Multiquark Hadrons - A New Facet of QCD

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Albufeira, Portugal

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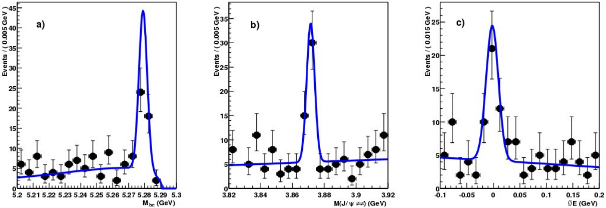
Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays

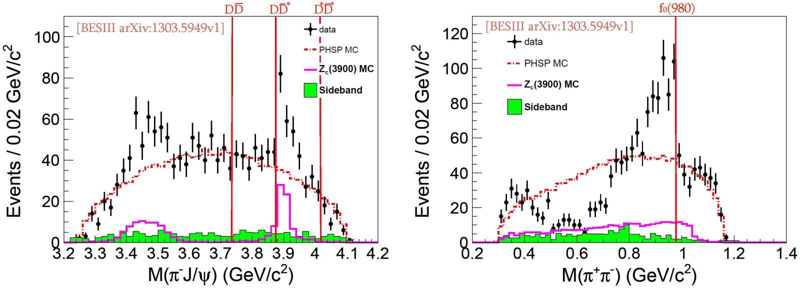
S.-K. Choi,[5] S. L. Olsen,[6] K. Abe,[7] T. Abe,[7] I. Adachi,[7] Byoung Sup Ahn,[14] H. Aihara,[43] K. Akai,[7] M. Akatsu,[20] M. Akemoto,[7] Y. Asano,[48] T. Aso,[47] V. Aulchenko,[1] T. Aushev,[11] A. M. Bakich,[38] Y. Ban,[31] S. Banerjee,[39] A. Bondar,[1] A. Bozek,[25] M. Bračko,[18,12] J. Brodzicka,[25] 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)]



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

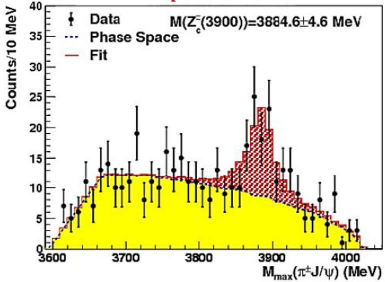


- discovered in $J/\psi\pi\pi$ by BaBar, confirmed by CLEO, Belle, and BESIII
- [BaBar, PRL 05] : $m = 4252 \pm 73$ MeV, $\Gamma = 105 \pm 20$ MeV
  $B(J/\psi\pi\pi)\Gamma_{e+e-} = 7.5 \pm 1.2$ eV
  $\Gamma(Y_c(4260) \to J/\psi\pi\pi) > 0.5$ MeV (limit on Γ_{e+e-})
  (at least $\mathcal{O}(10)$ enhanced vs charmonia)
- candidates: hybrids, tetraquarks, $D_1\bar{D}$ molecule, ...
- Dipion mass spectrum dominated by $f_0(980)$- a tetraquark candidate itself

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

K. Seth & co. @ 4.170 GeV

hep-ex:1304.3036

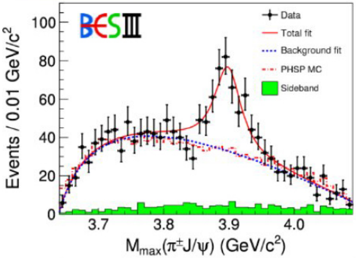


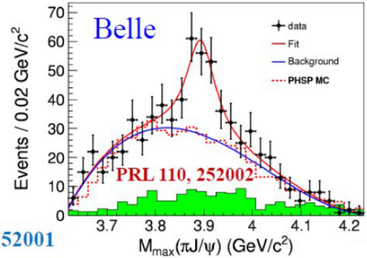
$M = (3885 \pm 5 \pm 1)$ MeV/c²

$\Gamma = (34 \pm 12 \pm 4)$ MeV/c²

81±20 events

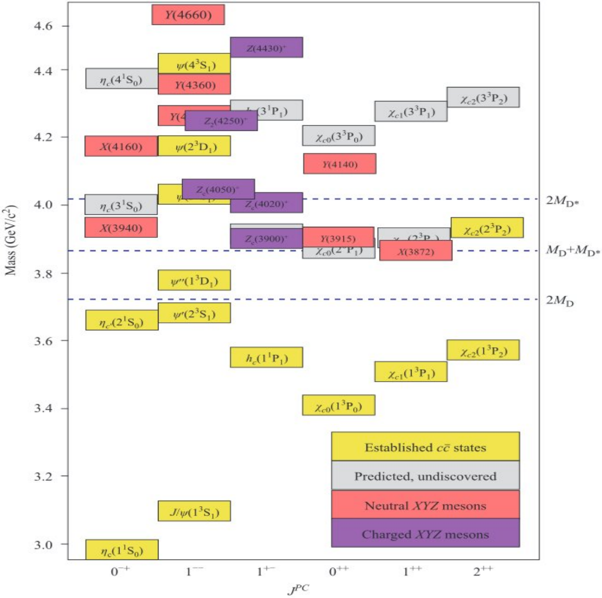
6.1σ





PRL 110, 252001

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



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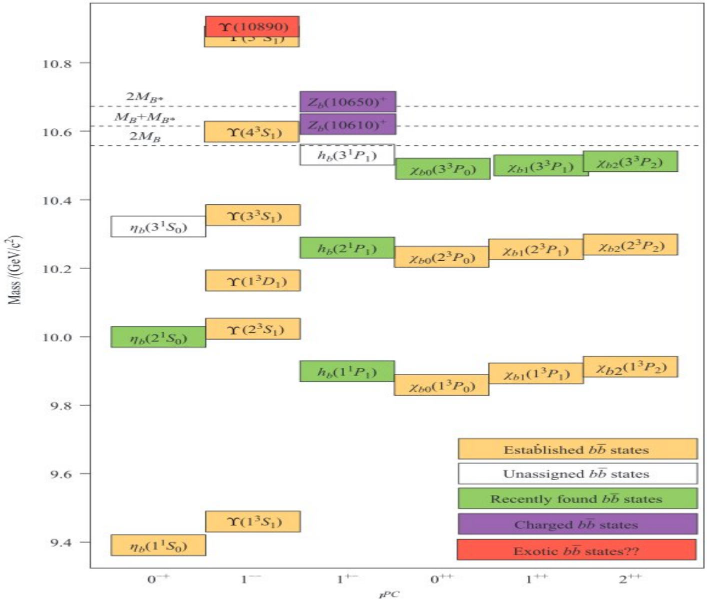
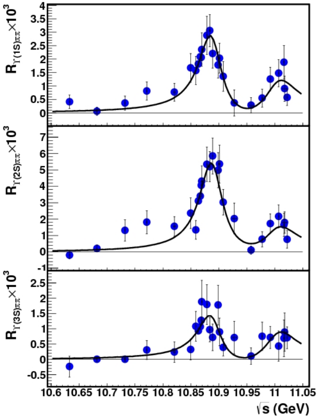


$\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)$ in the $\Upsilon(10860)$ and $\Upsilon(11020)$ resonance region

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

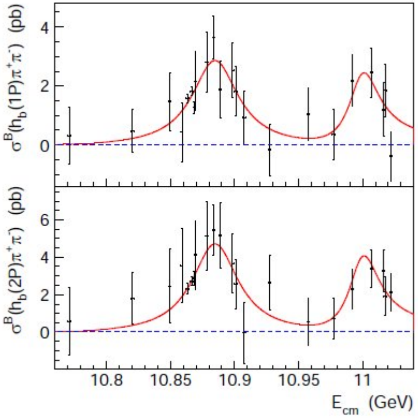
- Fit Values (MeV): $M_{10860} = 10891.1 \pm 3.2^{+0.6}_{-1.5}$; $\Gamma_{10860} = 53.7^{+7.1}_{-5.6}{}^{+0.9}_{-5.4}$
- $M_{5S}(\Upsilon(nS)\pi\pi) - M_{5S}(b\bar{b}) = 9.2 \pm 3.4 \pm 1.9$ MeV ?
- Fit Values (MeV): $M_{11020} = 10987.5^{+6.4}_{-2.5}{}^{+9.0}_{-2.1}$; $\Gamma_{11020} = 61^{+9}_{-19}{}^{+2}_{-20}$



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

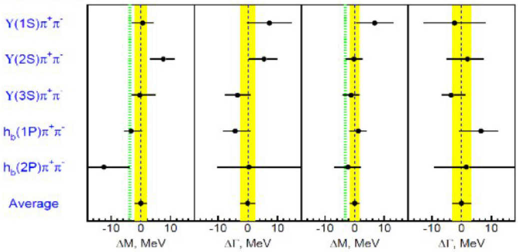
[A. Abdesselam et al. (Belle), arxiv:1508.06562 (2015)]

- 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 $\mathbf{J^P = 1^+}$

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

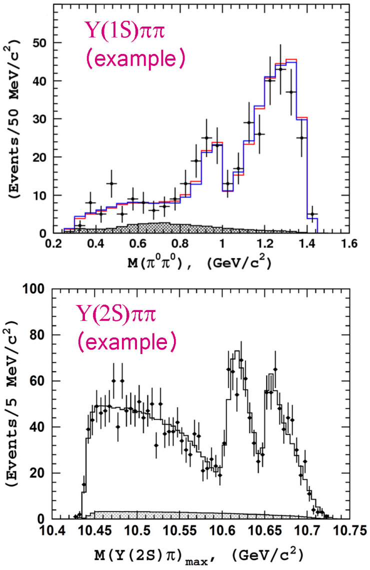
The Di Pion transitions from the Y(5S) proceed via the intermediate charged state Z_b

The transition does not imply spin flip

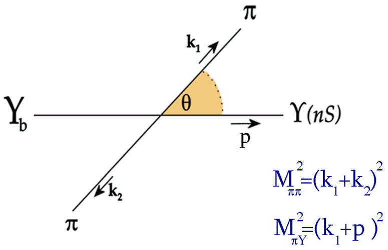
Masses are close to B*B and B*B* theresholds Molecules?

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

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



[Belle Collaboration (2012)]



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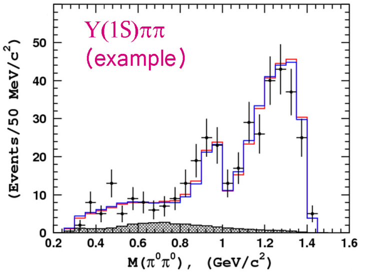

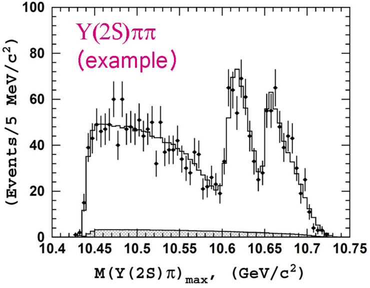

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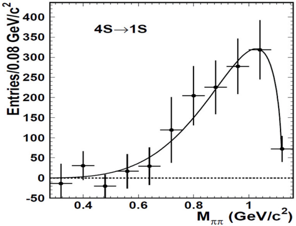

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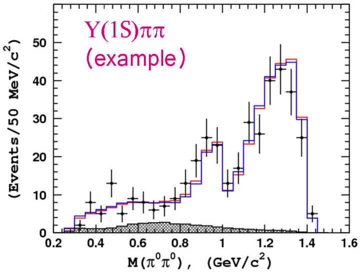

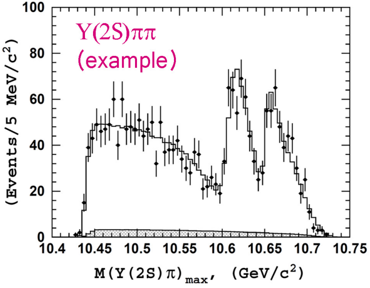

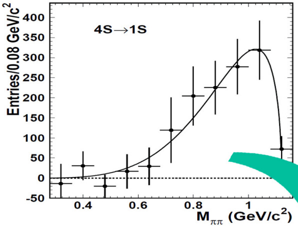

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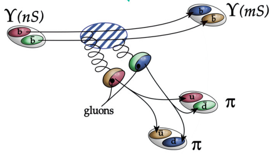

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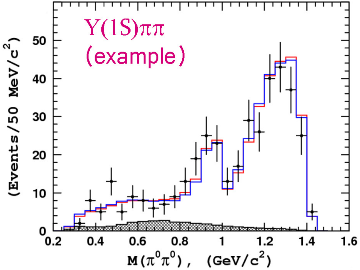

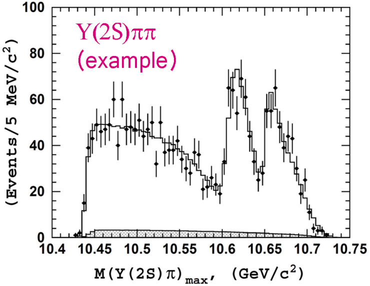

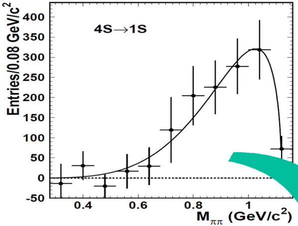

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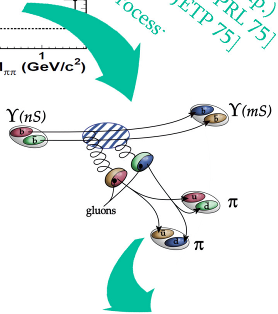

- NO resonant structure
- Zweig forbidden

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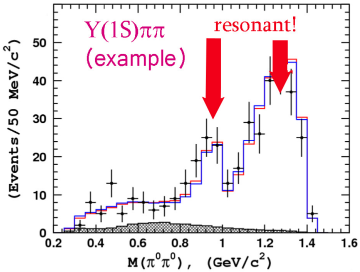

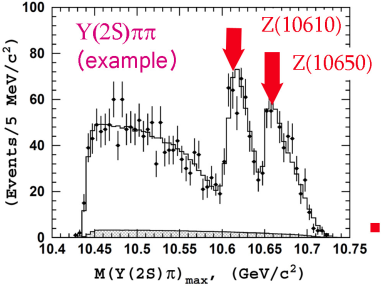

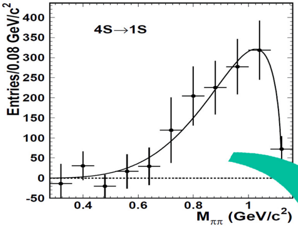

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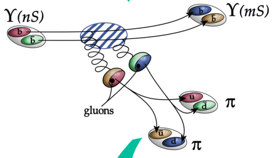

- distinct resonant structure
- NO resonant structure
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Dipion mass distributions in $\Upsilon(5S) \to \Upsilon(nS)\pi\pi$ decays?

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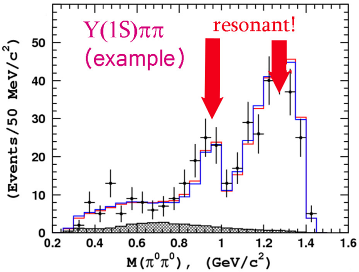

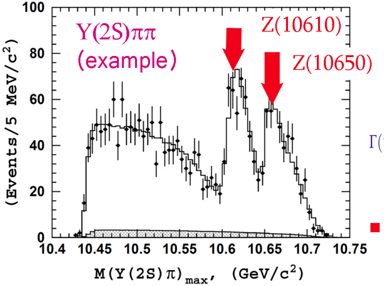

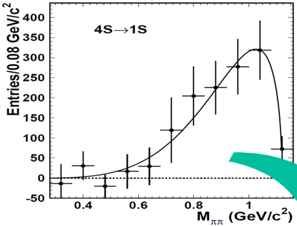

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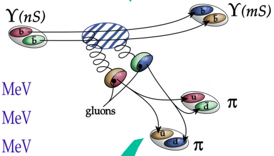

$\Gamma(\Upsilon(2S) \to \Upsilon(1S)\pi\pi) \approx 0.0060$ MeV

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

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

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

- distinct resonant structure ↯

- NO resonant structure
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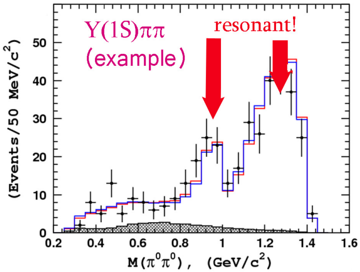

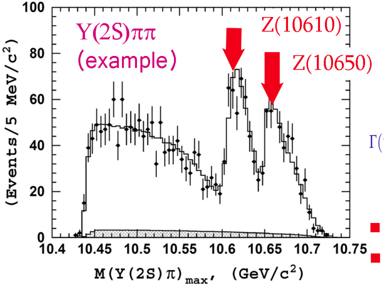

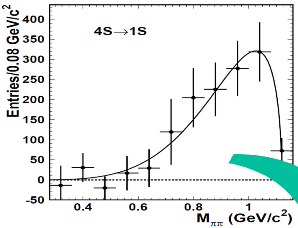

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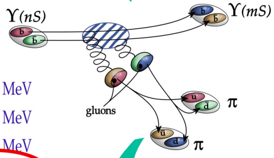

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- distinct resonant structure ↯
- differs by two orders of Magnitude! ↯

- NO resonant structure
- Zweig forbidden

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

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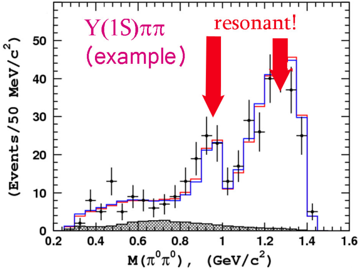

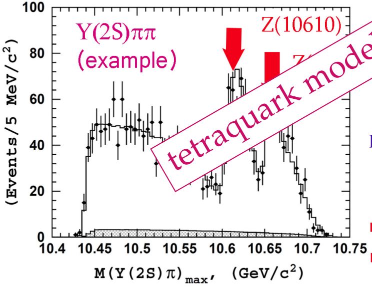

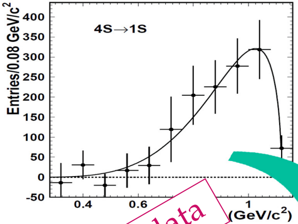

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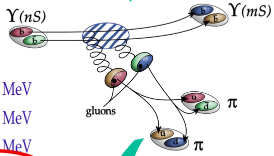

tetraquark model can explain data

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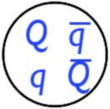
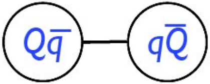
Models for *XYZ* Mesons

Quarkonium Tetraquarks

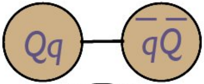
- compact tetraquark



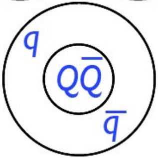
- meson molecule



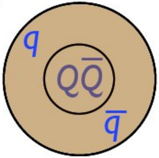
- diquark-onium



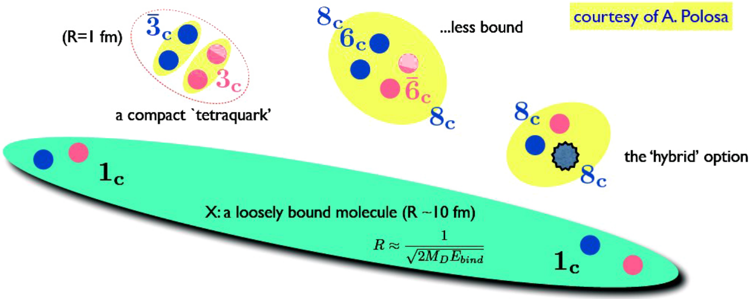
- hadro-quarkonium



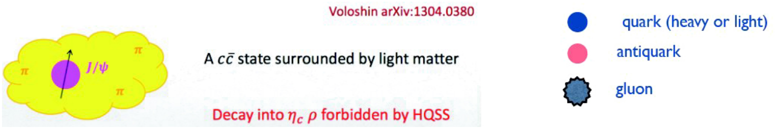
- quarkonium adjoint meson



X, Y, Z Exotics



Hadro-charmonium



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

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

α, β, γ: $SU(3)_C$ indices

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α, β, γ: $SU(3)_C$ indices

NR limit: States parametrized by Pauli matrices :

$$\begin{array}{lccl} \text{Scalar:} & 0^+ & \Gamma^0 & = \frac{\sigma_2}{\sqrt{2}} \\ \text{Axial-Vector:} & 1^+ & \vec{\Gamma} & = \frac{\sigma_2 \vec{\sigma}}{\sqrt{2}} \end{array}$$

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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:

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

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

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constituent mass

with

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

NR Hamiltonian for Tetraquarks with hidden charm

States need to diagonalize Hamiltonian:

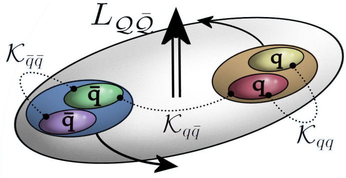
$$H = 2m_{\mathcal{Q}} + H_{SS}^{(qq)} + H_{SS}^{(q\bar{q})} + H_{SL} + H_{LL}$$

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

with

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

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



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

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

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

NR Hamiltonian for Tetraquarks with hidden charm

States need to diagonalize Hamiltonian:

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

LS coupling *LL* coupling

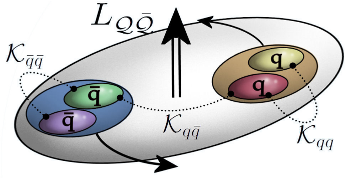
with

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

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

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

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



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

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

Charmonium-like and Bottomonium-like Tetraquark Spectrum

(with Satoshi Mishima)

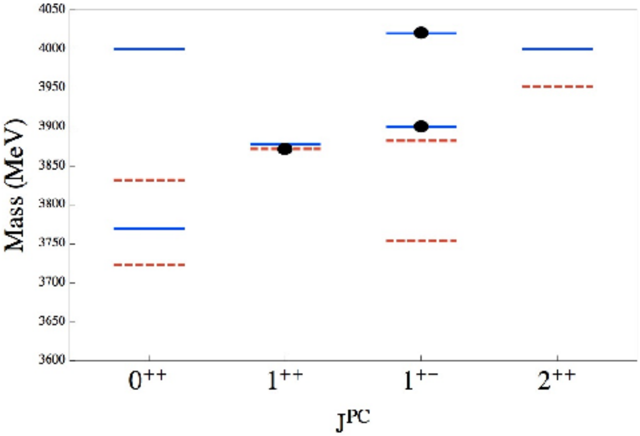
Parameters in the Mass Formula

	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

		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

- 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



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

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

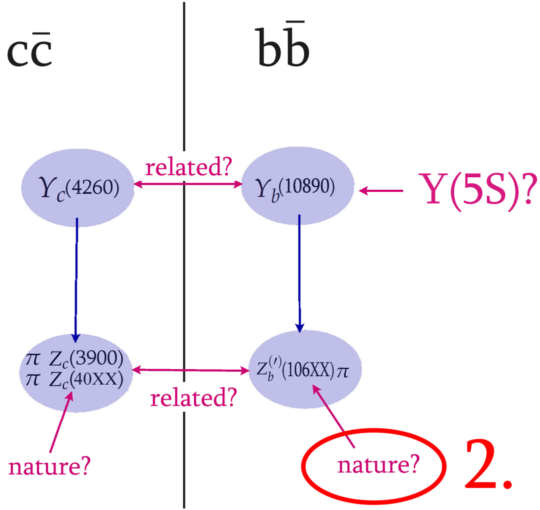
$$\begin{aligned} & s_{b\bar{b}} : 1 \to 0 \text{ transition :} \\ & \overline{\text{Rel.Norm.}} = 1.4 \pm 0.3 \\ & \overline{\text{Rel.Phase}} = (185 \pm 42)^\circ \end{aligned}$$

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

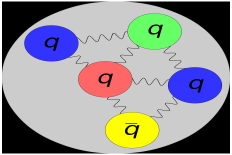
$$|Z_b\rangle = \frac{|1_{bq}, 0_{\bar{b}\bar{q}}\rangle - |0_{bq}, 1_{\bar{b}\bar{q}}\rangle}{\sqrt{2}}, \quad |Z_b'\rangle = |1_{bq}, 1_{\bar{b}\bar{q}}\rangle_{J=1}$$

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

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})

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

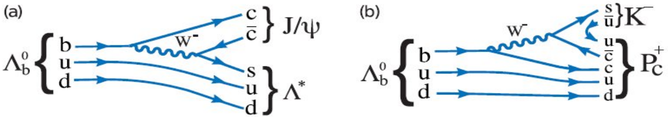


Figure 1: Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

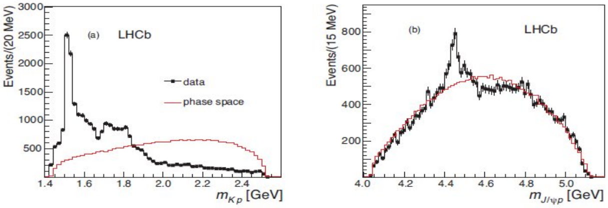
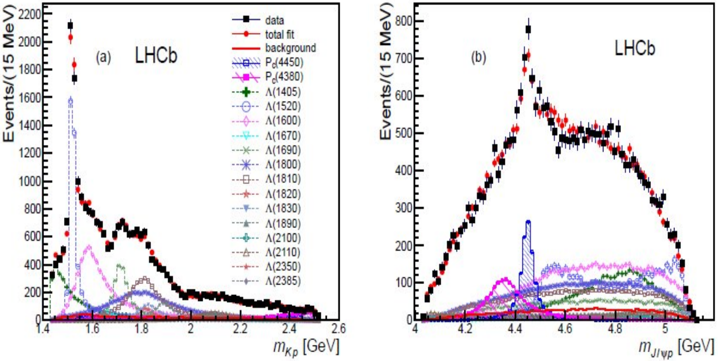


Figure 2: Invariant mass of (a) $K^- p$ and (b) $J/\psi p$ combinations from $\Lambda_b^0 \to J/\psi K^- p$ decays. The solid (red) curve is the expectation from phase space. The background has been subtracted.

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



Summary of the LHCb Pentaquark Measurements

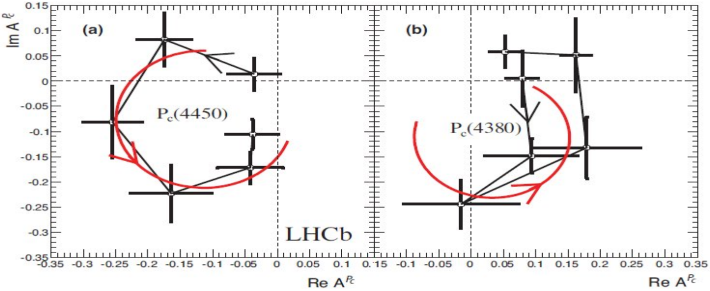
- Higher mass state (statistical significance 12σ)

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

- 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

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.)

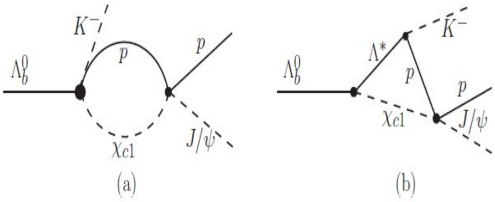
Compact Pentaquarks

- 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

Pentaquarks as rescattering-induced kinematic effects

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

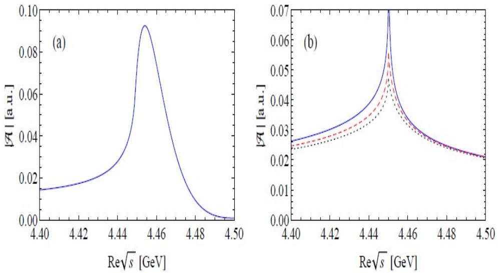
- Hypothesis: Kinematic effects can result in a narrow structure around the $\chi_{c1}\,p$ threshold in the $J/\psi\,p$ invariant mass of the decay $\Lambda_b^0 \to K^-\,J/\psi\,p$
  $M_{P_c(4450)} - M_{\chi_{c1}} - M_p = (0.9 \pm 3.1)$ MeV
- Two possible mechanisms:
  a) 2-point loop with a 3-body production $\Lambda_b^0 \to K^-\,\chi_{c1}\,p$ 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 $J/\psi\,p$



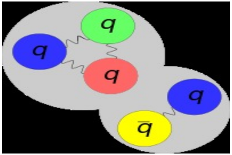
Pentaquarks as rescattering-induced kinematic effects (Contd.)

[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]



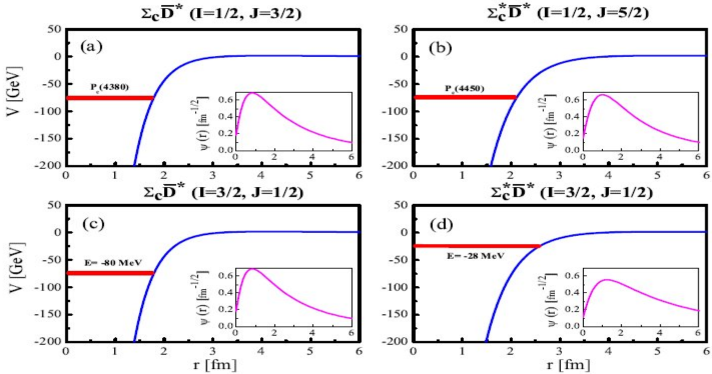
- Identify $\mathbb{P}_c^+(4380)$ with $\Sigma_c(2455)\bar{D}^*$ and $\mathbb{P}_c^+(4450)$ with $\Sigma_c(2520)\bar{D}^*$ bound by a pion exchange
- Effective Lagrangians:

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

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

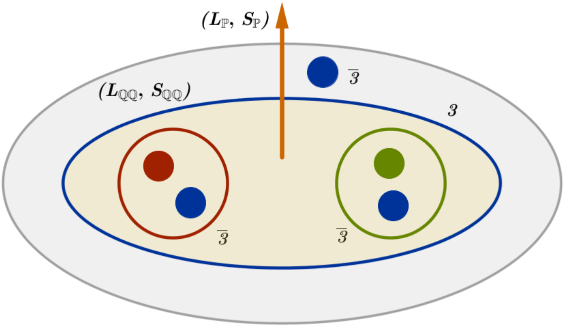
- $H_a^{(\bar{Q})} = [P_a^{*(\bar{Q})\,\mu}\gamma_\mu - P_a^{(\bar{Q})}\gamma_5](1-\not{v})/2$; $v = (0,\vec{1})$ is a pseudoscalar and vector charmed meson multiplet (D, D^*);
  $\mathcal{S}_\mu = \sqrt{1/3}(\gamma_\mu + v_\mu)\gamma^5\mathcal{B}_6 + \mathcal{B}_{6\mu}^*$ stands for the charmed baryon 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

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



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

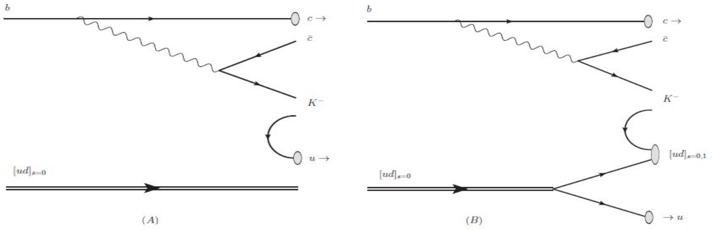
Pentaquark production mechanisms in $\Lambda_b^0 \to K^- J/\psi p$

- 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

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

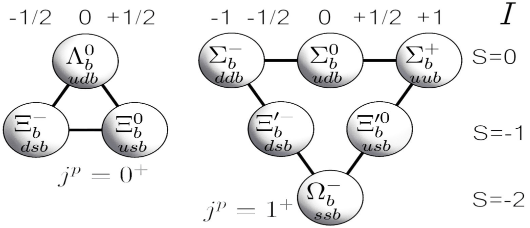
- For S waves, the first and the second series have the angular momenta (multipicity)

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

- 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

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 ($q = u, d$)

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

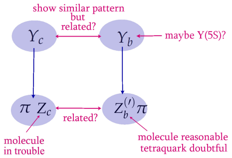
- These transitions are on firmer theoretical footings, as the initial $[ss]$ diquark in Ω_b is left unbroken; more transitions can be found relaxing this condition

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?

- Line shape of multiquark resonances, such as $X(3872)$ and $\mathbb{P}(4450)$ can be measured at $\overline{\text{P}}ANDA$, which will help in understanding the dynamics

- We look forward to decisive experimental results from Belle-II, LHC and $\overline{\text{P}}ANDA$