Multiquark systems by a quark model

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work with
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Mini-workshop on exotic hadrons from LHCb@Tokai 19 Feb. 2016

Contents

1. Recent LHCb experiments show us that there is two resonances in the N-J/ψ channel, whose spin and parity are most probably *(3/2- 5/2+)*, or maybe *(3/2+ 5/2-)*, *(5/2+ 3/2-)*.
   - In this talk, we will show that there is a state which gains a large attraction from the color-magnetic interaction in the $uudc\bar{c}$ *I(JP)=1/2(3/2-)* channel.
   - This state may be seen as a resonance in the N-J/ψ channel.
2. We also found that there is an equally or more attractive state in the channel with strangeness, $udsc\bar{c}$, *I(JP)=0(1/2-)*.
   - We would like to discuss the possibility to find it as a resonance in the Λ-J/ψ or Λ-η_c channels.
3. We also would like to show a brief summary on the possibility that the 1++ $c\bar{c}$-component of the X(3872) is seen in the X (3872) radiative decay in the LHCb experiments.

Today's menu No.1

qqqc$\bar{c}$ pentaquarks are investigated by a simple quark cluster model

- The model can give the single baryon and meson spectra
- c$\bar{c}_8$-qqq$_8$ state can be attractive.
- There may be a $\Sigma_c^* \overline{D}(\frac{3}{2}^-)$ bound state,
- which mixes with $\Lambda_c \overline{D}^*$ strongly, but with $N J/\psi$ weakly.
- Scattering calc suggests rich spectrum.

Quark Model

- hamiltonian

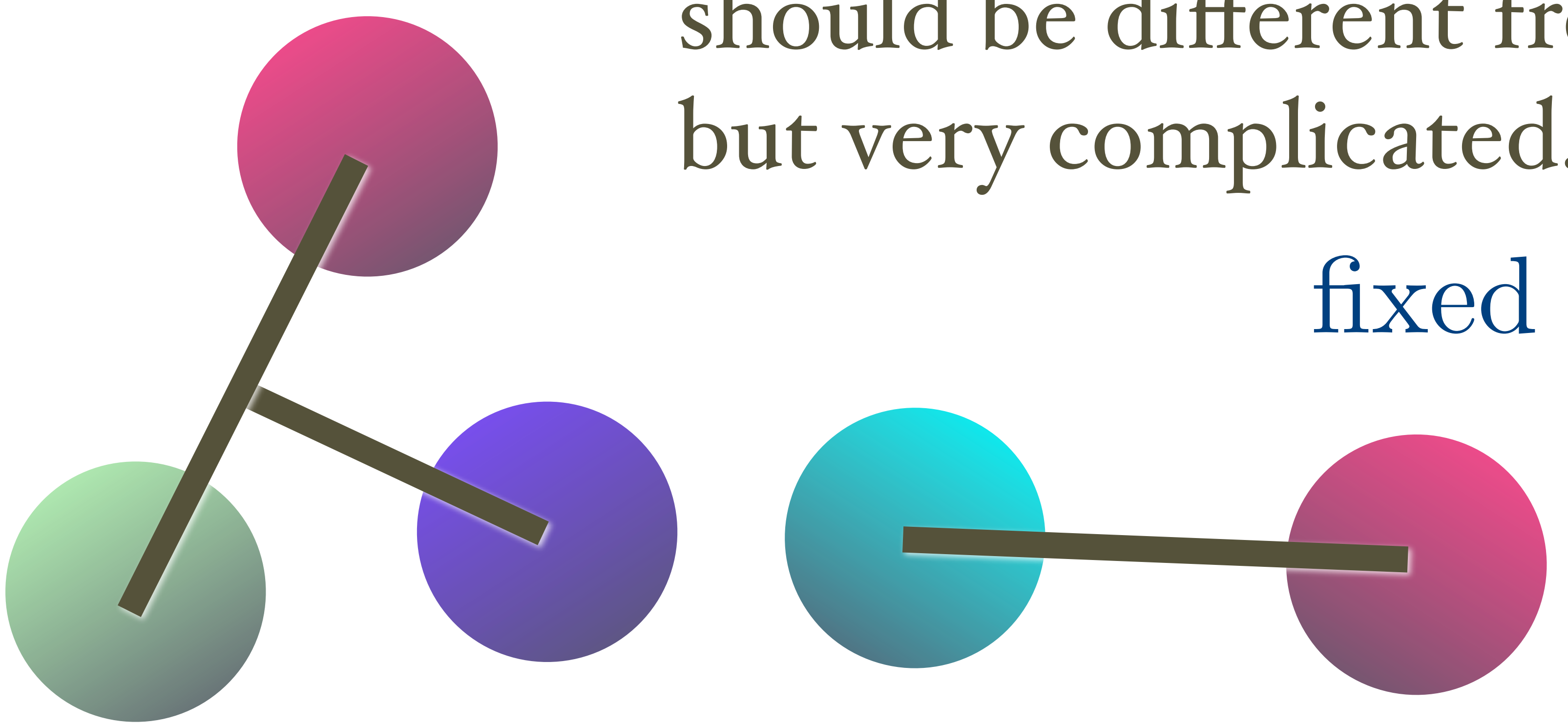
$$H = K + V^{\rm Conf} + V^{\rm Coul} + V^{\rm CEI} + V^{\rm CMI}$$

- orbital configuration: $(0s)^n$

$\phi(r, b)$: gaussian with size parameter b

should be different from each other,
but very complicated. So, as a first step,

fixed b for all flavors



Quark Model (simple version)

- hamiltonian

$$H = K + V^{\mathrm{Conf}} + V^{\mathrm{Coul}} + V^{\mathrm{CEI}} + V^{\mathrm{CMI}}$$

$$V^{\mathrm{Conf}} = -a_c \sum (\lambda_i \cdot \lambda_j) r_{ij}$$

$\xi_{qc} \neq \xi_{q\bar{c}}$

b

$$V^{\mathrm{Coul}} = -\sum \frac{(\lambda_i \cdot \lambda_j)}{4} \frac{\alpha_s}{r_{ij}}$$

Mqqq, Mq$\bar{\mathrm{q}}$

$$V^{\mathrm{CEI}} = \sum (\lambda_i \cdot \lambda_j) \alpha_s \zeta_{qq'} \delta^3(\vec{r}_{ij})$$

$$V^{\mathrm{CMI}} = -\sum (\lambda_i \cdot \lambda_j)(\sigma_i \cdot \sigma_j) \alpha_s \xi_{qq'} \delta^3(\vec{r}_{ij})$$

hfs

Baryons

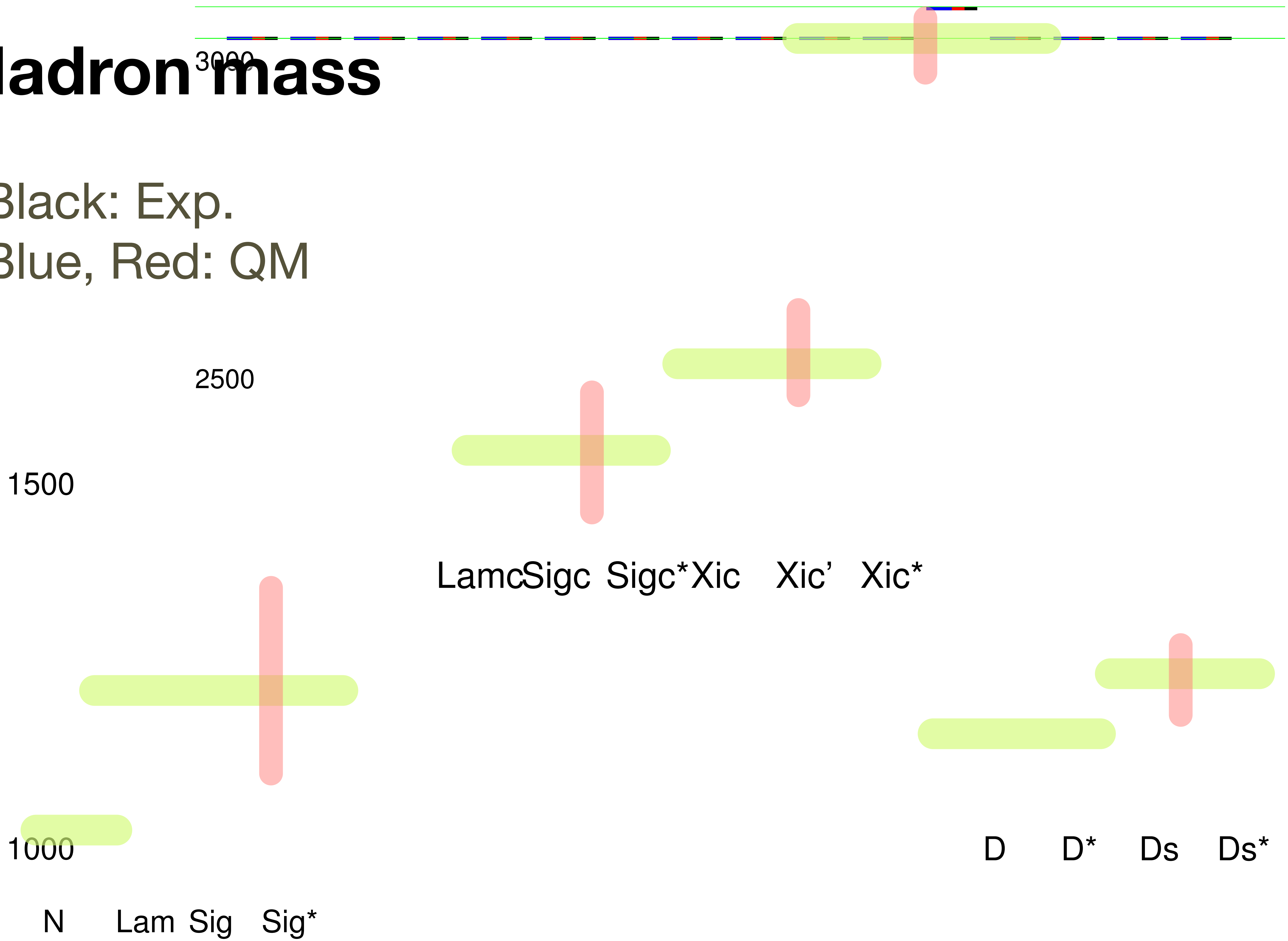
Baryon	CMI	av mass	model A	model B
N	-8	939	937.04	937.04
Λ	-8	1116	1113.80	1113.80
Σ	$\frac{8}{3}-\frac{32}{3}\xi_s$	1193	1193.78	1193.78
Σ^*	$\frac{8}{3}+\frac{16}{3}\xi_s$	1385	1385.19	1385.19
Λ_c	-8	2286	2288.34	2288.34
Σ_c	$\frac{8}{3}-\frac{32}{3}\xi_c$	2454	2452.91	2425.23
Σ_c^*	$\frac{8}{3}+\frac{16}{3}\xi_c$	2518	2517.44	2531.28
Ξ_c	$-8\xi_s$	2469	2486.10	2488.79
Ξ_c'	$-\frac{8}{3}(2\xi_c+2\xi_{cs}-\xi_s)$	2577	2560.09	2545.11
Ξ_c-Ξ_c'	$-\frac{8\sqrt{3}}{3}(\xi_c-\xi_{cs})$			
Ξ_c^*	$\frac{8}{3}(\xi_s+\xi_c+\xi_{cs})$	2646	2645.90	2652.05

Mesons

Meson	CMI	av mass	model A	model B
η_c	$-16\xi_{cc}$	2984	2983.60	2983.60
J/ψ	$\frac{16}{3}\xi_{cc}$	3097	3096.92	3096.92
$\overline{D}$	$-16\xi_c$	1867	1908.10	1866.58
$\overline{D}^*$	$\frac{16}{3}\xi_c$	2009	1994.14	2007.98
D_s	$-16\xi_{cs}$	1968	1964.32	1968.94
D_s^*	$\frac{16}{3}\xi_{cs}$	2112	2114.28	2112.74

Hadron mass

Black: Exp.
Blue, Red: QM



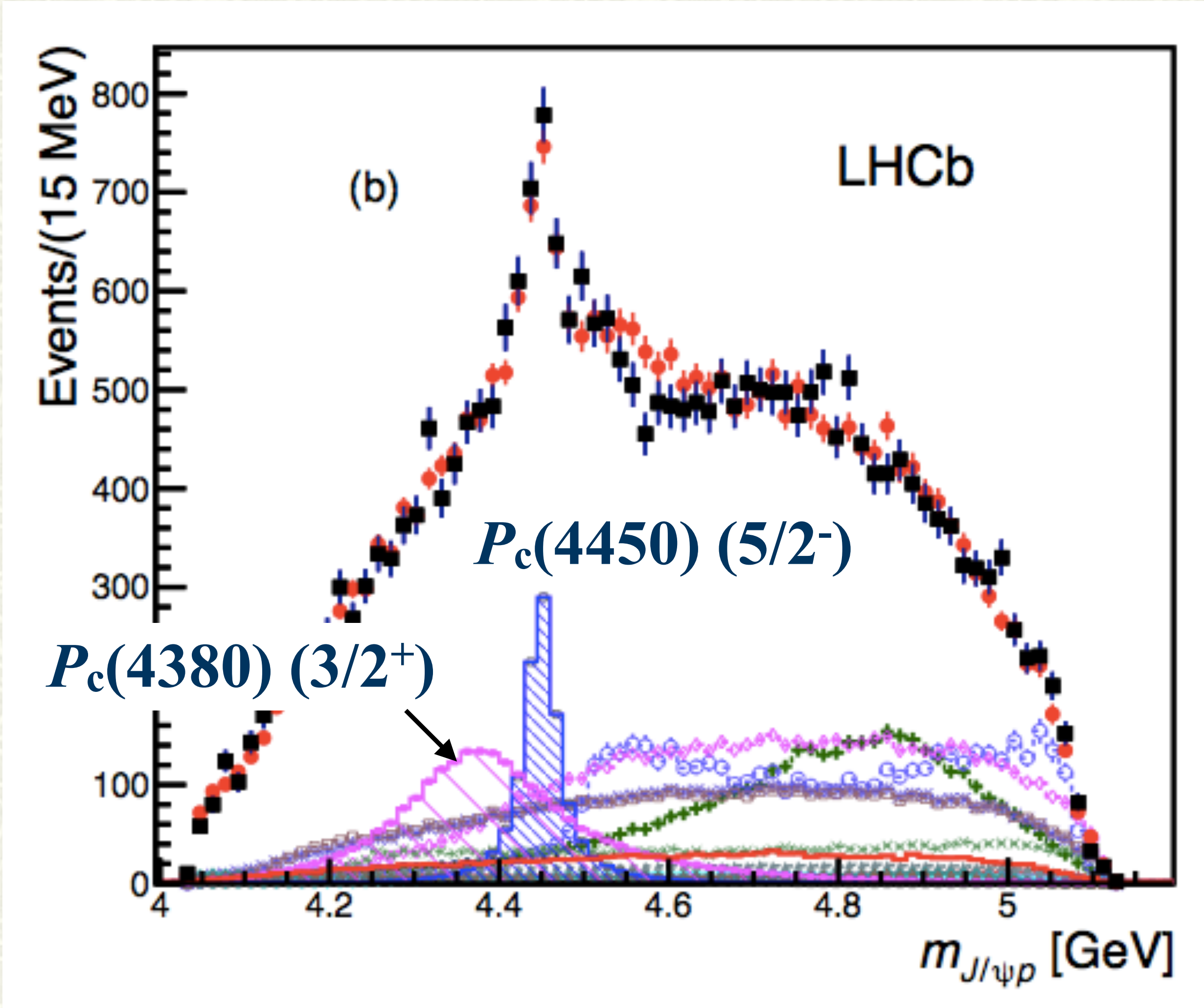
Pentaquarks

P_c Pentaquark

- $P_c \to J/\psi + p$ **July 13, 2015**

two penta-quark states with (hidden) cc^bar

$P_c(4380)$ $(3/2^{+}?)$
$P_c(4450)$ $(5/2^{-}?)$



P_c Pentaquark

- **SU(3) quark model**

  c-c^bar **spin 0 or 1** η_c J/ψ

  color 1 or 8 η_c^8 ψ^8

  qqq (uud, . .)

  color 1 or 8

  SU(6): even L → 56 [3] or 70 [21]

  odd L → 70 [21] or 56[3]+70[21]+20[1^3]

- **This can be B_8 spectroscopy.**

  (Ref: S.G. Yuan, et al., EPJ A48 (2012) 61, ArXiv:1201.0807)

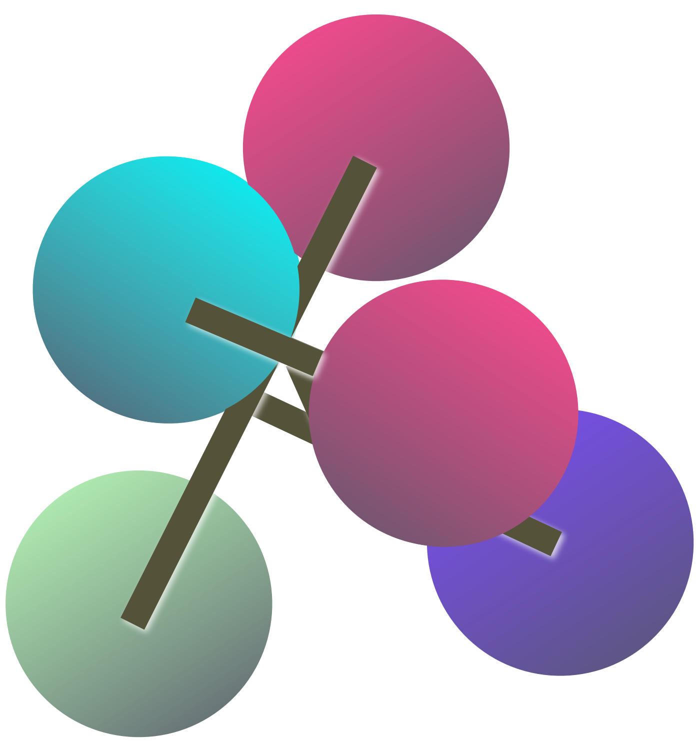
Quark Model

- hamiltonian

$$H = K + V^{\mathrm{Conf}} + V^{\mathrm{Coul}} + V^{\mathrm{CEI}} + V^{\mathrm{CMI}}$$

- configuration

$\phi(r, b)$: gaussian with size parameter b



fixed b for all flavors

Quark Model

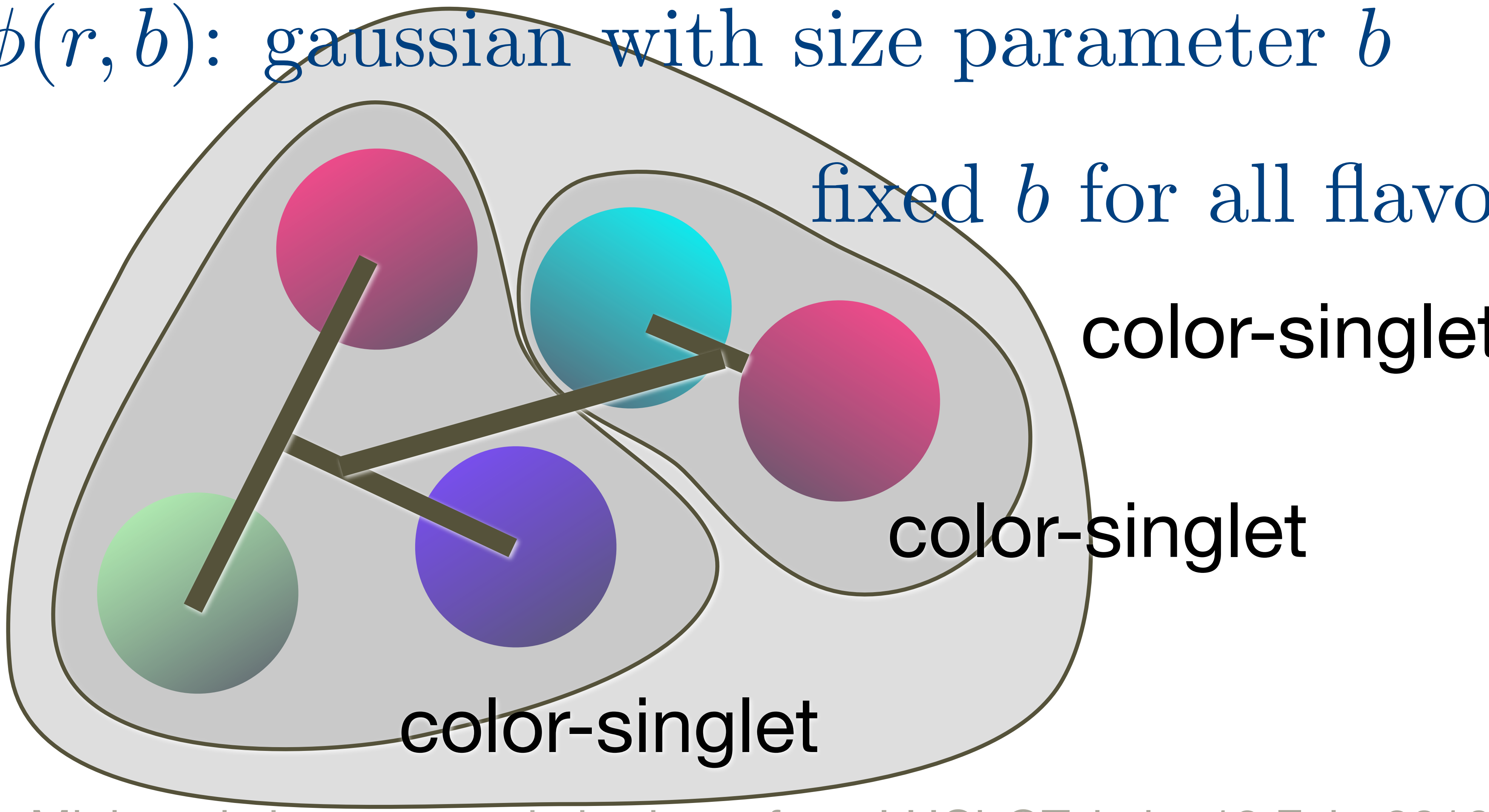
- hamiltonian

$$H = K + V^{\mathrm{Conf}} + V^{\mathrm{Coul}} + V^{\mathrm{CEI}} + V^{\mathrm{CMI}}$$

- configuration

$\phi(r, b)$: gaussian with size parameter b

fixed b for all flavors



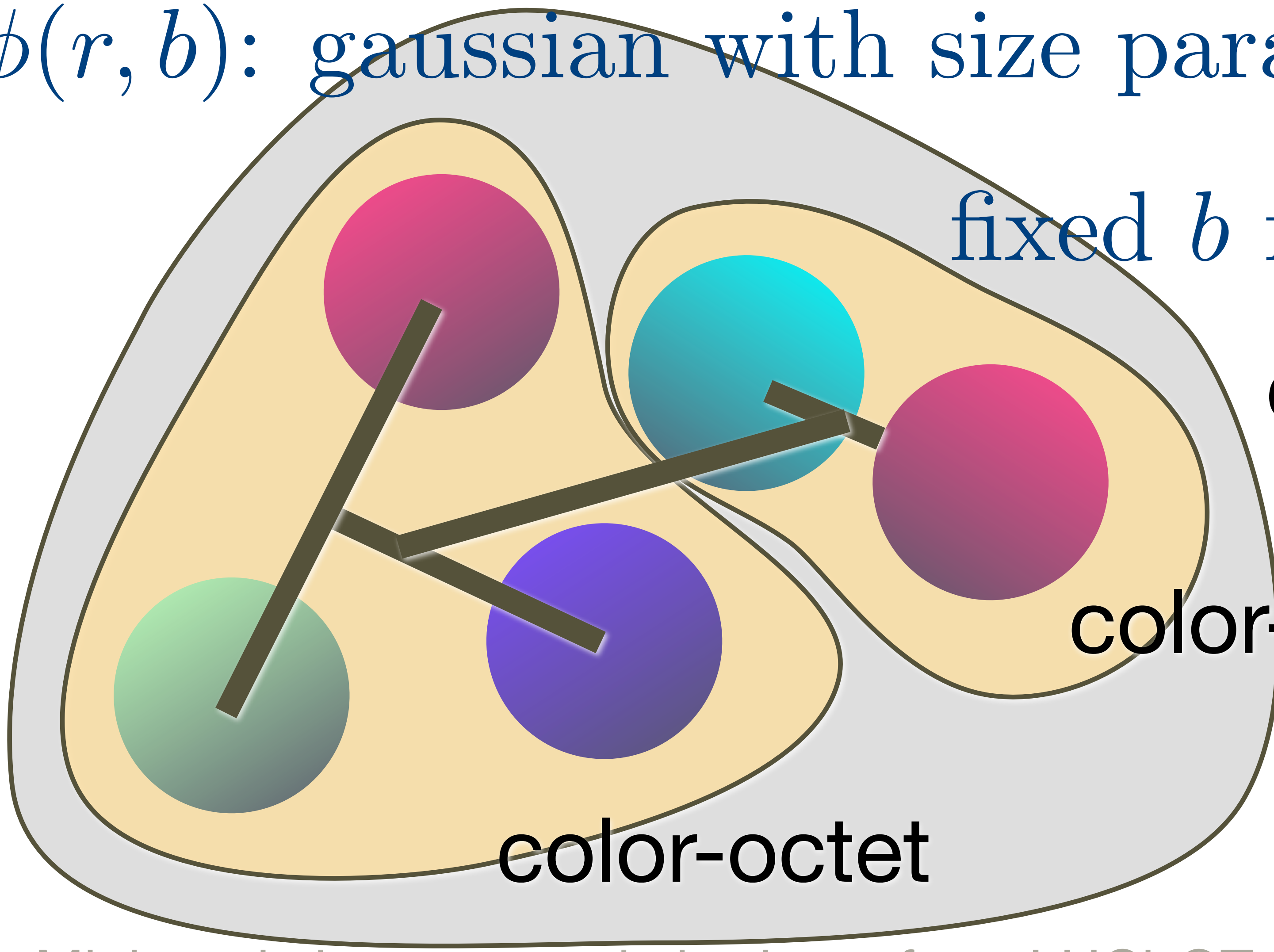
Quark Model

- hamiltonian

$$H = K + V^{\rm Conf} + V^{\rm Coul} + V^{\rm CEI} + V^{\rm CMI}$$

- configuration

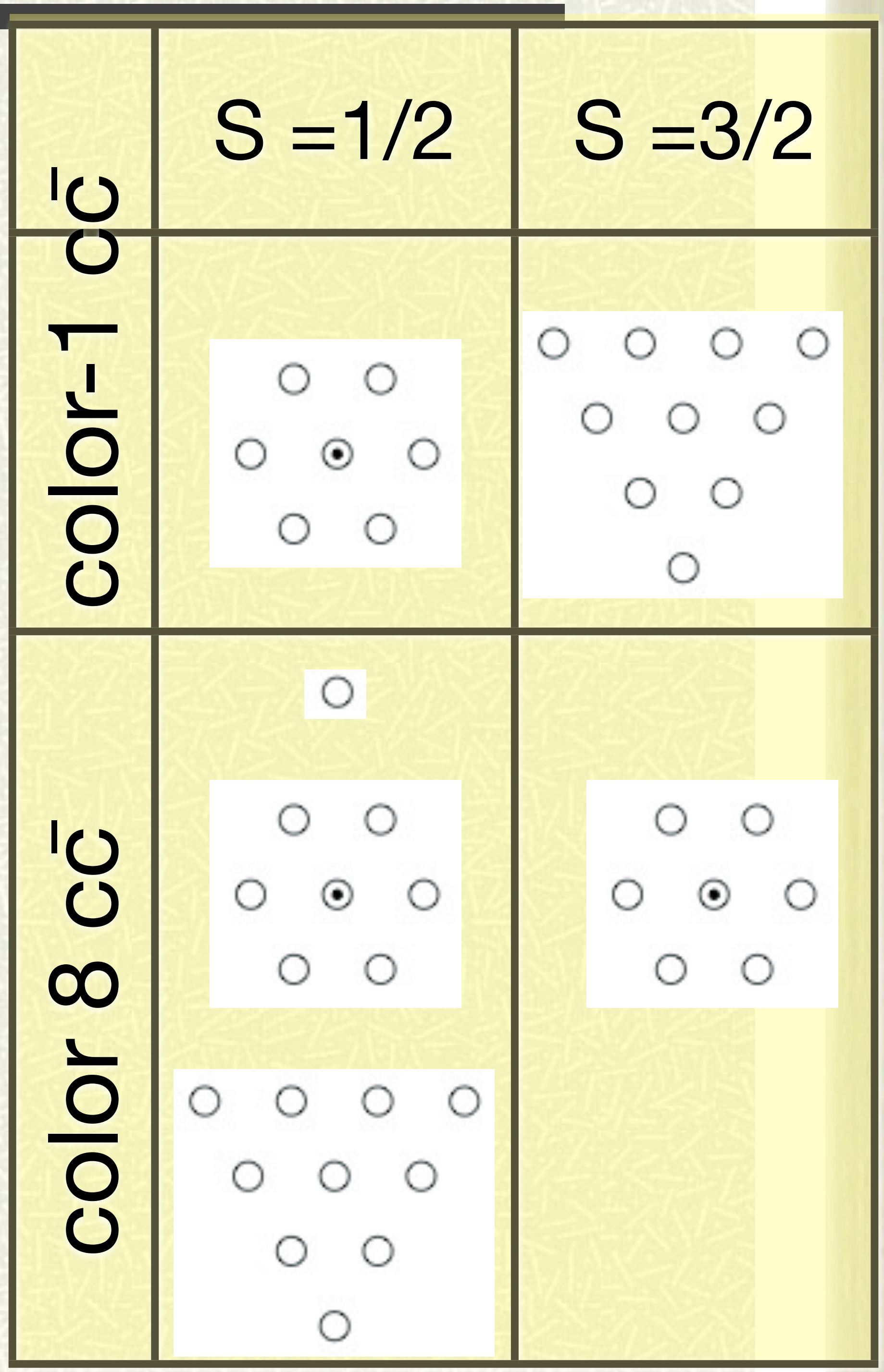
$\phi(r, b)$: gaussian with size parameter b



Spin dependence

- color 1 $c\bar{c}$
  - $56 = (8, 1/2) + (10, 3/2)$
  - $(8,1/2) \quad \Delta = -8 \quad c\bar{c}\,uud\,(udd) = J/\psi + p$
  - $(10,1/2) \quad \Delta = 8$
- color 8 $c\bar{c}$
  - $70 = (1, 1/2) + (8, 1/2) + (8, 3/2) + (10, 1/2)$
  - $(1,1/2) \quad \Delta = -14 \quad c\bar{c}\,uds = \psi_8 + \Lambda_8$
  - $(8,1/2) \quad \Delta = 0$
  - $(8,3/2) \quad \Delta = 4$
  - $(10,1/2) \quad \Delta = 10$

flavor sym.



qqqcc I(JP)=1/2(1/2-)

- 7 BM channels:

$$N\eta_c,\ NJ/\psi,\ \Lambda_c\overline{D},\ \Lambda_c\overline{D}^*,\ \Sigma_c\overline{D},\ \Sigma_c\overline{D}^*,\ \Sigma_c^*\overline{D}^*$$

- 2 forbidden states for totally symmetric in the orbital space:

$$|Q_1\rangle = \sqrt{\frac{1}{32}}\Big(\sqrt{8}|N\eta_c\rangle + \sqrt{3}|\Lambda_c\overline{D}\rangle + \sqrt{9}|\Lambda_c\overline{D}^*\rangle + \sqrt{3}|\Sigma_c\overline{D}\rangle - \sqrt{1}|\Sigma_c\overline{D}^*\rangle + \sqrt{8}|\Sigma_c^*\overline{D}^*\rangle\Big)$$

$$|Q_2\rangle = \sqrt{\frac{1}{96}}\Big(\sqrt{24}|NJ/\psi\rangle + \sqrt{27}|\Lambda_c\overline{D}\rangle - \sqrt{9}|\Lambda_c\overline{D}^*\rangle - \sqrt{3}|\Sigma_c\overline{D}\rangle + \sqrt{25}|\Sigma_c\overline{D}^*\rangle + \sqrt{8}|\Sigma_c^*\overline{D}^*\rangle\Big).$$

- 2 color-singlet c$\bar{c}$ states: $N\eta_c,\ NJ/\psi$
- 3 color-octet c$\bar{c}$ states
  - 2 qqq spin 1/2 and 1 qqq spin 3/2 states

qqqc$\bar{c}$ I(JP)=1/2(1/2-)

state	⟨cmi$_4$⟩	⟨cmi$_3$⟩	c-1	s-$\frac{1}{2}$	$\vert N\eta_c\rangle$	$\vert NJ/\psi\rangle$	$\vert\Lambda_c\overline{D}\rangle$	$\vert\Lambda_c\overline{D}^*\rangle$	$\vert\Sigma_c\overline{D}\rangle$	$\vert\Sigma_c\overline{D}^*\rangle$	$\vert\Sigma_c^*\overline{D}^*\rangle$
SU4 $\vert A\rangle$	−36.2	−3.6	0.50	0.66	−0.611	0.048	0.249	−0.020	0.748	−0.059	0
$\vert B\rangle$	−18.7	−2.7	0.33	0.67	−0.433	−0.250	0.530	0.306	−0.530	−0.306	0
$\vert C\rangle$	−6.5	−4.4	0.50	0.84	−0.048	−0.611	0.020	0.249	0.059	0.748	0
$\vert D\rangle$	−5.8	−4.1	0.39	0.94	0.427	−0.327	0.523	−0.400	0.174	−0.133	−0.477
$\vert E\rangle$	11.1	−3.2	0.28	0.89	−0.069	−0.453	−0.085	−0.555	−0.028	−0.185	0.662
SU3 $\vert 1_A\rangle$	−24	−8	1	1	0.866	0	−0.177	−0.306	−0.177	0.102	−0.289
$\vert 1_B\rangle$	$-\frac{8}{3}$	−8	1	1	0	0.866	−0.306	0.177	0.102	−0.295	−0.167
$\vert 8_A\rangle$	$-\frac{8}{3}$	−2	0	1	0	0	0	0.707	−0.408	0.471	−0.333
$\vert 8_B\rangle$	−8	−2	0	1	0	0	0.707	0	0	−0.408	−0.577
$\vert 8_C\rangle$	$-\frac{56}{3}$	2	0	0	0	0	0	0	0.816	0.471	−0.333

qqqc$\bar{c}$ I(JP)=1/2(1/2-) $(0s)^5$ calc

state	energy (MeV)	c-1	s-$\frac{1}{2}$	$\lvert N\eta_c\rangle$	$\lvert NJ/\psi\rangle$	$\lvert\Lambda_c\overline{D}\rangle$	$\lvert\Lambda_c\overline{D}^*\rangle$	$\lvert\Sigma_c\overline{D}\rangle$	$\lvert\Sigma_c\overline{D}^*\rangle$	$\lvert\Sigma_c^*\overline{D}^*\rangle$
Parameter set A										
$\lvert 1_a\rangle\rangle$	3915	0.99	0.99	0.860	−0.002	−0.223	−0.271	−0.260	0.115	−0.236
$\lvert 1_b\rangle\rangle$	4030	0.99	1.00	0.003	0.862	−0.339	0.116	0.145	−0.307	−0.115
$\lvert 8_a\rangle\rangle$	4361	0.01	0.56	0.089	−0.048	0.163	−0.536	0.805	−0.085	−0.143
$\lvert 8_b\rangle\rangle$	4383	0.00	0.86	0.031	0.039	0.633	−0.036	−0.289	−0.586	−0.411
$\lvert 8_c\rangle\rangle$	4463	0.01	0.59	−0.032	−0.057	−0.179	−0.499	−0.236	−0.500	0.639
Thresholds (MeV)				3921	4034	4196	4282	4361	4447	4512
SU3 $\lvert 1_A\rangle$	−24	−8	1	1	0.866	0	−0.177	−0.306	−0.177	0.102	−0.289
$\lvert 1_B\rangle$	$-\frac{8}{3}$	−8	1	1	0	0.866	−0.306	0.177	0.102	−0.295	−0.167
$\lvert 8_A\rangle$	$-\frac{8}{3}$	−2	0	1	0	0	0	0.707	−0.408	0.471	−0.333
$\lvert 8_B\rangle$	−8	−2	0	1	0	0	0.707	0	0	−0.408	−0.577
$\lvert 8_C\rangle$	$-\frac{56}{3}$	2	0	0	0	0	0	0	0.816	0.471	−0.333

qqqcc I(JP)=1/2(3/2-)

- 5 BM channels:

  $N J/\psi,\ \Lambda_c \overline{D}^*,\ \Sigma_c \overline{D}^*,\ \Sigma_c^* \overline{D},\ \Sigma_c^* \overline{D}^*$

- 1 forbidden states for totally symmetric in the orbital space:

$$|Q\rangle = \sqrt{\frac{1}{24}}\Big(\sqrt{6}|NJ/\psi\rangle + \sqrt{9}|\Lambda_c\overline{D}^*\rangle + \sqrt{1}|\Sigma_c\overline{D}^*\rangle - \sqrt{3}|\Sigma_c^*\overline{D}\rangle + \sqrt{5}|\Sigma_c^*\overline{D}^*\rangle\Big)$$

- 1 color-singlet c$\bar{c}$ states: $N J/\psi$
- 3 color-octet c$\bar{c}$ states
  - 1 qqq spin 1/2 and 2 qqq spin 3/2 states

qqqc$\bar{c}$ I(JP)=1/2(3/2-)

state	$\langle \mathrm{cmi}_4 \rangle$	$\langle \mathrm{cmi}_3 \rangle$	c-1	s-$\frac{1}{2}$	$\lvert NJ/\psi\rangle$	$\lvert \Lambda_c \overline{D}^* \rangle$	$\lvert \Sigma_c \overline{D}^* \rangle$	$\lvert \Sigma_c^* \overline{D} \rangle$	$\lvert \Sigma_c^* \overline{D}^* \rangle$
SU4 $\lvert A \rangle$	-12.0	-0.1	0.079	0.395	0.243	0.298	0.099	0.918	0
$\lvert B \rangle$	-6.7	-3.0	0.500	0.500	-0.612	0.250	0.750	0	0
$\lvert C \rangle$	1.3	-2.7	0.333	0.667	-0.500	0.612	-0.612	0	0
$\lvert D \rangle$	13.3	-0.3	0.088	0.439	-0.256	-0.314	-0.105	0.181	0.890
SU3 $\lvert 1_A \rangle$	$-\frac{8}{3}$	-8	1	1	0.866	-0.354	-0.118	0.204	-0.264
$\lvert 8_A \rangle$	$\frac{4}{3}$	-2	0	1	0	0.707	-0.236	0.408	-0.527
$\lvert 8_B \rangle$	$-\frac{8}{3}$	2	0	0	0	0	0.943	0.204	-0.264
$\lvert 8_C \rangle$	0	2	0	0	0	0	0	0.791	0.612

$qqqc\bar{c}$ I(JP)=1/2(3/2-) $(0s)^5$ calc

state	energy (MeV)	c-1	s-$\frac{1}{2}$	$\|NJ/\psi\rangle$	$\|\Lambda_c\overline{D}^*\rangle$	$\|\Sigma_c\overline{D}^*\rangle$	$\|\Sigma_c^*\overline{D}\rangle$	$\|\Sigma_c^*\overline{D}^*\rangle$
parameter set A								
$\|1_a\rangle\rangle$	4032	0.997	0.997	0.865	−0.350	−0.151	0.234	−0.229
$\|8_a\rangle\rangle$	4399	0.000	0.745	−0.018	0.617	−0.052	0.759	−0.198
$\|8_b\rangle\rangle$	4461	0.000	0.115	0.016	−0.246	0.912	0.298	0.135
$\|8_c\rangle\rangle$	4513	0.003	0.143	−0.043	−0.247	−0.317	0.394	0.826
Thresholds (MeV)				4034	4282	4447	4426	4512

	state	⟨cmi$_4$⟩	⟨cmi$_3$⟩	c-1	s-$\frac{1}{2}$	$\|NJ/\psi\rangle$	$\|\Lambda_c\overline{D}^*\rangle$	$\|\Sigma_c\overline{D}^*\rangle$	$\|\Sigma_c^*\overline{D}\rangle$	$\|\Sigma_c^*\overline{D}^*\rangle$
SU4	$\|A\rangle$	−12.0	−0.1	0.079	0.395	0.243	0.298	0.099	0.918	0
	$\|B\rangle$	−6.7	−3.0	0.500	0.500	-0.612	0.250	0.750	0	0
	$\|C\rangle$	1.3	−2.7	0.333	0.667	-0.500	0.612	-0.612	0	0
	$\|D\rangle$	13.3	−0.3	0.088	0.439	-0.256	-0.314	-0.105	0.181	0.890
SU3	$\|1_A\rangle$	$-\frac{8}{3}$	−8	1	1	0.866	-0.354	-0.118	0.204	-0.264
	$\|8_A\rangle$	$\frac{4}{3}$	−2	0	1	0	0.707	-0.236	0.408	-0.527
	$\|8_B\rangle$	$-\frac{8}{3}$	2	0	0	0	0	0.943	0.204	-0.264
	$\|8_C\rangle$	0	2	0	0	0	0	0	0.791	0.612

Quark Cluster Model

- hamiltonian

$$H = K + V^{\text{Conf}} + V^{\text{Coul}} + V^{\text{CEI}} + V^{\text{CMI}}$$

$$V^{\text{Conf}} = -a_c \sum (\lambda_i \cdot \lambda_j) r_{ij}$$

$$\xi_{qc} \neq \xi_{q\bar{c}}$$

$$b$$

$$V^{\text{Coul}} = -\sum \frac{(\lambda_i \cdot \lambda_j)}{4} \frac{\alpha_s}{r_{ij}}$$

$$V^{\text{CEI}} = \sum (\lambda_i \cdot \lambda_j) \alpha_s \zeta_{qq'} \delta^3(\vec{r}_{ij})$$

$$V^{\text{CMI}} = -\sum (\lambda_i \cdot \lambda_j)(\sigma_i \cdot \sigma_j) \alpha_s \xi_{qq'} \delta^3(\vec{r}_{ij})$$

Quark Cluster Model

- parameter set

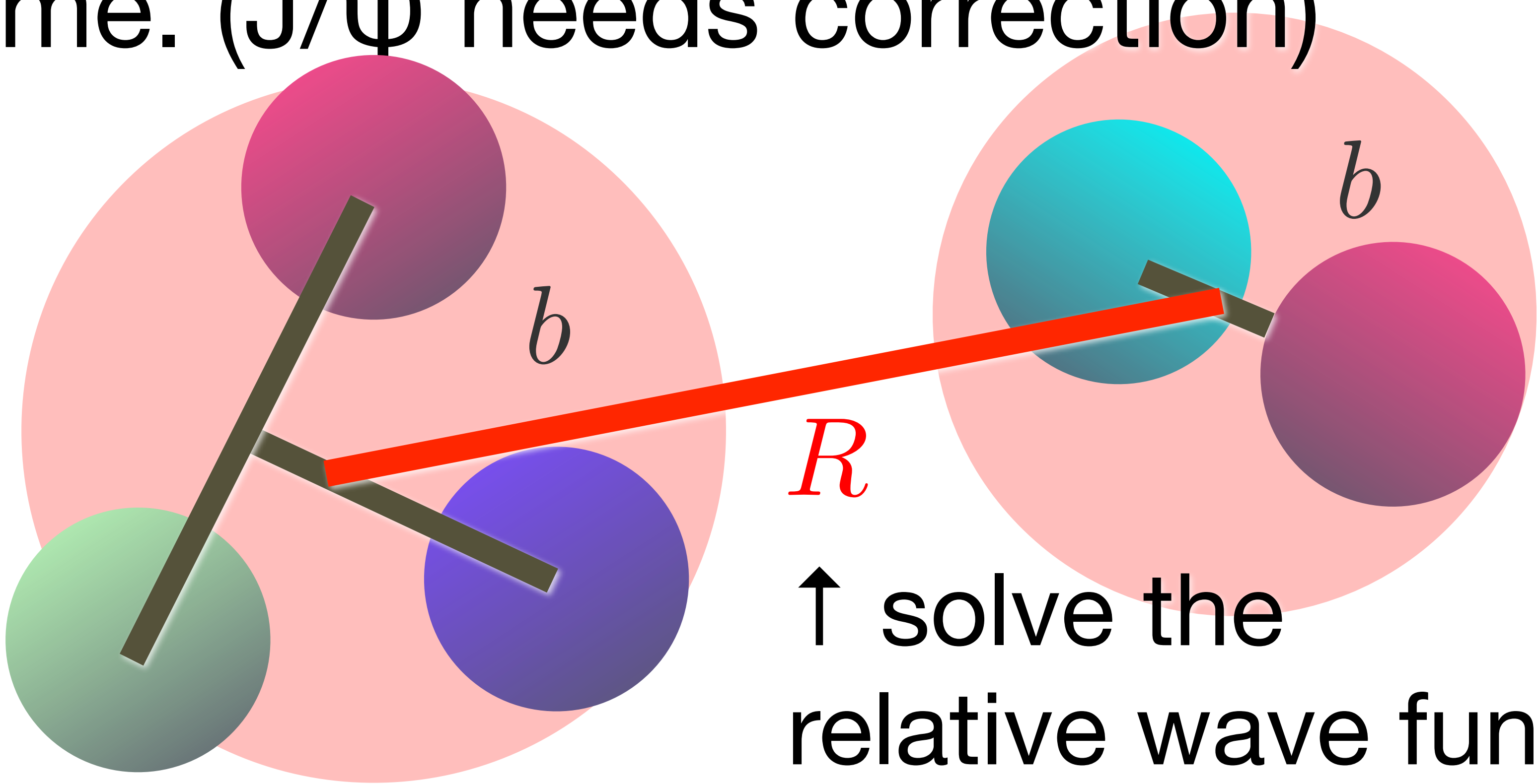
Takeuchi Shimzu PRC76 035204 modified

- m_u = 313 MeV, m_c = 1548 MeV
- α_s = 0.878, a_c = 163.33 MeV/fm
- b = 0.49 fm (fixed for all flavors)
- No instanton induced interaction
- CEM, CMI flavor-dependent factors
  ← hadron masses
- Kin replaced by the real masses

$$K_R(\boldsymbol{R},\boldsymbol{R}) \to K_R(\boldsymbol{R},\boldsymbol{R}) \times \frac{6m_q}{5}\frac{1}{\mu}$$

Quark Cluster Model

- configuration
  - 2 clusters (baryon-meson) whose orbital wave function is the gaussian.
  - The size parameter for all flavors are the same. (J/ψ needs correction)

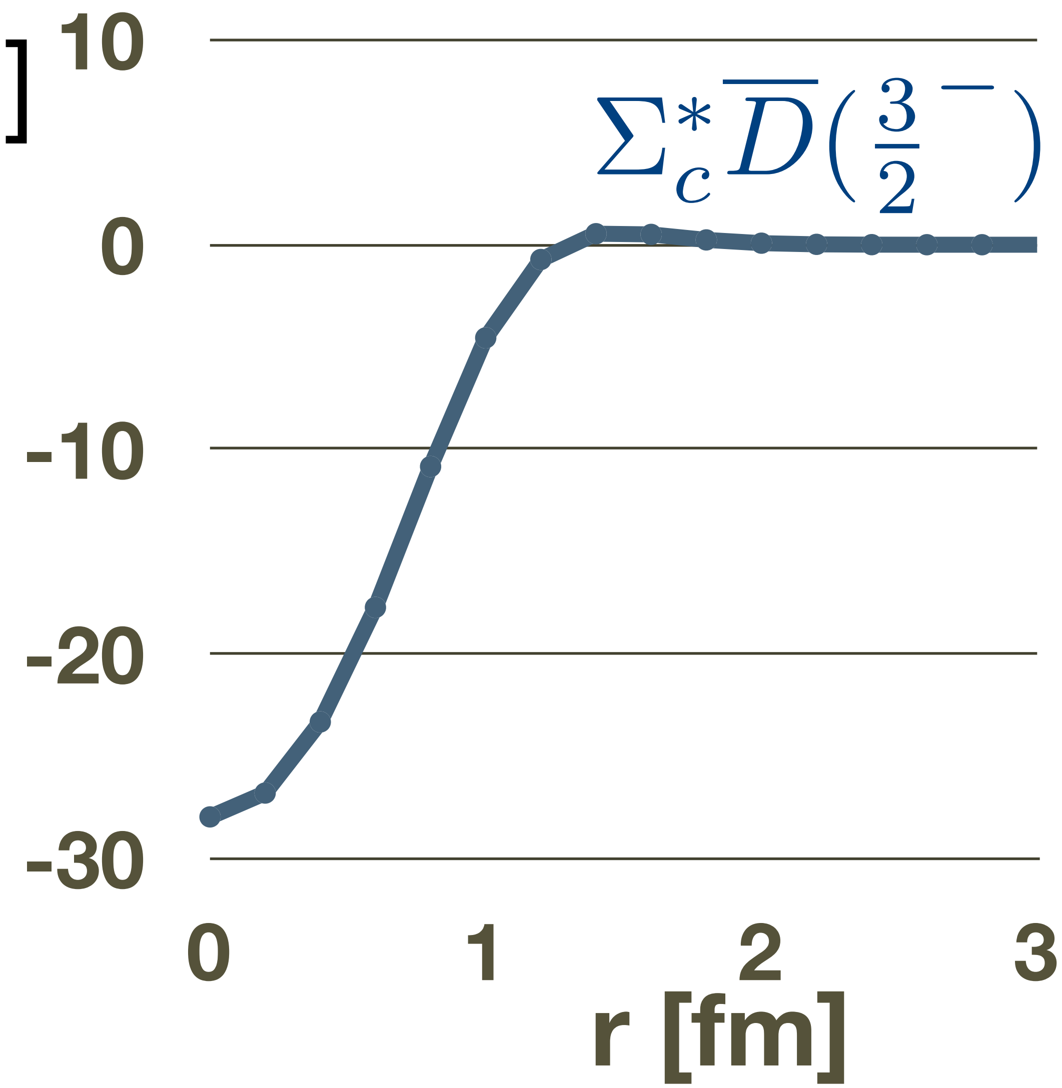


Potential

- Potential calculated by $\frac{\langle H - K \rangle}{\langle 1 \rangle}_{GCM}$ [MeV]
  - put the two clusters r[fm] apart from each other,
  - obtain the energy: H(r,r)
  - V = H(r,r)-H(∞, ∞)

    w/o Kinetic term
- Kinetic energy:

$\frac{3}{4\mu b^2}$ ~ 30 MeV (b=1fm)



Σc*D is weakly bound? or resonance?

A bound state in 3/2- ?

- Single channel calculation:

  $\Sigma_c^*\overline{D}$

  YES   BE = 0.7 MeV (No J/ψ correction)

- 3 channel calculation:

  $\Sigma_c^*\overline{D}$-$\Sigma_c\overline{D}^*$-$\Sigma_c^*\overline{D}^*$

  YES   BE = 5.8 MeV (No J/ψ correction)

$\Sigma_c^*\overline{D}\ (\frac{3}{2}^-)$ bound state?

A bound state in 3/2- ?

preliminary

- Single channel calculation:

$\Sigma_c^* \overline{D}$

YES BE ~ 0 MeV (w/ J/ψ correction)

- 3 channel calculation:

$\Sigma_c^* \overline{D}$-$\Sigma_c \overline{D}^*$-$\Sigma_c^* \overline{D}^*$

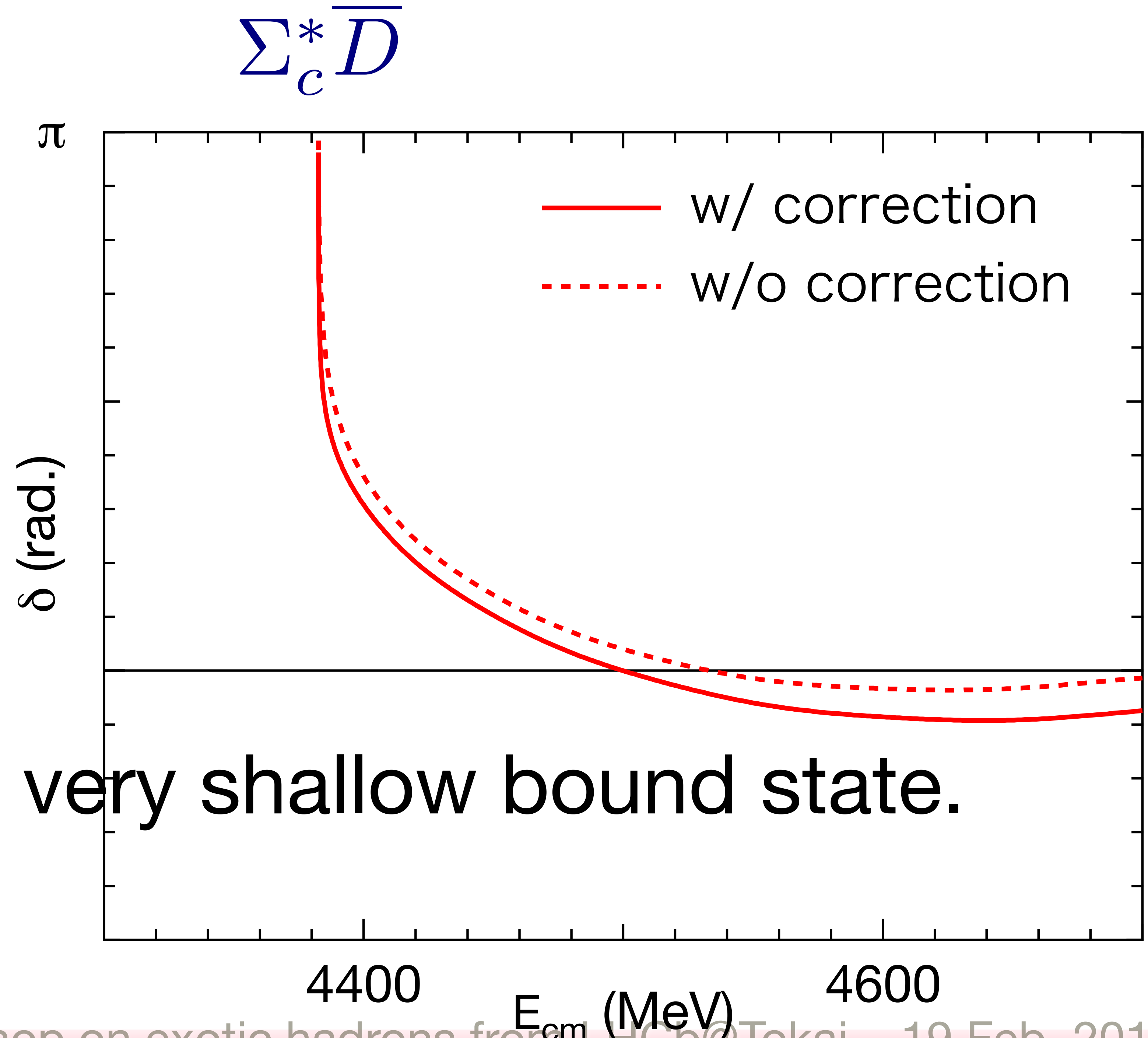
YES BE = 9.8 MeV (w/ J/ψ correction)

It seems the bound state survives the correction.

Phase shifts

preliminary

- Σc*D single channel calculations

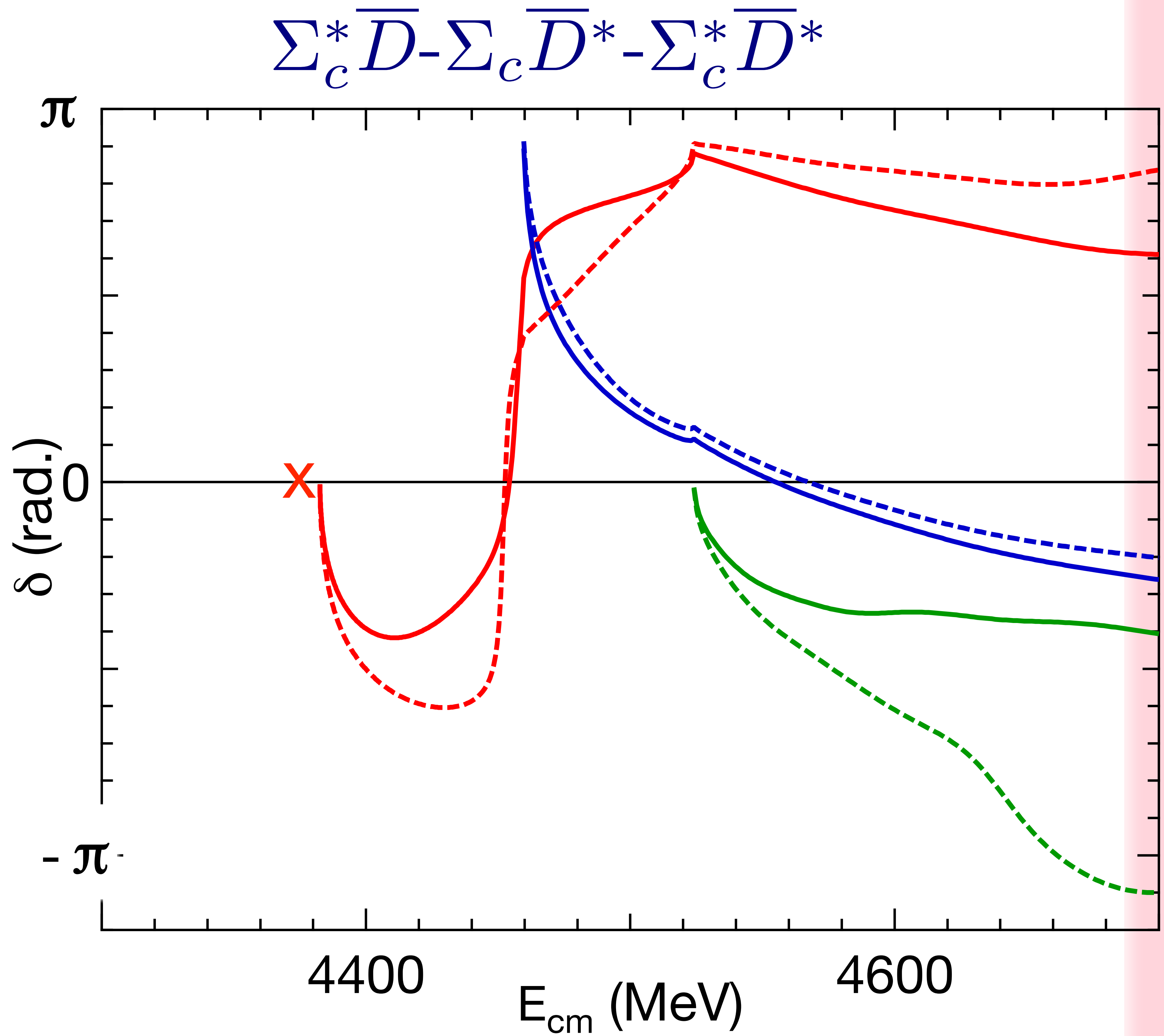


- There is a very shallow bound state.

Phase shifts

very very preliminary

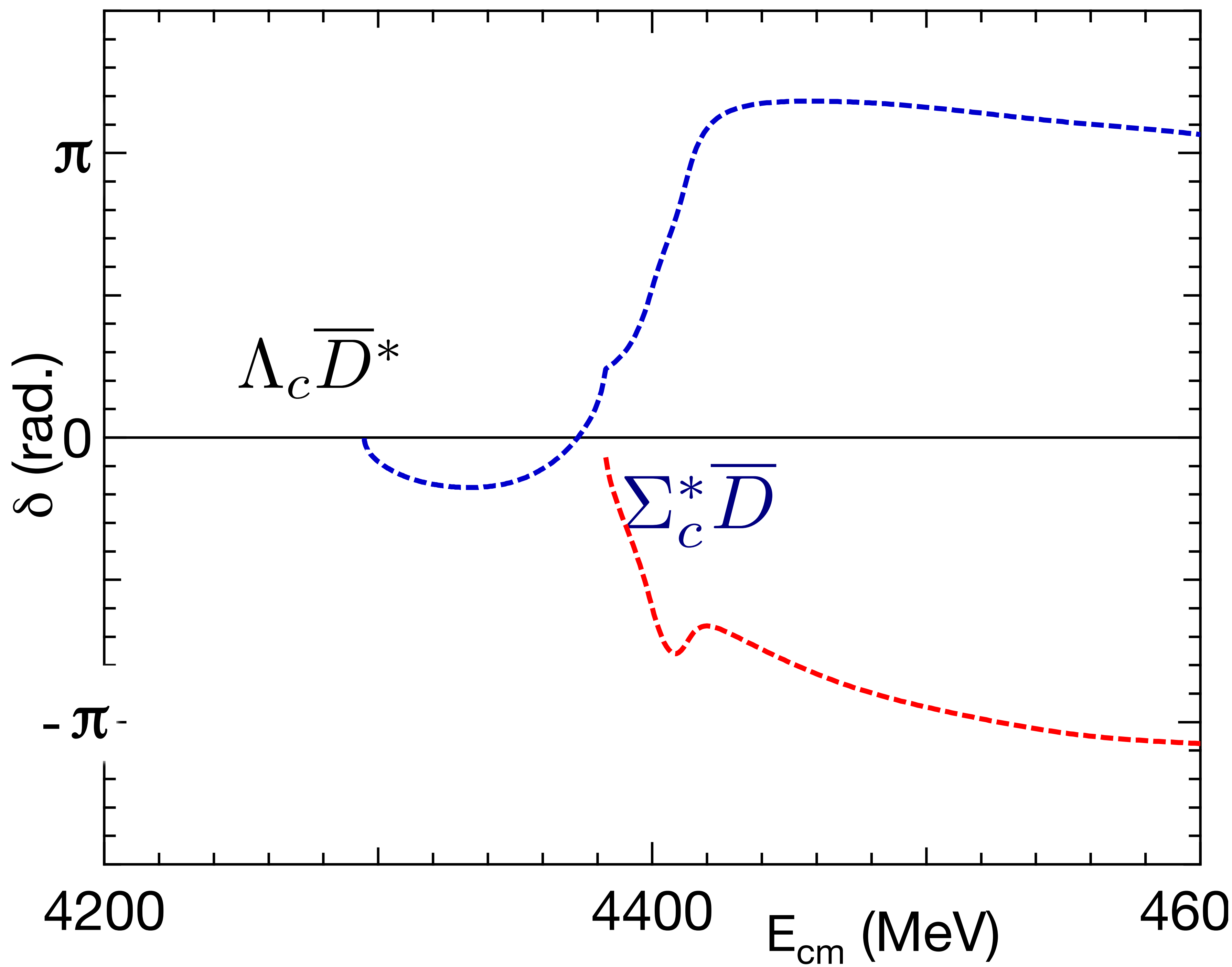
- Σc*D-ΣcD*-Σc*D* coupled channel
- There are a bound state and a resonance state.



Phase shifts

very very preliminary

- Λc*D-Σc*D coupled channel
- there is a resonance around the Σc*D threshold.



other quark models

- Quark model (OGE + OBE, Chiral)
  - Pc(4380) is a bound state of ΣcD*? (similar to our results with a bound state approach)

[H Huang, C Deng J Ping F Wang,arXiv:1510.04648]
[G.Yang J Ping arXiv:151109053]

- Diquark-diquark-qbar
  - K-J/ψ for Pc(4380)? Strangeness is important.

[V.V. Anisovich etal arXiv:1509.04898]

- Review

[HX Chen W Chen X Liu S-L Zhu,arXiv:1601.02092]

Today's menu No.2

qqsc$\bar{c}$ pentaquarks are investigated by a simple quark model

- The model can give the single baryon and meson spectra
- $c\bar{c}_8$-qqq_8 state can be attractive (flavor singlet state!).
- There may be a $\Lambda_c D_s$-$\Xi_c \overline{D}$ bound state,
- which mixes with Ληc, ΛJ/ψ weakly.

qqscc I(JP)=0(1/2-)

- 9 BM channels:

$$\Lambda\eta_c,\ \Lambda J/\psi,\ \Lambda_c D_s,\ \Lambda_c D_s^*,\ \Xi_c\overline{D},\ \Xi_c\overline{D}^*,\ \Xi_c'\overline{D},\ \Xi_c'\overline{D}^*,\ \Xi_c^*\overline{D}^*$$

- 2 forbidden states for totally symmetric in the orbital space:

$$|Q_1\rangle = \sqrt{\frac{1}{32}}\Big(\sqrt{8}|\Lambda\eta_c\rangle + \sqrt{2}|\Lambda_c D_s\rangle + \sqrt{6}|\Lambda_c D_s^*\rangle + \sqrt{1}|\Xi_c\overline{D}\rangle + \sqrt{3}|\Xi_c\overline{D}^*\rangle + \sqrt{3}|\Xi_c'\overline{D}\rangle - \sqrt{1}|\Xi_c'\overline{D}^*\rangle + \sqrt{8}|\Xi_c^*\overline{D}^*\rangle\Big) \quad (53)$$

$$|Q_2\rangle = \sqrt{\frac{1}{96}}\Big(\sqrt{24}|\Lambda J/\psi\rangle + \sqrt{18}|\Lambda_c D_s\rangle - \sqrt{6}|\Lambda_c D_s^*\rangle + \sqrt{9}|\Xi_c\overline{D}\rangle - \sqrt{3}|\Xi_c\overline{D}^*\rangle - \sqrt{3}|\Xi_c'\overline{D}\rangle + \sqrt{25}|\Xi_c'\overline{D}^*\rangle + \sqrt{8}|\Xi_c^*\overline{D}^*\rangle$$

- 2 color-singlet $c\bar{c}$ states: $\Lambda\eta_c,\ \Lambda J/\psi$
- 5 color-octet $c\bar{c}$ states
  - 4 qqq spin 1/2 and 1 qqq spin 3/2 states
  - 2 flavor singlet states

qqscc̄ I(JP)=0(1/2-)

state	$\langle\mathrm{cmi}\rangle$	c-1	s-$\frac{1}{2}$	f-1	$\lvert\Lambda\eta_c\rangle$	$\lvert\Lambda J/\psi\rangle$	$\lvert\Lambda_c D_s\rangle$	$\lvert\Lambda_c D_s^*\rangle$	$\lvert\Xi_c\overline{D}\rangle$	$\lvert\Xi_c\overline{D}^*\rangle$	$\lvert\Xi_c'\overline{D}\rangle$	$\lvert\Xi_c'\overline{D}^*\rangle$	$\lvert\Xi_c^*\overline{D}^*\rangle$
SU4 $\lvert A\rangle$	-36.2	0	1	1	0	0	-0.576	0.045	0.814	-0.064	0	0	0
$\lvert B\rangle$	-6.5	0	1	1	0	0	-0.045	-0.576	0.064	0.814	0	0	0
$\lvert C\rangle$	-36.2	0.500	0.660	0	-0.611	0.048	0.204	-0.016	0.144	-0.011	0.748	-0.059	0
$\lvert D\rangle$	-6.5	0.500	0.840	0	-0.048	-0.611	0.016	0.204	0.011	0.144	0.059	0.748	0
$\lvert E\rangle$	-18.7	0.333	0.667	0	0.433	0.250	-0.433	-0.250	-0.306	-0.177	0.530	0.306	0
$\lvert F\rangle$	-5.8	0.386	0.943	0	-0.427	0.327	-0.427	0.327	-0.302	0.231	-0.174	0.133	0.477
$\lvert G\rangle$	11.1	0.281	0.890	0	-0.069	-0.453	-0.069	-0.453	-0.049	-0.321	-0.028	-0.185	0.662
SU3 $\lvert 1_A\rangle$	-8	1	1	0	0.866	0	-0.144	-0.250	-0.102	-0.177	-0.177	0.102	-0.289
$\lvert 1_B\rangle$	-8	1	1	0	0	0.866	-0.250	0.144	-0.177	0.102	0.102	-0.295	-0.167
$\lvert 8_A\rangle$	-14	0	1	1	0	0	-0.577	0	0.816	0	0	0	0
$\lvert 8_B\rangle$	-14	0	1	1	0	0	0	-0.577	0	0.816	0	0	0
$\lvert 8_C\rangle$	-2	0	1	0	0	0	0	0.577	0	0.408	-0.408	0.471	-0.333
$\lvert 8_D\rangle$	-2	0	1	0	0	0	0.577	0	0.408	0	0	-0.408	-0.577
$\lvert 8_E\rangle$	2	0	0	0	0	0	0	0	0	0	0.816	0.471	-0.333

$qqsc\bar{c}$ I(JP)=0(1/2-)

	state	energy	c-1	s-$\frac{1}{2}$	f-1	$\|\Lambda\eta_c\rangle$	$\|\Lambda J/\psi\rangle$	$\|\Lambda_c D_s\rangle$	$\|\Lambda_c D_s^*\rangle$	$\|\Xi_c \overline{D}\rangle$	$\|\Xi_c \overline{D}^*\rangle$	$\|\Xi_c' \overline{D}\rangle$	$\|\Xi_c' \overline{D}^*\rangle$	$\|\Xi_c^* \overline{D}^*\rangle$
thresholds						4097.40	4210.72	4252.66	4402.63	4394.21	4480.24	4468.19	4554.22	4640.04
A	$\|1_a\rangle\rangle$	4083.52	0.946	0.992	0.020	0.842	0.003	-0.299	-0.173	-0.046	-0.170	-0.279	0.151	-0.198
	$\|1_b\rangle\rangle$	4197.95	0.901	0.999	0.061	-0.033	0.821	-0.447	0.025	-0.027	0.106	0.183	-0.279	-0.031
	$\|8_a\rangle\rangle$	4240.75	0.091	1.000	0.844	-0.149	-0.215	-0.579	0.120	0.708	-0.052	-0.033	0.191	0.204
	$\|8_b\rangle\rangle$	4390.37	0.024	0.996	0.852	-0.053	0.125	0.021	0.762	-0.141	-0.581	-0.165	0.102	-0.076
	$\|8_c\rangle\rangle$	4473.84	0.012	0.459	0.048	0.037	-0.089	-0.189	-0.152	-0.295	-0.322	0.744	0.397	0.176
	$\|8_d\rangle\rangle$	4490.96	0.016	0.940	0.127	0.110	0.003	0.287	-0.141	0.495	-0.424	0.363	-0.401	-0.411
	$\|8_e\rangle\rangle$	4594.79	0.009	0.614	0.049	-0.031	-0.078	-0.086	-0.286	-0.141	-0.460	-0.225	-0.492	0.616
SU3	$\|1_A\rangle$	-8	1	1	0	0.866	0	-0.144	-0.250	-0.102	-0.177	-0.177	0.102	-0.289
	$\|1_B\rangle$	-8	1	1	0	0	0.866	-0.250	0.144	-0.177	0.102	0.102	-0.295	-0.167
	$\|8_A\rangle$	-14	0	1	1	0	0	-0.577	0	0.816	0	0	0	0
	$\|8_B\rangle$	-14	0	1	1	0	0	0	-0.577	0	0.816	0	0	0
	$\|8_C\rangle$	-2	0	1	0	0	0	0	0.577	0	0.408	-0.408	0.471	-0.333
	$\|8_D\rangle$	-2	0	1	0	0	0	0.577	0	0.408	0	0	-0.408	-0.577
	$\|8_E\rangle$	2	0	0	0	0	0	0	0	0	0	0.816	0.471	-0.333

A bound state in JP=1/2- ?

- An attractive state in the $\Lambda_c D_s$-$\Xi_c \overline{D}$ channels.
  - There, uds is in the color octet, spin 1/2, flavor singlet. CMI is very attractive in the SU(3)$_f$ limit as well as in the SU(4)$_f$ limit.
  - can be a resonance in the ΛJ/ψ?

I'm working on the QCM calc...

Summary of $c\bar{c}$ Pentaquarks

- It seems there is a bound state of $\Sigma_c^*\overline{D}$ I(JP)=1/2(3/2-), which can be seen in the $\Lambda_c\overline{D}^*$
- There is probably a bound state of I(JP)=0(1/2-) $\Lambda_c D_s$-$\Xi_c\overline{D}$
  - attraction due to the color-magnetic interaction
  - To include J/ψ, one needs to introduce the quark cluster with different b. (which is complicated)

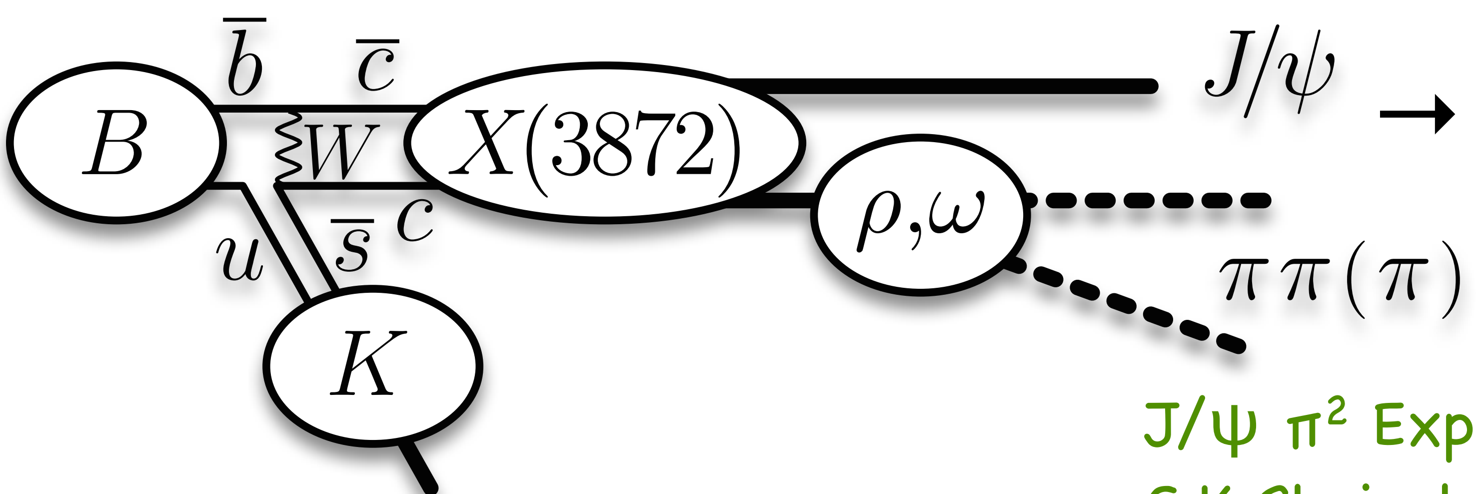
Today's menu No.3

The 1^{++} $c\bar{c}$-component of the X(3872) may be seen in the X(3872) radiative decay?

- All the quark model predict that there is The 1++ $c\bar{c}$(2P) state.
- But, the 1++ $c\bar{c}$(2P) state is missing because the mass should be above the open charm threshold, DD*.
- Its pole may have been seen in the X(3872) γ decay spectrum by LHCb.
- It is because $c\bar{c}$(2P) decays to ψ', but not to J/ψ (or only weekly).

X(3872) γ-decay

- $B^+ \rightarrow$ X(3872) + K^+

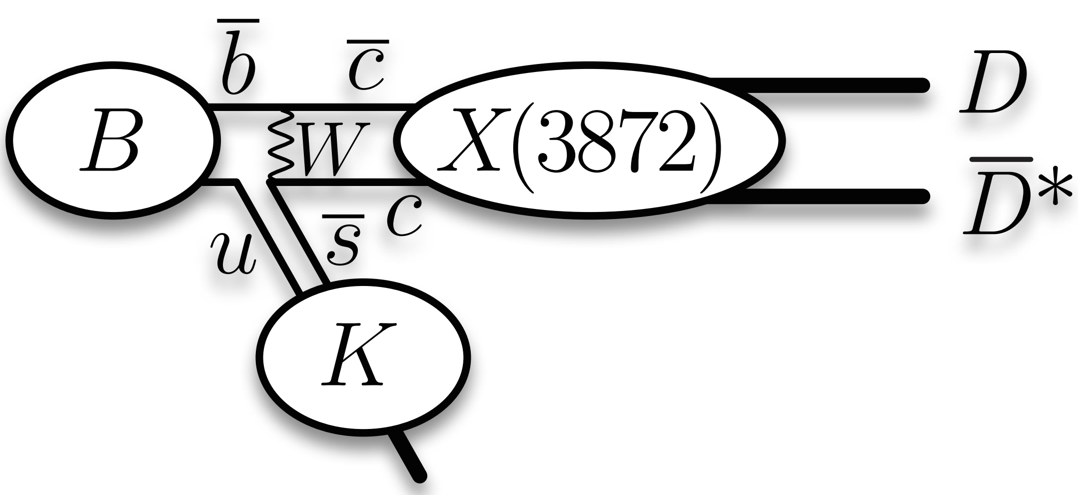


$\rightarrow J/\psi + \rho$ or $\omega \rightarrow \pi^n$

$J/\psi\ \pi^2$ Exp:

S.K.Choi et al. [Belle] PRL91, 262001 (2003)

B.Aubert et al. [BaBar] PRD71, 071103 (2005)



$\rightarrow D + \bar{D}^*$

$D^0\bar{D}^{*0}$ exp

T.Aushev et al. [Belle] PRD81, 031103 (2010)

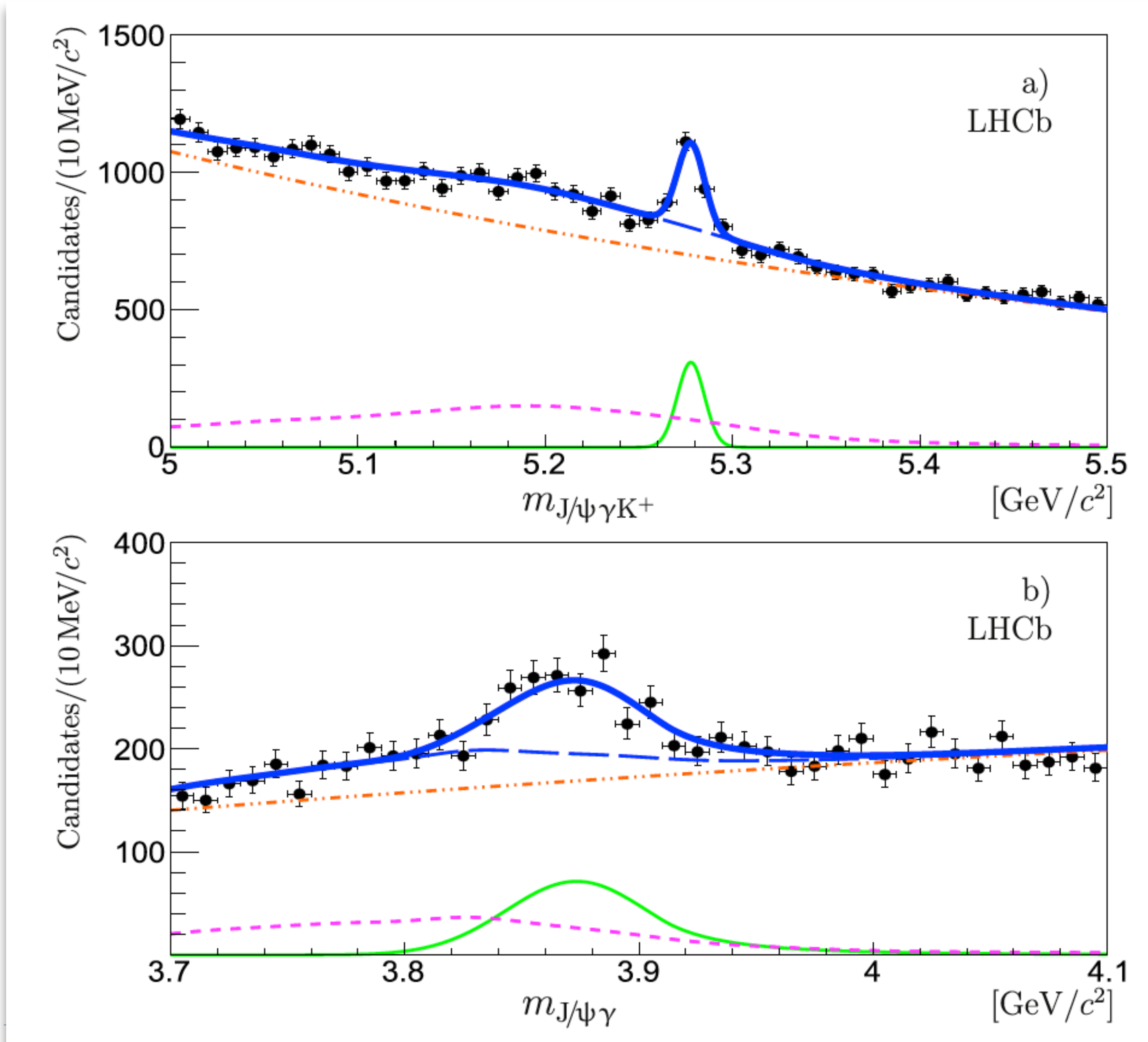
B.Aubert et al. [BaBar] PRD77, 011102 (2008)

S.Takeuchi, M.Takizawa, and K.Shimizu, arXiv:1602.04297 [hep-ph]

LHCb's results: X(3872)→ J/ψγ

Invariant mass of $J/\psi\gamma K^{+}$

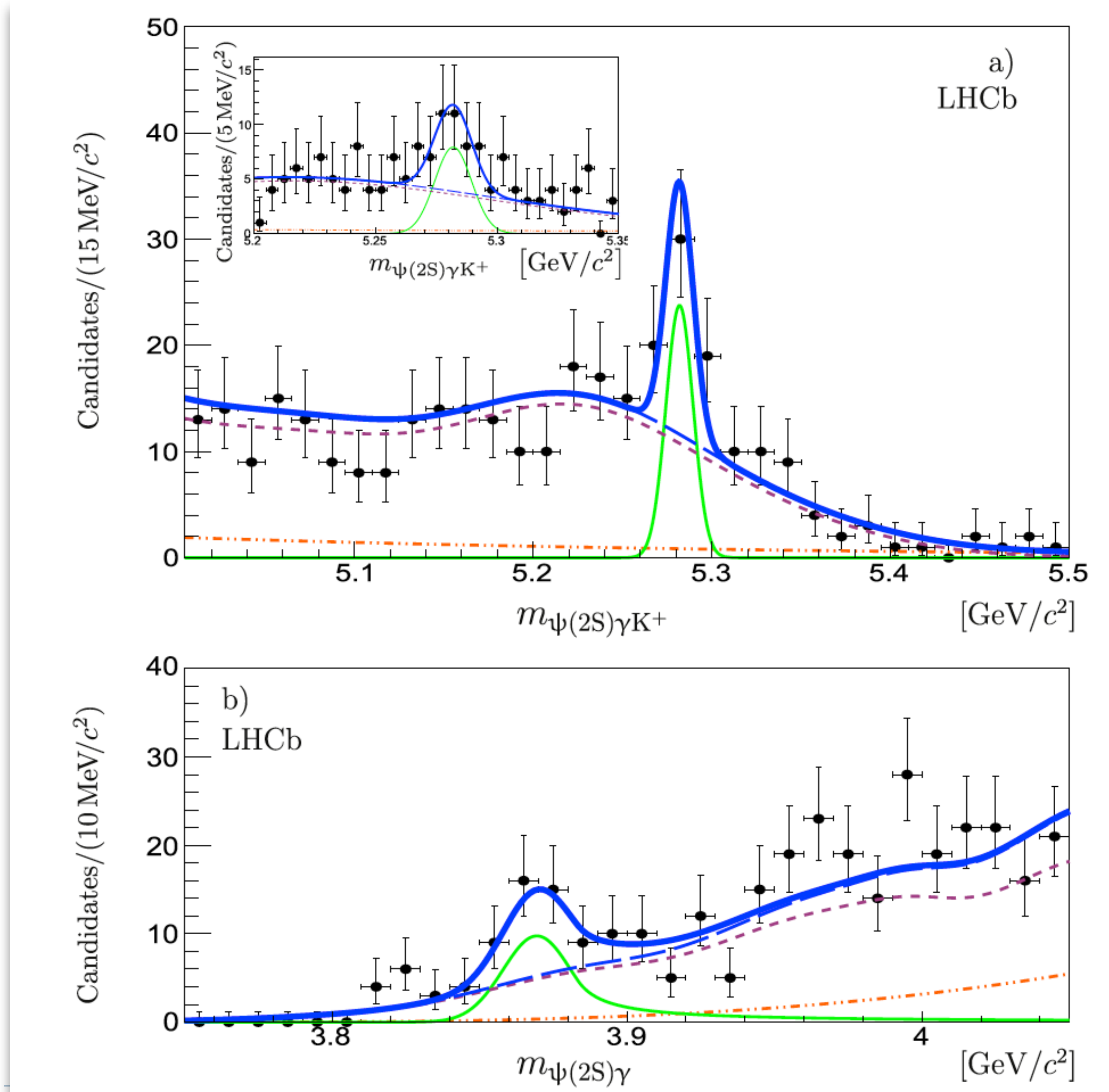
Invariant mass of $J/\psi\gamma$



LHCb's results: X(3872)→ ψ(2S)γ

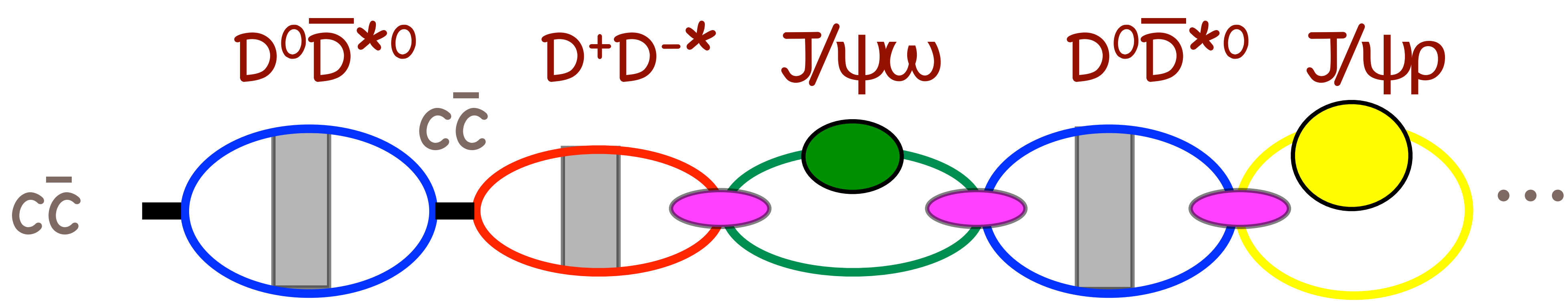
Invariant mass of $\psi(2S)\,\gamma\,K^{+}$

Invariant mass of $\psi(2S)\,\gamma$



Our picture of X(3872)

- Two-meson molecule with a $c\bar{c}$ core:
  - $c\bar{c}(1P)$ – $c\bar{c}(2P)$ – $D^0\bar{D}^{*0}$ – D^+D^{-*} – $J/\psi\omega$ – $J/\psi\rho$
  - ω and ρ have width.
  - $J/\psi\omega$ and $J/\psi\rho$ couple to $c\bar{c}$ only via $D\bar{D}^*$ channels (OZI).



M. Takizawa and S. Takeuchi, Prog. Theor. Exp. Phys. 2013, 0903D01
S.Takeuchi, K.Shimizu, and M.Takizawa, Prog. Theor. Exp. Phys. 2014, 123D01

Radiative decay width: bound X(3872)

- E1 transition of χ_{c1}($c\bar{c}$ core) to $J/\psi(\psi')\,\gamma$

$$\Gamma\Big(X(3872)\to J/\psi(\psi')+\gamma\Big)=\frac{4}{9}|Q_c|^2\alpha\,\frac{\omega_\gamma^3 E_\psi}{M_X}\Big|Z_{c\bar{c}}\langle c\bar{c}|r|\psi\rangle\Big|^2$$

$Z_{c\bar{c}}^2$: $c\bar{c}$ probability in $X(3872)$.

$\langle c\bar{c}|r|\psi\rangle$: the $c\bar{c}$ core in $X(3872)$ to the final J/ψ or $\psi(2S)$ by E1.

  - harmonic oscillator

$\langle\chi\|r\|\psi\rangle$	J/ψ	$\psi(2S)$
$\chi_{c1}(2P)$	0	$\sqrt{5/2}$ b
$\chi_{c1}(1P)$	$\sqrt{3/2}$ b	-b

Radiative decay width: bound X(3872)

- E1 transiton of cc^{bar} core to J/ψ(ψ') γ

$$\Gamma\Big(X(3872) \to J/\psi(\psi') + \gamma\Big) = \frac{4}{9}|Q_c|^2\alpha\,\frac{\omega_\gamma^3 E_\psi}{M_X}\Big|Z_{c\bar{c}}\langle c\bar{c}|r|\psi\rangle\Big|^2$$

$Z_{c\bar{c}}^2$: $c\bar{c}$ probability in $X(3872)$.

$\langle c\bar{c}|r|\psi\rangle$: the $c\bar{c}$ core in $X(3872)$ to the final J/ψ or $\psi(2S)$ by E1.

- To see the $\chi_{c1}(2P)$ pole, look into ψ(2S)γ

r	J/ψ	ψ(2S)
$\chi_{c1}(2P)$	0.04	0.52
$\chi_{c1}(1P)$	0.33	-0.41

- To explain the final J/ψ γ, χ_{c1}(1P) should be included.

Radiative decay : γ spectrum

- X(3872), created from cc^{bar}(2P), decays into ψγ :

$$\frac{\mathrm{d}W(c\bar{c} \to \psi\gamma)}{\mathrm{d}E} = -\frac{1}{\pi}\mathrm{Im}\ {G_Q}^{\gamma}$$

$$= \delta(E-(\Omega_\psi+\omega_\gamma))\sum_\epsilon \left|\langle\psi\gamma_{k\epsilon}|(V_{\gamma Q} \sout{+ V_{\gamma P}G^{(P)}V_{PQ}})G_Q|c\bar{c}\rangle\right|^2$$

$$= \sum_\epsilon \left|\sum_\beta \underline{\langle\psi\gamma_{k\epsilon}|V_{\gamma Q}|c\bar{c}_\beta\rangle}\langle c\bar{c}_\beta|G_Q|c\bar{c}\rangle\right|^2_{E=\Omega_\psi+\omega_\gamma}$$

$$\Gamma\Big(\chi_{c1}(mP) \to \psi(nS)+\gamma\Big)$$

phase is not phenomenologically determined.

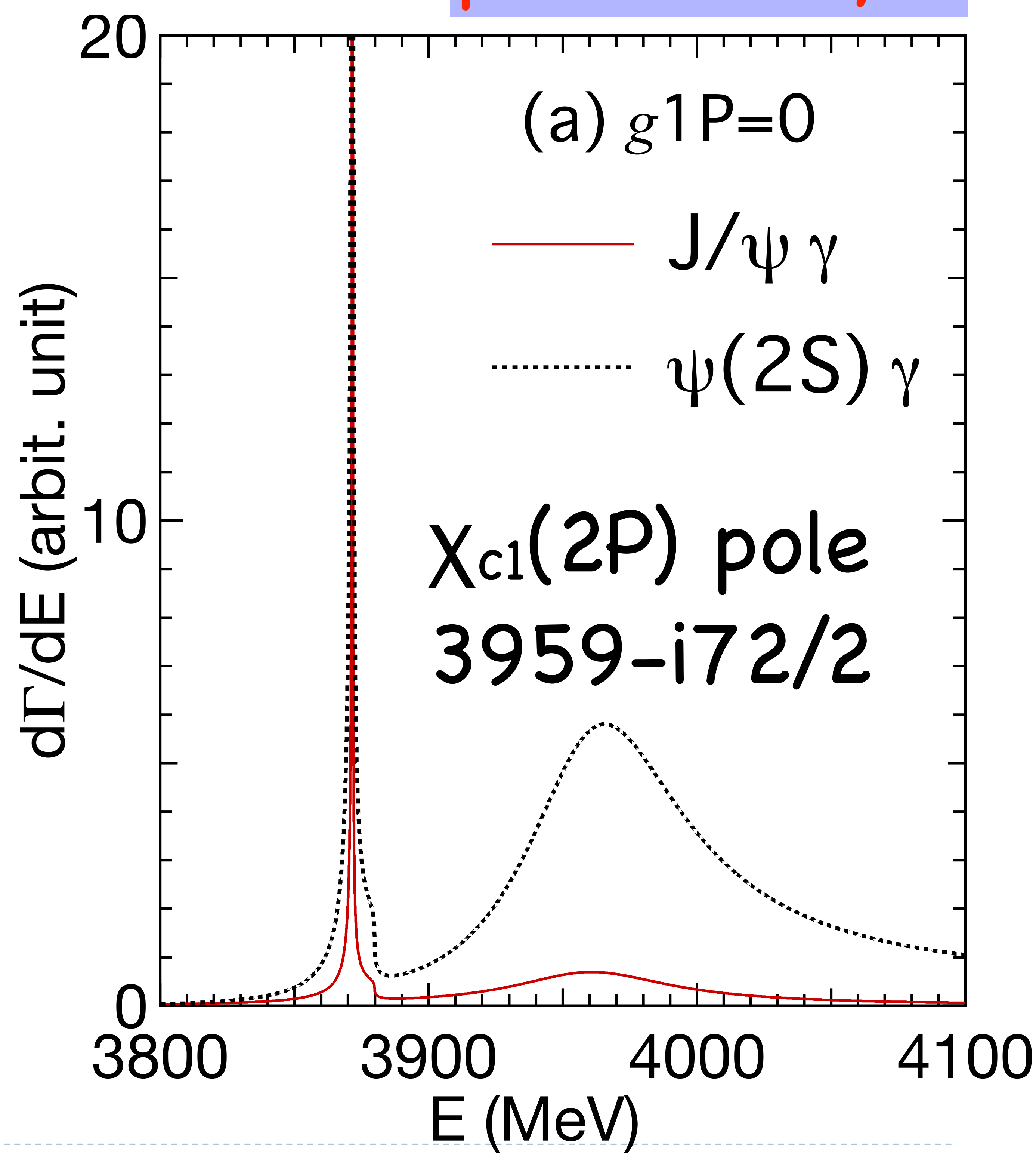
Radiative decay : γ spectrum

- $d\Gamma(X\to\psi\gamma)/dE$
  - model only with $c\bar{c}$(2P)
  - Ratio of the strength at peak

$$R_\gamma = \frac{B(X(3872)\to\psi(2S)\gamma)}{B(X(3872\to J/\psi\gamma)}$$

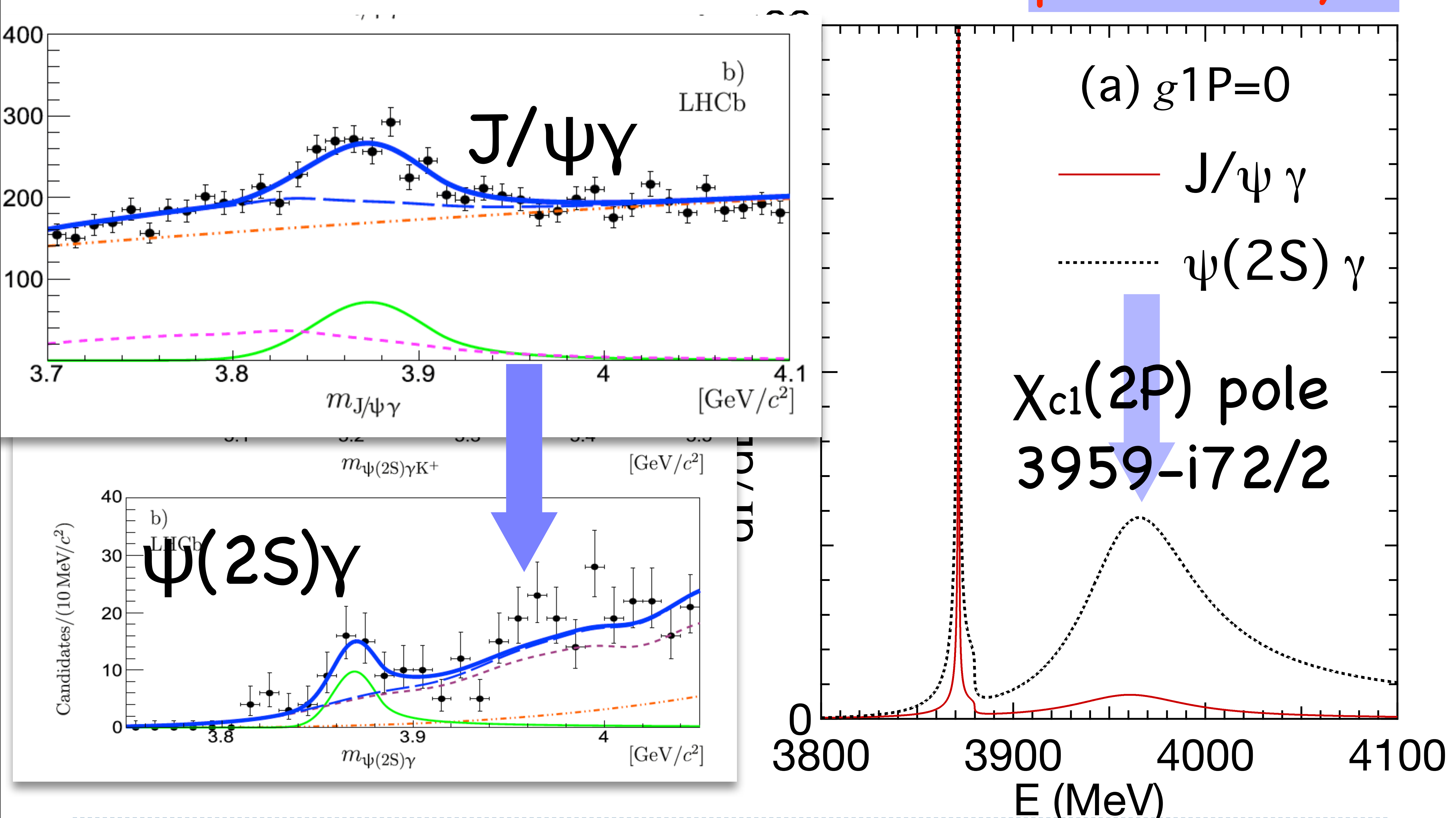
= 3.43

  - ψ(2S)γ spectrum shows the χ_{c1}(2P) pole.



Radiative decay : γ spectrum

preliminary



2016年 2月 29日 月曜日

Summary

- Radiative decay of X(3872) is calculated by using the model which includes
  - $\chi_{c1}(1P)$ - $c\bar{c}(2P)$ - $D^0\bar{D}^{*0}$ - D^+D^{-*} - $J/\psi\omega$ - $J/\psi\rho$
- X(3872) feature can be explained by a two-meson molecule with the $c\bar{c}$ components.
- The structure of X(3872), such as $\chi_{c1}(2P)$ pole may be seen in the radiative decay spectrum.
- The ratio of the decay is sensitive to the $\chi_{c1}(1P)$ component.

$$R_\gamma = \frac{B(X(3872) \to \psi(2S)\gamma)}{B(X(3872 \to J/\psi\gamma)}$$