Heavy quark exotic mesons and possible tetraquarks

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- $cs\bar{c}\bar{s}$ states
- $Q_1Q_2\bar{Q}_3\bar{Q}_4$ states
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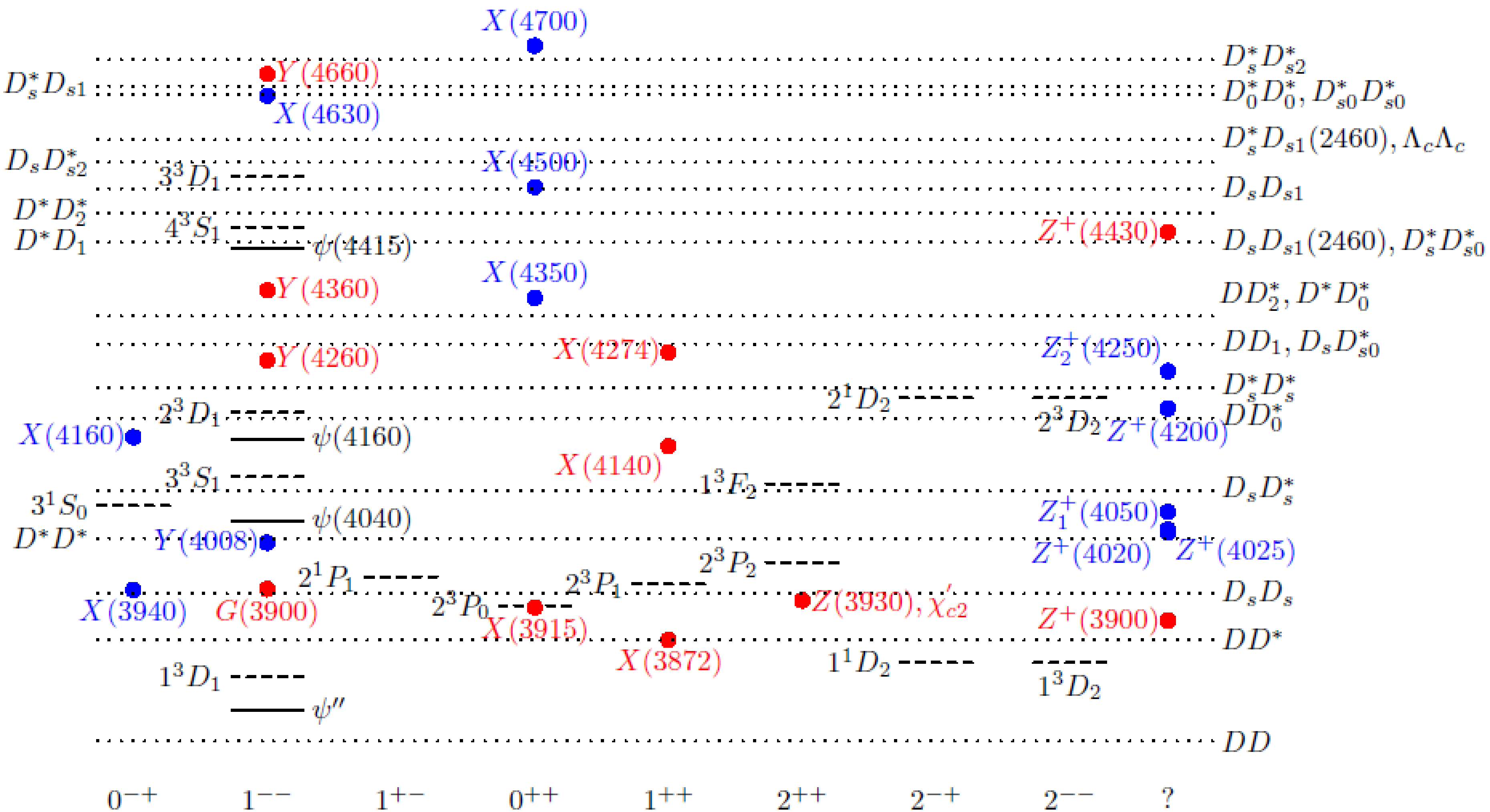
Exotic mesons

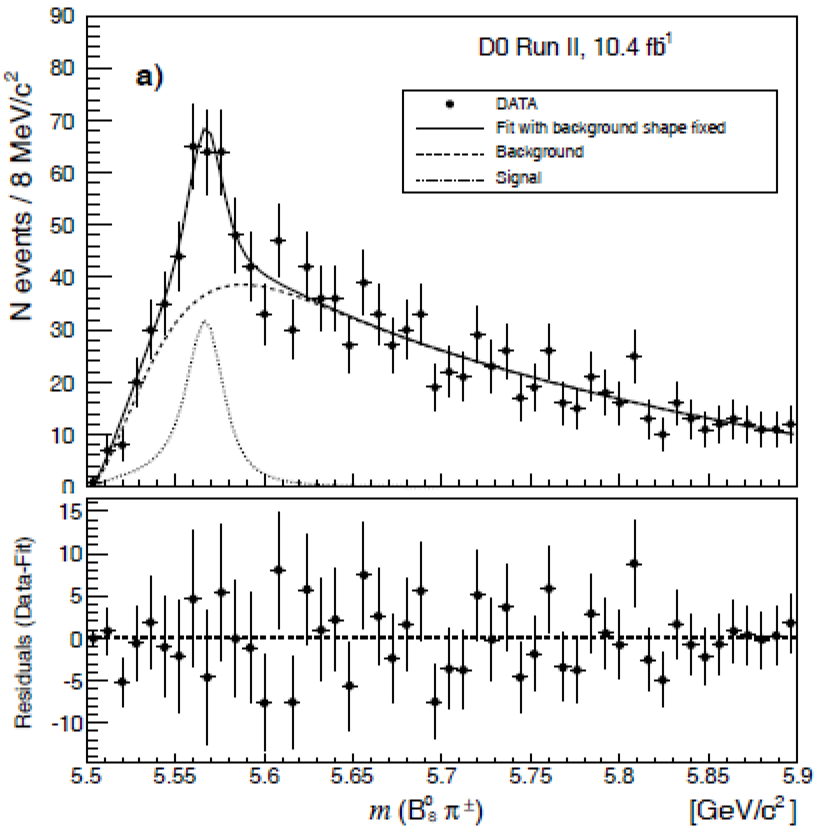


Exotic mesons

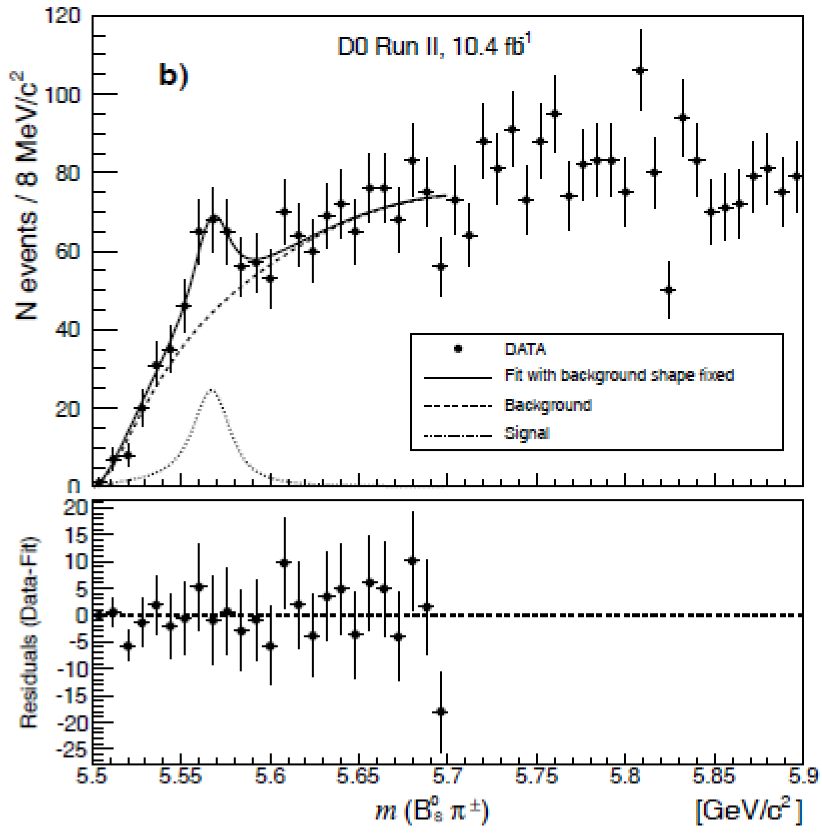
- Charged Z: ~3900 (BES3), 4020 (BES3), 4025(BES3), 4050(Belle), 4200(Belle), 4250(Belle), 4430(Belle, LHCb)
- X and Y: charmonia interpretation not excluded
- Z: at least 4 quarks, molecules? tetraquark? Cases to identify tetraquark possible

X(5568) in $B_s^0\pi^\pm$

- D0 (1602.07588)



a) after the cone cut



b) without the cone cut

X(5568) in $B_s^0\pi^\pm$

$$m = 5567.8 \pm 2.9\,(\text{stat})^{+0.9}_{-1.9}\,(\text{syst})\ \text{MeV}/c^2 \text{ and } \Gamma = 21.9 \pm 6.4\,(\text{stat})^{+5.0}_{-2.5}\,(\text{syst})\ \text{MeV}/c^2.$$

- Quark content bsud, a possible tetraquark (BK: ~200 MeV higher & W-T term=0; molecule not favored)
- If exists, can be a partner of the non-confirmed $D_{sJ}(2632)$

  (a tetraquark assignment can naturally interpret its abnormal decay into DK & $D_s\eta$ from PRD70,094009)
- Unfortunately, difficult to understand both low mass (many papers) and its production

  (1603.03250 , Y. Jin, S.Y. Li, S.Q. Li)
- LHCb does not confirm it (no formal paper)
- A real challenge for theorists?

Other tetraquark systems exist?

- Here:

(1) $Q_1Q_2\bar{Q}_3\bar{Q}_4$

Molecule $\rightarrow$ tetraquark since only short-range gluon-exchange contributes

(2) $cs\bar{c}\bar{s}$

LHCb observed 4 states in J/ψϕ channel

Simple color-magnetic interaction(CMI) model

X's in J/ψ+φ ($c\bar{c}$+$s\bar{s}$)

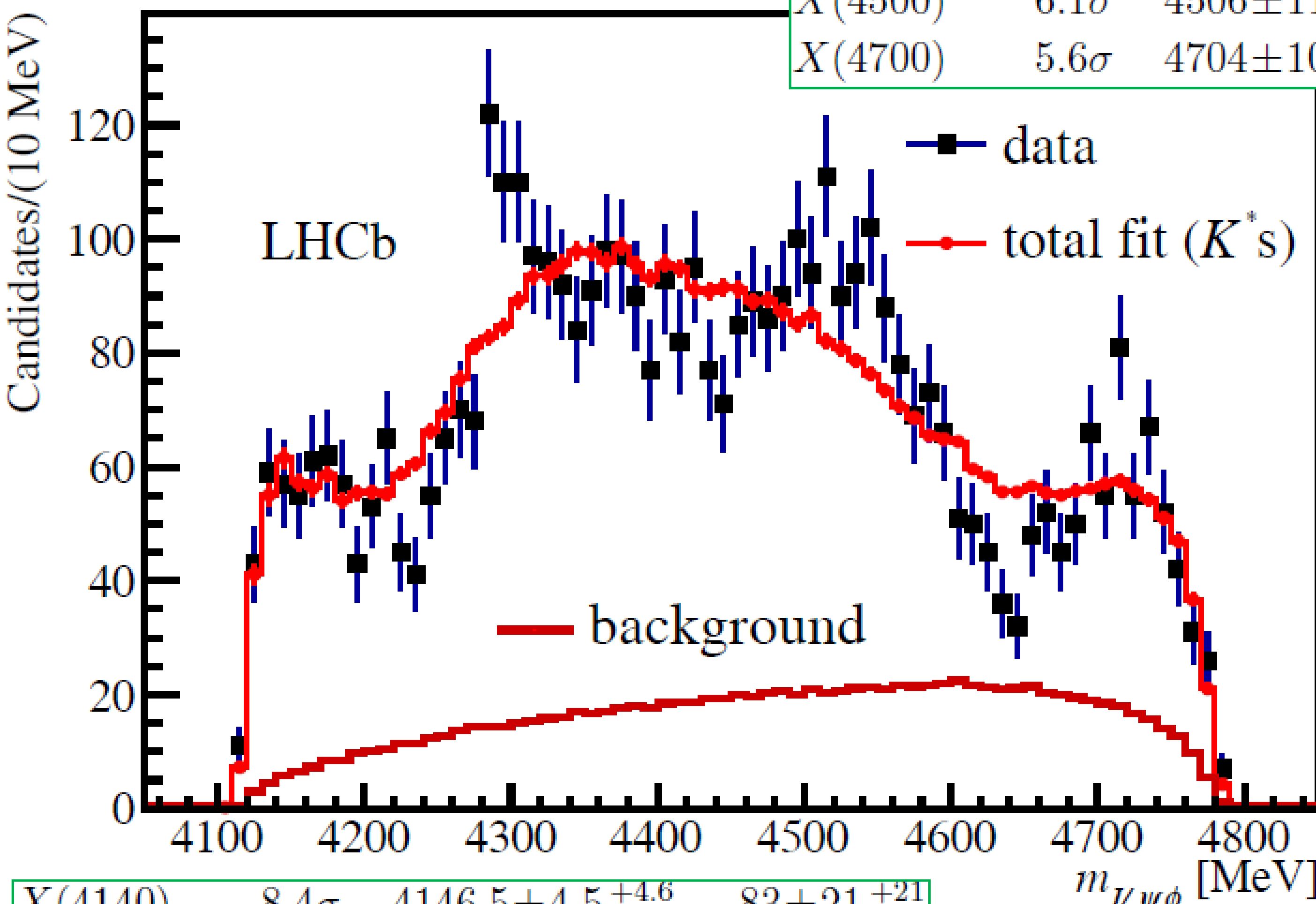
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF[PRL102-242002;1101.6058]
				$e^+e^- \to e^+e^-(\phi J/\psi)$	~~Belle~~[PRL104-112004]
				$B \to K(\phi J/\psi)$	~~Belle~~[CPC34-615]
				$B \to K(\phi J/\psi)$	~~LHCb~~[PRD85-091103]
				$B \to K(\phi J/\psi)$	~~Babar~~[PRD91,012003]
	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1}_{-8}$		$B^+ \to J/\psi \phi K^+$	D0[PRD89,012004]
	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$		$p\bar{p} \to J/\psi\phi + others$	D0[PRL115,232001]
	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$		$B^+ \to J/\psi \phi K^+$	CMS[PLB734,261]
				$e^+e^- \to \gamma\phi J/\phi$	~~BESIII~~[PRD91,032002]

$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF[1101.6058]
				$B \to K(\phi J/\psi)$	~~Babar~~[PRD91,012003]

$X(4350)$	$4350.6^{+4.6}_{-5.1} \pm 0.7$	$13^{+18}_{-9} \pm 4$	$0/2^+$	$\gamma\gamma \to J/\psi\phi$	Belle[PRL104,112004]
	4328.5 ± 12.0			$B^+ \to J/\psi \phi K^+$	D0[PRD89,012004]
$??(4315)$	$4313.8 \pm 5.3 \pm 7.3$	$38^{+30}_{-15} \pm 16$	$??$	$B^+ \to J/\psi \phi K^+$	CMS[PLB734,261]

LHCb new data: 1606.07895

$X(4500)$	6.1σ	$4506\pm11\,^{+12}_{-15}$	$92\pm21\,^{+21}_{-20}$
$X(4700)$	5.6σ	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$



0^{++} resonances

Broader 4140

$X(4140)$	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$
$X(4274)$	6.0σ	$4273.3\pm8.3\,^{+17.2}_{-\ \ 3.6}$	$56\pm11\,^{+\ 8}_{-11}$

1^{++}

Theoretical interpretations

- Charmonium? Open charm decay channels dominate
- Two 1^{++} states X(4140) and X(4274): not hybrids (1^{-+})
- X(4140) as 0^{++} or 2^{++} $D_s^{*+}D_s^{*-}$ molecule not supported, but may be a cusp due to $D_s^{\pm}D_s^{*\mp}$
- X(4274) molecule and cusp not supported
- Dynamically generated resonances?
- Coupled channel effects?

$cs\bar{c}\bar{s}$ tetraquark?

(1) QSR, 1606.03179, Chen et al.:

X(4500) and X(4700) as D-wave 0^{+-} tetraquarks

(2) QSR, 1606.05872,1607.00701, Wang:

X(4500): first radially excited $[cs]_{1^+}[\bar{c}\bar{s}]_{1^+}$

X(4700): ground $[cs]_{1^-}[\bar{c}\bar{s}]_{1^-}$

X(4140): diquark-antidiquark not favored

(3) Diquark-antidiquark model, 1607.02405, Maiani et al.:

X(4140), X(4274): 1S multiplet;

X(4500), X(4700): 2S multiplet;

J^PC of 4274=1^++?

$cs\bar{c}\bar{s}$ tetraquark?

(4) Diquark-antidiquark, 1607.02799, Zhu:

X(4140), X(4274): $J^P = 1^+ \; \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})c\bar{c}$

X(4500): $J^P = 0^+$ radially excited $\frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})c\bar{c}$

X(4700): $J^P = 0^+$ radially excited $\frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})c\bar{c}$

(5) Rescattering mechanism, 1607.01385, Liu:

X(4140), X(4700): OK

X(4274), X(4500): genuine resonances, 4274 as $\chi_{c1}(3P)$

(6) Quark potential model, 1607.05570, Lu and Dong:

X(4140): ground tetraquark

X(4700): 2S excited tetraquark

X(4500): $[cs]_{2S,0^+}[\bar{c}\bar{s}]_{1S,0^+}$

X(4274): $\chi_{c1}(3P)$

$cs\bar{c}\bar{s}$ tetraquarks in CMI model

- Stancu in 0906.2485:

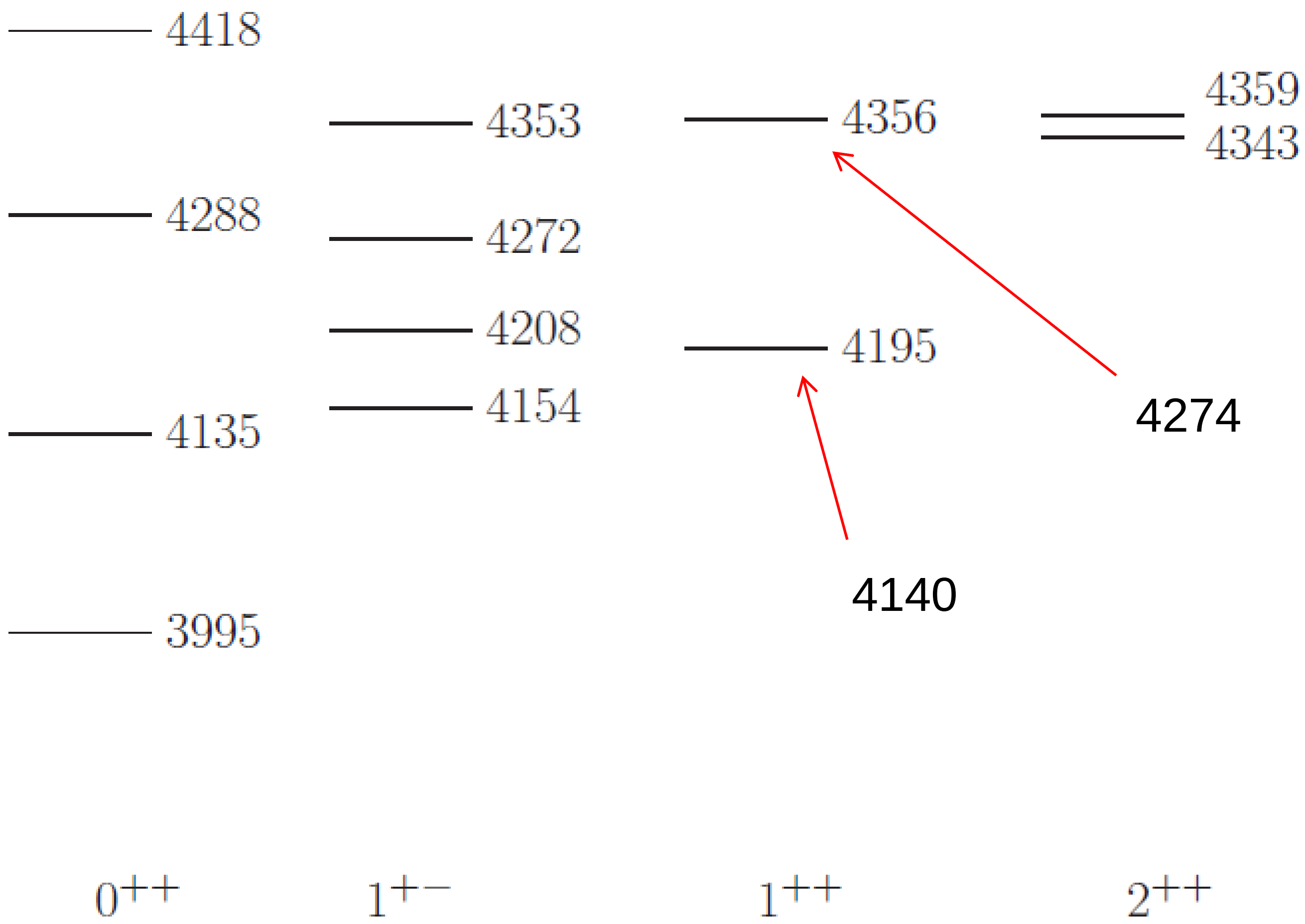
$$H = \sum_i m_i + H_{CM} = \sum_i m_i - \sum_{i<j} C_{ij} \widetilde{\lambda}_j \cdot \widetilde{\lambda}_j \sigma_i \cdot \sigma_j$$

$$M = \sum_i m_i + \langle H_{CM} \rangle$$

effective m_i contains kinetic energy, Coulomb, confinement

- Diagonalizing the basis $(s\bar{s})_{1_c}(c\bar{c})_{1_c}$ and $(s\bar{s})_{8_c}(c\bar{c})_{8_c}$ with various spin combinations to get $\langle H_{CM} \rangle$

$cs\bar{c}\bar{s}$ tetraquarks in CMI model



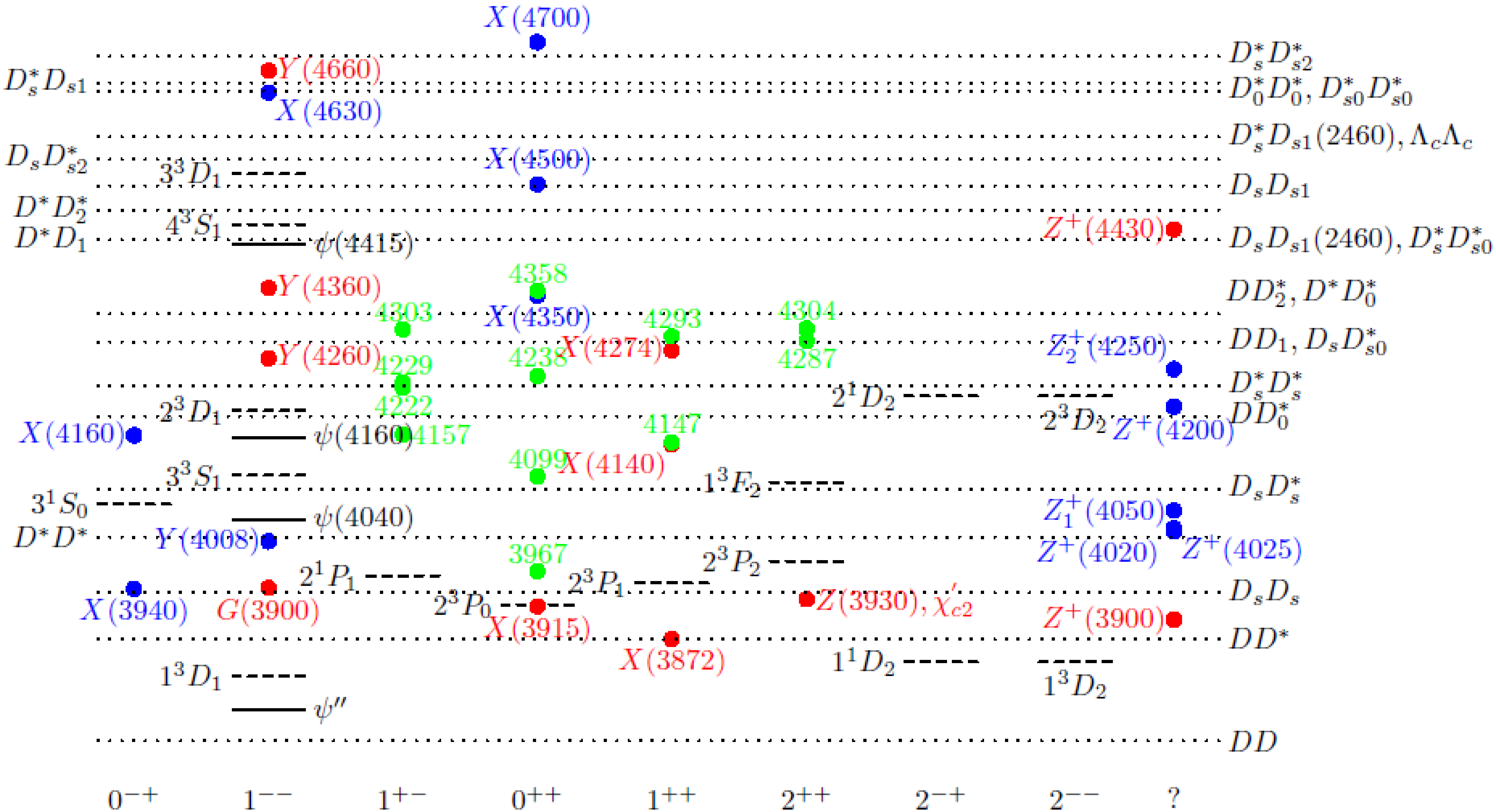
$cs\bar{c}\bar{s}$ tetraquarks in CMI model

- We use diquark-antidiquark picture, diagonalize $(cs)_{\bar{3}_c}(\bar{c}\bar{s})_{3_c}$ and $(cs)_{6_c}(\bar{c}\bar{s})_{\bar{6}_c}$ with various combinations to get $\langle H_{CM} \rangle$
- Because effective mass not well determined, several methods to estimate the tetraquark masses and check consistency (coupling constants from hadron masses)
- One of them: if we assume Y(4140) as the lowest 1^{++} tetraquark, the spectrum is estimated with

$$M - M_{ref} = \langle H_{CM} \rangle - \langle H_{CM} \rangle_{ref}$$

(Used to estimate Tcc mass in PLB721,56 Hyodo et al.)

$cs\bar{c}\bar{s}$ tetraquarks in CMI model



$cs\bar{c}\bar{s}$ tetraquarks in CMI model

- Y(4274) as a tetraquark OK;
- X(4350) observed by Belle (also D0 and CMS?) probably a scalar state;
- More ground tetraquarks are possible
- X(4500) and X(4700) not ground tetraquarks
- Also: obtained $\langle H_{CM} \rangle$ not always consistent with Stancu’s picture. Should be?

$Q_1 Q_2 \bar{Q}_3 \bar{Q}_4$ tetraquarks?

- Pauli principle may work
  (again diquark-antidiquark picture)

System	J^{PC}	$\langle H_{CM} \rangle$	Eigenvalue	Eigenvector	$(\Upsilon\Upsilon)/(\psi\psi)$
$(bb\bar{b}\bar{b})$	2^{++}	32.0	32.0	1	18920
	1^{+-}	0.0	0.0	1	18889
	0^{++}	$\begin{pmatrix} -16.0 & 58.8 \\ 58.8 & 24.0 \end{pmatrix}$	$\begin{bmatrix} 66.1 \\ -58.1 \end{bmatrix}$	$\begin{bmatrix} (0.58, 0.81) \\ (-0.81, 0.58) \end{bmatrix}$	$\begin{bmatrix} 18955 \\ 18831 \end{bmatrix}$
$(cc\bar{c}\bar{c})$	2^{++}	56.5	56.5	1	6194
	1^{+-}	0	0	1	6137
	0^{++}	$\begin{pmatrix} -28.3 & 103.9 \\ 103.9 & 42.4 \end{pmatrix}$	$\begin{bmatrix} 116.8 \\ -102.6 \end{bmatrix}$	$\begin{bmatrix} (0.58, 0.81) \\ (-0.81, 0.58) \end{bmatrix}$	$\begin{bmatrix} 6254 \\ 6035 \end{bmatrix}$

Reference mass

$Q_1Q_2\bar{Q}_3\bar{Q}_4$ tetraquarks?

Reference masses

$bb\bar{c}\bar{c}$ and $cc\bar{b}\bar{b}$

J^P	$\langle H_{CM}\rangle$	Eigenvalue	Eigenvector	(B_cB_c)
2^+	39.7	39.7	1	12697
1^+	4.5	4.5	1	12661
0^+	$\begin{pmatrix}-13.1 & 64.7\\ 64.7 & 33.2\end{pmatrix}$	$\begin{bmatrix}78.7\\ -58.6\end{bmatrix}$	$\begin{bmatrix}(0.58, 0.82)\\ (-0.82, 0.58)\end{bmatrix}$	$\begin{bmatrix}12736\\ 12598\end{bmatrix}$

$bb\bar{b}\bar{c}$ and $cb\bar{b}\bar{b}$

J^P	$\langle H_{CM}\rangle$	Eigenvalue	Eigenvector	(ΥB_c)
2^+	33.6	33.6	1	15806
1^+	$\begin{pmatrix}0.0 & -1.1 & 2.4\\ -1.1 & -18.4 & -35.6\\ 2.4 & -35.6 & 7.6\end{pmatrix}$	$\begin{bmatrix}32.7\\ -0.2\\ -43.3\end{bmatrix}$	$\begin{bmatrix}(0.07, -0.57, 0.82)\\ (1.00, 0.05, -0.06)\\ (0.01, -0.82, -0.57)\end{bmatrix}$	$\begin{bmatrix}15805\\ 15773\\ 15729\end{bmatrix}$
0^+	$\begin{pmatrix}-16.8 & 61.7\\ 61.7 & 25.2\end{pmatrix}$	$\begin{bmatrix}69.4\\ -61.0\end{bmatrix}$	$\begin{bmatrix}(0.58, 0.81)\\ (-0.81, 0.58)\end{bmatrix}$	$\begin{bmatrix}15842\\ 15712\end{bmatrix}$

$cc\bar{c}\bar{b}$ and $bc\bar{c}\bar{c}$

J^P	$\langle H_{CM}\rangle$	Eigenvalue	Eigenvector	(ψB_c)
2^+	45.9	45.9	1	9443
1^+	$\begin{pmatrix}0.0 & -7.5 & 16.0\\ -7.5 & -12.3 & -48.6\\ 16.0 & -48.6 & 16.8\end{pmatrix}$	$\begin{bmatrix}58.2\\ -4.9\\ -48.8\end{bmatrix}$	$\begin{bmatrix}(0.29, -0.56, 0.77)\\ (0.96, 0.23, -0.18)\\ (0.08, -0.79, -0.61)\end{bmatrix}$	$\begin{bmatrix}9455\\ 9392\\ 9348\end{bmatrix}$
0^+	$\begin{pmatrix}-22.9 & 84.3\\ 84.3 & 34.4\end{pmatrix}$	$\begin{bmatrix}94.7\\ -83.3\end{bmatrix}$	$\begin{bmatrix}(0.58, 0.81)\\ (-0.81, 0.58)\end{bmatrix}$	$\begin{bmatrix}9492\\ 9314\end{bmatrix}$

$Q_1Q_2\bar{Q}_3\bar{Q}_4$ tetraquarks?

Reference masses

$bc\bar{b}\bar{c}$

J^{PC}	$\langle H_{CM} \rangle$	Eigenvalue	Eigenvector	$(\Upsilon\psi)$	(B_cB_c)
2^{++}	$\begin{pmatrix} 40.9 & 4.8 \\ 4.8 & 37.5 \end{pmatrix}$	$\begin{bmatrix} 44.3 \\ 34.1 \end{bmatrix}$	$\begin{bmatrix} (0.82, 0.58) \\ (0.58, -0.82) \end{bmatrix}$	$\begin{bmatrix} 12557 \\ 12547 \end{bmatrix}$	$\begin{bmatrix} 12701 \\ 12691 \end{bmatrix}$
0^{++}	$\begin{pmatrix} -108.1 & -9.8 & 9.6 & 73.0 \\ -9.8 & 26.4 & 73.0 & 0 \\ 9.6 & 73.0 & -22.1 & -3.9 \\ 73.0 & 0 & -3.9 & -52.8 \end{pmatrix}$	$\begin{bmatrix} 79.2 \\ -2.2 \\ -73.2 \\ -160.5 \end{bmatrix}$	$\begin{bmatrix} (-0.02, 0.81, 0.58, -0.03) \\ (0.57, -0.01, 0.08, 0.81) \\ (0.08, -0.58, 0.80, -0.14) \\ (0.82, 0.09, -0.12, -0.56) \end{bmatrix}$	$\begin{bmatrix} 12592 \\ 12511 \\ 12440 \\ 12352 \end{bmatrix}$	$\begin{bmatrix} 12736 \\ 12655 \\ 12584 \\ 12496 \end{bmatrix}$
1^{++}	$\begin{pmatrix} 14.5, -42.1 \\ -42.1, -15.3 \end{pmatrix}$	$\begin{bmatrix} 44.3 \\ -45.1 \end{bmatrix}$	$\begin{bmatrix} (-0.82, 0.58) \\ (0.58, 0.82) \end{bmatrix}$	$\begin{bmatrix} 12557 \\ 12468 \end{bmatrix}$	$\begin{bmatrix} 12701 \\ 12612 \end{bmatrix}$
1^{+-}	$\begin{pmatrix} -58.5 & 4.8 & -15.3 & 13.0 \\ 4.8 & -2.3 & 13.0 & -6.1 \\ -15.3 & 13.0 & 3.1 & 42.1 \\ 13.0 & -6.1 & 42.1 & -19.9 \end{pmatrix}$	$\begin{bmatrix} 36.7 \\ -0.3 \\ -36.6 \\ -77.3 \end{bmatrix}$	$\begin{bmatrix} (0.04, -0.17, -0.80, -0.57) \\ (0.01, 0.96, 0.00, -0.29) \\ (0.68, 0.17, -0.42, 0.59) \\ (-0.74, 0.16, -0.43, 0.50) \end{bmatrix}$	$\begin{bmatrix} 12550 \\ 12513 \\ 12476 \\ 12436 \end{bmatrix}$	$\begin{bmatrix} 12694 \\ 12657 \\ 12620 \\ 12580 \end{bmatrix}$

Lowest state is expected to be J=0 !

Summary

- Lowest $Q_1Q_2\bar{Q}_3\bar{Q}_4$ tetraquarks are scalars with attractive CMI
- Assignment for X(4140), X(4274), X(4350) as ground tetraquarks is consistent
- More tetraquark states expected to be announced

Thank you very much for your attention!