Flavor-singlet strange pentaquarks with hidden heavy quark pairs [udsQ$\bar{Q}$]

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What we would like to discuss

By adding a heavy quark pair to baryon:

- we can see the nature of color-octet 3-light quarks — some of them are attractive.

  (1) color-8 flavor-1 isospin-0 spin1/2 uds

  (2) color-8 flavor-8 spin3/2 uud, uds

- These modes can be observed by the Baryon-Meson scattering. More clearly with $b\bar{b}$.
- (2) is probably responsible to Pc peaks (with OPEP.)
- (1) can be seen by looking into BM interaction

uudc$\bar{c}$ pentaquarks @ LHCb

Pc(4312), Pc(4440), Pc(4457)

- Found in the $\Lambda_b \to J/\psi$ K p decay, by LHCb

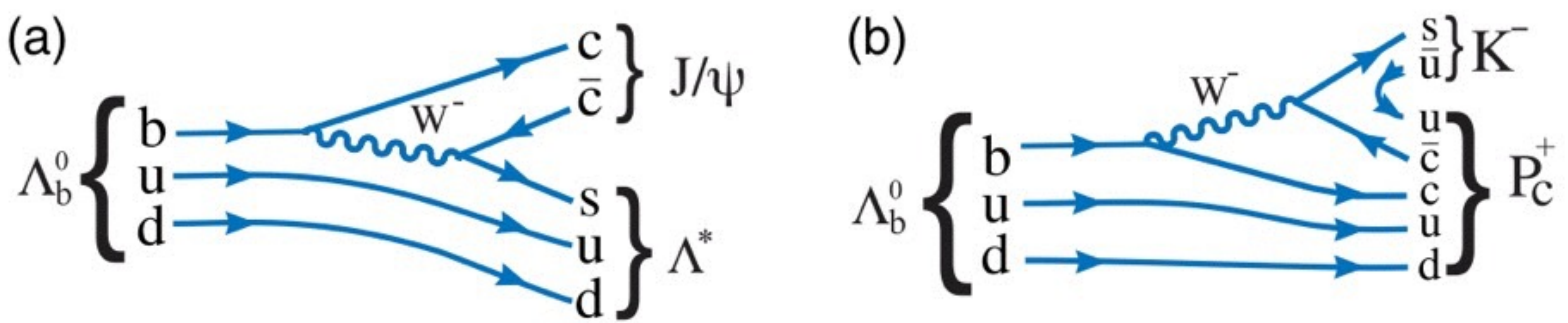


FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi\Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

LHCb,PRL115(2015)07201

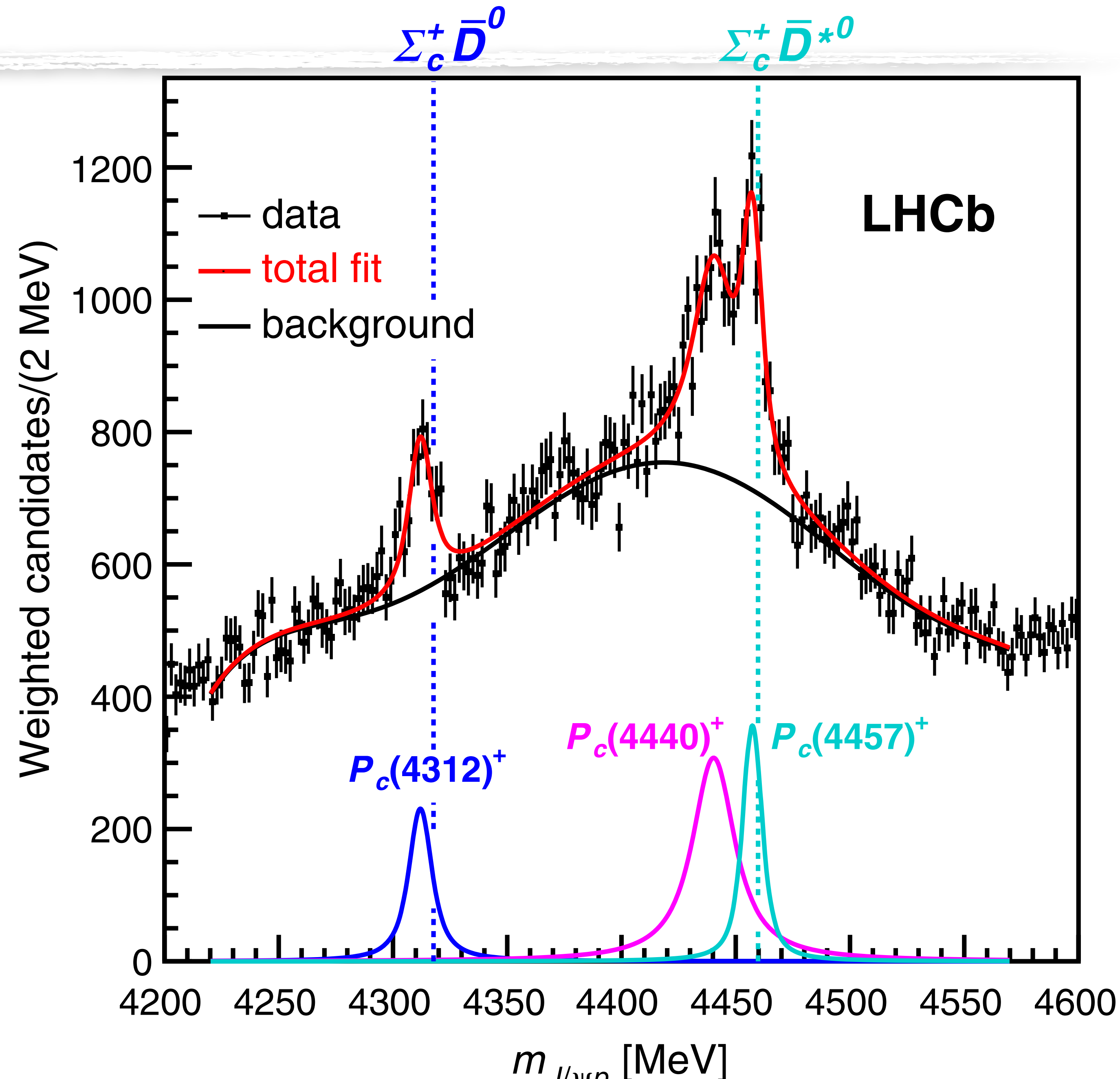
LHCb,PRL122(2019)222001

Pc

LHCb,PRL122(2019)222001

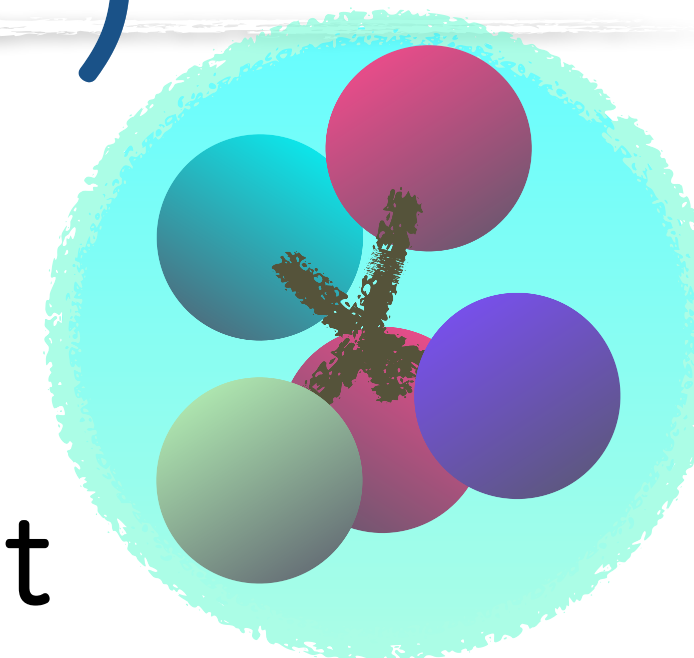
Sharp peaks found below $\Sigma_c\bar{D}^{(*)}$ thresholds

- Molecular state?
- Attraction comes from where?



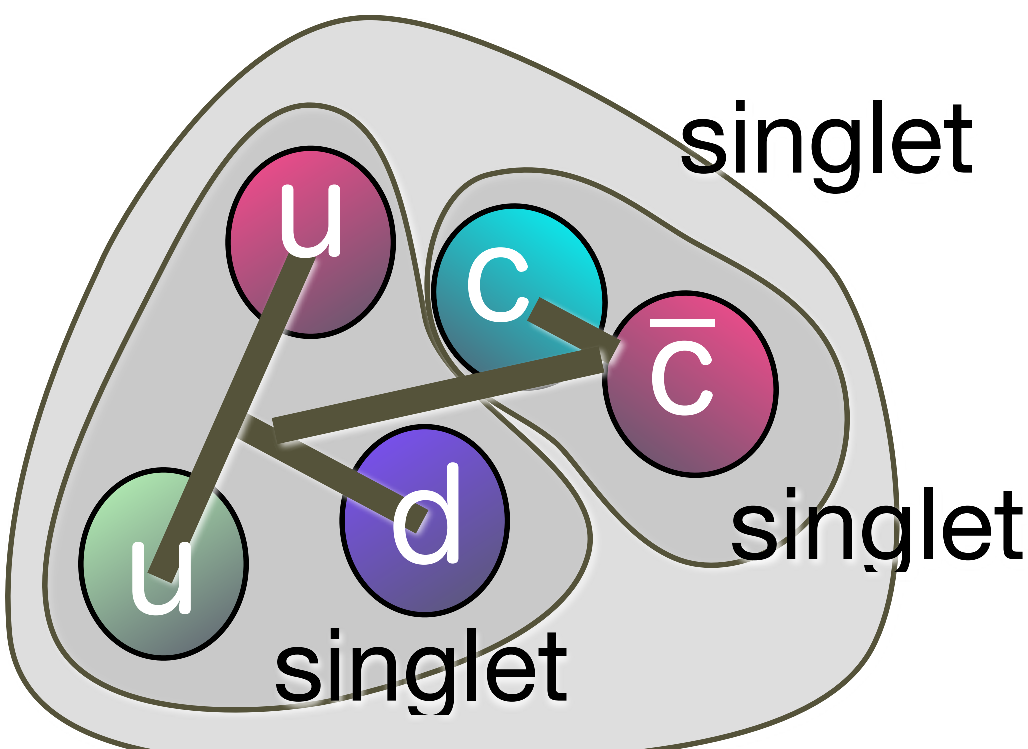
- OPEP ←Yamaguchi (Aug 18 talk)
- color-octet uud? ←This talk

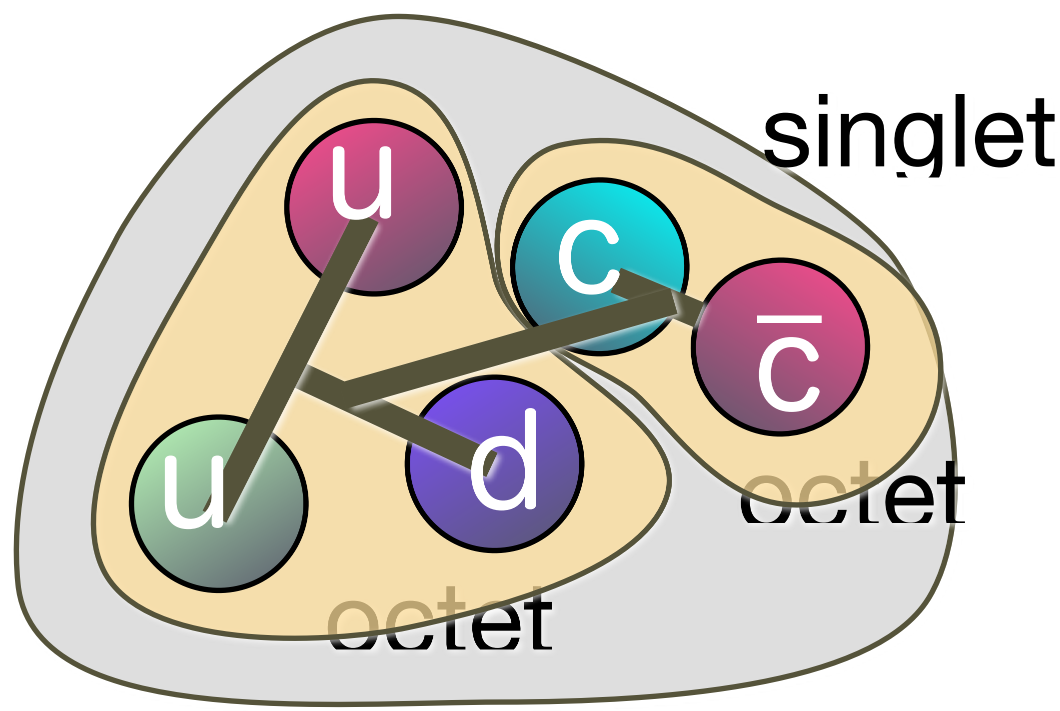
uudc$\bar{c}$ $I(J^P)=1/2(J^-)$



S-wave 5 quark systems

- total: color singlet
  - c$\bar{c}$ part: color singlet or octet
  - qqq part: color singlet or octet

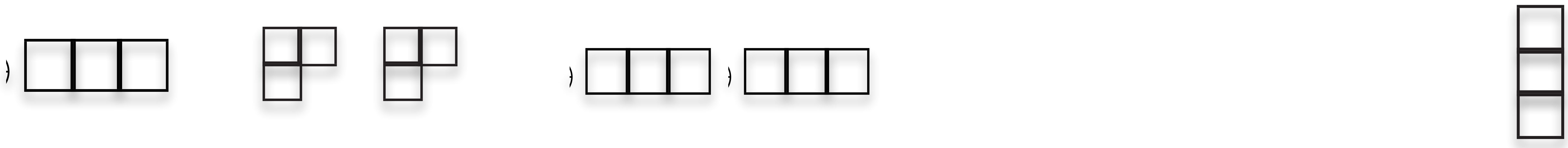


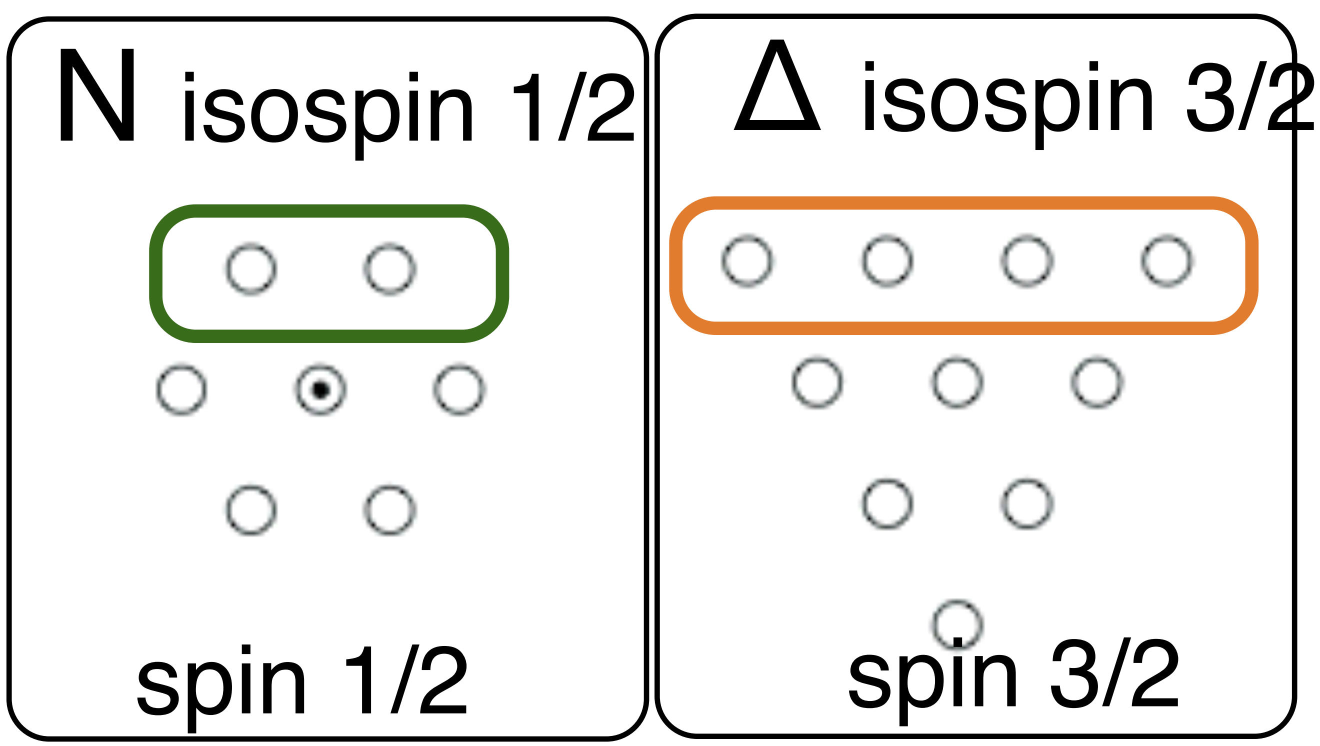


flavor-spin SU(6) for qqq

flavor spin

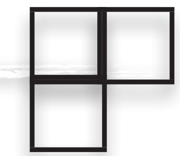
- 56 = 8×2 + 10×4 for color singlet uud



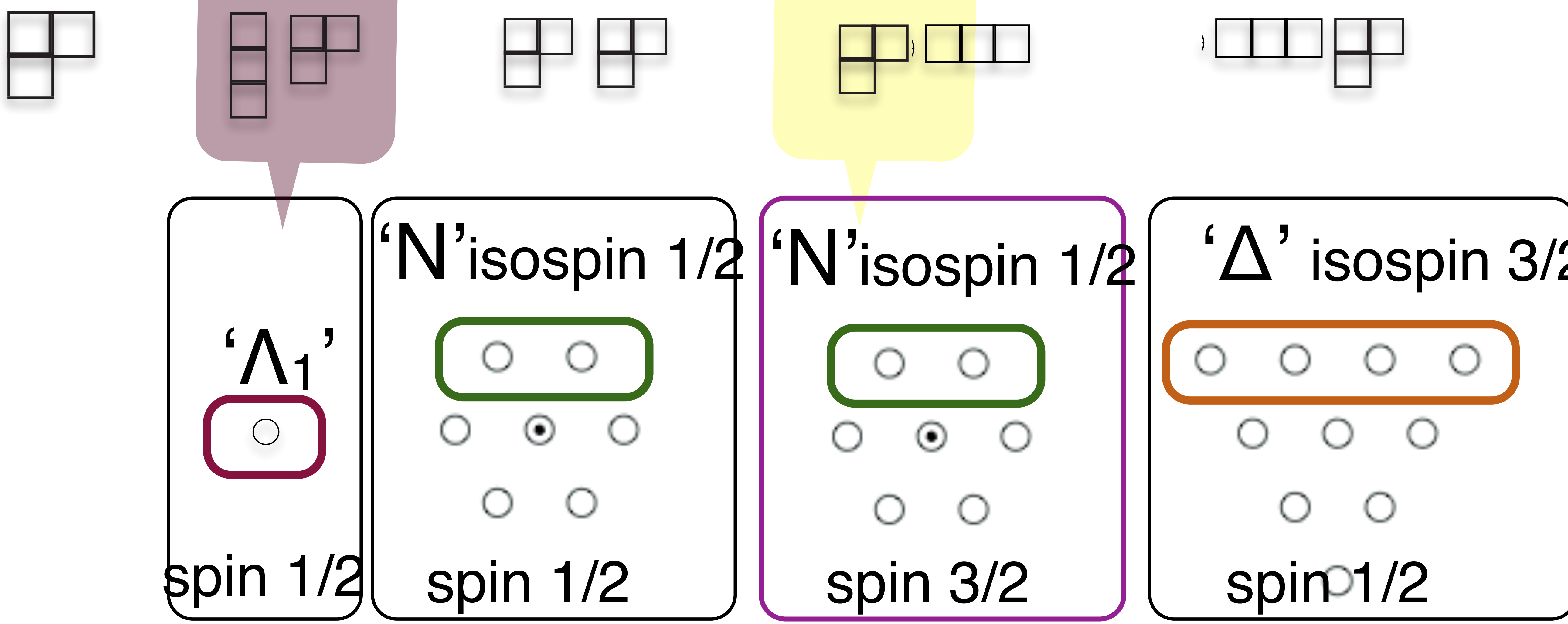


flavor-spin SU(6) for qqq

for color octet



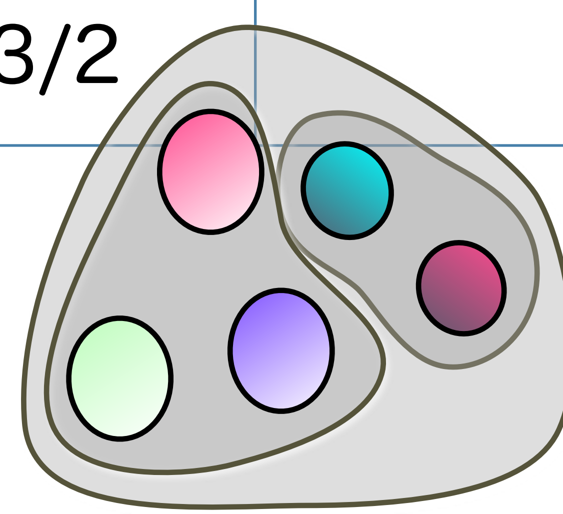
- $70 = 1\times2 + 8\times2 + 8\times4 + 10\times2$



flavor-spin SU(6) for qqq in Pc

S-wave 5 quark system configurations:

flavor	qqq color	qqq spin	$Q\bar{Q}$ spin	Total spin
1	8	1/2	0 or 1	1/2, 3/2
8	1	1/2		1/2, 3/2
8	8	1/2		1/2, 3/2
8	8	3/2		1/2, 3/2, 5/2



flavor-spin SU(6) for qqq in Pc

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

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flavor-spin SU(6) for qqq in Pc

e.g. (I,J)=(1/2, 3/2) : NJ/ψ, ⋯, $\Sigma c^* \bar{D}^*$

flavor	qqq color	qqq spin	$Q\bar{Q}$ spin	Total spin
1	8	1/2	0 or 1	1/2, 3/2
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8	8	1/2	0 or 1	1/2, 3/2
8	8	3/2	0 or 1	1/2, 3/2, 5/2

4 five-quark states v.s. 5 BM states

→ 1 forbidden state + 4 allowed states

flavor-spin SU(6) for qqq in Pc

e.g. flavor-singlet qqq's are in J=1/2, 3/2

flavor	qqq color	qqq spin	$Q\bar{Q}$ spin	Total spin
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Roles of flavor-spin SU(6) for qqq in Pc

Estimate of color-spin int =

< color-spin interaction among light qqq >

 - < color-spin int. among each hadrons >

flavor	qqq color	qqq spin	qqq CMI	Lowest Threshold e.g.	CMI at ∞	Diff
1	8	1/2	-14	Λ_c D_s	-8 (Λ_Q)	-6
8	1	1/2	-8	N J/ψ	-8 (N, Λ)	0
8	8	1/2	-2	Λ_c D_s	-8 (Λ_Q)	+4
8	8	3/2	+2	Σ_c D^*	+8/3 (Σ_Q)	-2/3

Attraction

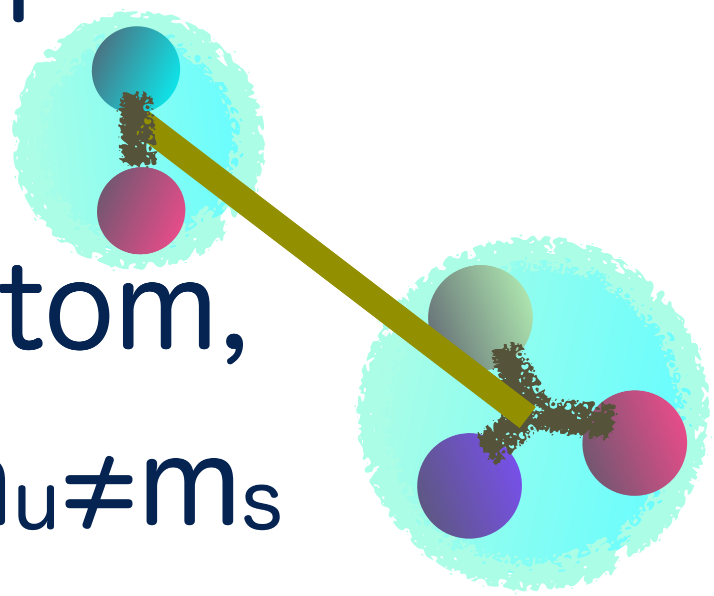
Attraction

Dynamical calc. with finite m_Q, $m_u \neq m_s$

Now we know what kind of configurations we have in each channel, and which of the configurations are attractive.

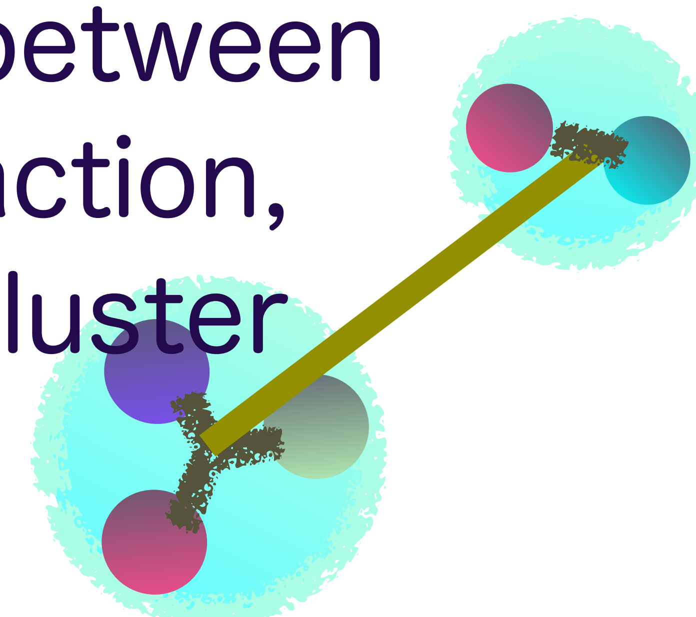
(Non strange part [PLB764(2017)254])

- Dynamical calculation by the quark cluster model.
- finite mass for charm and bottom,
- flavor SU(3) sym broken by $m_u \neq m_s$



Quark Cluster model

- ✓Hadrons are clustered quarks.
- ✓Interaction between the quarks consists of confinement, color-coulomb, and color-spin.
- ✓It gives the observed hadron mass spectra.
- ✓Quark interchange between the hadrons occurs at the short range.
- ✓Quark d.o.f. and the Interaction between quarks produce the hadron interaction,
- ✓The wave function for the inter-cluster mode is solved.



$uudc\bar{c}$ $I(J^P)=1/2(J^-)$

flavor	qqq color	qqq spin	$Q\bar{Q}$ spin	Total spin
8	8	3/2	1	5/2
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8	8	3/2	1	1/2

channel (J^P)		E
$(\frac{5}{2}^-)$	bound state	4519.9
$(\frac{3}{2}^-)$	cusp	4458.0
$(\frac{3}{2}^-)$	resonance	4379.3
$(\frac{1}{2}^-)$	resonance	4316.5

PLB764(2017)254]

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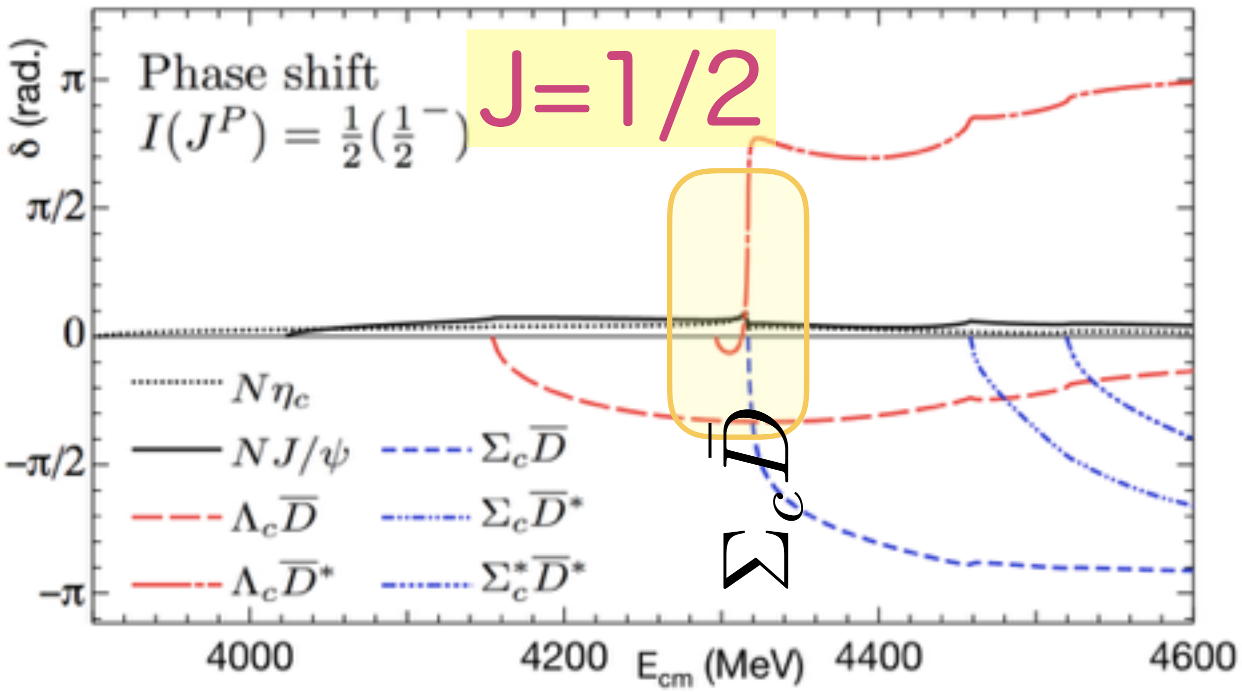

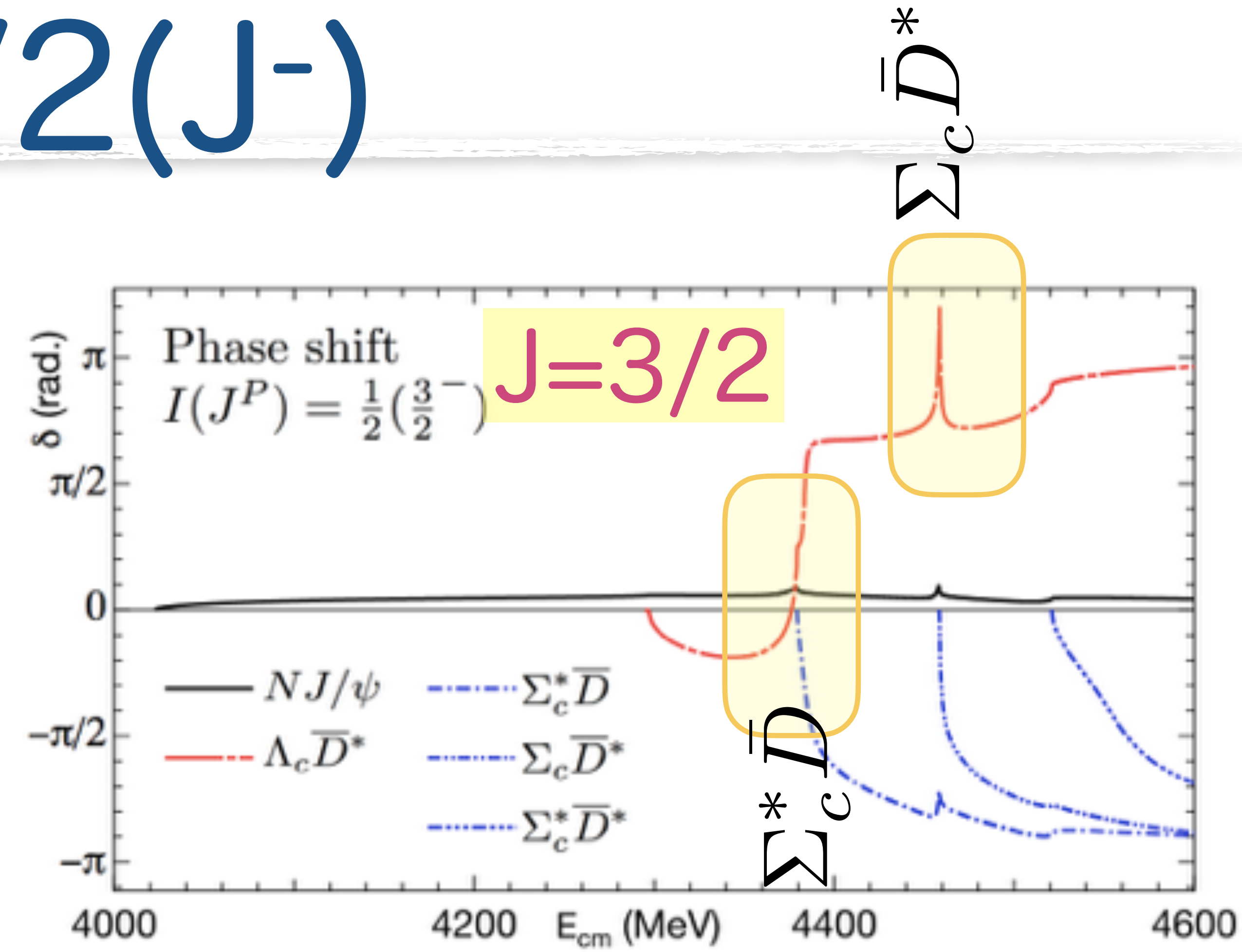

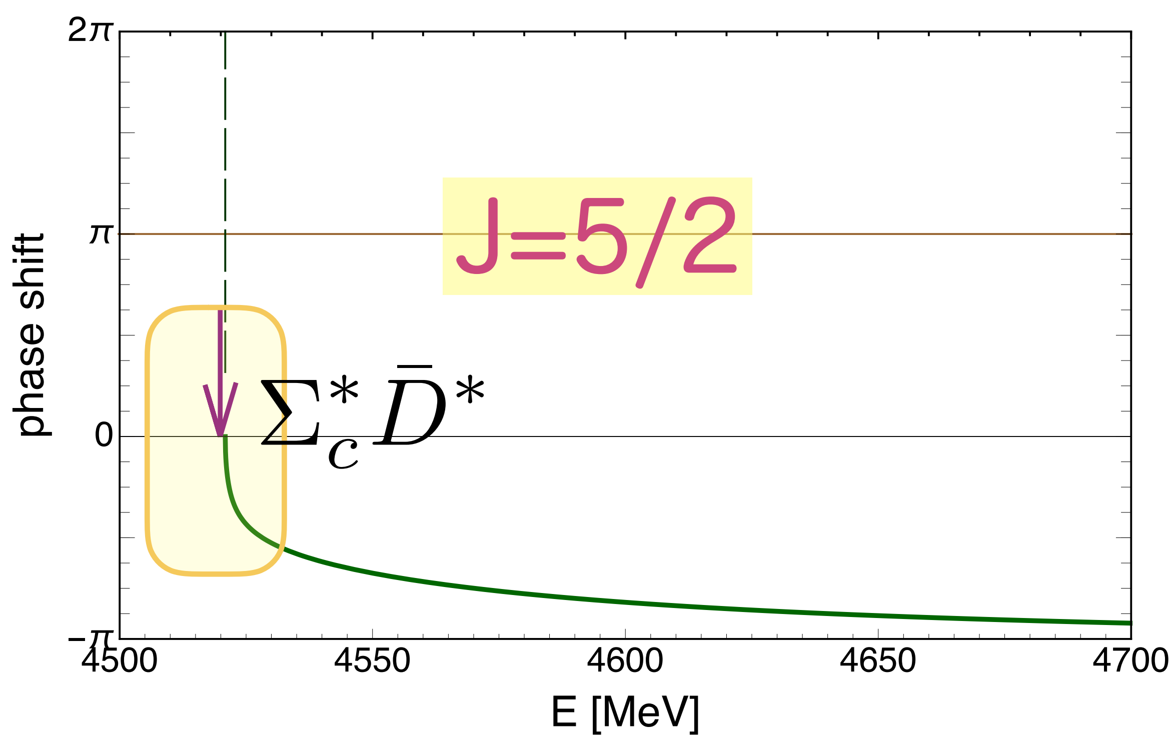

l channel (J^P)		E	
$(\frac{5}{2}^-)$	bound state	4519.9	$\Sigma_c^* \bar{D}^*$
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PLB764(2017)254

Pc by LHCb

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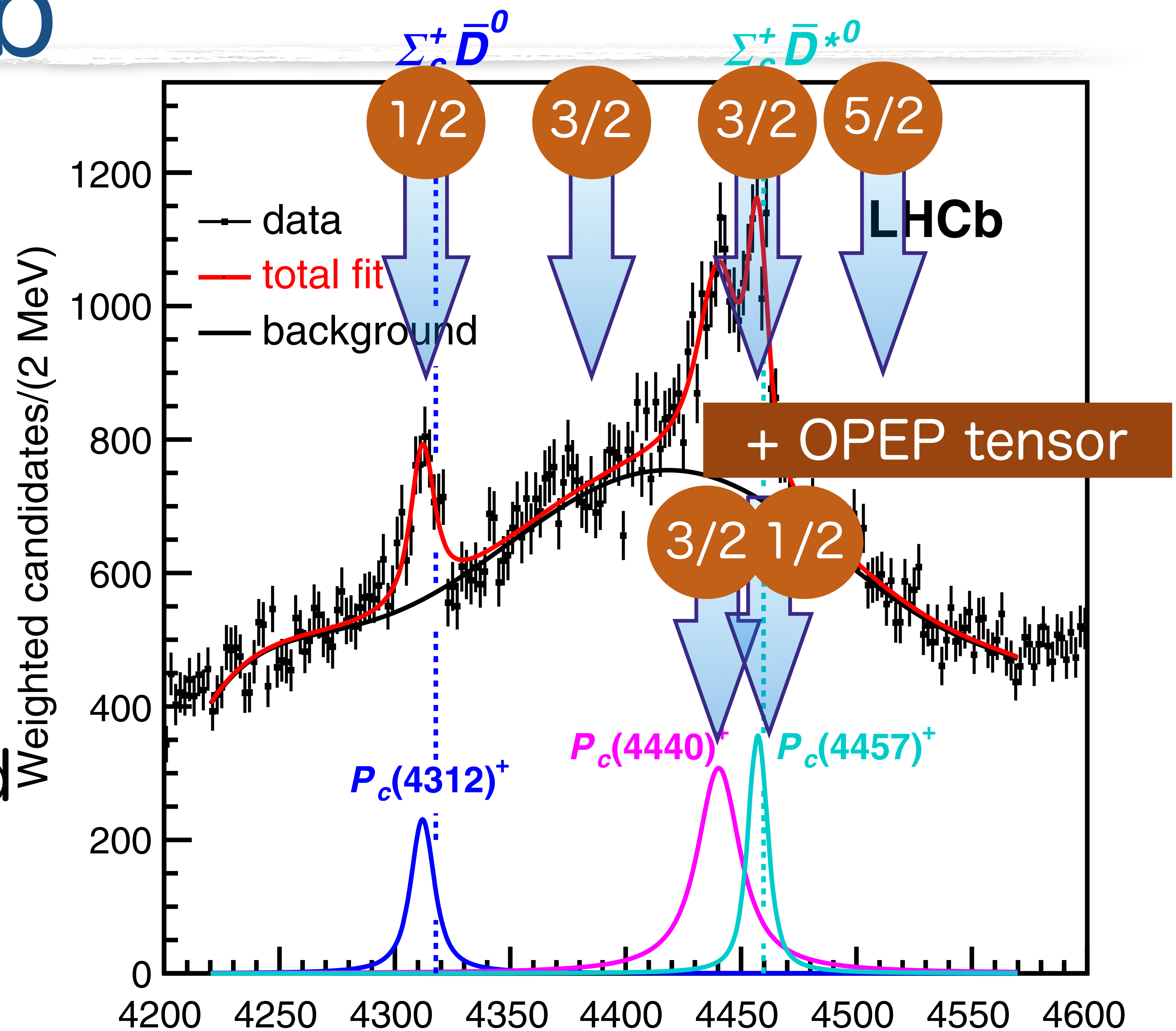

Attraction for color-8 spin-3/2 uud gives 3 peaks. With OPEP, it reproduce the observed peaks. (talk by Yamaguchi)

PLB764(2017)254
PRDD96 (2017)114031

Roles of flavor-spin SU(6) for qqq in Pc

Estimate of color-spin int =

< color-spin interaction among light qqq >

\- < color-spin int. among each hadrons >

flavor	qqq color	qqq spin	qqq CMI	Lowest Threshold e.g.	CMI at ∞	Diff	
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8	1	1/2	-8	N J/ψ	-8 (N, Λ)	0	
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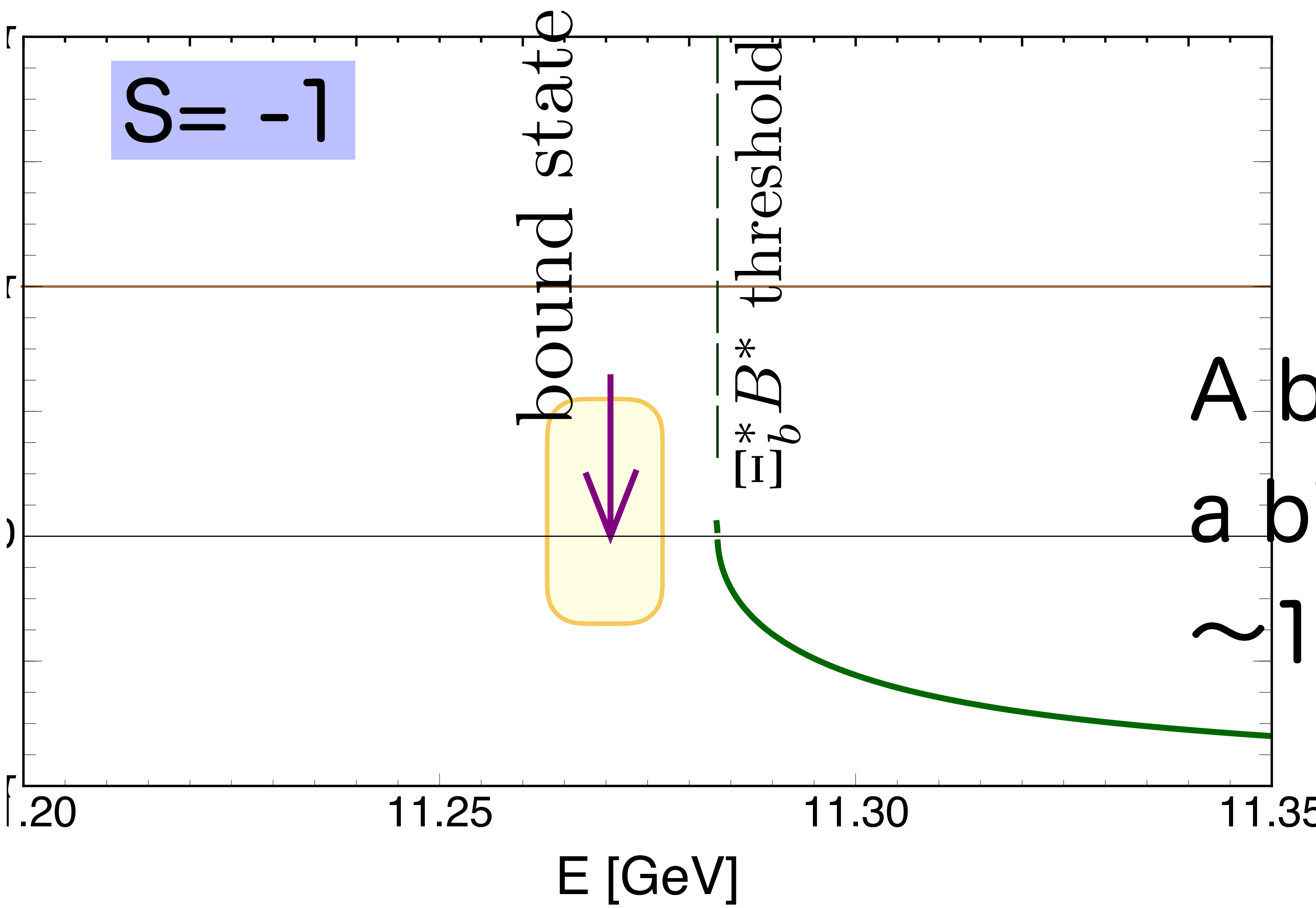
8	8	3/2	+2	$\Sigma_c D^*$	+8/3 (Σ_Q)	-2/3	Attraction

J=5/2

flavor	qqq color	qqq spin	$Q\bar{Q}$ spin	Total spin
8	8	3/2	1	5/2

$$udsb\bar{b}\ I(J^P) = 0(\frac{5}{2}^-)$$



A bound state with a binding energy of ~10 MeV

J=5/2

flavor	qqq color	qqq spin	$Q\bar{Q}$ spin	Total spin
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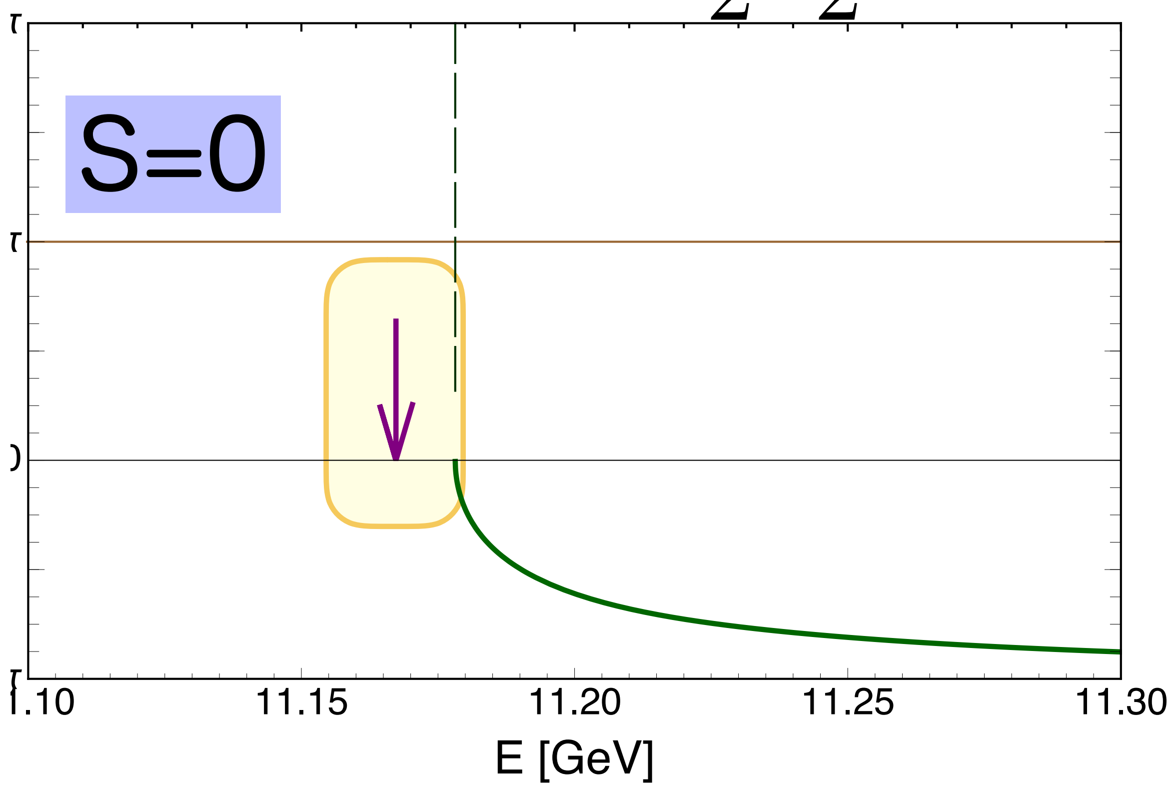
hidden bottom

A bound state with a binding energy of ~10 MeV

$$uudb\bar{b}\ I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$$



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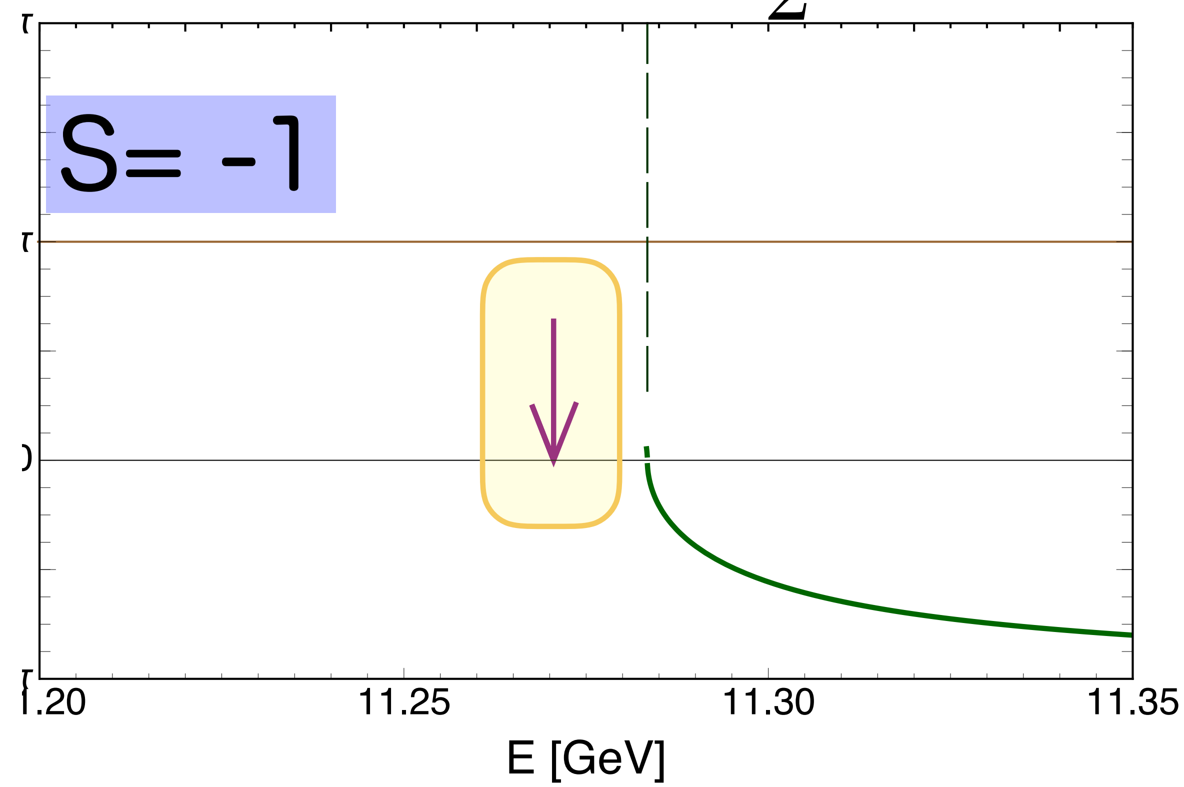


J=3/2

flavor	qqq color	qqq spin	$Q\bar{Q}$ spin	Total spin
1	8	1/2	1	3/2
8	8	3/2	0	3/2
8	8	3/2	1	3/2

hidden bottom

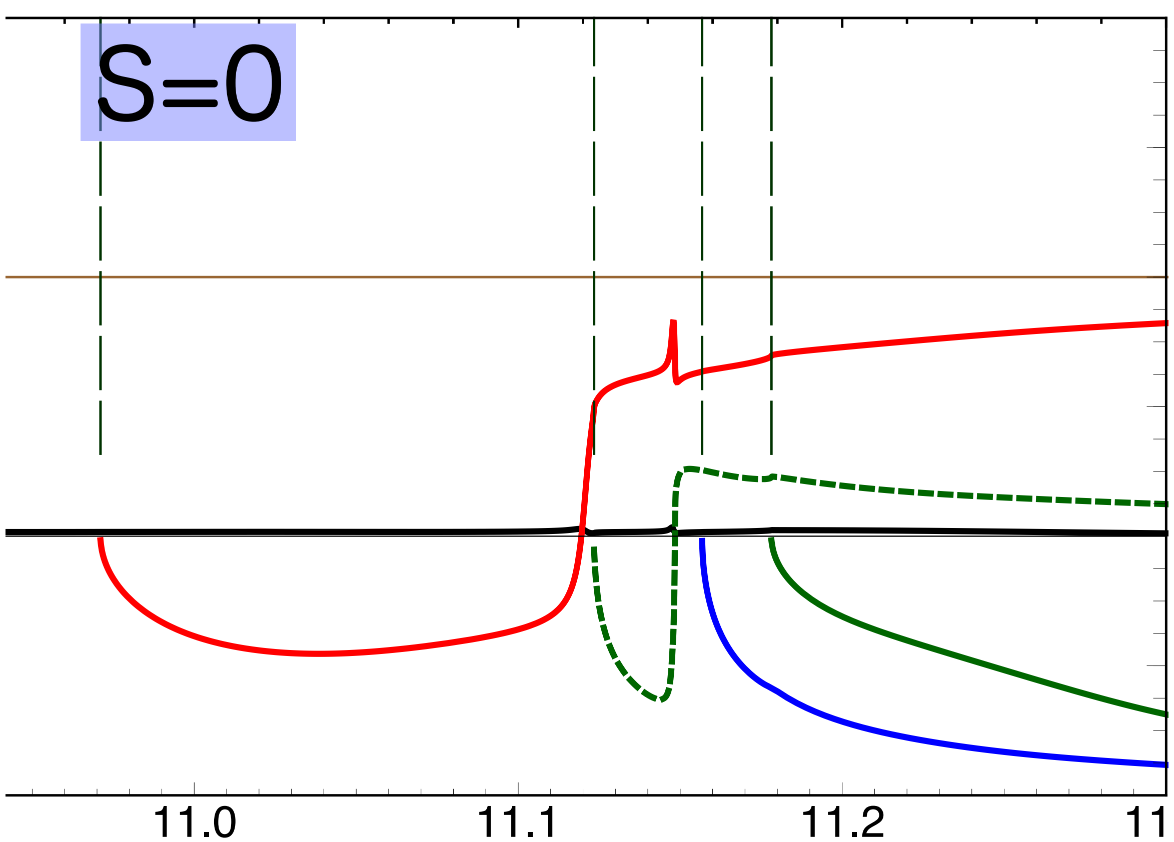
2 resonances

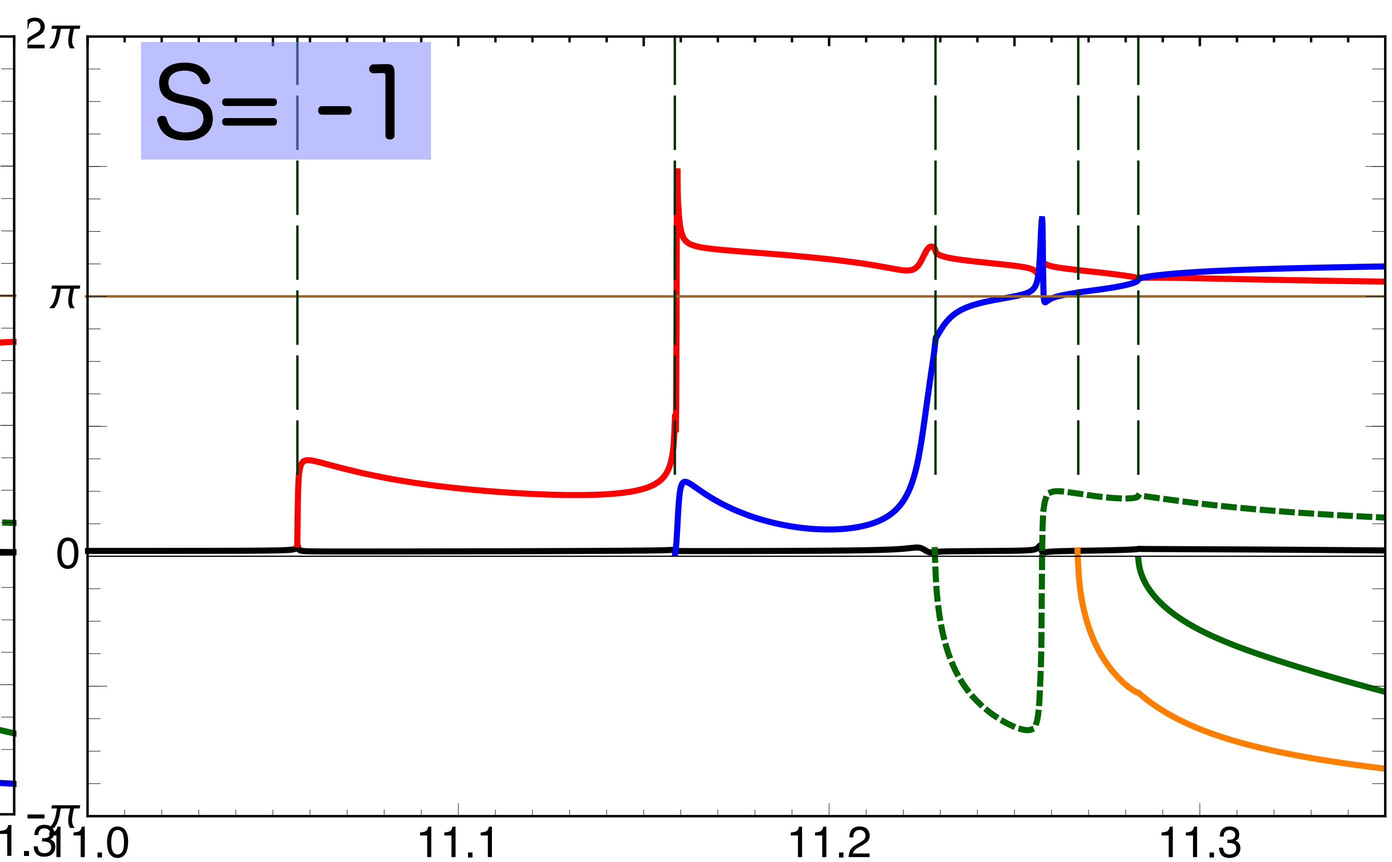
uud color-8 spin 3/2

3 resonances

uds flavor-1color-8 spin 1/2

uds color-8 spin 3/2





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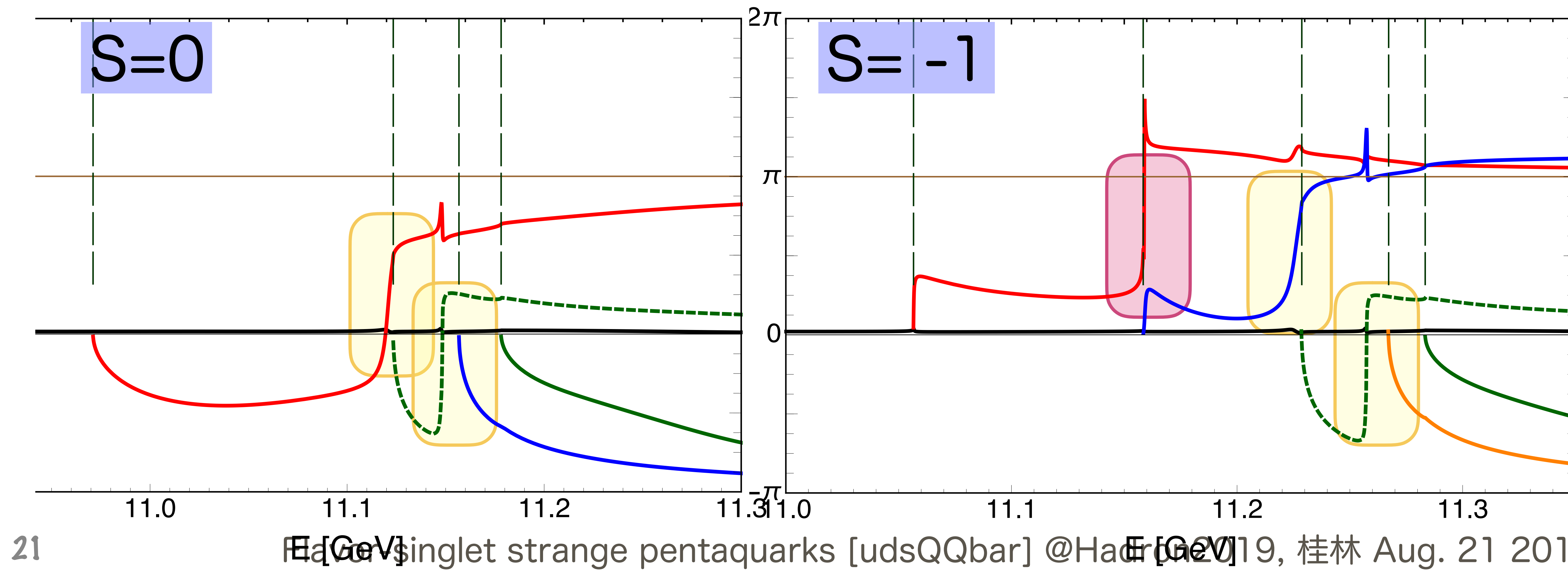


J=1/2

flavor	qqq color	qqq spin	$Q\bar{Q}$ spin	Total spin
1	8	1/2	0	1/2
1	8	1/2	1	1/2
8	8	3/2	1	1/2

hidden bottom

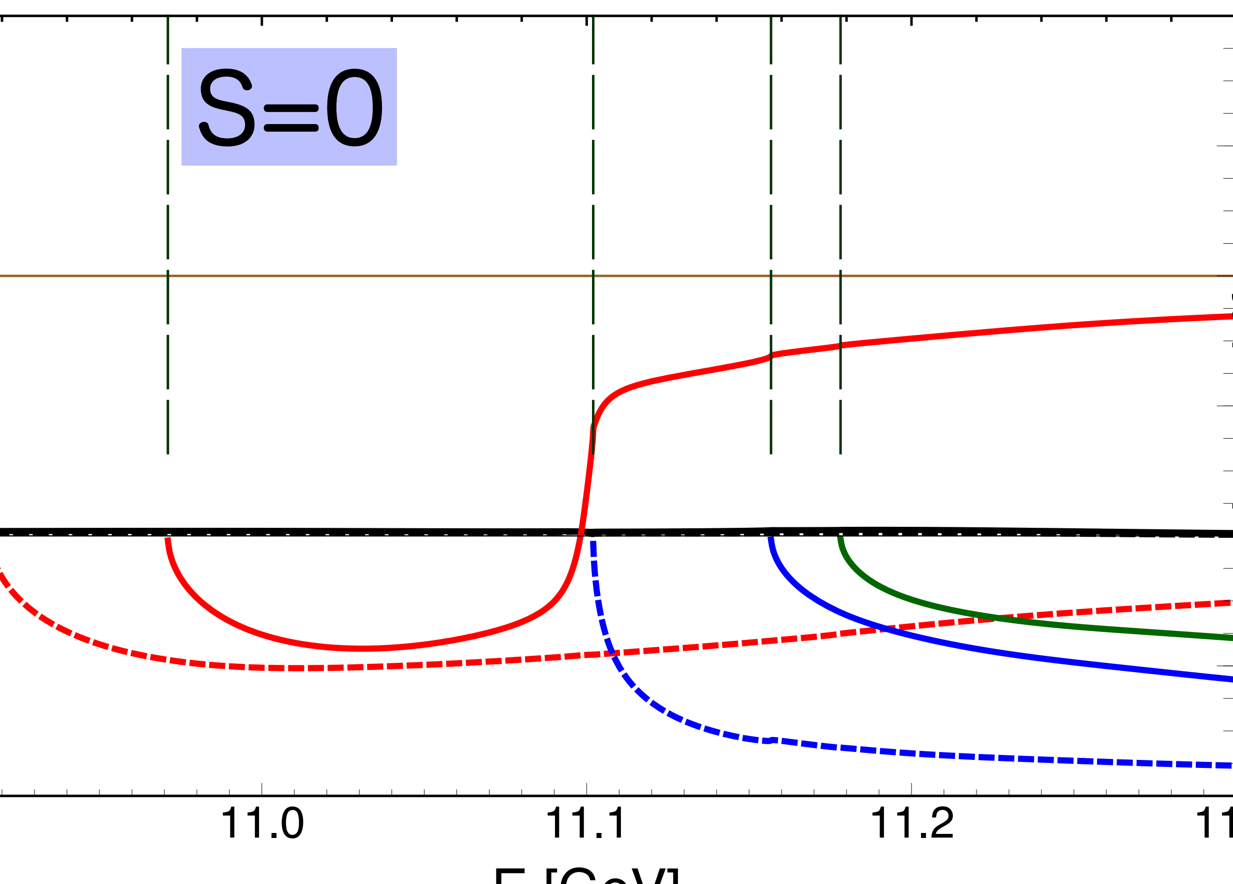
1 resonances

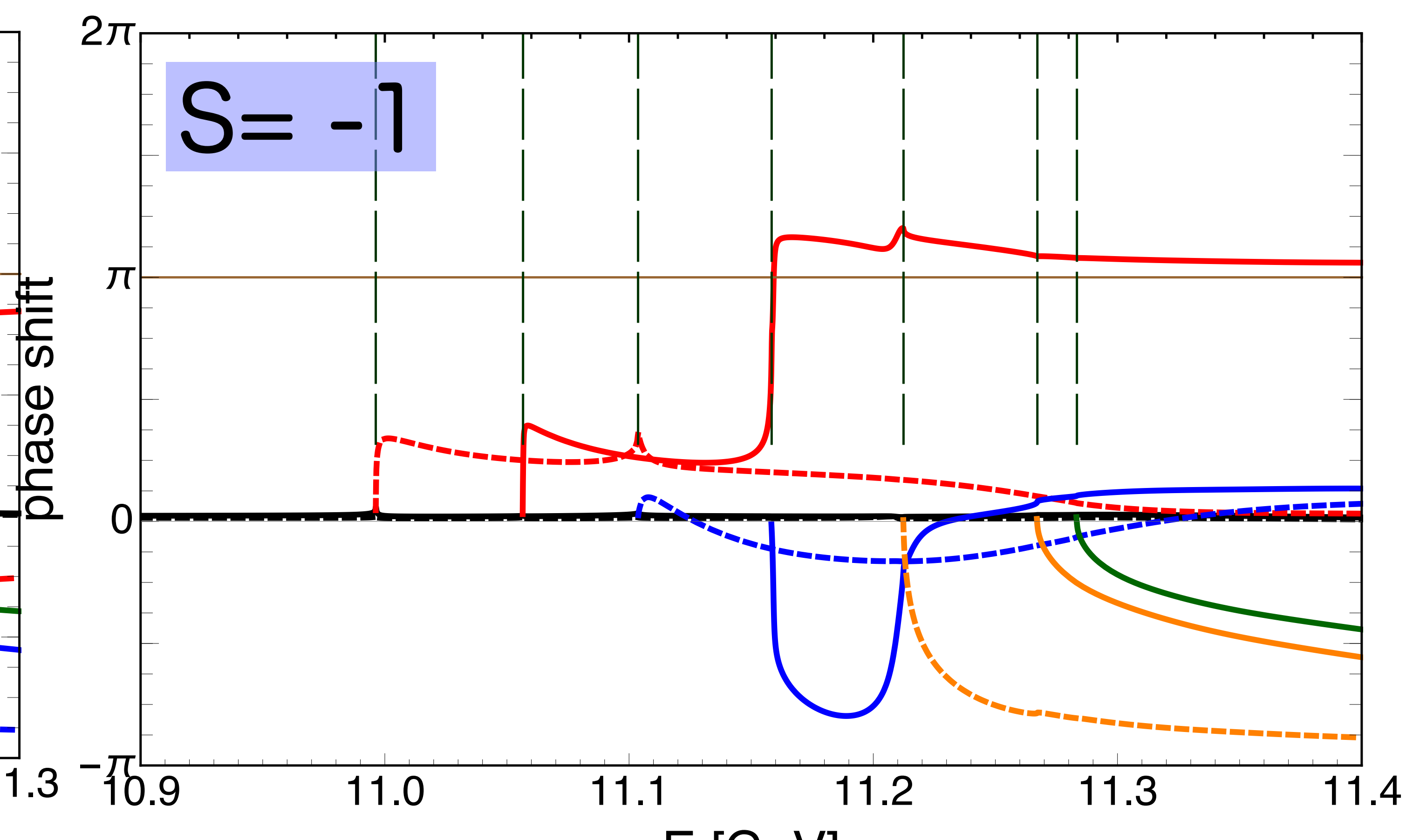
uud color-8 spin 3/2

3 structures

uds flavor-1color-8 spin 1/2

uds color-8 spin 3/2





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hidden bottom

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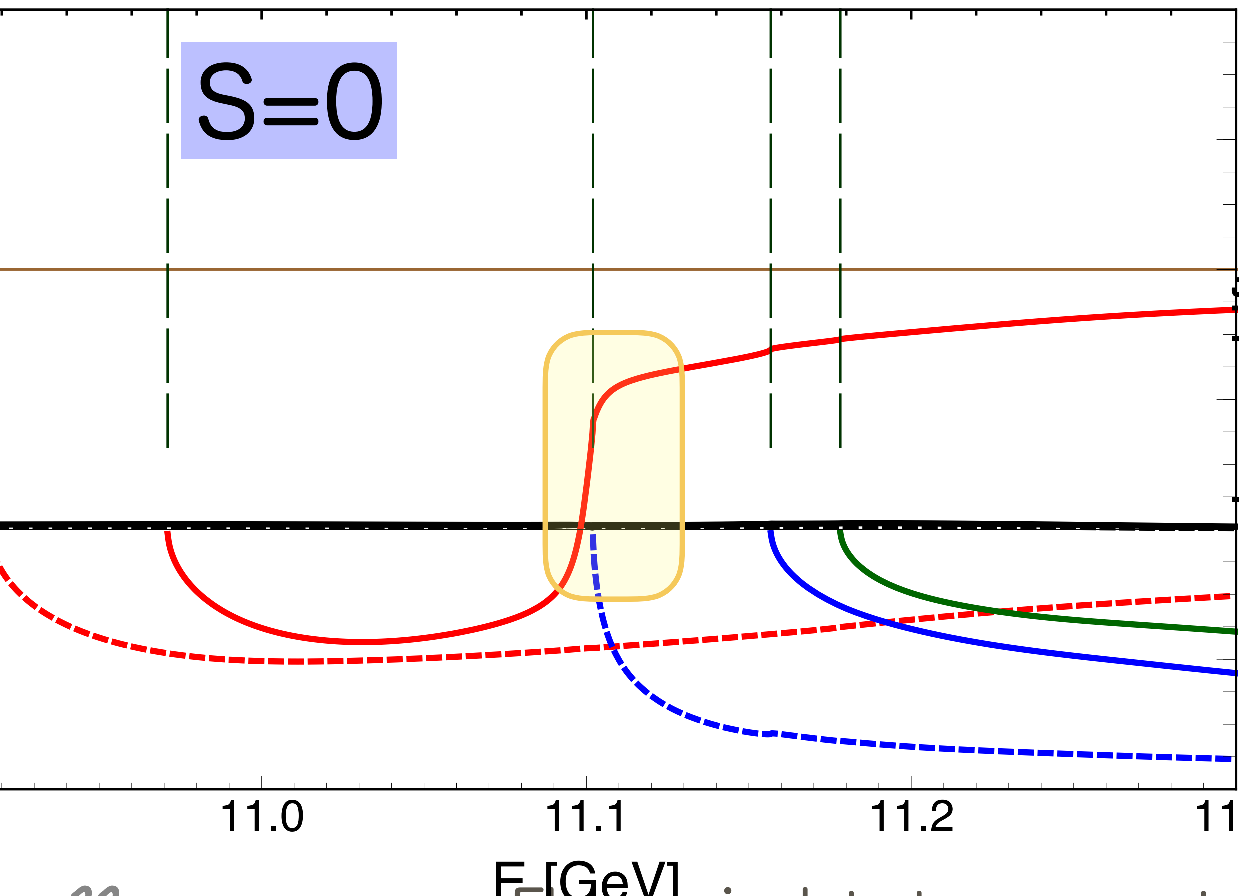
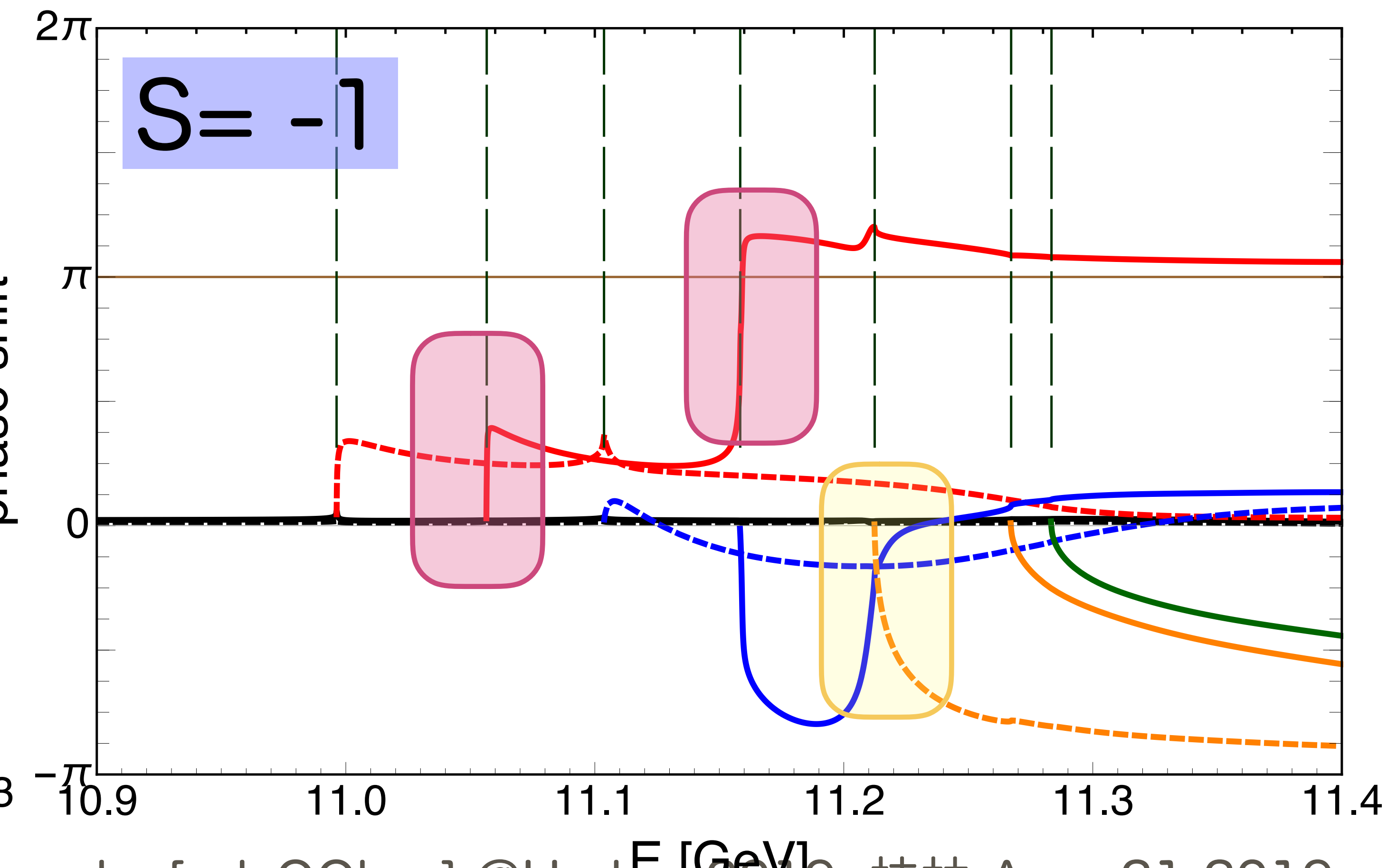
3 structures

uds flavor-1color-8 spin 1/2

uds color-8 spin 3/2





J=5/2

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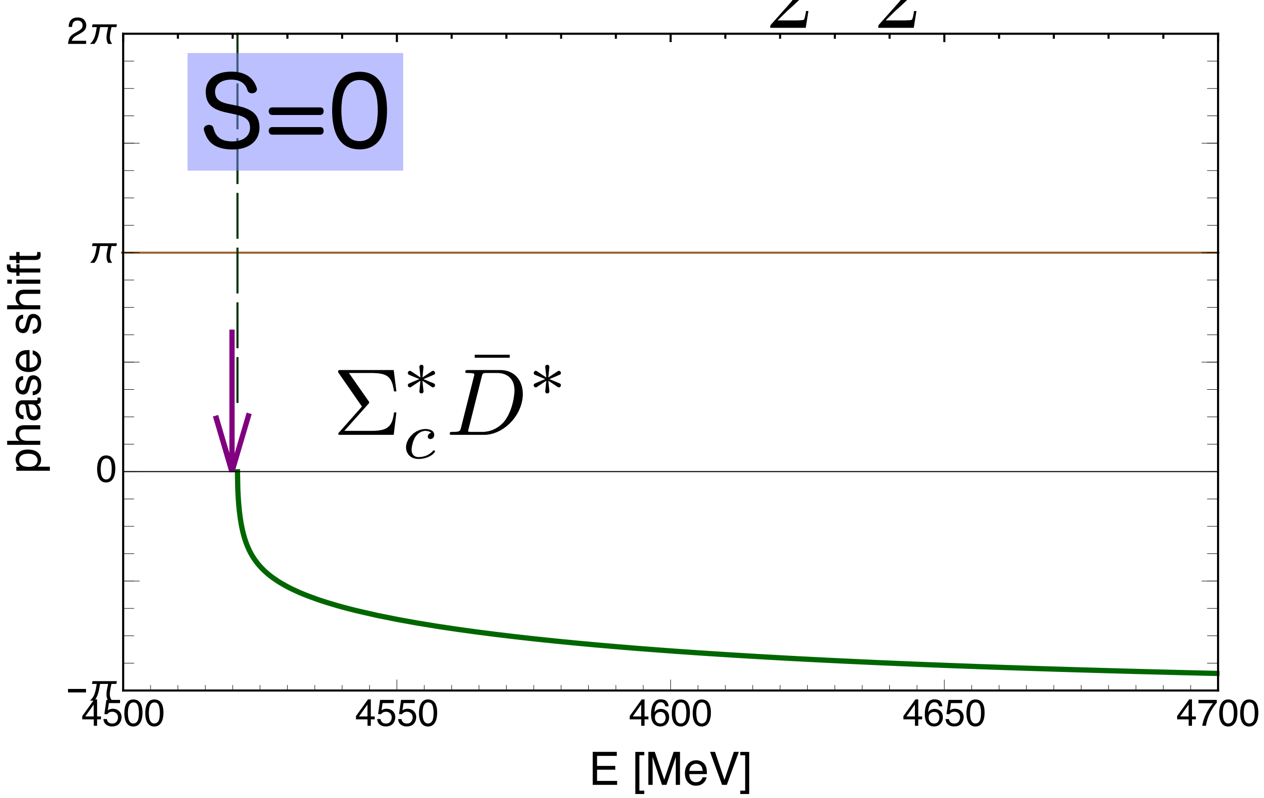
8	8	3/2	1	5/2

hidden charm

A bound state with a binding energy of ∼1 MeV

$$uud c\bar{c}\ I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$$



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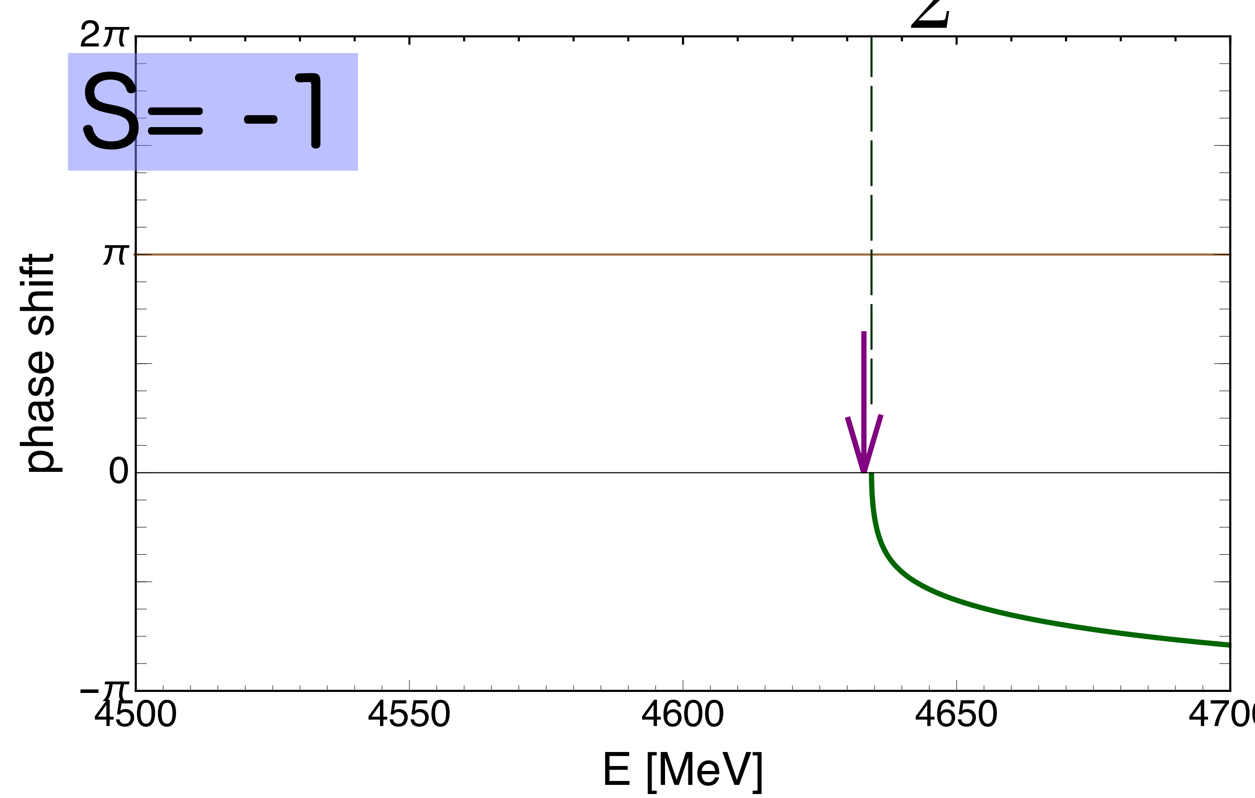

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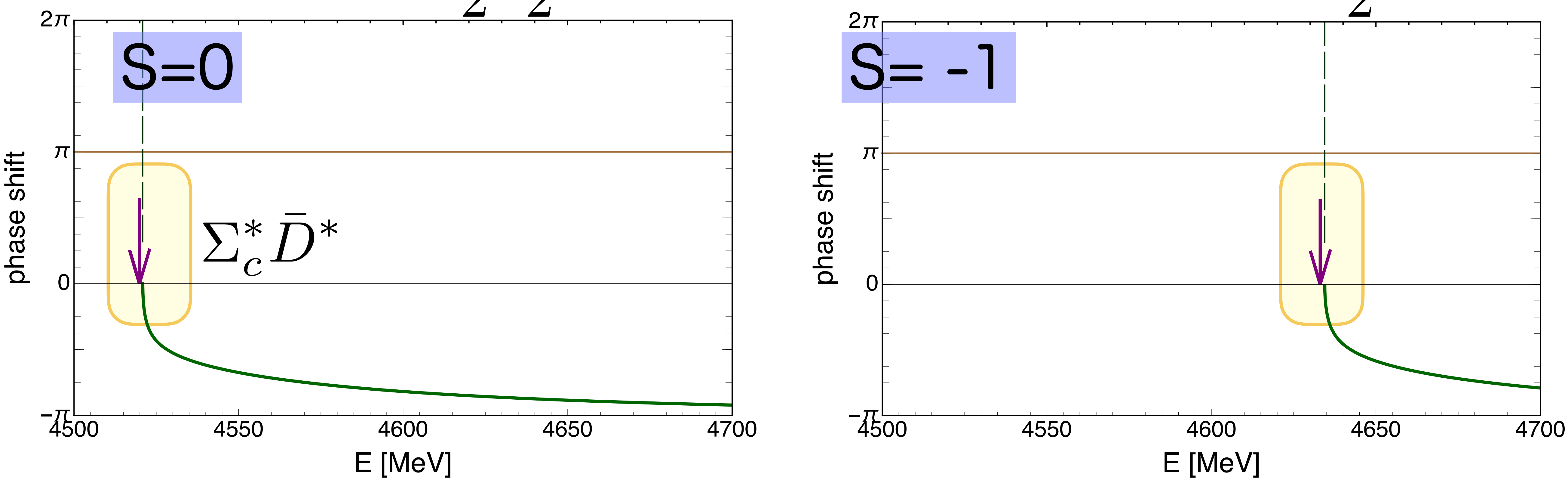


J=3/2

flavor	qqq color	qqq spin	$Q\bar{Q}$ spin	Total spin
1	8	1/2	1	3/2
8	8	3/2	0	3/2
8	8	3/2	1	3/2

hidden charm

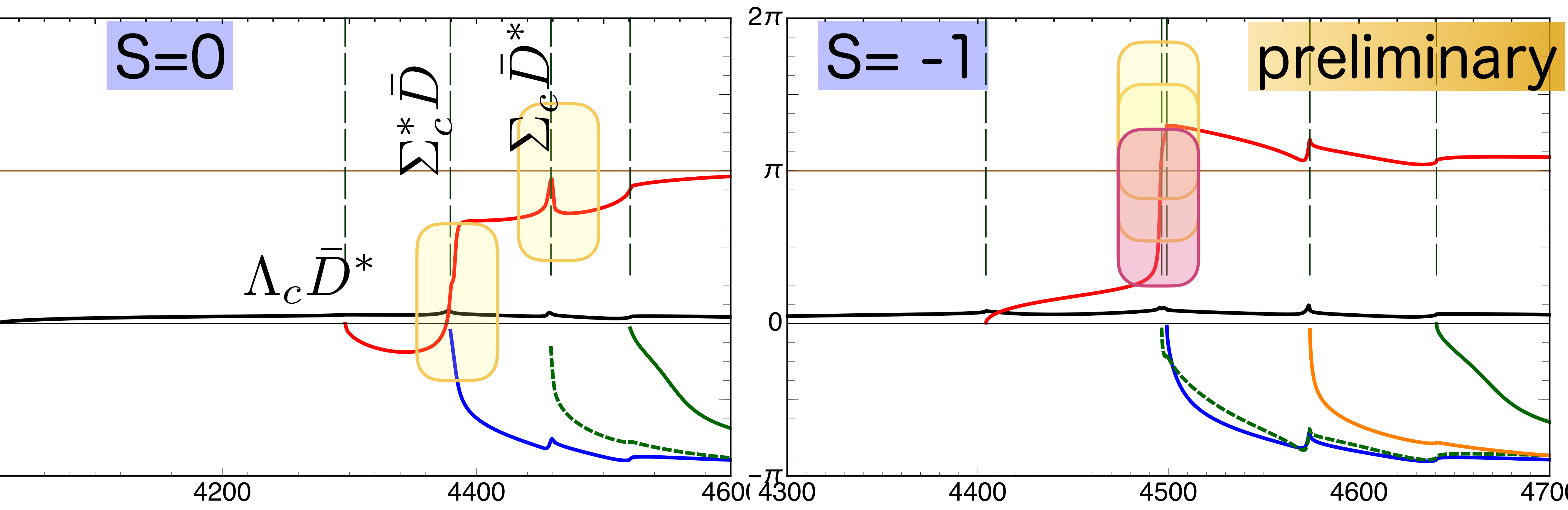
2 structures

uud color-8 spin 3/2

1 resonance

uds flavor-1color-8 spin 1/2

+ uds color-8 spin 3/2 mixed



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hidden charm

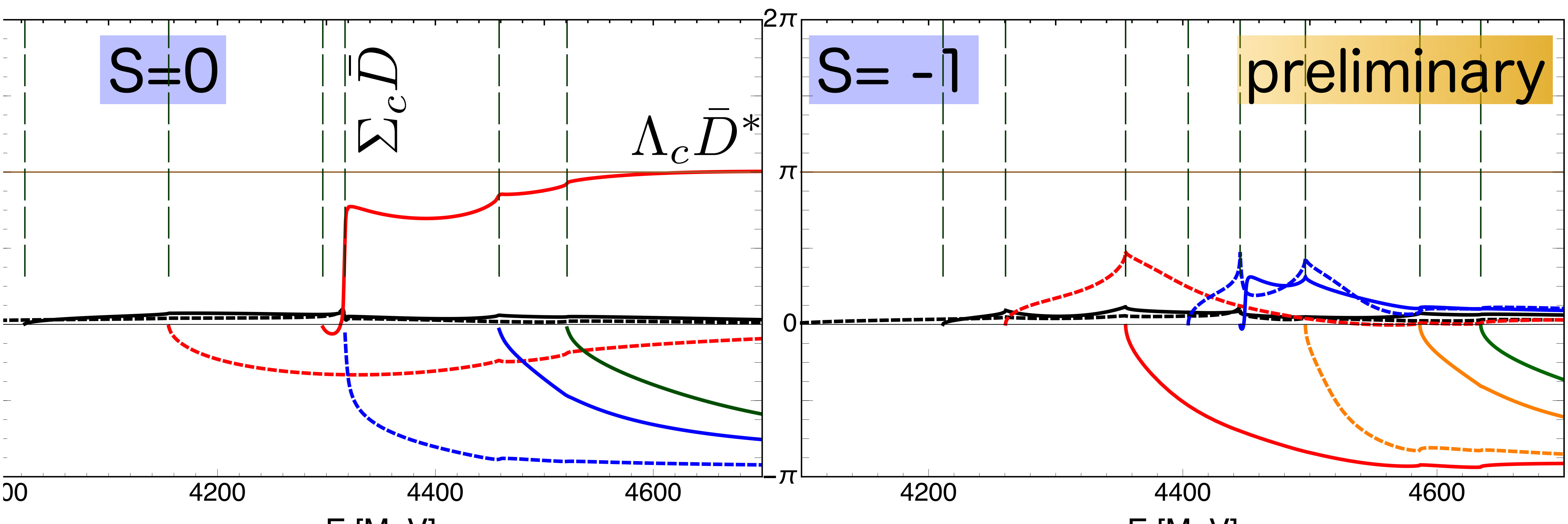
1 resonances

uud color-8 spin 3/2

3 structures

uds flavor-1color-8 spin 1/2

uds color-8 spin 3/2



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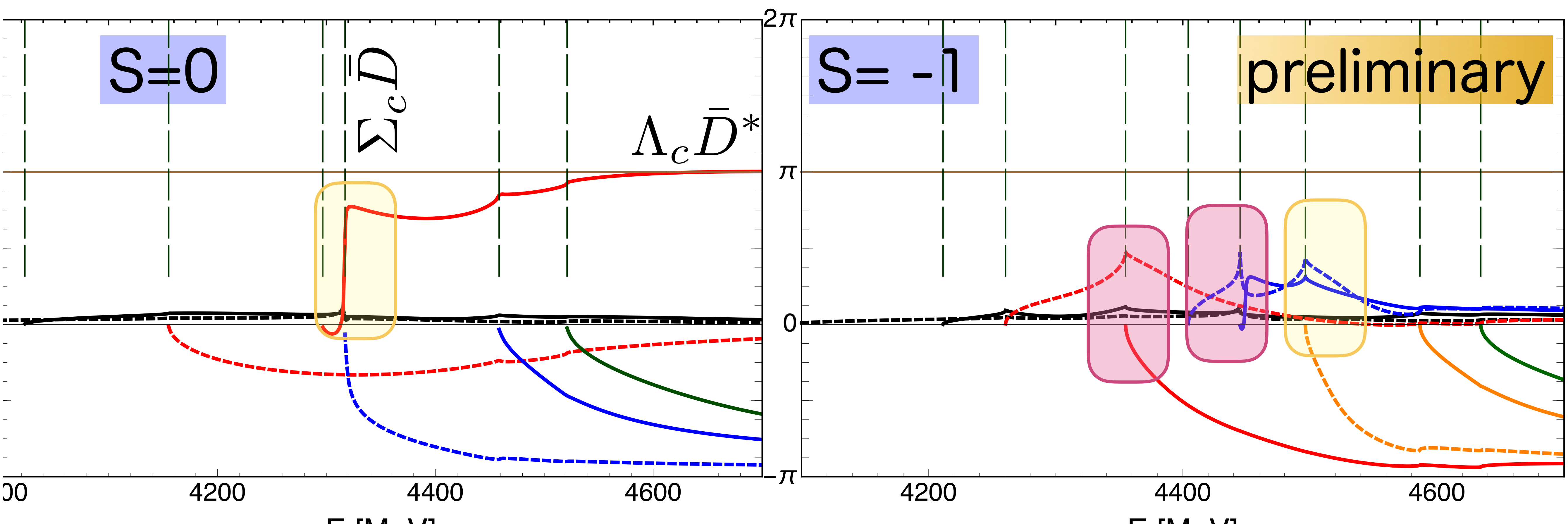


Summary

By adding a heavy quark pair to baryon:

- we can see the nature of color-octet 3-light quarks — some of them are attractive.

  (1) color-8 flavor-1 isospin-0 spin1/2 uds

  (2) color-8 flavor-8 spin3/2 uud, uds
- These modes can be observed by the Baryon-Meson scattering. More clearly with $b\bar{b}$.
- (2) is probably responsible to Pc peaks (with OPEP.)
- (1) can be seen by looking into BM interaction

Thank you very much for your attention!

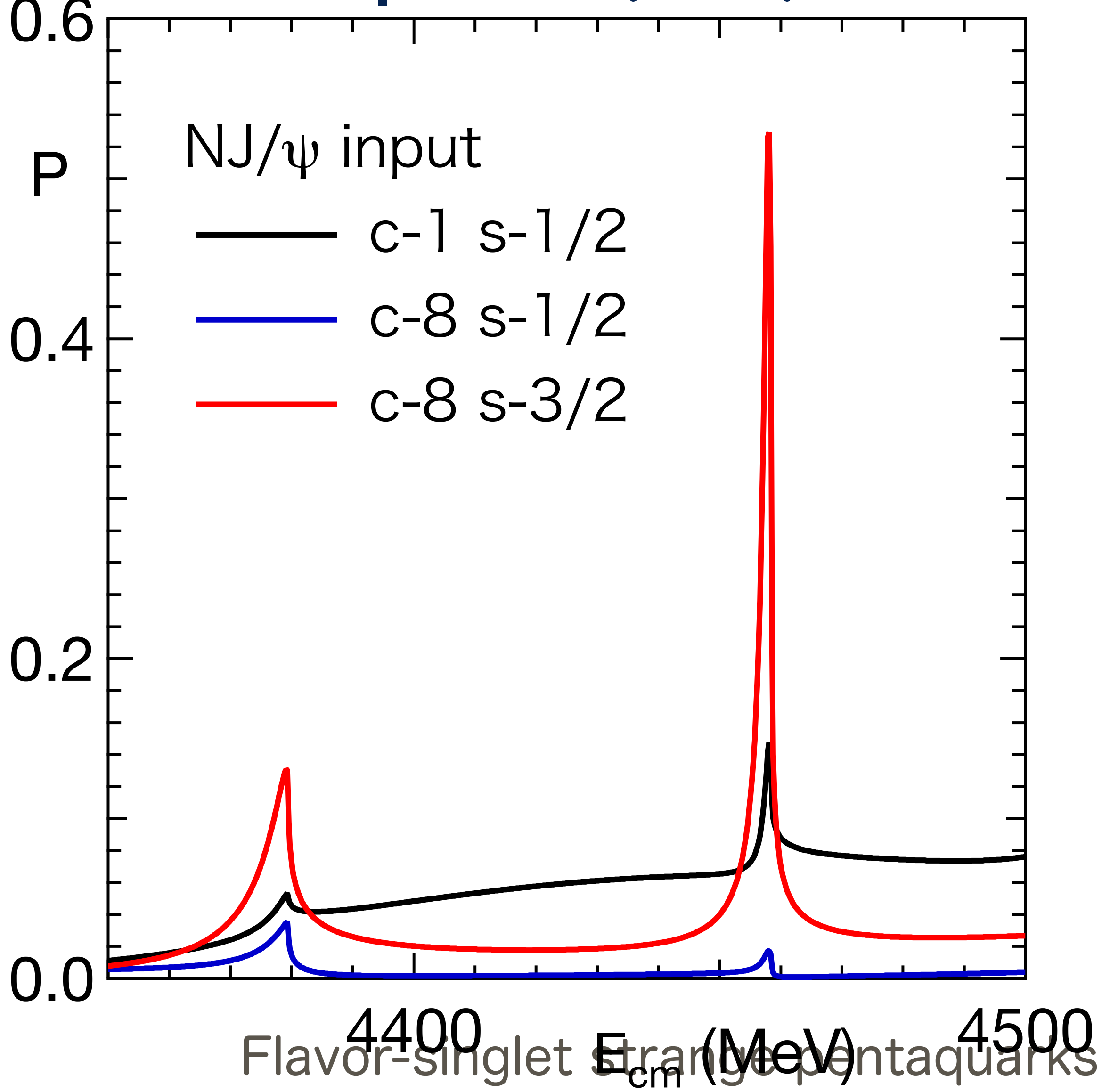
back up

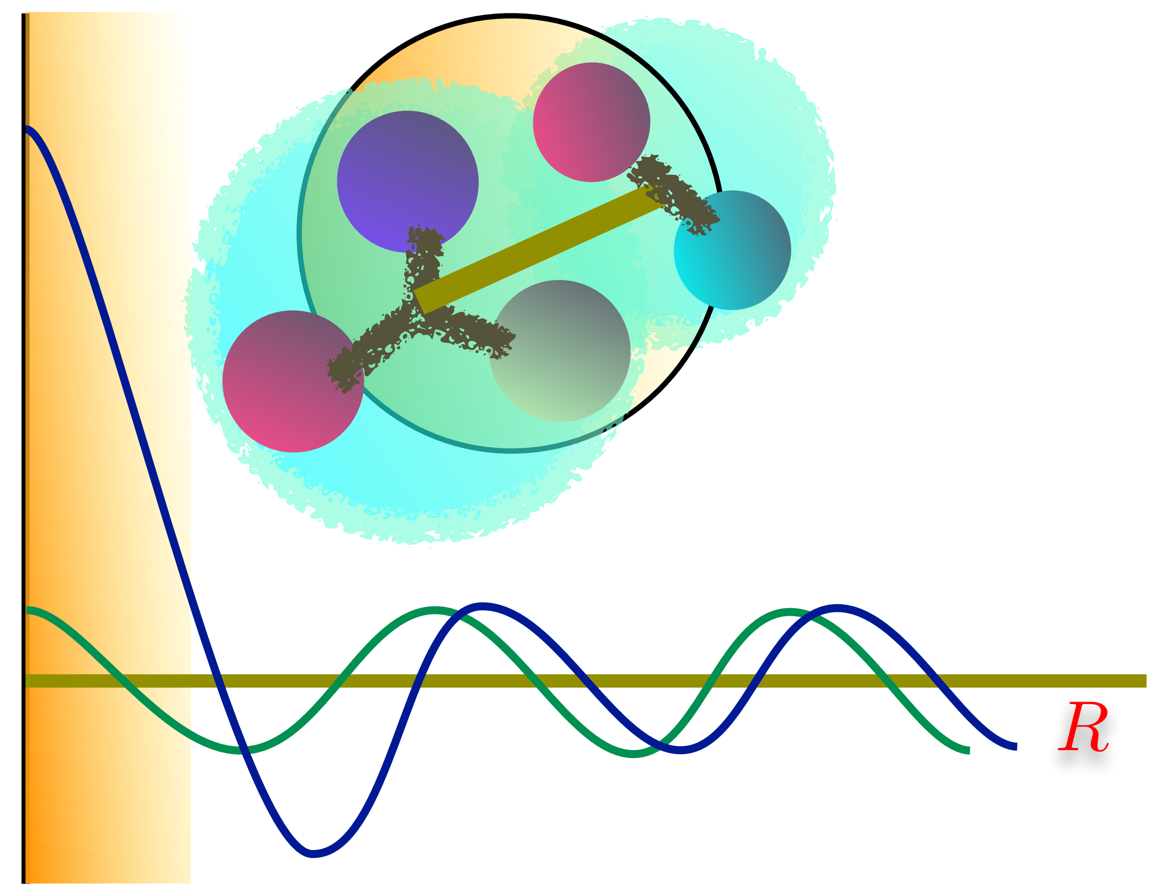
uudcc^{bar} I(JP)=1/2(3/2-)

[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

- $<\phi\ \phi\ \chi\ |$uud(0s)cs$><$uud(0s)cs$|\ \phi\ \phi\ \chi>$





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

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

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, $\sigma . \sigma$, LS, tensor. (No LS tensor is used this time)
  - Strong coupling constant $\alpha_s(Q^2)$:

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

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

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

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

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  - Strong coupling constant $\alpha_s(Q^2)$:

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

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

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

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

Model hamiltonian

- Color magnetic interaction (CMI)

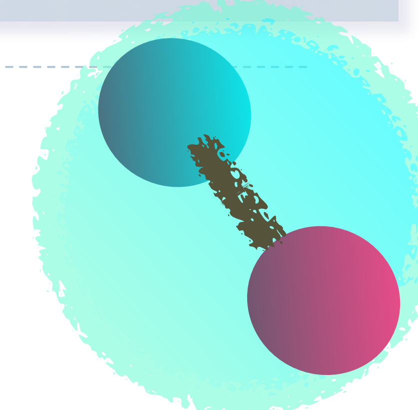
$$V_{\mathrm{CMI}} = -\frac{\lambda\cdot\lambda}{4}\alpha_s\frac{2\pi}{3m_i m_j}\sigma\cdot\sigma\delta^3(\boldsymbol{r})$$

- 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

Model wave function



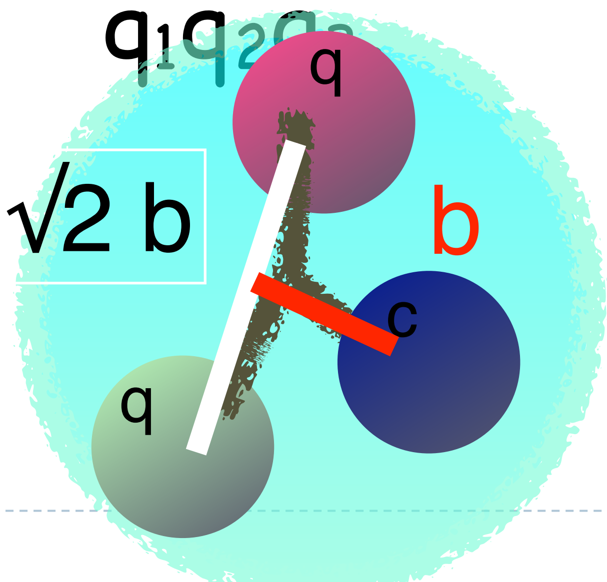
- Orbital wave functions
  - meson

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

  - 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～$\sqrt{0.7}$ b

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

BM v.s. qqq$Q\bar{Q}$ Transfer matrix

- e.g. S=-1, Isospin 0, Spin 3/2
  - uds

	$\lvert\Lambda J/\psi\rangle$	$\lvert\Lambda_c D_s^*\rangle$	$\lvert\Xi_c \overline{D}^*\rangle$	$\lvert\Xi_c' \overline{D}^*\rangle$	$\lvert\Xi_c^* \overline{D}\rangle$	$\lvert\Xi_c^* \overline{D}^*\rangle$
C-1 F-8 S-1/2	0.866	-0.289	-0.204	-0.118	0.204	-0.264
C-8 F-1 S-1/2	0	-0.577	0.816	0	0	0
C-8 F-8 S-1/2	0	0.577	0.408	-0.236	0.408	-0.527
C-8 F-8 S-3/2	0	0	0	0.866	0.500	0
C-8 F-8 S-3/2	0	0	0	-0.373	0.645	0.667

  - a forbidden state

$$\sqrt{\frac{1}{24}}\left(\sqrt{6}\lvert\Lambda J/\psi\rangle + \sqrt{6}\lvert\Lambda_c D_s^*\rangle + \sqrt{3}\lvert\Xi_c \overline{D}^*\rangle + \sqrt{1}\lvert\Xi_c' \overline{D}^*\rangle - \sqrt{3}\lvert\Xi_c^* \overline{D}\rangle + \sqrt{5}\lvert\Xi_c^* \overline{D}^*\rangle\right)$$