$c\bar{c}$ -pentaquarks by a quark model

Sachiko Takeuchi (Japan College of Social Work)

work with

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M. Takizawa (Showa Pharmaceutical U)

MENU2016@Kyoto U (26Jul.2018)

The LHCb pentaquarks are the color-octet baryons?

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Introduction

Pc Pentaquarks: $uudc\bar{c}$

- Pc(4380), Pc(4450)
  - Found in the $\Lambda_b \to J/\psi$ K p decay, by LHCb
  - JP = (3/2-,5/2+)   (or (3/2+,5/2-) or (5/2+,3/2-))

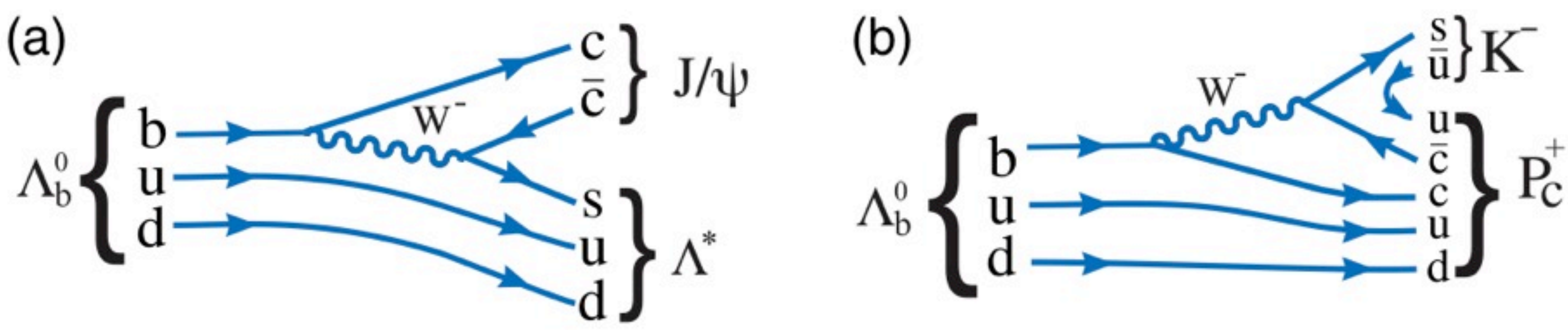
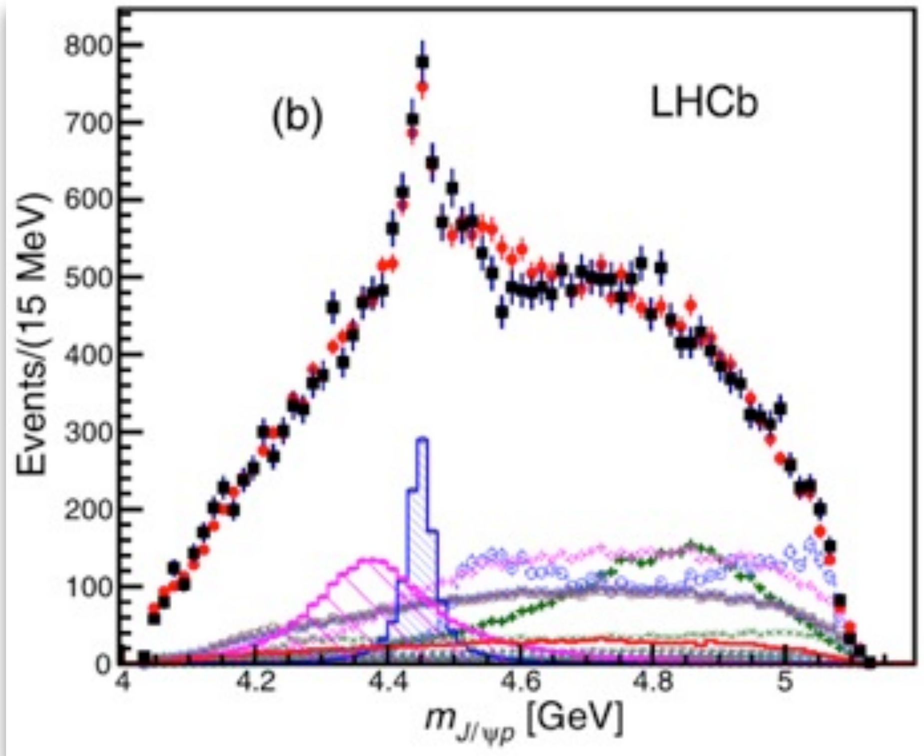


FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

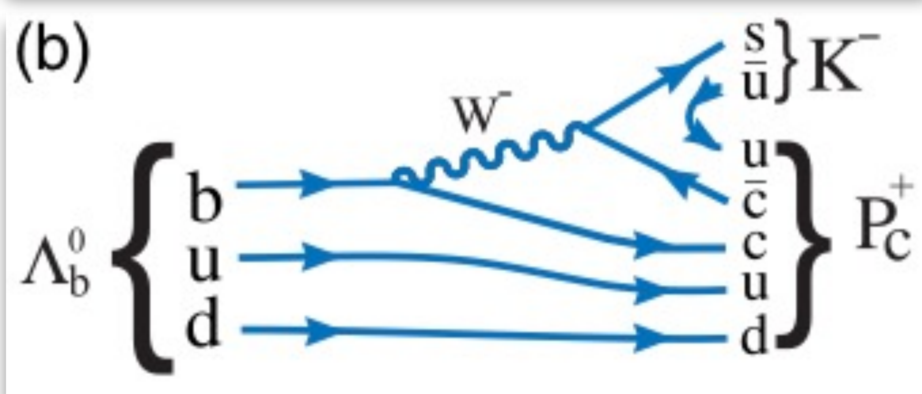
LHCb,PRL115(2015)07201

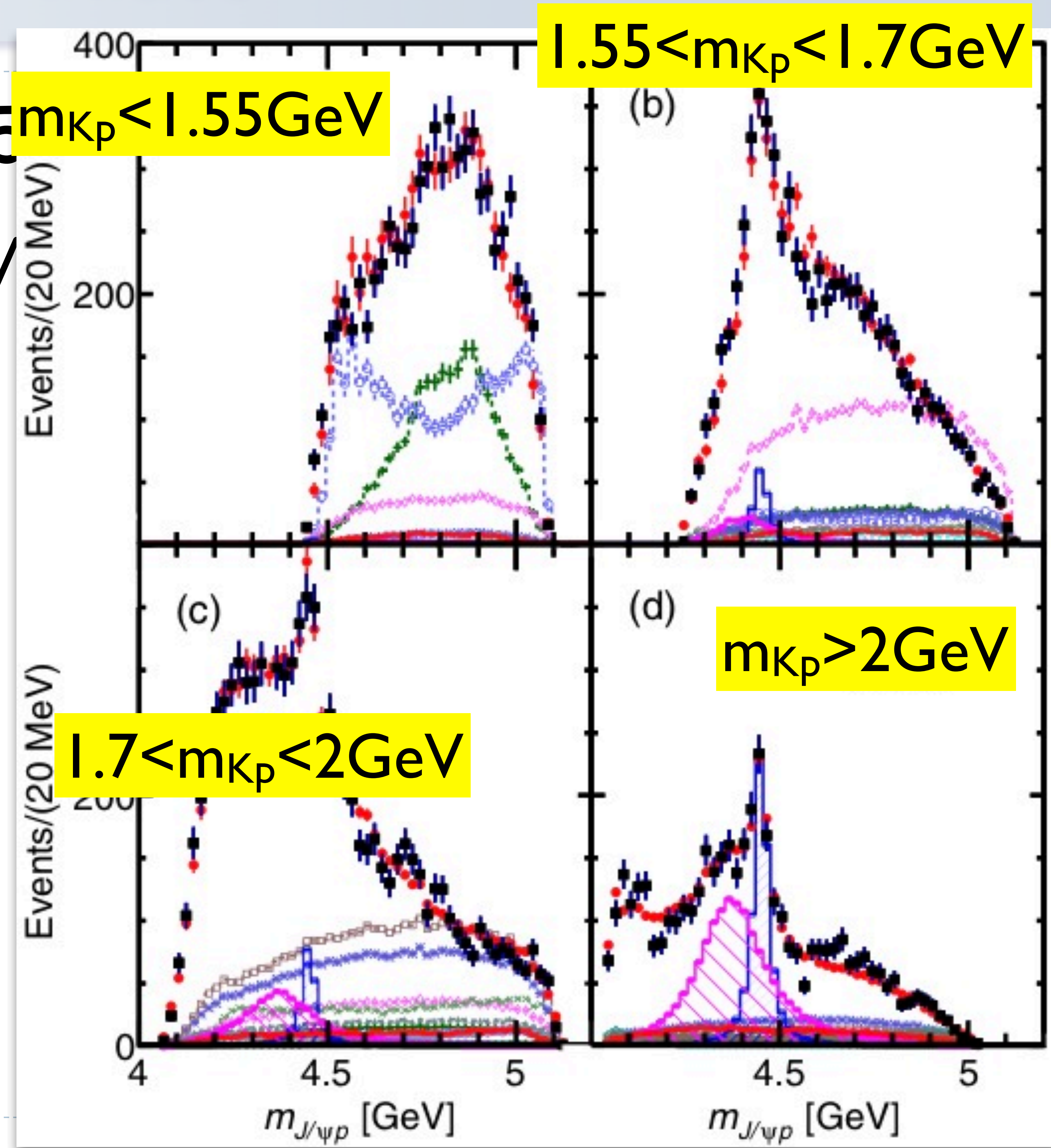
Pc Pentaquarks: $uudc\bar{c}$

- Pc(4380), Pc(445



→J/

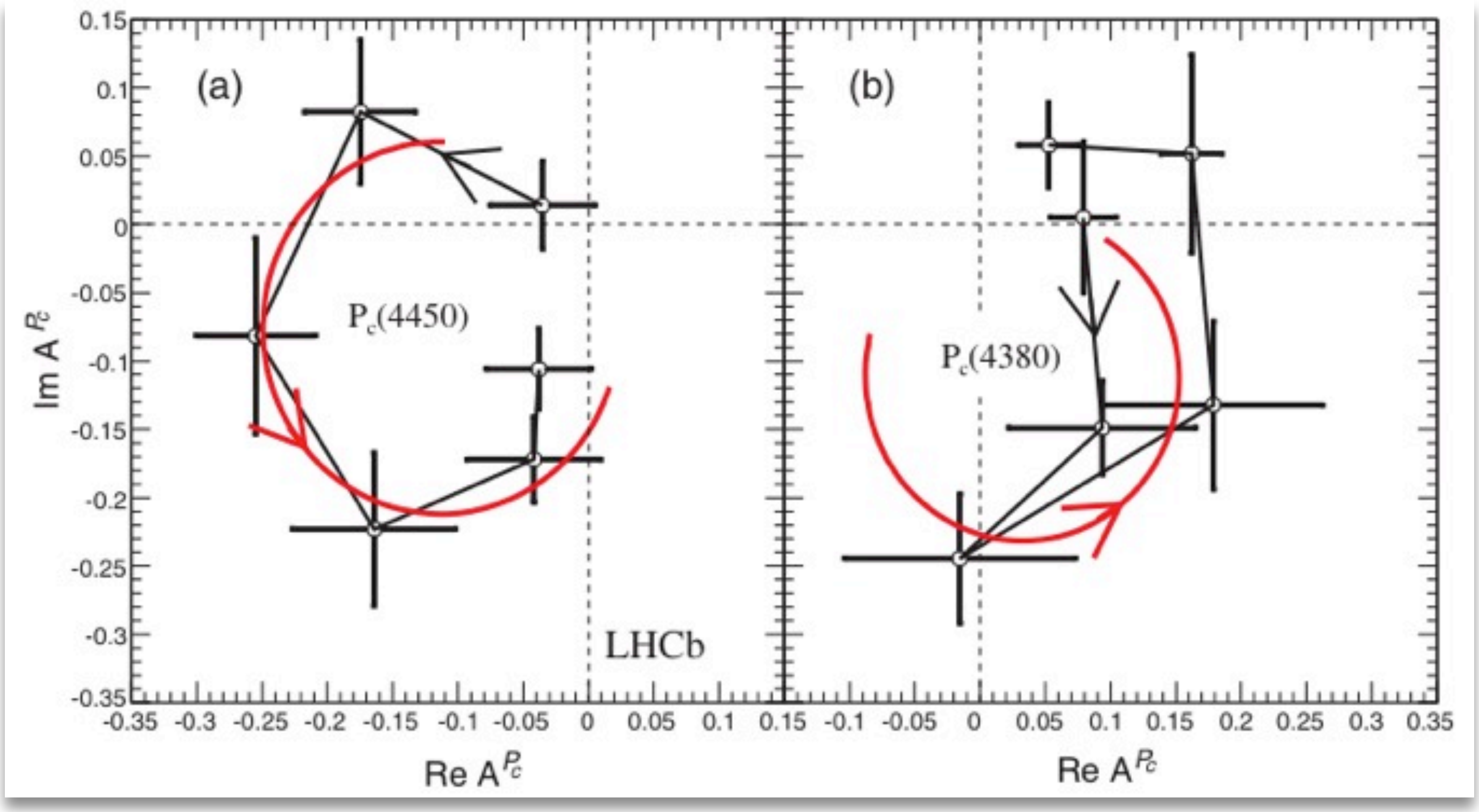




So, they are sure...

Pc Pentaquarks: uud$c\bar{c}$

- Pc(4380), Pc(4450)
  - Found in the Λb→J/ψ K p decay, by LHCb



So, they are sure that there are two peaks!

LHCb,PRL115(2015)07201

Pentaquark $P_c^+(4380)$ $P_c^+(4450)$

- In the $\Lambda_b \rightarrow J/\psi\, K^- p$ decay, mass(J/ψ p) has two peaks:
  - Pc(4450)
    - m =4449.8±1.7±2.5MeV
    - Γ =39±5±19MeV
  - Pc(4380)
    - m =4380±8±29MeV
    - Γ =205±18±86MeV
- seems parity opposite, JP = (3/2−,5/2+)
  - (or (3/2+,5/2−) or (5/2+,3/2−))

Negative parity → $qqqc\bar{c}$ S-wave

Neg. parity uudcc^{bar} isospin 1/2 BM Thresholds

▷ $\Sigma c^* + D^{bar*}$	4524.5 MeV	
▷ $\Sigma c + D^{bar*}$	4459.9 MeV	← $P_{c(4450)}$
▷ $\Sigma c^* + D^{bar}$	4382.3 MeV	← $P_{c(4380)}$
▷ $\Sigma c + D^{bar}$	4320.8 MeV	
▷ $\Lambda c + D^{bar*}$	4293.4 MeV	
▷ $\Lambda c + D^{bar}$	4153.7 MeV	
▷ $p + J/\psi$	4035.2 MeV	
▷ $p + \eta c$	3922.5 MeV	

JP=1/2-

Neg. parity uudcc^{bar} isospin 1/2 BM Thresholds

▷ Σ_c^*+D^{bar*}	4524.5 MeV	
▷ Σ_c+D^{bar*}	4459.9 MeV	← $P_c(4450)$
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▷ Λ_c+D^{bar*}	4293.4 MeV	
▷ Λ_c+D^{bar}	4153.7 MeV	
▷ p+J/ψ	4035.2 MeV	
▷ p+η_c	3922.5 MeV	

JP=3/2-

Neg. parity uudcc^{bar} isospin 1/2 BM Thresholds

▷ $\Sigma c^* + D^{bar*}$	4524.5 MeV	
▷ $\Sigma c + D^{bar*}$	4459.9 MeV	← $P_{c(4450)}$
▷ $\Sigma c^* + D^{bar}$	4382.3 MeV	← $P_{c(4380)}$
▷ $\Sigma c + D^{bar}$	4320.8 MeV	
▷ $\Lambda c + D^{bar*}$	4293.4 MeV	
▷ $\Lambda c + D^{bar}$	4153.7 MeV	
		JP=5/2-
▷ $p + J/\psi$	4035.2 MeV	
▷ $p + \eta c$	3922.5 MeV	

Pc Pentaquarks: $uud c\bar{c}$ Questions

- What is the mechanism to 'bind' the N and J/ψ ?
  - channel coupling to $\Lambda c\bar{D}$ and $\Sigma c\bar{D}$.
- Pc(4380), Pc(4450) are around thresholds ... threshold effect?
  - Thresholds are important, but the states exist.
- No clear peak is found in the $\pi N \to NJ/\psi$ may contradict with Pc's (Kim Kim Hosaka 1605.02919)?
  - Pc has very small decay fraction into N J/ψ ?? Need to check.
- S-wave Quark model gives only negative parity.
- Pentaquarks other than P_c ?
  - How about $_{\Lambda}P_c$? Need to check.

Contents

introduction

Quark model - idea

Phenomenological way to determine the interaction

single hadrons

Group theoretical method to evaluate the hyperfine splitting
color-octet baryons
  uudcc^{bar}

Pentaquark Pc by QM
(Baryon meson scattering by quark cluster model)

Other quark models

- Quark model (OGE + OBE, Chiral)
  - Pc(4380) is a bound state of $\Sigma_c D^*$? (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]

Quark model

low energy phenomenological theory

- Dynamical variables: quarks, antiquarks
  - No dynamical gluons
  - No diquarks
- Potential between quarks and antiquarks
  - Confinement ∼ (λ.λ) r

$$H_q = K + V_{\rm conf} + V_{\rm coul} + V_{\rm CMI}$$

  - One-gluon exchange: Coulomb, color-magnetic interaction.
  - Short range nonperturbative effects: instanton induced interaction.
  - light meson exchange: π σ-exchange force

Model hamiltonian

- Kinetic term:
  - Non-relativistic (to deal with scattering states):

$$K = \sum K_i \qquad K_i = m_i + \frac{1}{2m_i}\left(\boldsymbol{p}_i - \frac{m_i}{M_G}\boldsymbol{P}_G\right)^2$$

- Confinement term:
  - linear confinement: a_c ← LatticeQCD (Kawanai Sasaki)
  - constant term: c_1, c_2, c_{qqbar} ← qqq qq^{bar} mass fitting

$$V_{\mathrm{conf}} = \sum_{i<i} \lambda_i \cdot \lambda_j \left(-a_c r_{ij} + c_1 + \frac{c_2^2}{\mu_{ij}} + c_{q\bar{q}}\right)$$

Model hamiltonian

- one-gluon exchange term:
  - quark is static, plane wave, Brite potential for the vector particle exchange.
  - Take the lowest order (p/m) term of each spin operator: 1, σ.σ, LS, tensor. (No LS tensor is used this time)
  - Strong coupling constant, $\alpha_s(Q^2)$:

$$V_{\text{coul}} = \frac{\lambda \cdot \lambda}{4} \frac{\alpha_s}{r}$$

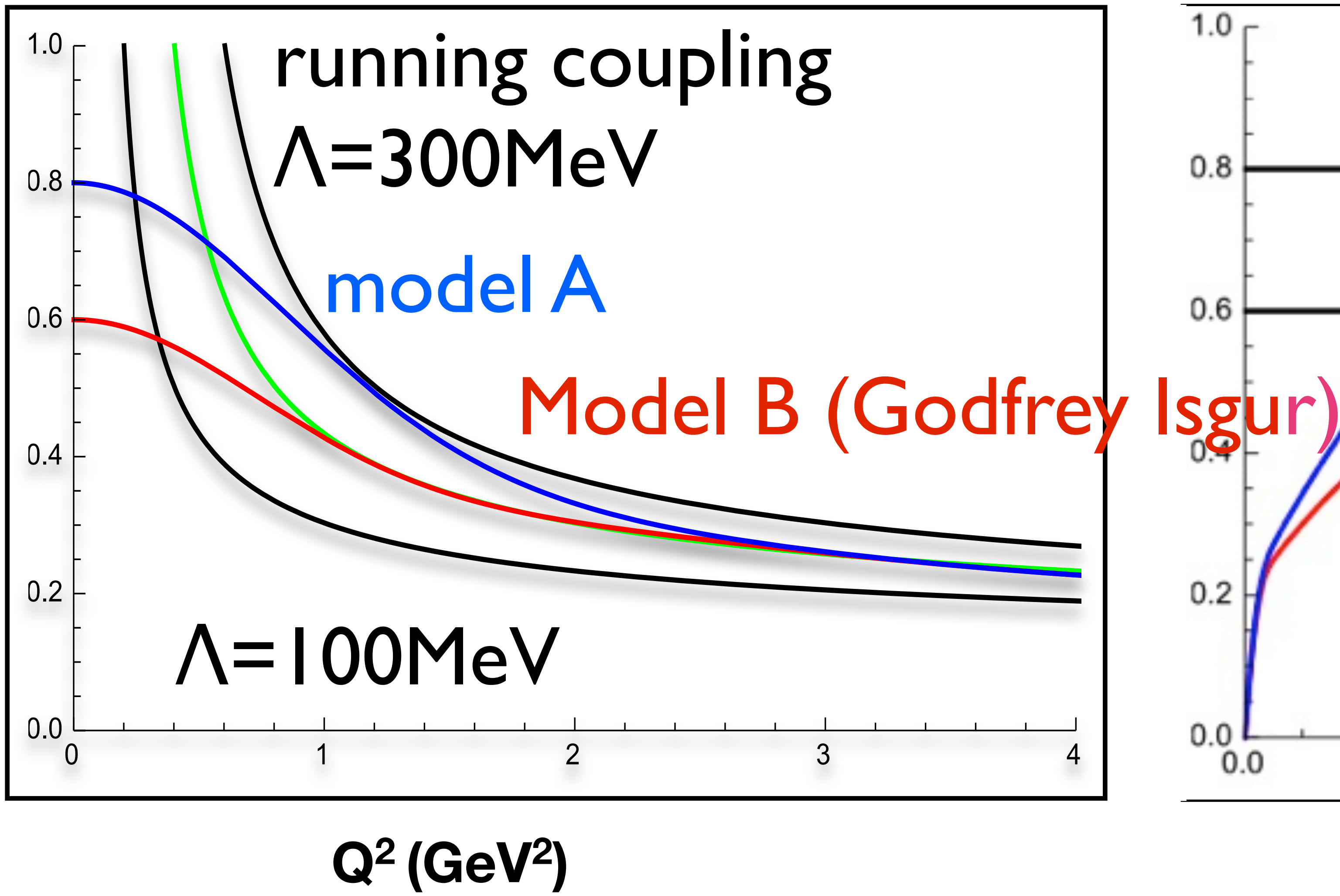
$$\alpha_s = \alpha_s^{(0)} + \frac{\alpha_s^{(1)}}{\mu} \quad \text{(Yoshida etal)}$$

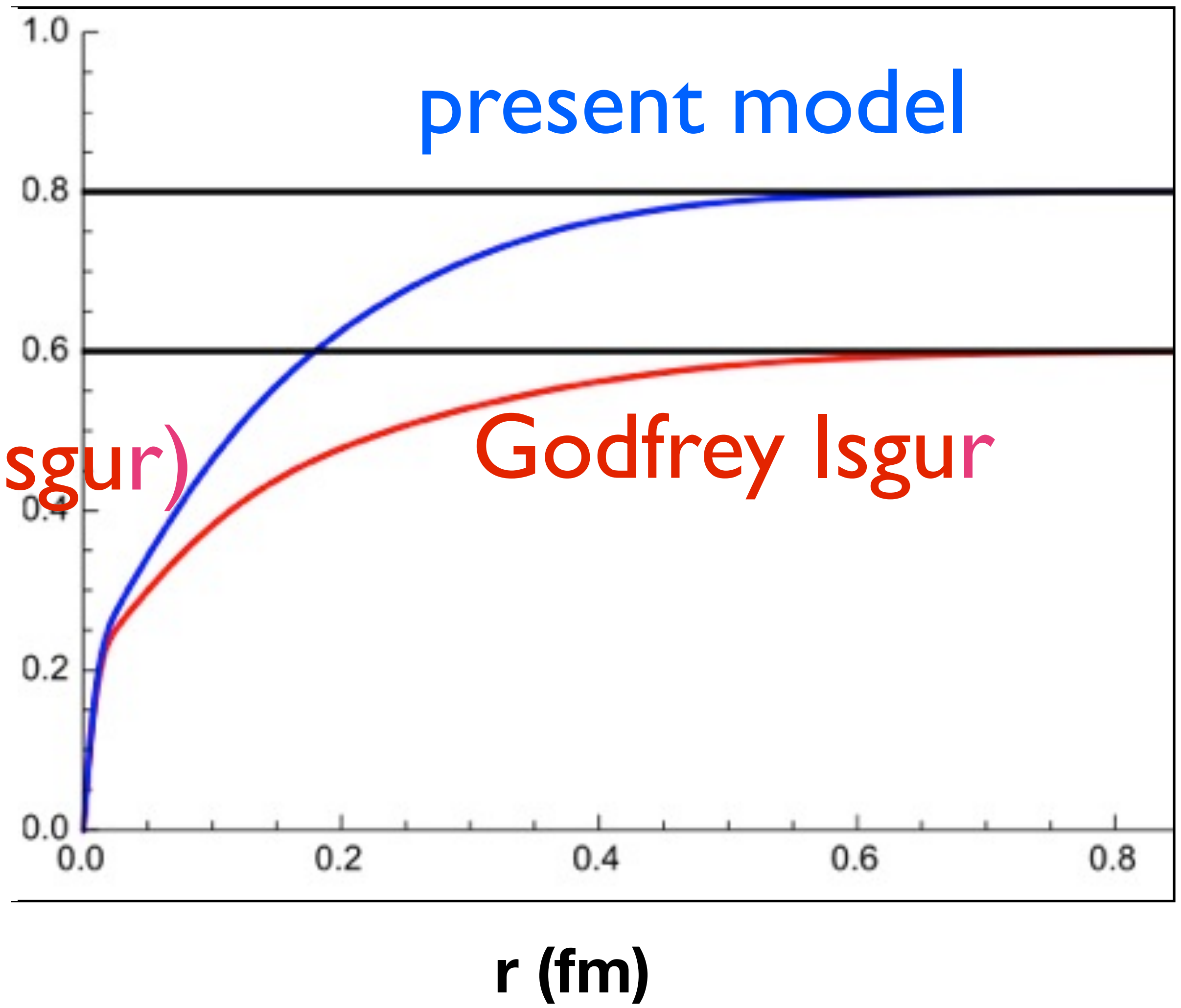
$$\alpha_s = 0.25 e^{-Q^2} + 0.15 e^{-Q^2/10} + 0.20 e^{-Q^2/1000} \quad \text{(Godfrey Isgur 86)}$$

$$\alpha_s = 0.45 e^{-Q^2/\frac{3}{2}} + 0.15 e^{-Q^2/10} + 0.20 e^{-Q^2/1000} \quad \text{(modified GI)}$$

Model hamiltonian

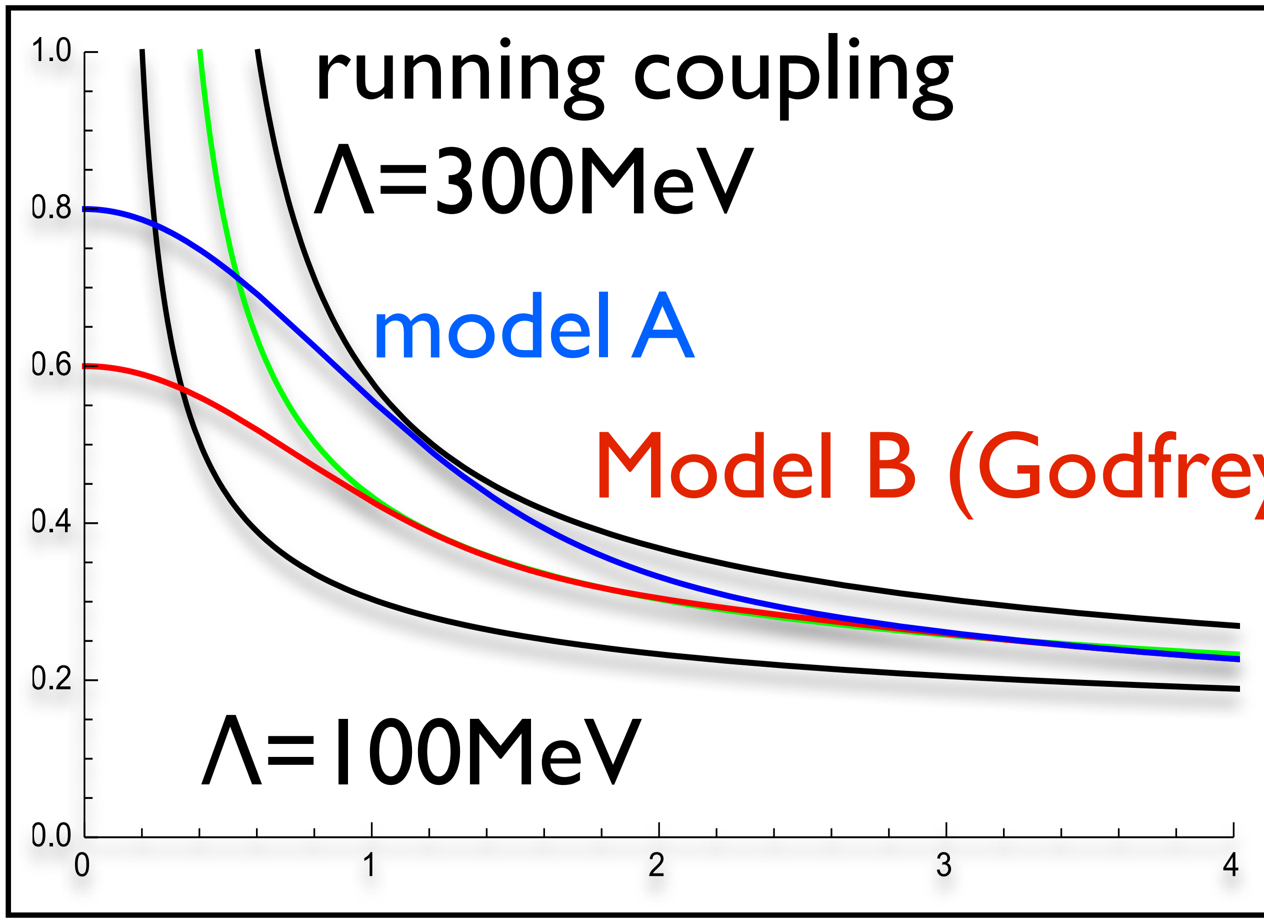
- Strong coupling constant, α_s:



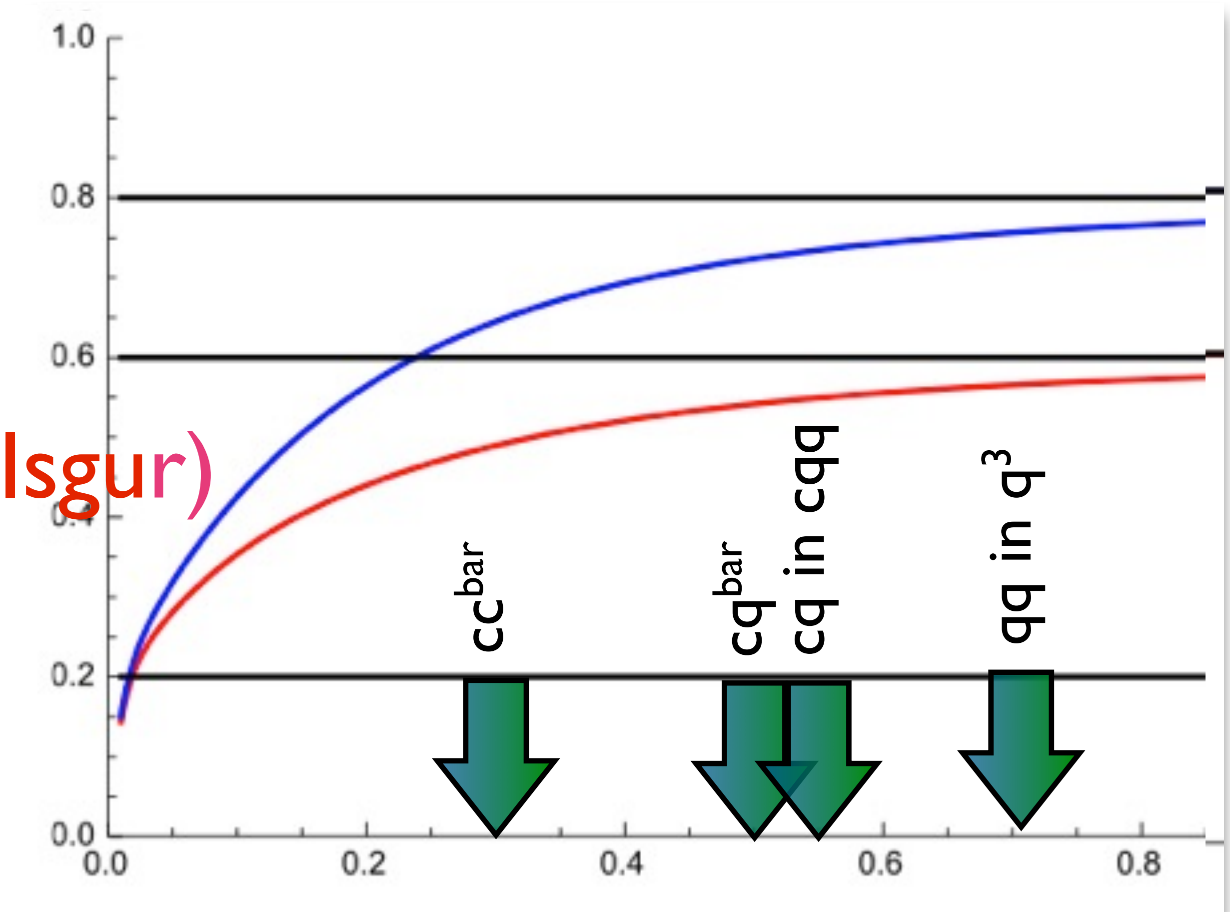


Model hamiltonian

- Strong coupling constant, α_s:



Q^2 (GeV^2)



b (fm)

Model hamiltonian

- Color magnetic interaction (CMI)

$$V_{\mathrm{CMI}} = -\frac{\lambda \cdot \lambda}{4} \alpha_s \frac{2\pi}{3 m_i m_j} \sigma \cdot \sigma \delta^3(\boldsymbol{r})$$

- This should be the same coupling constant, but we take it as a parameter:

$\alpha_s^{ss} = \alpha_{s1}^{ss} + \alpha_{s2}^{ss} \frac{m_u}{\mu}$ for quark-quark

α_{s3}^{ss} for quark-antiquark

quark model parameters (fit to hadron m)

- parameters
  - fitting all the S-wave qq^{bar} qqq charm hadron masses

(in MeV)

	$m_u(=m_d)$	m_s	m_c	m_b	c_1	c_2	$c_{q\bar{q}}$
A	300	510	1741.5	5110.9	86.4	113.9	−5.65
B	300	510	1723.7	5079.2	109.2	107.9	−6.04

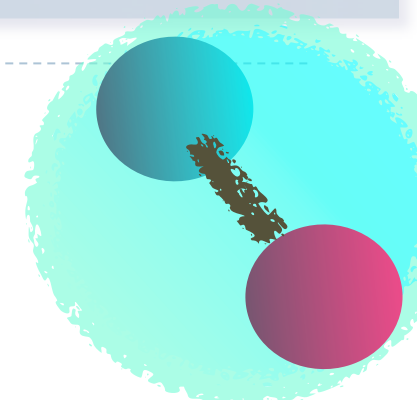
a_c
196.9 MeV/fm

← 1.05GeV/fm for mesons

	αs	α_{s1}^{ss}	α_{s2}^{ss}	α_{s3}^{ss}
A	Stronger (blue line)	−1.0967	0.4756	0.5668
B	Weaker (red line, GI)	0.7869	0	0.7869

Model wave function

Orbital wave functions



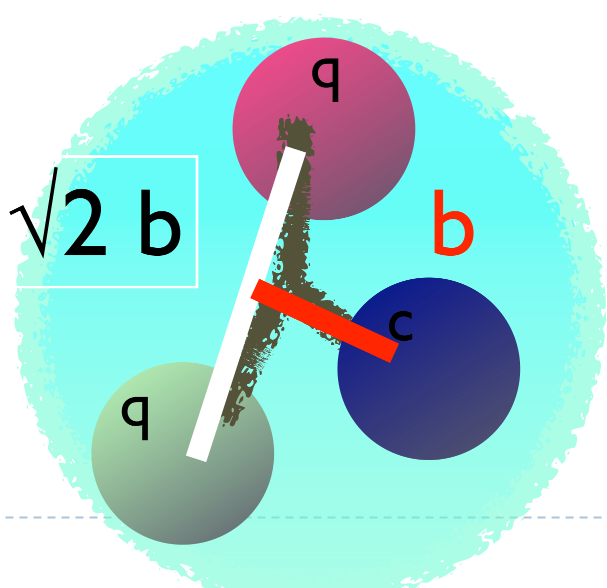
- meson

$$\psi_m(\boldsymbol{r}, x_0) = \phi(\boldsymbol{r}_{12}, b_{12}) = N_m \exp[-\frac{1}{2b_{12}^2} r_{12}^2] = N_m \exp[-\frac{1}{2}\frac{\mu_{12}}{x_0^2} r_{12}^2]$$

- baryons

$$\psi_b(\boldsymbol{r}, x_0) = \phi(\boldsymbol{r}_{12}, b_{12})\phi(\boldsymbol{r}_{12-3}, b_{12-3}) = N_b \exp[-\frac{1}{2}\frac{\mu_{12}}{x_0^2} r_{12}^2 - \frac{1}{2}\frac{\mu_{12-3}}{x_0^2} r_{12-3}^2]$$

- minimize H (w/o CMI) by x_0 for each $q_1 q_2^{bar}$ or $q_1 q_2 q_3$.



$b = \sqrt{m_q/\mu}\, b \sim \sqrt{0.7}\, b$

ratio of b and b is fixed for simplicity.
which is given by reduced mass of quarks
→ charm has smaller size parameter.

Hadron mass - mesons

	x0	obs	calc
pi	0.53	138	282
rho	0.53	775	710
phi	0.56	1020	1020
etac	0.61	2984	2981
Jpsi	0.61	3097	3101
etab	0.62	9398	9395
Ups	0.62	9460	9460
K	0.54	496	541
K*	0.54	894	873
		(MeV)	(MeV)

	x0	obs	calc
D	0.56	1867	1863
D*	0.56	2009	2005
Ds	0.58	1968	1969
Ds*	0.58	2112	2113
B	0.56	5280	5276
B*	0.56	5319	5331
Bs	0.59	5367	5356
Bs*	0.59	5415	5417
Bc	0.62	6275	6255
Bc*	0.62	-	6326

Hadron mass - baryons

	x0	obs	calc
Delta	0.60	1232	1261
Sig*	0.61	1385	1394
Xi*	0.62	1533	1523
Omg	0.63	1672	1647
Sigc*	0.62	2518	2516
Xic*	0.63	2646	2630
Omgc*	0.65	2766	2736
Xicc*	0.65	-	3681
Sigb*	0.62	5835	5847
	No mixing for Xic yet		

	x0	obs	calc
N	0.60	939	922
Sig	0.61	1193	1189
Lam	0.61	1116	1111
Xi	0.62	1318	1328
Sigc	0.62	2454	2454
Lamc	0.62	2287	2292
Xic	0.63	2469	2491
Xic'	0.63	2577	2582
Omgc	0.65	2695	2702
Xicc	0.65	-	3626
Sigb	0.62	5813	5828
Lamb	0.62	5620	5640

Size parameters of qq′

- $b = x0/\sqrt{\mu}$ seems valid approximation.
  - b_{qq} in qqq is close to the b_{qq} in qqc system → close to the value of the independent minimization.

b_{ij} (fm)		b_{qq}	b_{qc}	b_{cc}	b_{qb}	b_{bb}
baryons	qqq	0.68				
	qqc	0.71	0.54			
	qcc		0.57	0.31		
	qqb	0.71			0.52	
	qbb				0.55	0.18
mesons		0.61	0.49	0.29	0.47	0.17

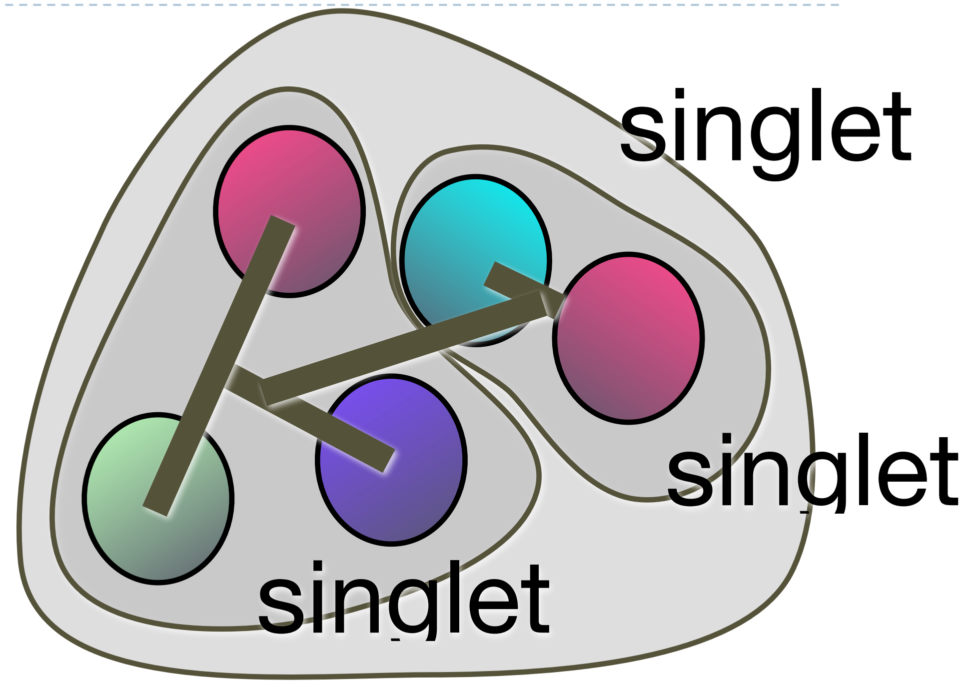
Hadron masses by QM

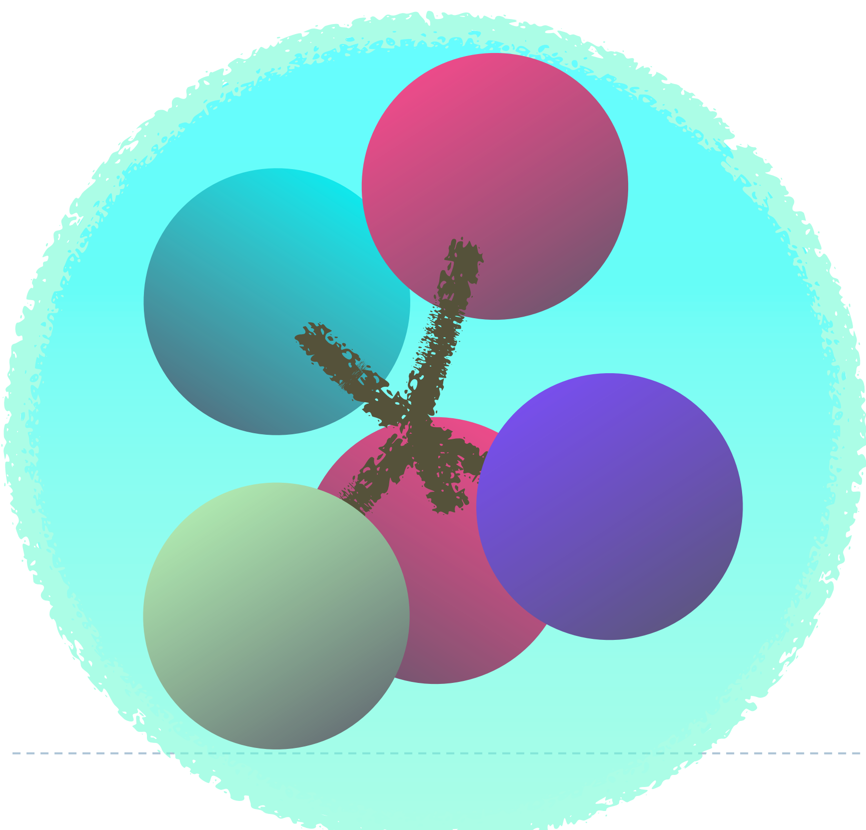
- The quark model which produces qqq qq^{bar} hadron masses is obtained.
  - nonrela, conf, color-Coulomb, color-magnetic int
  - heavy quark's size parameter is $1/\sqrt{m_Q}$.

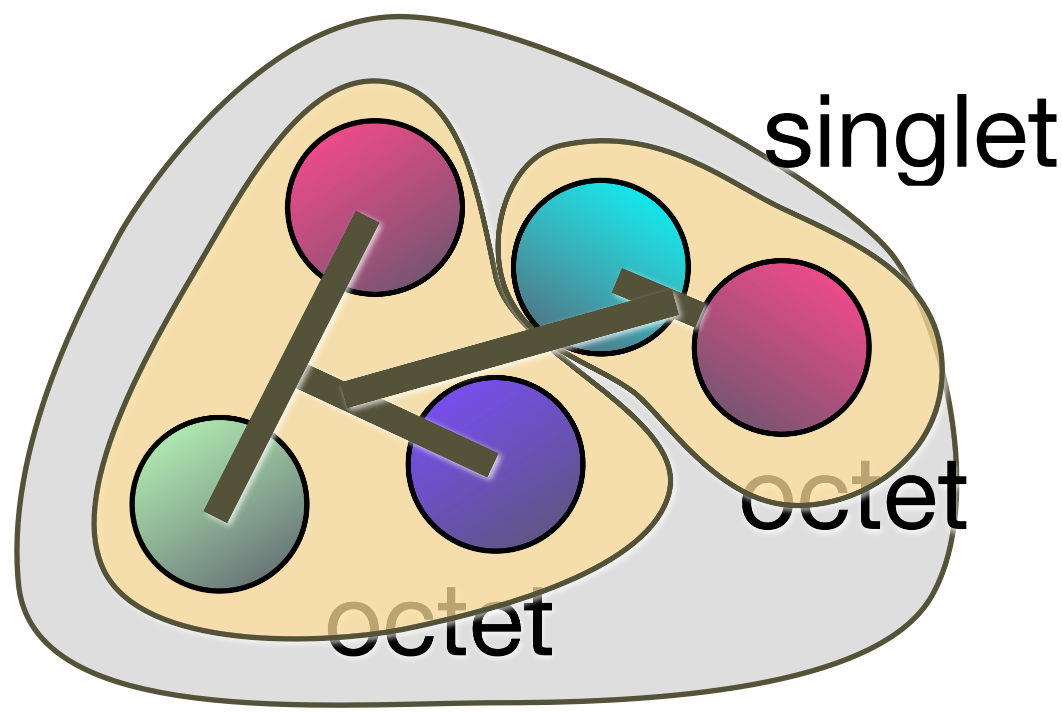
$(0s)^n$ Quark Model: the spin color flavor sym.

uudccbar I(JP)=1/2(J-)

- S-wave 5 quark systems
  - total: color singlet
  - ccbar part: color singlet or octet
  - → uud part: color singlet or octet

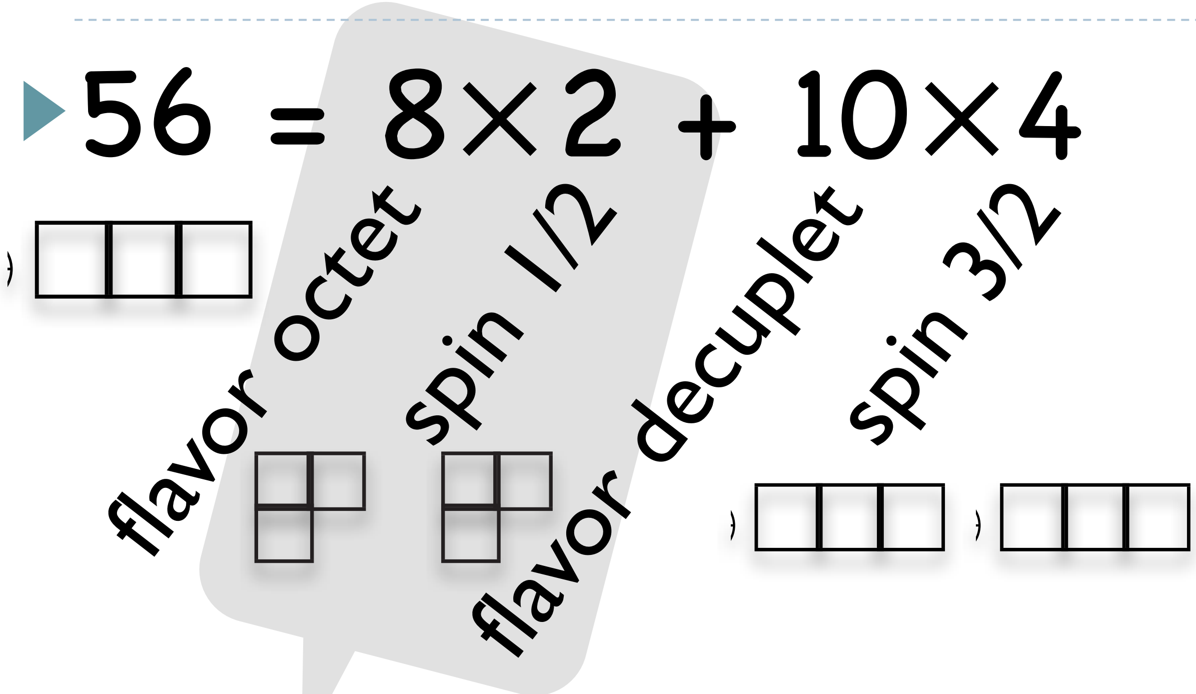


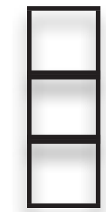


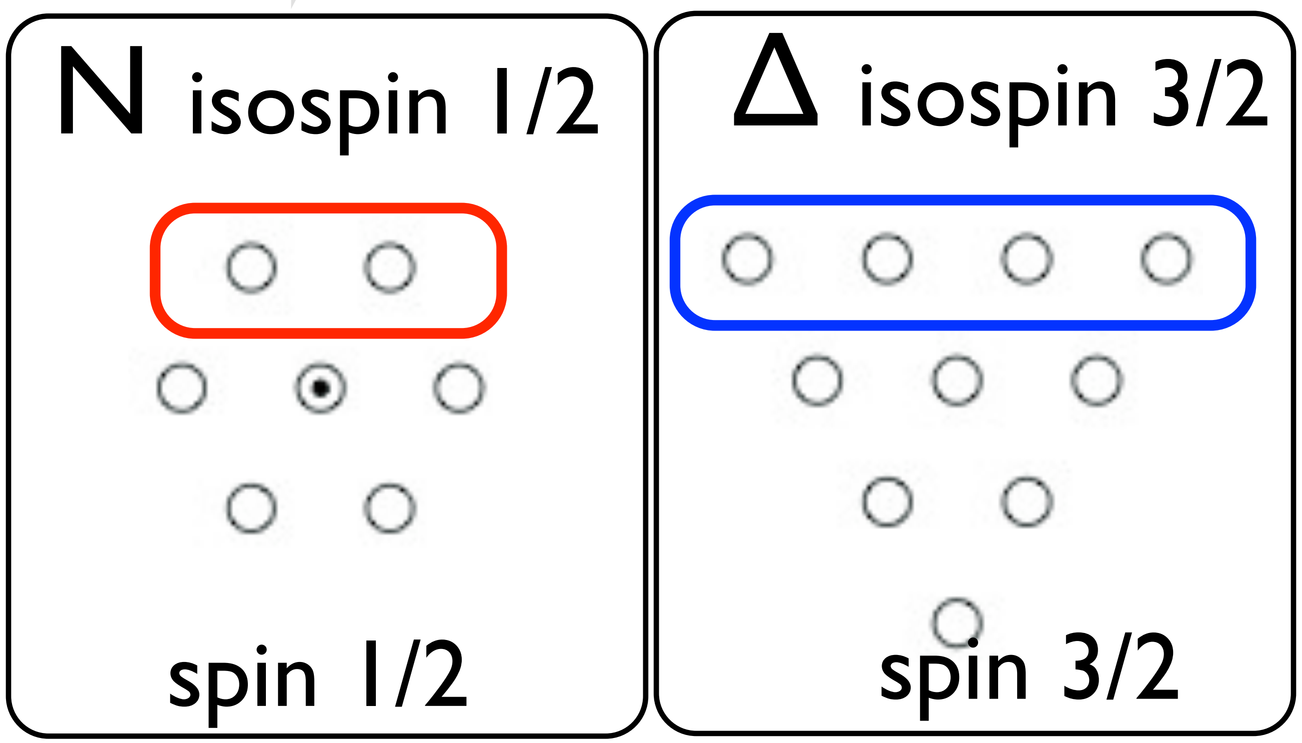


flavor-spin SU(6) for uud

- $56 = 8 \times 2 + 10 \times 4$ for color singlet uud

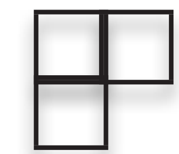




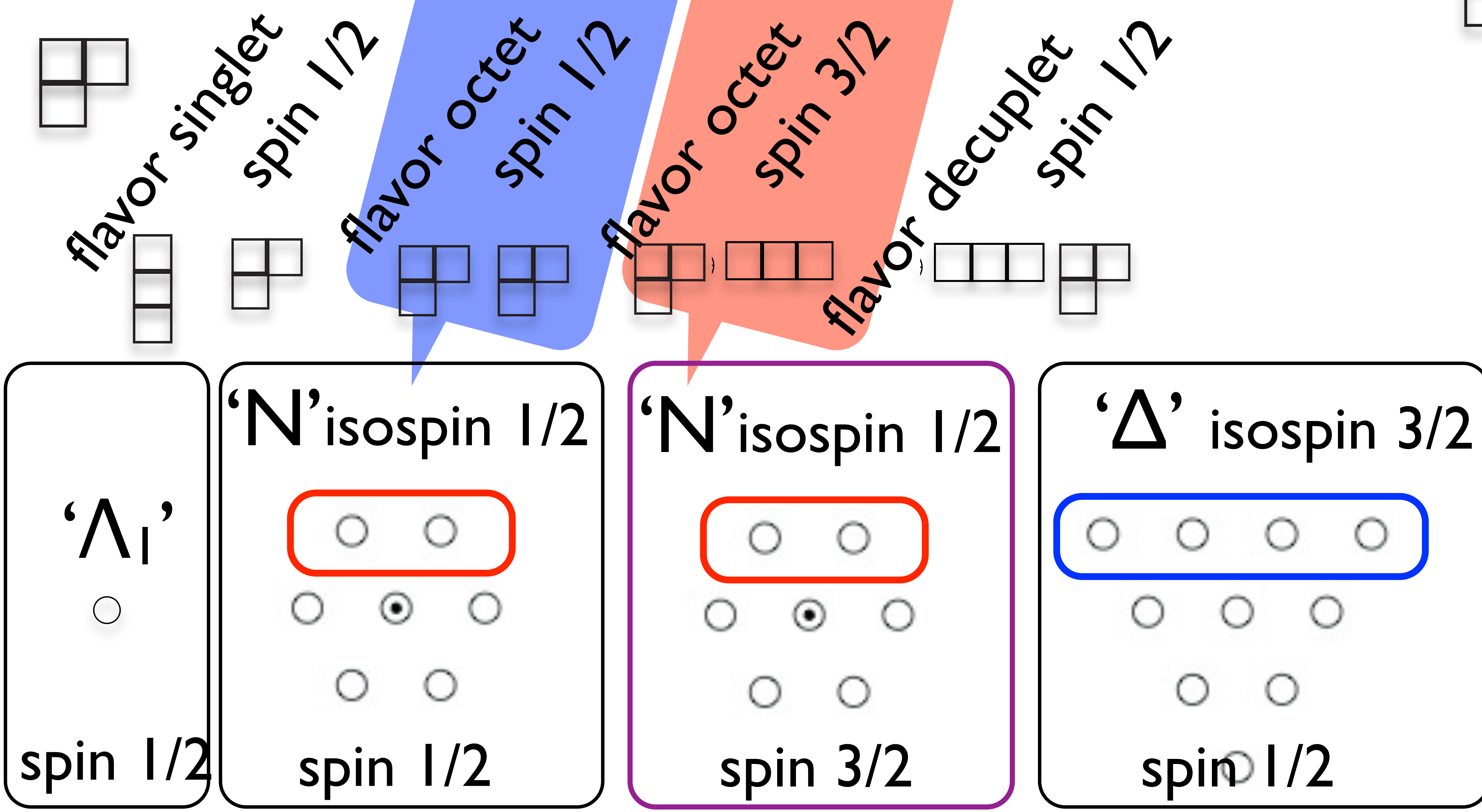


flavor-spin SU(6) for uud

for color octet



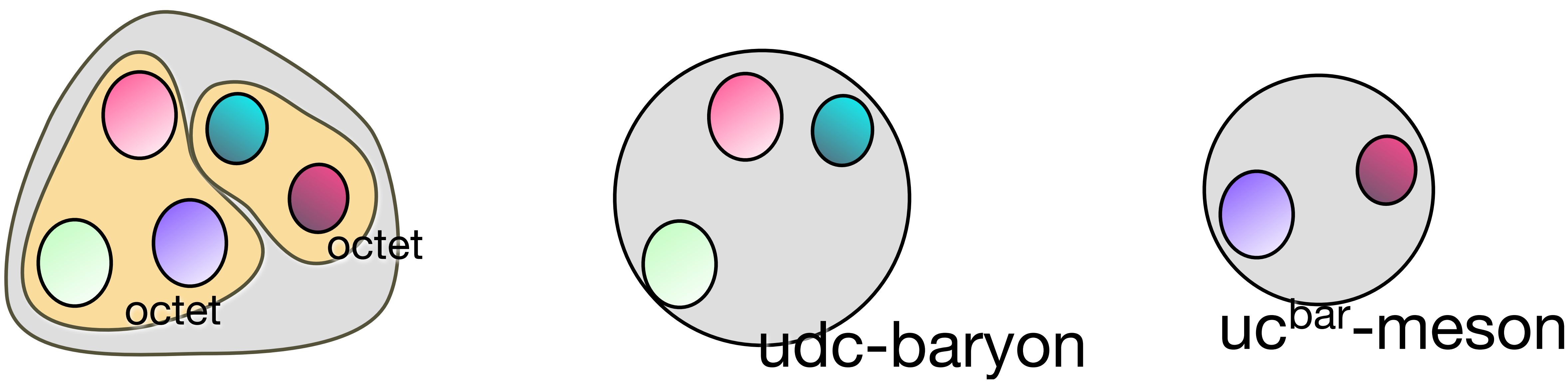
- $72 = 1\times2 + 8\times2 + 8\times4 + 10\times2$



flavor-spin SU(6) for uud

- isospin 1/2 uud in uudcc^{bar}
  - color 1 spin 1/2 <Vcmi>= -8 ↔ <Vcmi>$_{thre}$= -8 (N)
  - color 8 spin 1/2 -2 -8 (Λc)
  - color 8 spin 3/2 +2 < +8/3 (Σc)

CMI is attractive at heavy quark limit!



flavor-spin SU(6) for uud

- isospin 1/2 uud in uudcc^{bar}

color 1 spin 1/2	$\langle Vcmi \rangle$= -8	$\leftrightarrow$ $\langle Vcmi \rangle_{thre}$=	-8 (N)
color 8 spin 1/2	-2		-8 (Λc)
color 8 spin 3/2	+2	<	+8/3 (Σc)

CMI is attractive at heavy quark limit!

- + spin 0 cc^{bar} → uudcc^{bar} isospin 1/2 spin 3/2
- + spin 1 cc^{bar} → uudcc^{bar} isospin 1/2 spin 1/2
- uudcc^{bar} isospin 1/2 spin 3/2
- uudcc^{bar} isospin 1/2 spin 5/2

4 states

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

- 1 BM S-wave channel:

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

- Color magnetic int → weak attraction

▷ <Vcmi>	HeavyQ	SU(4)f	estimate
V_{5q}	2	40/3	～ 80 MeV
$V_{3q}+V_{qqbar}$	8/3	40/3	～90 MeV
$V_{eff} = V_{5q} - V_{3q} - V_{qqbar}$	-2/3	0	～ -10 MeV

- Normalization <N> = 4/3 → attraction

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

- 5 BM S-wave 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:

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

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

Table 6: Normalization

	NJ/ψ	$\Lambda_c \overline{D}^*$	$\Sigma_c \overline{D}^*$	$\Sigma_c^* \overline{D}$	$\Sigma_c^* \overline{D}^*$
NJ/ψ	1	$-\sqrt{\frac{1}{6}}$	$-\sqrt{\frac{1}{54}}$	$\sqrt{\frac{1}{18}}$	$-\sqrt{\frac{5}{54}}$
$\Lambda_c \overline{D}^*$		$\frac{5}{6}$	$-\frac{1}{6}$	$\sqrt{\frac{1}{12}}$	$-\sqrt{\frac{5}{36}}$
$\Sigma_c \overline{D}^*$			$\frac{23}{18}$	$\sqrt{\frac{1}{108}}$	$-\sqrt{\frac{5}{324}}$
$\Sigma_c^* \overline{D}$				$\frac{7}{6}$	$\sqrt{\frac{5}{108}}$
$\Sigma_c^* \overline{D}^*$					$\frac{19}{18}$

No strong
quark Pauli blocking.

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

- 5 BM S-wave channels:

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

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

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

- 1 color-singlet c$\bar{c}$ states: NJ/ψ
- 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(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:

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

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

- 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

What we learn from $(0s)^n$ QM?

- We can construct a phenomenological model for single baryon or mesons (we can reproduce their masses.)

- It seems there are states which get attraction from CMI, in which qqq are color-octet spin 3/2:
  - uudcc^{bar} I(J^P)=1/2(5/2-) $\Sigma c^* D^{bar*}$
  - uudcc^{bar} I(J^P)=1/2(3/2-) $\Sigma c D^{bar*}$,$\Sigma c^* D^{bar}$
  - uudcc^{bar} I(J^P)=1/2(1/2-) $\Sigma c D^{bar}$

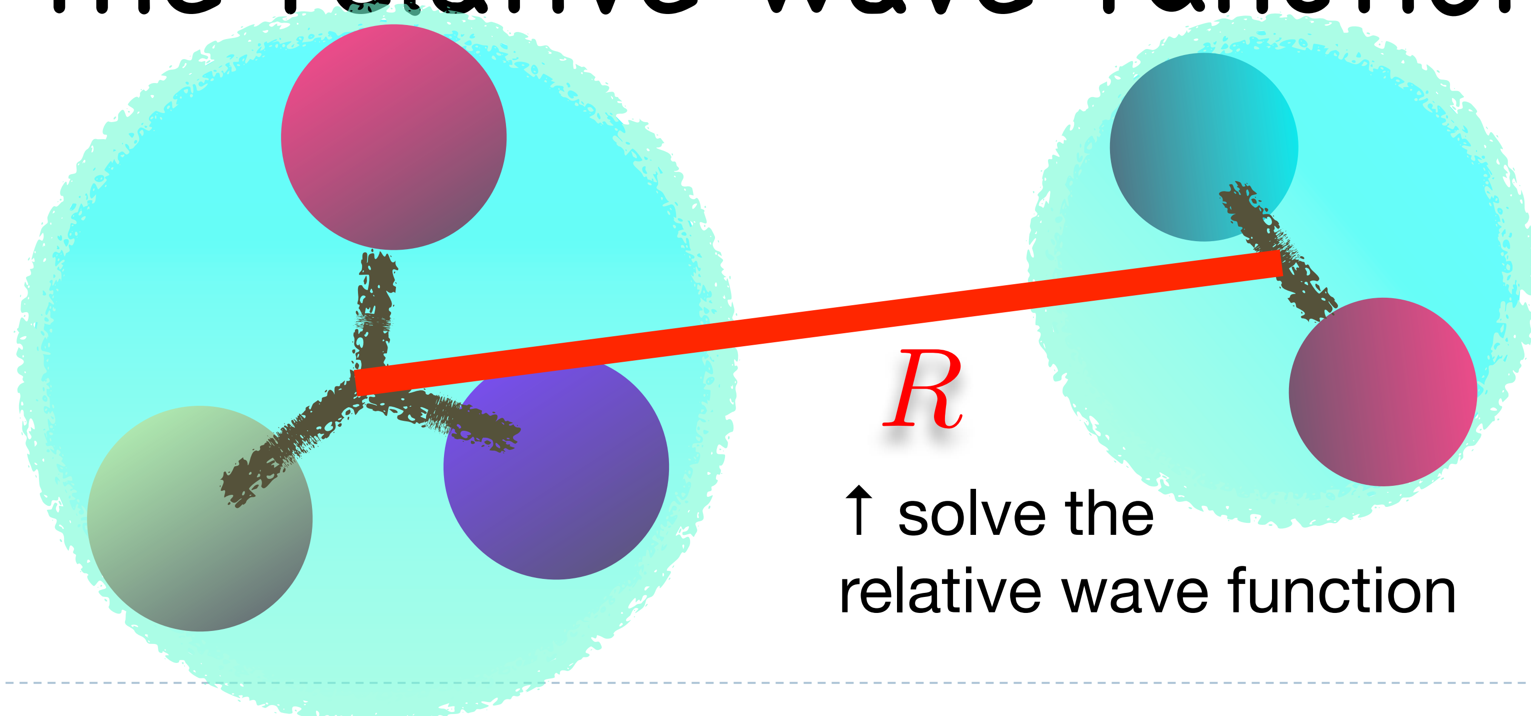
- Let's go to the dynamical calculation.

Baryon-Meson Scattering by Quark Cluster Model

MENU 2016 @ Kyoto U, Jul 26, 2016

Quark Cluster Model

- configuration
  - 2 clusters (B-M) whose orbital wave functions are the gaussian with the size parameter $b = x_0/\sqrt{\mu}$.
  - The quark antisymmetrization is fully introduced.
  - cc^{bar} does not vanish.
- Solve the relative wave function (function of R)



Quark Cluster Model

- Wave function:

$$\Psi(\xi_B, \xi_M, \boldsymbol{R}_{BM}) = \mathcal{A}[\phi_B(\xi_B)\phi_M(\xi_M)\chi(\boldsymbol{R}_{BM})],$$

$\mathcal{A} = 1 - 3P_{34}$ Antisymmetrization operator for q^4

$\phi_B(\xi_B)$ Single hadron gaussian wave function

$\phi_M(\xi_M)$ with the size parameter $x_0/\sqrt{\mu}$

- Resonating group method equation:

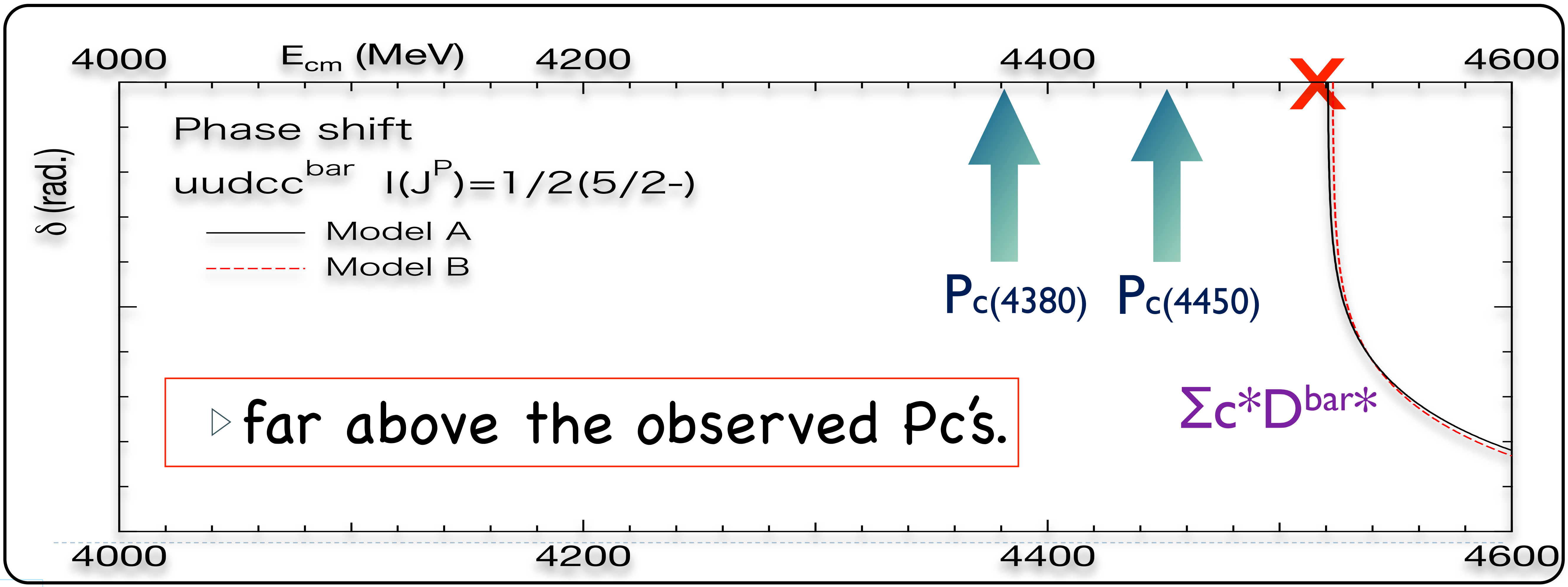
$$\int [H_{\mathrm{RGM}}(\boldsymbol{R}, \boldsymbol{R}') - E N_{\mathrm{RGM}}(\boldsymbol{R}, \boldsymbol{R}')]\chi(\boldsymbol{R}')\, d\boldsymbol{R}' = 0,$$

$$\begin{Bmatrix} H_{\mathrm{RGM}}(\boldsymbol{R}, \boldsymbol{R}') \\ N_{\mathrm{RGM}}(\boldsymbol{R}, \boldsymbol{R}') \end{Bmatrix} = \int \phi_B^\dagger(\xi_B)\phi_M^\dagger(\xi_M)\delta(\boldsymbol{R} - \boldsymbol{R}_{BM}) \begin{Bmatrix} H \\ 1 \end{Bmatrix} \times \mathcal{A}[\phi_B(\xi_B)\phi_M(\xi_M)\delta(\boldsymbol{R}' - \boldsymbol{R}_{BM})] d\xi_B d\xi_M d\boldsymbol{R}_{BM}.$$

Normalization/hamiltonian kernel

uudcc^{bar} I(JP)=1/2(5/2-) [$\Sigma c^*\bar{D}^*$]

- There is a very shallow bound state of $\Sigma c^* D^{bar*}$!
  - BE < 1MeV by both of the parameter sets A and B.
  - uud(0s)^3 compo = 0.2 (uud is in color 8 spin 3/2 config)
  - BE～10MeV for charm -> bottom

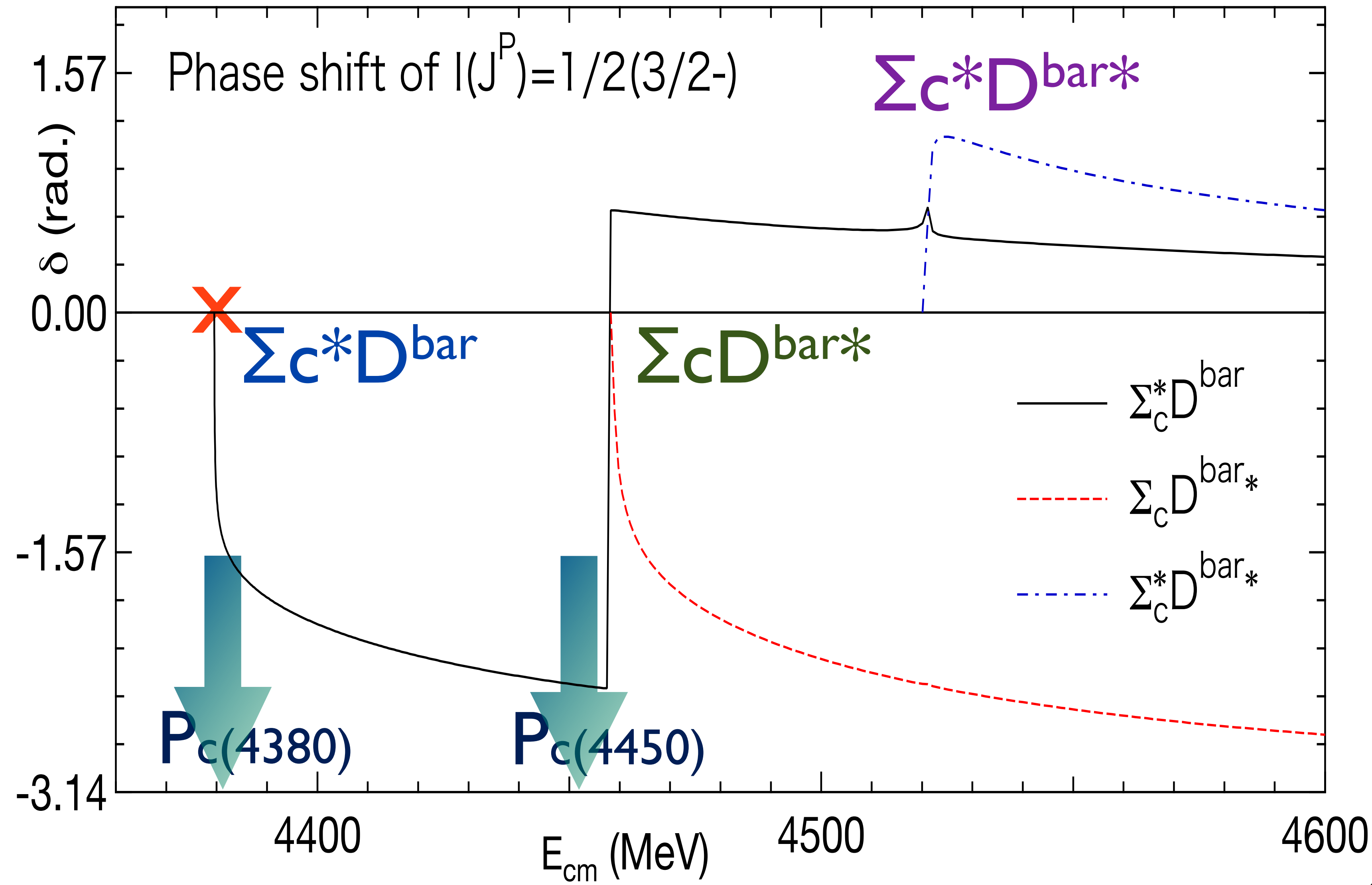


uudcc^{bar} I(JP)=1/2(3/2-) [NJ,$\Lambda c\bar{D}^*$,$\Sigma c^*\bar{D}$,$\Sigma c\bar{D}^*$,$\Sigma c^*\bar{D}^*$]

- 3 channel calc (Σc^*D^{bar}–ΣcD^{bar*}–Σc^*D^{bar*})
  - There is a bound state (just below Σc^*D^{bar} thre) and a (sharp) resonance (just below ΣcD^{bar*} thre)

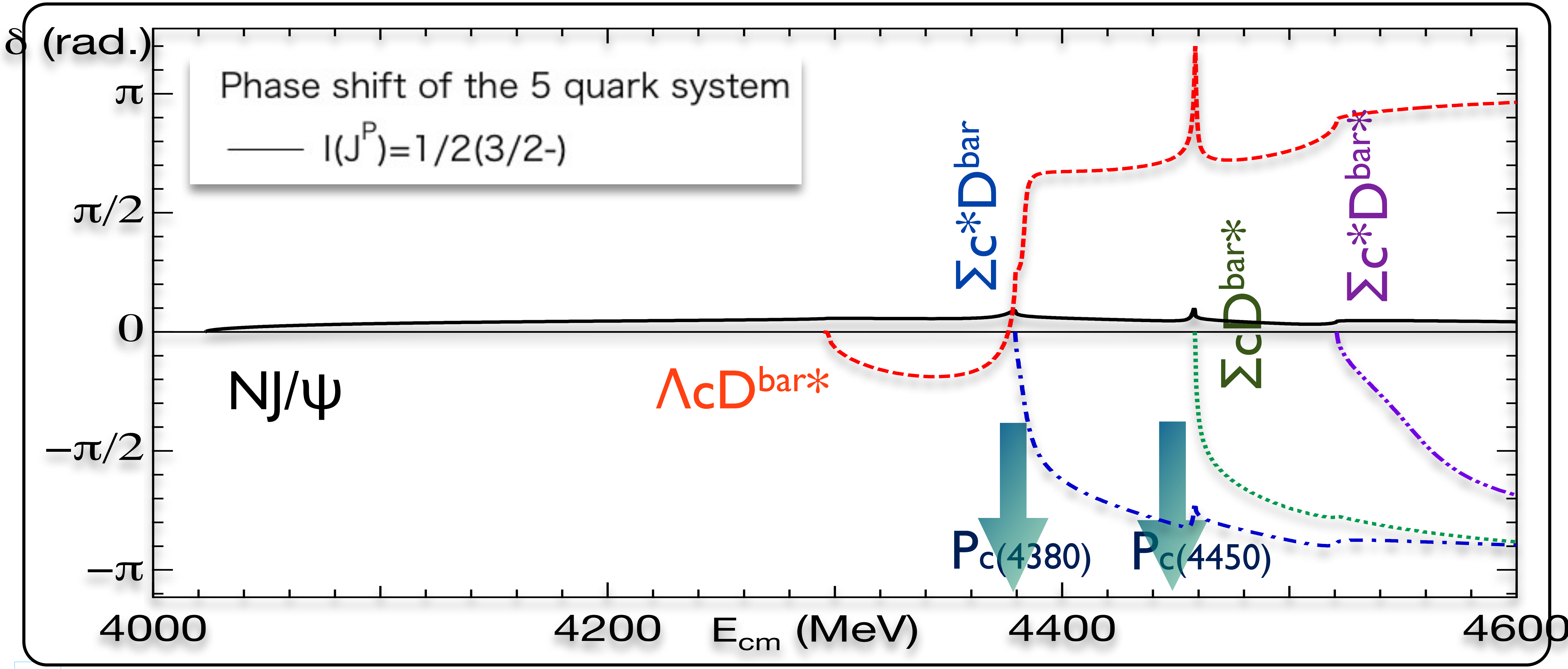
× B.E. = 0.08 MeV

Note: when $(0s)^3$, 2 color-octet spin 3/2 uud's in these 3 channles



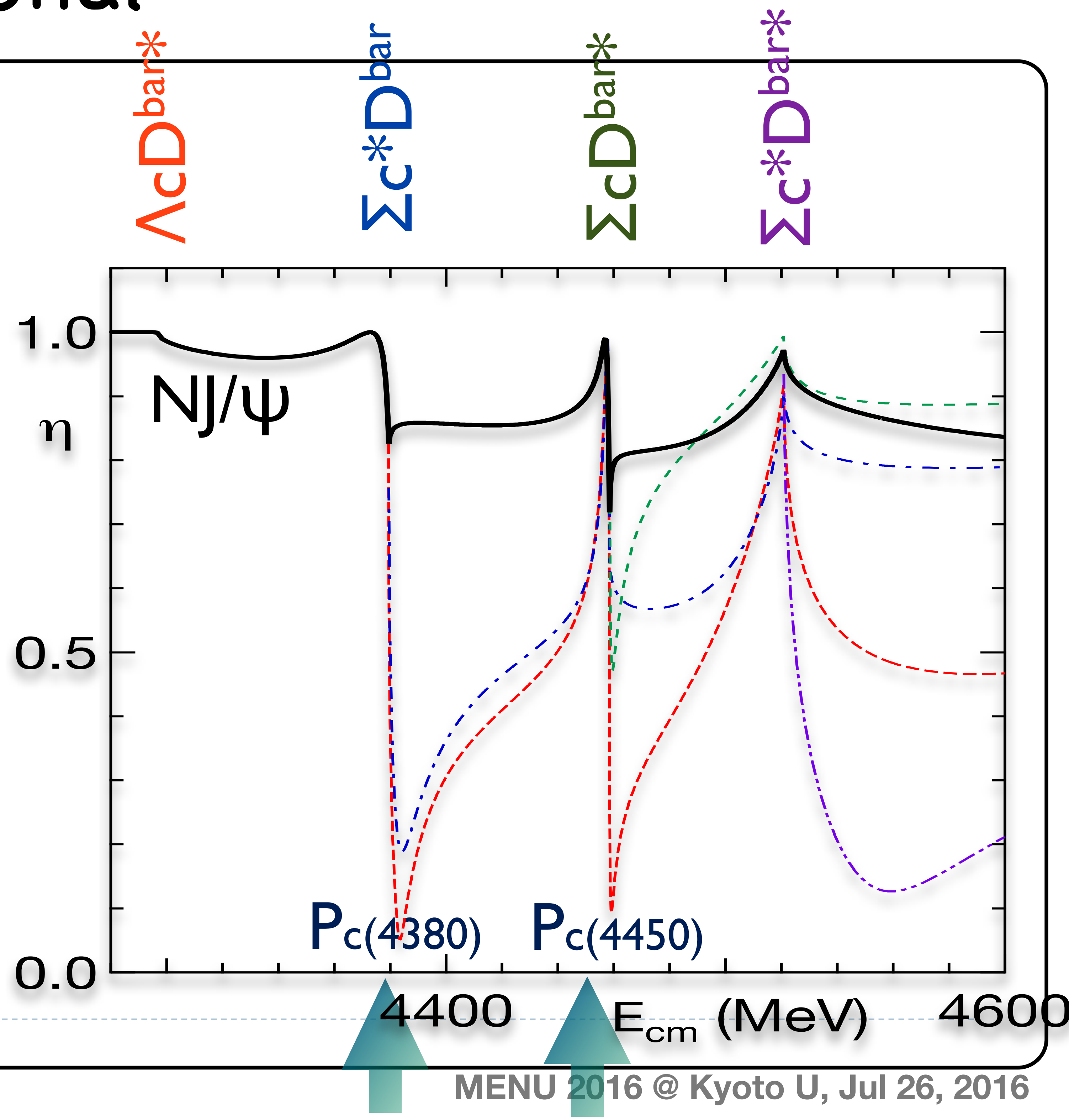
uudcc^{bar} I(JP)=1/2(3/2-) [NJ,$\Lambda c\bar{D}^*$,$\Sigma c^*\bar{D}$,$\Sigma c\bar{D}^*$,$\Sigma c^*\bar{D}^*$]

- There is a (sharp) resonance whose components are mostly $\Lambda c D^{bar*}$ and $\Sigma c^* D^{bar}$ at 4385 MeV. (just above $\Sigma c^* D^{bar}$ thre)



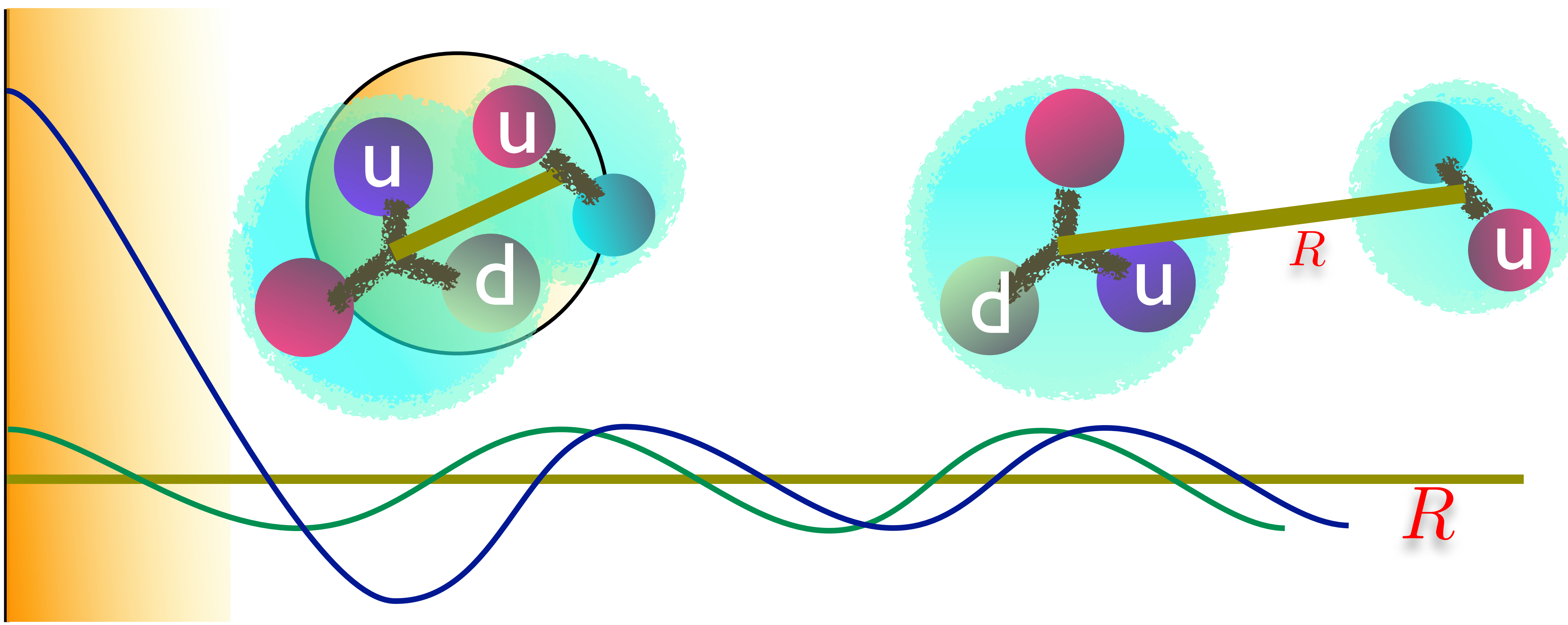
uudcc^{bar} I(JP)=1/2(3/2-) [NJ,$\Lambda c\bar{D}^*$,$\Sigma c^*\bar{D}$,$\Sigma c\bar{D}^*$,$\Sigma c^*\bar{D}^*$]

- inelasticity η_diagonal
  - mixing is rather small.
    - η < 0.2
    - (consistent with πN→NJ/ψ?)



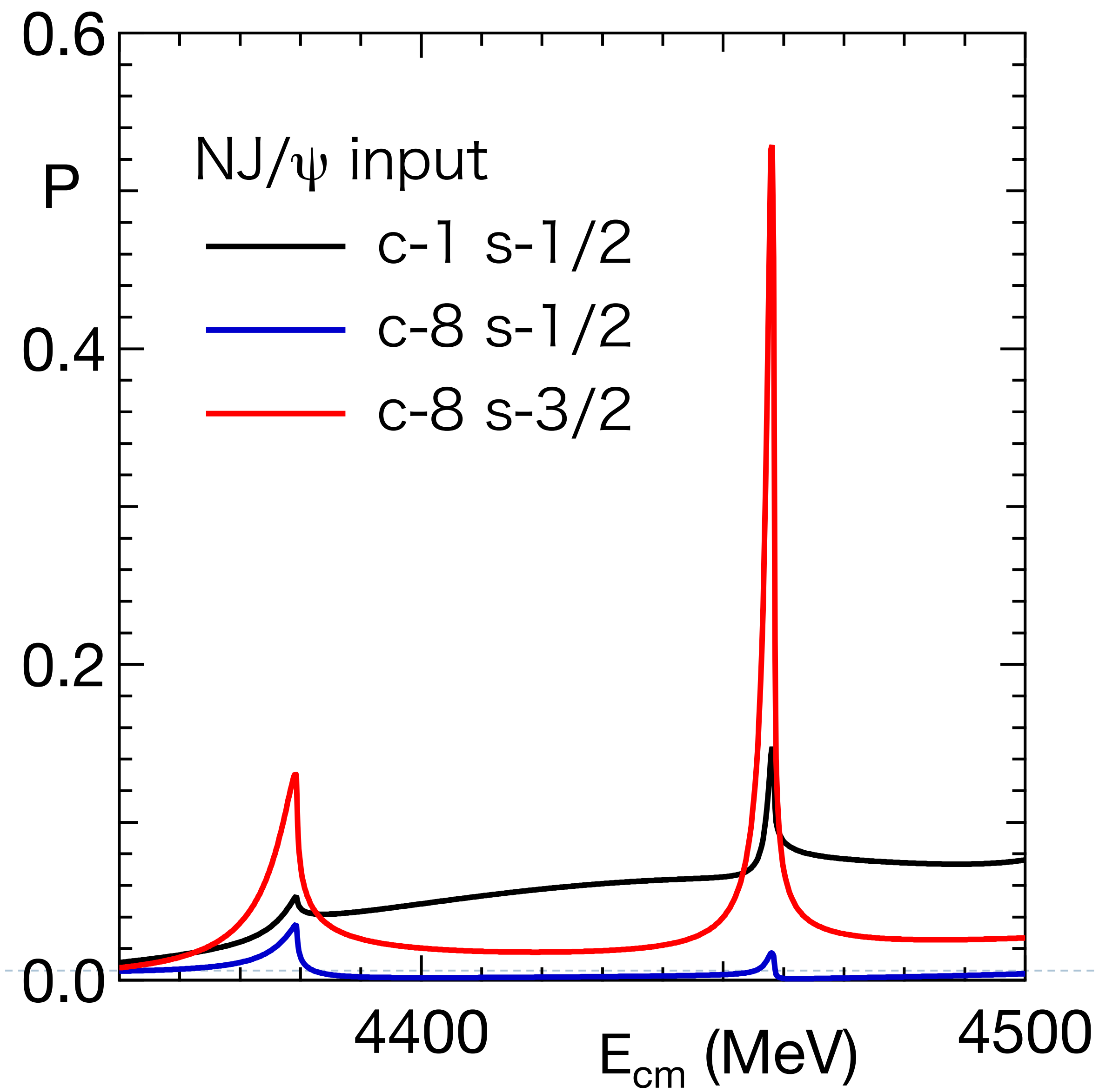
uudcc^{bar} I(JP)=1/2(3/2-) [NJ,$\Lambda_c\bar{D}^*$,$\Sigma_c^*\bar{D}$,$\Sigma_c\bar{D}^*$,$\Sigma_c^*\bar{D}^*$]

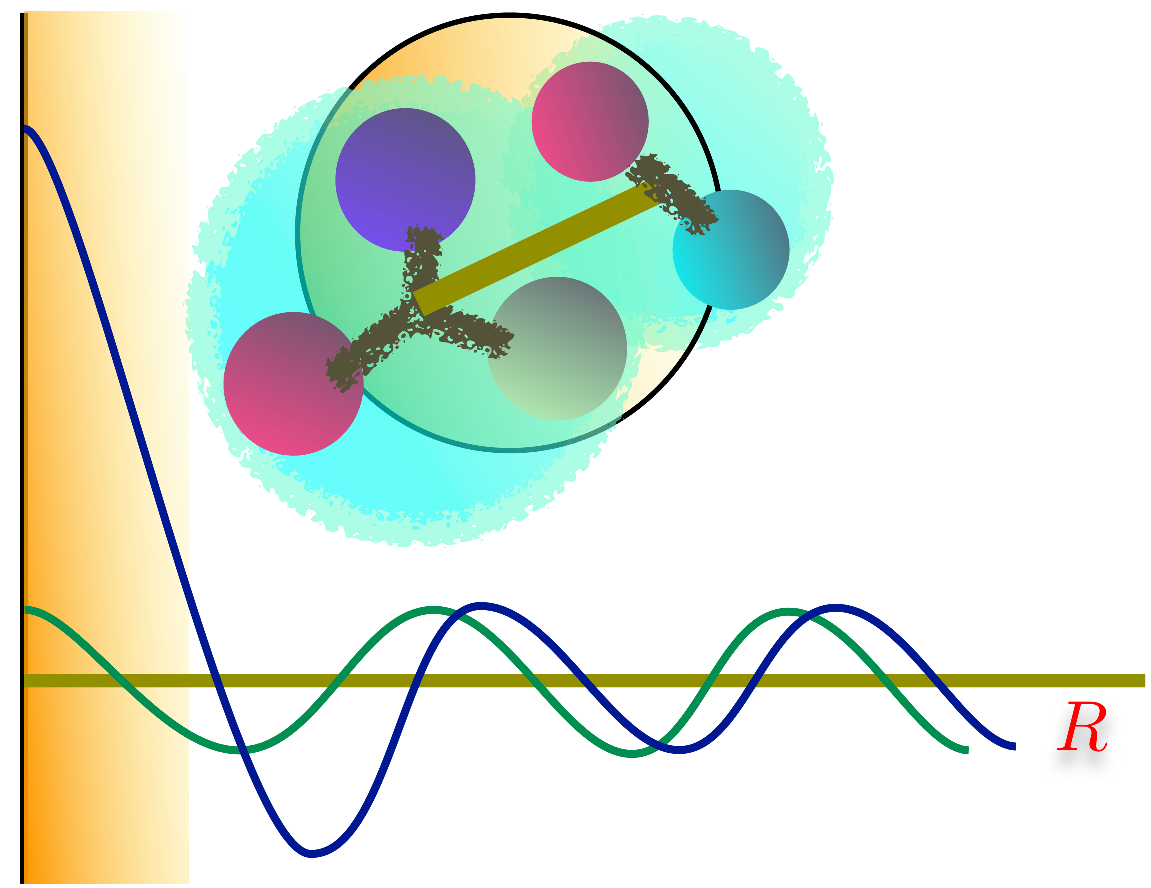
- size of uud(0s)^3 color-c spin-s states in scattering wave function
  - <φφχ|uud(0s)cs><uud(0s)cs|φφχ>
  - exists in the short range, large at the resonance



uudcc^{bar} I(JP)=1/2(3/2-) [NJ,$\Lambda c\bar{D}^*$,$\Sigma c^*\bar{D}$,$\Sigma c\bar{D}^*$,$\Sigma c^*\bar{D}^*$]

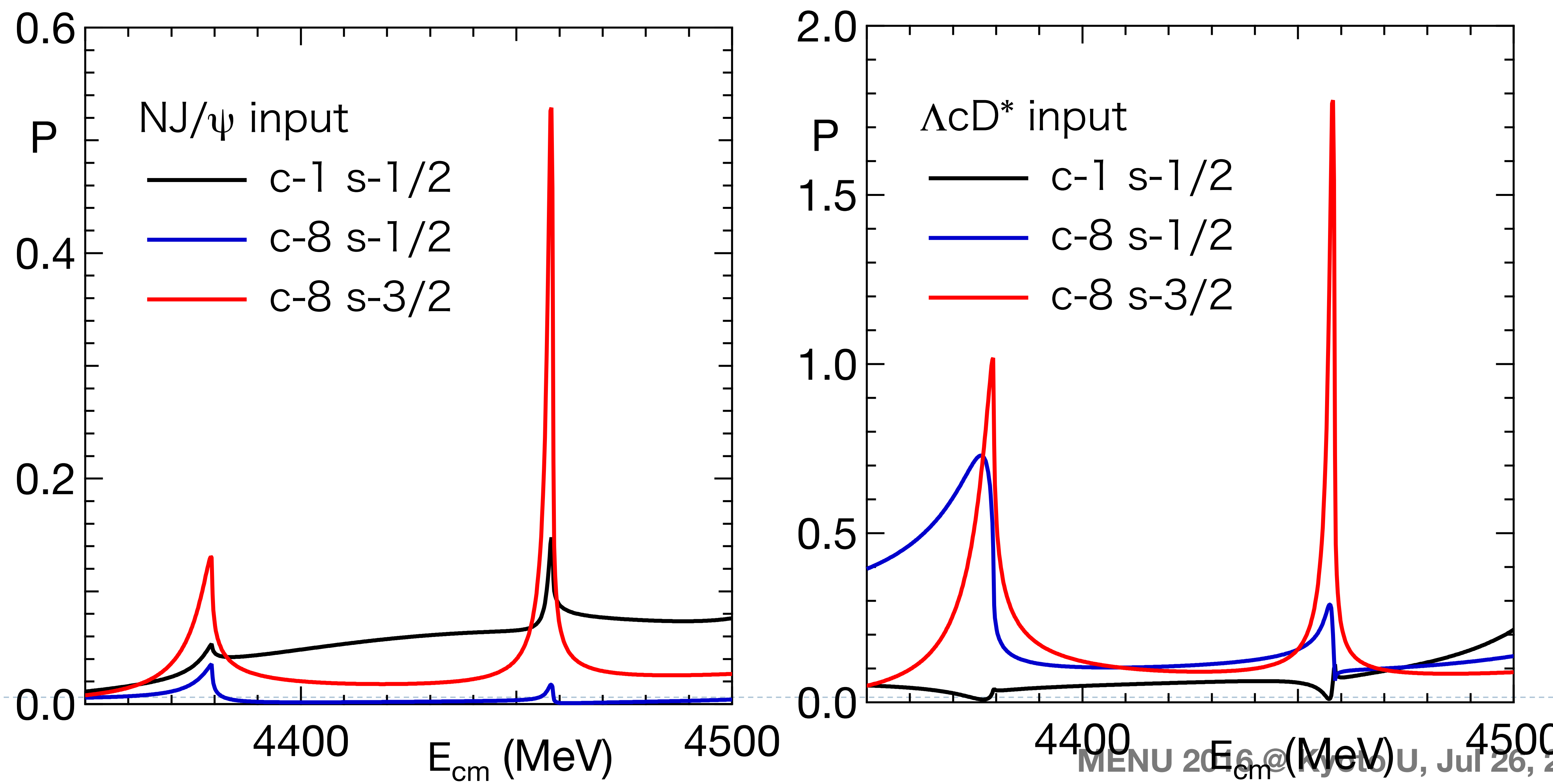
- size of uud(0s)^3 color-c spin-s states in scattering wave function
  - <φφχ|uud(0s)cs><uud(0s)cs|φφχ>





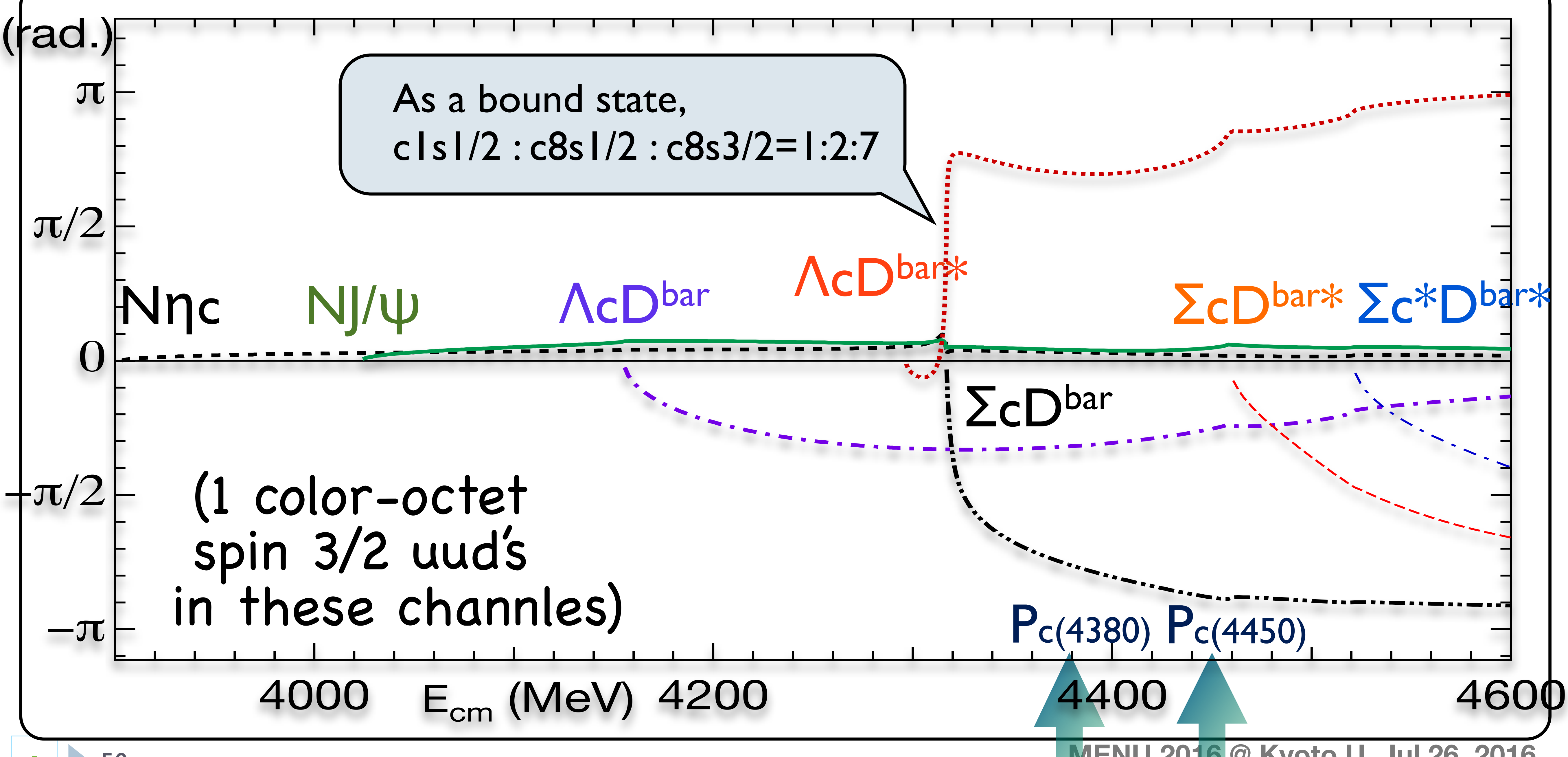
uudcc^{bar} I(JP)=1/2(3/2-) [NJ,$\Lambda c\bar{D}^*$,$\Sigma c^*\bar{D}$,$\Sigma c\bar{D}^*$,$\Sigma c^*\bar{D}^*$]

- uud$(0s)^3$ color-8 spin-3/2 states are dominant at the resonance (cusp)
  - in hadron language, they're superposition of $\Sigma c\bar{D}$'s, but!



uudcc^{bar} I(JP)=1/2(1/2-) [Nηc,NJ,ΛcD̄,ΛcD̄*,ΣcD̄,ΣcD̄*,Σc*D̄*]

- There is a sharp resonance of ΛcD^{bar*} due to the attraction in the ΣcD^{bar}

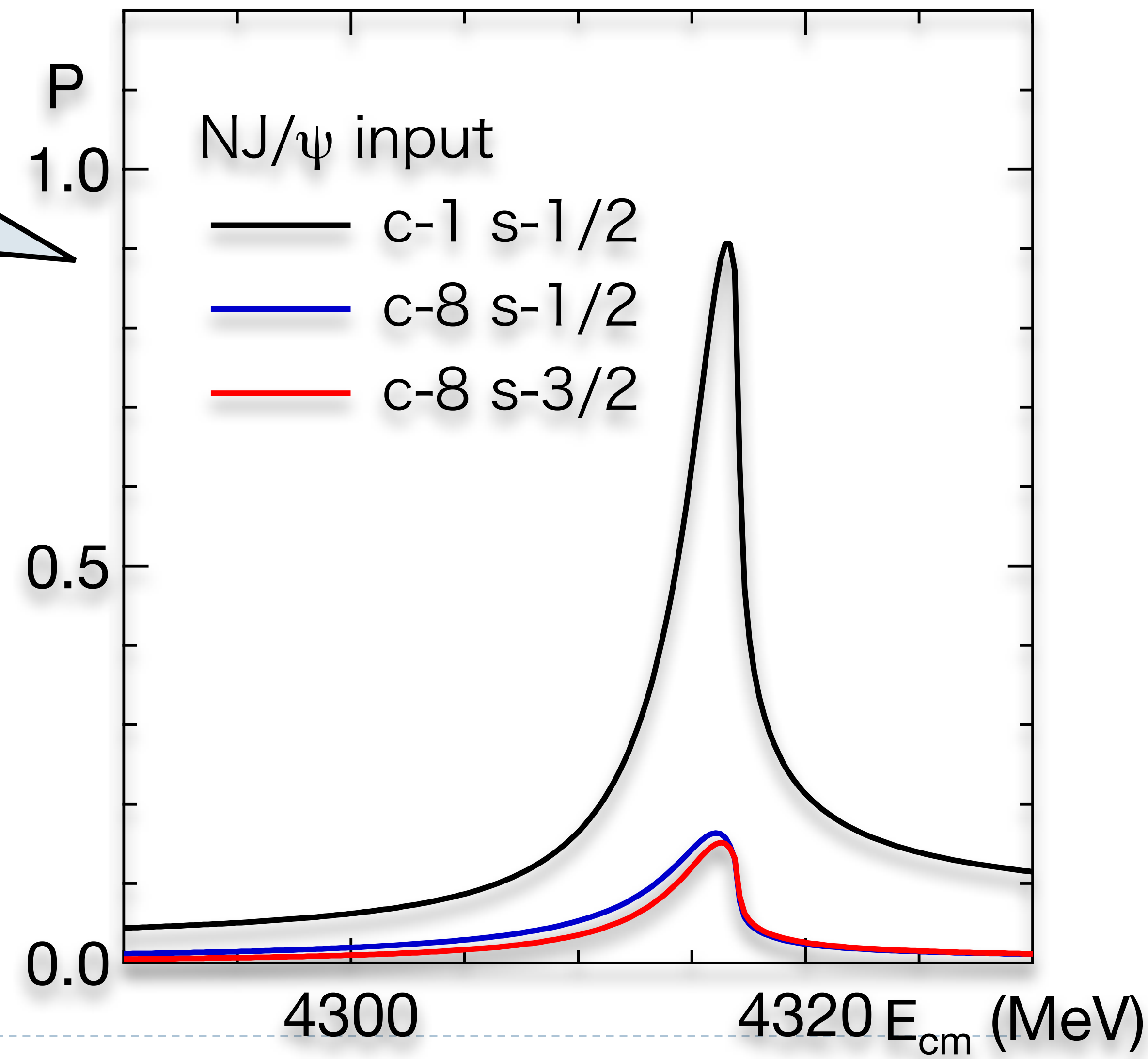


uudcc^{bar} I(JP)=1/2(1/2-) [Nηc,NJ,Λc$\bar{D}$,Λc$\bar{D}$*,Σc$\bar{D}$,Σc$\bar{D}$*,Σc*$\bar{D}$*]

- size of uud(0s)^3 color-c spin-s states in scattering wave function

As a bound state,
c1s1/2 : c8s1/2 : c8s3/2=1:2:7

  - The Σc$\bar{D}$ bound state, couples to Nηc and NJ/ψ, becomes a resonance. The color singlet component dominates at the resonance energy.



$c\bar{c}$-N scattering length

- spin averaged J/ψN scattering length, $\sigma = 4\pi a^2$

	scattering length	cross section at the threshold
QCD SR (Hayashigaki 1999)	-0.10±0.02 fm	(0.8〜1.8 mb)
QCD van der Waals (Brodsky Miller 1997)	-0.24 fm	7 mb
LatticeQCD (Yokokawa2006, Kawanai 2010)	-0.71±0.48 fm -0.39±0.14 fm (〜 -0.3 fm)	
QCM	-0.09 fm	0.9 mb
estimate from γN→J/ψN exp. (Anderson 1977)	(0.14 〜 0.19 fm)	3.5±0.8±0.5 mb

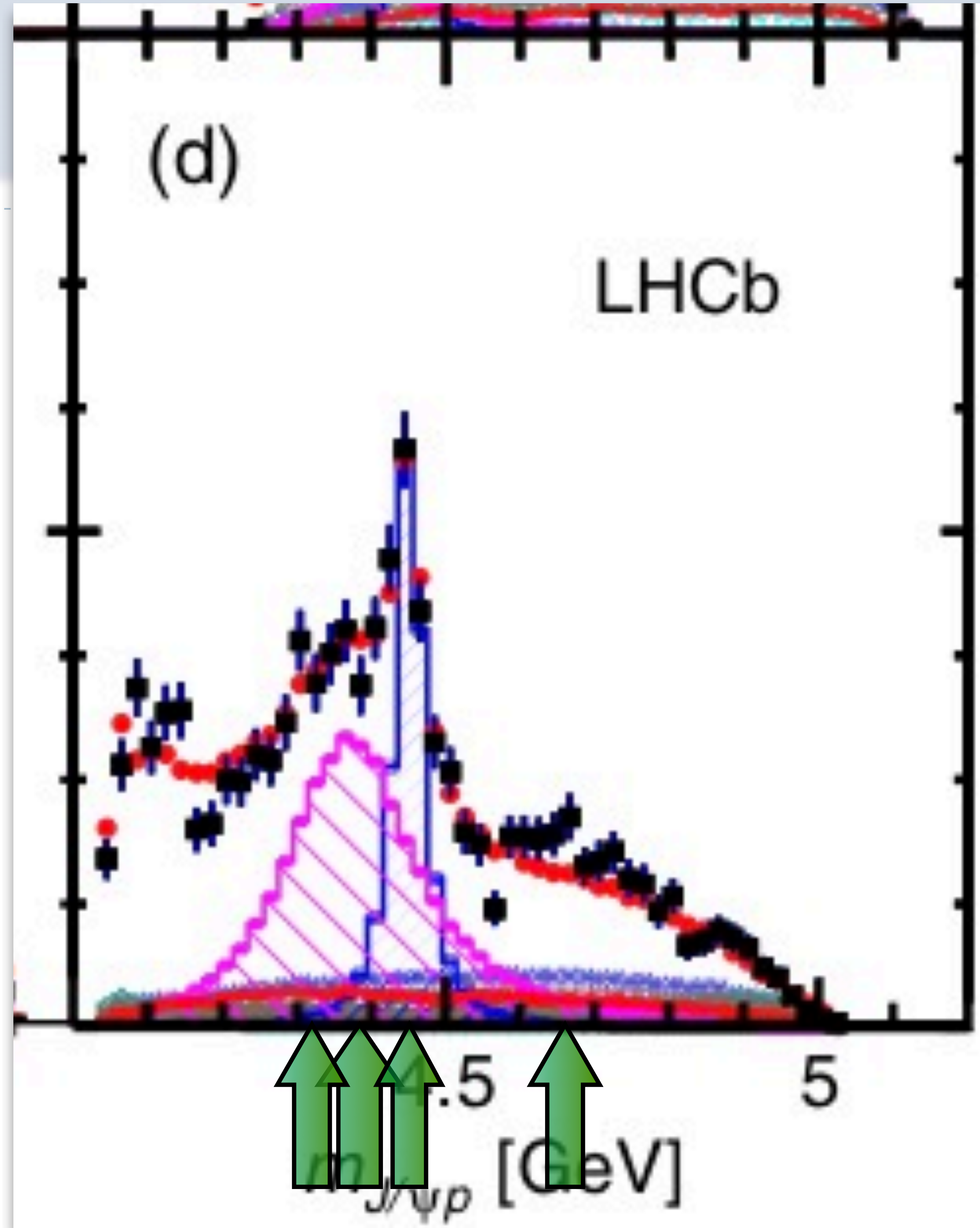
half of the attraction comes from the hadron channel coupling.

..we find a lot ...

- a bound state
  - 4527 MeV (NJ/ψ D-wave)
- resonances
  - 4385 MeV
  - 4320 MeV
- a cusp
  - 4462 MeV

v.s.

- Pc(4450) 4449.8±1.7±2.5MeV
- Pc(4380) 4380±8±29MeV



[multiple peaks with larger width?]

Summary and Outlook

- Resonances or a bound state for each J=1/2 3/2 5/2 !
  - COLOR-OCTET BARYONS?!
- More conservative way to say is:
  - NJ/ψ - $\Lambda_c\bar{D}^{(*)}$ - $\Sigma_c^{(*)}\bar{D}^{(*)}$

There is an attraction in this channel.
The attraction comes from
the uud color octet component.

Summary and Outlook

- Resonances or a bound state for each J=1/2 3/2 5/2 !
  - COLOR-OCTET BARYONS?!
  - Do they survive the meson exchange?
- All the current 'peaks' have very narrow width.
  - To have a broad width of Pc(4380), one needs something else. [Or, multiple peaks with larger width?]
- These 'peak' strength is ok?
  - large enough to observe Pc from NJ/ψ channel?
  - small enough to be consistent with πN → NJ/ψ exp?
  - Need to calculate Λb →J/ψ p K transfer strength.
- All the current 'peaks' have negative parity.
  - Need BM P-wave, and/or the positive parity mesons.