Multiquark Hadrons - A New Facet of QCD

Ahmed Ali

DESY, Hamburg

Nov. 9-14, 2015

Regional Meeting, Islamabad
Experimental Evidence for Multiquark states $X, Y, Z$

Models for $X, Y, Z$ Mesons

Phenomenology of the diquark model of Tetraquarks

The LHCb Pentaquarks $P^\pm(4380)$ and $P^\pm(4450)$

Theoretical interpretations of the Pentaquarks

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

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

S.-K. Choi, S. L. Olsen, K. Abe, T. Abe, T. Adachi, Byoung Sup Ahn, H. Aihara, K. Akai, M. Akatsuka, M. Akemoto, Y. Asano, T. Asao, V. Aulchenko, T. Aushev, A. M. Bakich, Y. Ban, S. Banerjee, A. Bondar, A. Bozek, M. Brack, J. Brodzicka, T. E. Browder, P. Chang, Y. Chao, K.-F. Chen, G. Cheon, R. Chistov, Y. Choi, K. Choi, M. Danilov, L. Y. Dong, A. Drutskoy, S. Eidelman, V. Eisner, J. Flanagan, C. Fukugita, K. Furukawa, N. Gabyushvili, T. Gerarden, B. Golob, H. Guler, R. Guo, C. Hagner, F. Handa, T. Hara, N. C. Hastings, H. Hayashii, M. Hazumi, L. Hinz, Y. Hoshi, W.-S. Hou, Y. B. Hsiung, H.-C. Huang, T. Iijima, K. Inami, A. Ishikawa, R. Itoh, M. Iwasaki, Y. Iwasaki, J. H. Kang, S. U. Kataoka, N. Katayama, H. Kawai, T. Kawasaki, H. Kichimi, E. Kikutani, H. J. Kim, H. H. Kim, S. K. Kim, K. Kinoshita, H. Koiso, P. Koppenburg, S. Korpar, P. Krizan, P. Krokovny, S. Kumar, A. Kuzmin, J. S. Lange, G. Leder, S. H. Lee, T. Lesiak, S. W. Lin, D. Liventsev, J. MacNaughton, G. Majumder, F. Mandl, D. Marlow, T. Matsumoto, S. Michizono, T. Mimashi, W. Mitaroff, K. Miyabayashi, H. Miyake, D. Mohapatra, G. R. Moloney, N. Nam, Y. Nagasaka, T. Nakadaira, T. Nakamura, M. Nakao, Z. Natkaniec, S. Nishida, O. Nitoh, T. Nozaki, S. Ogawa, Y. Ogawa, K. Ohmi, Y. Ohnishi, T. Ohshima, N. Ohuchi, K. Oide, T. Okabe, S. Okuno, W. Ostrowicz, H. Ozaki, H. Palka, H. Park, N. Parslow, L. E. Piilonen, H. Sagawa, S. Saitoh, Y. Sakai, T. R. Sarangi, M. Satapathy, A. Sapaty, O. Schneider, A. J. Schwartz, S. Semenov, K. Senyo, R. Seuster, M. E. Sevior, H. Shibuya, T. Shidara, B. Shwartz, V. Sidorov, N. Soni, S. Stanić, M. Starić, A. Sugiyama, T. Sumiyoshi, C. Suzuki, F. Takasaki, K. Tamai, N. Tamura, M. Tanaka, M. Tawada, G. N. Taylor, Y. Takeda, T. Tomura, K. Tsubaki, Y. Uehara, K. Ueno, Y. Unno, S. Uno, G. Varner, K. E. Varvell, C. W. Wang, C. W. Wang, J. G. Wang, Y. Watanabe, E. Won, B. D. Yabsley, Y. Yamada, A. Yamaguchi, Y. Yamashita, H. Yanai, Heyoung Yang, J. Ying, M. Yoshida, C. C. Zhang, Z. P. Zhang, D. Zontar

(Belle Collaboration)

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

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

| State   | $M$ (MeV)     | $\Gamma$ (MeV) | $J^P_C$ | Decay Modes                                      | Production Modes           | Also observed by         |
|---------|---------------|----------------|---------|-------------------------------------------------|---------------------------|--------------------------|
| $Y_s$   | 2175 ± 8      | 58 ± 26        | 1$^-$   | $\phi_0(980)$                                   | $e^+e^-$ (ISR)            | BaBar*, BESII            |
|         |               |                |         | $\pi^+\pi^-$/$J/\psi,$                          | $J/\psi \rightarrow \eta Y_s(2175)$ | BaBar                    |
| $X$     | 3871.68 ± 0.17| < 1.2          | 1$^+$   | $\gamma/\psi, DD^*$                             | $B \rightarrow KX(3872), p\bar{p}$ | CDF, D0, BaBar, LHCb     |
| $Z$     | 3891.2 ± 3.3  | 40 ± 8         | 1$^+$   | $\pi^\pm J/\psi$                                | $Y(4260) \rightarrow Z(3900)\pi$ | BESIII*, CLEO            |
| $X$     | 3914 ± 4      | 28$^{+12}_{-14}$| 0/2$^{++}$| $\omega J/\psi$                                 | $\gamma\gamma \rightarrow X(3915)$ |                         |
| $Z$     | 3929 ± 5      | 29 ± 10        | 2$^{++}$ | $DD$                                            | $\gamma\gamma \rightarrow Z(3940)$ |                         |
|         |               |                |         | $DD^*$ (not $DD$)                                |                           |                          |
| $X$     | 3942 ± 9      | 37 ± 17        | 0$^+$   | $\omega J/\psi$ (not $DD^*$)                    | $e^+e^- \rightarrow J/\psi X(3940)$ | BaBar                    |
| $Y$     | 3943 ± 17     | 87 ± 34        | 0$^+$   | $\omega J/\psi$ (not $DD^*$)                    | $B \rightarrow KY(3940)$ |                         |
| $Y$     | 4008$^{+82}_{-49}$ | 226$^{+97}_{-80}$ | 1$^-$   | $\pi^+\pi^- J/\psi$                            | $e^+e^- (ISR)$             |                         |
| $Z$     | 4022 ± 3      | 8 ± 4          | 1$^+$   | $\pi^\pm J/\psi$                                | $Y(4260) \rightarrow Z(4020)\pi$ | BESIII* (only)           |
| $Z$     | 4025 ± 5      | 25 ± 10        | 1$^+$   | $\pi^\pm J/\psi$                                | $Y(4260) \rightarrow Z(4025)\pi$ | BESIII* (only)           |
| $X$     | 4156 ± 29     | 139$^{+113}_{-65}$ | 0$^+$   | $D^*\bar{D}^*$ (not $DD$)                       | $e^+e^- \rightarrow J/\psi X(4160)$ |                         |
| $Y$     | 4264 ± 12     | 83 ± 22        | 1$^-$   | $\pi^+\pi^- J/\psi$                            | $e^+e^- (ISR)$             | BaBar*, CLEO             |
| $Y$     | 4361 ± 13     | 74 ± 18        | 1$^-$   | $\pi^+\pi^- \psi'$                             | $e^+e^- (ISR)$             | BaBar*                   |
| $X$     | 4634$^{+9}_{-11}$ | 92$^{+41}_{-32}$ | 1$^-$   | $\Lambda_c^+\Lambda_c^-$                       | $e^+e^- (ISR)$             |                         |
| $Y$     | 4664 ± 12     | 48 ± 15        | 1$^-$   | $\pi^+\pi^- \psi'$                             | $e^+e^- (ISR)$             |                         |
| $Z$     | 4051$^{+24}_{-23}$ | 82$^{+51}_{-29}$ | 0$^-$   | $\pi^\pm \chi_c$                               | $B \rightarrow KZ\pm(4050)$ |                         |
| $Z$     | 4248$^{+185}_{-45}$ | 177$^{+320}_{-72}$ | 0$^-$   | $\pi^\pm \chi_c$                               | $B \rightarrow KZ\pm(4250)$ |                         |
| $Z$     | 4475 ± 7      | 172 ± 37       | 1$^+$   | $\pi^\pm \psi'$                                | $B \rightarrow KZ\pm(4430)$ | LHCb                    |

**Discussion reopened:** ['t Hooft, Isidori, Maiani, Polosa, Riquer, PLB 08]
Belle & others [Liu et al., 13], [Ablikim et al., 13], [Brambilla et al., 14]

| State     | $M$ (MeV)  | $\Gamma$ (MeV) | $J^{PC}$ | Decay Modes                     | Production Modes | Also observed by                   |
|-----------|------------|----------------|----------|---------------------------------|------------------|------------------------------------|
| $Y_s(2175)$ | 2175 ± 8   | 58 ± 26        | 1$^-$   | $\phi_0(980)$                  |                  | $e^+e^-$ (ISR)                     |
| $X(3872)$  | 3871.68 ± 0.17 | < 1.2       | 1$^{++}$ | $\pi^+\pi^-J/\psi.$          |                  | $e^+e^- \to J/\psi X(3872)$       |
| $Z(3900)$  | 3891.2 ± 3.3 | 40 ± 8        | 1$^+$   | $\gamma J/\psi,DD^*$          |                  | $B \to KX(3872), p\bar{p}$        |
| $X(3915)$  | 3914 ± 4    | 28$^{+12}_{-14}$ | 0/2$^{++}$ | $\omega J/\psi.$              |                  | $Y(4260) \to Z(3900)\pi$           |
| $Z(3930)$  | 3929 ± 5    | 29 ± 10        | 2$^{++}$ | $DD^*$                         |                  | $\gamma \gamma \to Z(3915)$       |
| $X(3940)$  | 3942 ± 9    | 37 ± 17        | 0$^2$+  | $DD^*$ (not DD)                |                  | $e^+e^- \to J/\psi X(3940)$       |
| $Y(3940)$  | 3943 ± 17   | 87 ± 34        | ?$^?$+  | $\omega J/\psi$ (not DD$^*$)  |                  | $B \to KY(3940)$                   |
| $Y(4008)$  | 4008$^{+82}_{-49}$ | 226$^{+97}_{-80}$ | 1$^{--}$ | $\pi^+\pi^-J/\psi.$          |                  | $e^+e^-$ (ISR)                     |
| $Z(4020)$  | 4022 ± 3    | 8 ± 4          | 1$^+$   | $\pi^+J/\psi,$                |                  | $Y(4260) \to Z(4020)\pi$           |
| $Z(4025)$  | 4026 ± 5    | 25 ± 10        | 1$^+$   | $\pi^+J/\psi,$                |                  | $Y(4260) \to Z(4025)\pi$           |
| $X(4160)$  | 4156 ± 29  | 139$^{+113}_{-65}$ | 0$^2$+  | $D^*D^*$ (not DD)             |                  | $e^+e^- \to J/\psi X(4160)$       |
| $Y(4260)$  | 4264 ± 12   | 83 ± 22        | 1$^{--}$ | $\pi^+\pi^-J/\psi.$          |                  | $e^+e^-$ (ISR)                     |
| $Y(4350)$  | 4361 ± 13   | 74 ± 18        | 1$^{--}$ | $\pi^+\pi^-\psi'$           |                  | $e^+e^-$ (ISR)                     |
| $X(4630)$  | 4634$^{+9}_{-11}$ | 92$^{+41}_{-32}$ | 1$^{--}$ | $\Lambda^+_c \Lambda^-_c$     |                  | $e^+e^-$ (ISR)                     |
| $Y(4660)$  | 4664 ± 12   | 48 ± 15        | 1$^{--}$ | $\pi^+\pi^-\psi'$           |                  | $e^+e^-$ (ISR)                     |
| $Z(4050)$  | 4051$^{+24}_{-23}$ | 82$^{+51}_{-29}$ | ?       | $\pi^\pm \chi_c^0$           |                  | $B \to KZ^\pm(4050)$              |
| $Z(4250)$  | 4248$^{+185}_{-45}$ | 177$^{+320}_{-72}$ | ?       | $\pi^\pm \chi_c^0$           |                  | $B \to KZ^\pm(4250)$              |
| $Z(4430)$  | 4475 ± 7    | 172 ± 13$^{+37}_{-34}$ | 1$^+$   | $\pi^\pm \psi'$              |                  | $B \to KZ^\pm(4430)$              |

Light states [PDG]:

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

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

| State       | $M$ (MeV)   | $\Gamma$ (MeV) | $J^{PC}$ | Decay Modes                          | Production Modes                  | Also observed by                  |
|-------------|-------------|----------------|----------|--------------------------------------|-----------------------------------|-----------------------------------|
| $Y_s(2175)$ | 2175 ± 8    | 58 ± 26        | $1^{--}$ | $\phi_0(980)$                        | $e^+e^-$ (ISR) $J/\psi \rightarrow \eta Y_s(2175)$ | BaBar*, BESII                     |
| $X(3872)$   | 3871.68 ± 0.17 | < 1.2            | $1^{++}$ | $\pi^+\pi^-/J/\psi$, $\gamma/J/\psi, DD^*$ | $B \rightarrow KX(3872), p\bar{p}$ | BaBar                            |
| $Z(3900)$   | 3891.2 ± 3.3 | 40 ± 8          | $1^{+}$  | $\pi^\pm J/\psi$                     | $Y(4260) \rightarrow Z(3900)\pi$ | BESIII*, CLEO                     |
| $X(3915)$   | 3914 ± 4    | 28^{+12}_{-14} | $0/2^{++}$ | $\omega J/\psi$                      | $\gamma\gamma \rightarrow X(3915)$ |                                   |
| $Z(3930)$   | 3929 ± 5    | 29 ± 10         | $2^{++}$ | $DD^*$                               | $\gamma\gamma \rightarrow Z(3940)$ |                                   |
| $X(3940)$   | 3942 ± 9    | 37 ± 17         |          |                                      |                                   |                                   |
| $Y(3940)$   | 3943 ± 17   | 87 ± 34         |          |                                      |                                   |                                   |
| $Y(4008)$   | 4008^{+82}_{-49} | 226^{+97}_{-80} |          |                                      |                                   |                                   |
| $Z(4020)$   | 4022 ± 5    | 8 ± 4           |          |                                      |                                   |                                   |
| $Z(4025)$   | 4026 ± 5    | 25 ± 10         |          |                                      |                                   |                                   |
| $X(4160)$   | 4156 ± 29   | 139^{+113}_{-65} |          |                                      |                                   |                                   |
| $Y(4260)$   | 4264 ± 12   | 83 ± 22         |          |                                      |                                   |                                   |
| $Y(4350)$   | 4361 ± 13   | 74 ± 18         |          |                                      |                                   |                                   |
| $X(4630)$   | 4634^{+9}_{-11} | 92^{+41}_{-23}     | $1^{--}$ | $\Lambda_c^+\Lambda_c^-$                  | $e^+e^- \rightarrow J/\psi X(3940)$ |                                   |
| $Y(4660)$   | 4664 ± 12   | 48 ± 15         | $1^{--}$ | $\pi^+\pi^-\phi'$                   | $e^+e^-$ (ISR)                   |                                   |
| $Z(4050)$   | 4051^{+24}_{-23} | 82^{+51}_{-29}     | ?        | $\pi^\pm \chi_c$                     | $B \rightarrow KZ(4050)$         |                                   |
| $Z(4250)$   | 4248^{+185}_{-45} | 177^{+320}_{-72} | ?        | $\pi^\pm \chi_c$                     | $B \rightarrow KZ(4250)$         |                                   |
| $Z(4430)$   | 4475 ± 29   | 172 ± 13^{+37}_{-34} | $1^{+}$  | $\pi^\pm \psi'$                      | $B \rightarrow KZ(4430)$         | LHCb                             |

**Light states [PDG]**:

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

Discussion reopened: [’t Hooft, Isidori, Maiani, Polosa, Riquer, PLB 08]

Ahmed Ali (DESY, Hamburg)
Constituent Quark Model and Light States

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

- Tetraquark interpretation in agreement with experiment
  [’t Hooft, Isidori, Maiani, Polosa, Riquer, PLB (2008)]
$Y_c(4260), J^{PC} = 1^{--}$

- 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 $\Gamma_{e^+e^-}$)

  (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

$M(Z_c(3900)) = 3884.6 \pm 4.6$ MeV

$M = (3885 \pm 5 \pm 1)$ MeV/c$^2$

$\Gamma = (34 \pm 12 \pm 4)$ MeV/c$^2$

81 ± 20 events

6.1σ

Belle

PRL 110, 252001
Summary of Charmonia and Charmonium-like Hadrons (Olsen, 1411.7738)
Summary of Bottomonia and Bottomonium-like Hadrons (Olsen, 1411.7738)
Enigmatic $\Upsilon(5S)$ Decays!

$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$ \quad 0.59 \pm 0.04 \pm 0.09

$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ \quad 0.85 \pm 0.07 \pm 0.16

$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$ \quad 0.52^{+0.20}_{-0.17} \pm 0.10

$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ \quad 0.0060

$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$ \quad 0.0009

$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$ \quad 0.0019

---

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

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

Ahmed Ali (DESY, Hamburg)
\( \sigma(e^+e^- \rightarrow b\bar{b}) \) in the \( \Upsilon(10860) \) and \( \Upsilon(11020) \) resonance region [Belle]

\[ R'_b \quad \text{data and fit} \]

- \( F_{b\bar{b}} = |A_{nr}|^2 + |A_r + A_5e^{i\phi_5}f_{5S} + A_6e^{i\phi_6}f_{6S}|^2 \)
- \( f_{nS} = M_{ns}\Gamma_{nS}/[\left(s - M_{ns}^2\right) + iM_{ns}\Gamma_{nS}] \) [BW]; \( A_r \) and \( A_{nr} \) [Continuum]
- No peaking structure seen at 10.9 GeV, hinted by the BaBar data; \( \Gamma(e^+e^-) < 9 \text{ eV} \) (@ 90% C.L.)
σ(e^+e^- → Y(nS)π^+π^-) in the Y(10860) and Y(11020) resonance region

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

- Fit Values (MeV): $M_{10860} = 10891.1 \pm 3.2_{-1.5}^{+0.6}$; $\Gamma_{10860} = 53.7_{-5.6}^{+7.1}_{+0.9}$
- $M_{5S}(Y(nS)\pi\pi) - M_{5S}(b\bar{b}) = 9.2 \pm 3.4 \pm 1.9$ MeV
- Fit Values (MeV): $M_{11020} = 10987.5_{-2.5}^{+6.4}_{-2.1} + 9.0$; $\Gamma_{11020} = 61_{-19}^{+9}_{+2}$
\[ \sigma(e^+e^- \rightarrow h_b(1P, 2P)\pi^+\pi^-) \text{ in the } \Upsilon(10860) \text{ and } \Upsilon(11020) \text{ resonance region} \]

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

- **Fit Values (MeV):**
  \[ M_{10860} = 10884.7^{+3.2}_{-2.9}^{+8.6}_{-0.6}; \quad \Gamma_{10860} = 44.2^{+1.9}_{-7.8}^{+2.2}_{-15.8} \]

- **Fit Values (MeV):**
  \[ M_{11020} = 10998.6 \pm 6.1^{+16.1}_{-1.1}; \quad \Gamma_{11020} = 29^{+20}_{-11}^{+2}_{-7} \]
Evidence for $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$ (Belle)

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

- $Z_b(10610)$
  - $M = 10608 \text{ pm } 2.0 \text{ MeV}$
  - $\Gamma = 15.6 \text{ pm } 2.5 \text{ MeV}$

- $Z_b(10650)$
  - $M = 10653 \text{ pm } 1.5 \text{ MeV}$
  - $\Gamma = 14.4 \text{ pm } 3.2 \text{ MeV}$

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 $B^*B^*$ thresholds

Molecules?

The $Y(5S)$ is an unexpected source of $h_b$
Dipion mass distributions in $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi\pi$ decays?

$\Upsilon(1S)\pi\pi$
(example)

$\Upsilon(2S)\pi\pi$
(example)

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

$M_{\pi\Upsilon}^2 = (k_1 + p)^2$
Dipion mass distributions in $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi\pi$ decays?

- $\Upsilon(1S)\pi\pi$ (example)
- $\Upsilon(2S)\pi\pi$ (example)
Dipion mass distributions in $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi\pi$ decays?

- $\Upsilon(1S)\pi\pi$ (example)
- $\Upsilon(2S)\pi\pi$ (example)

Theoretical works well (multipole exp.)

[Voloshin, Cahn PRL 75]

Process:

$\Upsilon(nS)$

$\Upsilon(mS)$

Gluons

$\pi$

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

[Belle Collaboration (2012)]

- $\Upsilon(1S)\pi\pi$ (example)

- $\Upsilon(2S)\pi\pi$ (example)

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

- Process:
  - NO resonant structure
  - Zweig forbidden
Dipion mass distributions in $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi\pi$ decays?

- $\Upsilon(1S)\pi\pi$ (example) resonant!
- $\Upsilon(2S)\pi\pi$ (example)
  - $Z(10610)$
  - $Z(10650)$

distinct resonant structure

NO resonant structure

Zweig forbidden
Dipion mass distributions in $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi\pi$ decays?

- **Y(1S)$\pi\pi$ (example)**
  - Resonant!

- **Y(2S)$\pi\pi$ (example)**
  - Z(10610)
  - Z(10650)

- **Process**
  - $\Gamma(\Upsilon(2S) \rightarrow \Upsilon(1S)\pi\pi) \approx 0.0060$ MeV
  - $\Gamma(\Upsilon(3S) \rightarrow \Upsilon(1S)\pi\pi) \approx 0.0009$ MeV
  - $\Gamma(\Upsilon(4S) \rightarrow \Upsilon(1S)\pi\pi) \approx 0.0019$ MeV
  - $\Gamma(\Upsilon(5S) \rightarrow \Upsilon(1S)\pi^+\pi^-) \approx 0.59$ MeV

- **Belle Collaboration (2012)**

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

- **Distinct resonant structure**
  - NO resonant structure
  - Zweig forbidden

Ahmed Ali (DESY, Hamburg)
Dipion mass distributions in $\Upsilon(5S) \to \Upsilon(nS)\pi\pi$ decays?

Ahmed Ali (DESY, Hamburg)

Belle Collaboration (2012)

Y(1S)$\pi\pi$ (example) resonant!

Y(2S)$\pi\pi$ (example) Z(10610)

Z(10650)

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

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

distinct resonant structure

differs by two orders of magnitude!

NO resonant structure

Zweig forbidden

theory works well (multipole exp.)
[Brown, Cahn PRL 75]
[Voloshin, JETP 75]
Dipion mass distributions in $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi\pi$ decays?

\[ \Upsilon(1S)\pi\pi \quad {\text{(example)}} \]

\[ \Upsilon(2S)\pi\pi \quad Z(10610) \]

\[ \text{tetraquark model can explain data} \]

\[ \text{(Belle Collaboration (2012))} \]

\[ \begin{align*}
\Gamma(\Upsilon(2S) \rightarrow \Upsilon(1S)\pi\pi) &\approx 0.0060 \text{ MeV} \\
\Gamma(\Upsilon(3S) \rightarrow \Upsilon(1S)\pi\pi) &\approx 0.0009 \text{ MeV} \\
\Gamma(\Upsilon(4S) \rightarrow \Upsilon(1S)\pi\pi) &\approx 0.0019 \text{ MeV} \\
\Gamma(\Upsilon(5S) \rightarrow \Upsilon(1S)\pi^+\pi^-) &\approx 0.59 \text{ MeV}
\end{align*} \]

- distinct resonant structure
- differs by two orders of magnitude!
- NO resonant structure
- Zweig forbidden
Models for XYZ Mesons

Quarkonium Tetraquarks

- compact tetraquark
  \[
  Q \bar{q} q \bar{Q}
  \]
- meson molecule
  \[
  Q \bar{q} \quad q \bar{Q}
  \]
- diquark-onium
  \[
  Q q \quad \bar{q} \bar{Q}
  \]
- hadro-quarkonium
  \[
  q \quad \bar{Q} \quad \bar{Q} \quad \bar{q}
  \]
- quarkonium adjoint meson
  \[
  Q \bar{Q} \quad \bar{q}
  \]
X, Y, Z Exotics

(R=1 fm) a compact ‘tetraquark’

$X$: a loosely bound molecule ($R \sim 10$ fm)

$$ R \approx \frac{1}{\sqrt{2M_D E_{\text{bind}}}} $$

Hadro-charmonium

Voloshin arXiv:1304.0380

A $c\bar{c}$ state surrounded by light matter

Decay into $\eta_c \rho$ forbidden by HQSS
Diquarks: Color Representation

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

- Color factor determines binding:
  - Negative sign $\rightarrow$ Attractive

\[ t_{ij}^{ab} = -\frac{2}{3} (\delta_{ij} \delta_{kl} - \delta_{ik} \delta_{jl}) \]

\[ \delta_{ik}^{ab} \] projects $\bar{3} + \frac{1}{3}$

\[ \delta_{ij}^{ab} \] projects $6$
Diquarks: Color Representation

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

  \[ \text{Color factor determines binding:} \]
  \[ \text{Negative sign} \Rightarrow \text{Attractive} \]

- Quarks in diquark transform as:

  \[ 3 \otimes 3 = \bar{3} \oplus 6 \]
Diquarks: Color Representation

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

  Color factor determines binding:
  Negative sign $\rightarrow$ Attractive

- Quarks in diquark transform as:

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

- $qq$ bound state color factor:

  $t_{ij}^a t_{kl}^a = -\frac{2}{3} \left( \delta_{ij} \delta_{kl} - \delta_{il} \delta_{kj} \right)/2 + \frac{1}{3} \left( \delta_{ij} \delta_{kl} + \delta_{il} \delta_{kj} \right)/2$

  antisymmetric: projects $\bar{3}$
  symmetric: projects $6$
Diquarks: Color Representation

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

- Color factor determines binding:
  - Negative sign \(\rightarrow\) Attractive

- Quarks in diquark transform as:
  \[
  3 \otimes 3 = \bar{3} \oplus 6
  \]

- \(qq\) bound state color factor:
  \[
  t^a_{ij} t^a_{kl} = -\frac{2}{3} \left( \delta_{ij} \delta_{kl} - \delta_{il} \delta_{kj} \right) / 2 + \frac{1}{3} \left( \delta_{ij} \delta_{kl} + \delta_{il} \delta_{kj} \right) / 2
  \]
  - antisymmetric: projects \(\bar{3}\)
  - symmetric: projects \(6\)
Diquarks: Color Representation

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

- Color factor determines binding:
  - Negative sign → Attractive

- Quarks in diquark transform as:

\[
\begin{align*}
\mathbf{3} \otimes \mathbf{3} & \quad = \quad \bar{\mathbf{3}} \oplus \mathbf{6} \\
\end{align*}
\]

- Quark bound state color factor:

\[
\begin{align*}
t_{ij}^a t_{kl}^a & = -\frac{2}{3} \left( \delta_{ij} \delta_{kl} - \delta_{il} \delta_{kj} \right) / 2 + \frac{1}{3} \left( \delta_{ij} \delta_{kl} + \delta_{il} \delta_{kj} \right) / 2 \\
\end{align*}
\]

antisymmetric: projects \( \bar{\mathbf{3}} \)

symmetric: projects \( \mathbf{6} \)
Diquarks: Spin representation

- Calculation of 2 quark correlation strength
- Decreasing distance increasing strength for "good" diquarks
- Diquark size $O(1\,\text{fm})$
- Lattice simulations for light quarks [Alexandrou, Forcrand, Lucini, PRL (2006)]
  - Binding for "good" spin 0 diquarks
  - No binding for "bad" spin 1 diquarks

Spin decoupling in HQ-Limit: "Bad" diquarks in $b$-sector might bind
Diquarks: Spin representation

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

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

- Binding for "good" spin 0 diquarks
- No binding for "bad" spin 1 diquarks
- Spin decoupling in HQ-Limit
- "Bad" diquarks in $b$-sector might bind
Diquarks: Spin representation

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

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

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

Spin decoupling in HQ-Limit

"Bad" diquarks in $b$-sector might bind
Diquark Model of Tetra- and Pentaquarks

Diquarks and Anti-diquarks are the building blocks of Tetraquarks

Color representation: $3 \otimes 3 = \bar{3} \oplus 6$; only $\bar{3}$ is attractive; $C_{\bar{3}} = 1/2 C_3$

Interpolating diquark operators for the two spin-states of diquarks

Scalar: $0^+$ \quad $Q_{i\alpha} = \epsilon_{\alpha\beta\gamma} (\bar{b}_c^B \gamma_5 q^\gamma_i - \bar{q}^B_i \gamma_5 b^\gamma)$

Axial-Vector: $1^+$ \quad $\tilde{Q}_{i\alpha} = \epsilon_{\alpha\beta\gamma} (\bar{b}_c^B \gamma_5 q^\gamma_i + \bar{q}^B_i \gamma_5 b^\gamma)$

$\alpha, \beta, \gamma$: $SU(3)_C$ indices
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

Scalar: $0^+ \quad Q_{i\alpha} = \epsilon_{\alpha\beta\gamma}(\bar{b}_c^\beta\gamma q_i^\gamma - \bar{q}_{ic}^\beta\gamma b^\gamma) \quad \alpha, \beta, \gamma: SU(3)_{C} indices$

Axial-Vector: $1^+ \quad \bar{Q}_{i\alpha} = \epsilon_{\alpha\beta\gamma}(\bar{b}_c^\beta\gamma\gamma q_i^\gamma + \bar{q}_{ic}^\beta\gamma b^\gamma)$

NR limit: States parametrized by Pauli matrices:

Scalar: $0^+ \quad \Gamma^0 = \frac{\sigma_2}{\sqrt{2}}$

Axial-Vector: $1^+ \quad \bar{\Gamma} = \frac{\sigma_2 \sigma}{\sqrt{2}}$
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

Scalar: $0^+ \quad Q_{i\alpha} = \epsilon_{\alpha\beta\gamma} (\bar{b}_c^\beta \gamma^5 q^\gamma_i - \bar{q}_i^\beta \gamma^5 b^\gamma)$

Axial-Vector: $1^+ \quad \bar{Q}_{i\alpha} = \epsilon_{\alpha\beta\gamma} (\bar{b}_c^\beta \gamma q^\gamma_i + \bar{q}_i^\beta \gamma b^\gamma)$

NR limit: States parametrized by Pauli matrices:

Scalar: $0^+ \quad \Gamma^0 = \frac{\sigma_2}{\sqrt{2}}$

Axial-Vector: $1^+ \quad \bar{\Gamma} = \frac{\sigma_2 \bar{\sigma}}{\sqrt{2}}$

Diquark spin $s_Q$  =>  tetraquark total angular momentum $J$:

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

Tetraquarks: $|0_Q, 0_{\bar{Q}}; 0_J \rangle = \Gamma^0 \otimes \Gamma^0$

$$|1_Q, 1_{\bar{Q}}; 0_J \rangle = \frac{1}{\sqrt{3}} \Gamma^i \otimes \Gamma_i ...$$

$$|0_Q, 1_{\bar{Q}}; 1_J \rangle = \Gamma^0 \otimes \Gamma^i$$
NR Hamiltonian for Tetraquarks with hidden charm

States need to diagonalize Hamiltonian:

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

\[
H_{\text{eff}}(X, Y, Z) = 2m_Q + \frac{B_Q}{2} \langle L^2 \rangle - 2a \langle L \cdot S \rangle + 2\kappa_{qQ} \left[ \langle s_q \cdot s_Q \rangle + \langle s_{\bar{q}} \cdot s_{\bar{Q}} \rangle \right] \\
= 2m_Q - aJ(J + 1) + \left( \frac{B_Q}{2} + a \right) L(L + 1) + aS(S + 1) - 3\kappa_{qQ} \\
+ \kappa_{qQ} \left[ s_{qQ}(s_{qQ} + 1) + s_{\bar{q}\bar{Q}}(s_{\bar{q}\bar{Q}} + 1) \right]
\]
NR Hamiltonian for Tetraquarks with hidden charm

States need to diagonalize Hamiltonian:

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

with

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

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

\[ + \kappa_{qQ} [s_Q(s_Q + 1) + s_{\bar{q}}\bar{Q}(s_{\bar{q}}\bar{Q} + 1)] \]
NR Hamiltonian for Tetraquarks with hidden charm

States need to diagonalize Hamiltonian:

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

with

- **qq spin coupling**
  
  \[ H_{SS}^{(qq)} = 2(K_{cq})_3 [(S_c \cdot S_q) + (S_{\bar{c}} \cdot S_{\bar{q}})] \]
  
  \[ H_{SS}^{(q\bar{q})} = 2(K_{c\bar{c}}) (S_c \cdot S_{\bar{q}} + S_{\bar{c}} \cdot S_q) + 2K_{c\bar{c}} (S_c \cdot S_{\bar{c}}) + 2K_{q\bar{q}} (S_q \cdot S_{\bar{q}}) \]

- **q\bar{q} spin coupling**

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

\[
= 2m_Q - aJ(J + 1) + \left( \frac{B_Q}{2} + a \right) L(L + 1) + aS(S + 1) - 3\kappa_{qQ} + \kappa_{qQ} [s_qQ(s_qQ + 1) + s_{\bar{q}}\bar{Q}(s_{\bar{q}}\bar{Q} + 1)]
\]
NR Hamiltonian for Tetraquarks with hidden charm

States need to diagonalize Hamiltonian:

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

with

\[ H_{SS}^{(qq)} = 2(\mathcal{K}_{cq})_3[(S_c \cdot S_q) + (S_{\bar{c}} \cdot S_{\bar{q}})] \]
\[ H_{SS}^{(q\bar{q})} = 2(\mathcal{K}_{c\bar{q}})(S_c \cdot S_{\bar{q}} + S_{\bar{c}} \cdot S_q) \]
\[ + 2\mathcal{K}_{c\bar{c}}(S_c \cdot S_{\bar{c}}) + 2\mathcal{K}_{q\bar{q}}(S_q \cdot S_{\bar{q}}) \]
\[ H_{SL} = 2A_Q(S_Q \cdot L + S_{\bar{Q}} \cdot L) \]
\[ H_{LL} = B_Q \frac{L_Q \bar{Q}(L_Q \bar{Q} + 1)}{2} \]

\[ H_{\text{eff}}(X, Y, Z) = 2m_Q + \frac{B_Q}{2} \langle L^2 \rangle - 2a \langle L \cdot S \rangle + 2\kappa_Q [\langle s_q \cdot s_Q \rangle + \langle s_{\bar{q}} \cdot s_{\bar{Q}} \rangle] \]
\[ = 2m_Q - aJ(J + 1) + \left( \frac{B_Q}{2} + a \right)L(L + 1) + aS(S + 1) - 3\kappa_Q \]
\[ + \kappa_Q [s_Q(s_Q + 1) + s_{\bar{Q}}(s_{\bar{Q}} + 1)] \]
Low-lying $S$- and $P$-wave Tetraquark States

**S-wave states**

- In the $|s_qQ, s_{ar{q}ar{Q}}; S, L\rangle_j$ and $|s_{ar{q}q}, s_QQ; S', L'\rangle_j$ 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 | $J^{PC}$ | $|s_qQ, s_{ar{q}ar{Q}}; S, L\rangle_j$ | $|s_{ar{q}q}, s_QQ; S', L'\rangle_j$ | Mass |
|-------|---------|-------------------------------|--------------------------------|------|
| $X_0$ | 0++ | $|0, 0; 0, 0\rangle_0$ | $(|0, 0; 0, 0\rangle_0 + \sqrt{3}|1, 1; 0, 0\rangle_0) / 2$ | $M_{00} - 3\kappa_{qQ}$ |
| $X'_0$ | 0++ | $|1, 1; 0, 0\rangle_0$ | $(\sqrt{3}|0, 0; 0, 0\rangle_0 - |1, 1; 0, 0\rangle_0) / 2$ | $M_{00} + \kappa_{qQ}$ |
| $X_1$ | 1++ | $(|1, 0; 1, 0\rangle_1 + |0, 1; 1, 0\rangle_1) / \sqrt{2}$ | $|1, 1; 1, L'\rangle_1$ | $M_{00} - \kappa_{qQ}$ |
| $Z$ | 1+- | $(|1, 0; 1, 0\rangle_1 - |0, 1; 1, 0\rangle_1) / \sqrt{2}$ | $(|1, 0; 1, L'\rangle_1 - |0, 1; 1, L'\rangle_1) / \sqrt{2}$ | $M_{00} - \kappa_{qQ}$ |
| $Z'$ | 1+- | $|1, 1; 1, 0\rangle_1$ | $(|1, 0; 1, L'\rangle_1 + |0, 1; 1, L'\rangle_1) / \sqrt{2}$ | $M_{00} + \kappa_{qQ}$ |
| $X_2$ | 2++ | $|1, 1; 2, 0\rangle_2$ | $|1, 1; 2, L'\rangle_2$ | $M_{00} + \kappa_{qQ}$ |

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

| Label | $J^{PC}$ | $|s_qQ, s_{ar{q}ar{Q}}; S, L\rangle_j$ | $|s_{ar{q}q}, s_QQ; S', L'\rangle_j$ | Mass |
|-------|---------|-------------------------------|--------------------------------|------|
| $Y_1$ | 1-- | $|0, 0; 0, 1\rangle_1$ | $(|0, 0; 0, 1\rangle_1 + \sqrt{3}|1, 1; 0, 1\rangle_1) / 2$ | $M_{00} - 3\kappa_{qQ} + B_Q$ |
| $Y_2$ | 1-- | $(|1, 0; 1, 1\rangle_1 + |0, 1; 1, 1\rangle_1) / \sqrt{2}$ | $|1, 1; 1, L'\rangle_1$ | $M_{00} - \kappa_{qQ} + 2a + B_Q$ |
| $Y_3$ | 1-- | $|1, 1; 0, 1\rangle_1$ | $(\sqrt{3}|0, 0; 0, 1\rangle_1 - |1, 1; 0, 1\rangle_1) / 2$ | $M_{00} + \kappa_{qQ} + B_Q$ |
| $Y_4$ | 1-- | $|1, 1; 2, 1\rangle_1$ | $|1, 1; 2, L'\rangle_1$ | $M_{00} + \kappa_{qQ} + 6a + B_Q$ |
| $Y_5$ | 1-- | $|1, 1; 2, 3\rangle_1$ | $|1, 1; 2, L'\rangle_1$ | $M_{00} + \kappa_{qQ} + 16a + 6B_Q$ |
Charmonium-like and Bottomonium-like Tetraquark Spectrum

(with Satoshi Mishima)

Parameters in the Mass Formula

| Parameters | charmonium-like | bottomonium-like |
|------------|-----------------|------------------|
| $M_{00}$ [MeV] | 3957 | 10630 |
| $\kappa_{qQ}$ [MeV] | 67 | 22.5 |
| $B_Q$ [MeV] | 268 | 329 |
| $a$ [MeV] | 52.5 | 26 |

| 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   | $Z_c^+$ (3900) | 3890    |
| $Z$   | 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
states are iso-doublets \( q = u, d \)

With the old Maiani et al. Paradigm, tetraquark \( Z_b \) masses do not agree with Belle.

However tetraquarks with mixing & self energy corrections in principle allowed in parts of parameter space [AA, Hambrock, Wang, PRD 11], but with the new Maiani et al. paradigm, \( M(Z_b) - M(Z_b') \) fixes \( 2\kappa_{qb} = 45\text{MeV} \sim 2\kappa_{qc} \), in agreement with the heavy quark symmetry: \( \kappa_{qb}/\kappa_{qc} \approx m_c/m_b \)
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       | $Y(1S)\pi^+\pi^-$ | $Y(2S)\pi^+\pi^-$ | $Y(3S)\pi^+\pi^-$ | $h_b(1P)\pi^+\pi^-$ | $h_b(2P)\pi^+\pi^-$ |
|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| 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 $Z_b h_b \pi$)

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

$$ g_{Z'} \equiv g(Y \to Z'_b \pi)g(Z'_b \to h_b \pi) \propto \alpha \beta \langle h_b | Z'_b \rangle \langle Z'_b | Y \rangle $$
Heavy-Quark-Spin Flip in $Y(10890) \rightarrow Z_b/Z'_b + \pi \rightarrow h_b(1P,2P)\pi\pi$

- Within errors, Belle data is consistent with heavy quark spin conservation, which requires $g_Z = -g_{Z'}$.

- To determine the coefficients $\alpha$ and $\beta$, one has to resort to $s_{b\bar{b}}$: $1 \rightarrow 1$ transitions

  $$Y(10890) \rightarrow Z_b/Z'_b + \pi \rightarrow Y(nS)\pi\pi \ (n = 1,2,3)$$

- The analogous effective couplings are

  $$f_Z = f(Y \rightarrow Z_b\pi)f(Z_b \rightarrow Y(nS)\pi) \propto |\beta|^2 \langle Y(nS)|0_{\bar{q}q},1_{b\bar{b}}\rangle \langle 0_{\bar{q}q},1_{b\bar{b}}|Y\rangle$$

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

- Dalitz analysis indicates:

  $Y(10890) \rightarrow Z_b/Z'_b + \pi \rightarrow Y(nS)\pi\pi \ (n = 1,2,3)$ proceed mainly through the resonances $Z_b$ and $Z'_b$, though $Y(10890) \rightarrow Y(1S)\pi\pi$ has a significant direct component, expected in tetraquark interpretation of $Y(10890)$.

  [A.A., S. Mishima, C. Hambrock, PRL 106, 092002 (2011)]
Determination of $\alpha/\beta$ from $Y(10890) \to Z_b/Z'_b + \pi \to Y(nS)\pi\pi \ (n = 1, 2, 3)$

- 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 $\alpha/\beta$

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

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

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

\[
|Z_b\rangle = \frac{|1_{bq}, 0_{\bar{b}q}\rangle - |0_{bq}, 1_{\bar{b}q}\rangle}{\sqrt{2}}, \quad |Z'_b\rangle = |1_{bq}, 1_{\bar{b}q}\rangle_{J=1} \\
|Z_b\rangle = \frac{|1_{q\bar{q}}, 0_{b\bar{b}}\rangle - |0_{q\bar{q}}, 1_{b\bar{b}}\rangle}{\sqrt{2}}, \quad |Z'_b\rangle = \frac{|1_{q\bar{q}}, 0_{b\bar{b}}\rangle + |0_{q\bar{q}}, 1_{b\bar{b}}\rangle}{\sqrt{2}} \\
\]
Tetraquark model for $Y_b$ production and decays

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

**Assumption: Point-like diquarks**

[AA, Hambrock, Mishima, PRL 106 (2011), 092002]
Tetraquark model for $Y_b$ production and decays

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

Assumption: Point-like diquarks

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

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

Ahmed Ali (DESY, Hamburg)
Tetraquark model for $Y_b$ production and decays

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

**Assumption: Point-like diquarks**

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

\[
\Gamma_{ee}(Y_{[b,l/h]}) = \frac{24\alpha^2 Q^2_{[b,l/h]}}{M^4_{Y_{[b,l/h]}}} \kappa^2 \left| R_{11}^{(1)}(0) \right|^2
\]
Tetraquark model for $Y_b$ production and decays

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

**Assumption:** Point-like diquarks

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

Radial tetraquark WF @ origin

\[ \Gamma_{ee}(Y_{[b,l/h]}) = \frac{24\alpha^2 Q_{[b,l/h]}^2}{M_{Y_{[b,l/h]}}^4} \kappa^2 \left| R_{11}^{(1)}(0) \right|^2 \]
Tetraquark model for $Y_b$ production and decays

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

**Assumption: Point-like diquarks**
[AA, Hambrock, Mishima, PRL 106 (2011), 092002]

**Hadronic size parameter**
\[
\Gamma_{ee}(Y_{[b,l/h]}) = \frac{24\alpha^2 Q^2_{[b,l/h]}}{M^4_{Y_{[b,l/h]}}} \kappa^2 \left| R_{11}^{(1)}(0) \right|^2
\]
Tetraquark model for $Y_b$ production and decays

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

Assumption: Point-like diquarks

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

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

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

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

Ahmed Ali (DESY, Hamburg)
$Y_b$ decay

- Continuum

$$e^+ - Y_b - e^- \quad \gamma(nS)$$

$$p - p'$$

- Resonance

$$e^+ - Y_b - e^- \quad \gamma(nS)$$

$$p - p'$$

Breit-Wigner shape for resonance:

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

$$q^2 \equiv M_{pp'}^2 \quad \rightarrow \quad \text{Resonances show in } M_{pp'} \text{ spectrum}$$

$$\text{Not in } M_{YP} \text{ spectrum since } Z_b \text{ negligible}$$
Fit to $\sigma(e^+e^- \rightarrow Y_b \rightarrow Y(1S)\pi^+\pi^-)$

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

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

Fit results, data from [Belle, PRL 08]

$\chi^2$/d.o.f. = 21.5/15  $\Rightarrow$ Good agreement with data

Clear resonance dominance!

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

2$^{++}$ meson $f_2(1270)$
Predictions for $Y(1S)(K^+K^-,\eta\pi^0)$

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

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

- Predictions for spectra:

- Agreement with $\tilde{\sigma}_{K^+K^-} = 0.11^{+0.04}_{-0.03}$ (BELLE)
  - $1.0 \lesssim \tilde{\sigma}_{\eta\pi^0} \lesssim 2.0$ predicted

- Resonance dominance
  - Characteristic shape
  - **Good tests** (relying on $\Upsilon_b$ has 2 flavor states)
Are $Y_c$, $Z_c$s, $Y_b$ and $Z_b$s related?

2.
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.
Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_{b}^{0} \rightarrow J/\psi K^{-} p$ decays

The LHCb collaboration

Abstract
Observations of exotic structures in the $J/\psi p$ channel, which we refer to as charmonium-pentaquark states, in $\Lambda_{b}^{0} \rightarrow J/\psi K^{-} p$ decays are presented. The data sample corresponds to an integrated luminosity of $3 \, \text{fb}^{-1}$ 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 $4380 \pm 8 \pm 29 \, \text{MeV}$ and a width of $205 \pm 18 \pm 86 \, \text{MeV}$, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5 \, \text{MeV}$ and a width of $39 \pm 5 \pm 19 \, \text{MeV}$. 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; $\int Ldt = 3 \text{ fb}^{-1}$)

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

![Feynman diagrams](image-url)

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

![Invariant mass distributions](image-url)

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

Ahmed Ali (DESY, Hamburg)
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 $12\sigma$)
  \[ M = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}; \Gamma = 39 \pm 5 \pm 19 \text{ MeV} \]

- Lower mass state (statistical significance $9\sigma$)
  \[ M = 4380 \pm 8 \pm 29 \text{ MeV}; \Gamma = 205 \pm 18 \pm 86 \text{ MeV} \]

- 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     | $5/2^+$                                       | $3/2^-$                                       |
| $\Sigma_c^{*+} \bar{D}^0$ | $4382.3 \pm 2.4$                           |                                               |
| $\chi_{c1}p$     |                                               | $4448.93 \pm 0.07$                           |
| $\Lambda_c^{*+} \bar{D}^0$ |                                               | $4457.09 \pm 0.35$                           |
| $\Sigma_c^+ \bar{D}^{*0}$ |                                               | $4459.9 \pm 0.5$                            |
| $\Sigma_c^+ \bar{D}^0 \pi^0$ |                                               | $4452.7 \pm 0.5$                            |
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

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 $\Lambda^0_b \rightarrow K^- J/\psi p$

$$ M_{P_c(4450)} - M_{\chi_{c1}} - M_p = (0.9 \pm 3.1) \text{ MeV}$$

Two possible mechanisms:

a) 2-point loop with a 3-body production $\Lambda^0_b \rightarrow K^- \chi_{c1} p$ followed by the rescattering process $\chi_{c1} p \rightarrow J/\psi p$

b) The $K^- p$ is produced from an intermediate $\Lambda^*$ and the proton rescatters with the $\chi_{c1}$ into a $J/\psi p$
Pentaquarks as rescattering-induced kinematic effects (Contd.)

- Amplitude for Fig. (a) ($\mu = \text{reduced mass}$ 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 $A_{(a)} = N(b + G_\Lambda(E))$ determines the normalization $N$, the constant background $b$ and $\Lambda$

- 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 $\text{Re}\sqrt{s} = 4450$ MeV
Pentaquarks as hadronic molecular states [Rui Chen et al., arxiv:1507.03704]

- Identify \( \Xi_c^+(4380) \) with \( \Sigma_c(2455)\bar{D}^* \) and \( \Xi_c^+(4450) \) with \( \Sigma_c(2520)\bar{D}^* \) bound by a pion exchange.

- Effective Lagrangians:

\[
L_P = ig \text{Tr} \left[ \bar{H}_a^{(\bar{Q})} \gamma^\mu A^\mu_{ab} \gamma_5 H_b^{(\bar{Q})} \right]
\]

\[
L_S = -\frac{3}{2} g_1 \epsilon^{\mu\lambda\nu\kappa} v_\kappa \text{Tr} \left[ \bar{S}_\mu A_\nu S_\lambda \right]
\]

- \( H_a^{(\bar{Q})} = [P_a^{*(\bar{Q})} \gamma_\mu - P_a^{(\bar{Q})} \gamma_5](1 - v)/2; \ v = (0, \vec{1}) \) is a pseudoscalar and vector charmed meson multiplet \( (D, D^*) \);

\( S_\mu = \sqrt{1/3}(\gamma_\mu + v_\mu)\gamma^5 B_6 + B^*_6 \) stands for the charmed baryon multiplet, with \( B_6 \) and \( B^*_6 \) corresponding to the \( J^P = 1/2^+ \) and \( J^P = 3/2^+ \) in \( 6_F \) flavor representation;

\( A_\mu \) is an axial-vector current, containing a pion chiral multiplet.
Eff. potentials, energy levels & wave-functions of the $\Sigma_c^{(*)}\bar{D}^*$ systems

$\Sigma_c\bar{D}^*$ (I=1/2, J=3/2)

$\Sigma_c\bar{D}^*$ (I=1/2, J=5/2)

$\Sigma_c\bar{D}^*$ (I=3/2, J=1/2)

$\Sigma_c\bar{D}^*$ (I=3/2, J=1/2)

- $P_c(4380)$ is a $\Sigma_c\bar{D}^*$ (I = 1/2, J = 3/2) molecule
- $P_c(4450)$ 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 $P_c(4380)$ and $P_c(4450)$, decaying into $\Delta(1232)J/\psi$ and $\Delta(1232)\eta_c$

- A rich pentaquark spectrum of states for the hidden-bottom ($\Sigma_bB^*,\Sigma_b^*B^*$), $B_c$-like ($\Sigma_cB^*,\Sigma_c^*B^*$) and ($\Sigma_b\bar{D}^*,\Sigma_b^*\bar{D}^*$) with well-defined (I,J) are predicted
Effective Hamiltonian for Pentaquarks

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

- \( S_{[QQ]} \) 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

Ahmed Ali (DESY, Hamburg)
Pentaquarks in the diquark model [Maiani et al., arxiv:1507.04980]

- $\Lambda_b(bud) \rightarrow \Lambda^+K^-$ decaying according to $\Lambda^+ \rightarrow J/\Psi + p$
- $\Lambda^+$ carry a unit of baryonic number and have the valence quarks $\Lambda^+ = \bar{c}cuud$

Assume the assignments

\[
\begin{align*}
\Lambda^+(3/2^-) &= \{\bar{c}[cq]_{s=1}[q'q'']_{s=1}, L = 0\} \\
\Lambda^+(5/2^+) &= \{\bar{c}[cq]_{s=1}[q'q'']_{s=0}, L = 1\}
\end{align*}
\]

Mass difference:

- Level spacing for $\Delta L = 1$ in light baryons; $\Lambda(1405) - \Lambda(1116) \sim 290$ MeV
- Light-light diquark mass difference for $\Delta S = 1$:
  \[ [qq']_{s=1} - [qq']_{s=0} = \Sigma_c(2455) - \Lambda_c(2286) \approx 170 \text{ MeV} \]

Orbital gap $\Lambda^+(3/2^-) - \Lambda^+(5/2^+)$ is thereby reduced to 120 MeV, more or less in agreement with data, 70 MeV
Pentaquark production mechanisms in $\Lambda_b^0 \rightarrow K^− J/\psi p$

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 $\Lambda_b$ hint that the mechanism in Fig. B is dynamically suppressed.
Flavor $SU(3)$ structure of Pentaquarks

Pentaquarks are of two types:

\[ P_u = \epsilon^{\alpha\beta\gamma} \bar{c}_\alpha [cu]_{\beta,s=0,1} [ud]_{\gamma,s=0,1} \]
\[ P_d = \epsilon^{\alpha\beta\gamma} \bar{c}_\alpha [cd]_{\beta,s=0,1} [uu]_{\gamma,s=1} \]

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

\[ P_A = \epsilon^{\alpha\beta\gamma} \left\{ \bar{c}_\alpha [cq]_{\beta,s=0,1} [q'q'']_{\gamma,s=0,L} \right\} = 3 \otimes \bar{3} = 1 \oplus 8 \]
\[ P_S = \epsilon^{\alpha\beta\gamma} \left\{ \bar{c}_\alpha [cq]_{\beta,s=0,1} [q'q'']_{\gamma,s=1,L} \right\} = 3 \otimes 6 = 8 \oplus 10 \]

For $S$ waves, the first and the second series have the angular momenta (multiplicity)

\[ P_A (L = 0) : \quad J = 1/2(2), \ 3/2(1) \]
\[ P_S (L = 0) : \quad J = 1/2(3), \ 3/2(3), \ 5/2(1) \]

Maiani et al. propose to assign $P(3/2^-)$ to the $P_A$ and $P(5/2^+)$ to the $P_S$ series of Pentaquarks

Ahmed Ali (DESY, Hamburg)
SU(3) based analysis of $\Lambda_b \to P^+ K^- \to (J/\psi p)K^-$

- 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:
  
  \[ H^{(3)}_W (\Delta I = 0, \Delta S = -1) \]

- With $M$ a nonet of SU(3) light mesons, $\langle P, M | H_W | \Lambda_b \rangle$ requires $P + M$ to be in $8 \oplus 1$ representation
- Recalling the SU(3) group multiplication rule
  
  \[
  8 \otimes 8 = 1 \oplus 8 \oplus 8 \oplus 10 \oplus 10 \oplus 27 \\
  8 \otimes 10 = 8 \oplus 10 \oplus 27 \oplus 35
  \]

  the decay $\langle P, M | H_W | \Lambda_b \rangle$ can be realized with $P$ in either an octet (8) or a decuplet (10)
- The discovery channel $\Lambda_b \to P^+ K^- \to J/\psi pK^-$ corresponds to $P$ in an octet (8)
Decays involving the decuplet (10) pentaquarks may also occur, if the light diquark pair having spin-0 \([ud]_{s=0}\) in \(\Lambda_b\) gets broken to produce a spin-1 light diquark \([ud]_{s=1}\)

\[
\Lambda_b \rightarrow \pi P_{10}^{(S=-1)} \rightarrow \pi (J/\psi \Sigma (1385))
\]

\[
\Lambda_b \rightarrow K^+ P_{10}^{(S=-2)} \rightarrow K^+ (J/\psi \Xi^- (1530))
\]

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.
Apart from $\Lambda_b(bud)$, several $b$-baryons, such as $\Xi^0_b(usb)$, $\Xi^-_b(dsb)$ 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:

$$\Xi^0_b(5794) \rightarrow K(J/\psi \Sigma(1385))$$

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 $P$ in Decuplet representation - Contd.

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

\[
\Omega_b(6049) \rightarrow \phi(J/\psi \Omega^- (1672)) \\
\Omega_b(6049) \rightarrow K(J/\psi \Xi (1387))
\]

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

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

- These transitions are on firmer theoretical footings, as the initial $[ss]$ diquark in $\Omega_b$ 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 $P(4380)$ and $P(4450)$
- 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 $Y(10888)$? Is it just $Y(5S)$? Does $Y_b(10890)$ still exist?
  - Line shape of multiquark resonances, such as $X(3872)$ and $P(4450)$ can be measured at $\bar{PANDA}$, which will help in understanding the dynamics
  - We look forward to decisive experimental results from Belle-II, LHC and $\bar{PANDA}$
Backup Slides
Hadroproduction of Bottomonia & Exotic States

- $\mu^+\mu^-$ channel: Common particle detection for bottomonia

![Graph showing CMS data for $\mu^+\mu^-$ events at $\sqrt{s} = 7$ TeV with $L = 3$ pb$^{-1}$ and $|\eta\mu| < 2.4$. Peaks at $1S$, $2S$, and $3S$. ]

Different final states (e.g. $\mu^+\mu^-\pi^+\pi^-$) allow for exotic searches.

[Ali, Hambrock, Wang, PRD 13]:

Acquire knowledge of bottomonia above hadronic thresholds (NRQCD, pNRQCD [Brambilla, Pineda, Soto, Vairo, NP 00]) to clarify the nature of observed states.
Hadroproduction of Bottomonia & Exotic States

- $\mu^+\mu^-$ channel: Common particle detection for bottomonia
- Above threshold difficult ($\text{BR}(\mu^+\mu^-)$ drops)
  - present research focused on $1S, 2S, 3S$
Hadroproduction of Bottomonia & Exotic States

- $\mu^+ \mu^-$ channel: Common particle detection for bottomonia
- Above threshold difficult ($BR(\mu^+ \mu^-) \text{ drops}$)
- Present research focused on $1S, 2S, 3S$
- Different final states (e.g. $\mu^+ \mu^- \pi^+ \pi^-$) allow for exotic searches
Hadroproduction of Bottomonia & Exotic States

- $\mu^+ \mu^-$ channel: Common particle detection for bottomonia
- Above threshold difficult ($\text{BR}(\mu^+ \mu^-)$ drops)
  - present research focused on $1S, 2S, 3S$
- Different final states (e.g. $\mu^+ \mu^- \pi^+ \pi^-$) allow for exotic searches

[Ali, Hambrock, Wang, PRD 13]:
Acquire knowledge of bottomonia above hadronic thresholds
(NRQCD, pNRQCD [Brambilla, Pineda, Soto, Vairo, NP 00])
clarify nature of observed states
NRQCD Framework

\[ \sigma_N(p\bar{p}(p) \rightarrow Y + X) \]
NRQCD Framework

\[
\sigma_N(p\bar{p}(p) \rightarrow Y + X) = \int dx_1 dx_2 \sum_{i,j} f_i(x_1)f_j(x_2)
\]
NRQCD Framework

\[\sigma_N(p\bar{p}(p) \rightarrow Y + X) = \int dx_1 dx_2 \sum_{ij} f_i(x_1)f_j(x_2) \times \hat{\sigma}(ij \rightarrow \bar{b}b + X)\]
NRQCD Framework

\[ \sigma_N(p\bar{p}(p) \rightarrow Y + X) = \int dx_1 dx_2 \sum_{ij} f_i(x_1)f_j(x_2) \times \hat{\sigma}(ij \rightarrow \langle \bar{b}b \rangle_N + X) \]
NRQCD Framework

\[
\sigma_N(p\bar{p}(p) \rightarrow Y + X) = \int dx_1 dx_2 \sum_{ij} f_i(x_1)f_j(x_2) \times \hat{\sigma}(ij \rightarrow \langle \bar{b}b \rangle_N + X) \langle O[N] \rangle
\]
NRQCD Framework

$$\sigma_N(p\bar{p}(p) \rightarrow Y + X) = \int dx_1 dx_2 \sum_{i,j} f_i(x_1)f_j(x_2) \times \sigma(ij \rightarrow \langle \bar{b}b \rangle_N + X) \langle O[N] \rangle$$

- partonic channels (include NLO for CS):
  - $gg \rightarrow Y[[3 S^1_1] + g$, $gg \rightarrow Y^{[1 S^8_0, 3 S^8_1]} + g$
  - $gq \rightarrow Y^{[1 S^8_0, 3 S^8_1]} + q$, $q\bar{q} \rightarrow Y^{[1 S^8_0, 3 S^8_1]} + g$

- calculate $p_t$ distribution - take $p_t > 3$ GeV $\rightarrow$ avoid soft gluon resummation
  - $p_Y = \left( \sqrt{M^2_Y + p_t^2 \cosh(y)}, p_t, 0, \sqrt{M^2_Y + p_t^2 \sinh(y)} \right)$

Ahmed Ali (DESY, Hamburg)
**LD-Matrix-Elements & BRs**

- **CS LDMEs** from potential models via VRW (well-known)
- Currently **CO LDMEs** not known → large uncertainties if contribution sizable
- Model dependence enters via $B(\Upsilon(6S) \rightarrow \Upsilon(nS)\pi\pi)$ estimate

---

**CS LDMEs:**

- at NLO
  - $|R(0)|^2_{\Upsilon(5S)} = 2.37$ GeV$^3$
  - $|R(0)|^2_{\Upsilon(6S)} = 1.02$ GeV$^3$
- $<O^H 3S_1^8 >= 3|R(0)|^2/(4\pi)$

**CO LDMEs from $\Upsilon(3S)$:**

- Error estimate (including correlation):
  - Lower bound: no CO
  - Upper bound: full CO

We find

- $<O^H 1S_0^8 >= (-0.95 \pm 0.38)10^{-2}$ GeV$^3$
- $<O^H 3S_1^8 >= (3.46 \pm 0.21)10^{-2}$ GeV$^3$

$\chi^2$/d.o.f. = 4.3/5

---

**Branching Ratios:**

| Branching Ratio | Value |
|-----------------|-------|
| $B(\Upsilon(5S) \rightarrow \Upsilon(1S)\pi^+\pi^-)$ | $(0.53 \pm 0.06)$% |
| $B(\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-)$ | $(0.78 \pm 0.13)$% |
| $B(\Upsilon(5S) \rightarrow \Upsilon(3S)\pi^+\pi^-)$ | $(0.48 \pm 0.18)$% |
| $B(\Upsilon(6S) \rightarrow \Upsilon(1S)\pi^+\pi^-)$ | $\approx 0.4\%$ |
| $B(\Upsilon(6S) \rightarrow \Upsilon(2S)\pi^+\pi^-)$ | $(0.4 - 1.2)$% |
| $B(\Upsilon(6S) \rightarrow \Upsilon(3S)\pi^+\pi^-)$ | $(1.2 - 2.5)$% |
| $B(\Upsilon(1S) \rightarrow \mu^+\mu^-)$ | $(2.48 \pm 0.05)$% |
| $B(\Upsilon(2S) \rightarrow \mu^+\mu^-)$ | $(1.93 \pm 0.17)$% |
| $B(\Upsilon(3S) \rightarrow \mu^+\mu^-)$ | $(2.18 \pm 0.21)$% |

---

**Data @ $\Upsilon(5S)$**

Rescattering model => **data**

---

Ahmed Ali (DESY, Hamburg)
$p\bar{p}(p) \rightarrow Y(5S, 6S) \rightarrow (Y(nS) \rightarrow \mu^+\mu^-)\pi^+\pi^- \text{ in pb}$

[Ali, Hambrock, Wang, PRD 13]

LHCb (7 TeV) \hspace{1cm} ATLAS & CMS (7 TeV)

|       | $n = 1$  | $n = 2$  | $n = 3$  | $n = 1$  | $n = 2$  | $n = 3$  |
|-------|----------|----------|----------|----------|----------|----------|
| Tevatron | [0.18,0.98] | [0.18,1.35] | [0.09,1.03] | [0.06,0.57] | [0.04,1.38] | [0.15,3.26] |
| LHC 7   | [0.86,5.26] | [0.86,6.74] | [0.44,5.56] | [0.29,3.13] | [0.21,7.57] | [0.72,17.9] |
| LHCb 7  | [0.20,1.48] | [0.20,1.89] | [0.10,1.56] | [0.07,0.89] | [0.05,2.16] | [0.17,5.13] |
| LHC 8   | [0.99,6.17] | [0.99,7.89] | [0.51,6.52] | [0.34,3.67] | [0.25,8.87] | [0.83,21.0] |
| LHCb 8  | [0.25,1.78] | [0.25,2.28] | [0.13,1.88] | [0.08,1.08] | [0.06,2.61] | [0.20,6.19] |
| LHC 14  | [1.79,11.7] | [1.79,14.9] | [0.92,12.3] | [0.61,7.02] | [0.45,17.0] | [1.50,40.2] |
| LHCb 14 | [0.52,3.70] | [0.52,4.74] | [0.27,3.91] | [0.18,2.25] | [0.13,5.43] | [0.43,12.9] |
Search for $X_b$ decaying into $Y(1S)\pi^+\pi^-$

[CMS Collaboration: BPH11016 (Kai Feng Chen)]

- Exclusion limits as a function of the $X_b$ mass at 95% C.L.

For $X_b = Y_b(10876)$, the limit is: $\frac{\sigma(pp \rightarrow X_b \rightarrow Y(1S)\pi^+\pi^-)}{\sigma(pp \rightarrow Y(2S) \rightarrow Y(1S)\pi^+\pi^-)} < 0.02$.

Using the CMS measurement $\sigma(pp \rightarrow Y(2S)X)\mathcal{B}(Y(2S) \rightarrow \mu^+\mu^-) = 1.55\text{nb}$, we get $\sigma(pp \rightarrow X_b \rightarrow Y(1S)\pi^+\pi^-)\mathcal{B}(Y(1S) \rightarrow \mu^+\mu^-) < 7.1\text{ pb}$.

This is typically $\mathcal{O}(10)$ away from theoretical estimates.

Ahmed Ali (DESY, Hamburg)