Static properties of light and heavy baryons

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in collaboration with
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[Joint Workshop on Hadron-Nuclear Physics and Astrophysics]

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- **Motivation and Theoretical Framework**

  (Chiral soliton model)

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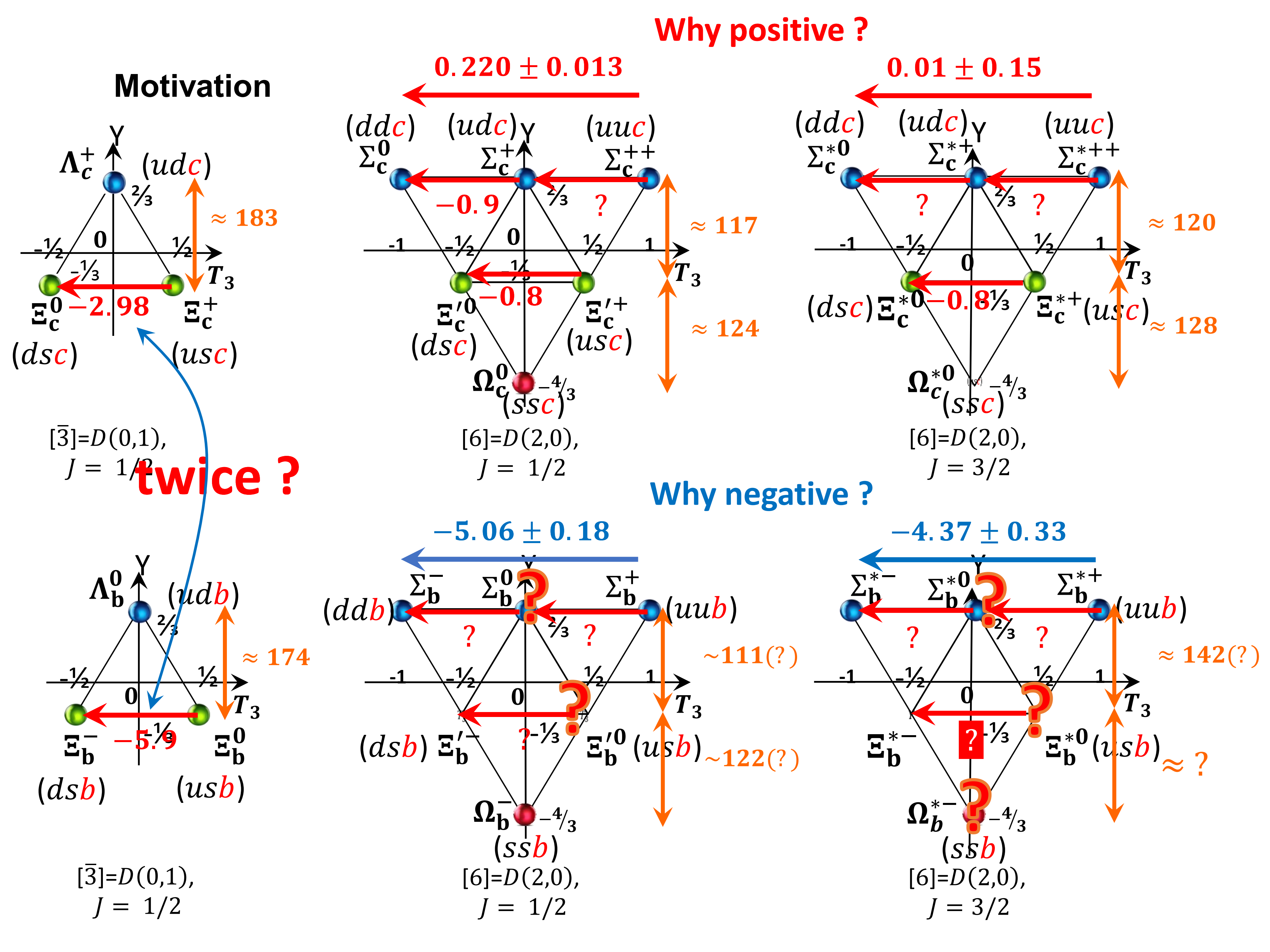


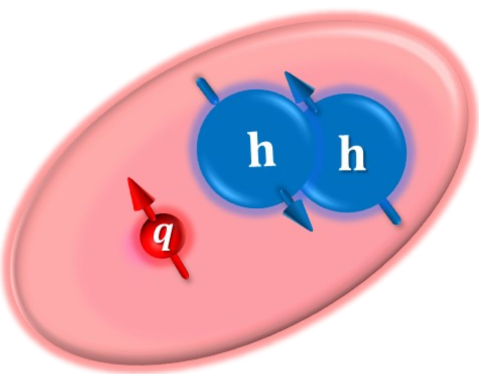
Motivation
Why positive ?
0.220 ± 0.013
0.01 ± 0.15
(udc)
(ddc)
(uuc)
(dsc)
(usc)
(ssc)
−2.98
−0.9
−0.8
≈ 183
≈ 117
≈ 124
≈ 120
≈ 128
[3̄]=D(0,1), J = 1/2
[6]=D(2,0), J = 1/2
[6]=D(2,0), J = 3/2
twice ?
Why negative ?
−5.06 ± 0.18
−4.37 ± 0.33
(udb)
(ddb)
(uub)
(dsb)
(usb)
(ssb)
−5.9
≈ 174
~111(?)
~122(?)
≈ 142(?)
≈ ?
[3̄]=D(0,1), J = 1/2
[6]=D(2,0), J = 1/2
[6]=D(2,0), J = 3/2

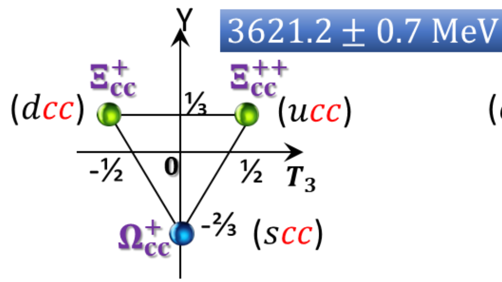
2020 Review of Particle Physics.
P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

DOUBLY CHARMED BARYONS
(C = +2)
$\Xi_{cc}^{++} = ucc$, $\Xi_{cc}^{+} = dcc$, $\Omega_{cc}^{+} = scc$

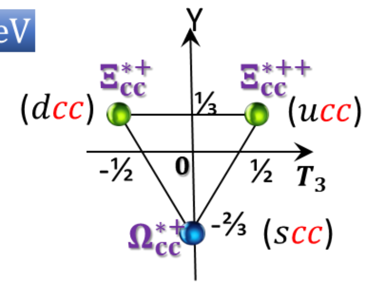
Ξ_{cc}^{++} $\quad I(J^P)$ = ?(?$^?$)

Ξ_{cc}^{++} MASS	3621.2 ± 0.7 MeV
Ξ_{cc}^{++} MEAN LIFE	$(2.56 \pm 0.27) \times 10^{-13}$ s

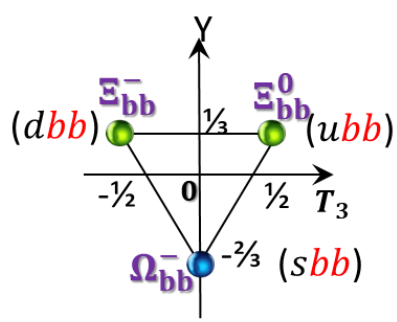




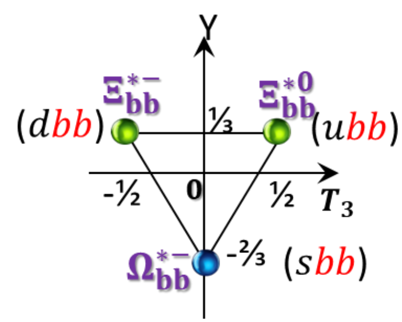
[**3**]=$D(1,0)$,
J = 1/2



[**3**]=$D(1,0)$,
J = 3/2



[**3**]=$D(1,0)$,
J = 1/2

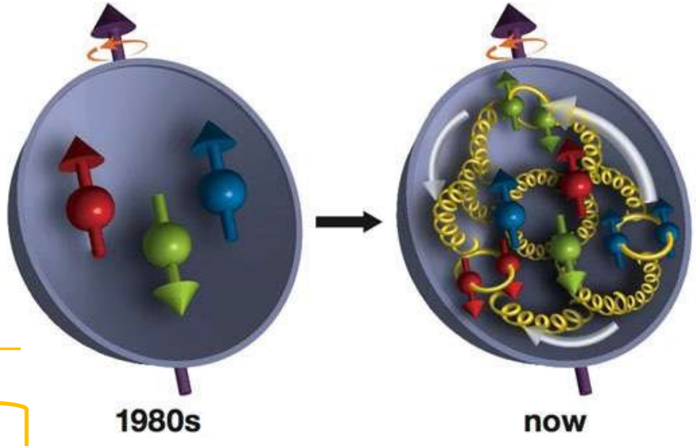


[**3**]=$D(1,0)$,
J = 3/2

- **Theoretical framework: Chiral soliton model**

Large N_c arguments allows us to consider a classical pion mean field (Witten): Relativistic Mean Field Approximation

Fig: https://phys.org/news/2017-03-proton.html



sea quarks
(pion mean fields)

The presence N_c **valence quarks** creates the **pion mean fields** and valence quarks are **self-consistently bound** by it in the **large N_c limit**.

One can put the **real-world value 3 into N_c** at the end of the calculation.

- **Theoretical framework: Chiral soliton model**

: Effective and relativistic low energy theory

: **Large N_c limit : meson fields**
→ Soliton (No quark degree of freedom)

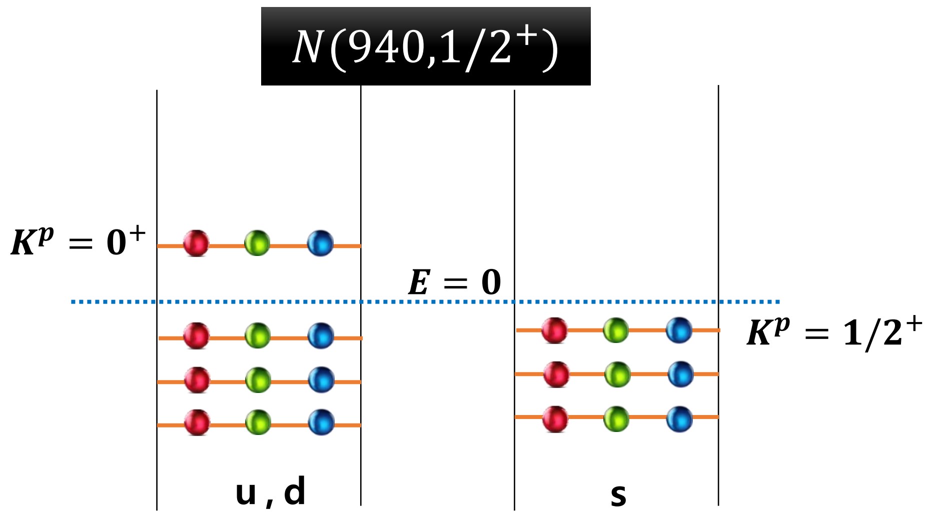
: Quantizing SU(3) meson fields rotated in flavor and spin space
→ Collective Hamiltonian, model baryon states

Hedgehog Ansatz:

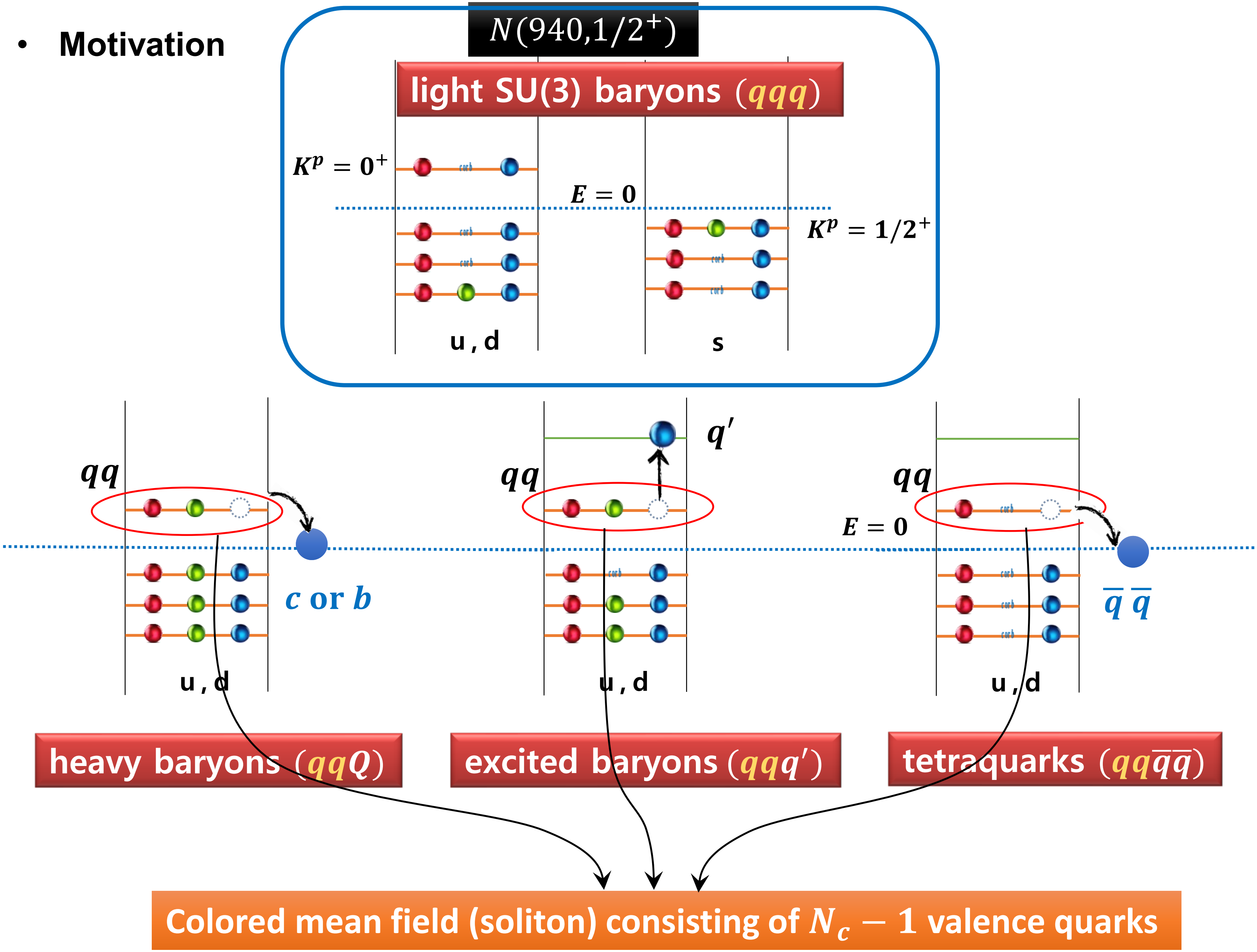
$$U_0 = \begin{bmatrix} e^{i\boldsymbol{n}\cdot\boldsymbol{\tau}\,P(r)} & 0 \\ 0 & 1 \end{bmatrix}$$

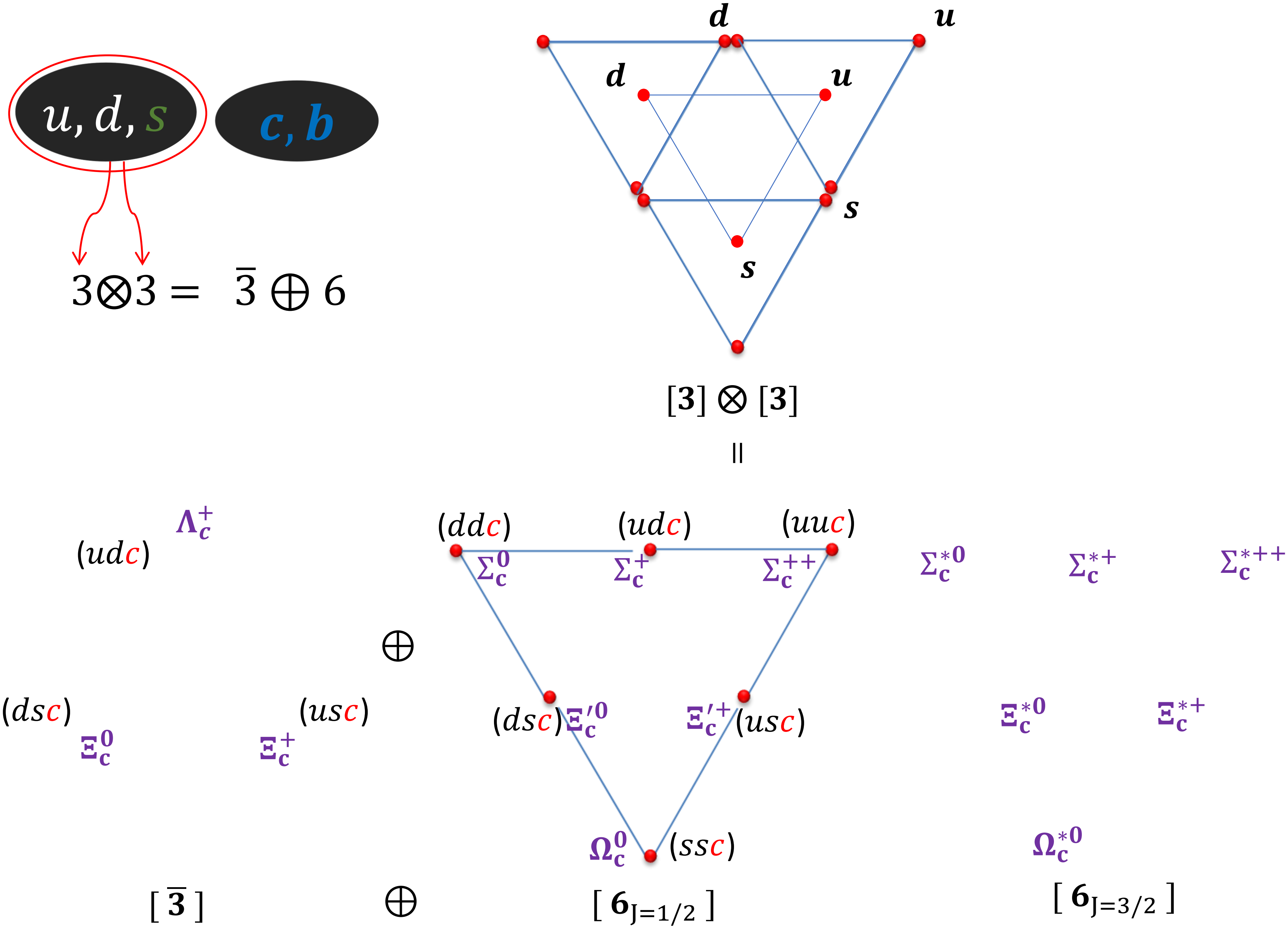
SU(2) Witten imbedding

into **SU(3)**: SU(2) X U(1)

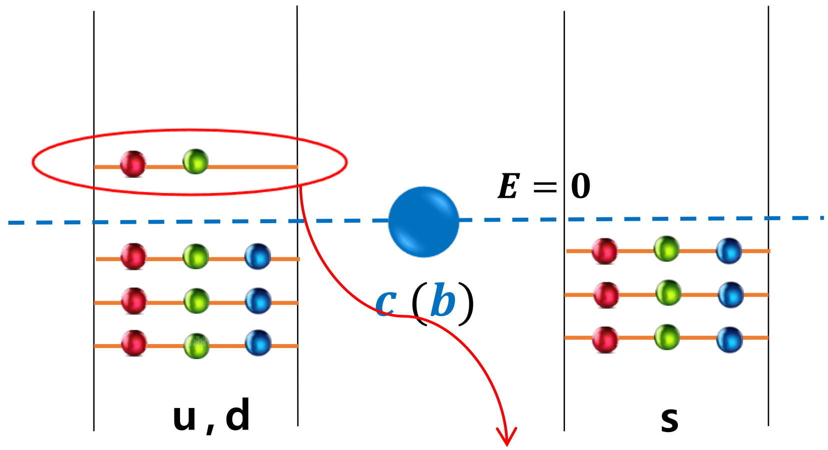


- **Motivation**

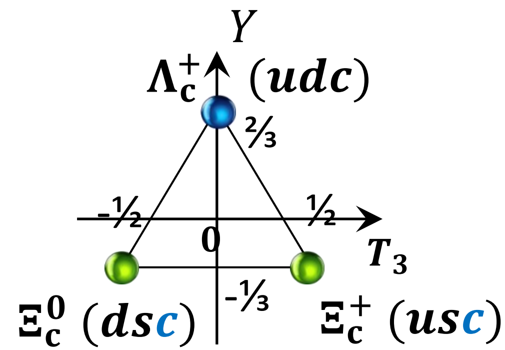

$N(940, 1/2^+)$
light SU(3) baryons (qqq)
$K^p = 0^+$
$E = 0$
$K^p = 1/2^+$
u , d
s
qq
c or b
q'
$E = 0$
$\bar{q}\,\bar{q}$
heavy baryons (qqQ)
excited baryons (qqq')
tetraquarks $(qq\bar{q}\bar{q})$
Colored mean field (soliton) consisting of $N_c - 1$ valence quarks



u, d, s
c, b
3⊗3 = 3̄ ⊕ 6
d
u
d
u
s
s
[3] ⊗ [3]
=
(udc)
Λc+
(dsc)
(usc)
Ξc0
Ξc+
[3̄]
⊕
⊕
(ddc)
(udc)
(uuc)
Σc0
Σc+
Σc++
(dsc)
Ξ'c0
Ξ'c+
(usc)
Ωc0
(ssc)
[6J=1/2]
Σc*0
Σc*+
Σc*++
Ξc*0
Ξc*+
Ωc*0
[6J=3/2]



Mean meson field : $N_c - 1$ valence quarks



For $S_z = +1/2$

$$\begin{cases} \Psi_{B_Q}^{\left(\mathcal{R}_0^{1/2}\right)} = \chi_\uparrow \psi_{B\left(-\frac{2}{3},0,0\right)}^{(\mathcal{R})}, \\ \Psi_{B_Q}^{\left(\mathcal{R}_1^{1/2}\right)} = -\sqrt{\frac{1}{3}}\chi_\uparrow \psi_{B\left(-\frac{2}{3},1,0\right)}^{(\mathcal{R})} + \sqrt{\frac{2}{3}}\chi_\downarrow \psi_{B\left(-\frac{2}{3},1,1\right)}^{(\mathcal{R})} \\ \Psi_{B_Q}^{\left(\mathcal{R}_1^{3/2}\right)} = \sqrt{\frac{2}{3}}\chi_\uparrow \psi_{B\left(-\frac{2}{3},1,0\right)}^{(\mathcal{R})} + \sqrt{\frac{1}{3}}\chi_\downarrow \psi_{B\left(-\frac{2}{3},1,1\right)}^{(\mathcal{R})} \end{cases}$$

: ψ from light baryons

$$\bar{\Psi}\gamma^\mu \frac{\lambda^a}{2}\Psi A_\mu^a \sim \Psi^\dagger \frac{\lambda^a}{2}\Psi A_0^a - \frac{1}{m_Q}\Psi^\dagger \vec{\sigma}\frac{\lambda^a}{2}\Psi \cdot \left(\vec{\nabla} \times A^a\right)$$

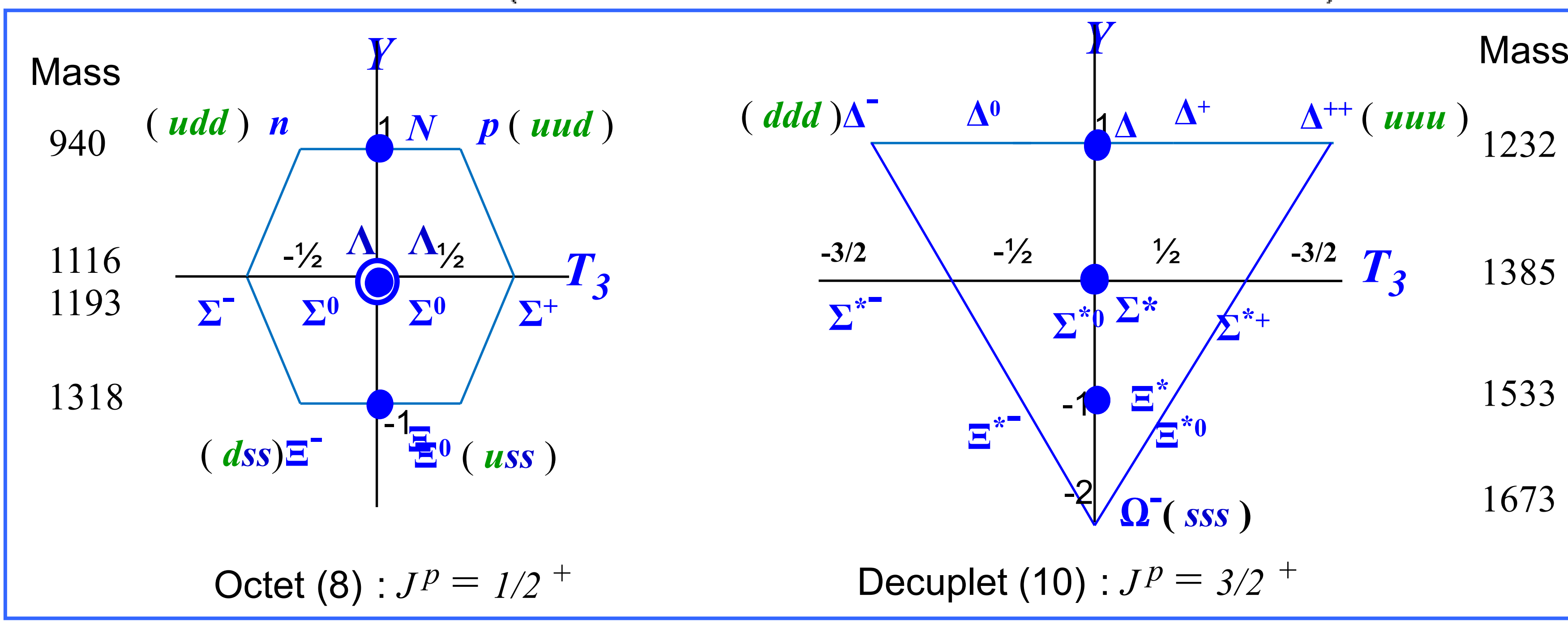
Heavy quark spin-flip is not taken into account : Heavy quark (spin) symmetry

- **Theoretical framework: Chiral soliton model (Collective hamiltonian)**

$$H_{\rm sym} = M_{\rm cl} + \frac{1}{2}\left(\frac{1}{I_1} - \frac{1}{I_2}\right)\sum_{i=1}^{3} R_i R_i + \frac{1}{2}\frac{1}{I_2}\sum_{i=1}^{8} R_i R_i - \frac{3}{8I_2}$$

$$H_{\rm sb} = (m_{\rm s} - \hat{m})\left(\alpha D^{(8)}_{88}(\mathcal{R}) + \beta \hat{Y} + \frac{1}{\sqrt{3}}\gamma \sum_{i=1}^{3} D^{(8)}_{8i}(\mathcal{R})\,\hat{J}_i\right)$$

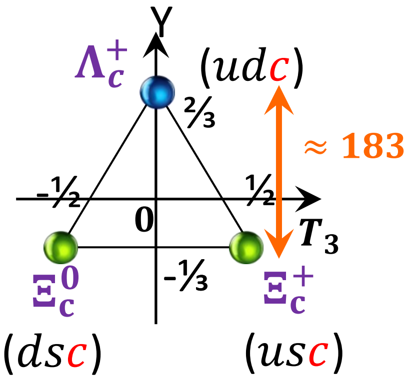
$$+ (m_{\rm d} - m_{\rm u})\left(\frac{\sqrt{3}}{2}\alpha D^{(8)}_{38}(\mathcal{R}) + \beta \hat{T}_3 + \frac{1}{2}\gamma \sum_{i=1}^{3} D^{(8)}_{3i}(\mathcal{R})\,\hat{J}_i\right)$$



SU(3) flavor symmetry breaking **+ Isospin symmetry breaking**

Recent results for heavy baryons in a chiral soliton model

- **Mass splittings from SU(3) flavor symmetry breakings**



$[\bar{3}]=D(0,1)$,
$J = 1/2$

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

where

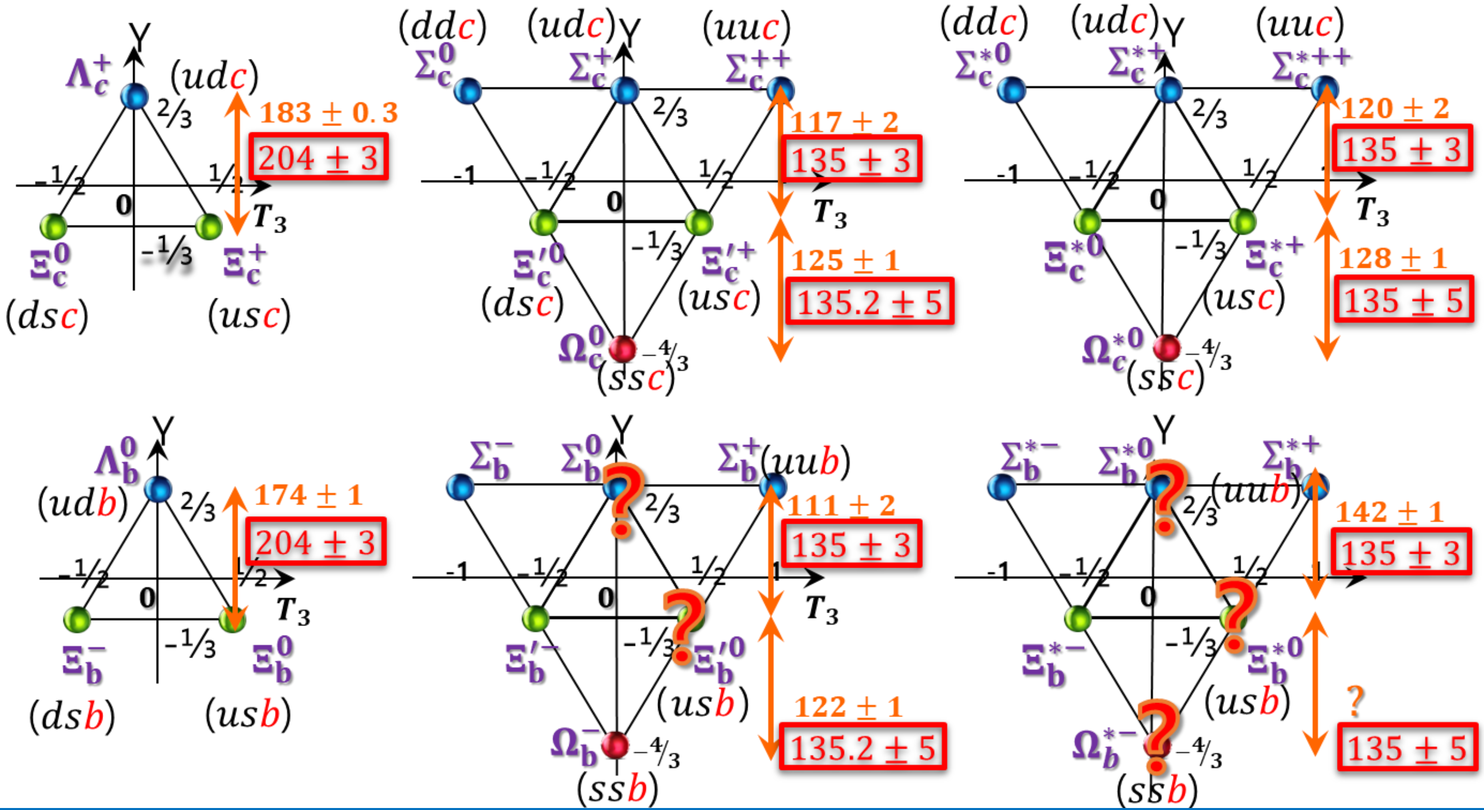
$$\alpha = -\frac{2}{3}\sigma - \beta Y', \quad \Rightarrow \quad \tilde{\alpha} = \frac{N_c - 1}{N_c}\left(-\frac{2}{3}\sigma - \beta Y'\right),$$

$$\beta = -\frac{K_2}{I_2}, \quad \Rightarrow \quad \beta = -\frac{K_2}{I_2},$$

$$\gamma = \frac{2K_1}{I_1} + 2\beta. \quad \Rightarrow \quad \gamma = \frac{2K_1}{I_1} + 2\beta.$$

For $a, b = 4,5,6,7$

$$K_2 = K_{ab}^{\rm val} = \frac{N_c}{2}\sum_{n\neq{\rm val}} \frac{\langle n|\lambda_a|{\rm val}\rangle\langle {\rm val}|\lambda_b\gamma_0|n\rangle}{E_n - E_{\rm val}}$$



This results are from the soliton for the light baryons with a factor $(N_c - 1)/N_c$

$\mathcal{R}_J^Q$	B_c	Mass	Experiment [17]	Deviation ξ_c
$\bar{\mathbf{3}}_{1/2}^c$	Λ_c	2272.5 ± 2.3	2286.5 ± 0.1	-0.006
	Ξ_c	2476.3 ± 1.2	2469.4 ± 0.3	0.003
	Σ_c	2445.3 ± 2.5	2453.5 ± 0.1	-0.003
$\mathbf{6}_{1/2}^c$	Ξ_c'	2580.5 ± 1.6	2576.8 ± 2.1	0.001
	Ω_c	2715.7 ± 4.5	2695.2 ± 1.7	0.008
	Σ_c^*	2513.4 ± 2.3	2518.1 ± 0.8	-0.002
$\mathbf{6}_{3/2}^c$	Ξ_c^*	2648.6 ± 1.3	2645.9 ± 0.4	0.001
	Ω_c^*	2783.8 ± 4.5	2765.9 ± 2.0	0.006

$\mathcal{R}_J^Q$	B_b	Mass	Experiment [17]	Deviation ξ_b
$\bar{\mathbf{3}}_{1/2}^b$	Λ_b	5599.3 ± 2.4	5619.5 ± 0.2	-0.004
	Ξ_b	5803.1 ± 1.2	5793.1 ± 0.7	0.002
	Σ_b	5804.3 ± 2.4	5813.4 ± 1.3	-0.002
$\mathbf{6}_{1/2}^b$	Ξ_b'	5939.5 ± 1.5	5935.0 ± 0.05	0.001
	Ω_b	6074.7 ± 4.5	6048.0 ± 1.9	0.004
	Σ_b^*	5824.6 ± 2.3	5833.6 ± 1.3	-0.002
$\mathbf{6}_{3/2}^b$	Ξ_b^*	5959.8 ± 1.2	5955.3 ± 0.1	0.001
	Ω_b^*	6095.0 ± 4.4	–	–

G.S Yang et al., Phys.Rev.D 94, 071502(R) (2016)

Recent results for heavy baryons in a chiral soliton model

- **Strong decay widths of heavy baryons**

$$\hat{g}_1^{(0)} = a_1 D_{\varphi 3}^{(8)} + a_2 d_{3bc} D_{\varphi b}^{(8)} \hat{J}_c + \frac{a_3}{\sqrt{3}} D_{\varphi 8}^{(8)} \hat{J}_3,$$

$$= \left[M_3 - \frac{2iQ_{12}}{I_1}\right] D_{X3}^{(8)} + \left[-\frac{4M_{44}}{I_2}\right] d_{pq3} D_{Xp}^{(8)} \hat{J}_q + \left[-\frac{2M_{83}}{I_1}\right] \frac{1}{\sqrt{3}} D_{X8}^{(8)} \hat{J}_3 + \cdots$$

where

$$M_{3,\,\mathrm{val}} = N_c \langle v | \gamma_0 \gamma_3 \gamma_5 \lambda_3 | v \rangle ,$$

$$Q_{bc,\,\mathrm{val}} = \frac{N_c}{2} \sum_n \frac{\langle n | \sigma_3 \lambda_b | v \rangle \langle v | \lambda_c | n \rangle}{E_n - E_v} \mathrm{sign} E_n,$$

$$M_{bc} = \frac{N_c}{4} \sum_{n,m} \langle n | \sigma_3 \lambda_b | m \rangle \langle m | \lambda_c | n \rangle \frac{1}{2} \frac{\mathrm{sign}(E_n - \mu) - \mathrm{sign}(E_m - \mu)}{E_n - E_m}$$

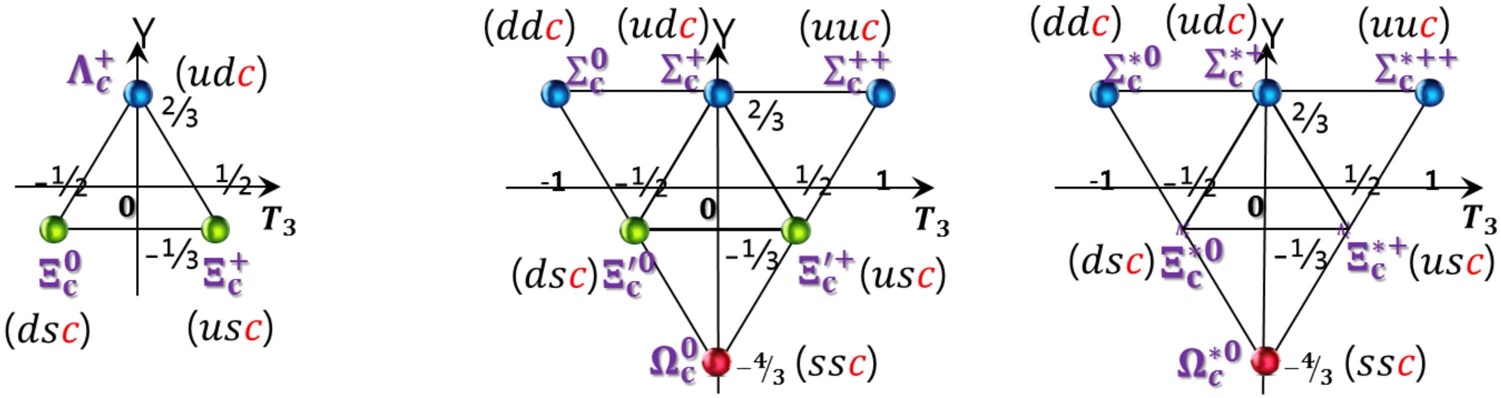
$N_c - 1$

For heavy baryons

$$M_{3,\,\mathrm{val}} = \frac{N_c - 1}{N_c} \boxed{N_c \langle v | \gamma_0 \gamma_3 \gamma_5 \lambda_3 | v \rangle}$$

from octet baryons

➢ Strong decay widths of charmed baryons



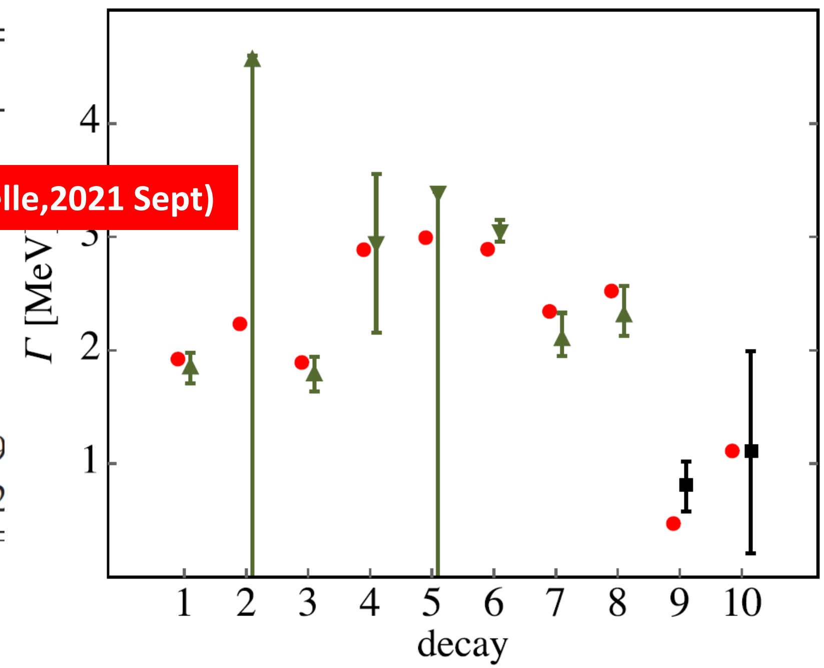
$[\bar{3}]=D(0,1)$, $J = 1/2$

$[6]=D(2,0)$, $J = 1/2$

$[6]=D(2,0)$, $J = 3/2$

#	Decay	This work	Exp.
1	$\Sigma_c^{++}(\mathbf{6}_1, 1/2) \to \Lambda_c^+(\bar{\mathbf{3}}_0, 1/2) + \pi^+$	1.93	$1.89^{+0.09}_{-0.18}$
2	$\Sigma_c^{+}(\mathbf{6}_1, 1/2) \to \Lambda_c^+(\bar{\mathbf{3}}_0, 1/2) + \pi^0$	2.24	2.3 ± 0.3(Belle,2021 Sept)
3	$\Sigma_c^{0}(\mathbf{6}_1, 1/2) \to \Lambda_c^+(\bar{\mathbf{3}}_0, 1/2) + \pi^-$	1.90	$1.83^{+0.11}_{-0.19}$
4	$\Sigma_c^{++}(\mathbf{6}_1, 3/2) \to \Lambda_c^+(\bar{\mathbf{3}}_0, 1/2) + \pi^+$	14.47	$14.78^{+0.30}_{-0.19}$
5	$\Sigma_c^{+}(\mathbf{6}_1, 3/2) \to \Lambda_c^+(\bar{\mathbf{3}}_0, 1/2) + \pi^0$	15.02	<17
6	$\Sigma_c^{0}(\mathbf{6}_1, 3/2) \to \Lambda_c^+(\bar{\mathbf{3}}_0, 1/2) + \pi^-$	14.49	$15.3^{+0.4}_{-0.5}$
7	$\Xi_c^{+}(\mathbf{6}_1, 3/2) \to \Xi_c(\bar{\mathbf{3}}_0, 1/2) + \pi$	2.35	2.14 ± 0.19
8	$\Xi_c^{0}(\mathbf{6}_1, 3/2) \to \Xi_c(\bar{\mathbf{3}}_0, 1/2) + \pi$	2.53	2.35 ± 0.22

Yang, et al., Phys.Rev.D 96 (2017) 094021



Light quarks govern their structure of singly heavy baryons.

PHYSICAL REVIEW D **104,** 052003 (2021)

Measurement of the masses and widths of the $\Sigma_c(2455)^+$ and $\Sigma_c(2520)^+$ baryons

(Belle Collaboration)

Measurements of the masses of all members of the two isotriplets allow tests of models of isospin mass splittings. In the model of Yang and Kim [4], for instance, the mass splittings from the following four sources add: the electromagnetic corrections due to the light quarks, the differences of the masses of the *u* and *d* quarks, the hyperfine interactions between the light quarks, and the Coulomb interactions between the soliton and charm quark. Most

Physics Letters B 808 (2020) 135619

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Isospin mass differences of singly heavy baryons

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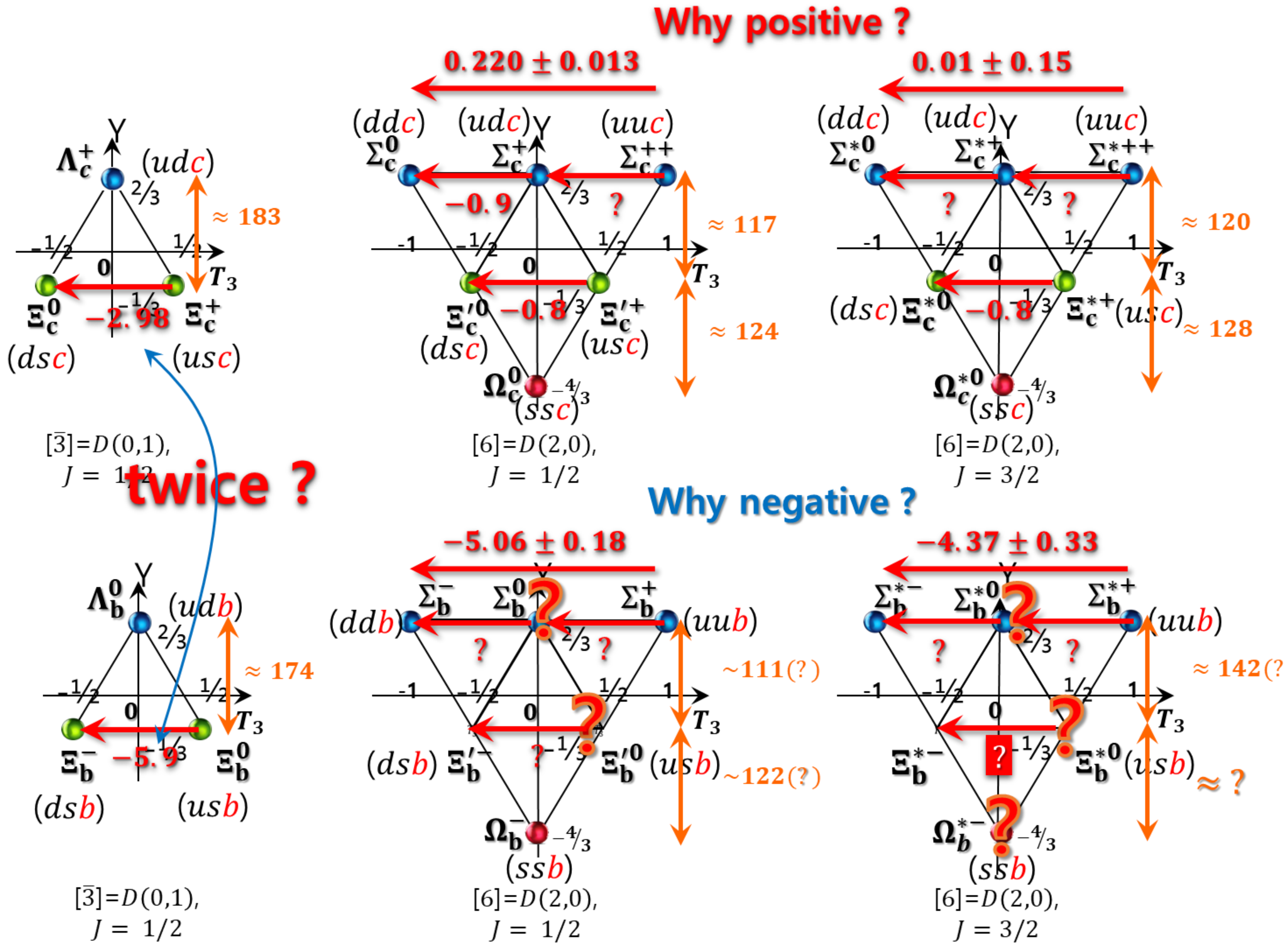
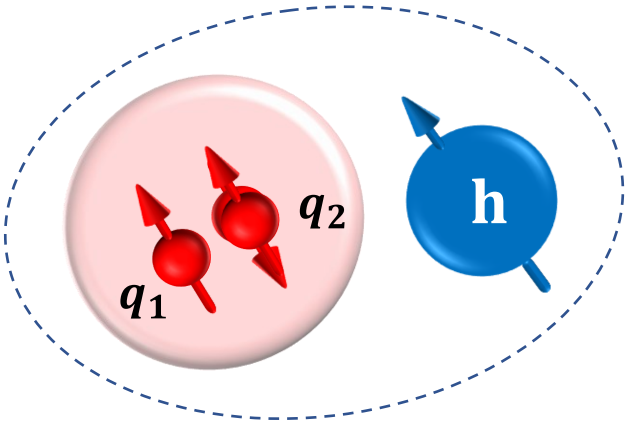
Motivation for isospin mass differences of singly heavy baryons

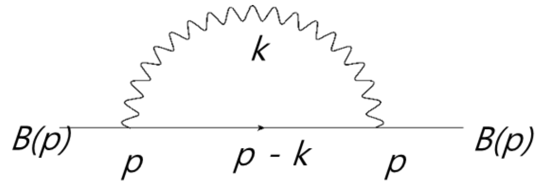


$$\Delta M_{B_h}^{\text{total}} = \Delta M_{\text{sol}}^{\text{EM}} + \Delta M_{sb}^{iso} + \Delta M_{\text{hf}} + \Delta M_{\text{sol-h}}^{\text{Coul}}$$



- EM self-energy for a soliton

$$\Delta M_{\text{sol}}^{\text{EM}} =$$



G. S. Yang, et al., Phys. Lett. B 695, 214 (2011)

- Hadronic contributions from m_d-m_u

$$\Delta M_{\text{sb}}^{\text{iso}} = H_{\text{sb}}^{\text{iso}} = (m_d - m_u)\left(\frac{\sqrt{3}}{2}\boldsymbol{\alpha} D_{38}^{(8)} + \boldsymbol{\beta}\hat{T}_3 + \frac{\boldsymbol{\gamma}}{2}\sum_{i=1}^{3} D_{3i}^{(8)}\hat{J}_i\right)$$

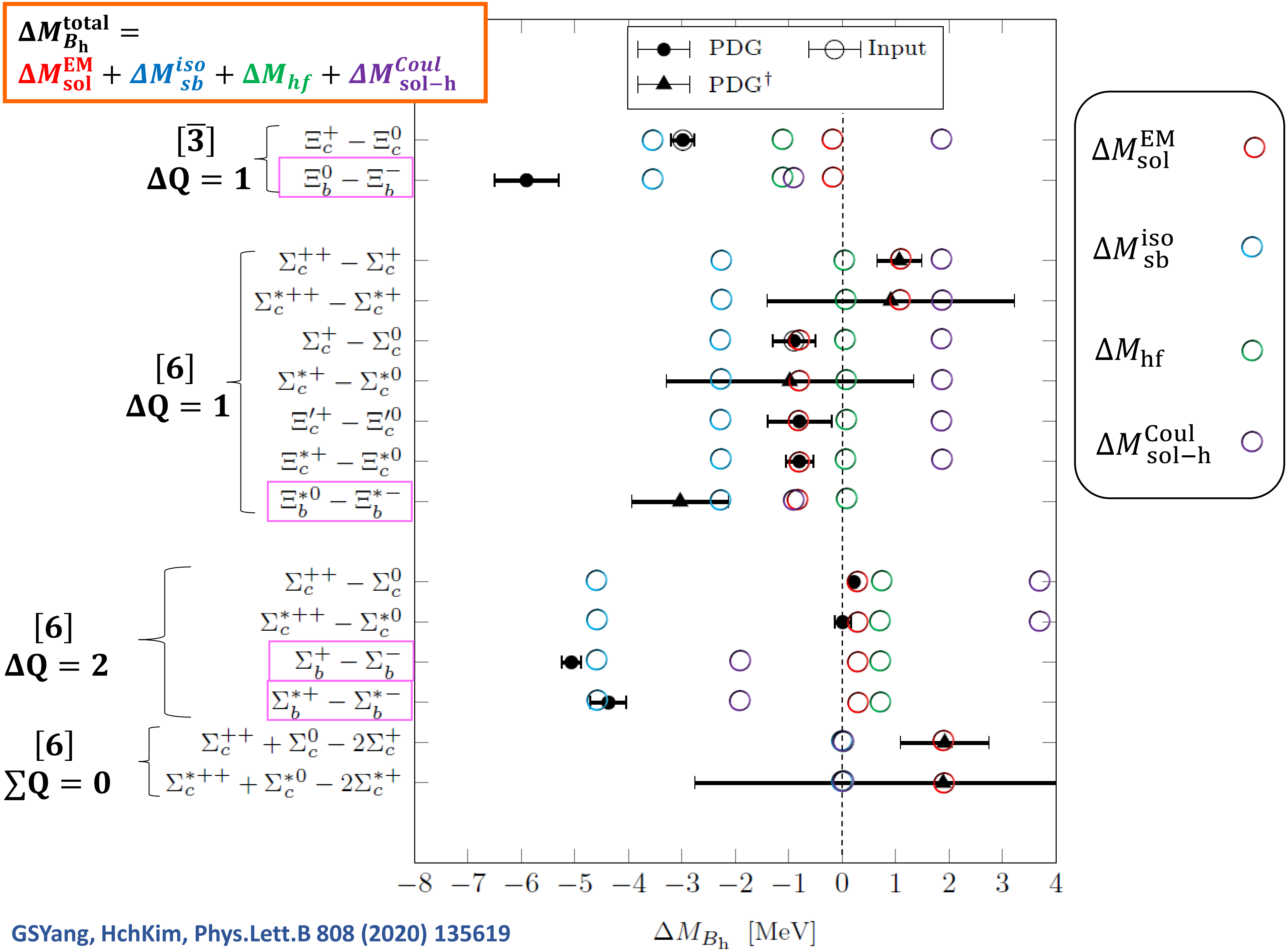
with $\boldsymbol{N_c - 1}$

- Strong hyperfine interaction for the light quarks inside a heavy baryon

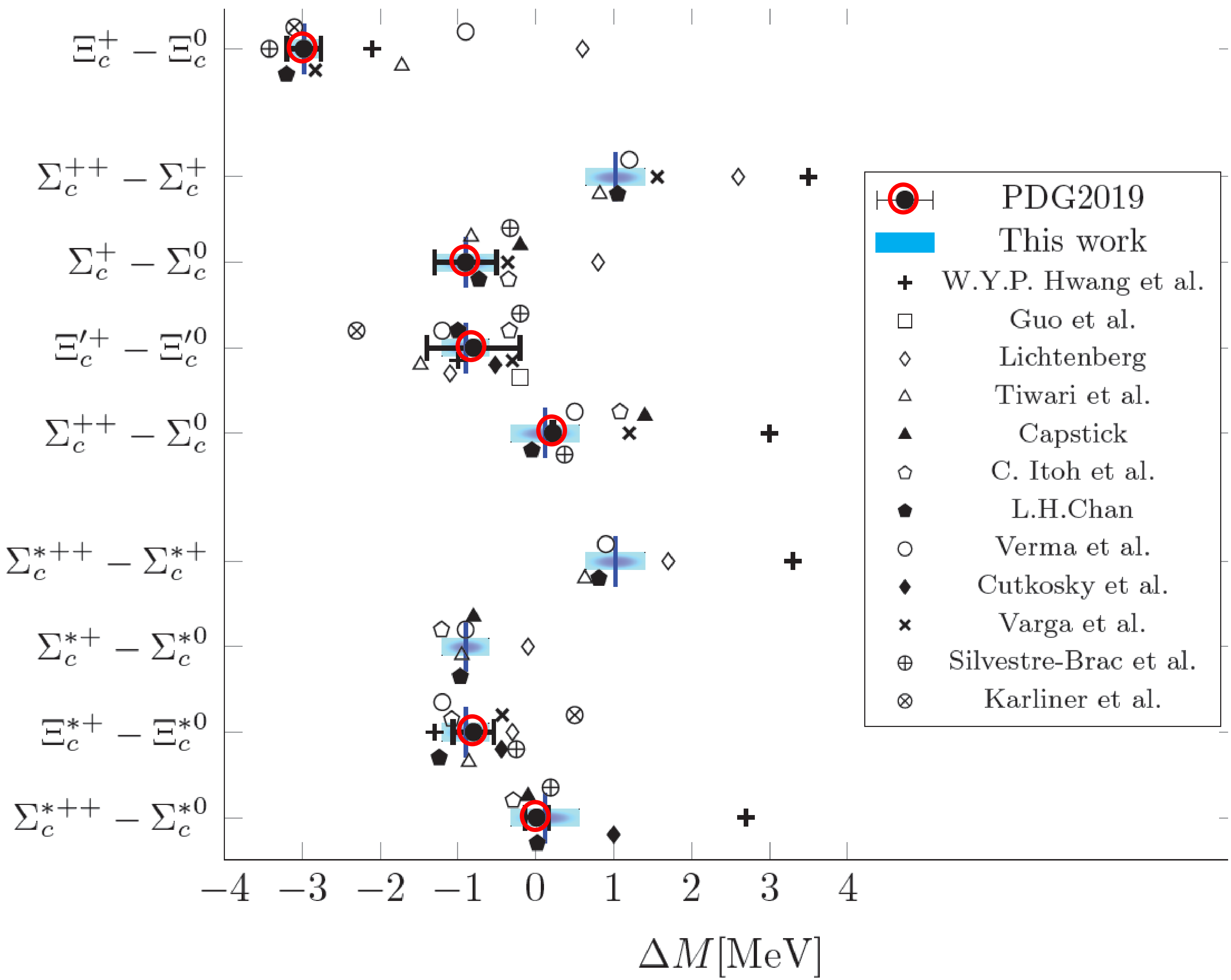
$$\Delta M_{\text{hf}} = \delta^{\text{hf}}\, \boldsymbol{S_1} \cdot \boldsymbol{S_2}$$

- Coulomb interaction between a soliton and a heavy quark

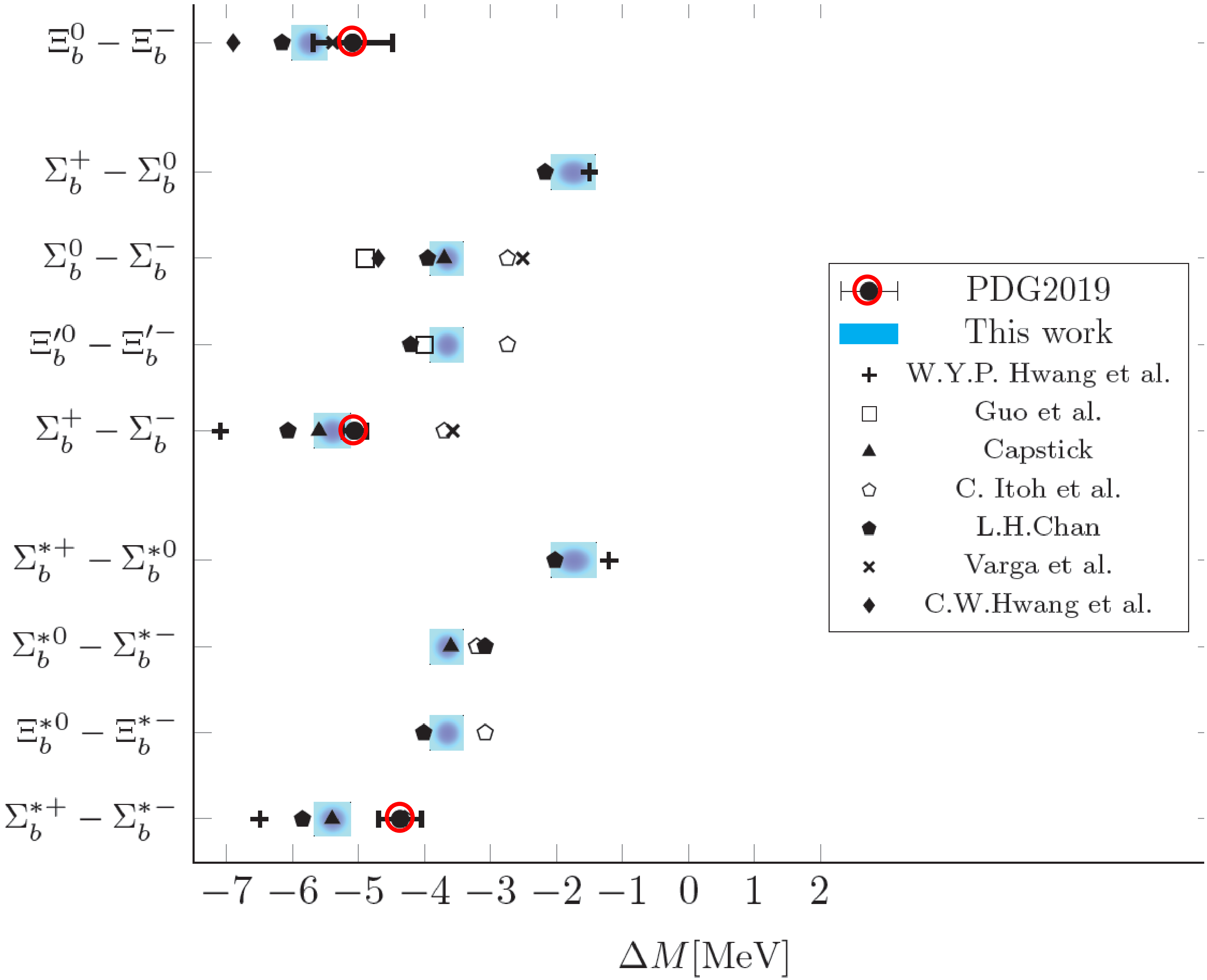
$$\Delta M_{\text{sol-h}}^{\text{Coul}} = \alpha_{\text{sol-h}}\, \hat{Q}_{\text{sol}}\hat{Q}_{\text{h}}$$



GSYang, HchKim, Phys.Lett.B 808 (2020) 135619



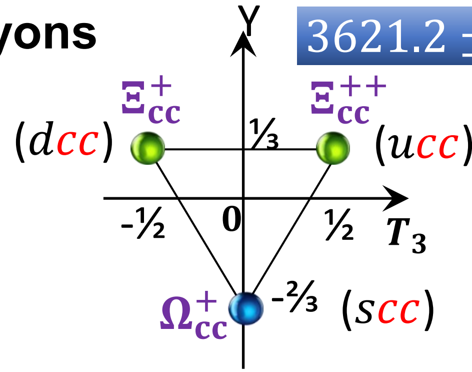
$\Xi_c^+ - \Xi_c^0$
$\Sigma_c^{++} - \Sigma_c^+$
$\Sigma_c^+ - \Sigma_c^0$
$\Xi_c^{\prime +} - \Xi_c^{\prime 0}$
$\Sigma_c^{++} - \Sigma_c^0$
$\Sigma_c^{*++} - \Sigma_c^{*+}$
$\Sigma_c^{*+} - \Sigma_c^{*0}$
$\Xi_c^{*+} - \Xi_c^{*0}$
$\Sigma_c^{*++} - \Sigma_c^{*0}$
PDG2019
This work
W.Y.P. Hwang et al.
Guo et al.
Lichtenberg
Tiwari et al.
Capstick
C. Itoh et al.
L.H.Chan
Verma et al.
Cutkosky et al.
Varga et al.
Silvestre-Brac et al.
Karliner et al.
−4 −3 −2 −1 0 1 2 3 4
ΔM[MeV]



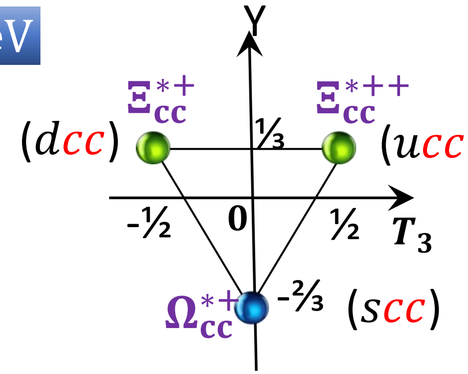
$\Xi_b^0 - \Xi_b^-$
$\Sigma_b^+ - \Sigma_b^0$
$\Sigma_b^0 - \Sigma_b^-$
$\Xi_b^{\prime 0} - \Xi_b^{\prime -}$
$\Sigma_b^+ - \Sigma_b^-$
$\Sigma_b^{*+} - \Sigma_b^{*0}$
$\Sigma_b^{*0} - \Sigma_b^{*-}$
$\Xi_b^{*0} - \Xi_b^{*-}$
$\Sigma_b^{*+} - \Sigma_b^{*-}$
PDG2019
This work
W.Y.P. Hwang et al.
Guo et al.
Capstick
C. Itoh et al.
L.H.Chan
Varga et al.
C.W.Hwang et al.
−7 −6 −5 −4 −3 −2 −1 0 1 2
ΔM [MeV]

- **Doubly heavy baryons**

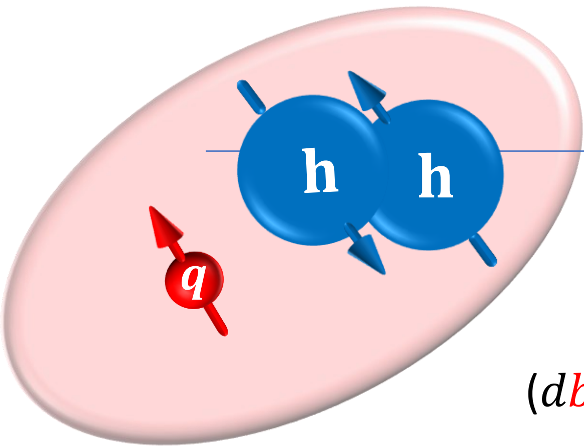
3621.2 ± 0.7 MeV

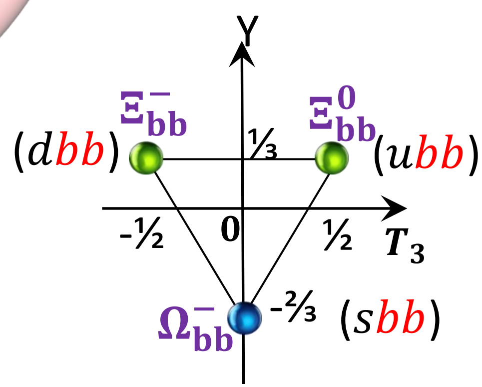


[**3**]=$D(1,0)$,
$J = 1/2$

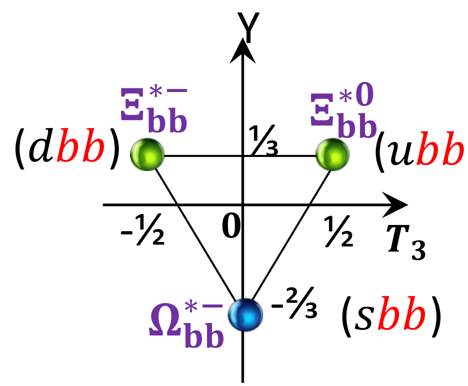


[**3**]=$D(1,0)$,
$J = 3/2$

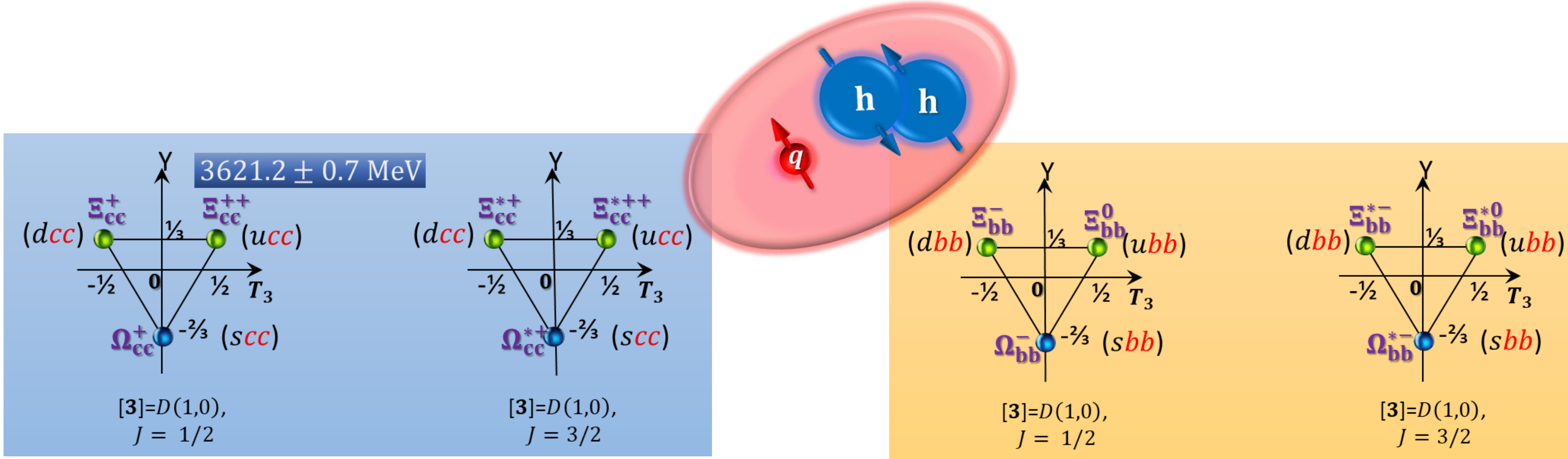




[**3**]=$D(1,0)$,
$J = 1/2$

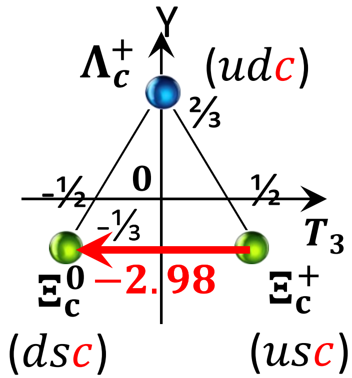


[**3**]=$D(1,0)$,
$J = 3/2$

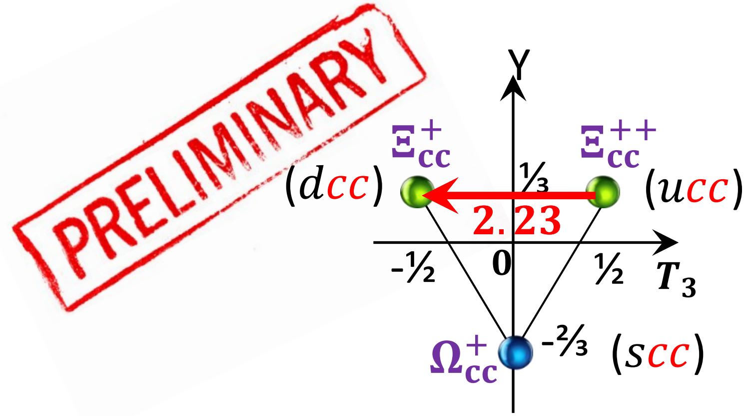


	$\mathcal{R}_J$	$\Delta B_{\rm hh}$	$\Delta M^{\rm EM}_{\rm sol}$	$\Delta M^{\rm iso}_{\rm sb}$	$\Delta M_{\rm hf}$	$\Delta M^{\rm Coul}_{\text{sol-hh}}$	
2.23 ± 0.91	$\mathbf{3}_{1/2}$	$\Xi^{++}_{\rm cc}(ucc) - \Xi^{+}_{\rm cc}(dcc)$	$3c^{(8)}/8$	$\delta^{\rm iso}_{\mathbf{3}}$	$\cdot$	$4\alpha_{\rm sol-h}/3$	4.48 ± 0.91
-4.49 ± 0.46		$\Xi^{0}_{\rm bb}(ubb) - \Xi^{-}_{\rm bb}(dbb)$	-0.06 ± 0.09	-2.20 ± 0.01		$-2\alpha_{\rm sol-h}/3$	-2.24 ± 0.45
2.23 ± 0.91	$\mathbf{3}_{3/2}$	$\Xi^{*++}_{\rm cc}(ucc) - \Xi^{*+}_{\rm cc}(dcc)$				$4\alpha_{\rm sol-h}/3$	4.48 ± 0.91
-4.49 ± 0.46		$\Xi^{*0}_{\rm bb}(ubb) - \Xi^{*-}_{\rm bb}(dbb)$				$-2\alpha_{\rm sol-h}/3$	-2.24 ± 0.45

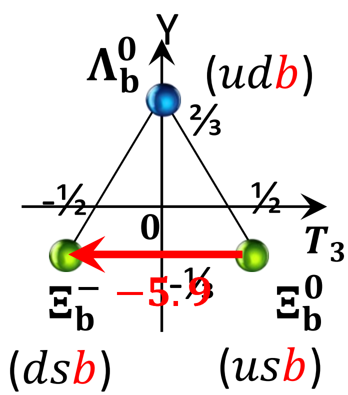
where $\delta^{\rm iso}_{\mathbf{3}} = \frac{3}{16}(m_d - m_u)\left(\overline{\alpha} + \frac{16}{3}\beta - \frac{3}{2}\gamma\right)$ in which $\overline{\alpha} = \left(\frac{N_c - 2}{N_c}\right)$.



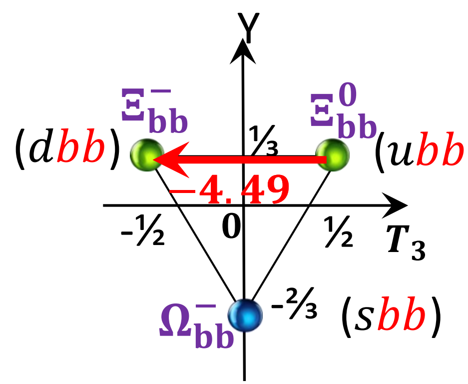
$[\bar{3}]=D(0,1)$,
$J = 1/2$



$[\mathbf{3}]=D(1,0)$,
$J = 1/2$



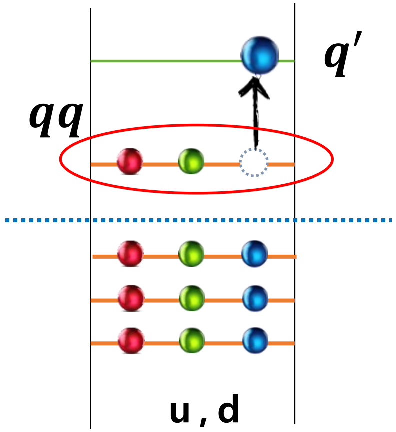
$[\bar{3}]=D(0,1)$,
$J = 1/2$



$[\mathbf{3}]=D(1,0)$,
$J = 1/2$

GSYang, HchKim, Phys.Lett.B 808 (2020) 135619

- **Excited SU(3) baryons**



Full expression with the grand spin K is

$$M = M_{\rm sol} + \Delta\mathcal{E}\left(J_i \to J_f\right) + \mathcal{E}_K + M_{\rm sb}^K.$$

$$H_{\rm sb}^K = \alpha \mathcal{D}_{88}^{(8)}\left(\mathcal{A}\right) + \beta Y - \frac{\gamma}{\sqrt{3}} \sum_i \mathcal{D}_{8i}^{(8)}\left(\mathcal{A}\right) \tilde{T}_i - \frac{\delta}{\sqrt{3}} \sum_i \mathcal{D}_{8i}^{(8)}\left(\mathcal{A}\right) \hat{K}_i,$$

where $\boldsymbol{K} = \widetilde{\boldsymbol{T}} + \widetilde{\boldsymbol{J}}$ and $\widetilde{Y}_K = N_c/3$.

D. Diakonov etal. PhysRev D88 074030, 2013

Excited baryons (qqq')

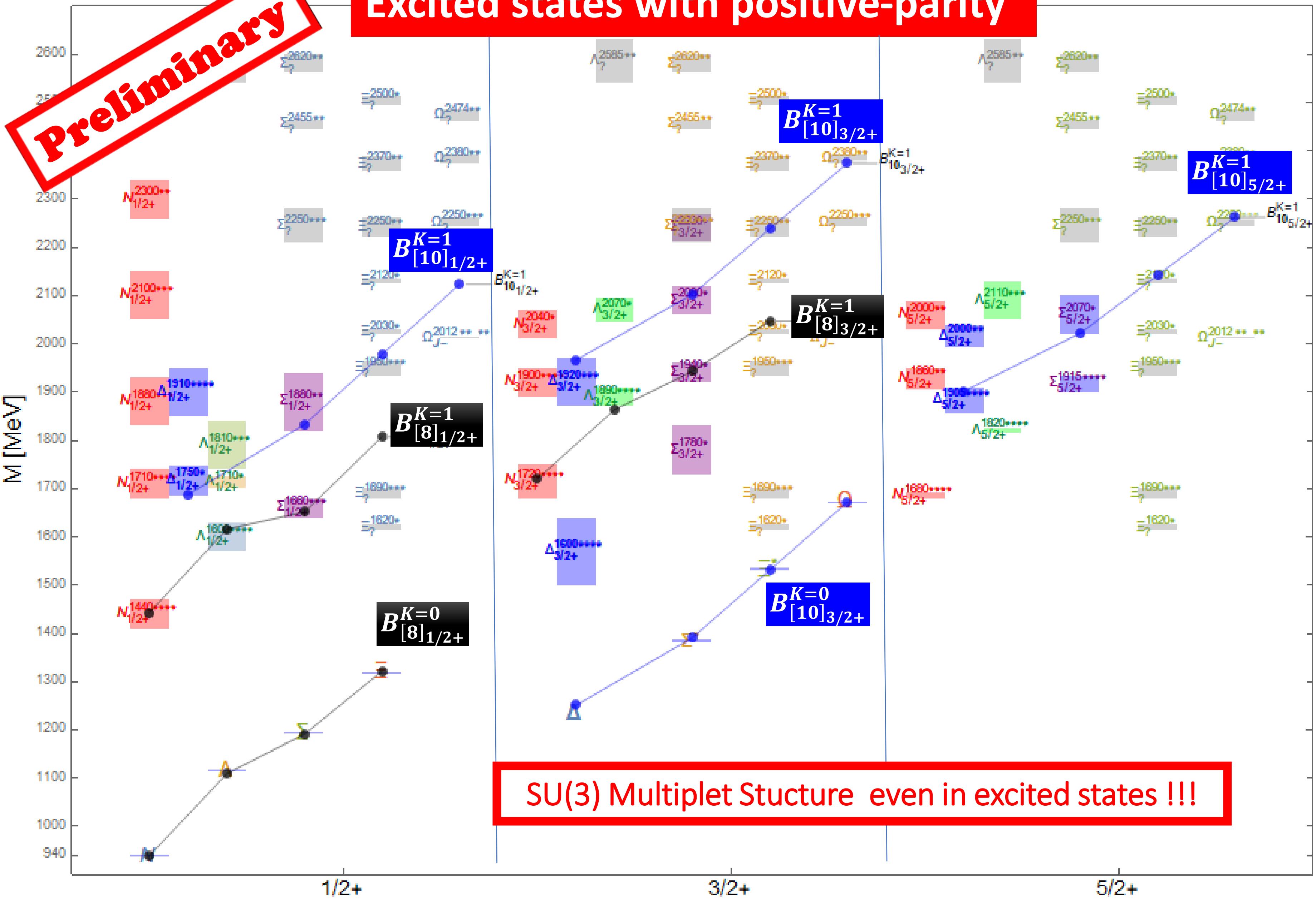
$$\begin{aligned} \alpha &\to \left(N_c - 1\right)/N_c\, \alpha \equiv \overline{\alpha}, \\ \widetilde{Y}_K = N_c/3 &\to \left(N_c - 1\right)/3, \\ I_{1,2} &\to \left(N_c - 1\right)/N_c\, I_{1,2} \equiv \overline{I}_{1,2}, \end{aligned}$$

for one-quark (u, d) excited baryons

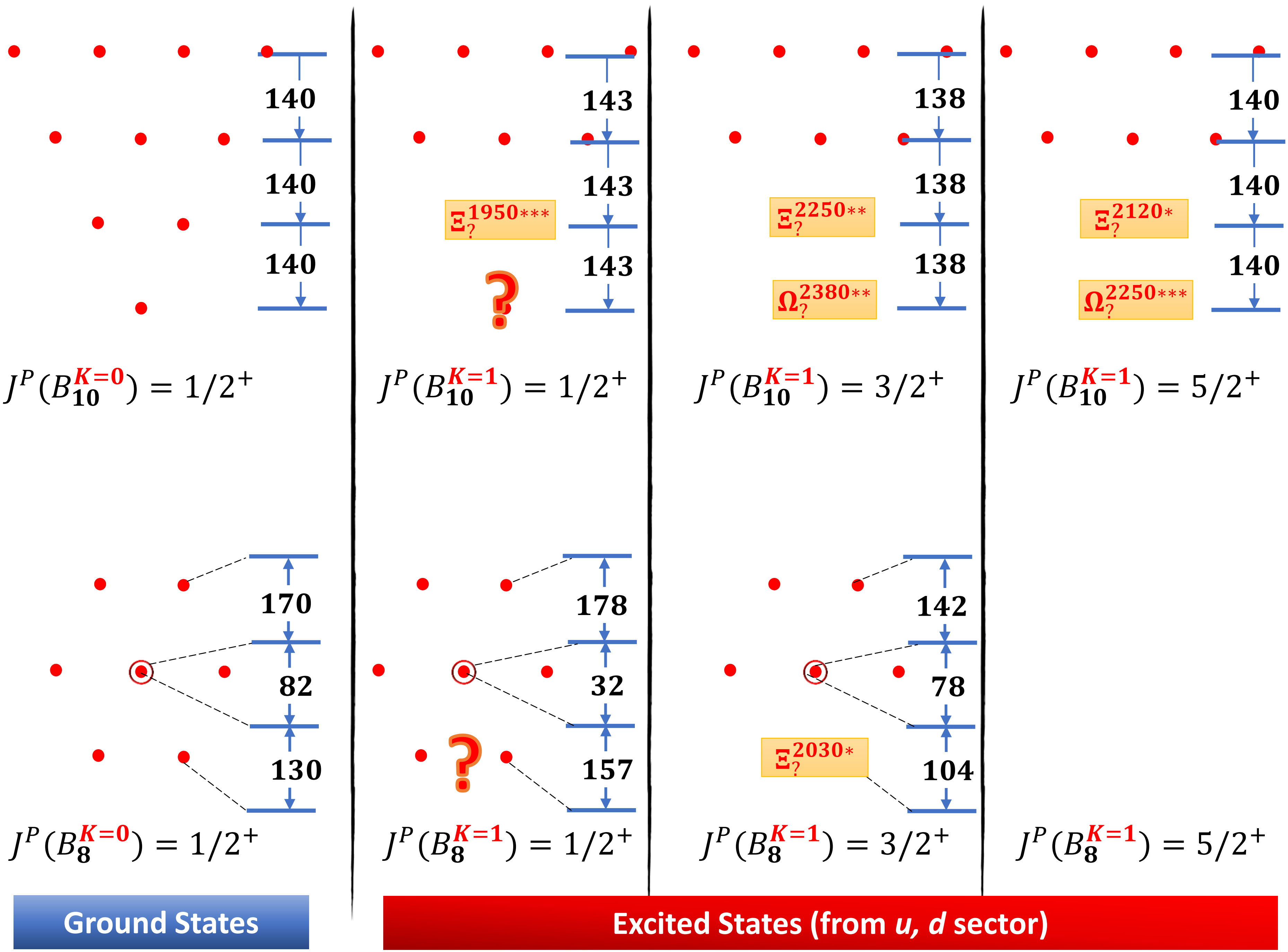
$$\mathcal{E}_{\mathcal{R}_J}^K = \frac{\mathcal{C}_2(\mathcal{R}) - \widetilde{T}\left(\widetilde{T}+1\right) - \frac{3}{4}\widetilde{Y}_K^2}{2I_2} + \frac{1}{2I_1}\left[\widetilde{a}_K J(J+1) + (1-\widetilde{a}_K)\widetilde{T}\left(\widetilde{T}+1\right) - \widetilde{a}_K(1-\widetilde{a}_K)K(K+1)\right],$$

$$\Psi_K^{(\mathcal{R})}\left(\mathcal{A},\, \mathcal{S},\, \chi\right) = \sqrt{\frac{\dim\left(\mathcal{R}\right)\ \left(2J+1\right)}{2K+1}} \sum_{\tilde{T},\tilde{T}_3,\tilde{J}_3} C_{\tilde{T}\tilde{T}_3;J\tilde{J}_3}^{K\,K_3}\, \mathcal{D}_{\tilde{Y}\tilde{T}\tilde{T}_3;YTT_3}^{(\mathcal{R})}\left(\mathcal{A}^{+}\right)\, \mathcal{D}_{\tilde{J}_3;J_3}^{J}\left(\mathcal{S}^{+}\right)\, \chi_{K_3},$$

Excited states with positive-parity



Study for negative-parity excited states are in progress



140
140
140
$J^P(B_{10}^{K=0}) = 1/2^+$
143
143
143
$\Xi_?^{1950***}$
?
$J^P(B_{10}^{K=1}) = 1/2^+$
138
138
138
$\Xi_?^{2250**}$
$\Omega_?^{2380**}$
$J^P(B_{10}^{K=1}) = 3/2^+$
140
140
140
$\Xi_?^{2120*}$
$\Omega_?^{2250***}$
$J^P(B_{10}^{K=1}) = 5/2^+$
170
82
130
$J^P(B_8^{K=0}) = 1/2^+$
178
32
157
?
$J^P(B_8^{K=1}) = 1/2^+$
142
78
104
$\Xi_?^{2030*}$
$J^P(B_8^{K=1}) = 3/2^+$
$J^P(B_8^{K=1}) = 5/2^+$
Ground States
Excited States (from *u*, *d* sector)

Summary

- Assuming that the valence quarks are bound by the pion mean fields, we can regard the nucleon as a chiral soliton.

- The present pion mean-field approach indeed explains consistently both the SU(3) light baryons and the heavy baryons.

- Dynamical parameters and flavor quantum numbers of the collective operators and wave functions are modified by $\boldsymbol{N_c - (\# \ of \ heavy \ quarks)}$ **mean field for the heavy baryons** based on $\boldsymbol{N_c}$ **mean field for** the light baryons

- We have obtained excellent description of various physical observables (Masses from isospin and SU(3) flavor symmetry breakings, widths of strong and radiative decays, magnetic moments and transitions)

- Contributions from isospin symmetry breaking for a soliton are significant to describe the isospin mass differences of singly and doubly charmed and beauty baryons.

- It is shown that light quarks govern their structure of heavy baryons.

- We can see the multiplet stucture even in excited states as like octet, decuplet.


THANK
YOU
GRACIAS
ARIGATO
SHUKURIA
DANKSCHEEN
BIYAN
SHUKRIA
TASHAKKUR ATU
YAQHANYELAY
SUKSAMA
EKHMET
MEHRBANI
GRAZIE
PALDIES
KOMAPSUMNIDA
MAAKE
GOZAIMASHITA
EFCHARISTO
JUSPAXAR
BOLZÏN
MERCI
TINGKI

- **Strong decay widths of decuplet baryons**

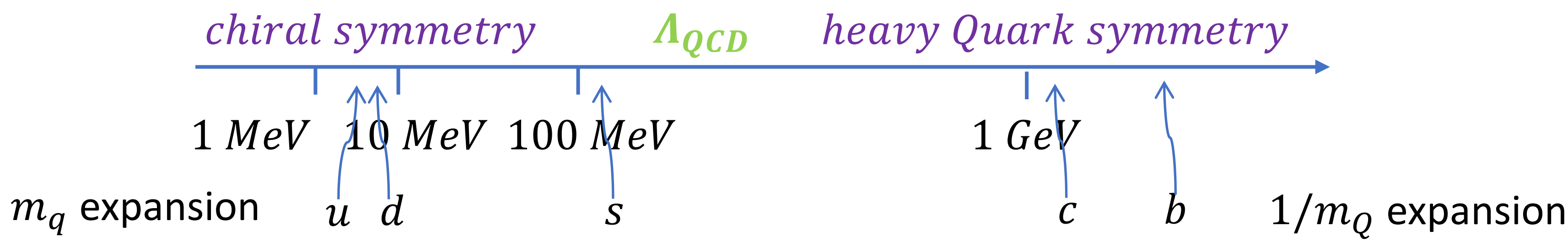
Decay modes	$\Gamma_i^{(0)}$	$\Gamma_i^{(total)}$	Γ	Γ(Exp.) [2]
$\Delta \to N\pi$	75.98 ± 1.01		88.58 ± 1.31	116–120
$\Sigma^{*+} \to \Sigma^0\pi^+$	2.59 ± 0.03	3.22 ± 0.06		
$\Sigma^{*+} \to \Sigma^+\pi^0$	3.17 ± 0.05	2.62 ± 0.05	36.25 ± 0.42	36.0 ± 0.7
$\Sigma^{*+} \to \Lambda\pi^+$	29.68 ± 0.26	30.41 ± 0.33		
$\Sigma^{*0} \to \Sigma^0\pi^0$	0	0		
$\Sigma^{*0} \to \Sigma^+\pi^-$	3.61 ± 0.11	2.98 ± 0.1	37.21 ± 0.69	36 ± 5
$\Sigma^{*0} \to \Sigma^-\pi^+$	2.78 ± 0.1	2.30 ± 0.09		
$\Sigma^{*0} \to \Lambda\pi^0$	31.15 ± 0.47	31.92 ± 0.52		
$\Sigma^{*-} \to \Sigma^-\pi^0$	3.50 ± 0.06	2.89 ± 0.06		
$\Sigma^{*-} \to \Sigma^0\pi^-$	3.64 ± 0.06	3.01 ± 0.06	38.18 ± 0.48	39.4 ± 2.1
$\Sigma^{*-} \to \Lambda\pi^-$	31.50 ± 0.30	32.28 ± 0.37		
$\Xi^{*0} \to \Xi^0\pi^0$	4.76 ± 0.05	4.33 ± 0.06	11.26 ± 0.17	9.1 ± 0.5
$\Xi^{*0} \to \Xi^-\pi^+$	7.61 ± 0.08	6.93 ± 0.10		
$\Xi^{*-} \to \Xi^-\pi^0$	4.76 ± 0.05	4.33 ± 0.06	13.01 ± 0.21	$9.9^{+1.7}_{-1.9}$
$\Xi^{*-} \to \Xi^0\pi^-$	8.20 ± 0.13	8.68 ± 0.16		

a_1	a_2	a_3	a_4	a_5	a_6
-3.509 ± 0.011	3.437 ± 0.028	0.604 ± 0.030	-1.213 ± 0.068	0.479 ± 0.025	-0.735 ± 0.040

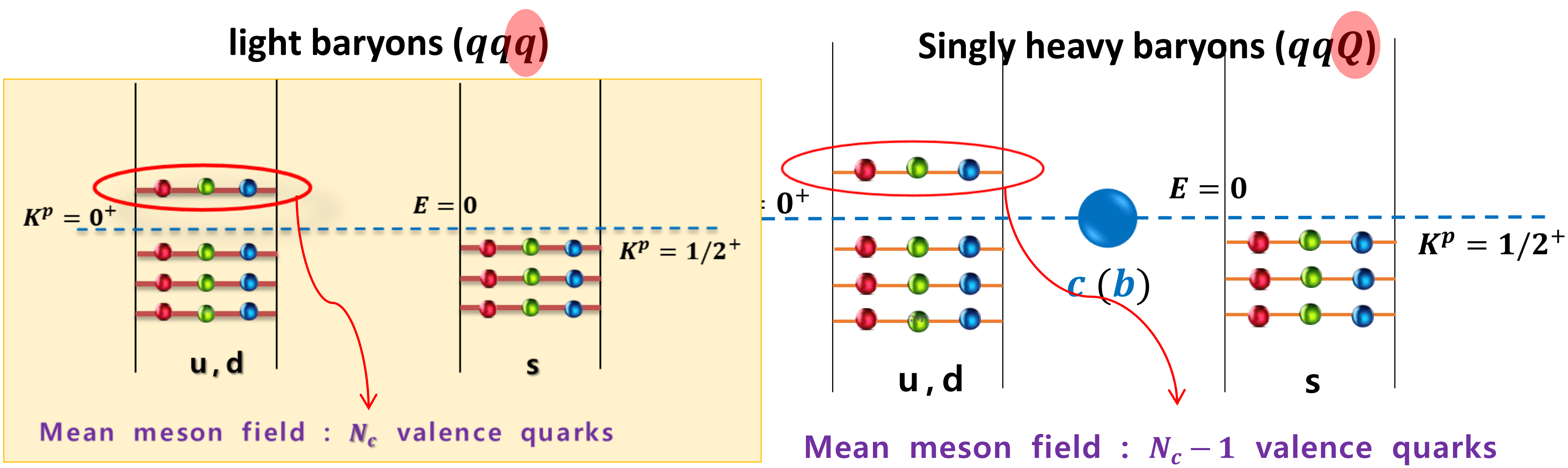
Yang, et al. Rev. C **92** 035206 (2015)
Yang, et al, Phys. Lett. B **785** 434 (2018)

Heavy quarks are too heavy !

$$\Lambda_{QCD}(210\sim340\ MeV) \ll m_c\ (\sim1.2\ GeV) \ll m_b(\sim4.5\ GeV)$$



[M. Oka, Nucl.Phys A 914, 447 (2013)]



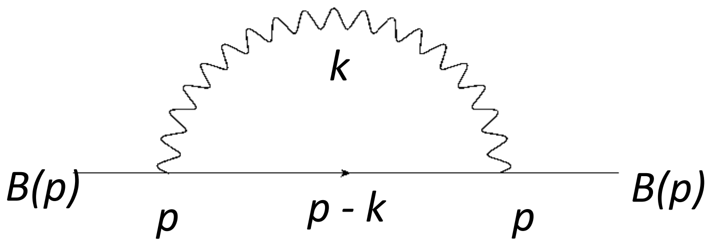
$\delta^{\rm hf} = (0.40 \pm 0.06)$ MeV $\alpha_{\text{sol-h}} = (2.76 \pm 0.28)$ MeV

$\mathcal{R}_J$	B_c	$\Delta M^{\rm EM}_{\rm sol}$	$\Delta M^{\rm iso}_{\rm sb}$	$\Delta M_{\rm hf}$	$\Delta M^{\rm Coul}_{\text{sol-h}}$	$\Delta M^{\rm total}$	PDG [56]	PDG†
$\bar{\mathbf{3}}_{1/2}$	$\Xi_c^+ - \Xi_c^0$	-0.11 ± 0.17	-3.51	-1.20 ± 0.18	1.84 ± 0.19	input	-2.98 ± 0.22	–
	$\Sigma_c^{++} - \Sigma_c^+$	1.10 ± 0.33	-2.33	0.40 ± 0.06	1.84 ± 0.19	1.02 ± 0.38	–	1.07 ± 0.42
$\mathbf{6}_{1/2}$	$\Sigma_c^+ - \Sigma_c^0$	-0.81 ± 0.22	-2.33	0.40 ± 0.06	1.84 ± 0.19	input	-0.9 ± 0.4	–
	$\Xi_c'^+ - \Xi_c'^0$	-0.81 ± 0.22	-2.33	0.40 ± 0.06	1.84 ± 0.19	-0.90 ± 0.30	-0.8 ± 0.6	–
	$\Sigma_c^{++} - \Sigma_c^0$	0.29 ± 0.17	-4.66	0.80 ± 0.12	3.68 ± 0.37	0.12 ± 0.43	0.220 ± 0.013	–
	$\Sigma_c^{++} + \Sigma_c^0 - 2\Sigma_c^+$	1.92 ± 0.53	0	0	0	1.92 ± 0.53	–	1.92 ± 0.82
	$\Sigma_c^{*++} - \Sigma_c^{*+}$	1.10 ± 0.33	-2.33	0.40 ± 0.06	1.84 ± 0.19	1.02 ± 0.38	–	0.91 ± 2.31
$\mathbf{6}_{3/2}$	$\Sigma_c^{*+} - \Sigma_c^{*0}$	-0.81 ± 0.22	-2.33	0.40 ± 0.06	1.84 ± 0.19	-0.90 ± 0.30	–	-0.98 ± 2.31
	$\Xi_c^{*+} - \Xi_c^{*0}$	-0.81 ± 0.22	-2.33	0.40 ± 0.06	1.84 ± 0.19	-0.90 ± 0.30	-0.80 ± 0.26	–
	$\Sigma_c^{*++} - \Sigma_c^{*0}$	0.29 ± 0.17	-4.66	0.80 ± 0.12	3.68 ± 0.37	0.12 ± 0.43	0.01 ± 0.15	–
	$\Sigma_c^{*++} + \Sigma_c^{*0} - 2\Sigma_c^{*+}$	1.92 ± 0.53	0	0	0	1.92 ± 0.53	–	1.89 ± 4.64

$\mathcal{R}_J$	B_b	$\Delta M^{\rm EM}_{\rm sol}$	$\Delta M^{\rm iso}_{\rm sb}$	$\Delta M_{\rm hf}$	$\Delta M^{\rm Coul}_{\text{sol-h}}$	$\Delta M^{\rm total}$	PDG [56]	PDG†
$\bar{\mathbf{3}}_{1/2}$	$\Xi_b^0 - \Xi_b^-$	-0.11 ± 0.17	-3.51	-1.20 ± 0.18	-0.92 ± 0.09	-5.74 ± 0.27	-5.9 ± 0.6	–
	$\Sigma_b^+ - \Sigma_b^0$	1.10 ± 0.33	-2.33	0.40 ± 0.06	-0.92 ± 0.09	-1.74 ± 0.34	–	–
$\mathbf{6}_{1/2}$	$\Sigma_b^0 - \Sigma_b^-$	-0.81 ± 0.22	-2.33	0.40 ± 0.06	-0.92 ± 0.09	-3.66 ± 0.25	–	–
	$\Xi_b'^0 - \Xi_b'^-$	-0.81 ± 0.22	-2.33	0.40 ± 0.06	-0.92 ± 0.09	-3.66 ± 0.25	–	–
	$\Sigma_b^+ - \Sigma_b^-$	0.29 ± 0.17	-4.66	0.80 ± 0.12	-1.84 ± 0.19	-5.40 ± 0.28	-5.06 ± 0.18	–
	$\Sigma_b^+ + \Sigma_b^- - 2\Sigma_b^0$	1.92 ± 0.53	0	0	0	1.92 ± 0.53	–	
	$\Sigma_b^{*+} - \Sigma_b^{*0}$	1.10 ± 0.33	-2.33	0.40 ± 0.06	-0.92 ± 0.09	-1.74 ± 0.34	–	–
$\mathbf{6}_{3/2}$	$\Sigma_b^{*0} - \Sigma_b^{*-}$	-0.81 ± 0.22	-2.33	0.40 ± 0.06	-0.92 ± 0.09	-3.66 ± 0.25	–	–
	$\Xi_b^{*0} - \Xi_b^{*-}$	-0.81 ± 0.22	-2.33	0.40 ± 0.06	-0.92 ± 0.09	-3.66 ± 0.25	–	-3.03 ± 0.91
	$\Sigma_b^{*+} - \Sigma_b^{*-}$	0.29 ± 0.17	-4.66	0.80 ± 0.12	-1.84 ± 0.19	-5.40 ± 0.28	-4.37 ± 0.33	–
	$\Sigma_b^{*+} + \Sigma_b^{*-} - 2\Sigma_b^{*0}$	1.92 ± 0.53	0	0	0	1.92 ± 0.53	–	–

➢ Electromagnetic self-energy

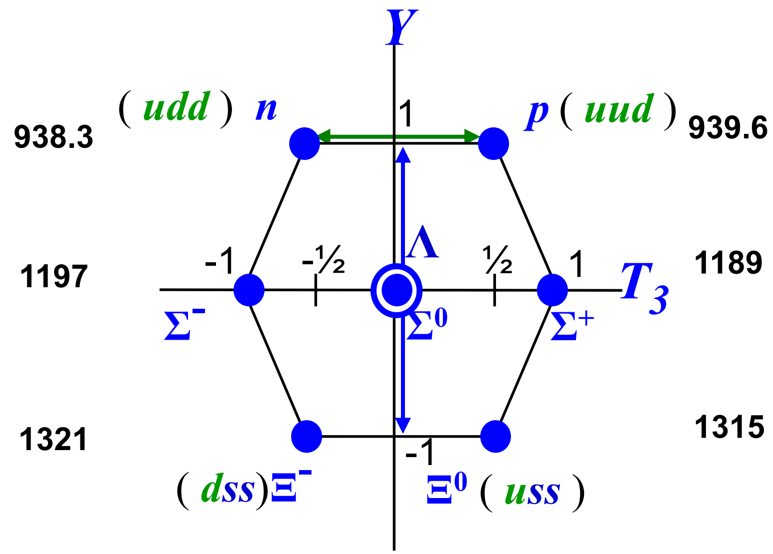
- **EM mass corrections**



Electromagnetic (*EM*) self-energy

EM [MeV]	Exp.
$(p-n)_{EM}$	**0.76**±0.30
$(\Sigma^+ - \Sigma^-)_{EM}$	-0.17±0.30
$(\Xi^0 - \Xi^-)_{EM}$	-0.86±0.30

Gasser, Leutwyler, **Phys.Rep 87, 77** *"Quark Masses"*



$$\Delta M_B = M_{B_1} - M_{B_2} = (\Delta M_B)_H + (\Delta M_B)_{EM}$$

$(p-n)_{exp} \sim -$ **1.293** MeV

$(p-n)_{EM} \sim$ **0.76** MeV

➢ Electromagnetic self-energy

In the ChSM, $(\Delta M_B)_{\mathrm{EM}} = \langle B|J_\mu(x)J^\mu(0)|B\rangle = \langle B|\mathcal{O}_{\mathrm{EM}}|B\rangle$

$$\mathcal{O}_{\mathrm{EM}} = -\frac{e^2}{2}\int d^3x\, d^3y D_\gamma(\boldsymbol{x},\boldsymbol{y})\int\frac{d\omega}{2\pi}\mathrm{tr}\left\langle \boldsymbol{x}\left|\frac{1}{\omega+iH}\gamma_\mu\lambda^a\right|\boldsymbol{y}\right\rangle\left\langle \boldsymbol{y}\left|\frac{1}{\omega+iH}\gamma_\mu\lambda^b\right|\boldsymbol{x}\right\rangle D^{(8)}_{Qa}D^{(8)}_{Qb}$$

$$= \alpha_1\sum_{i=1}^{3}D^{(8)}_{Qi}D^{(8)}_{Qi} + \alpha_2\sum_{p=4}^{7}D^{(8)}_{Qp}D^{(8)}_{Qp} + \alpha_3 D^{(8)}_{Q8}D^{(8)}_{Q8}$$

It can be further reduced to

$$\mathcal{O}^{\mathrm{EM}} = c^{(27)}\left(\sqrt{5}D^{(27)}_{\Sigma_2^0\Lambda_{27}} + \sqrt{3}D^{(27)}_{\Sigma_1^0\Lambda_{27}} + D^{(27)}_{\Lambda_{27}\Lambda_{27}}\right) + c^{(8)}\left(\sqrt{3}D^{(8)}_{\Sigma^0\Lambda} + D^{(8)}_{\Lambda\Lambda}\right) + c^{(1)}D^{(1)}_{\Lambda\Lambda}$$

$$c^{(27)} = \frac{1}{40}(\alpha_1 - 4\alpha_2 + 3\alpha_3),$$

$$c^{(8)} = \frac{1}{10}\left(\alpha_1 - \frac{2}{3}\alpha_2 - \frac{1}{3}\alpha_3\right),$$

$$c^{(1)} = \frac{1}{8}(\alpha_1 + \frac{4}{3}\alpha_2 + \frac{1}{3}\alpha_3)$$

$$\mathbf{8}\otimes\mathbf{8} = \mathbf{1}\oplus\mathbf{8}_s\oplus\mathbf{8}_a\oplus\mathbf{10}\oplus\overline{\mathbf{10}}\oplus\mathbf{27}$$

Because of Bose symmetry

G. S. Yang, H.-Ch. Kim and M. V. Polyakov, Phys. Lett. B 695, 214 (2011)