Spectroscopy and structure of excited heavy baryons

T.Yoshida[A,B], M.Oka[A], A.Hosaka[B], E.Hiyama [C], K.Sadato[B,D]
[A]Tokyo tech, [B]RCNP, [C]RIKEN, [D]G-search
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1. Introduction
   - -Spectroscopy of heavy baryons
   - -λ-mode and ρ-mode (**Main topic**)
     - →Definition of two modes
     - Separation of two modes
2. FORMARIZM
   - Hamiltonian
   - Calculation method (Gauss expansion method)
3. Results
   - Mass of Charm, Bottom baryons
   - HQ mass dependence of baryon mass and wave function
4. Summary

p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1685)$		*
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	***
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	**
$N(1895)$	$1/2^-$	**
$N(1900)$	$3/2^+$	***
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2300)$	$1/2^+$	**
$N(2570)$	$5/2^-$	**
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	*
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**
Λ	$1/2^+$	****
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	***
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1710)$	$1/2^+$	*
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$		*
$\Lambda(2020)$	$7/2^+$	*
$\Lambda(2050)$	$3/2^-$	*
$\Lambda(2100)$	$7/2^-$	****
[illegible]	[illegible]	[illegible]
$\Lambda(2585)$		**

Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	*
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1690)$		**
$\Sigma(1730)$	$3/2^+$	*
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1770)$	$1/2^+$	*
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(1840)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(1900)$	$1/2^-$	*
$\Sigma(1915)$	$5/2^+$	****
$\Sigma(1940)$	$3/2^+$	*
$\Sigma(1940)$	$3/2^-$	***
$\Sigma(2000)$	$1/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	**
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}^?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$		***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	***
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		*
$\Xi_c(2980)$		***
$\Xi_c(3055)$		**
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
Ξ_{cc}^+		*
Λ_b^0	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
Σ_b	$1/2^+$	[illegible]
Σ_b^*	[illegible]	[illegible]
Ξ_b^0, Ξ_b^-	[illegible]	[illegible]
[illegible]	[illegible]	***
[illegible]	[illegible]	***

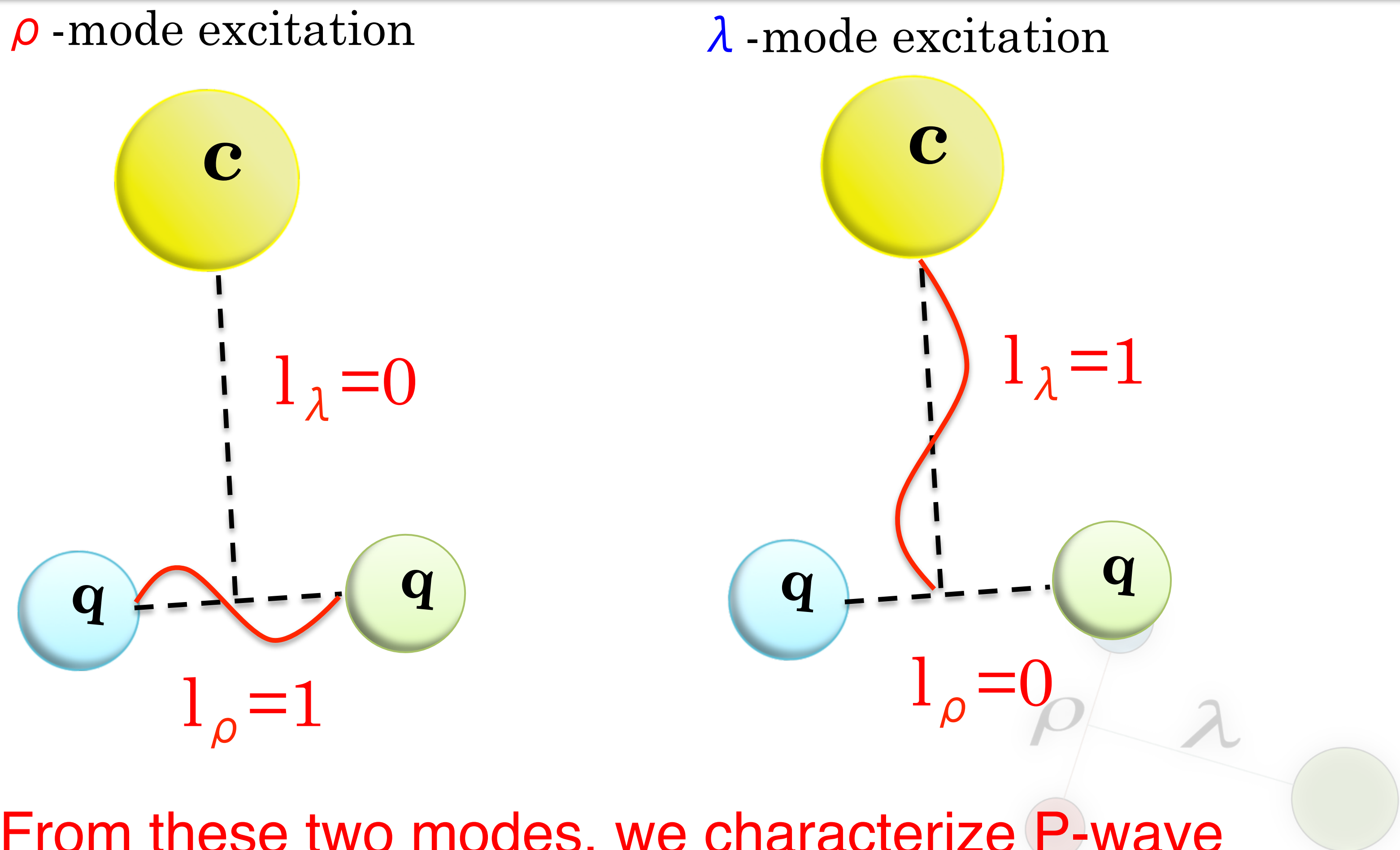
Light sector

Heavy sector

We do not have the information of the excited heavy baryons

ρ -mode and λ -mode

-Why we focus on the excited heavy baryons?-
(What is interesting?)



From these two modes, we characterize P-wave state of the heavy baryons.

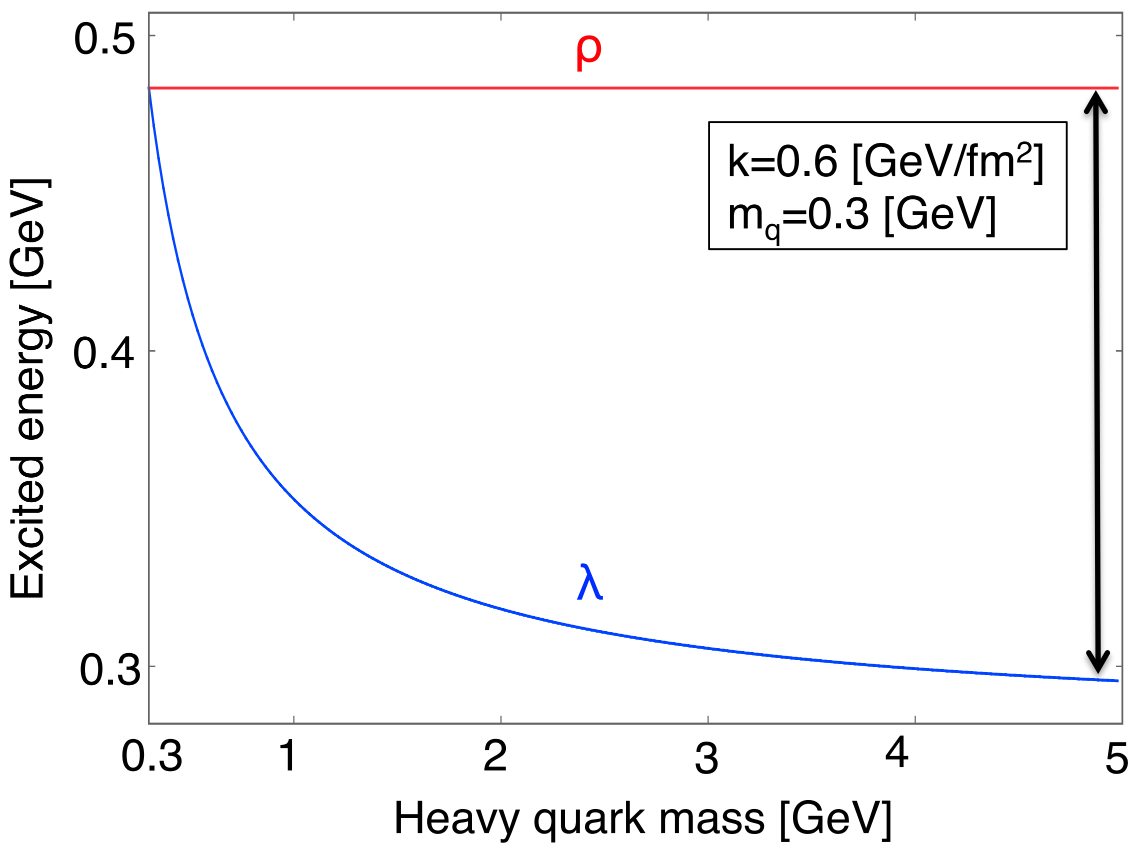
ρ -mode and λ -mode

-Why we focus on the excited heavy baryons?-

(What is interesting?)

Harmonic oscillator type potential

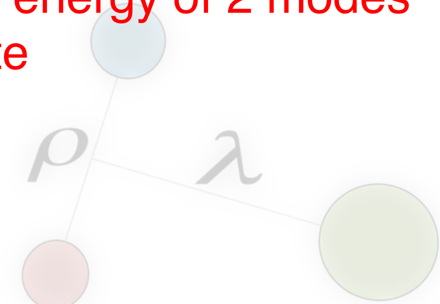
$$H=\sum_i \frac{p_i^2}{2m_i}+\sum_{i<j}\frac{3k}{2}|r_i-r_j|^2=\frac{p_\rho^2}{2m_\rho}+\frac{p_\lambda^2}{2m_\lambda}+\frac{m_\rho {\omega_\rho}^2}{2}\rho^2+\frac{m_\lambda {\omega_\lambda}^2}{2}\lambda^2$$



$$\omega_\rho=\sqrt{\frac{3k}{2m_\rho}} \quad \omega_\lambda=\sqrt{\frac{2k}{m_\lambda}}.$$

$$\frac{\omega_\lambda}{\omega_\rho}=\sqrt{\frac{1}{3}(1+2m_q/m_Q)}$$

Excited energy of 2 modes separate

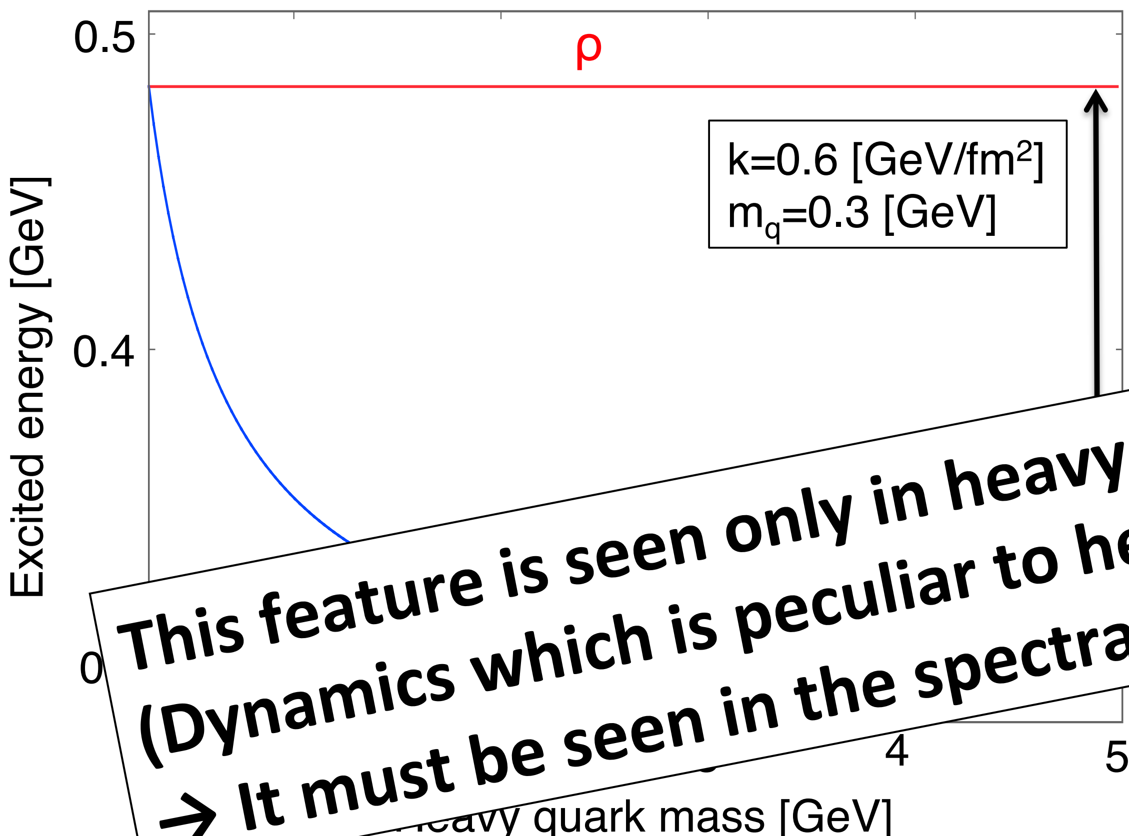


ρ -mode and λ -mode

-Why we focus on the excited heavy baryons?-
(What is interesting?)

Harmonic oscillator type potential

$$H = \sum_i \frac{p_i^2}{2m_i} + \sum_{i<j} \frac{3k}{2} |r_i - r_j|^2 = \frac{p_\rho^2}{2m_\rho} + \frac{p_\lambda^2}{2m_\lambda} + \frac{m_\rho {\omega_\rho}^2}{2}\rho^2 + \frac{m_\lambda {\omega_\lambda}^2}{2}\lambda^2$$



$$\omega_\rho = \sqrt{\frac{3k}{2m_\rho}} \quad \omega_\lambda = \sqrt{\frac{2k}{m_\lambda}}.$$

$$\frac{\omega_\lambda}{\omega_\rho} = \sqrt{\frac{1}{3}(1 + 2m_q/m_Q)}$$

This feature is seen only in heavy quark sector
(Dynamics which is peculiar to heavy quark region)
→ It must be seen in the spectra of heavy baryons

Mixing of λ and ρ-mode

Only central force

$$\begin{pmatrix} H_0 & 0 \\ 0 & H_0 \end{pmatrix}$$

$$+\ \frac{16\pi\alpha^{ss}}{9m_i m_j}\boldsymbol{S}_i\cdot\boldsymbol{S}_j\frac{\Lambda^2}{4\pi r_{ij}}\exp(-\Lambda r_{ij})\ \longrightarrow$$

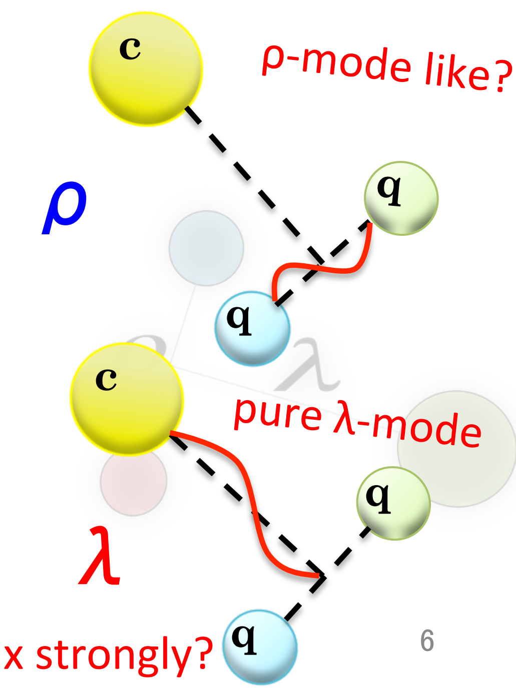
+ spin-spin force

$$\begin{pmatrix} H_0 & \varepsilon \\ \varepsilon & H_0 \end{pmatrix}\begin{matrix} \rho \\ \lambda \end{matrix}$$

Spin-Spin force induce the mixing of λ and ρ-mode

$$\left|\Psi_{B^-}\right\rangle = C_\rho\left|\rho\right\rangle + C_\lambda\left|\lambda\right\rangle \xrightarrow{\ |C_\lambda|^2\quad |C_\rho|^2\ }$$

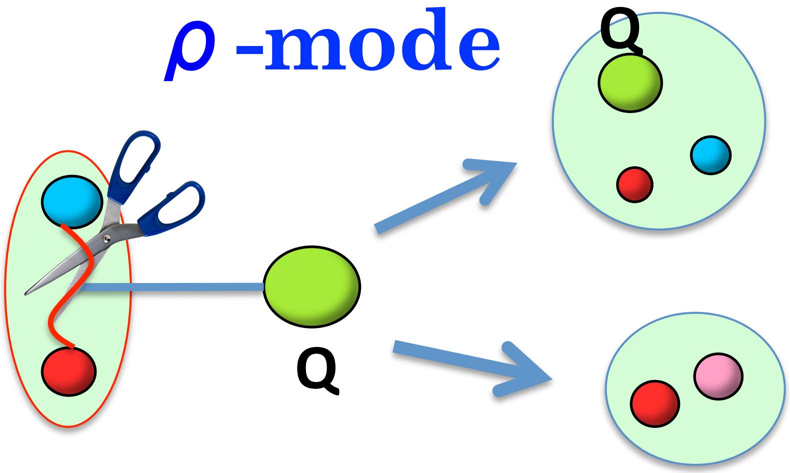
?

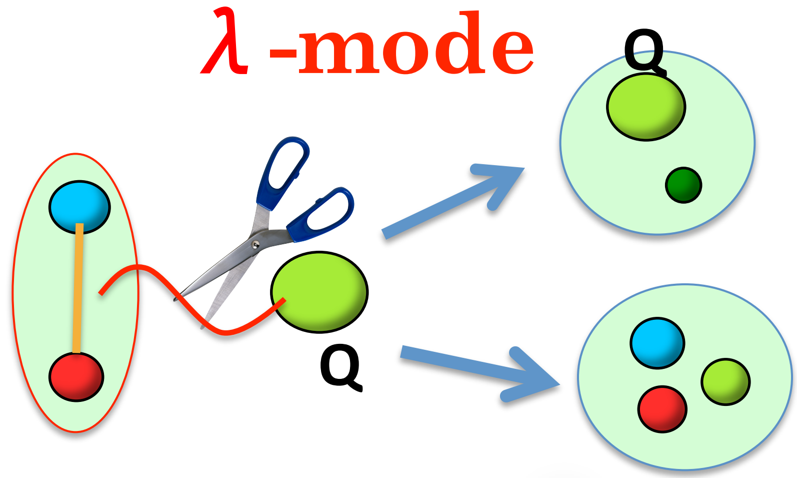


We can get the information of the structure of P-wave heavy baryons from the coefficients C_λ , C_ρ

Two modes mix strongly?

Decay pattern





$\Gamma(\Sigma_Q\pi) > \Gamma(pD)$

$\Gamma(\Sigma_Q\pi) < \Gamma(pD)$

Why we focus on the excited heavy baryons?

1.Prediction for the heavy baryon spectra of excited state

→・ It has not been observed experimentally

・ It is difficult to treat in the Lattice QCD

2. The separation of the λ- and ρ- modes

→・ It is seen only in the heavy quark sector.

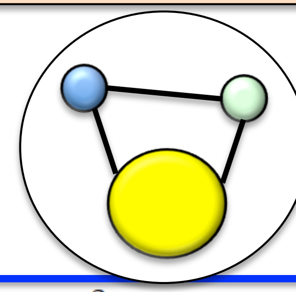
・ The feature is reflected on decay.

Constituent quark model

Schrödinger equation

$$V_{\rm con} = \sum_{i<j} \frac{b r_{ij}}{2} + C$$

$$\left[T + V_{conf} + V_{short} - E\right]\left|\Psi_{JM}\right\rangle = 0$$



Λ_Q

Σ_Q

$$V_{\rm short} = \sum_{i<j}[-\frac{2\alpha^{\rm Coul}}{3r_{ij}} + \left(\frac{1}{m_i^2} + \frac{1}{m_j^2}\right)\frac{\Lambda^2}{4\pi r_{ij}}\exp(-\Lambda r) + \frac{16\pi\alpha^{ss}}{9m_i m_j}\boldsymbol{S}_i\cdot\boldsymbol{S}_j\frac{\Lambda^2}{4\pi r_{ij}}\exp(-\Lambda r_{ij})$$

Anti-symmetric LS force

$$+\frac{\alpha^{\rm so}(1-\exp(-\Lambda r_{ij}))^2}{3{r_{ij}}^3}[(\frac{1}{m_i^2} + \frac{1}{m_j^2} + 4\frac{1}{m_i m_j})\boldsymbol{L}_{ij}\cdot(\boldsymbol{S}_j + \boldsymbol{S}_j) + (\frac{1}{m_i^2} - \frac{1}{m_j^2})\boldsymbol{L}_{ij}\cdot(\boldsymbol{S}_i - \boldsymbol{S}_j)]$$

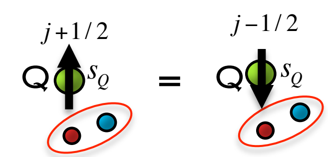
$$+\frac{2\alpha^{\rm ten}(1-\exp(-\Lambda r_{ij}))^2}{3m_i m_j {r_{ij}}^3}\left(\frac{3(\boldsymbol{S}_i\cdot\boldsymbol{r}_{ij})(\boldsymbol{S}_j\cdot\boldsymbol{r}_{ij})}{{r_{ij}}^2} - \boldsymbol{S}_i\cdot\boldsymbol{S}_j\right)].$$

$$\alpha^{Coul} \longrightarrow \alpha^{Coul}(\mu_{ij})$$

- Introduce color Coulomb force which depend on quark mass (Form recent Lattice QCD calculation)

Taichi Kawanai and Shoichi Sasaki. Phys.Rev.Lett.,107:091601, 2011.

- Introduce ALS force to guarantee HQ symmetry (Because now we focus on heavy quark sector)

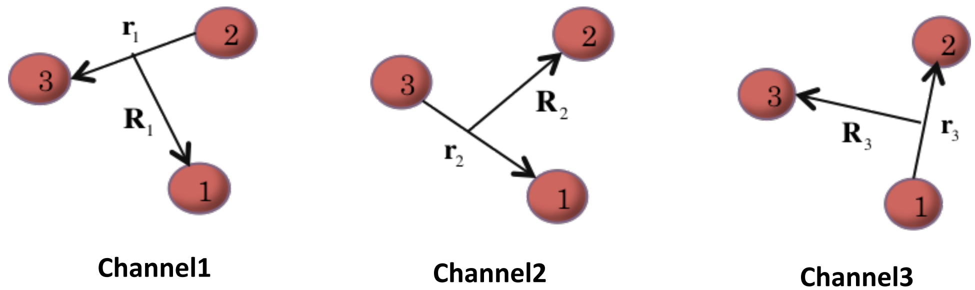


We will see two state degenerate in the heavy quark limit (HQS doublet)

- Parameters is determined by experimental data of strange baryons (we omit Λ(1405) and Roper like resonance to fit the data)

Gaussian Expansion Method

jacobi coodinate



Wave function

$$\Psi_{JM} = \Phi_{JM}^{(C=1)}(\mathbf{r}_1,\mathbf{R}_1) + \Phi_{JM}^{(C=2)}(\mathbf{r}_2,\mathbf{R}_2) + \Phi_{JM}^{(C=3)}(\mathbf{r}_3,\mathbf{R}_3)$$

$$\Phi_{JM}^{(C)} = \sum_{n_C l_C N_C L_C} A_{n_C l_C, N_C L_C}^{(C)} \left[\phi_{n_C l_C}^{G}(\mathbf{r}_C)\psi_{N_C L_C}^{G}(\mathbf{R}_C)\right]$$

Trial function

$$\phi_{nlm}^{G}(r) = N_{nl} r^{l} e^{-\nu_n r^2} Y_{lm}(\hat{\mathbf{r}})$$

$$\psi_{NLM}^{G}(R) = N_{NL} R^{L} e^{-\lambda_N r^2} Y_{LM}(\hat{\mathbf{R}})$$

Eigen value problem

$$\mathbf{Hc} = E\mathbf{Nc}$$

$$\begin{pmatrix} H_{11} & H_{12} & \cdots & H_{1N} \\ H_{21} & H_{22} & \cdots & H_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ H_{nN} & H_{nN} & \cdots & H_{NN} \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \\ \vdots \\ c_N \end{pmatrix} = E \begin{pmatrix} N_{11} & N_{12} & \cdots & N_{1N} \\ N_{21} & N_{22} & \cdots & N_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ N_{nN} & N_{nN} & \cdots & N_{NN} \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \\ \vdots \\ c_N \end{pmatrix}$$

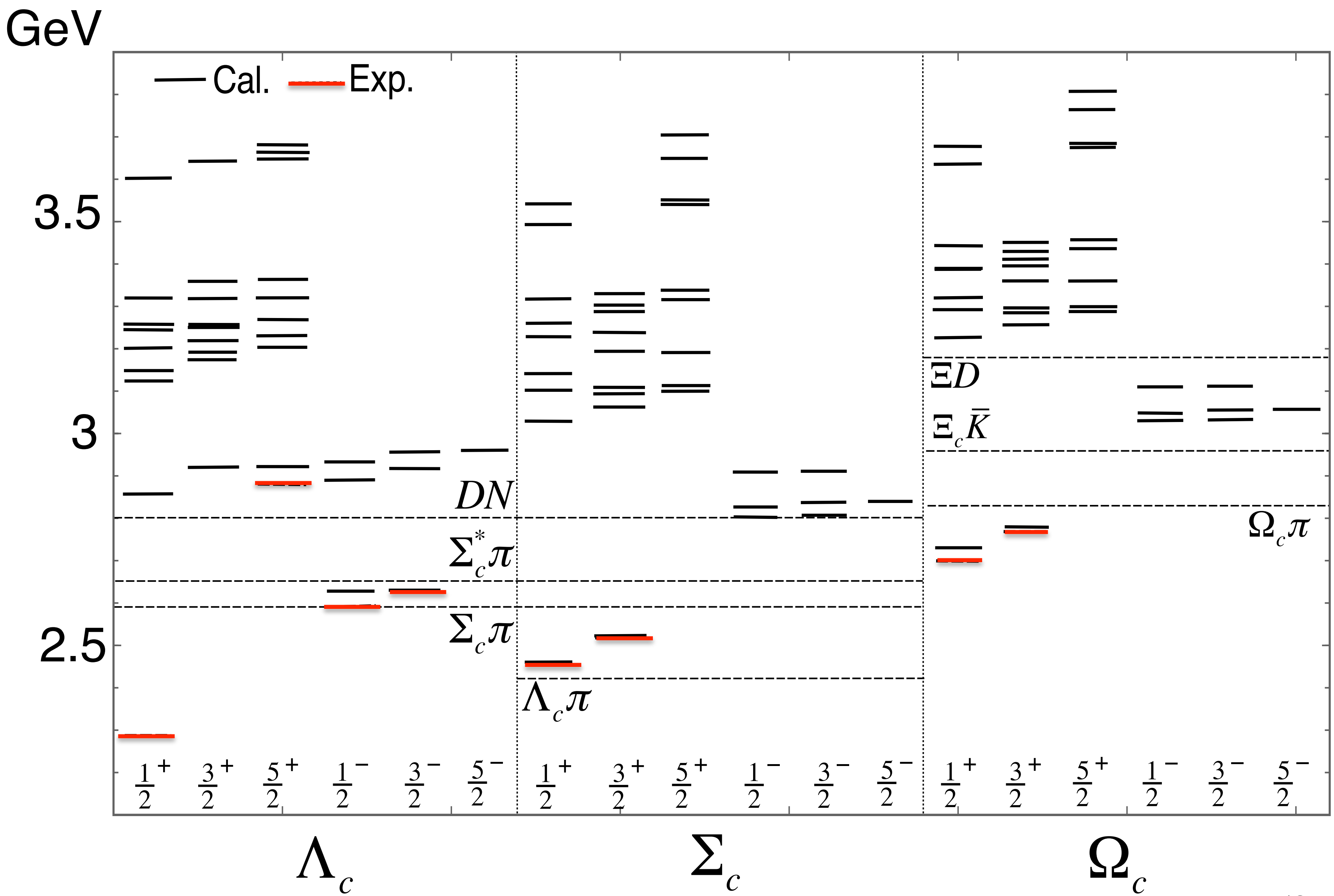
$$\left(\begin{array}{l} N_{ij} = \langle \phi_{JM}^{(i)} | \phi_{JM}^{(j)} \rangle \\ H_{ij} = \langle \phi_{JM}^{(i)} | H | \phi_{JM}^{(j)} \rangle \end{array} \right)$$

- ✓ We describe baryon wave function as sum of channels
- ✓ We use Gaussian basis function

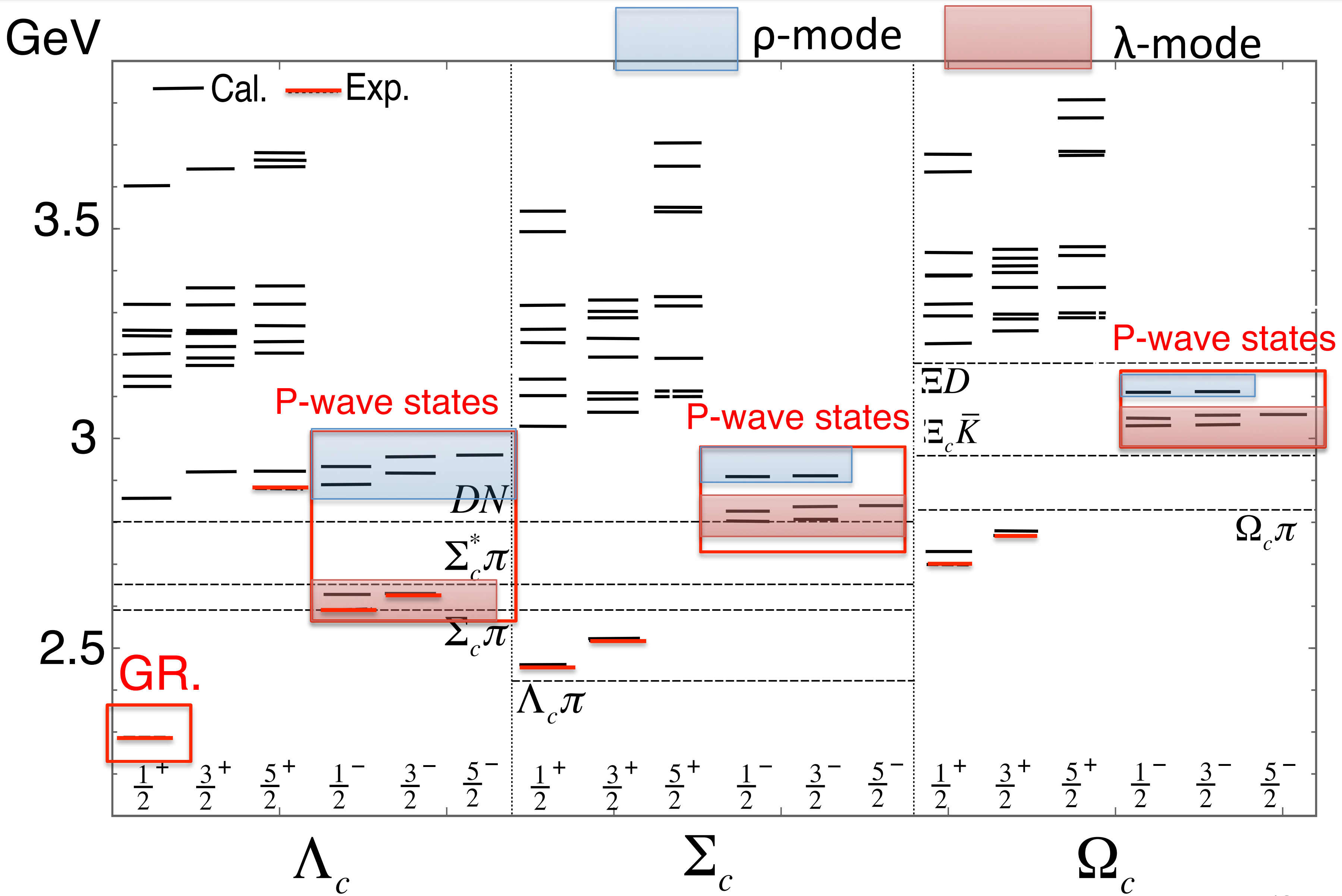
E. Hiyama, Y. Kino and M. Kamimura, Prog. Part. Nucl. Phys. 51 (2003) 223

Result

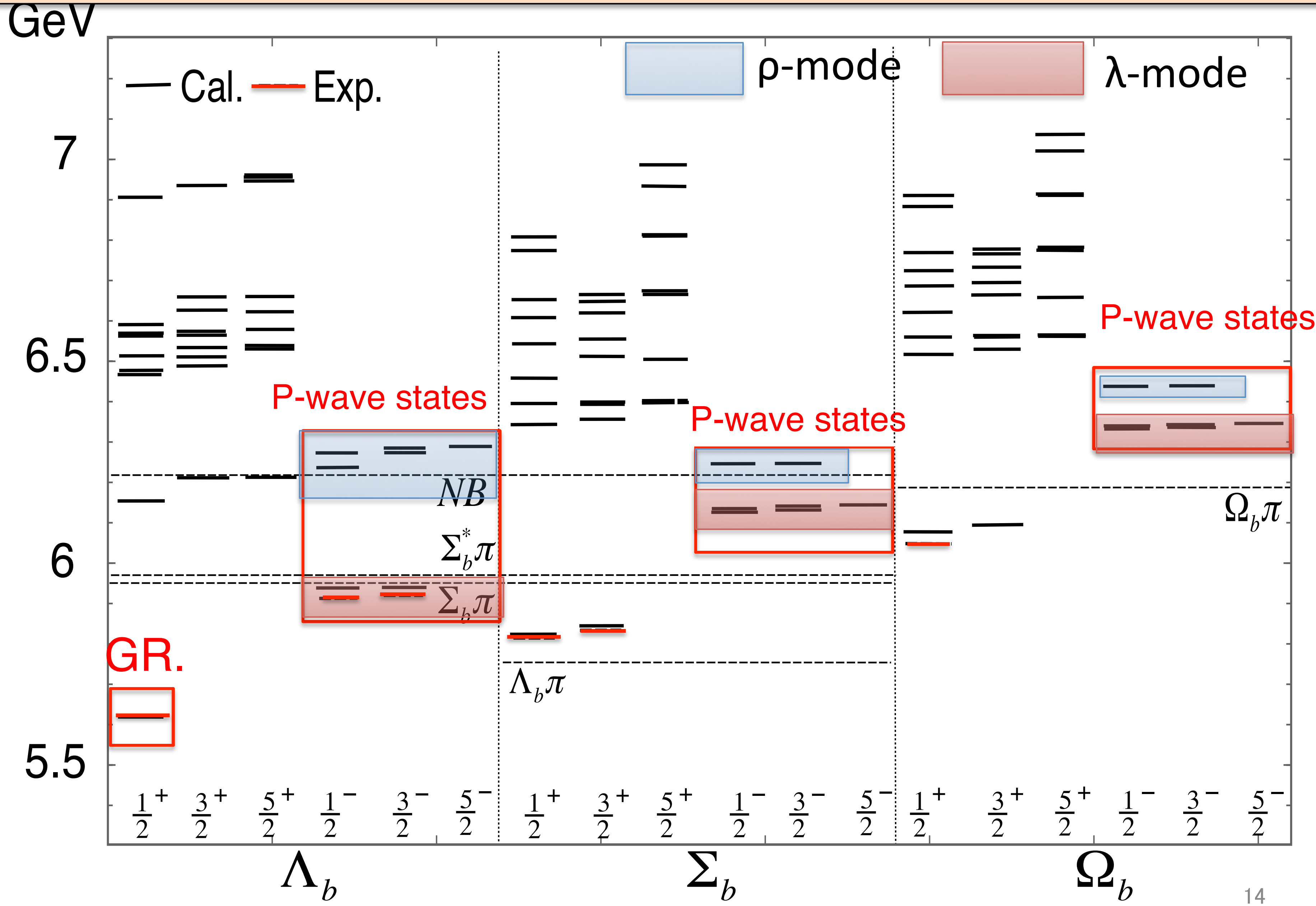
Spectra of Charmed baryons



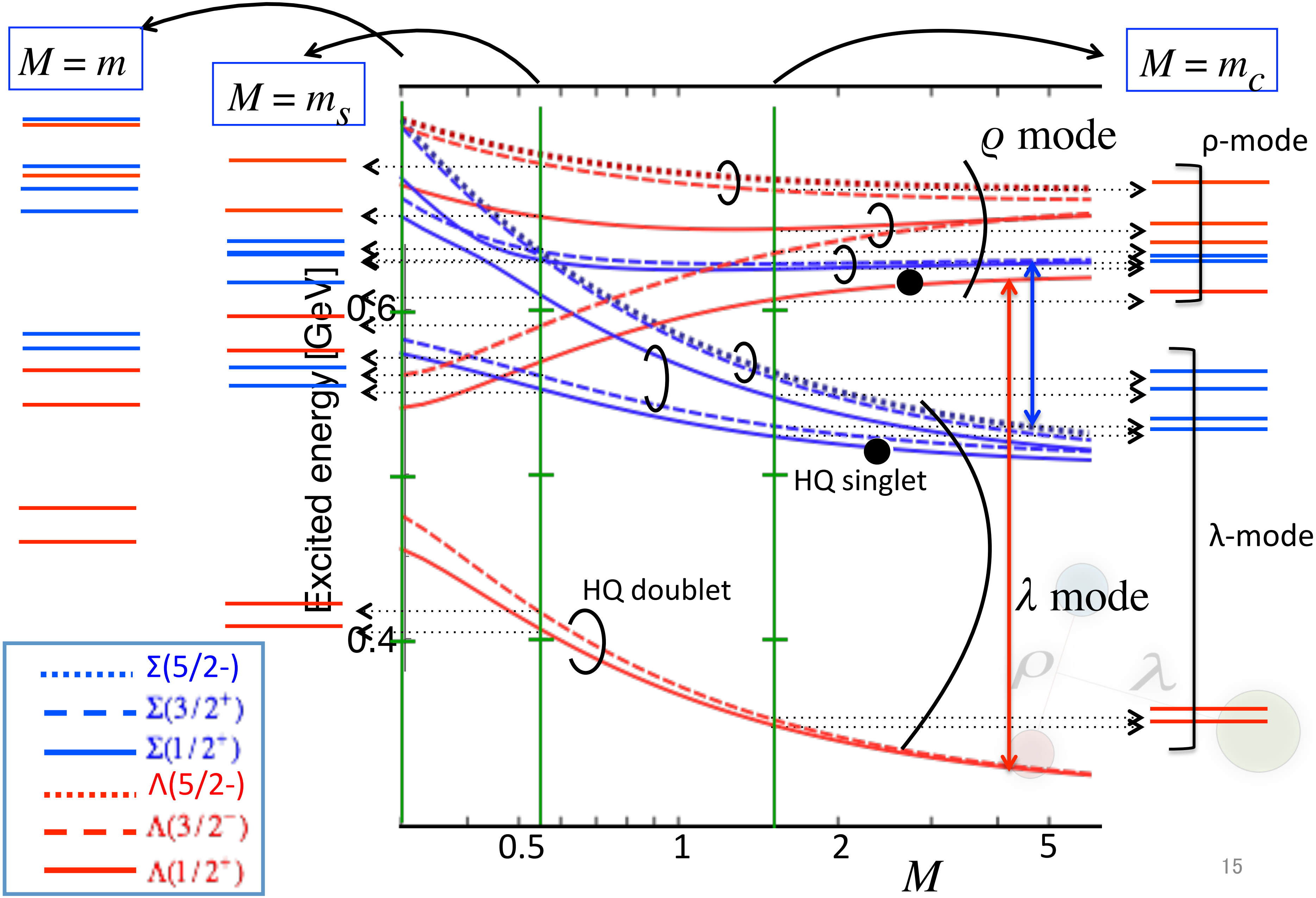
Spectra of Charmed baryons



Spectra of bottom baryons

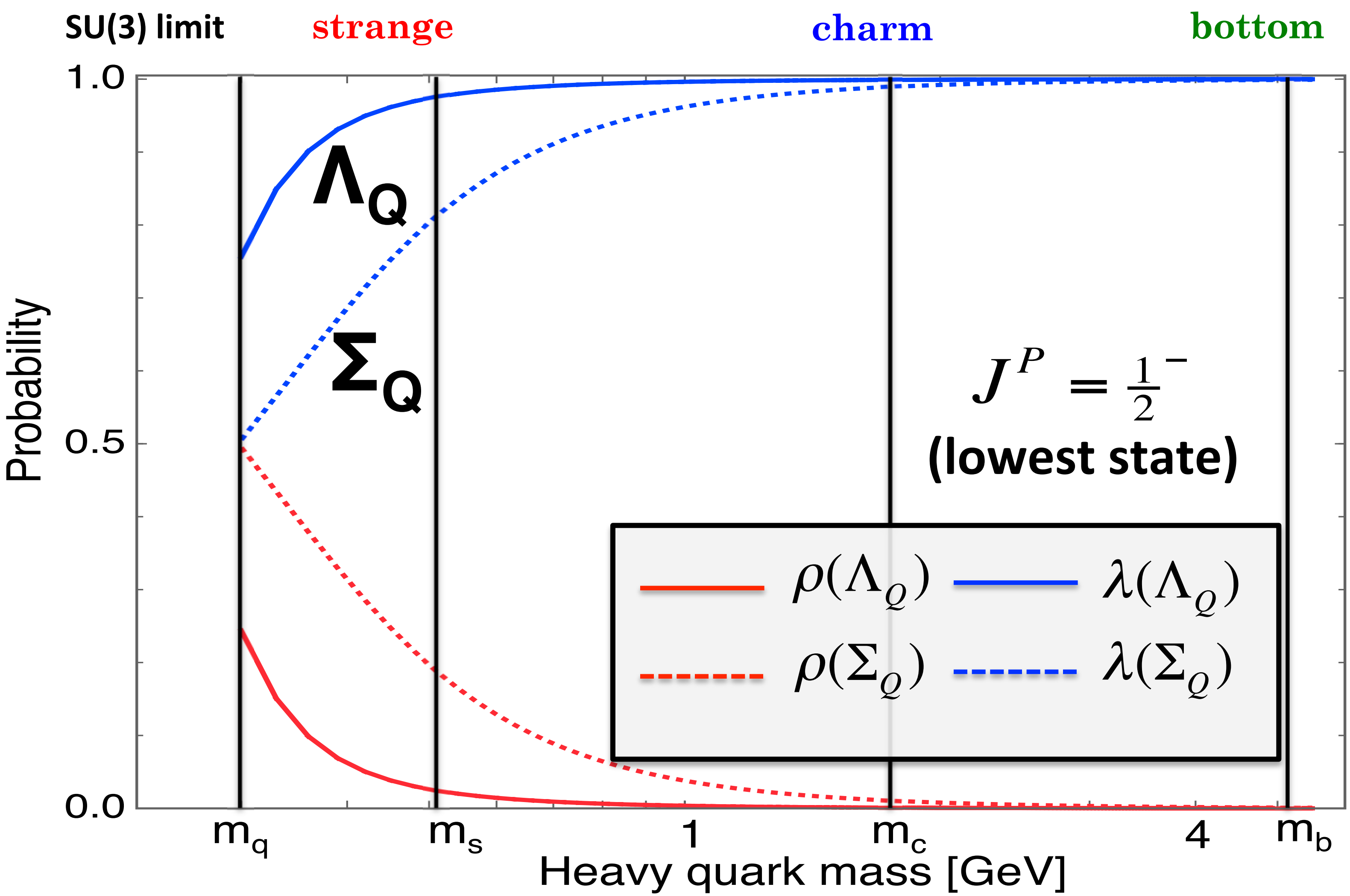


Negative parity states — p-wave excitations - 1/2⁻, 3/2⁻ , 5/2⁻



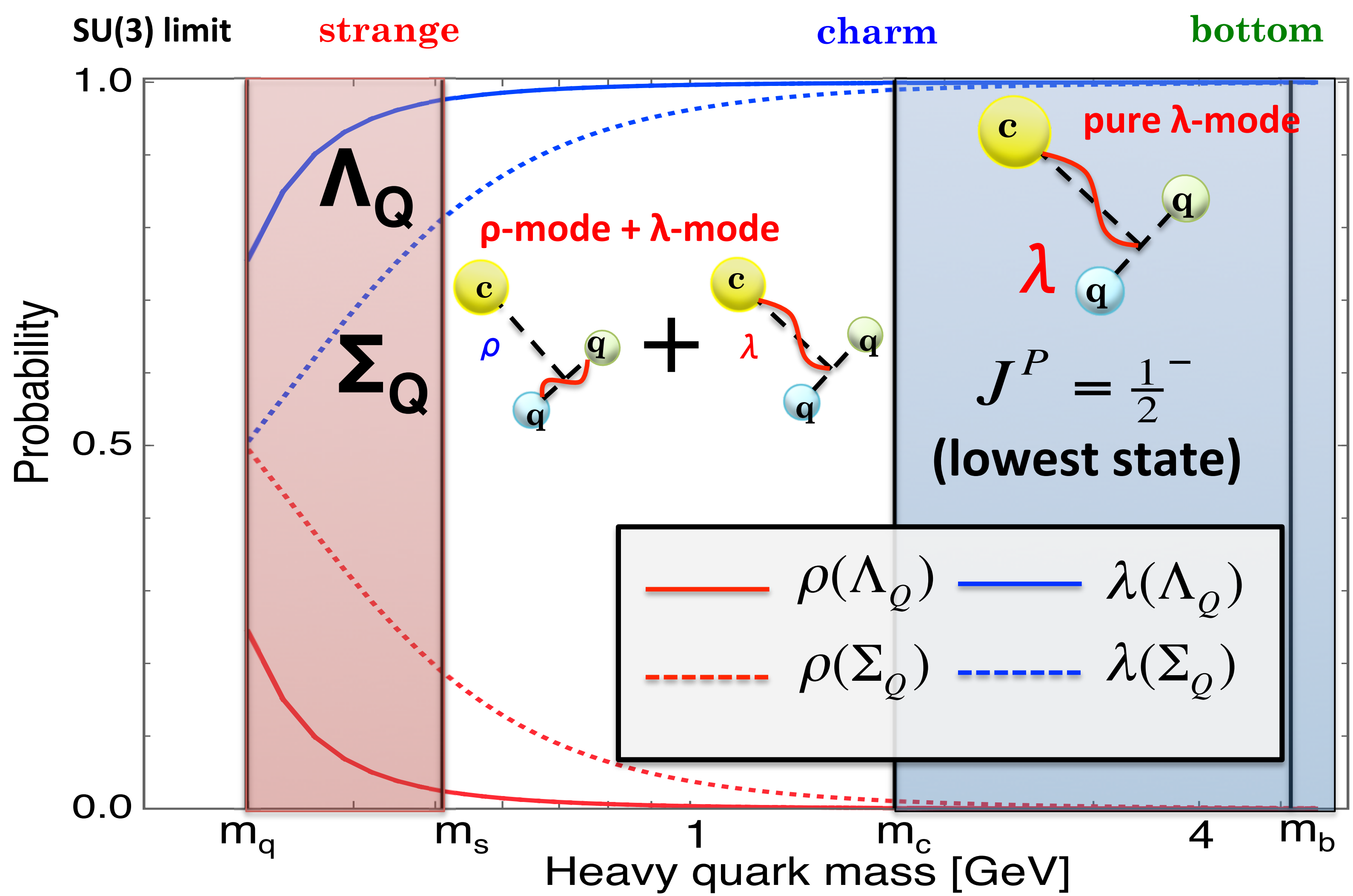
Quark mass dependence of Probability

$$\left|\Psi_{B^-}\right\rangle = C_\rho\left|\rho\right\rangle + C_\lambda\left|\lambda\right\rangle \qquad |C_\lambda|^2 : \qquad |C_\rho|^2 :$$



Quark mass dependence of Probability

$$\left|\Psi_{B^-}\right\rangle = C_\rho\left|\rho\right\rangle + C_\lambda\left|\lambda\right\rangle \qquad \left|C_\lambda\right|^2 : \qquad \left|C_\rho\right|^2 :$$



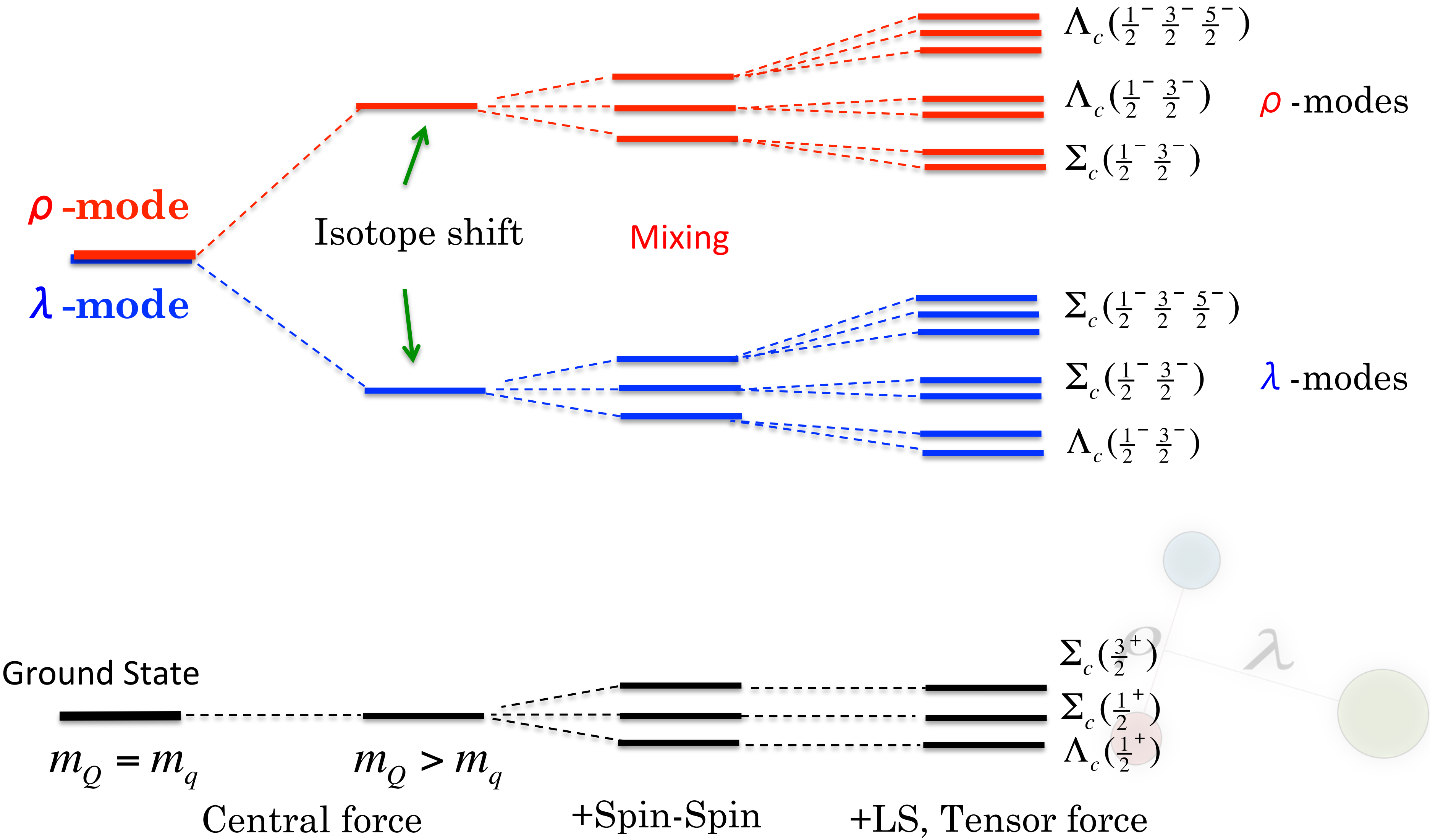
Summary

✓We calculate charmed baryon spectra and our result reproduce experimental data.
(except for Λ(1405))

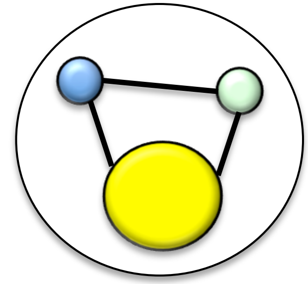
✓In heavy quark sector, states separate into λ-mode and ρ-mode. And one mode become quite dominant.
→This feature will reflect on decay of heavy baryons
(We need more information of decay of heavy baryons)

Thank you for your attention!!

Level structure of P-wave singly heavy baryon



Constituent quark model $\Lambda_Q \; \Sigma_Q$



Schrödinger equation

$$\left[T + V_{conf} + V_{short} - E\right]\left|\Psi_{JM}\right\rangle = 0$$

$$V_{\rm con} = \sum_{i<j} \frac{b r_{ij}}{2} + C$$

$$V_{\rm short} = \sum_{i<j} [-\frac{2\alpha^{\rm Coul}}{3 r_{ij}} + \left(\frac{1}{m_i^2} + \frac{1}{m_j^2}\right)\frac{\Lambda^2}{4\pi r_{ij}}\exp(-\Lambda r) + \frac{16\pi\alpha^{ss}}{9 m_i m_j}\boldsymbol{S}_i\cdot\boldsymbol{S}_j\frac{\Lambda^2}{4\pi r_{ij}}\exp(-\Lambda r_{ij})$$

$$+\frac{\alpha^{\rm so}(1-\exp(-\Lambda r_{ij}))^2}{3 {r_{ij}}^3}[(\frac{1}{m_i^2} + \frac{1}{m_j^2} + 4\frac{1}{m_i m_j})\boldsymbol{L}_{ij}\cdot(\boldsymbol{S}_j + \boldsymbol{S}_j) + (\frac{1}{m_i^2} - \frac{1}{m_j^2})\boldsymbol{L}_{ij}\cdot(\boldsymbol{S}_i - \boldsymbol{S}_j)]$$

Anti-symmetric LS force

$$+\frac{2\alpha^{\rm ten}(1-\exp(-\Lambda r_{ij}))^2}{3 m_i m_j {r_{ij}}^3}\left(\frac{3(\boldsymbol{S}_i\cdot\boldsymbol{r}_{ij})(\boldsymbol{S}_j\cdot\boldsymbol{r}_{ij})}{{r_{ij}}^2} - \boldsymbol{S}_i\cdot\boldsymbol{S}_j\right)].$$

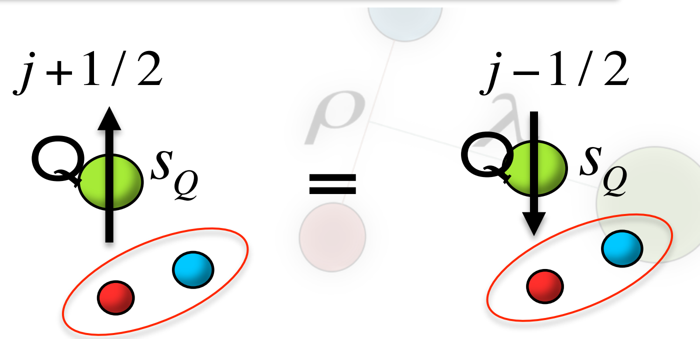
$$\alpha^{Coul} \longrightarrow \alpha^{Coul}(\mu_{ij})$$

Coulomb force depend on quark mass

Taichi Kawanai and Shoichi Sasaki. Phys.Rev.Lett.,107:091601, 2011.

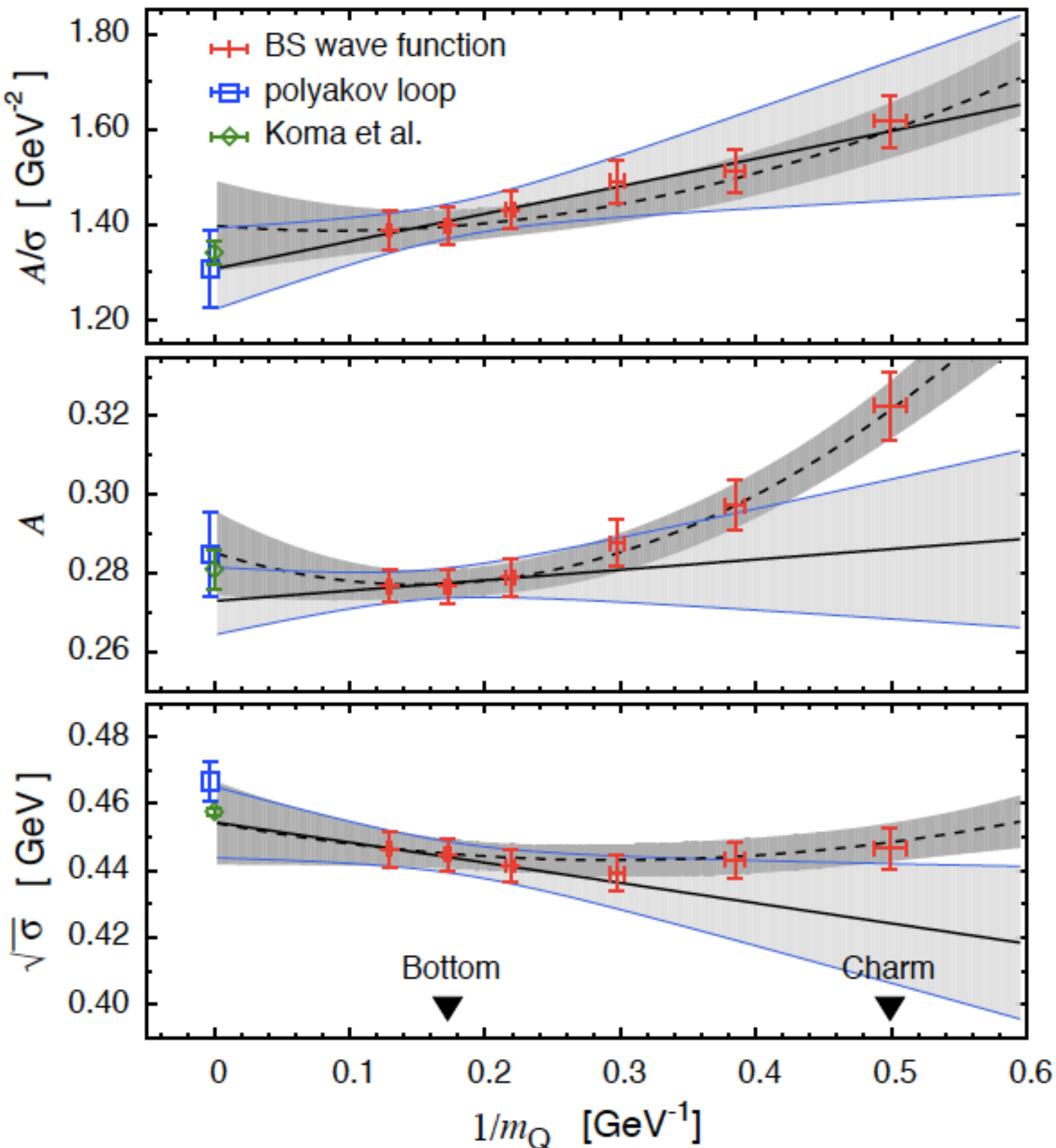
Heavy quark spin conserve in heavy quark limit

$$[H, \mathbf{s}_Q] = [H, \mathbf{J} - \mathbf{s}_Q] = [H, \mathbf{j}] = 0$$



We will see two state degenerate in the heavy quark limit (HQS doublet)

Constituent quark model



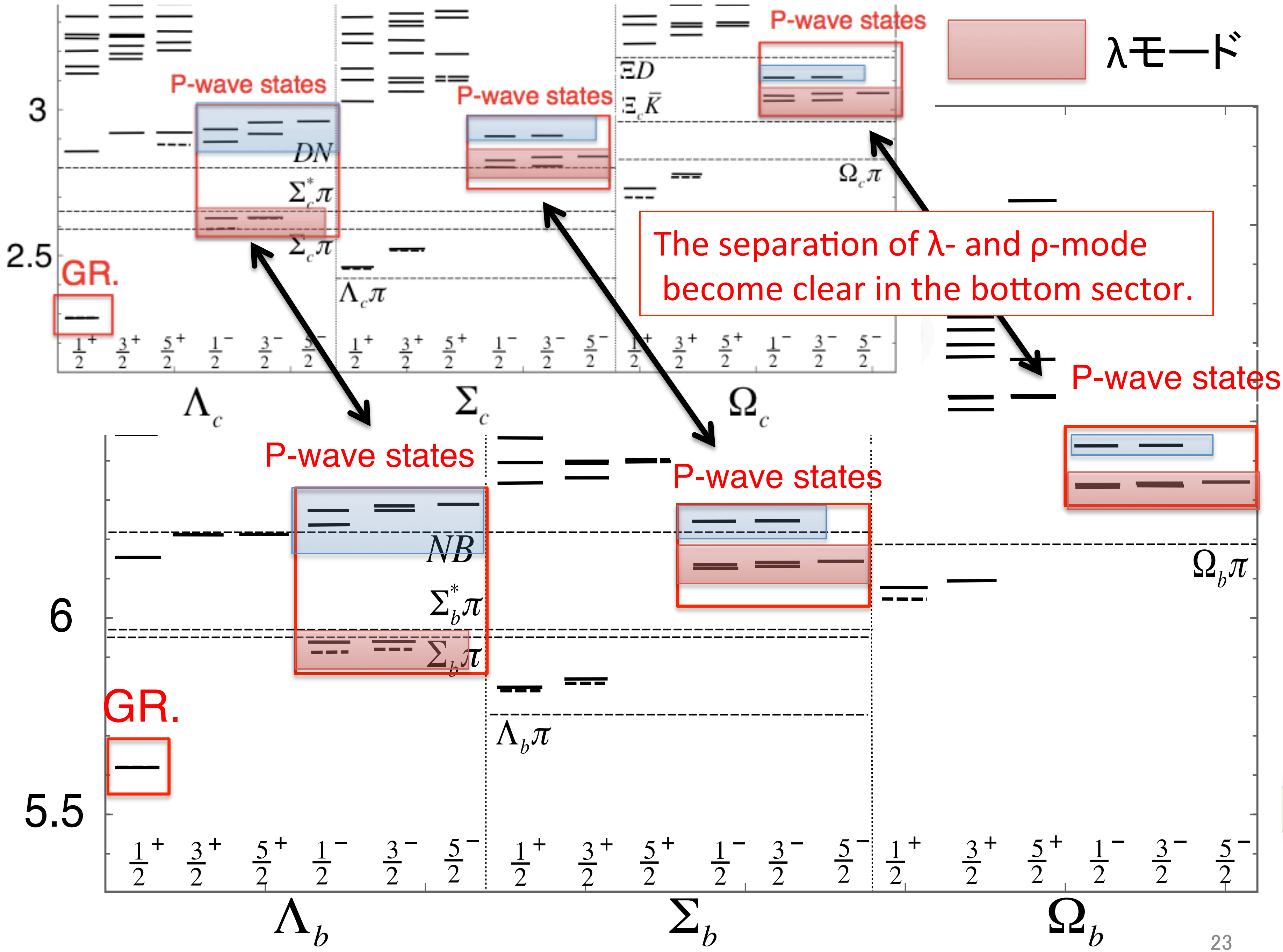
$$V_{q\bar{q}}(r) = -\frac{A}{r} + \sigma r + V_0,$$

$$\alpha_{\mathrm{coul}} = \frac{K}{\mu_{ij}}$$

κ	am_q	A	$a^2\sigma$	$A/a^2\sigma$
0.11456	0.493(18)	0.663(23)	0.0477(28)	13.9(7)
0.10190	0.833(31)	0.470(16)	0.0435(25)	10.8(6)
0.09495	1.006(41)	0.430(16)	0.0426(27)	10.1(6)
0.08333	1.288(30)	0.381(10)	0.0435(18)	8.8(4)
0.07490	1.484(22)	0.360(7)	0.0443(13)	8.1(3)
0.06667	1.720(18)	0.341(6)	0.0442(11)	7.7(3)
—	∞	0.236(39)	0.0465(34)	6.1(1.1)
Wilson loop		0.281(5)	0.0466(2)	6.03(11)

Coulomb force strongly depends on quark mass

Taichi Kawanai and Shoichi Sasaki. Phys.Rev.Lett.,107:091601, 2011.


P-wave states
P-wave states
P-wave states
λモード
3
2.5
GR.
DN
$\Sigma_c^*\pi$
$\Sigma_c\pi$
$\Lambda_c\pi$
ΞD
$\Xi_c\bar{K}$
$\Omega_c\pi$
Λ_c
Σ_c
Ω_c
The separation of λ- and ρ-mode
become clear in the bottom sector.
P-wave states
P-wave states
P-wave states
6
5.5
GR.
NB
$\Sigma_b^*\pi$
$\Sigma_b\pi$
$\Lambda_b\pi$
$\Omega_b\pi$
$\frac{1}{2}^+$ $\frac{3}{2}^+$ $\frac{5}{2}^+$ $\frac{1}{2}^-$ $\frac{3}{2}^-$ $\frac{5}{2}^-$
Λ_b
Σ_b
Ω_b

Constituent quark model

(a) Λ_s

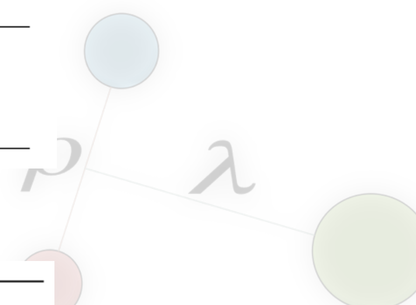
J^P	Theory [MeV]	Exp. [MeV]
$\frac{1}{2}^+$	1116	1116
	1799	1560-1700
	1922	1750-1850
$\frac{3}{2}^+$	1882	1850-1910
	2030	
	2100	
$\frac{5}{2}^+$	1891	1815-1825
	2045	2090-2140
	2143	
$\frac{1}{2}^-$	1526	1405
	1665	1660-1680
	1777	1720-1850
$\frac{3}{2}^-$	1537	1520
	1685	1685-1695
	1810	
$\frac{5}{2}^-$	1814	1810-1830
	2394	
	2448	

(b) Σ_s

J^P	Theory [MeV]	Exp. [MeV]
$\frac{1}{2}^+$	1197	1192
	1895	1630-1690
	2016	
$\frac{3}{2}^+$	1391	1385
	2004	
	2028	
$\frac{5}{2}^+$	2012	1900-1935
	2085	
	2091	
$\frac{1}{2}^-$	1654	(≈1620)
	1734	1730-1800
	1751	
$\frac{3}{2}^-$	1660	1665-1685
	1755	1900-1950
	1760	
$\frac{5}{2}^-$	1762	1770-1780
	2324	
	2427	

(c) Ξ_{ss}

J^P	Theory [MeV]	Exp. [MeV]
$\frac{1}{2}^+$	1325	1314
	1962	
	2131	
$\frac{3}{2}^+$	1525	1530
	2034	
	2115	
$\frac{5}{2}^+$	2040	
	2166	
	2211	
$\frac{1}{2}^-$	1778	
	1875	
	1910	
$\frac{3}{2}^-$	1782	1820
	1877	
	1920	
$\frac{5}{2}^-$	1933	
	2460	
	2518	



Parameters

m_q [MeV]	m_s [MeV]	m_c [MeV]	m_b [MeV]	b [GeV^2]	K [MeV]	α_{ss}	$\alpha_{so}(=\alpha_{ten})$	C [MeV]	Λ [fm^{-1}]
300	590	1841	5208	0.225	90	1.4	0.08	-1746.6	3.5

Constituent quark model

(a) Λ_s

J^P	Theory [MeV]	Exp. [MeV]
$\frac{1}{2}^+$	1116	1116
	1799	1560-1700
	1922	1750-1850
$\frac{3}{2}^+$	1882	1850-1910
	2030	
	[illegible]	
$\frac{5}{2}^+$	[illegible]	1815-1825
	[illegible]	2090-2140
	[illegible]	
$\frac{1}{2}^-$	1526	1405
	1665	1660-1680
	1777	1720-1850
$\frac{3}{2}^-$	1537	1520
	1685	1685-1695
	1810	
$\frac{5}{2}^-$	1814	1810-18[illegible]
	2394	
	2448	

(b) Σ_s

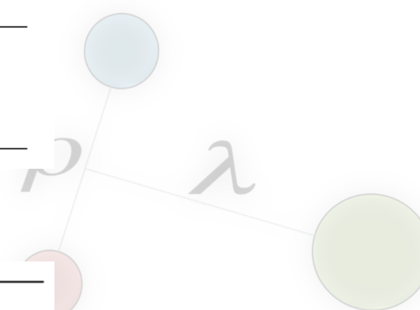
J^P	Theory [MeV]	Exp. [MeV]
$\frac{1}{2}^+$	1197	1192
	1895	1630-1690
	2016	
$\frac{3}{2}^+$	1391	1385
	2004	
	2028	
$\frac{5}{2}^+$	2012	1900-1935
	2085	
	2091	
$\frac{1}{2}^-$	1654	(≈1620)
	1734	1730-180[illegible]
	1751	[illegible]
$\frac{3}{2}^-$	166[illegible]	[illegible]
	[illegible]	[illegible]
	[illegible]	[illegible]
$\frac{5}{2}^-$	[illegible]	[illegible]-1780
	[illegible]	
	2427	

(c) Ξ_{ss}

J^P	Theory [MeV]	Exp. [MeV]
$\frac{1}{2}^+$	1325	1314
	1962	
	2131	
$\frac{3}{2}^+$	1525	1530
	2034	
	2115	
$\frac{5}{2}^+$	2040	
	216[illegible]	
	[illegible]	
[illegible]	[illegible]	[illegible]
	[illegible]	
	[illegible]	
$\frac{3}{2}^-$	1782	1820
	1877	
	1920	
$\frac{5}{2}^-$	1933	
	2460	
	2518	

We neglect Λ(1405) to fit the data

We determined 10 parameters for the experimental data of strange baryons (except for Λ(1405))



Parameters

m_q [MeV]	m_s [MeV]	m_c [MeV]	m_b [MeV]	b [GeV^2]	K [MeV]	α_{ss}	$\alpha_{so}(=\alpha_{ten})$	C [MeV]	Λ [fm^{-1}]
300	590	1841	5208	0.225	90	1.4	0.08	-1746.6	3.5

The number of λ and ρ -mode

flavor	l	L	I	s	S	mode	J
Λ_Q	0	1	1	0	1/2	$\lambda_{1/2}$	$1/2^-, 3/2^-$
	1	0	1	1	1/2	$\rho_{1/2}$	$1/2^-, 3/2^-$
	1	0	1	1	3/2	$\rho_{3/2}$	$1/2^-, 3/2^-, 5/2^-$
Σ_Q	0	1	1	1	1/2	$\lambda_{1/2}$	$1/2^-, 3/2^-$
	0	1	1	1	3/2	$\lambda_{3/2}$	$1/2^-, 3/2^-, 5/2^-$
	1	0	1	0	1/2	$\rho_{1/2}$	$1/2^-, 3/2^-$
Ξ_Q	0	1	1	0	1/2	$\lambda_{1/2}$	$1/2^-, 3/2^-$
	1	0	1	1	1/2	$\rho_{1/2}$	$1/2^-, 3/2^-$
	1	0	1	1	3/2	$\rho_{3/2}$	$1/2^-, 3/2^-, 5/2^-$
	0	1	1	1	1/2	$\lambda_{1/2}$	$1/2^-, 3/2^-$
	0	1	1	1	3/2	$\lambda_{3/2}$	$1/2^-, 3/2^-, 5/2^-$
	1	0	1	0	1/2	$\rho_{1/2}$	$1/2^-, 3/2^-$
Ξ_{QQ}	0	1	1	1	1/2	$\lambda_{1/2}$	$1/2^-, 3/2^-$
	0	1	1	1	3/2	$\lambda_{3/2}$	$1/2^-, 3/2^-, 5/2^-$
	1	0	1	0	1/2	$\rho_{1/2}$	$1/2^-, 3/2^-$
Ω_{QQ}	0	1	1	1	1/2	$\lambda_{1/2}$	$1/2^-, 3/2^-$
	0	1	1	1	3/2	$\lambda_{3/2}$	$1/2^-, 3/2^-, 5/2^-$
	1	0	1	0	1/2	$\rho_{1/2}$	$1/2^-, 3/2^-$
Ω_{QQQ}	0	1	1	1	1/2	$\lambda_{1/2}$	$1/2^-, 3/2^-$
	1	0	1	0	1/2	$\rho_{1/2}$	$1/2^-, 3/2^-$

Λ_Q

2 λ -modes 5 ρ -modes

Σ_Q

5 λ -modes 2 ρ -modes

Ξ_{QQ}

5 λ -modes 2 ρ -modes

Heavy baryons in the heavy quark limit

Heavy quark spin conserve in heavy quark limit

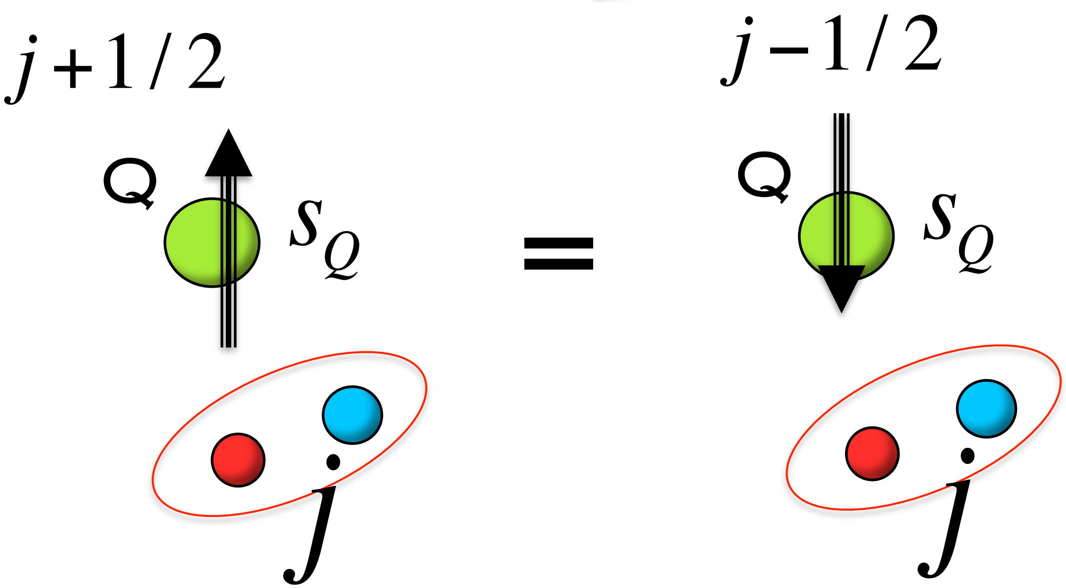
$$[H,\mathbf{s}_Q]=[H,\mathbf{J}-\mathbf{s}_Q]=[H,\mathbf{j}]=0$$

Heavy baryons in the heavy quark limit

Heavy quark spin conserve in heavy quark limit

$$[H, \mathbf{s}_Q] = [H, \mathbf{J} - \mathbf{s}_Q] = [H, \mathbf{j}] = 0$$

This leads to ..



We will see two state degenerate in the heavy quark limit (HQS doublet)

Heavy baryons in the heavy quark limit

The number of spin singlet and doublet for P-wave state

$$\mathbf{j} = \mathbf{s} + \mathbf{l} + \mathbf{L}$$

flavor	l	L	I	s	S	mode	J
Λ_Q	0	1	1	0	1/2	$\lambda_{1/2}$	$1/2^-, 3/2^-$
	1	0	1	1	1/2	$\rho_{1/2}$	$1/2^-, 3/2^-$
	1	0	1	1	3/2	$\rho_{3/2}$	$1/2^-, 3/2^-, 5/2^-$
Σ_Q	0	1	1	1	1/2	$\lambda_{1/2}$	$1/2^-, 3/2^-$
	0	1	1	1	3/2	$\lambda_{3/2}$	$1/2^-, 3/2^-, 5/2^-$
	1	0	1	0	1/2	$\rho_{1/2}$	$1/2^-, 3/2^-$

Heavy baryons in the heavy quark limit

The number of spin singlet and doublet for P-wave state

$$\mathbf{j} = \mathbf{s} + \mathbf{l} + \mathbf{L}$$

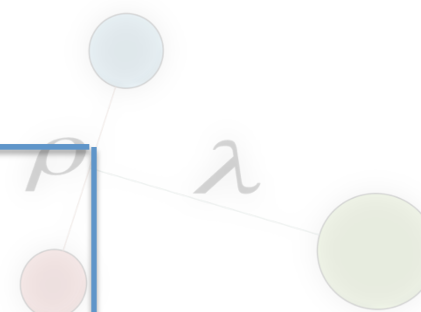
flavor	l	L	I	s	S	mode	J
Λ_Q	0	1	1	0	1/2	$\lambda_{1/2}$	$1/2^-, 3/2^-$
	1	0	1	1	1/2	$\rho_{1/2}$	$1/2^-, 3/2^-$
	1	0	1	1	3/2	$\rho_{3/2}$	$1/2^-, 3/2^-, 5/2^-$
Σ_Q	0	1	1	1	1/2	$\lambda_{1/2}$	$1/2^-, 3/2^-$
	0	1	1	1	3/2	$\lambda_{3/2}$	$1/2^-, 3/2^-, 5/2^-$
	1	0	1	0	1/2	$\rho_{1/2}$	$1/2^-, 3/2^-$

$$j = 1$$

$$j = 0, 1, 2$$

$$j = 0, 1, 2$$

$$j = 1$$



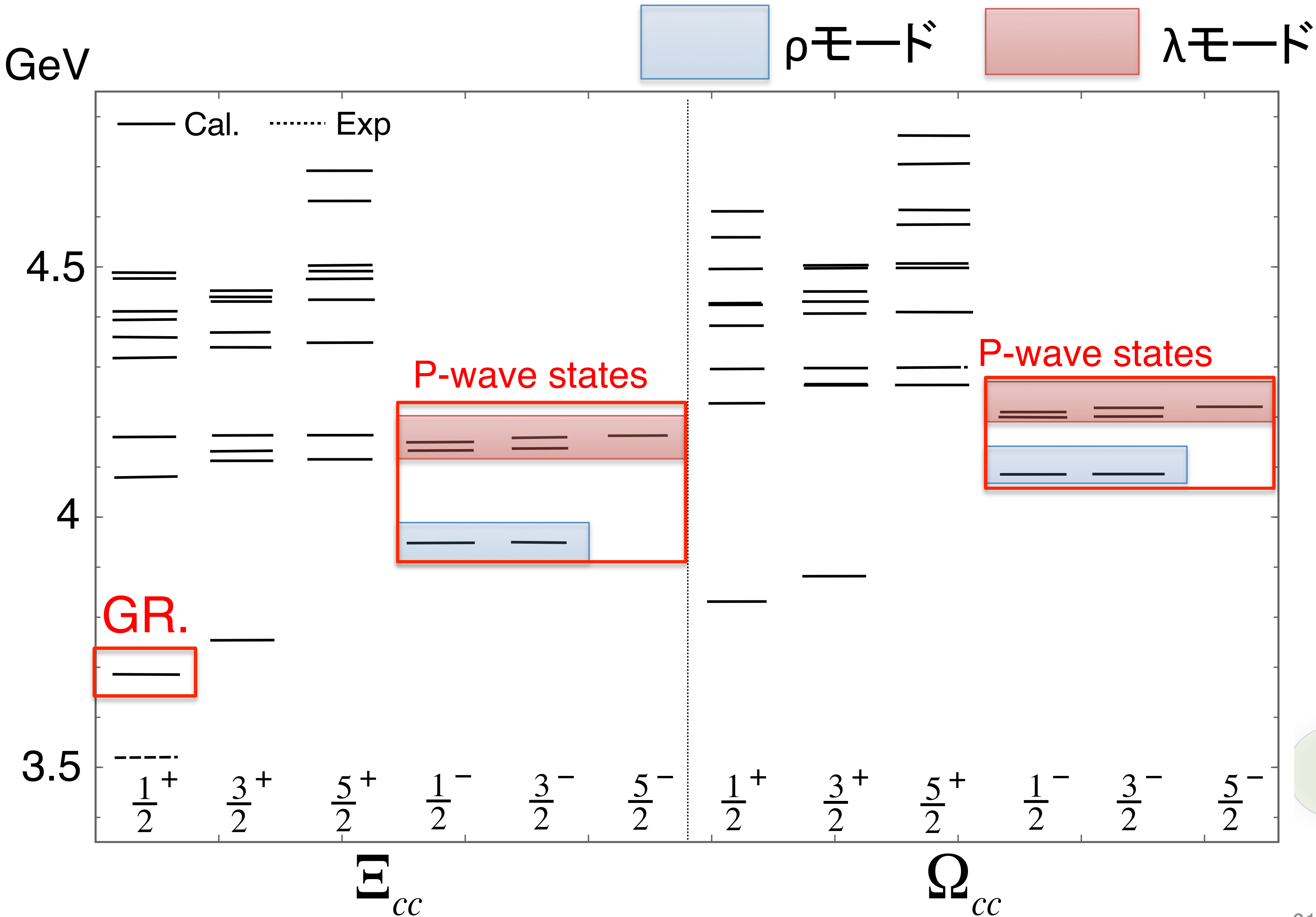
Λ_Q Σ_Q

Three Doublets and One Singlet

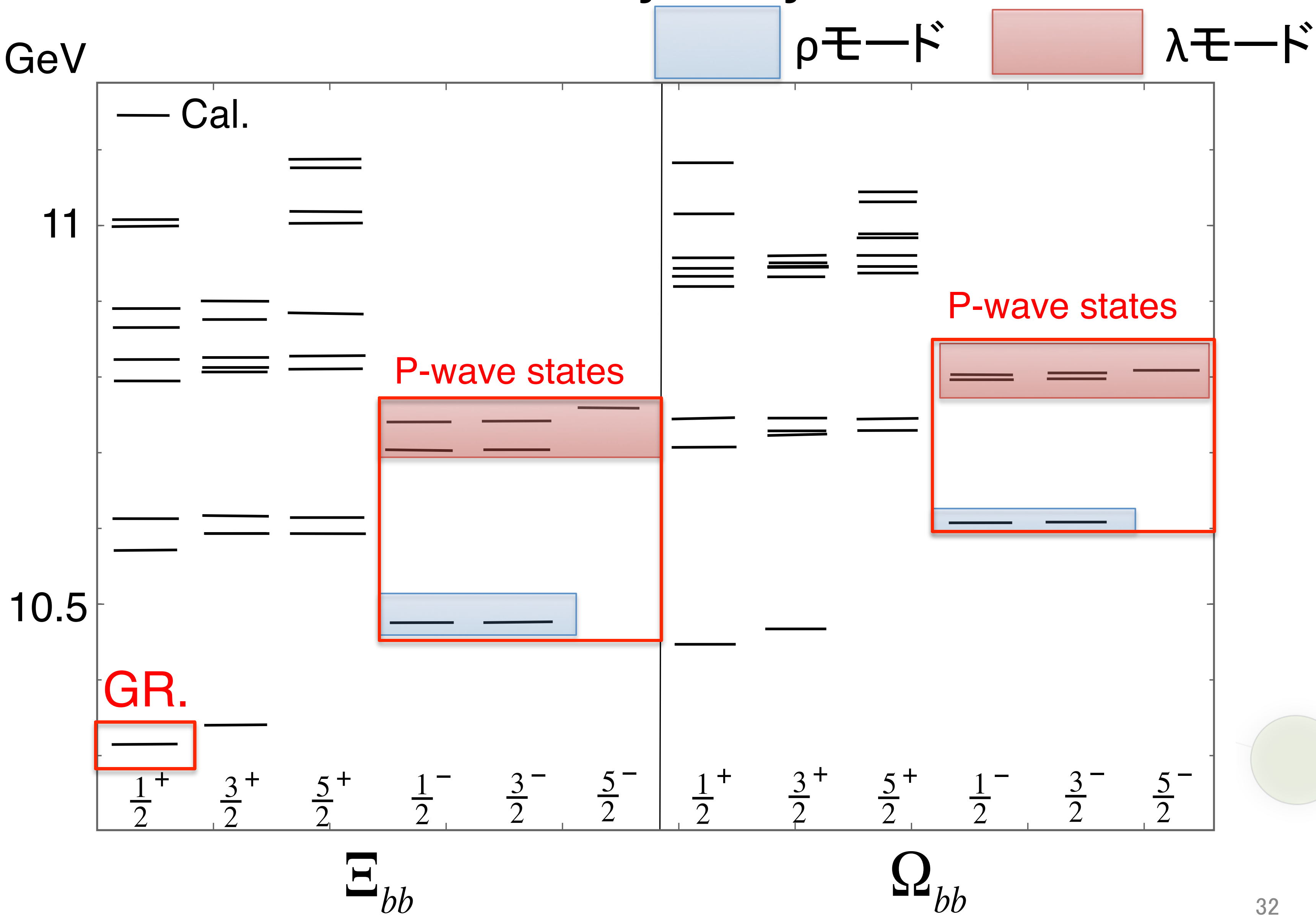
$$j = 0 \qquad j = 1 \qquad j = 2$$

$$\left(\frac{1}{2}\right) \qquad \left(1 \pm \frac{1}{2}\right)^2 \qquad \left(2 \pm \frac{1}{2}\right)^1$$

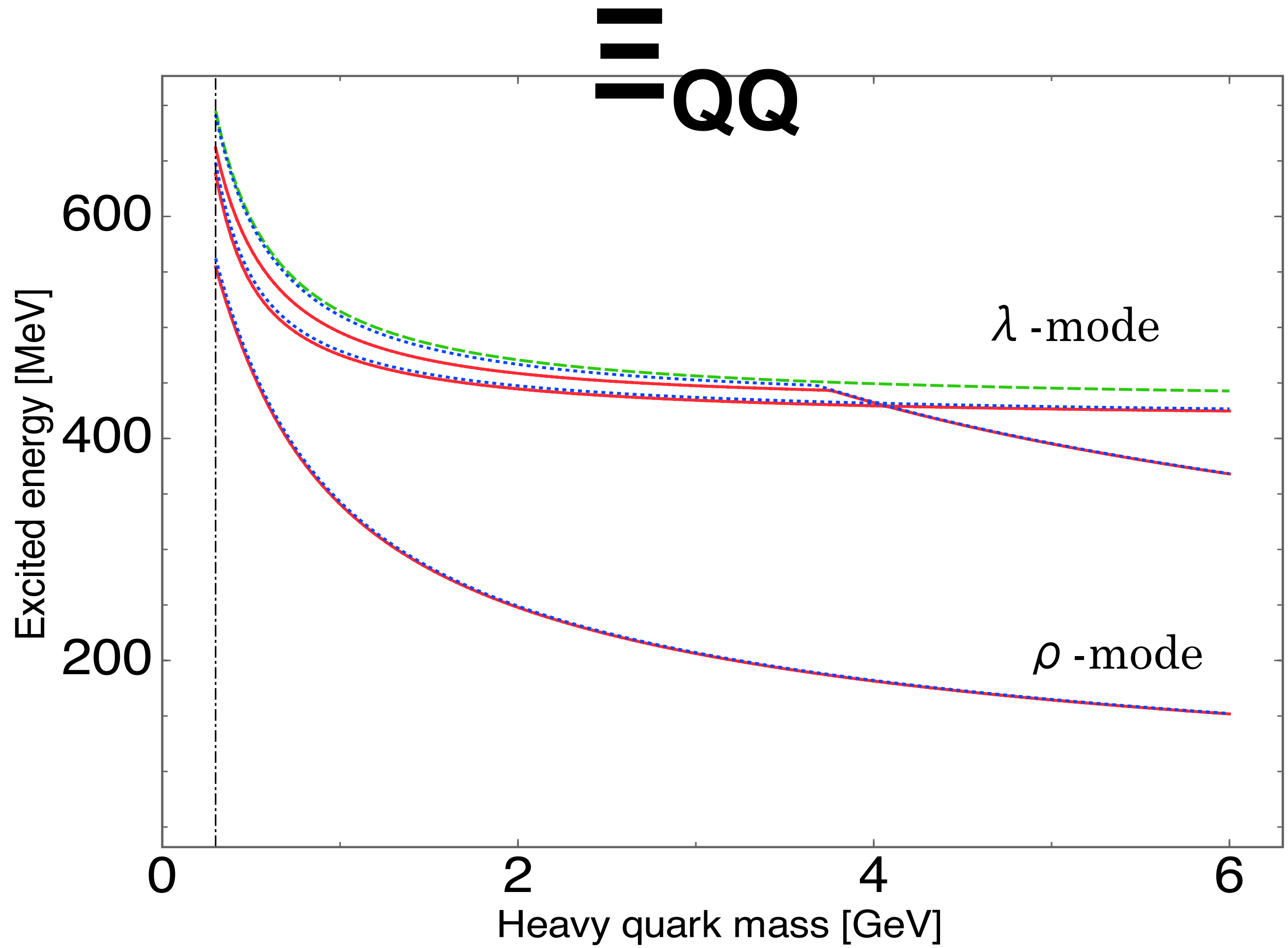
Double Heavy baryons

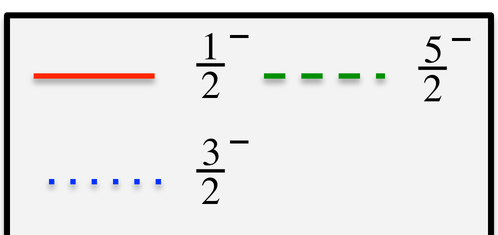


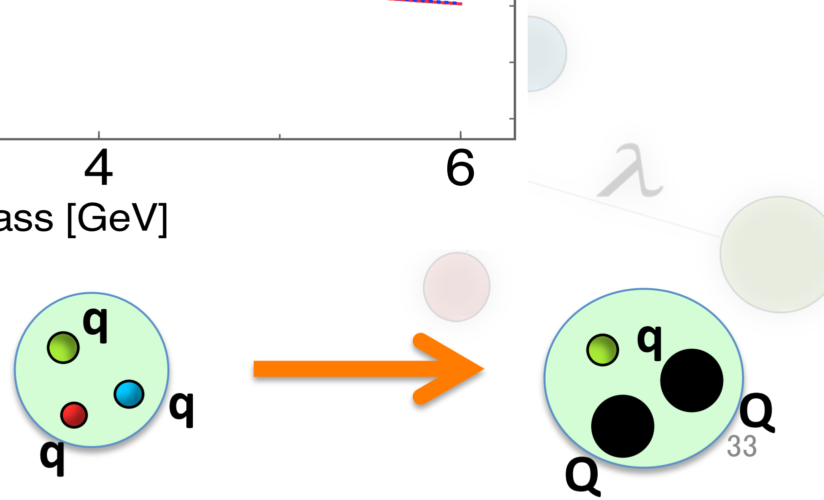
Double Heavy baryons



Quark mass dependence of Excited energy

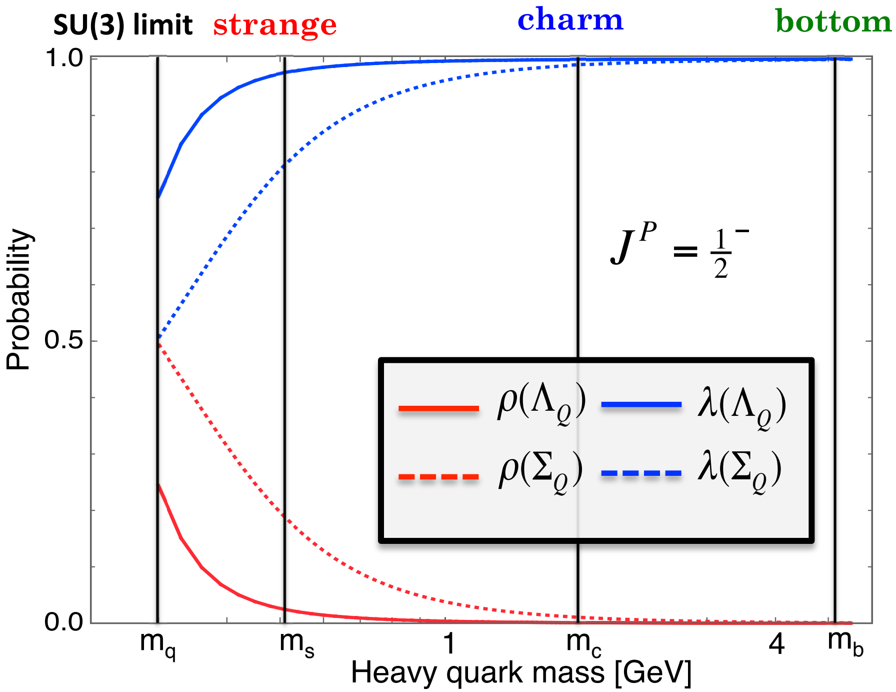




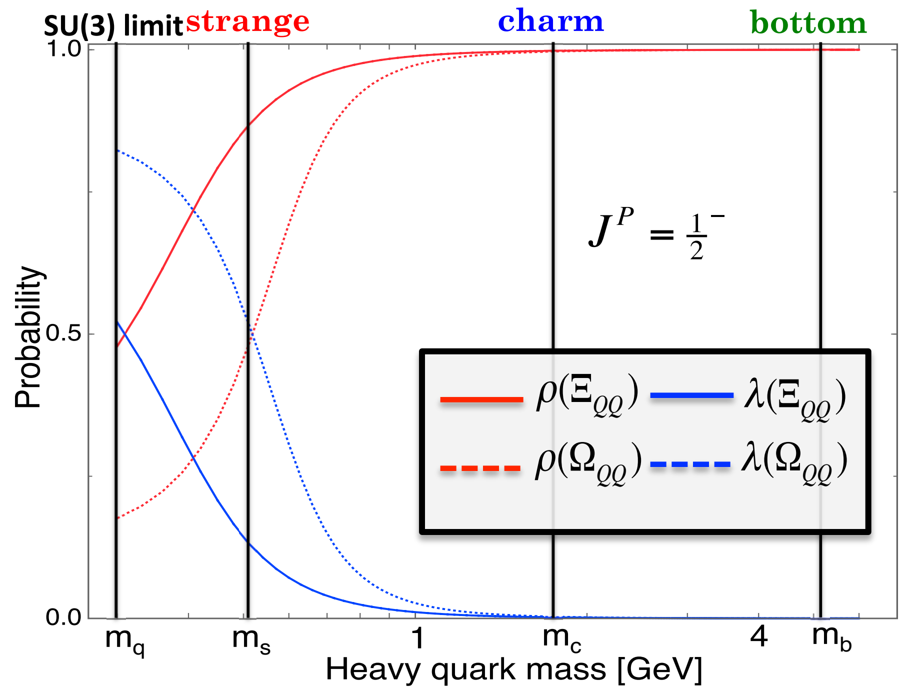


Quark mass dependence of Probability

Single heavy



Double heavy



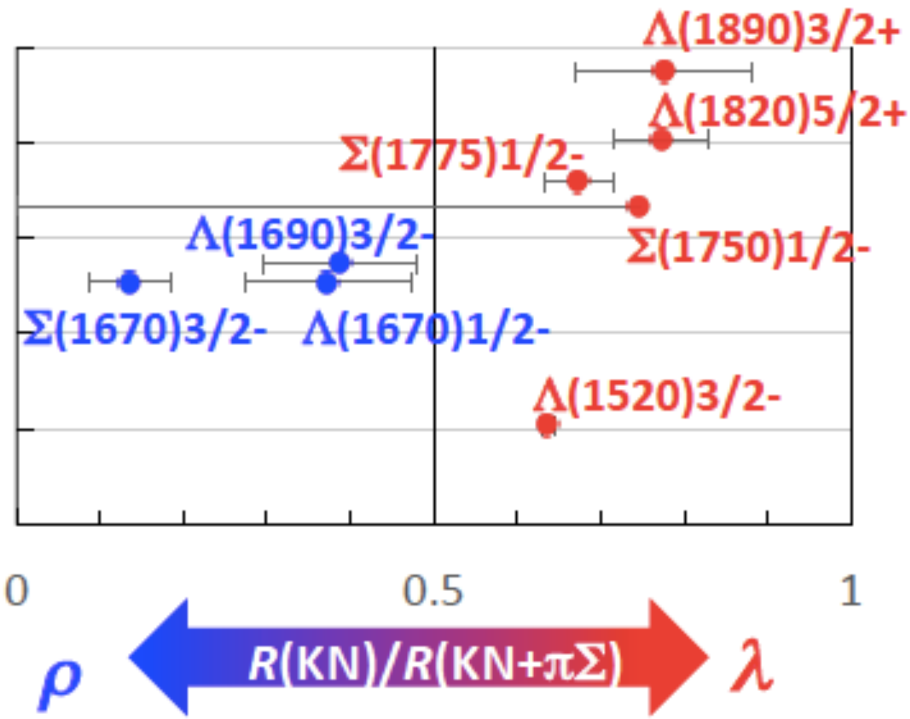
Λ baryon → **λ**-mode become dominant in the strange region

Σ baryon → **λ**-mode become dominant in the charm region

Ξ、Ω baryon → **ρ**-mode become dominant in the charm region

Decay pattern

PDG Data



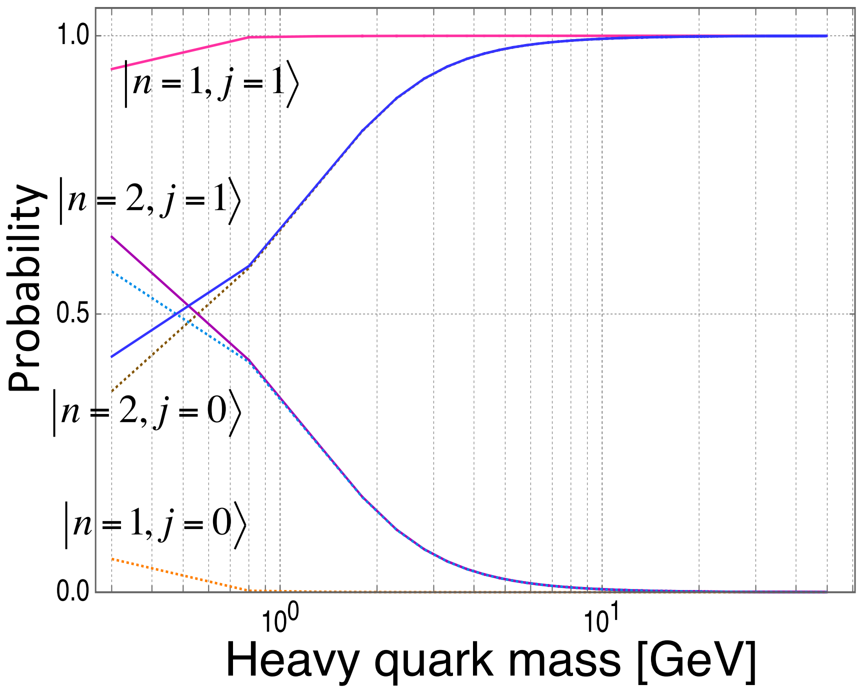
Our prediction

State	J^P	$P_\lambda : P_\rho$
Λ(1520)	3/2-	0.97:0.03
Λ(1670)	1/2-	0.065:0.935
Λ(1690)	3/2-	0.032:0.968
Λ(1890)	3/2+	0.99:0.001
Λ(1820)	5/2+	0.99:0.001
Σ(1750)	3/2-	0.11:0.89
Σ(1670)	3/2-	0.79:0.21

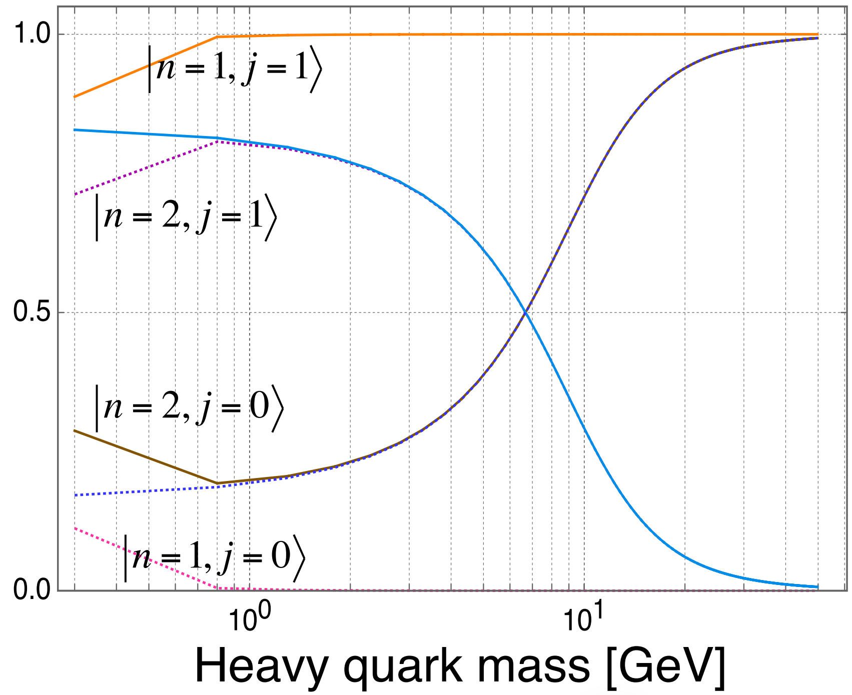
- ストレンジ領域においてもλ,ρ モード依存性が見られる.
- Λ粒子に対しては2つのモードは殆ど混ざらず、それが実験データに反映しているように見える
- チャーム領域での実験結果はまだほとんどない

Singlet and Doublet

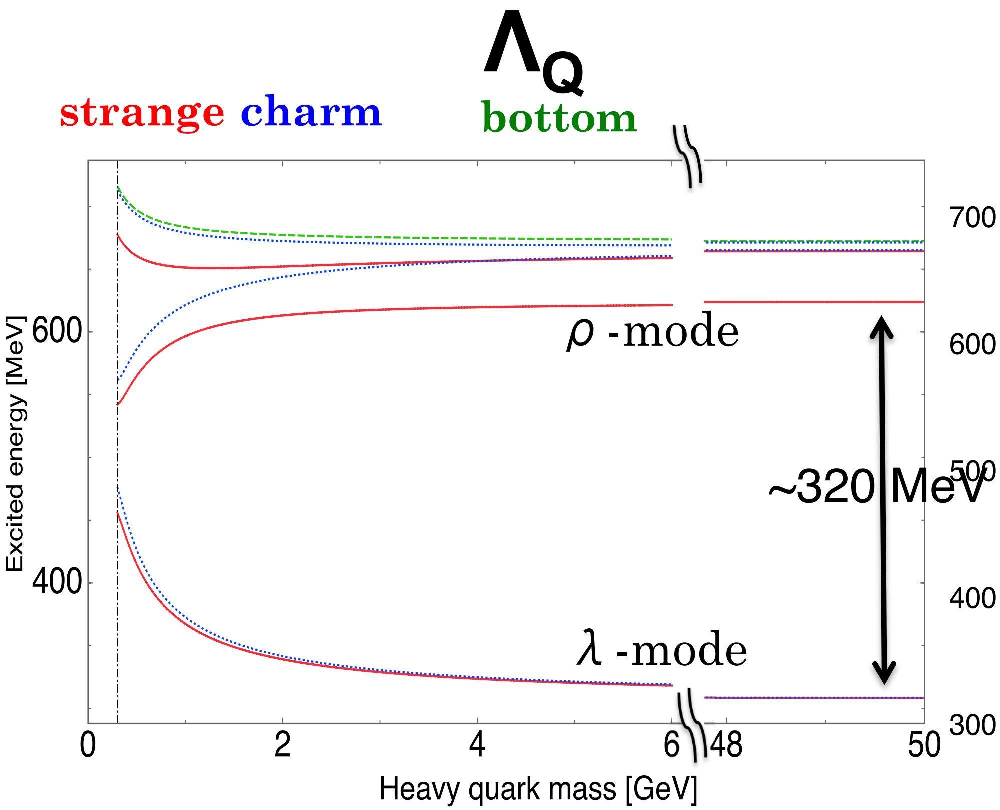
$\Lambda(1/2^-)$

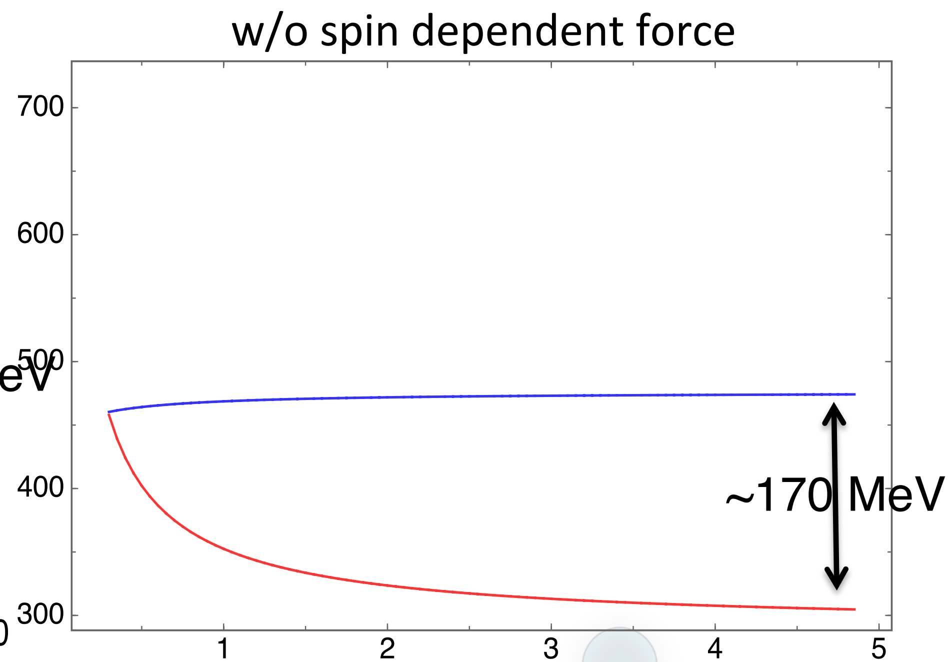


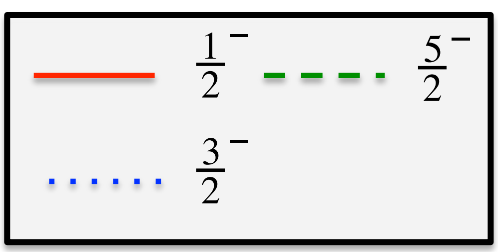
$\Lambda(3/2^-)$

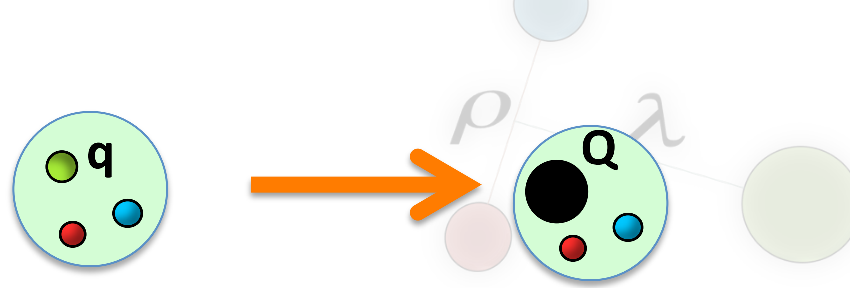


Quark mass dependence of Excited energy

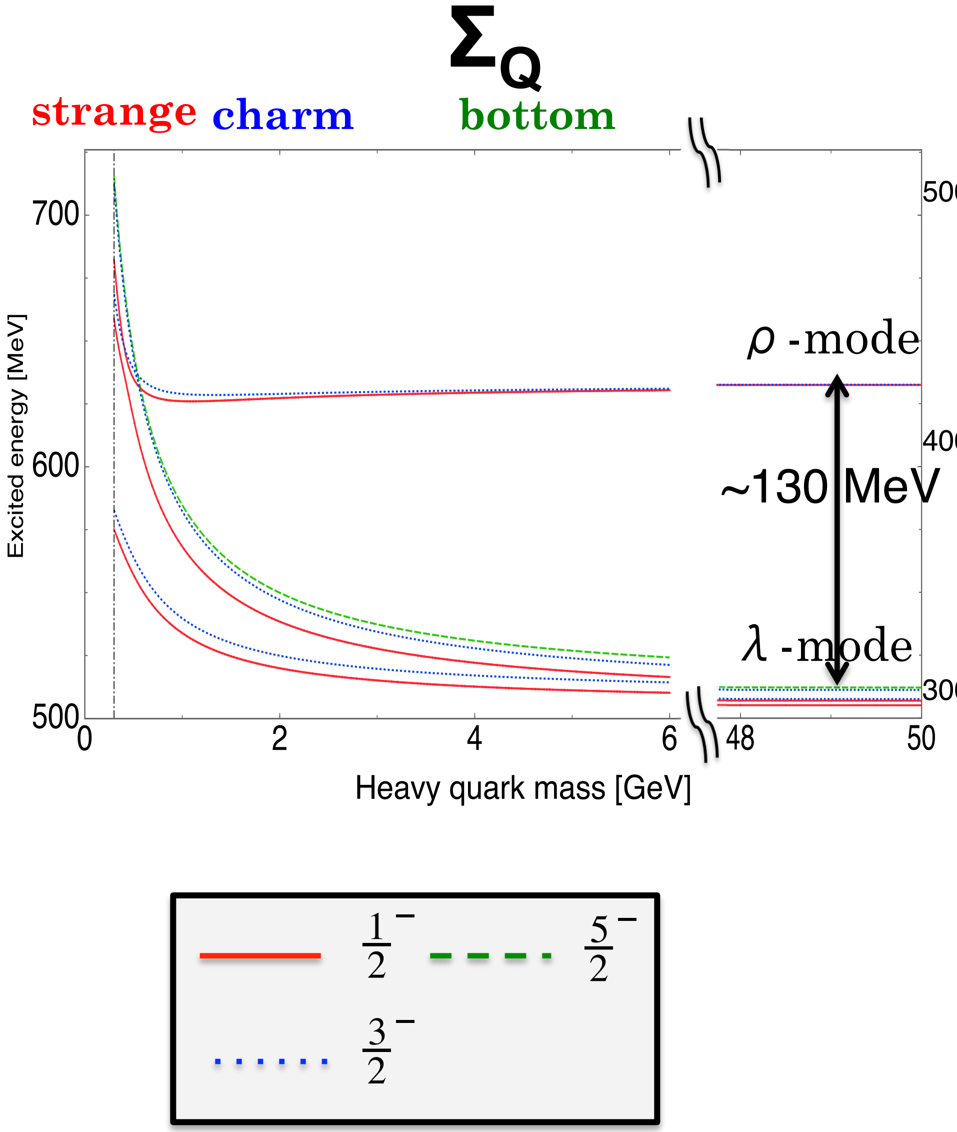




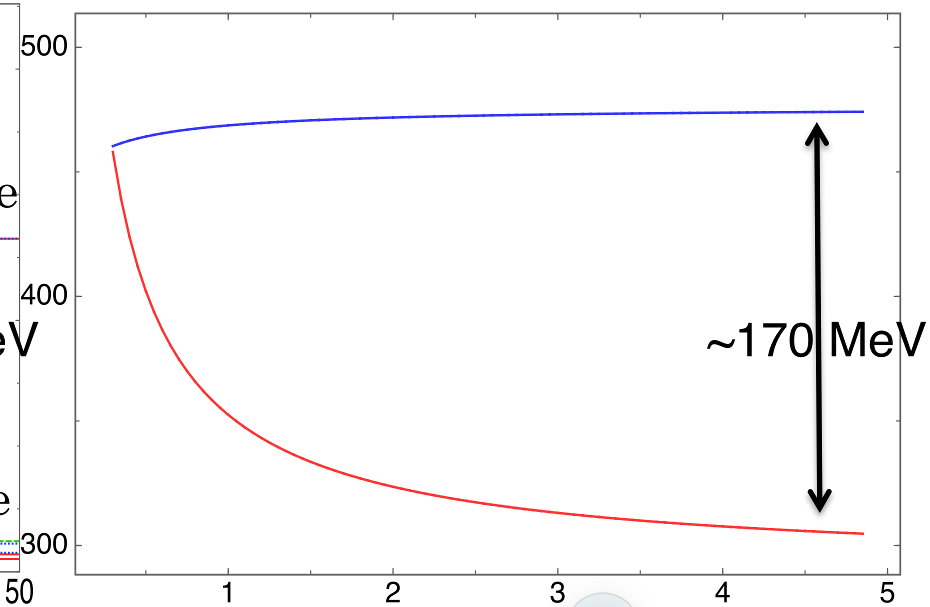


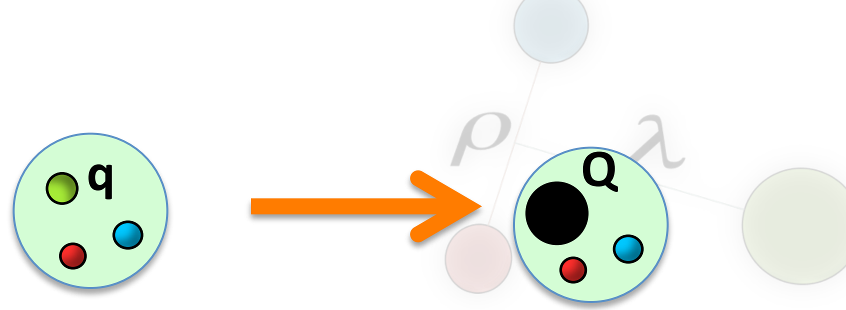


Quark mass dependence of Excited energy



w/o spin dependent force





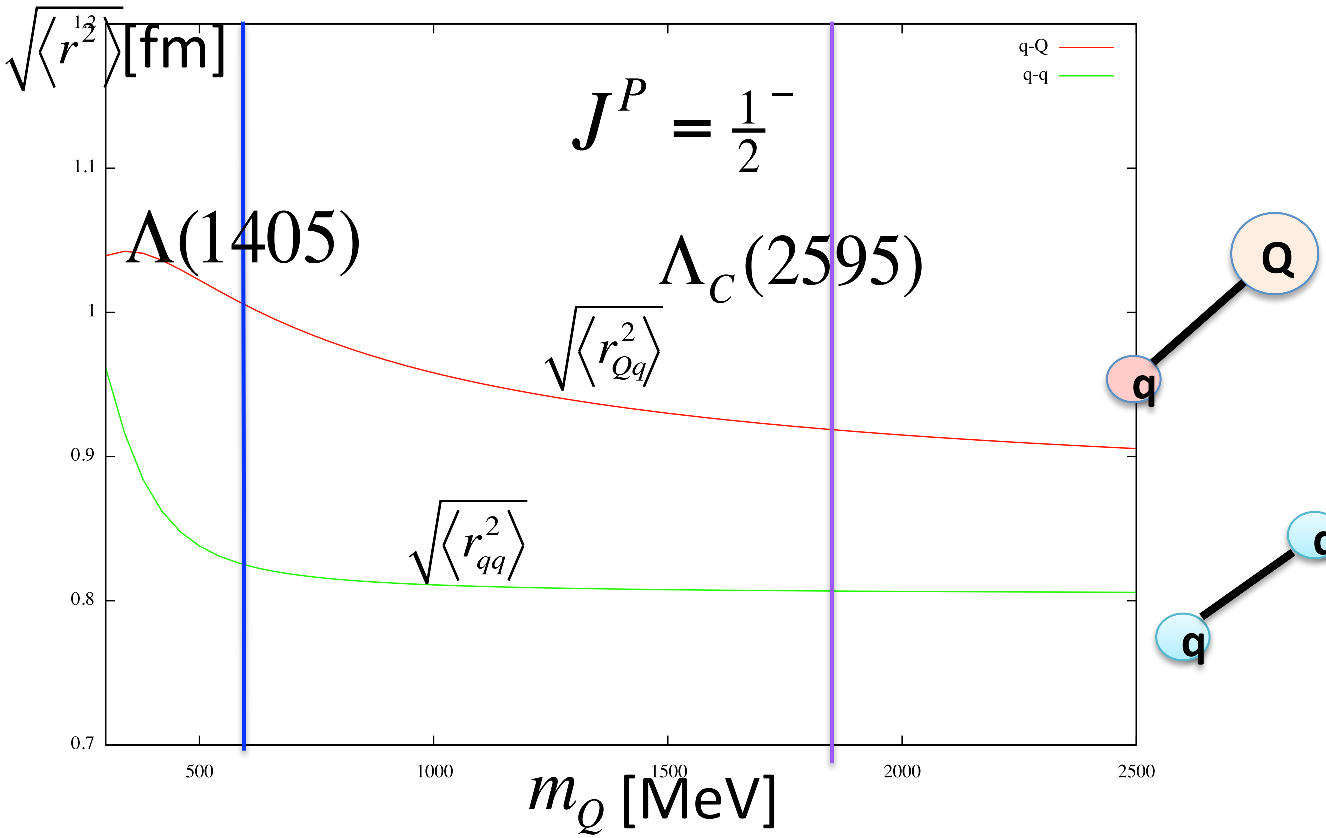
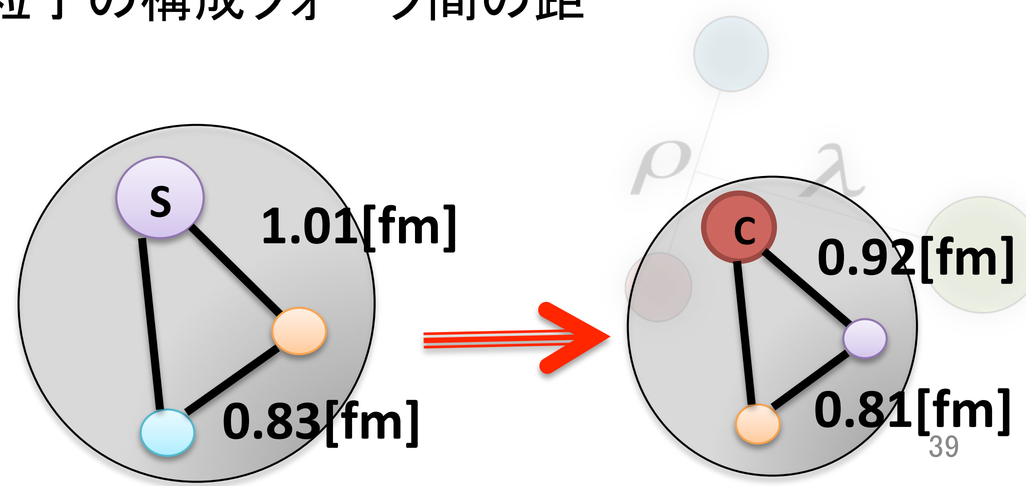


図6 Λ(1/2⁻)粒子の構成クォーク間の距離

ヘビーバリオンはヘビークォークの質量増大とともにコンパクトになっていくもののライトクォーク間距離とライトクォーク、ヘビークォーク間距離にはあまり大きな違いは見られない



Angular momentum

$\Lambda\left(\frac{1}{2}^+\right)$

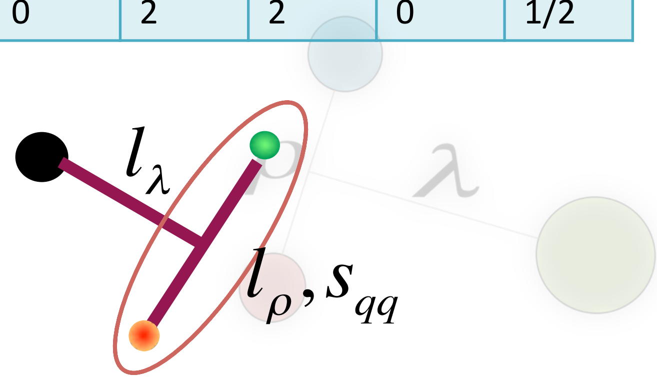
N	lρ	lλ	L	s_qq	S
1	0	0	0	0	1/2
2	1	1	0	1	1/2
3	1	1	1	1	1/2
4	1	1	1	1	3/2
5	1	1	2	1	3/2

$\Lambda\left(\frac{3}{2}^+\right)$

N	lρ	lλ	L	s_qq	S
1	1	1	0	1	3/2
2	1	1	1	1	1/2
3	1	1	1	1	3/2
4	1	1	2	1	1/2
5	1	1	2	1	3/2
6	2	0	2	0	1/2
7	0	2	2	0	1/2

$\Lambda\left(\frac{5}{2}^+\right)$

N	lρ	lλ	L	s_qq	S
1	1	1	1	1	3/2
2	1	1	2	1	1/2
3	1	1	2	1	3/2
4	2	0	2	0	1/2
5	0	2	2	0	1/2



Angular momentum

$\Sigma\left(\frac{1}{2}^+\right)$

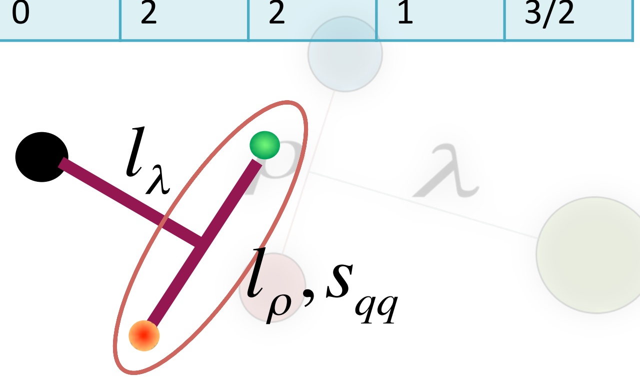
N	lρ	lλ	L	s_qq	S
1	0	0	0	1	1/2
2	1	1	0	0	1/2
3	1	1	1	0	1/2
4	2	0	2	1	3/2
5	0	2	2	1	3/2

$\Sigma\left(\frac{3}{2}^+\right)$

N	lρ	lλ	L	s_qq	S
1	0	0	0	1	3/2
2	1	1	1	0	1/2
3	1	1	2	0	3/2
4	2	0	2	1	1/2
5	2	0	2	1	3/2
6	0	2	2	1	1/2
7	0	2	2	1	3/2

$\Sigma\left(\frac{5}{2}^+\right)$

N	lρ	lλ	L	s_qq	S
1	1	1	2	0	1/2
2	2	0	2	1	1/2
3	2	0	2	1	3/2
4	0	2	2	1	1/2
5	0	2	2	1	3/2



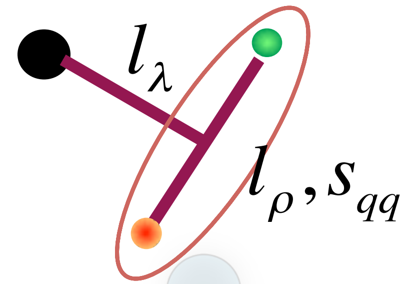
Angular momentum

$$\Lambda\left(\frac{1}{2}^-, \frac{3}{2}^-\right)$$

N	lρ	lλ	L	s_qq	S
1	0	1	1	0	1/2
2	1	0	1	1	1/2
3	1	0	1	1	3/2

$$\Lambda\left(\frac{5}{2}^-\right)$$

N	lρ	lλ	L	s_qq	S
1	1	0	1	1	3/2



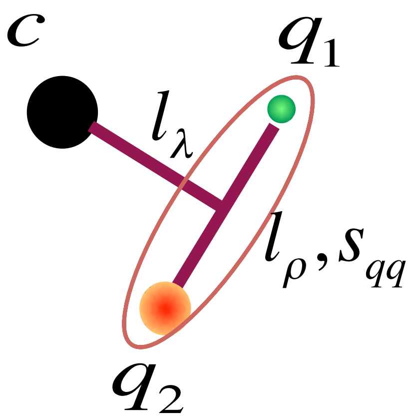
$$\Sigma\left(\frac{1}{2}^-, \frac{3}{2}^-\right)$$

N	lρ	lλ	L	s_qq	S
1	1	0	1	0	1/2
2	0	1	1	1	1/2
3	0	1	1	1	3/2

$$\Sigma\left(\frac{5}{2}^-\right)$$

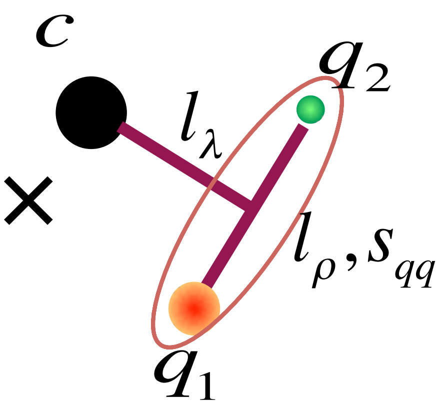
N	lρ	lλ	L	s_qq	S
1	0	1	1	1	3/2

Angular momentum



Exchange q_1 and q_2

$$(-1)^{s+l+t} \times$$



Because of Pauli principal

$$(-1)^{s+l+t} = 1$$


LHCb
panda
BESIII
Belle II
J-PARC
PHENIX