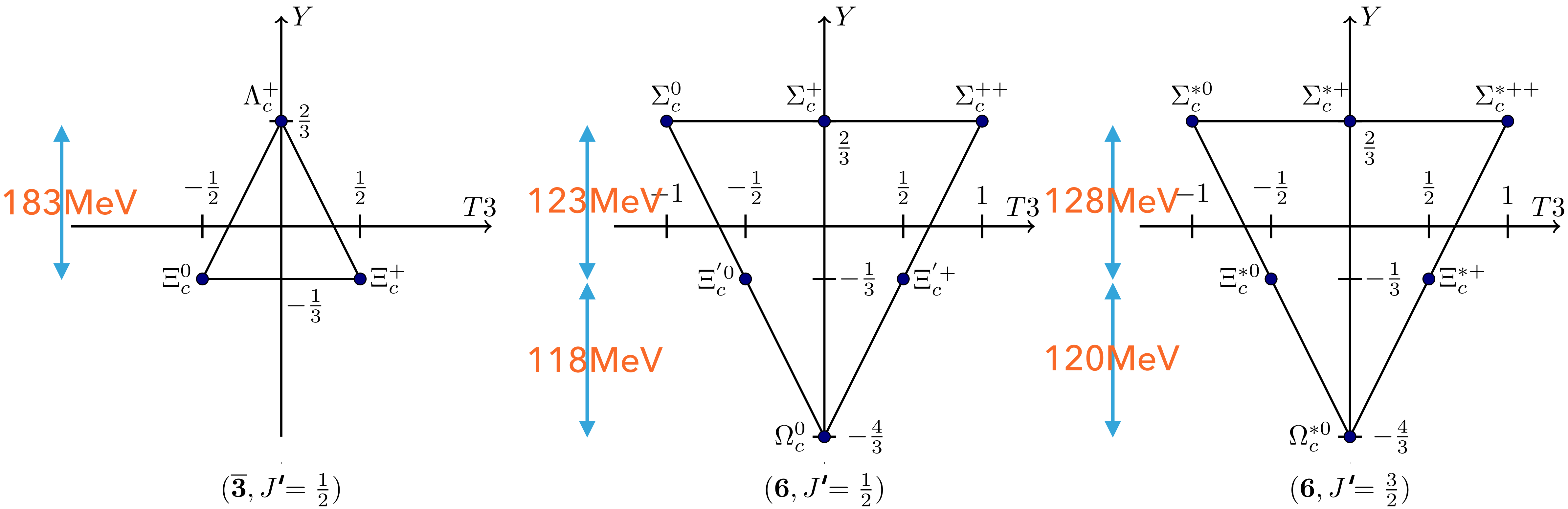
PUSAN WORKSHOP

Mass of singly and doubly heavy baryons within the SU(3) chiral quark-soliton model

CONTENTS

- Motivation
- Chiral quark-soliton model
- Mass splitting of the singly heavy baryons
- Masse of the singly heavy baryons
- Masse of the doubly heavy baryons

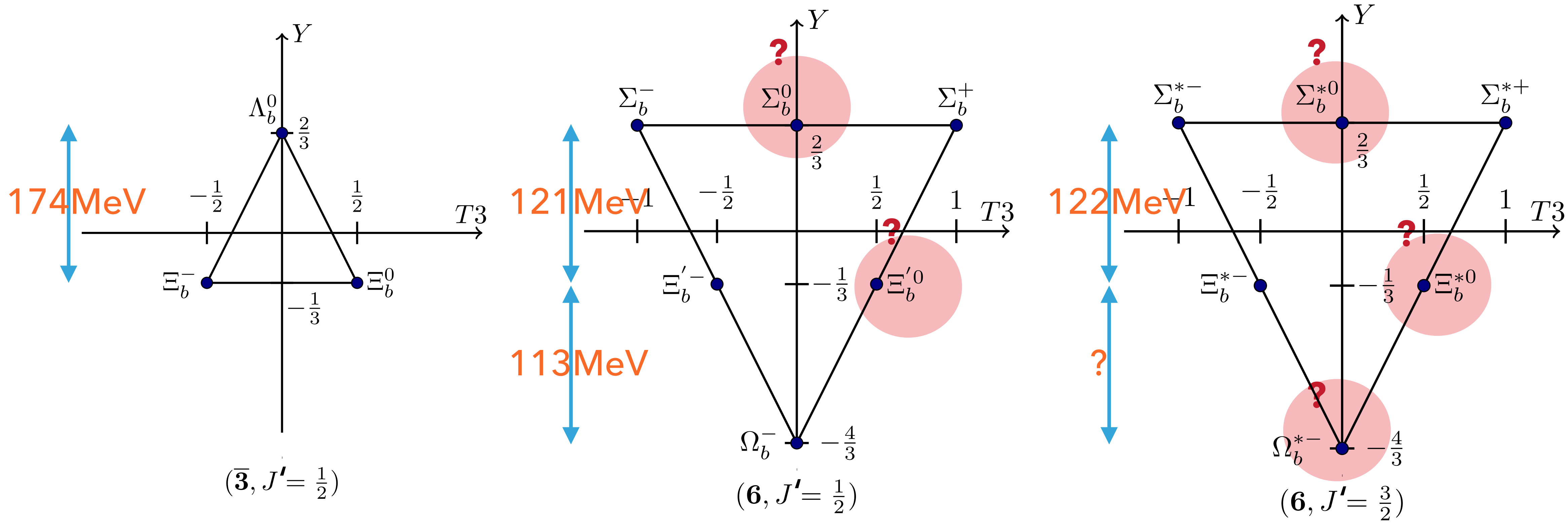
- The mass of light baryons are well known in the ground state and this model extremely well explain the mass splittings.
- We want to take account of the heavy baryon sector.



- Heavy quark spin is conserved. it indicates that the soliton spin is conserved. $m_Q \to \infty$
- The soliton and heavy quark is decoupled and the heavy quark play a role of the static color source.

C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update.

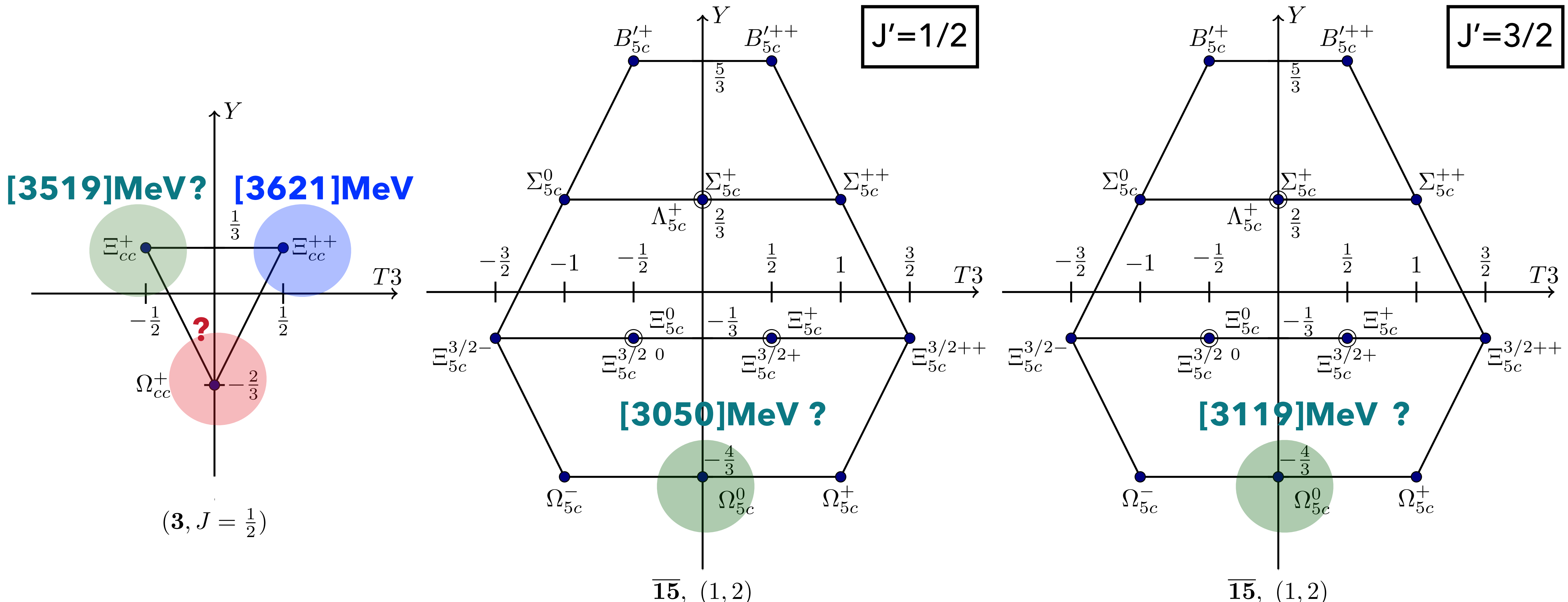
- The masse of charmed baryons are well known. Thus we will check the validity of the present approach.



- There are unknown baryon masses in the bottom baryon sector.
- We can predict the mass of the Ω_b^{*-} without isospin symmetry breaking.

C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update.

- Mass of the Ω_{cc}^{+} is unknown. Recently, mass of the Ξ_{cc}^{+} and Ξ_{cc}^{++} are founded [1] therefore we can predict mass of Ω_{cc}^{+} .



- Moreover, there are observed particles Ω_{c}^{0} in LHCb. The particle is classified within chiral-quark soliton model by using model independent calculation[2].

[1] M. Mattson *et al* [SELEX Collaboration],Phys. Rev. Lett. **89**, 112001 (2002).
[2] H. C. Kim, M. V. Polyakov and M. Praszałowicz, Phys. Rev. **D96**, no. 1, 014009 (2017)

- Effective chiral action

$$S_{\text{eff}} = -N_c \text{TrLn}(i\gamma_\mu \partial^\mu + i\hat{m} + iMU^{\gamma_5})$$

$$U^{\gamma_5} = e^{i\pi^a \tau^a \gamma_5} \qquad \hat{m} = \text{diag}(m_u, m_d, m_s)$$

- Classical soliton mass for light baryon

$$\underline{M_{cl} \approx 1300\text{MeV}}$$

- Collective Hamiltonian

$$H = H_{\text{sym}} + H_{\text{sb}}^{(1)} + H_{\text{hf}},$$

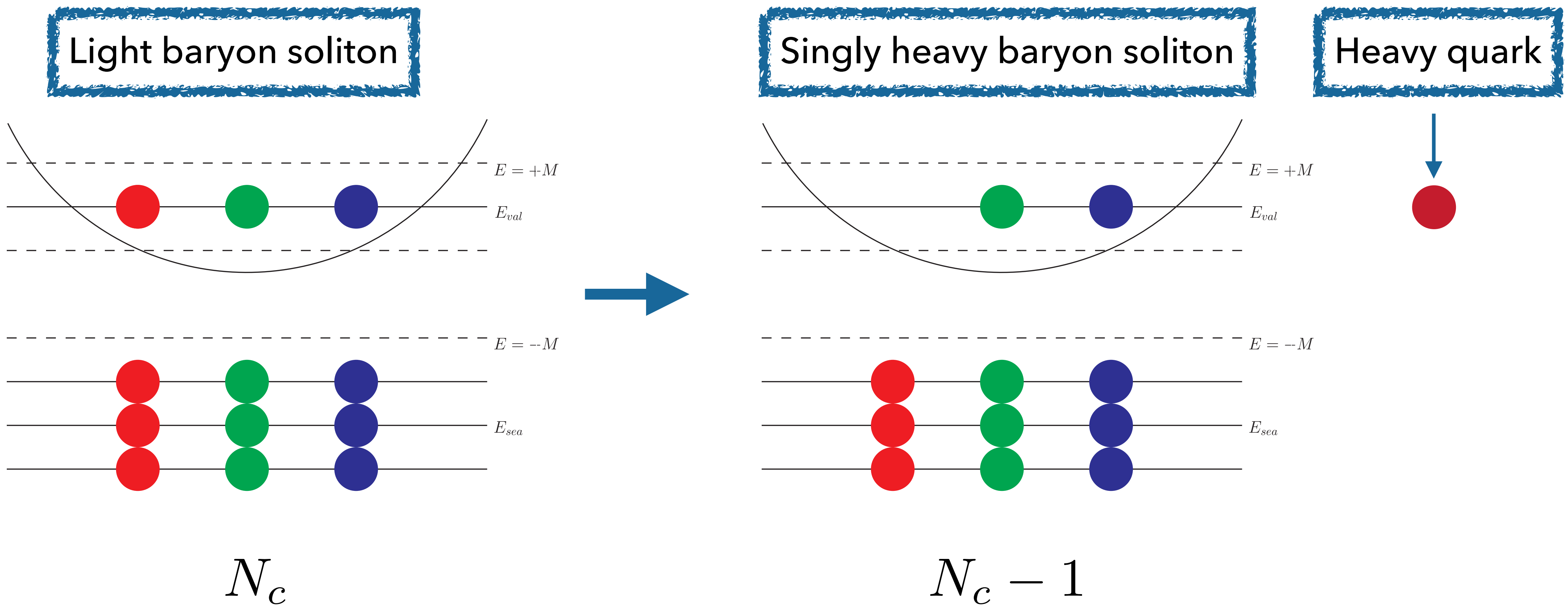
$$H_{\text{sym}} = M_{\text{cl}} + \frac{1}{2I_1}\sum_{i=1}^{3}\hat{J}_i^2 + \frac{1}{2I_2}\sum_{a=4}^{7}\hat{J}_a^2,$$

$$H_{\text{hf}} = \frac{2}{3}\frac{\kappa}{m_Q M_{\text{sol}}}\vec{J}\cdot\vec{J}_Q,$$

$$H_{\text{sb}}^{(1)} = \alpha D_{88}^{(8)} + \beta\hat{Y} + \frac{\gamma}{\sqrt{3}}\sum_{i=1}^{3} D_{8i}^{(8)}\hat{J}_i,$$

D. Diakonov, V. Y. Petrov and P. V. Pobylitsa, Nucl. Phys. **B306**, 809 (1988).

Change of the pion mean fields for Singly heavy baryon



- The mass of the heavy baryon soliton changed under the pion mean field change.

$$M_{\rm sol} = (N_c - 1)E_{\rm val} + E_{\rm sea} \approx 1100 {\rm MeV}.$$

D. Diakonov, V. Y. Petrov and P. V. Pobylitsa, Nucl. Phys. **B306**, 809 (1988).

Change of the pion mean fields for Singly heavy baryon

- The moment of inertias and dynamical parameters are also changed under the pion mean fields change. One can take account of the I_1.

$$I_1 = (N_c - 1)I_1^{\mathrm{val}} + I_1^{\mathrm{sea}}$$

Light baryon	This work	Ref [14]	Ref [32]	Singly heavy baryon	This work
$\tilde{I}_1$[fm]	1.108	1.230 ± 0.002	1.06	I_1[fm]	0.844
$\tilde{I}_2$[fm]	0.529	0.420 ± 0.006	0.48	I_2[fm]	0.404
$\tilde{K}_1$[fm]	0.428	-	0.42	K_1[fm]	0.286
$\tilde{K}_2$[fm]	0.272	-	0.26	K_2[fm]	0.181
$\tilde{N}_0$[fm]	0.457	-	-	N_0[fm]	0.499
$\tilde{N}_1$[fm]	0.410	-	-	N_1[fm]	0.380
$\tilde{N}_2$[fm]	0.323	-	-	N_2[fm]	0.286
$\tilde{\Sigma}_{\pi N}$[MeV]	43.7	36.4±3.9	41	$\Sigma_{\pi N}$[MeV]	40.0
$\tilde{\alpha}$[MeV]	-392.0	-262.9±5.9	-197.0	α[MeV]	-326.3
$\tilde{\beta}$[MeV]	-99.3	-144.3±3.2	-93.7	β[MeV]	-77.8
$\tilde{\gamma}$[MeV]	-49.4	-104.2±2.4	-52.6	γ[MeV]	-37.8
$\tilde{M}_{\mathrm{sol}}$[MeV]	1296.1	-	-	M_{sol}[MeV]	1099.9

$$m_s = 180\mathrm{MeV}$$

[14] Gh. S. Yang, H.-Ch. Kim, M. V. Polyakov and M. Praszalowicz, Phys. Rev. **D94**, 071502 (2016)
[32] T. Ledwig, A. Silva and H.-Ch. Kim, Phys. Rev. **D82**, 034022 (2010)

ROTATIONAL ENERGY

$$\overline{M}_{\mathcal{R},Q} = M_{\rm cl} + \frac{1}{2I_1}J(J+1) + \frac{1}{2I_2}\left[C_2(p,\,q) - J(J+1)\right] - \frac{3}{8I_2}\overline{Y}^2.$$

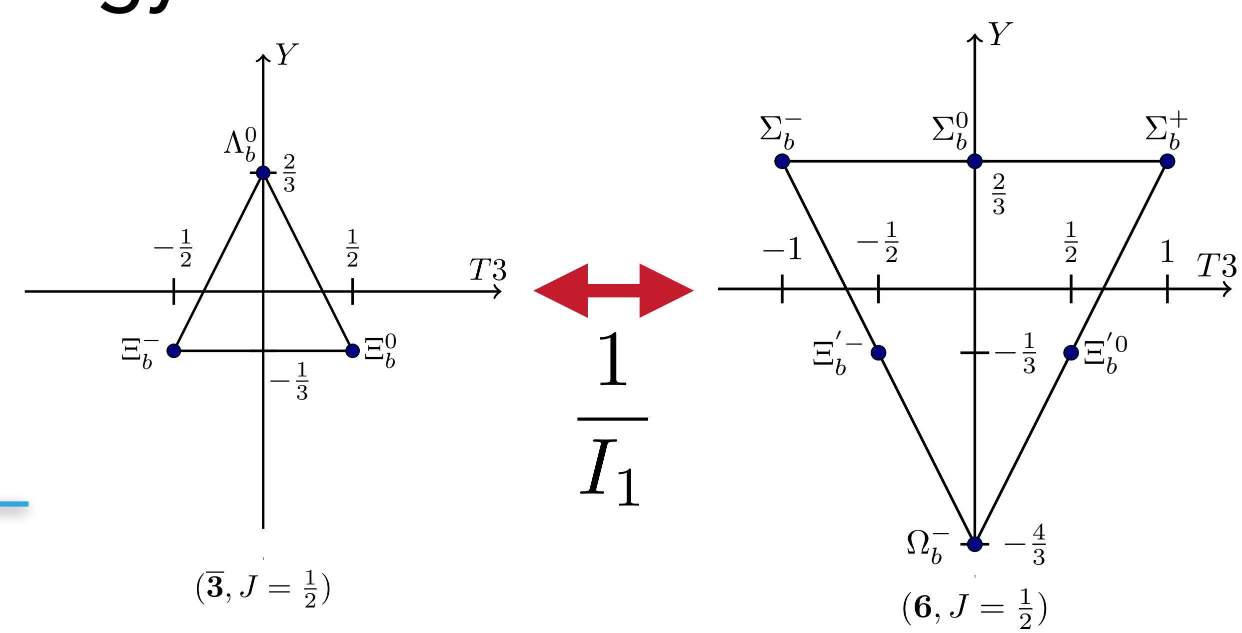
$$\begin{cases} M_{\rm cl} = M_{\rm sol} & \text{Light baryon} \\ M_{\rm cl} = M_{\rm sol} + m_Q & \text{Singly heavy baryon} \end{cases}$$

$$\begin{cases} \overline{Y} = N_c/3 & \text{Light baryon} \\ \overline{Y} = (N_c-1)/3 & \text{Singly heavy baryon} \end{cases}$$

$$\overline{\mathbf{3}} \to (p,\,q) = (0,\,1) \to J = 0 \ \ \text{antitriplet}$$
$$\mathbf{6} \to (p,\,q) = (2,\,0) \to J = 1 \ \ \text{sextet.}$$

- The rotational energy yields the energy difference between the $\overline{\mathbf{3}}$ and the $\mathbf{6}$.

$$\overline{M}_{\mathbf{6},c} - \overline{M}_{\overline{\mathbf{3}},c} = \frac{1}{I_1}.$$



D. Diakonov, V. Y. Petrov and P. V. Pobylitsa, Nucl. Phys. **B306**, 809 (1988).

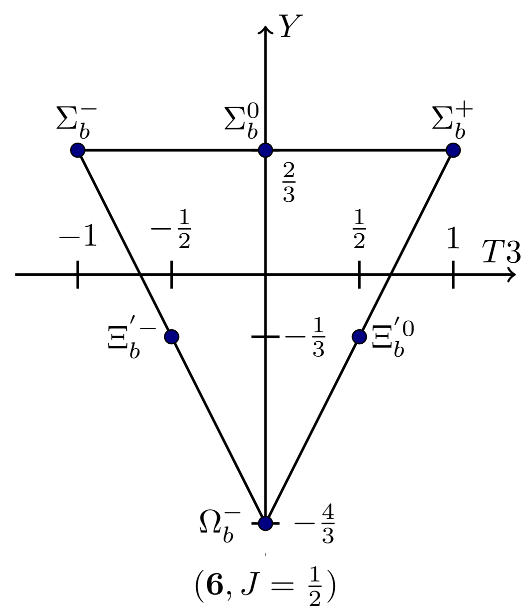
HYPERFINE MASS SPLITTING

- The mass difference between baryon spin 1/2 and 3/2 arised from the spin-spin interaction.

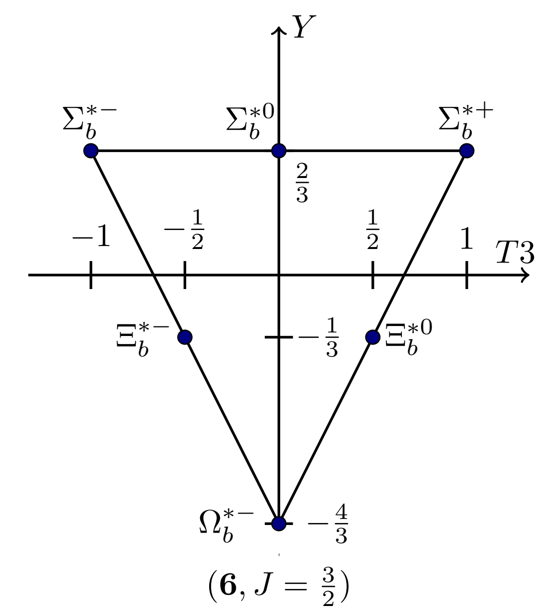
$$H_{\rm hf} = \frac{2}{3}\frac{\kappa}{m_Q M_{\rm sol}} \vec{J}\cdot\vec{J}_Q,$$

$$M^{(\rm hf)}_{\mathbf{6}_{1/2},Q} = -\frac{2\kappa}{3m_Q M_{\rm sol}},$$

$$M^{(\rm hf)}_{\mathbf{6}_{3/2},Q} = \frac{\kappa}{3m_Q M_{\rm sol}},$$



$$\frac{\kappa}{m_Q M_{\rm sol}}$$



- The hyperfine mass splitting is determined by using experimental data[1]

$$\frac{\kappa}{m_c M_{\rm sol}} = 68.1 \pm 1.1 {\rm MeV}$$

$$\frac{\kappa}{m_b M_{\rm sol}} = 20.3 \pm 1.0 {\rm MeV}$$

[1] Gh. S. Yang, H.-Ch. Kim, M. V. Polyakov and M. Praszalowicz, Phys. Rev. **D94**, 071502 (2016)

SU(3) SYMMETRY BREAKING

$$H_{\rm sb}^{(1)} = +\alpha D_{88}^{(8)} + \beta \hat{Y} + \frac{\gamma}{\sqrt{3}} \sum_{i=1}^{3} D_{8i}^{(8)} \hat{J}_i,$$

$$\alpha = \left(-\frac{\Sigma_{\pi N}}{3m_0} + \frac{K_2}{I_2}\overline{Y}\right) m_s, \quad \beta = -\frac{K_2}{I_2} m_s, \quad \gamma = 2\left(\frac{K_1}{I_1} - \frac{K_2}{I_2}\right) m_s.$$

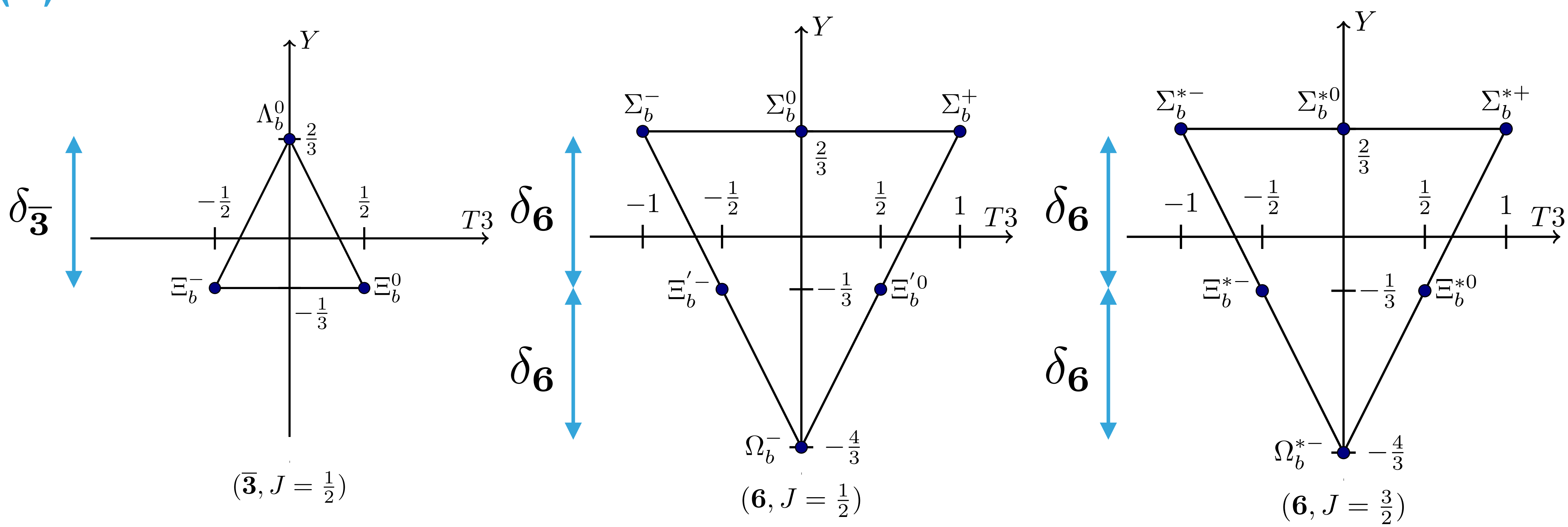
- Mass correction in the perturbation theory

$$M_{B,\mathcal{R}}^{(1)} = \langle B, \mathcal{R} | H_{\rm sb}^{(1)} | B, \mathcal{R} \rangle = Y \delta_{\mathcal{R}}$$

$$\delta_{\mathbf{3}} = \frac{3}{8}\alpha + \beta, \qquad \delta_{\mathbf{6}} = \frac{3}{20}\alpha + \beta - \frac{3}{10}\gamma.$$

D. Diakonov, V. Y. Petrov and P. V. Pobylitsa, Nucl. Phys. **B306**, 809 (1988).

SU(3) SYMMETRY BREAKING



model calculation

$$\delta_{\overline{\mathbf{3}}} = -203.6\text{MeV}, \quad \delta_{\mathbf{6}} = -117.4\text{MeV},$$

model independent value

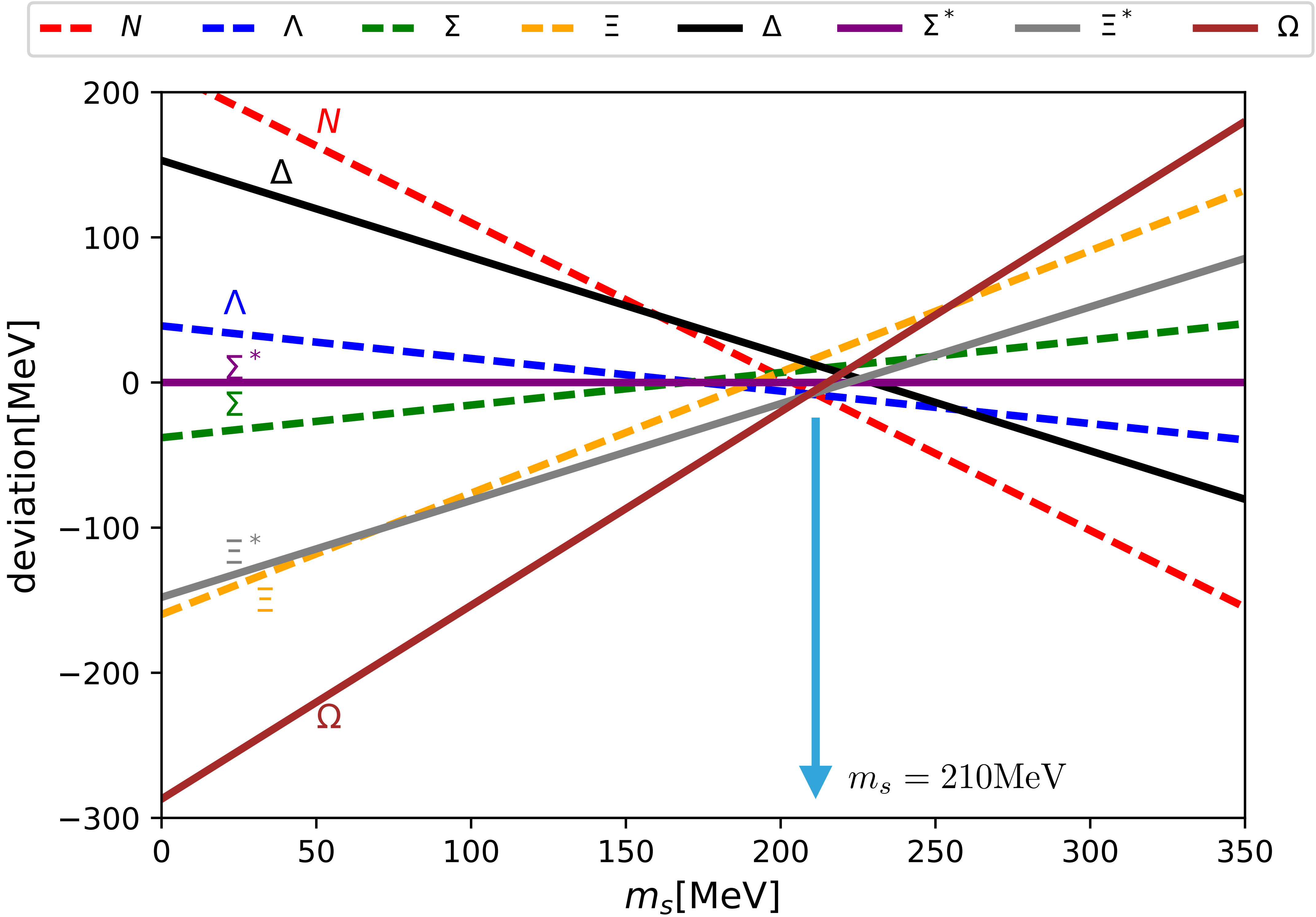
$$\delta_{\overline{\mathbf{3}}}^{\text{exp}} = -178.5\text{MeV}, \quad \delta_{\mathbf{6}}^{\text{exp}} = -120.7\text{MeV},$$

$$M_B^{(2)(\text{wf})} = \sum_{\mathcal{R}\neq\mathcal{R}'} \frac{\left|\langle B,\mathcal{R}'|H_{\text{sb}}^{(1)}|B,\mathcal{R}\rangle\right|^2}{\overline{M}_{\mathcal{R},Q} - \overline{M}_{\mathcal{R}',Q}}.$$

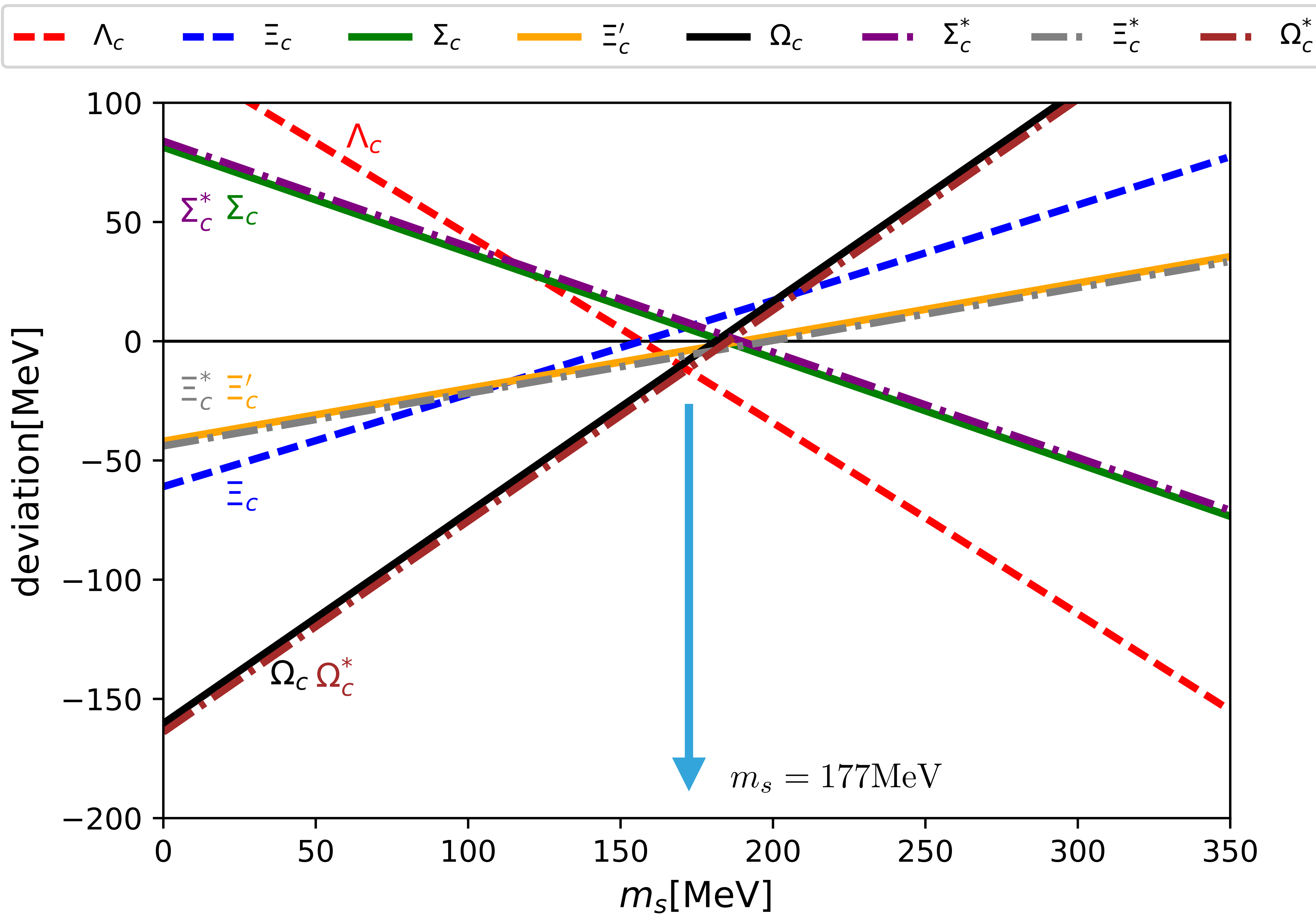
$$M_B^{(2)(\text{op})} = \langle B,\mathcal{R}|H_{\text{sb}}^{(2)}|B,\mathcal{R}\rangle.$$

D. Diakonov, V. Y. Petrov and P. V. Pobylitsa, Nucl. Phys. **B306**, 809 (1988).

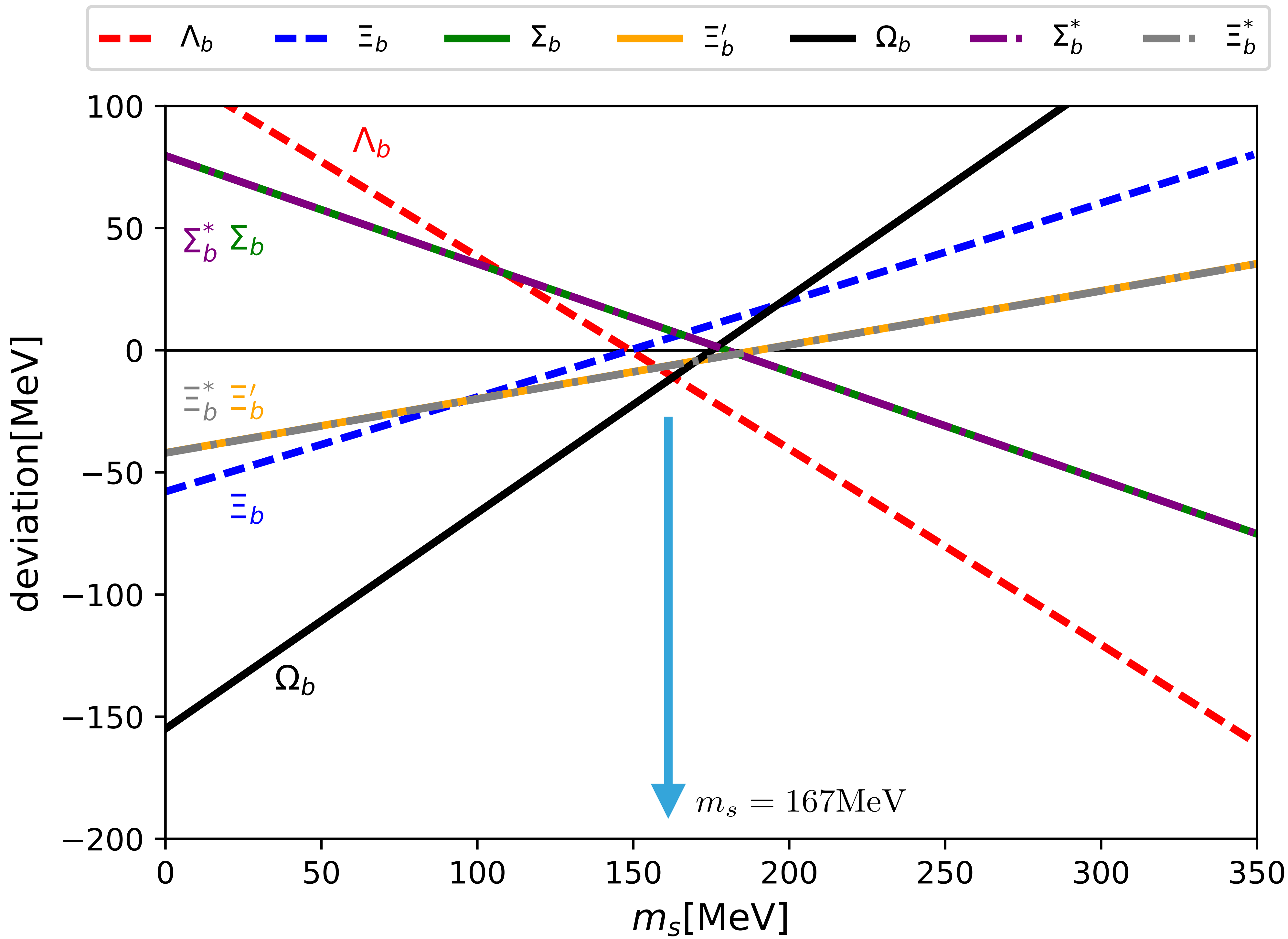
LIGHT BARYON



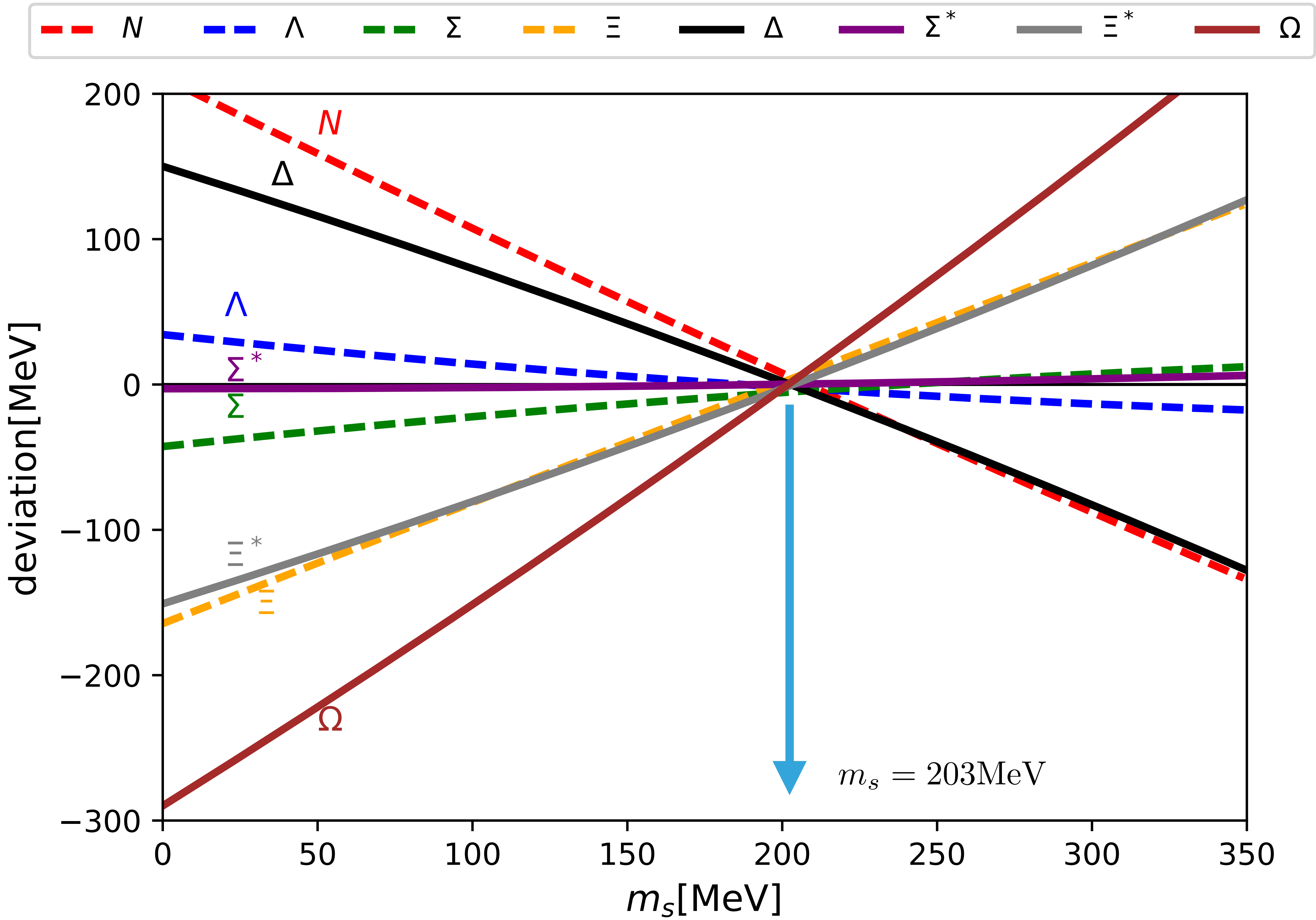
CHARMED BARYON



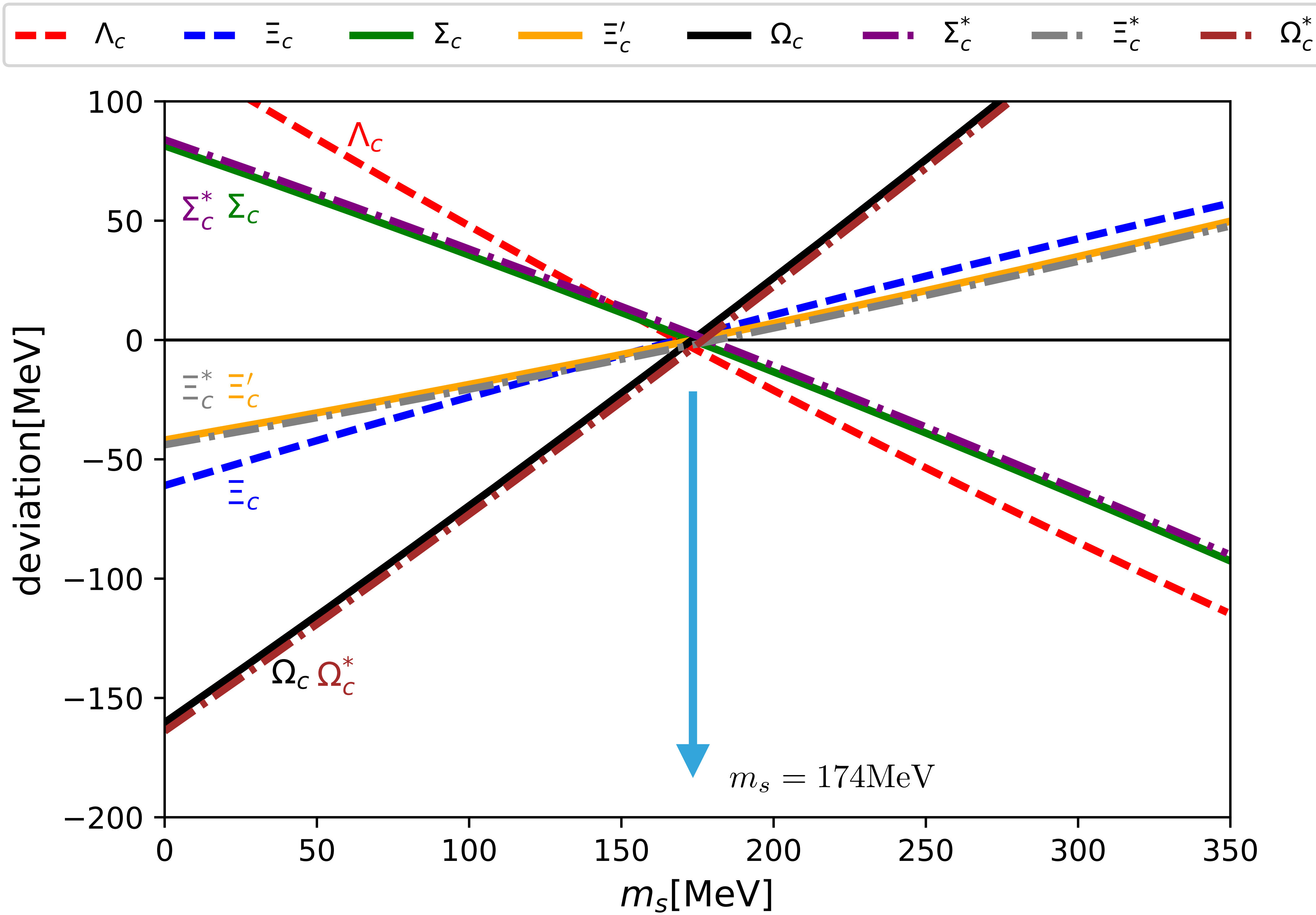
BOTTOM BARYON



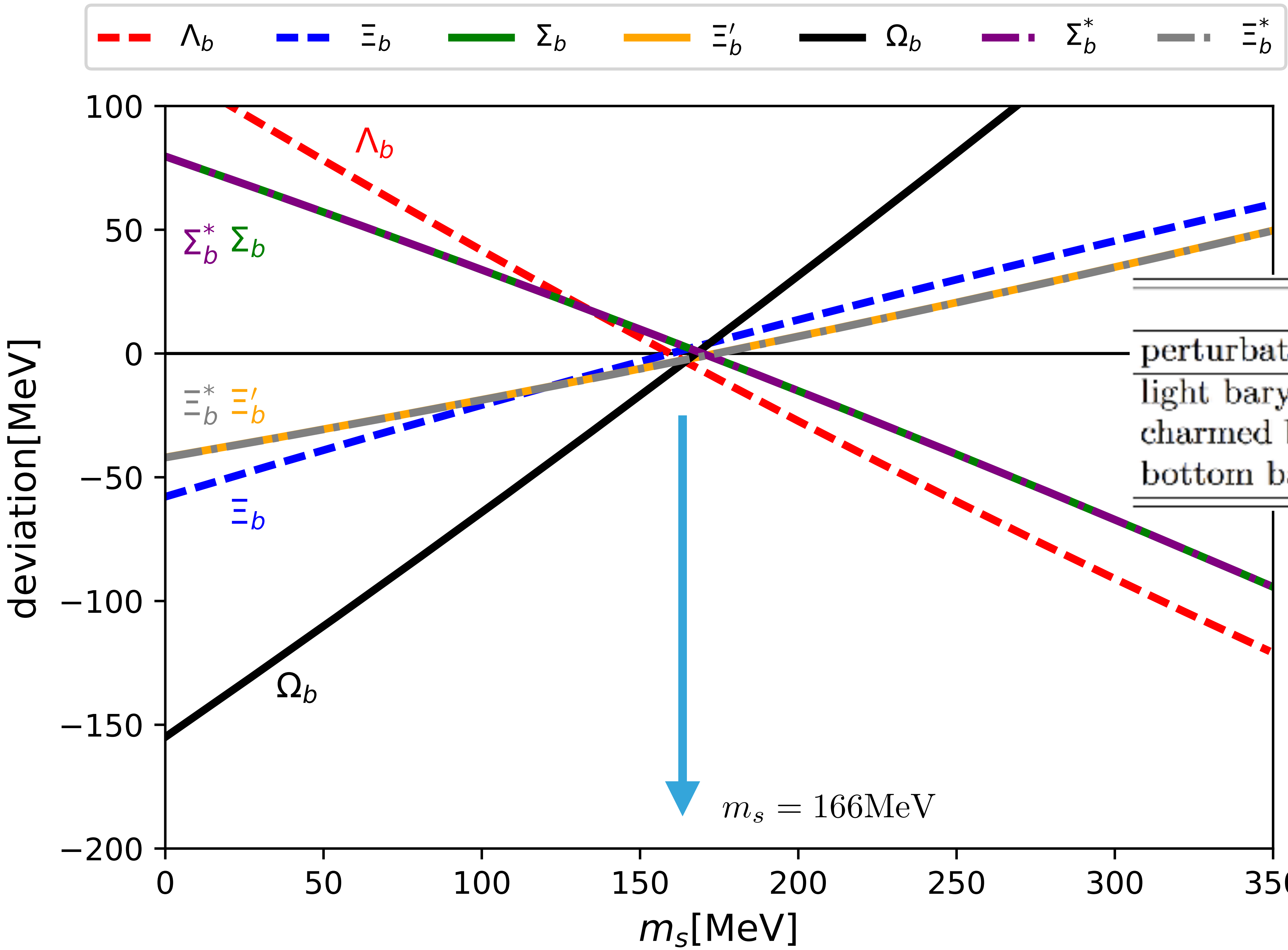
LIGHT BARYON



CHARMED BARYON



BOTTOM BARYON



	m_s[MeV]	
perturbation	1st	2nd
light baryon	210	202
charmed baryon	177	174
bottom baryon	167	166

CHARMED BARYON

- The heavy baryon masses can be calculated by using the determined strange current quark mass.

	m_s[MeV]	
perturbation	1st	2nd
light baryon	210	202
charmed baryon	177	174
bottom baryon	167	166

				Perturbative	
				1st order	2nd order
$\mathcal{R}_J^Q$	B_c	Experiment[MeV]	ref[14] [MeV]	m_s = 177[MeV]	m_s = 174[MeV]
$\overline{\mathbf{3}}_{1/2}^c$	Λ_c	2286.5±0.1	2272.5±2.3	2272.7	2282.8
$\overline{\mathbf{3}}_{1/2}^c$	Ξ_c	2469.4±0.3	2476.3±1.2	2476.3	2471.2
$\mathbf{6}_{1/2}^c$	Σ_c	2453.5±0.1	2445.3±2.5	2456.1	2453.2
$\mathbf{6}_{1/2}^c$	Ξ_c'	2576.8±2.1	2580.5±1.6	2573.6	2576.9
$\mathbf{6}_{1/2}^c$	Ω_c	2695.2±1.7	2715.7±4.5	2691.0	2695.9
$\mathbf{6}_{3/2}^c$	Σ_c^*	2518.1±0.8	2513.4±2.3	2525.0	2520.3
$\mathbf{6}_{3/2}^c$	Ξ_c^*	2645.9±0.4	2648.6±1.3	2642.4	2644.0
$\mathbf{6}_{3/2}^c$	Ω_c^*	2765.9±2.0	2783.8±4.5	2759.9	2763.1

[14]Gh. S. Yang, H.-Ch. Kim, M. V. Polyakov and M. Praszalowicz, Phys. Rev. **D94**, 071502 (2016)

BOTTOM BARYON

- Especially, the mass of Ω_b^* can be predicted in the chiral quark-soliton model.

	m_s[MeV]	
perturbation	1st	2nd
light baryon	210	202
charmed baryon	177	174
bottom baryon	167	166

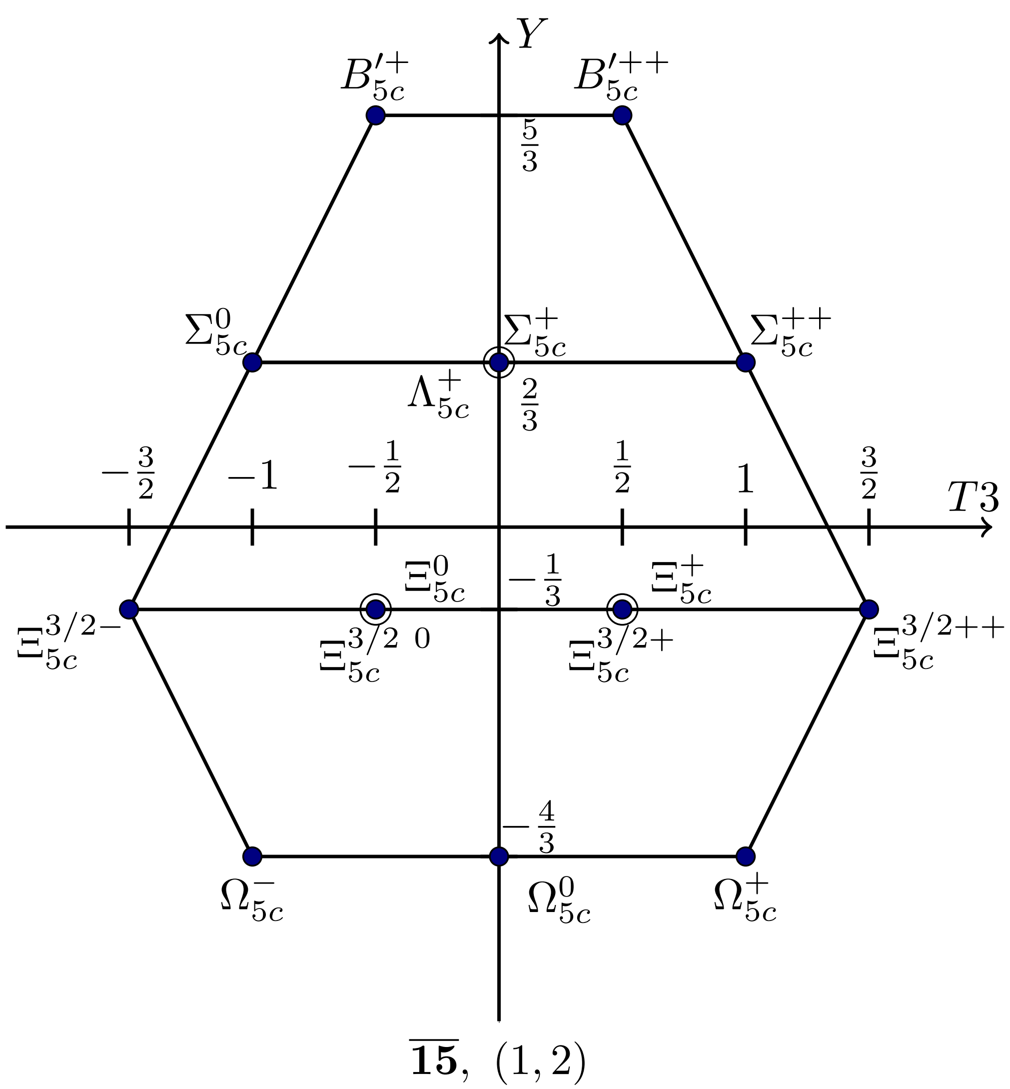
				Perturbative	
				1st order	2nd order
$\mathcal{R}_J^Q$	B_c	Experiment[MeV]	ref[14] [MeV]	m_s = 167[MeV]	m_s = 166[MeV]
$\overline{\mathbf{3}}_{1/2}^b$	Λ_b	5619.5±0.2	5599.3±2.4	5607.1	5615.1
$\overline{\mathbf{3}}_{1/2}^b$	Ξ_b	5793.1±0.7	5803.1±1.2	5799.3	5795.3
$\mathbf{6}_{1/2}^b$	Σ_b	5813.4±1.3	5804.3±2.4	5821.0	5815.3
$\mathbf{6}_{1/2}^b$	Ξ_b'	5935.0±0.05	5939.5±1.5	5931.8	5933.0
$\mathbf{6}_{1/2}^b$	Ω_b	6048.0±1.9	6074.7±4.5	6042.6	6046.4
$\mathbf{6}_{3/2}^b$	Σ_b^*	5833.6±1.3	5824.6±2.3	5840.9	5835.5
$\mathbf{6}_{3/2}^b$	Ξ_b^*	5955.3±0.1	5959.8±1.2	5951.7	5953.2
$\mathbf{6}_{3/2}^b$	Ω_b^*	-	6095.0±4.4	6062.5	6066.6

$$M_{\Omega_b^*} = M_{\Omega_b} + \frac{\kappa}{m_Q m_{\rm sol}} = 6068.0 \pm 2.1\text{MeV}$$

[14]Gh. S. Yang, H.-Ch. Kim, M. V. Polyakov and M. Praszalowicz, Phys. Rev. **D94**, 071502 (2016)

HEAVY PENTAQUARK

- The $\Omega_c^0[3050]$ and the $\Omega_c^0[3119]$ mass difference is 69MeV that would be hyperfine mass splitting for charmed baryon, which is the scenario of our model.



	$M^{(1)}_{B_5 c}$
$\langle B'_{5c}\|H_{coll}\|B'_{5c}\rangle$	$\frac{1}{8}\alpha+\frac{5}{3}\beta-\frac{1}{4}\gamma$
$\langle \Sigma_{5c}\|H_{coll}\|\Sigma_{5c}\rangle$	$\frac{1}{12}\alpha+\frac{2}{3}\beta-\frac{1}{6}\gamma$
$\langle \Xi^{3/2}_{5c}\|H_{coll}\|\Xi^{3/2}_{5c}\rangle$	$\frac{1}{24}\alpha-\frac{1}{3}\beta-\frac{1}{12}\gamma$
$\langle \Omega_{5c}\|H_{coll}\|\Omega_{5c}\rangle$	$-\frac{1}{6}\alpha-\frac{4}{3}\beta+\frac{1}{3}\gamma$
$\langle \Lambda_{5c}\|H_{coll}\|\Lambda_{5c}\rangle$	$\frac{2}{3}\beta$
$\langle \Xi_{5c}\|H_{coll}\|\Xi_{5c}\rangle$	$-\frac{1}{12}\alpha-\frac{1}{3}\beta+\frac{1}{6}\gamma$

$$\frac{\kappa}{m_c M_{\rm sol}} = 68.1 \pm 1.1\text{MeV}$$

[4] D. Diakonov, arXiv:1003.2157 [hep-ph].

HEAVY PENTAQUARK

- One can calculate the whole heavy pentaquark masses by using masses of the Ω_c^0 particles.

	Perturbative	
	1st order	2nd order
m_s	177	174
$M_{B_{5c}}$	2738.1	2751.7
$M_{\Sigma_{5c}}$	2827.9	2861.0
$M_{\Lambda_{5c}}$	2849.1	2859.9
$M_{\Xi_{5c}^{3/2}}$	2917.7	2923.3
$M_{\Xi_{5c}}$	2949.6	2964.3
M_{Ω_c}	[Input]	
$M_{B_{5c}}$	2808.1	2820.7
$M_{\Sigma_{5c}}$	2897.9	2930.0
$M_{\Lambda_{5c}}$	2919.1	2928.9
$M_{\Xi_{5c}^{3/2}}$	2987.7	2992.3
$M_{\Xi_{5c}}$	3019.6	3033.7
M_{Ω_c}	[Input]	

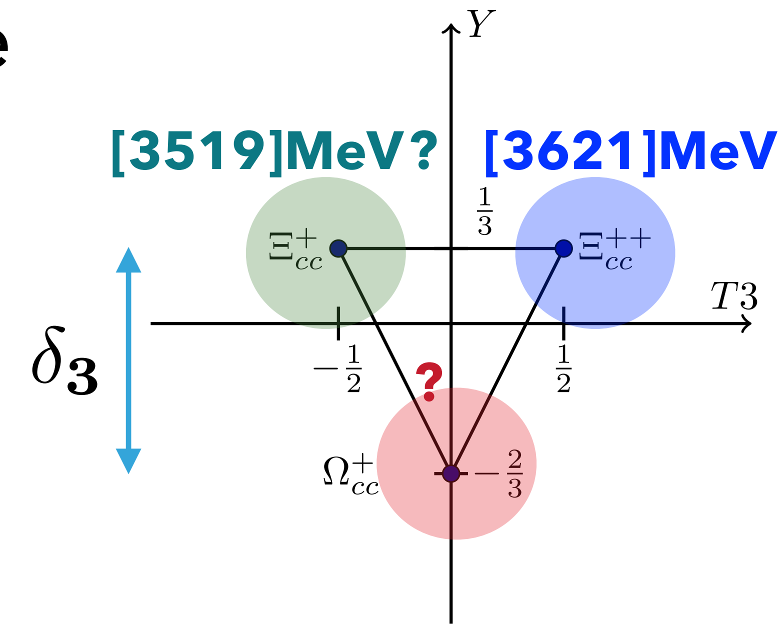
Gh. S. Yang, H.-Ch. Kim, M. V. Polyakov and M. Praszalowicz, Phys. Rev. **D94**, 071502 (2016)

DOUBLY CHARMED BARYON

- Doubly charmed baryon consist of the two heavy quarks and $N_c - 2$ light quark.
- One can get the masses of the Ω_{cc}^{+} by using masses of the Ξ_{cc}^{+} and Ξ_{cc}^{++}

$$M^{(1)}_{B_{Q_1Q_2}} = Y\delta_{\mathcal{R}}.$$

$$\delta_{\mathbf{3}} = \frac{3}{16}\alpha' + \beta' - \frac{9}{32}\gamma'.$$



$(\mathbf{3}, J = \frac{1}{2})$

M. Mattson *et al* [SELEX Collaboration],Phys. Rev. Lett. **89**, 112001 (2002).
R. Aaij *et al.* [LHCb Collaboration], arXiv:1707.01621 [hep-ex].

DOUBLY CHARMED BARYON

- There is dependence of the strange current quark mass as a result of the SU(3) symmetry breaking
- The strange current quark mass cannot be determined for now but one can predict the mass of the Ω_{cc}^{+} as a function of the quark mass.

		$M_{\Omega_{cc}}$ [MeV]	
	m_s [MeV]	1st order	2nd order
$M_{\Xi_{cc}}^{\text{exp}} = 3519.0$ MeV [43]	150	3613.3	3614.5
	160	3619.6	3621.0
	170	3625.8	3627.4
	180	3632.1	3633.9
$M_{\Xi_{cc}}^{\text{exp}} = 3621.4$ MeV [42]	150	3715.8	3717.0
	160	3722.1	3723.5
	170	3728.3	3729.9
	180	3734.6	3736.4

- Pion mean field play a important role in the heavy baryon sector.
- Unfortunately, mass difference of the representations undershoots by 25%.
- If the strange current quark mass determined in the doubly heavy baryon, one can predict the exact heavy baryon masses.
- Decay width of the heavy baryon can be calculated in the chiral quark-soliton model as well.

THANK YOU VERY MUCH!