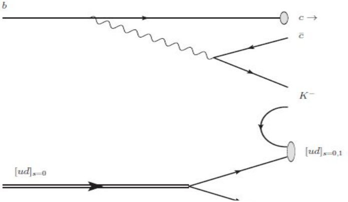
Pentaquark production mechanisms in $\Lambda_b^0 \to K^- J/\psi p$

- Two possible mechanisms are proposed by Maiani et al.. In the first, the 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)

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

- 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

$SU(3)$ 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:

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

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

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

  the decay $\langle \mathbb{P}, M | H_{\mathrm{W}} | \Lambda_b \rangle$ can be realized with $\mathcal{P}$ 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 $[ud]_{s=1}$

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

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

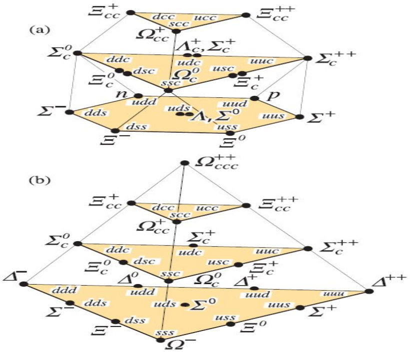
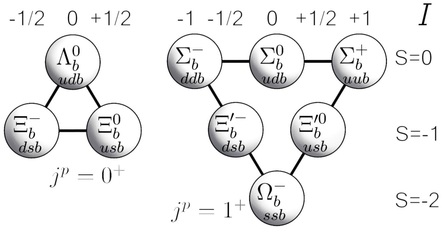


Figure 15.4: SU(4) multiplets of baryons made of u, d, s, and c quarks. (a) The 20-plet with an SU(3) octet. (b) The 20-plet with an SU(3) decuplet.

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

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

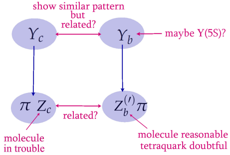
- These correspond, respectively, to the formation of the following pentaquarks ($q = u, d$)

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

- 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

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 $\mathbb{P}(4450)$
- 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?
- Branching ratios at $\Upsilon(5S)$ are enigmatic
- Need detailed Dalitz distributions of $Y(11020)$. Do Z_b, Z_b' (and related excited states) play a role in the the decays of $Y(11020)$?. Recent Belle studies confirm that they do.
- There is a good case for having dedicated runs above $\Upsilon(4S)$at KEK Super-B ; would be great if this machine can reach the $\Lambda_b\bar{\Lambda}_b$ energy threshold!
- We look forward to decisive experimental results from Belle-II and LHC

Hidden-Beauty Charged Tetraquarks and Heavy Quark Spin Conservation

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

- Interpret the $Z_b^{\pm,0}(10610) = Z_b$ and $Z_b^{\pm,0}(10650) = Z_b'$ as S-wave $J^{PG} = 1^{++}$ tetraquark states (in the notation $|s_{[bq]}, s_{[\bar{b}\bar{q}]}\rangle$)

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

- $J^P = 1^+$ multiplet is completed by X_b, given by the $C = +1$ combination

$$|X_b\rangle = \frac{|1_{bq}, 0_{\bar{b}\bar{q}}\rangle + |0_{bq}, 1_{\bar{b}\bar{q}}\rangle}{\sqrt{2}}$$

- Expect X_b and Z_b to be degenerate, with Z_b' heavier

$$M(Z_b') - M(Z_b) = 2\kappa_b$$

- A similar analysis for the hidden-charm charged tetraquarks Z_c and Z_c' yields

$$2\kappa_c = M(Z_c') - M(Z_c) \simeq 120 \text{ MeV}$$

- QCD expectation: $\kappa_b : \kappa_c = M_c : M_b$. With $\frac{M_c}{M_b} \simeq \frac{1.27}{4.18} = 0.30$, yields $2\kappa_b \simeq 36$ MeV, fits OK with the observed $Z_b' - Z_b$mass difference ($\simeq 45$ MeV)

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

- In $\Upsilon(10890)$, $S_{b\bar{b}} = 1$. In $h_b(nP)$, $S_{b\bar{b}} = 0$, so the above transition involves heavy-quark spin-flip, yet its rate is 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,

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

- More generally, admitting a subdominant spin-spin interaction, the above composition may be written as

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

- Define

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

  where g are the effective strong couplings at the vertices $\Upsilon\, Z_b\, \pi$ and $Z_b\, h_b\, \pi$
- Therefore, independently from the values of the mixing coefficients, the above equation and heavy quark spin conservation require $g_Z = -g_{Z'}$

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

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}	$181^{+65+74}_{-105-109}$

- Within errors, Belle data is consistent with heavy quark spin conservation
- 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

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

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

- Dalitz analysis indicate that $\Upsilon(10890) \to Z_b/Z'_b + \pi \to \Upsilon(nS)\pi\pi$ $(n = 1, 2, 3)$ 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 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.,

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

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