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

June-Young Kim

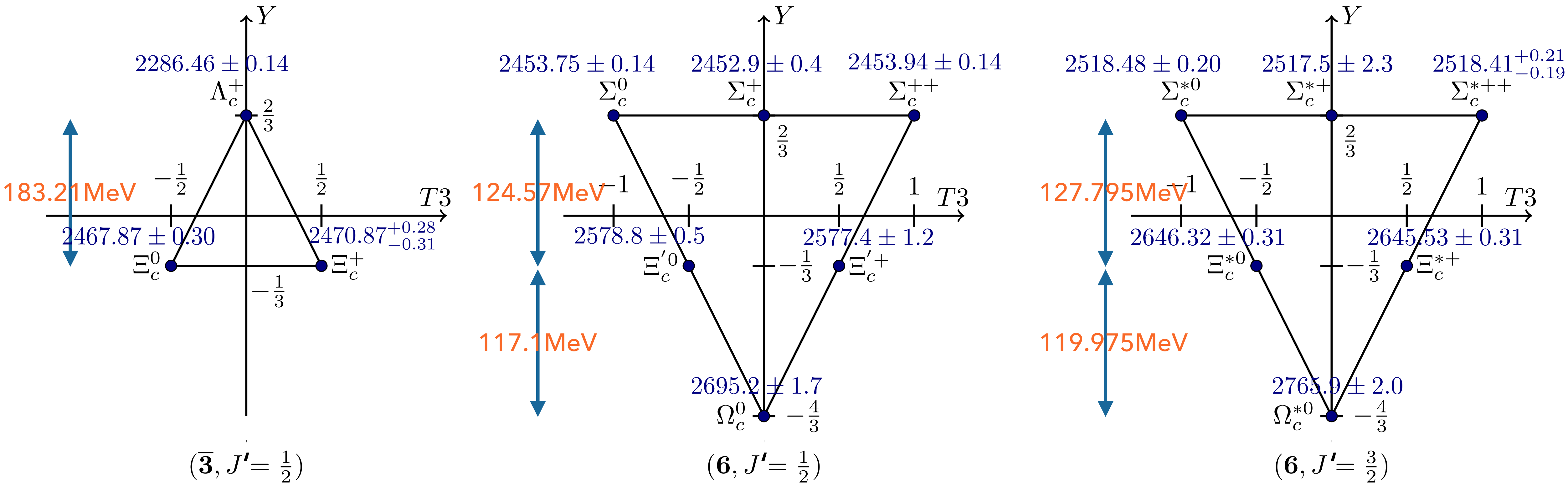
Department of Physics

Inha University

In collaboration with Ghil-Seok Yang, Hyun-Chul Kim and Michał Prasałowicz

- Motivation
- Chiral quark-soliton model
- Mass splittings of the singly heavy baryons
- Masses of the singly heavy baryons
- Masses of the doubly heavy baryons

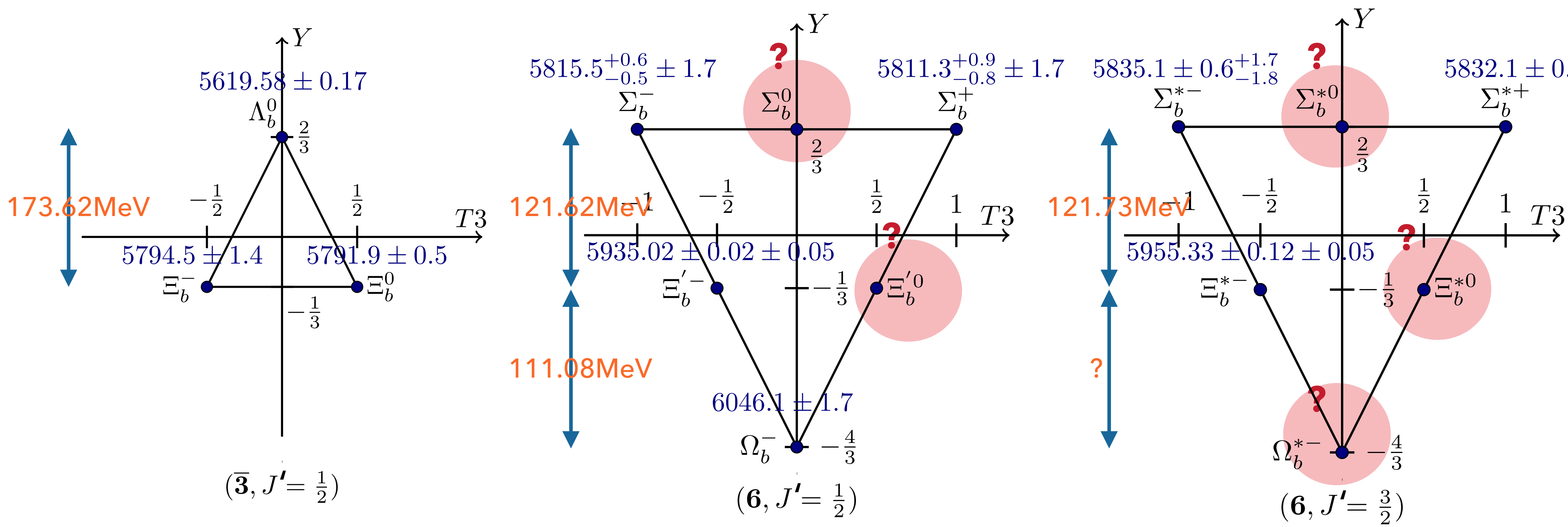
- The masses of light baryons are well known in the ground state and were described very well in the chiral quark-soliton model.
- We want to extend the model to explain the mass spectra of heavy baryons.



- As $m_Q \to \infty$, heavy quark spin is conserved, which leads to the fact that the light-quark spin is also conserved.
- The soliton and a heavy quark are decoupled and the heavy quark plays a role of the static color source.

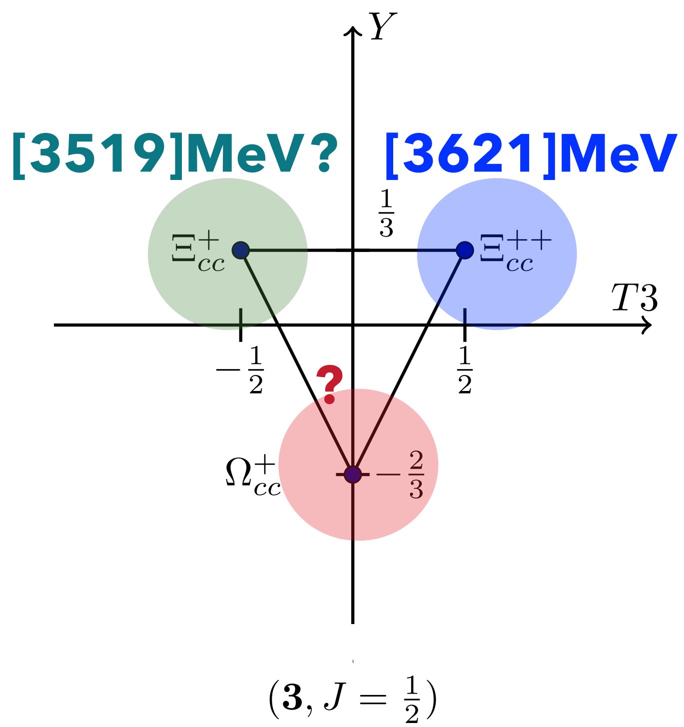
C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update.

- The masses of charmed baryons are well known. Thus we will first check the validity of the present approach in the charmed sector.



- On the other hand, some of bottom baryon masses are unknown.
- In this talk, we will show how the mass of Ω_b^{*-} is predicted.

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



M. Mattson *et al* [SELEX Collaboration],Phys. Rev. Lett. **89**, 112001 (2002) :

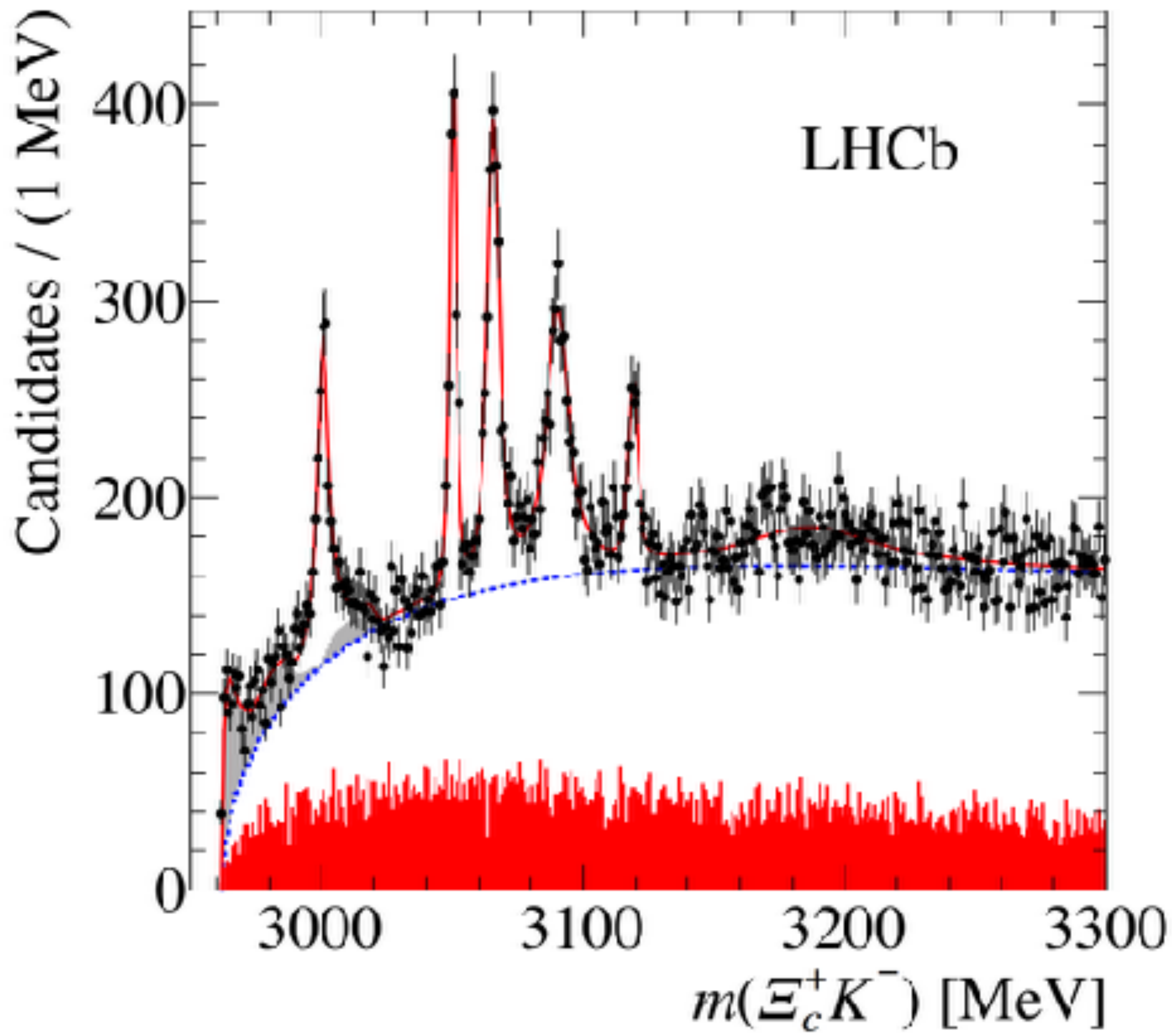
$$M_{\Xi_{cc}^{+}} = (3519 \pm 1)\,\mathrm{MeV}$$

R. Aaij *et al.* [LHCb Collaboration],arXiv:1707.01621 [hep-ex] :

$$M_{\Xi_{cc}^{++}} = (3621.4 \pm 0.72 \pm 0.27 \pm 0.14)\ \mathrm{MeV}$$

- The mass of the Ω_{cc}^{+} is unknown. Recently, the mass of the Ξ_{cc}^{++} was found. Using this data, we can predict that of Ω_{cc}^{+}

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



Five Ω_c^0s were announced by LHCb Coll.

R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **118**, no. 18, 182001 (2017)

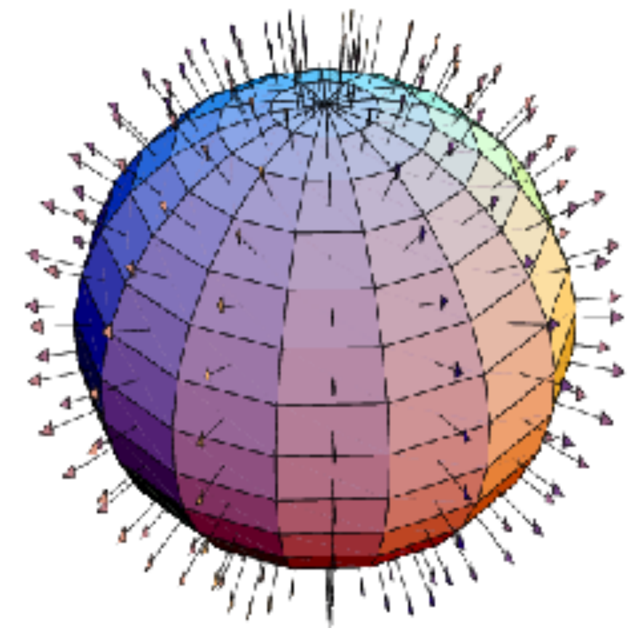
- Effective chiral action

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

$$\hat{m} = \text{diag}(m_u, m_d, m_s)$$

- Hedgehog Ansatz

$$U_c = e^{i\gamma_5 n^a \tau^a \pi(r)}$$



hedgehog

- Self-Consistent soliton solution

$$\frac{\delta}{\delta U}[N_c E_{\text{val}} + E_{\text{sea}}]\Big|_{U_c} = 0, \qquad \underline{M_{\text{cl}} \approx 1300 \text{ MeV}}$$

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

Zero-mode quantization

$$U(\boldsymbol{r}) = \begin{pmatrix} U_c(\boldsymbol{r}) & 0 \\ 0 & 1 \end{pmatrix}.$$

Witten's embedding

$$\vec{J} + \vec{T} = 0$$

$$U(\boldsymbol{r},\, t) = A(t) U(\boldsymbol{r}) A^{\dagger}(t),$$

Slowly rotating soliton

Collective Hamiltonian

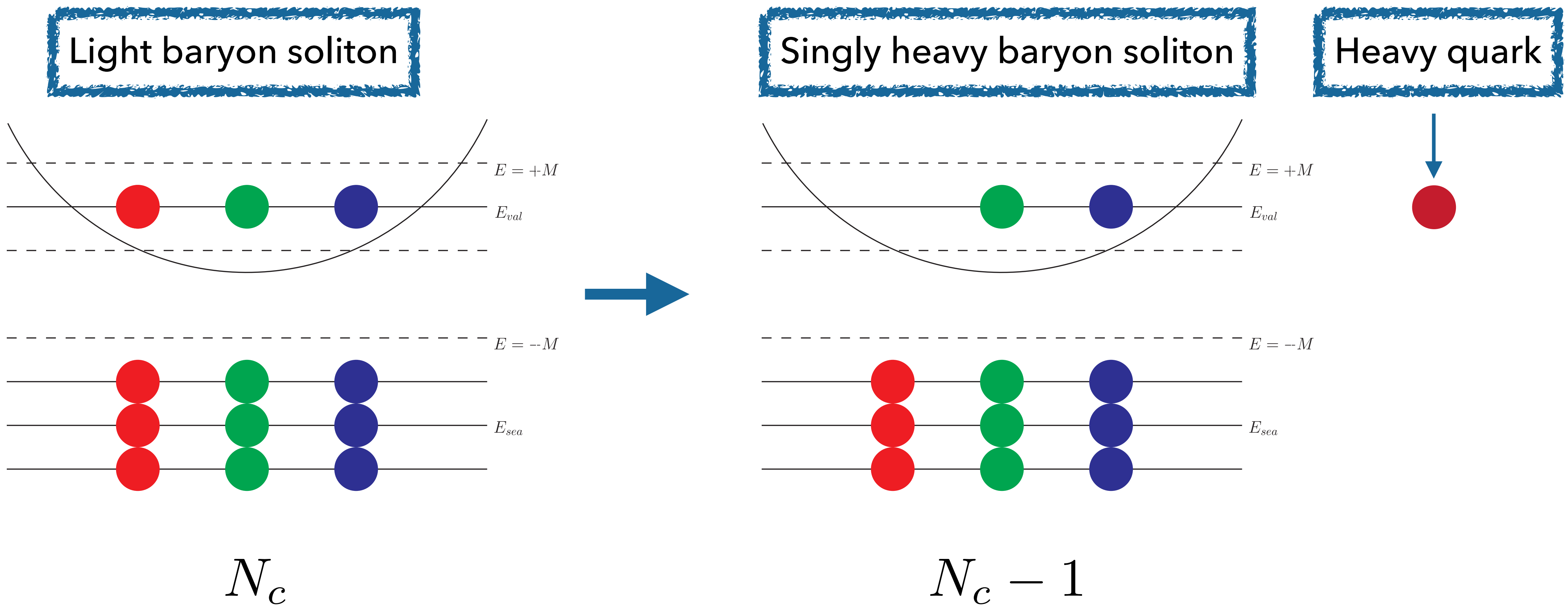
$$H = H_{\rm sym} + H_{\rm sb}^{(1)}$$

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

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

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 soliton mass formula is changed only for the valence part in the singly heavy baryon sector.

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

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

Light baryon	This work	Ref [14]	Singly heavy baryon	This work
$\tilde{I}_1$[fm]	1.108	1.230 ± 0.002	I_1[fm]	0.844
$\tilde{I}_2$[fm]	0.529	0.420 ± 0.006	I_2[fm]	0.404
$\tilde{K}_1$[fm]	0.428	-	K_1[fm]	0.286
$\tilde{K}_2$[fm]	0.272	-	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	$\Sigma_{\pi N}$[MeV]	40.0
$\tilde{\alpha}$[MeV]	-392.0	-262.9±5.9	α[MeV]	-326.3
$\tilde{\beta}$[MeV]	-99.3	-144.3±3.2	β[MeV]	-77.8
$\tilde{\gamma}$[MeV]	-49.4	-104.2±2.4	γ[MeV]	-37.8
$\tilde{M}_{sol}$[MeV]	1296.1	-	M_{sol}[MeV]	1099.9

[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

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

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

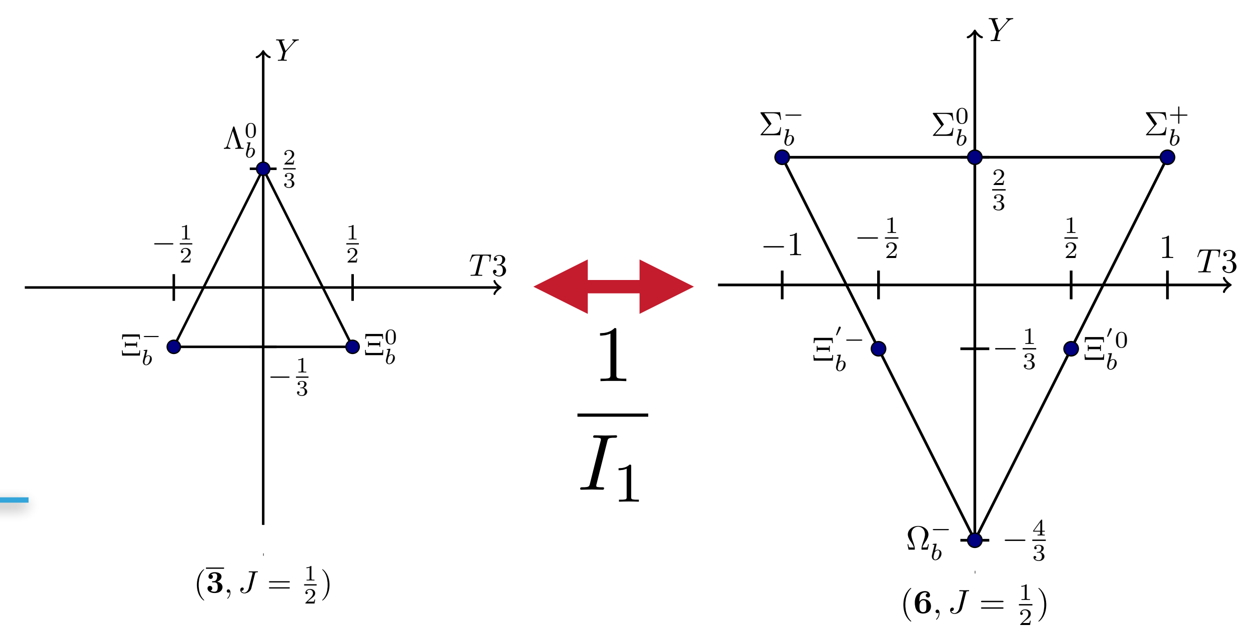
$$\begin{cases} \overline{Y} = N_c/3 & \text{Light baryon} \\ \overline{Y} = (N_c - 1)/3 & \text{Singly heavy baryon} \end{cases}$$

$$\psi_B^{(\mathcal{R})}(J'J_3', J; A) = \sum_{m_3=-1/2}^{1/2} \sqrt{\dim(p,\,q)}(-1)^{-\frac{\overline{Y}}{2}+J_3} C^{J'\,J_3'}_{J_Q m_3 J - J_3}\left[\langle Y, T, T_3 | D^{(8)}(A) | \overline{Y}, J, -J_3\rangle\right]^* \chi_{m_3},$$

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

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

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



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

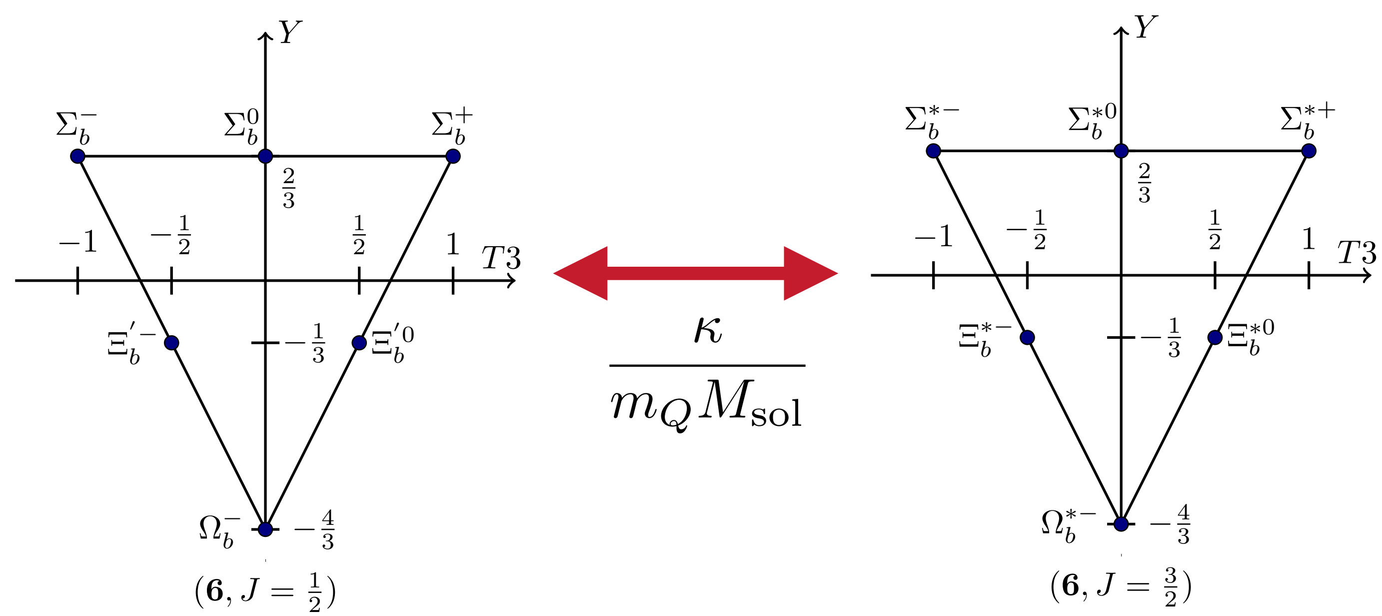
HYPERFINE MASS SPLITTING

- We have to introduce the hyperfine interaction to lift the degeneracy in the sextet representations.

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

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

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



- The hyperfine mass splittings are determined by using center values of the sextet masses [1]

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

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

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

SU(3) SYMMETRY BREAKING

m_s is considered as a perturbation.

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

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

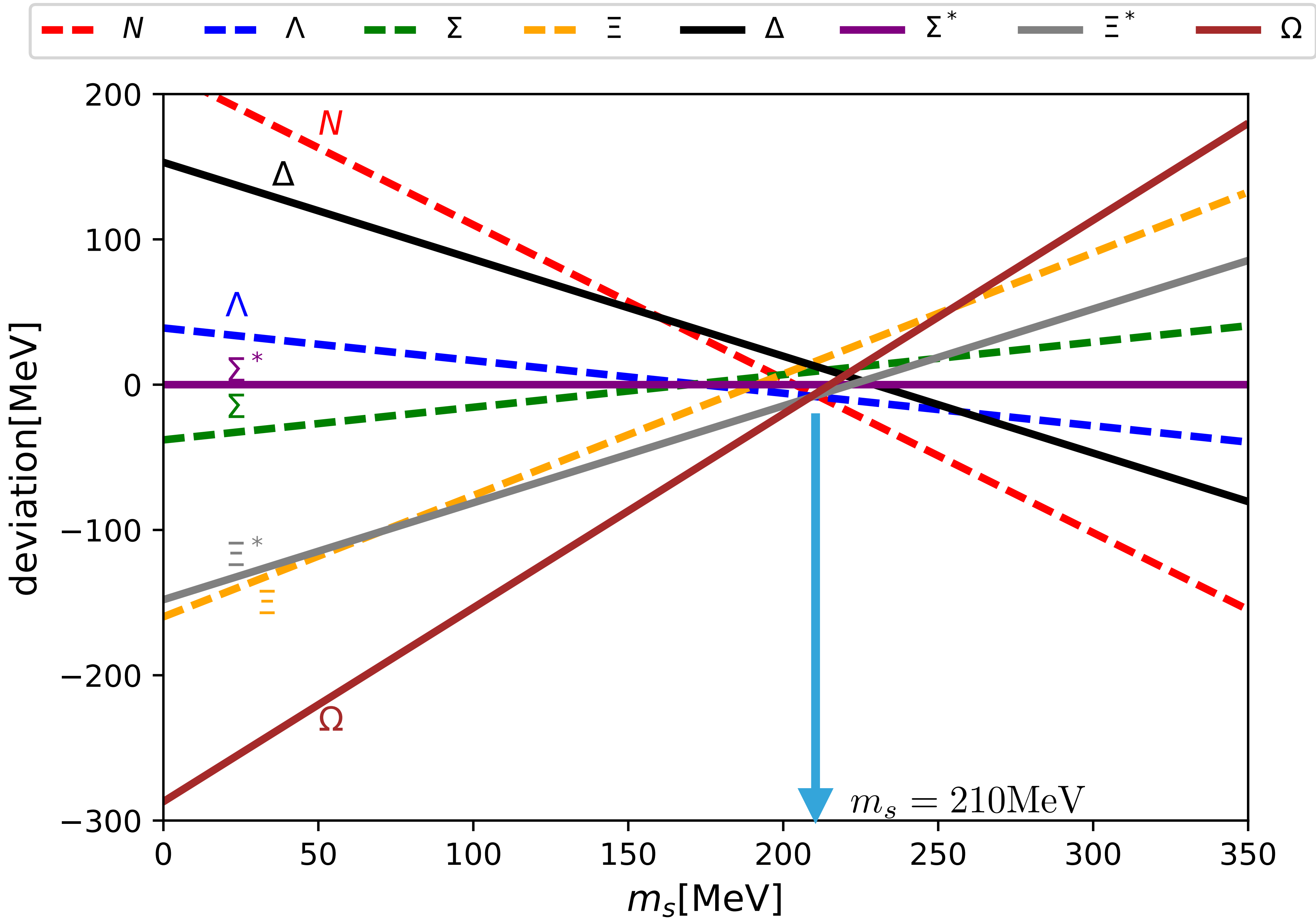
- Mass correction

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

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

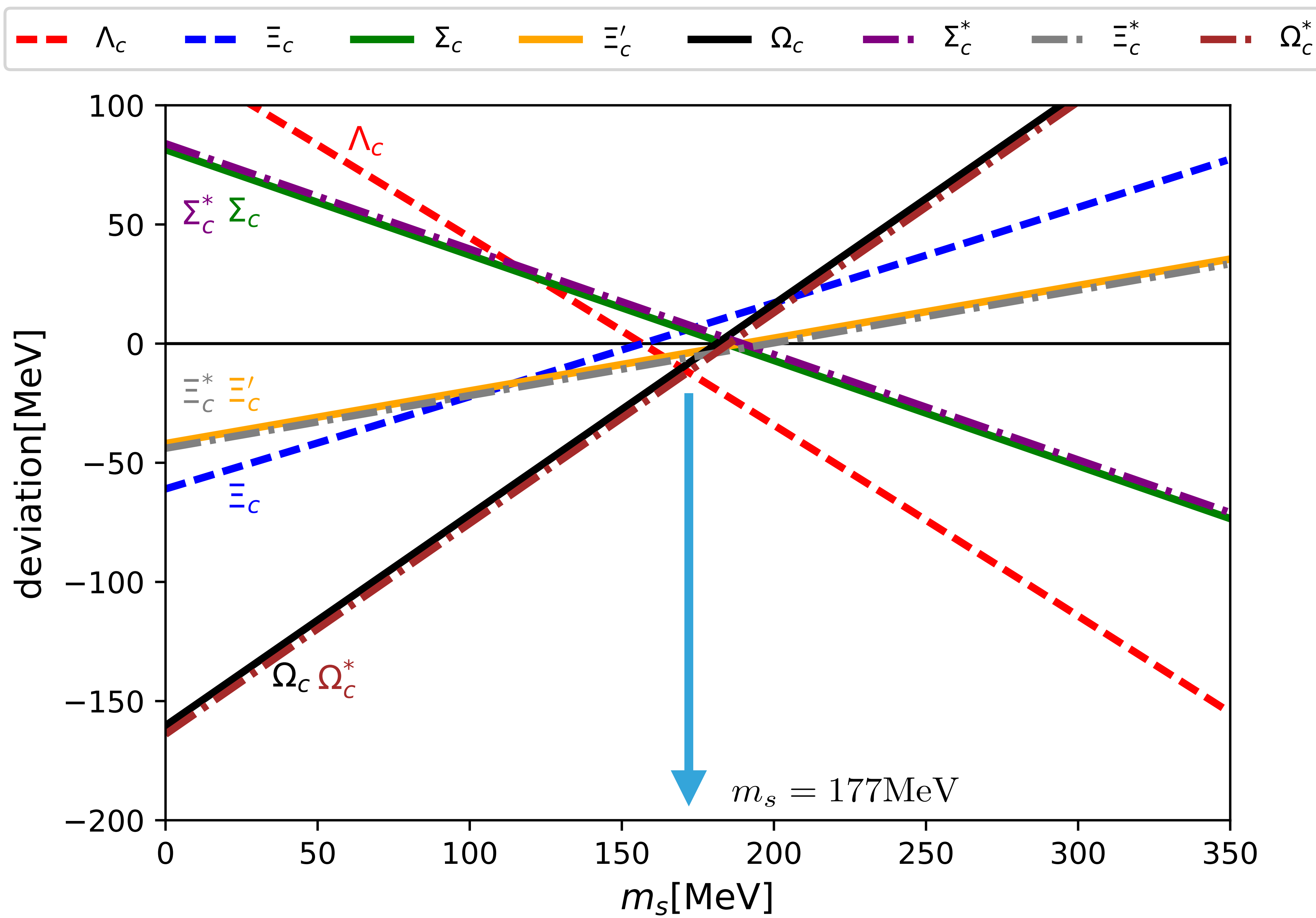
D. Diakonov, V. Y. Petrov and P. V. Pobylitsa, Nucl. Phys. **B306**, 809 (1988).

LIGHT BARYON (1st order mass correction)

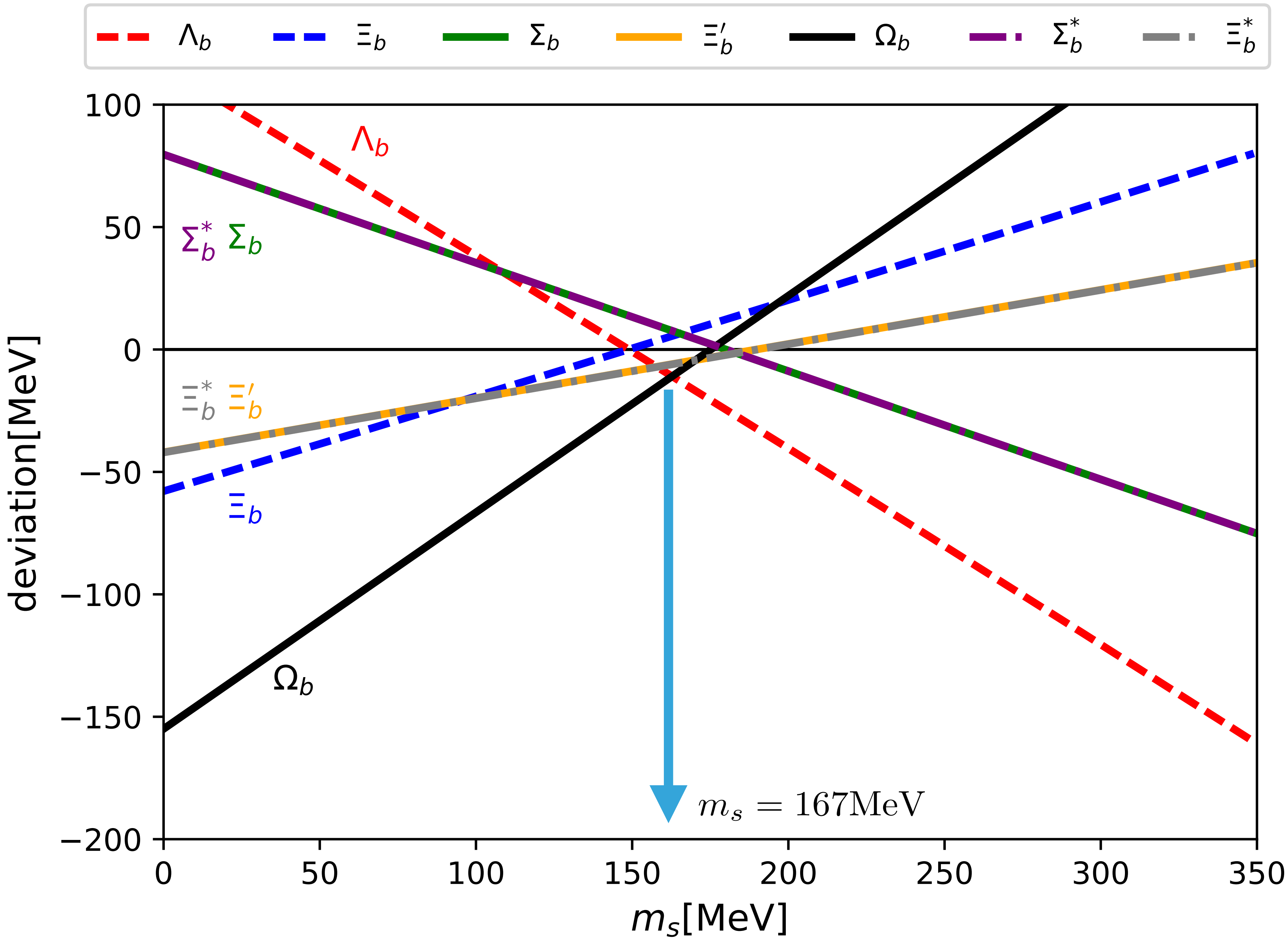


A. Blotz, D. Diakonov, K. Goeke, N. W. Park, V. Petrov and P. V. Pobylitsa, Nucl. Phys. **A555**, 765 (1993).

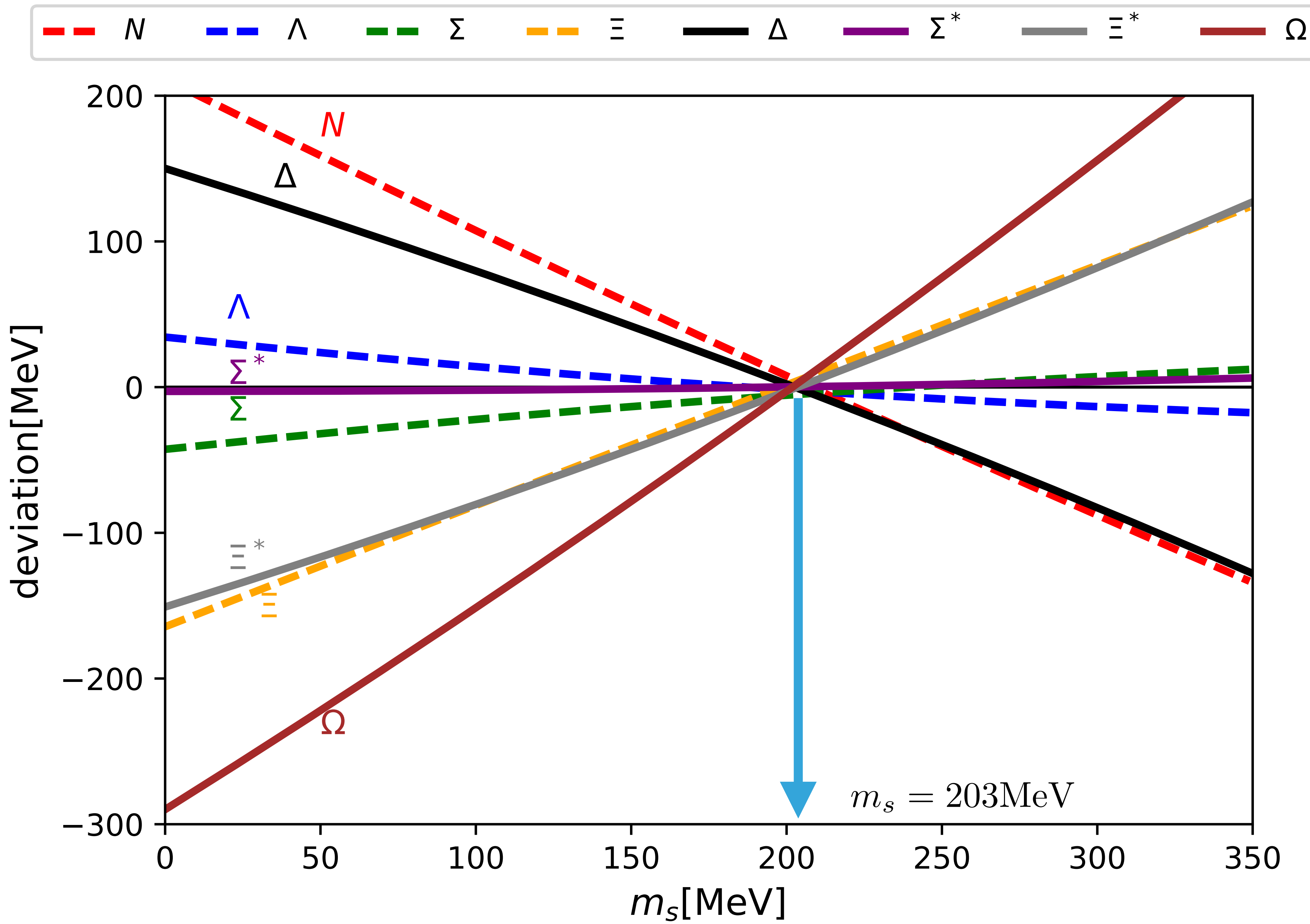
CHARMED BARYON (1st order mass correction)



BOTTOM BARYON (1st order mass correction)

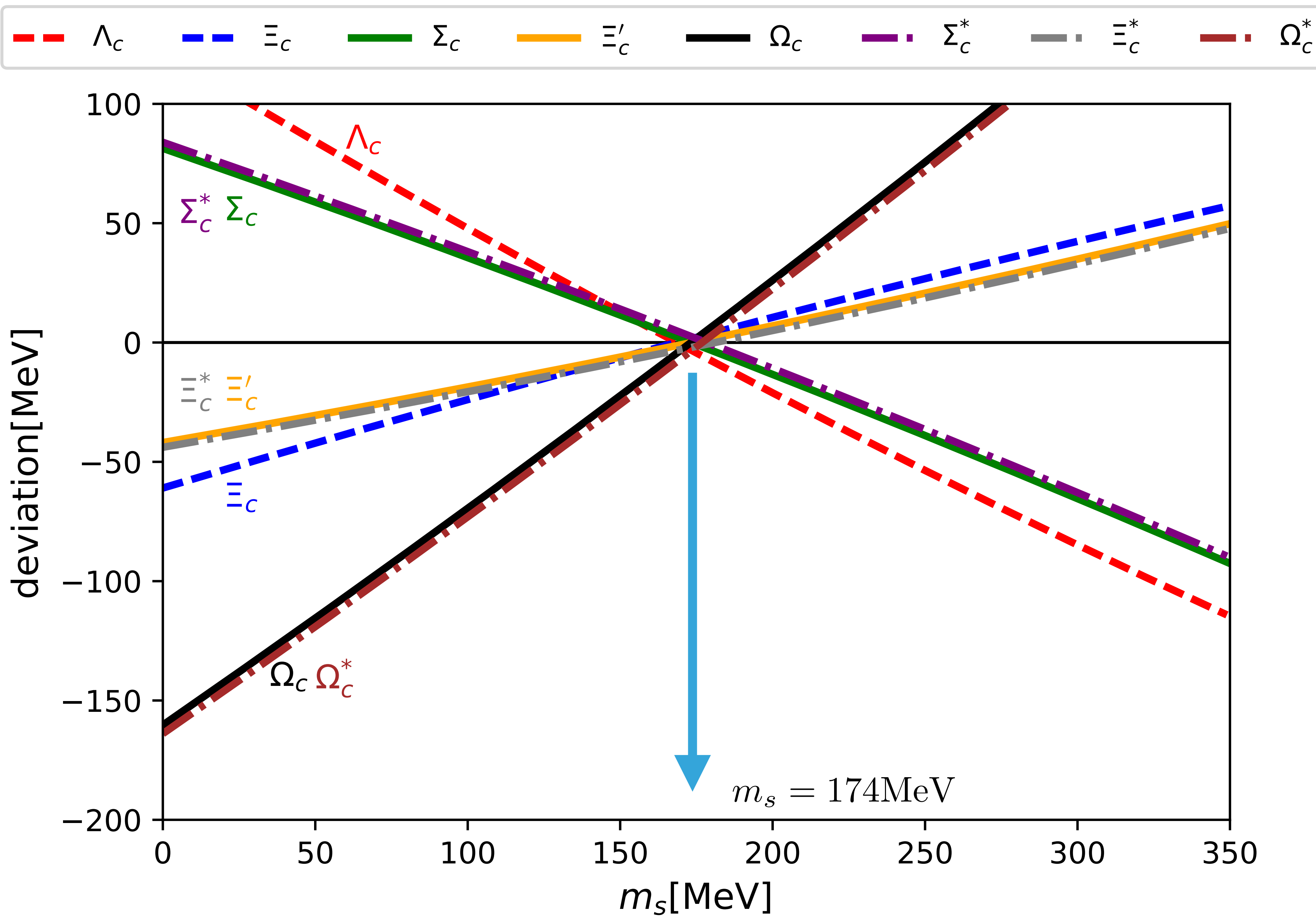


LIGHT BARYON (2nd order mass correction)

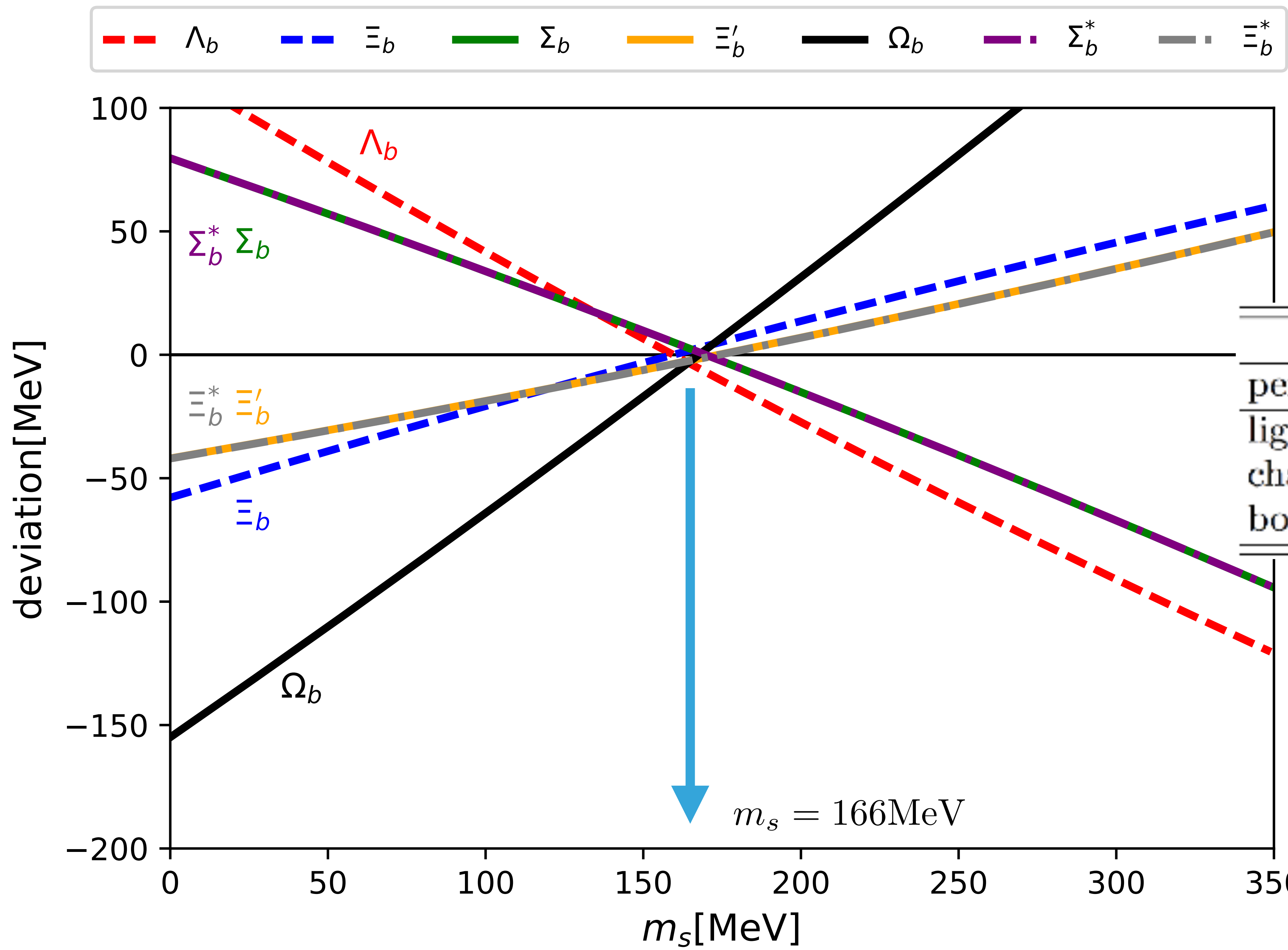


C. V. Christov, A. Blotz, H.-Ch. Kim, P. Pobylitsa, T. Watabe, T. Meissner, E. Ruiz Arriola and K. Goeke, Prog. Part. Nucl. Phys. **37**, 91 (1996).

CHARMED BARYON (2nd order mass correction)



BOTTOM BARYON (2nd order mass correction)



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

CHARMED BARYON

- The heavy baryon masses are calculated by using the determined strange current quark mass.
- The soliton mass is overestimated. Thus, instead of using it, we employ the experimental center mass, so we predict the all masses of $\overline{\mathbf{3}}$ and $\mathbf{6}$.

	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

The results obtatained are in good agreement with the experiment result !

[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^* is 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

Our prediction : $M_{\Omega_b^*} = 6066.6\ \mathrm{MeV}$

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

HEAVY PENTAQUARK

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

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2\,\mathrm{MeV}$, 95% CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		$< 2.6\,\mathrm{MeV}$, 95% CL		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\mathrm{fd}}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\mathrm{fd}}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\mathrm{fd}}$			$190 \pm 70 \pm 20$	

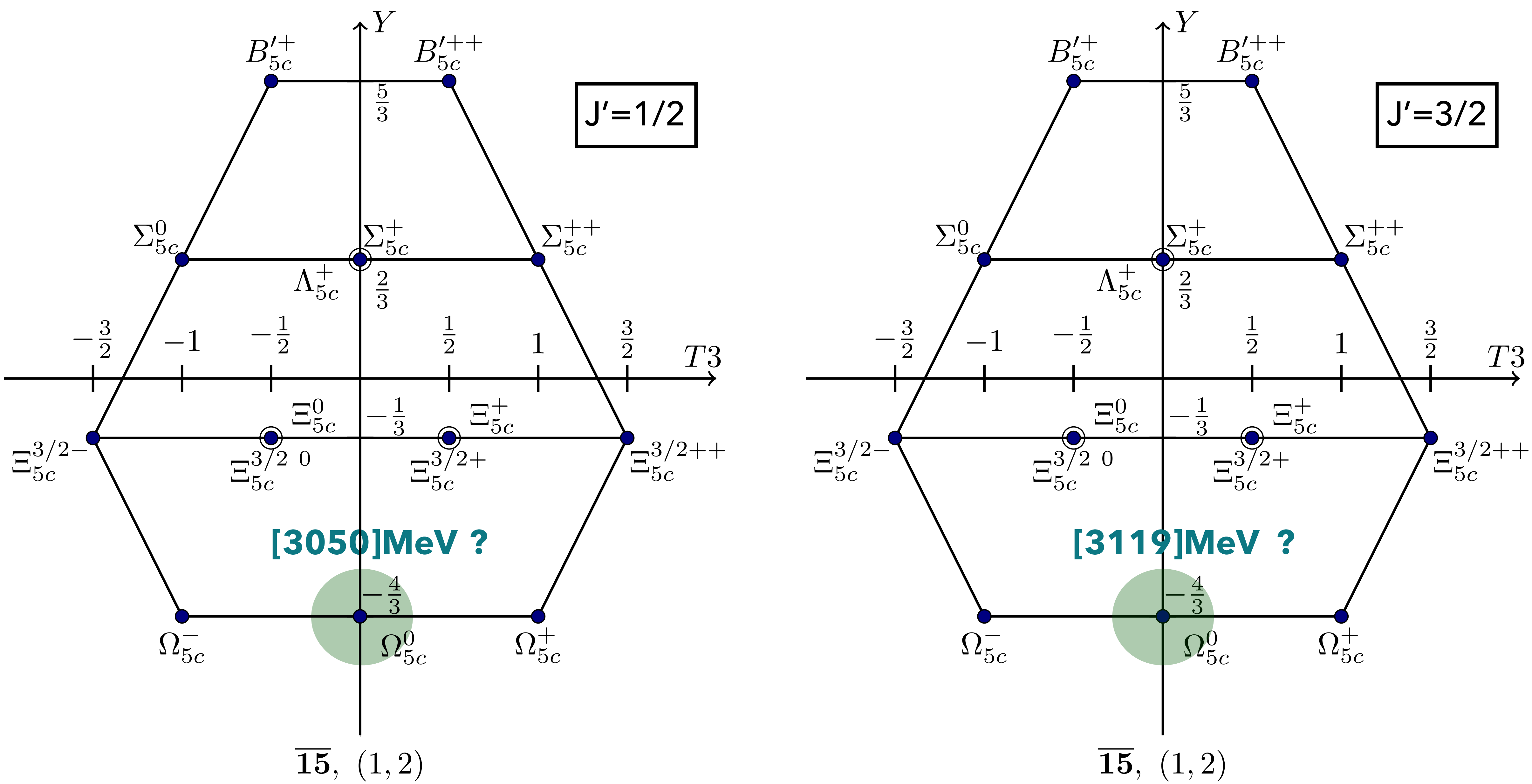
R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **118**, no. 18, 182001 (2017)

HEAVY PENTAQUARK

Prof. Hyun-Chul Kim - Possible existence of charmed exotics

The hyperfine mass splitting is determined in the charmed baryon sector.

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



	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]	

H. -Ch. Kim, M. V. Polyakov and M. Praszałowicz, Phys. Rev. **D96**, no. 1, 014009 (2017)

DOUBLY CHARMED BARYON

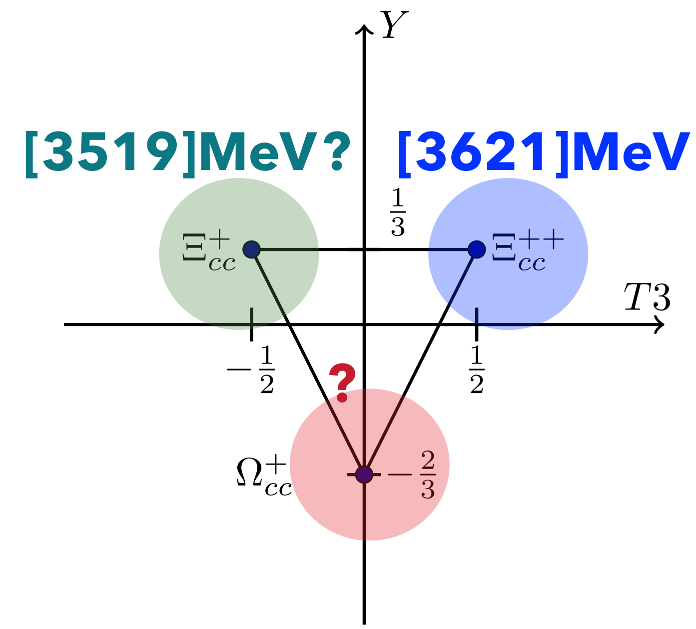
- The pion mean fields of the doubly heavy baryon is modified N_c to the $N_c - 2$

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

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

Our prediction

$$M_{\Omega_{cc}} = 3732.5\ \text{MeV}$$



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

Doubly heavy baryon	This work
I_1'[fm]	0.579
I_2'[fm]	0.280
K_1'[fm]	0.143
K_2'[fm]	0.090
N_0'[fm]	0.540
N_1'[fm]	0.348
N_2'[fm]	0.248
$\Sigma'_{\pi N}$[MeV]	36.3
α'[MeV]	-336.0
β'[MeV]	-57.6
γ'[MeV]	-26.1
$M'_{\rm sol}$[MeV]	903.7

- We investigated the mass splitting of the lowest-lying heavy baryons in a pion mean-field approach.
- We examined the dependence of the strange current quark mass on systems of heavy-quark baryons.
- We predicted the masses of particles Ω_b^{*-} and Ω_{cc}^{+} by using determined strange current quark masses and also the whole heavy pentaquark members.
- We also discussed the masses of the Ω_c^0 recently found by the LHCb Collaboration.
- Decay widths of the heavy baryons are under investigation in the chiral quark-soliton model.

THANK YOU VERY MUCH!