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Heavy baryons based on pion mean fields

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Heavy baryon:

One static color source

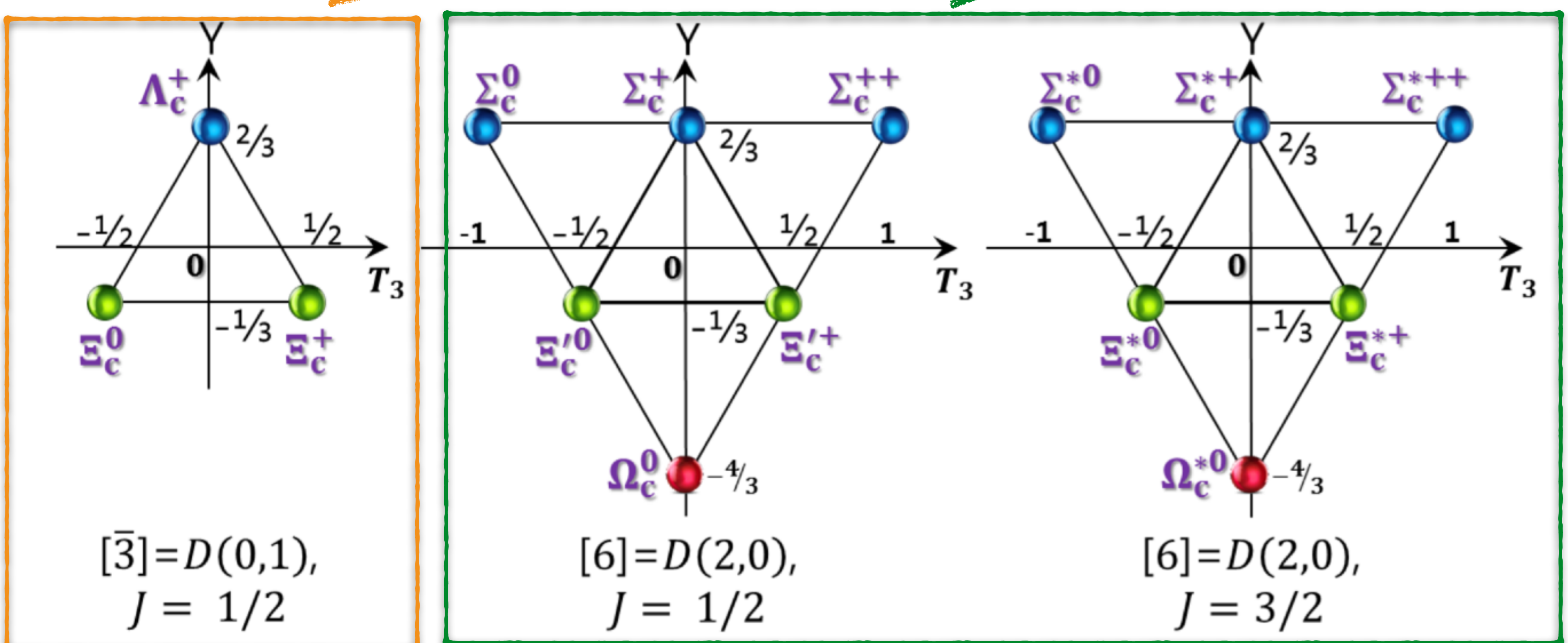
+

Nc-1 quarks

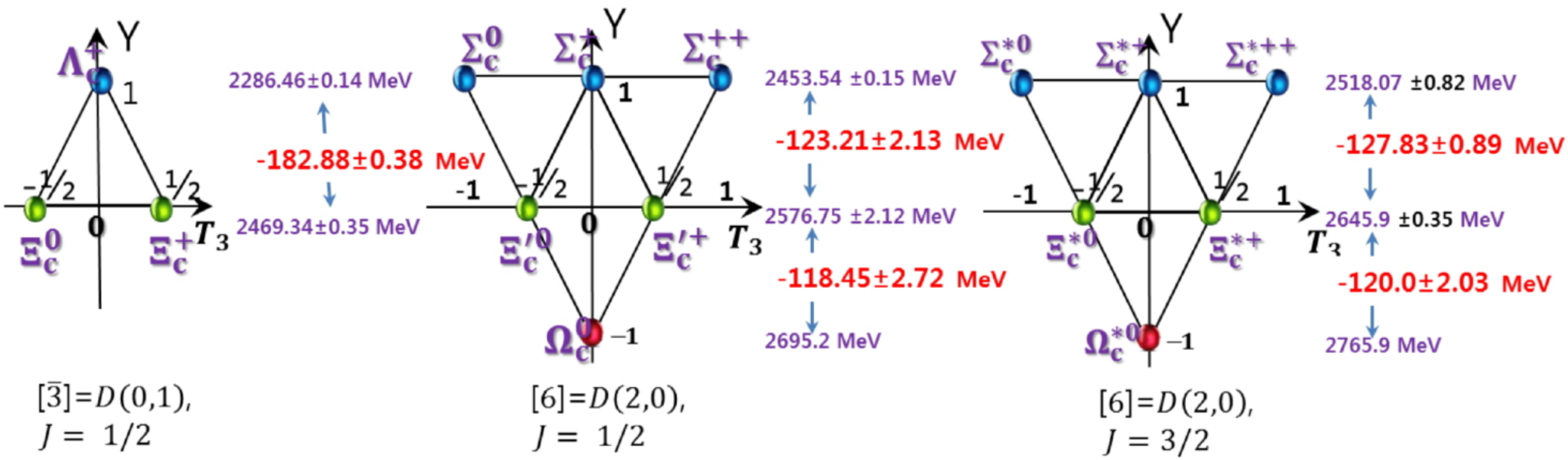
SU(3) representation for heavy baryons

- In the heavy quark mass limit, a heavy quark spin is conserved, so light-quark spin is also conserved.
- In this limit, a heavy quark can be considered as **a color static source**.
- Dynamics is governed by light quarks.

$$\mathbf{3} \otimes \mathbf{3} = \overline{\mathbf{3}} \oplus \mathbf{6}$$

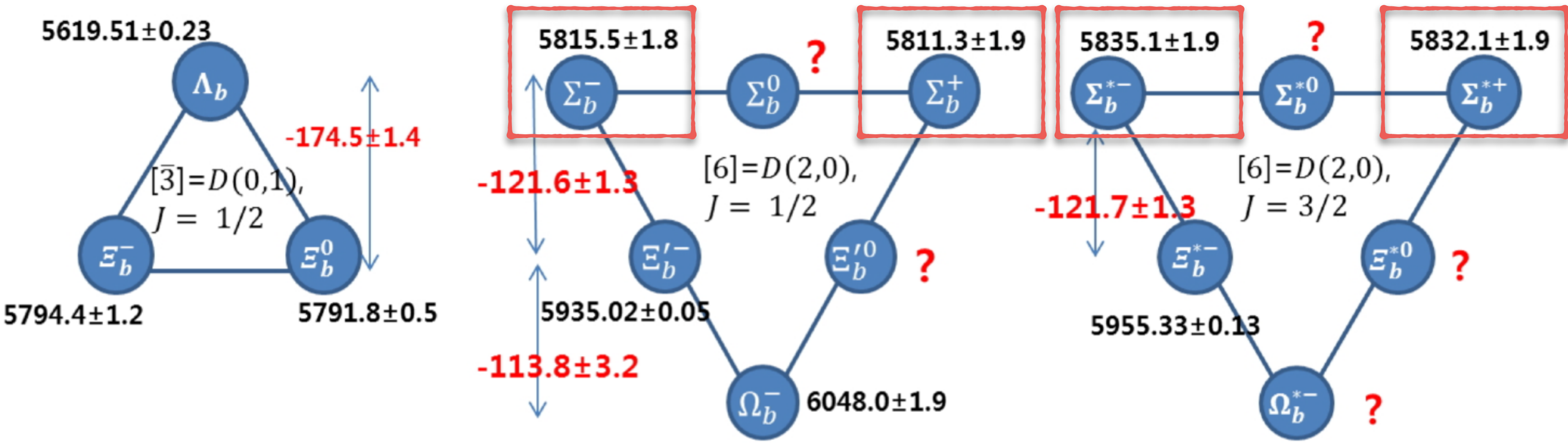


Experimental status: Charmed baryons



- The masses of charmed baryons are all well known experimentally.
- They can be used to check the validity of the present approach.

Experimental status: Bottom baryons

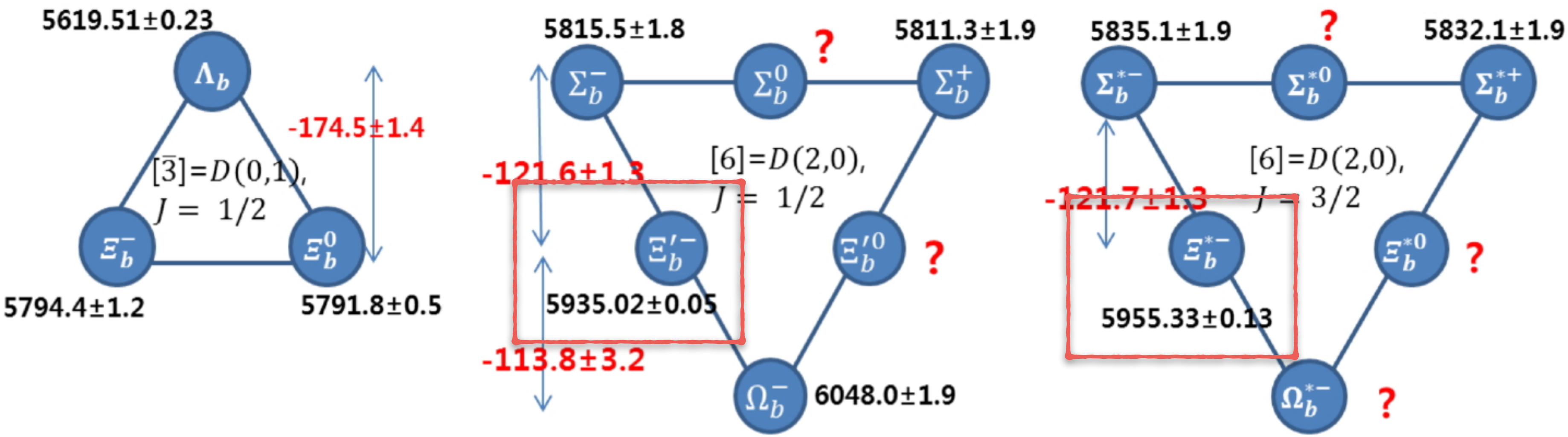


CDF, PRD85, 092011 (2012)

$$M_{\Sigma_b^+} = (5811.3^{+0.9}_{-0.8} \pm 1.7)\,\mathrm{MeV}, \quad M_{\Sigma_b^-} = (5815.5^{+0.6}_{-0.5} \pm 1.7)\,\mathrm{MeV}$$

$$M_{\Sigma_b^{*+}} = (5832.1 \pm 0.7^{+1.7}_{-1.8})\,\mathrm{MeV}, \quad M_{\Sigma_b^{*-}} = (5835.1 \pm 0.7^{+1.8}_{-1.7})\,\mathrm{MeV}$$

Experimental status: Bottom baryons



CMS, PRL 108, 252002 (2012)

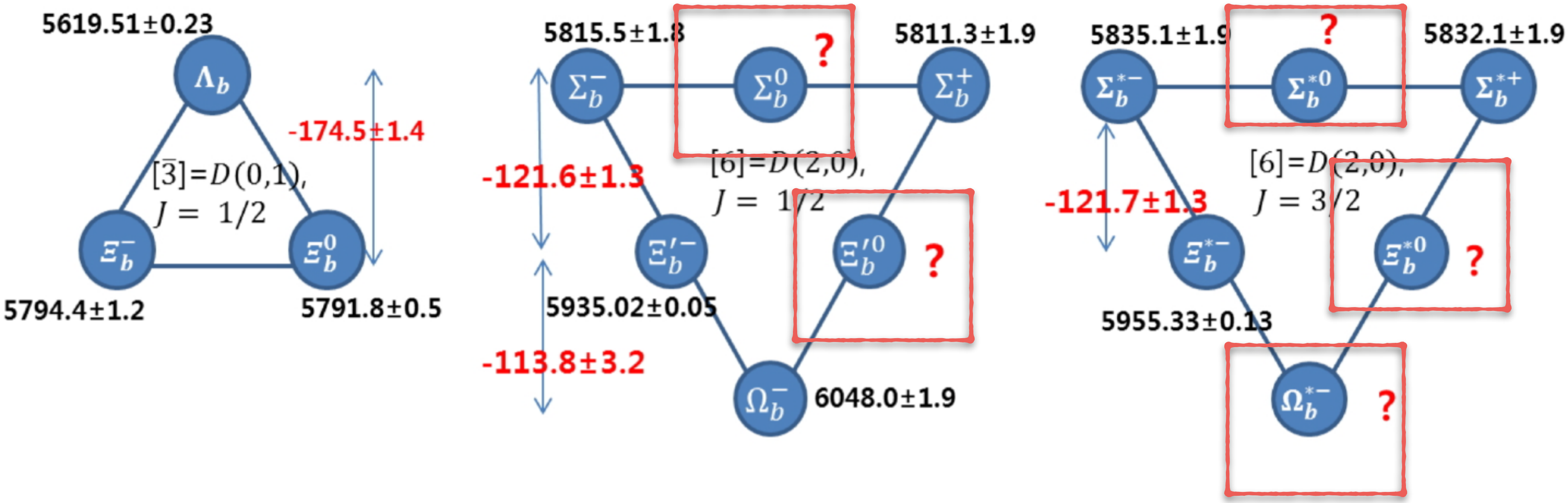
$$M_{\Xi_b} = (5948.9 \pm 0.8 \pm 1.2)\,\mathrm{MeV}$$

LHCb, PRL 114 062004 (2015)

$$M_{\Xi_b'} = (5935.02 \pm 0.02 \pm 0.05)\,\mathrm{MeV},$$

$$M_{\Xi_b^*} = (5955.33 \pm 0.12 \pm 0.05)\,\mathrm{MeV}$$

Experimental status: Bottom baryons



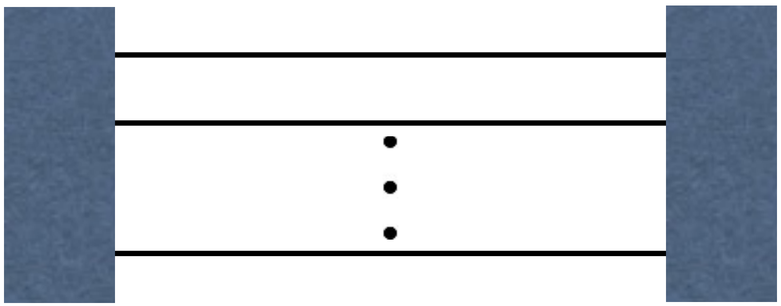
- Masses of the five bottom baryons are still unknown.

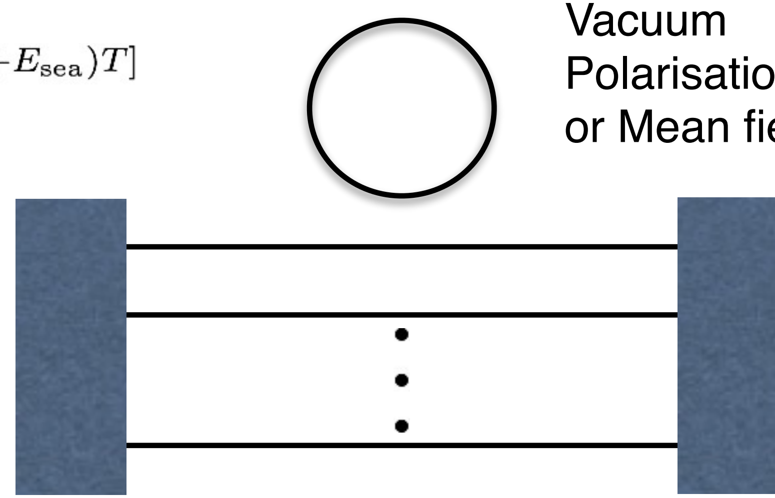
Ω_b^{*-} can soon be measured at the LHC.

Light baryons in pion mean fields

Classical solitons (Chiral Quark-soliton model)

$$\langle J_N(\vec{x},T) J_N^\dagger(\vec{y},-T)\rangle_0 \sim \Pi_N(T) \sim e^{-[(N_c E_{\text{val}}+E_{\text{sea}})T]}$$



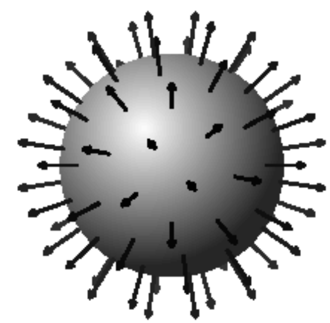


Vacuum
Polarisation
or Mean fields

$$\frac{\delta}{\delta U}(N_c E_{\text{val}} + E_{\text{sea}}) = 0 \rightarrow M_{\text{cl}} = N_c E_{\text{val}}(U_c) + E_{\text{sea}}(U_c)$$

Hedgehog Ansatz:

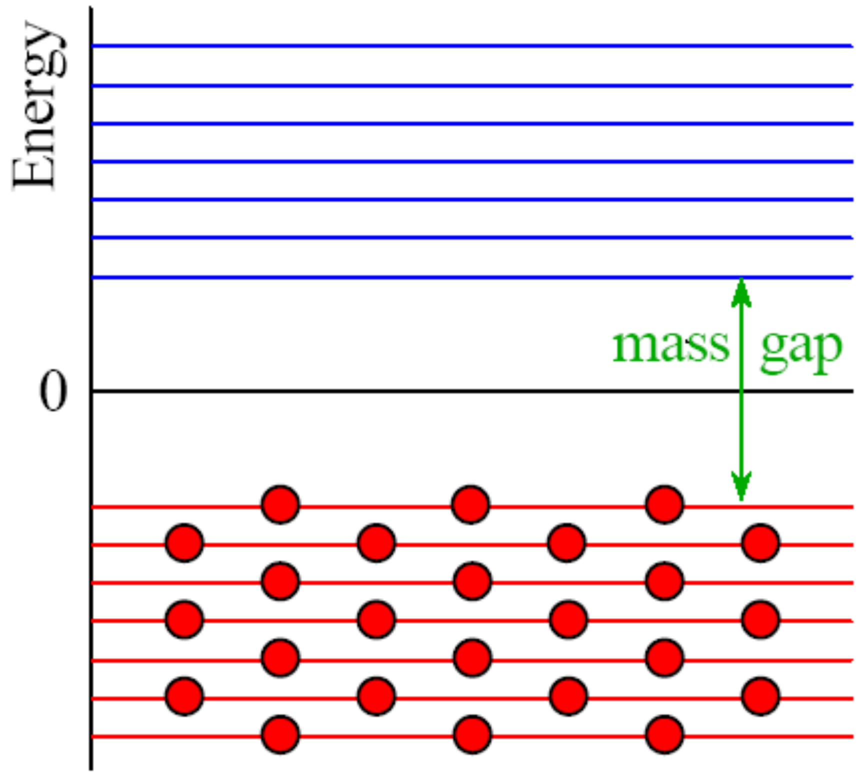
$$U_{\text{SU}(2)} = \exp\left[i\gamma_5 \mathbf{n}\cdot\boldsymbol{\tau} P(r)\right]$$



hedgehog

HChK et al. Prog. Part. Nucl. Phys. Vol.95, (1995)

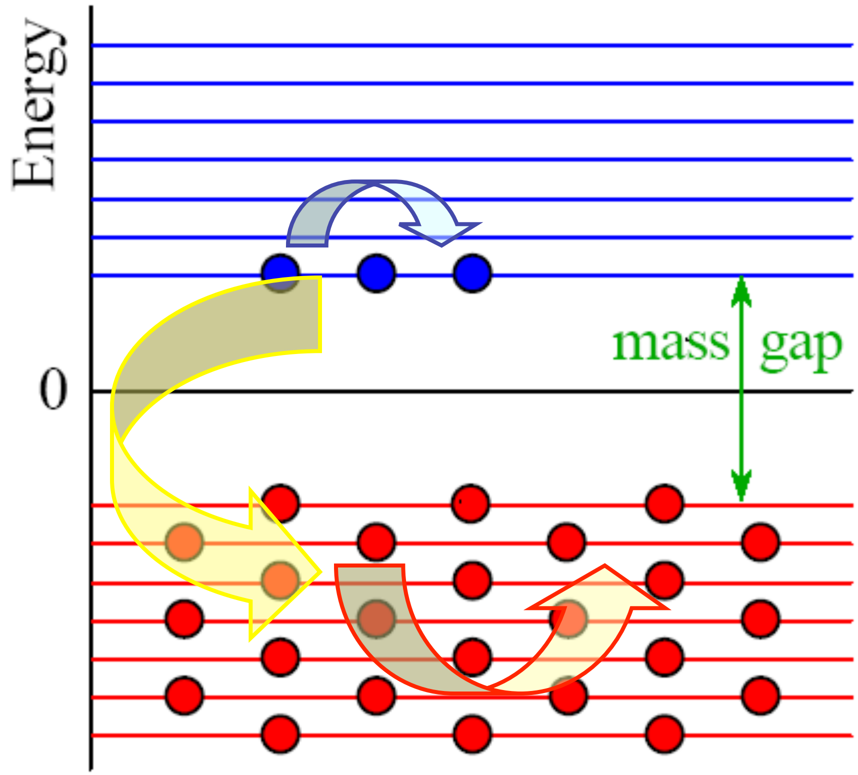
Light baryons in pion mean fields



Spontaneous chiral symmetry breaking

HChK et al. Prog. Part. Nucl. Phys. Vol.95, (1995)

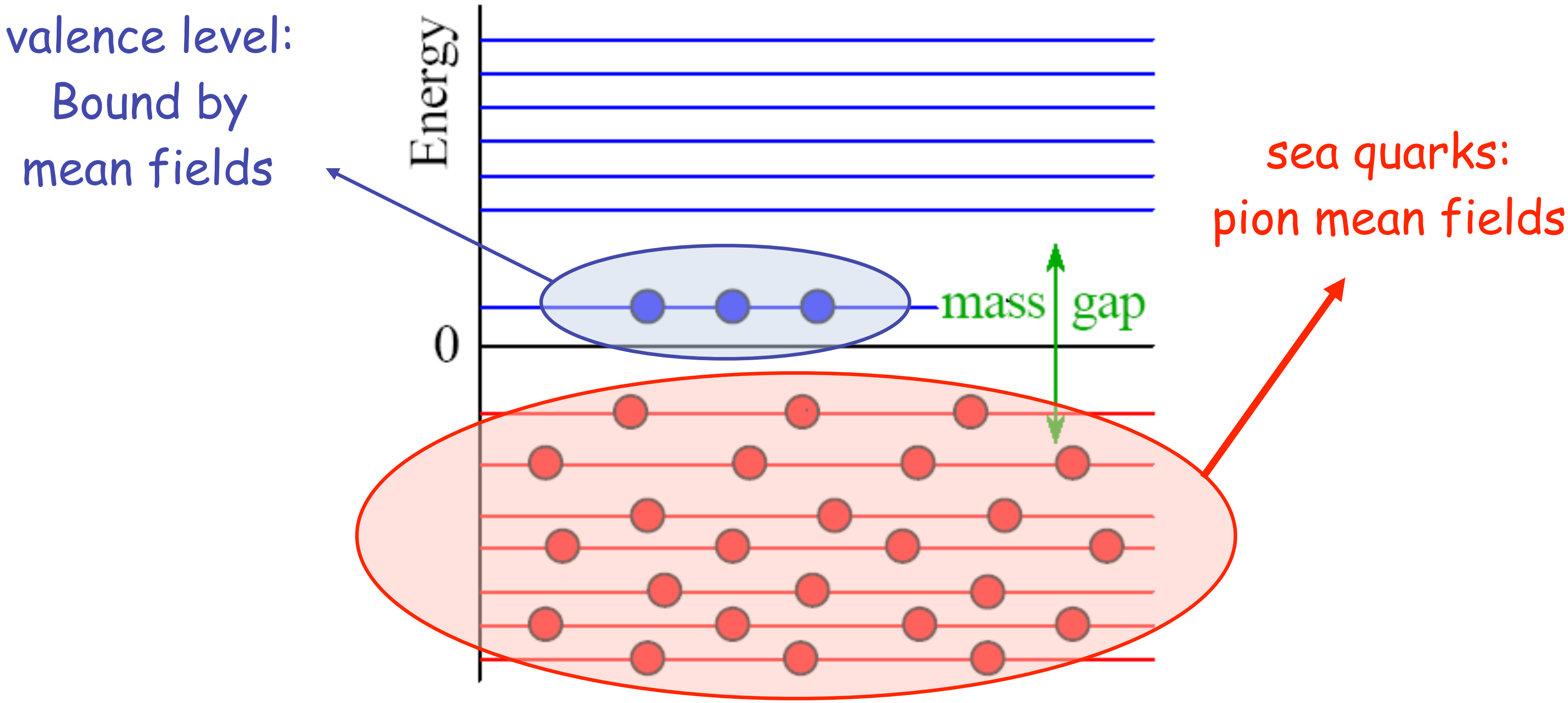
Light baryons in pion mean fields



The presence of the Nc valence quarks creates the pion mean fields.

HChK et al. Prog. Part. Nucl. Phys. Vol.95, (1995)

Light baryons in pion mean fields

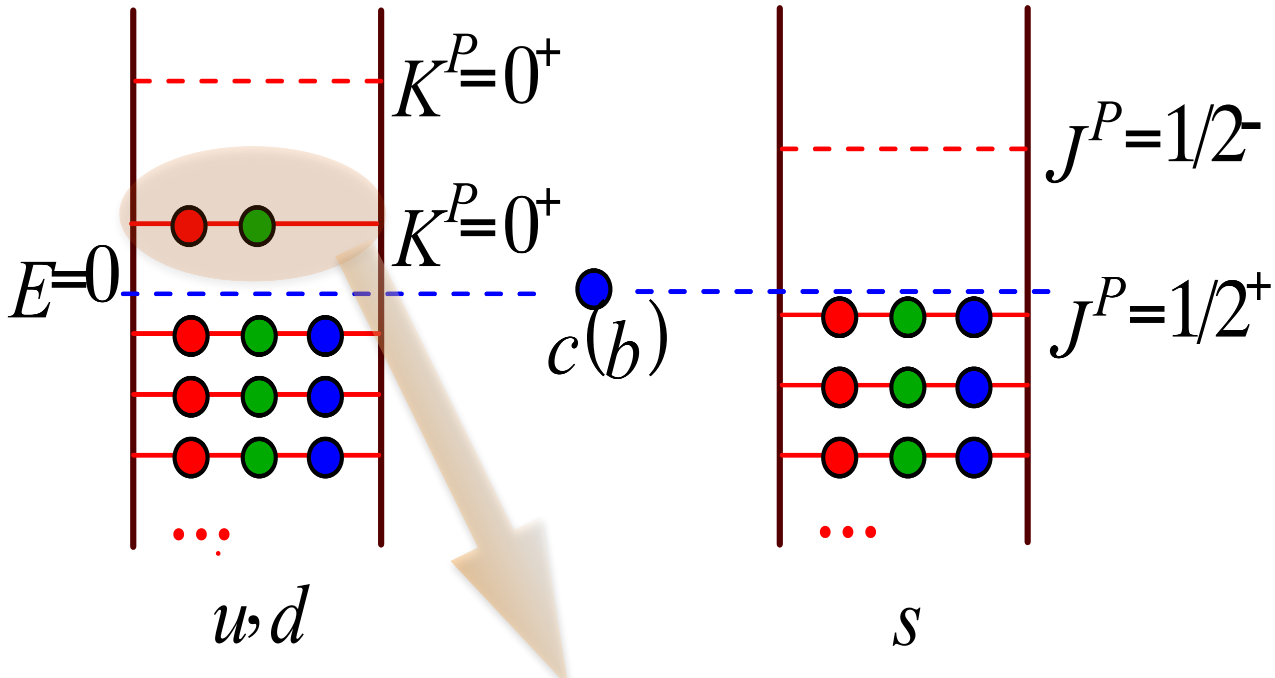


The valence quarks produce the mean field in the large Nc limit and are self-consistently bound by it!

HChK et al. Prog. Part. Nucl. Phys. Vol.95, (1995)

Heavy baryons

- Valence quarks are bound by the pion mean field.
- Light quarks govern a heavy-light quark system.
- Heavy quarks can be considered as merely **static color sources.**



Meson mean field by ***N_c*-1** valence quarks

Suggested by the late D. Diakonov

Collective Hamiltonian

Collective rotational Hamiltonian

$$H^{\mathrm{rot}}_{(p,q)} = M_{\mathrm{sol}} + \frac{1}{2I_1}\sum_{i=1}^{3}\hat{J}_i^2 + \frac{1}{2I_2}\sum_{a=4}^{7}\hat{J}_a^2$$

$$\mathcal{E}^{\mathrm{rot}}_{(p,\,q)} = M_{\mathrm{sol}} + \frac{J(J+1)}{2I_1} + \frac{C_2(p,q) - J(J+1) - 3/4\,Y'^2}{2I_2}$$

classical nucleon mass

$$Y' = \frac{N_c}{3}$$

Right hypercharge: Constraint on the quantization of the chiral soliton This constraint selects a tower of the allowed rotational excitations of the SU(3) hedgehog.

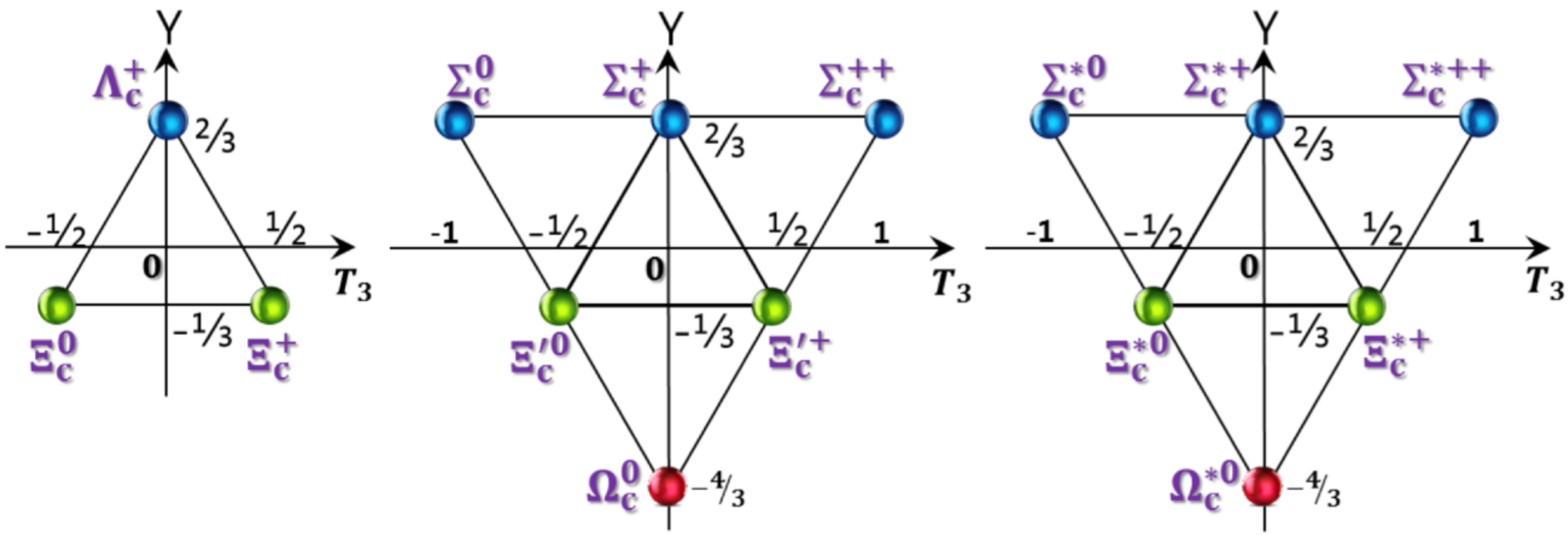
Collective Hamiltonian

In the case of a heavy baryon, we have Nc-1 light quarks.

$$Y' = \frac{N_c - 1}{3}$$

- The lowest rotational excites states

$$(p,\ q) = (0,1) = \overline{\mathbf{3}} \text{ with } S_L = 0$$
$$(p,\ q) = (2,0) = \mathbf{6} \text{ with } S_L = 1$$



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

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

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

Collective Hamiltonian

Modifying Collective rotational Hamiltonian

$$H^{\rm rot}_{(p,q)} = M_{\rm sol} + \frac{1}{2I_1}\sum_{i=1}^{3}\hat{J}_i^2 + \frac{1}{2I_2}\sum_{a=4}^{7}\hat{J}_a^2$$

$$\mathcal{E}^{\rm rot}_{(p,\,q)} = \boxed{M_{\rm sol}} + \frac{J(J+1)}{2I_1} + \frac{C_2(p,q) - J(J+1) - 3/4\,\boxed{Y'^2}}{2I_2}$$

Nc-1 soliton mass (B=2/3)

$$Y' = \frac{N_c - 1}{3}$$

Moments of Inertia and Sigma pi-N term: sum over valence quark states:

$$I_{1,2},\quad K_{1,2},\quad \Sigma_{\pi N} \longrightarrow \left(\frac{N_c-1}{N_c}\right)I_{1,2},\quad \left(\frac{N_c-1}{N_c}\right)K_{1,2},\quad \left(\frac{N_c-1}{N_c}\right)\Sigma_{\pi N},$$

SU(3) symmetry breaking

- The collective Hamiltonian for SU(3) symmetry breaking

$$H_{\rm br} = \alpha D^{(8)}_{88} + \beta Y + \frac{\gamma}{\sqrt{3}} \sum_{i=1}^{3} D^{(8)}_{8i} J_i$$

In the light-quark sector, we fix these dynamical parameters as

$$\alpha = -\frac{2m_s}{3}\sigma - \beta Y' = -(255.03 \pm 5.82)\,\mathrm{MeV}$$

$$\beta = -\frac{m_s K_2}{I_2} = -(140.04 \pm 3.20)\,\mathrm{MeV}$$

$$\gamma = \frac{2m_s K_1}{I_1} + 2\beta = -(101.08 \pm 2.33)\,\mathrm{MeV}$$

$$\alpha \to \bar{\alpha} = \frac{N_c - 1}{N_c}\alpha$$

G. S. Yang, HChK, PTP. 128, 397 (2012).

Masses of the heavy baryons

- Mass expressions

$$M^Q_{B,\mathcal{R}} = \boxed{M^Q_{\mathcal{R}}} + \delta_{\mathcal{R}} Y$$

Center values of the heavy baryon masses

$$M^Q_{\mathcal{R}} = m_Q + \mathcal{E}^{\mathrm{rot}}_{(p,q)}$$

$$M^Q_{\bar{3}} = m_Q + \left(\frac{N_c}{N_c - 1}\right)\frac{1}{2I_2}$$

$$M^Q_{6} = m_Q + \left(\frac{N_c}{N_c - 1}\right)\frac{1}{2I_1}$$

Modified mean fields

Gh.S. Yang, HChK, M. Polyakov, M. Praszalowicz, arXiv:1607.07089
To appear in Phys. Rev. D as a rapid comm in Nov. (2016).

Center values of the masses

$$M_{\bar{\mathbf{3}}}^{Q} = \frac{M_{\Lambda_Q} + 2M_{\Xi_Q}}{3}$$

$$M_{\mathbf{6}}^{Q} = \frac{M_{\Sigma_Q} + 2M_{\Sigma_Q^*} + 2M_{\Xi'_Q} + 4M_{\Xi_Q^*}}{9}$$

For the charmed sector

$$M_{\bar{\mathbf{3}}}^{c} = (2408.7 \pm 0.2)\,\mathrm{MeV}$$

$$M_{\mathbf{6}}^{c} = (2580.8 \pm 0.5)\,\mathrm{MeV}$$

For the bottom sector

$$M_{\bar{\mathbf{3}}}^{b} = (5735.2 \pm 0.4)\,\mathrm{MeV}$$

$$M_{\mathbf{6}}^{b} = (5908.0 \pm 0.3)\,\mathrm{MeV}$$

Sum rule for $M_{\Omega_Q^*}$

$$M_{\Omega_Q^*} = 2M_{\Xi'_Q} + M_{\Sigma_Q^*} - 2M_{\Sigma_Q}$$

Using this sum rule, we obtain

$$M_{\Omega_c^*} = (2764.5 \pm 3.1)\ \mathrm{MeV}$$

$$M_{\Omega_c^*} = (2765.9 \pm 2.0)\ \mathrm{MeV}\quad \mathrm{Experiment}$$

$$M_{\Omega_b^*} = (6076.8 \pm 2.25)\ \mathrm{MeV}$$

Experimentally unknown!

Masses of the heavy baryons

- Mass expressions

$$M^Q_{B,\mathcal{R}} = M^Q_{\mathcal{R}} + \delta_{\mathcal{R}} Y$$

SU(3) symmetry breaking

$$\delta_{\overline{3}} = \frac{3}{8}\overline{\alpha} + \beta$$

$$\delta_{6} = \frac{3}{20}\overline{\alpha} + \beta - \frac{3}{10}\gamma$$

$$\delta_{\overline{\mathbf{3}}} = (-203.8 \pm 3.5)\,\mathrm{MeV}$$

$$\delta_{\mathbf{6}} = (-135.2 \pm 3.3)\,\mathrm{MeV}$$

Modified mean fields

Gh.S. Yang, HChK, M. Polyakov, M. Praszalowicz, arXiv:1607.07089
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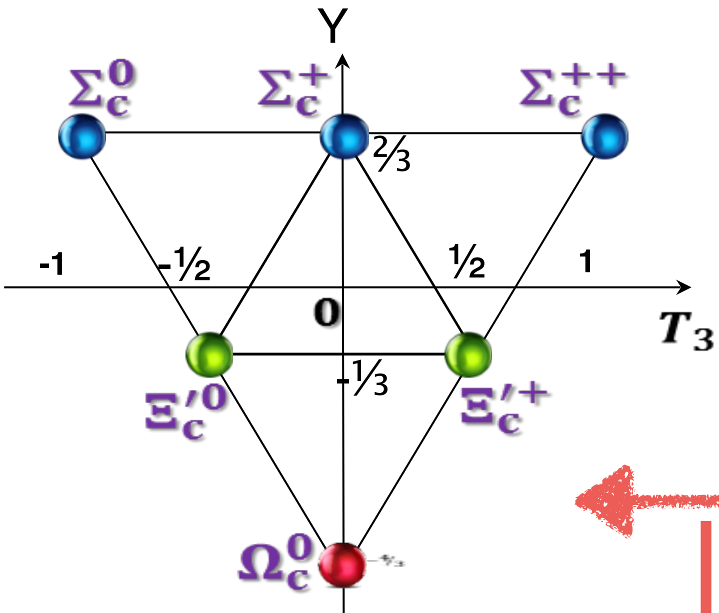
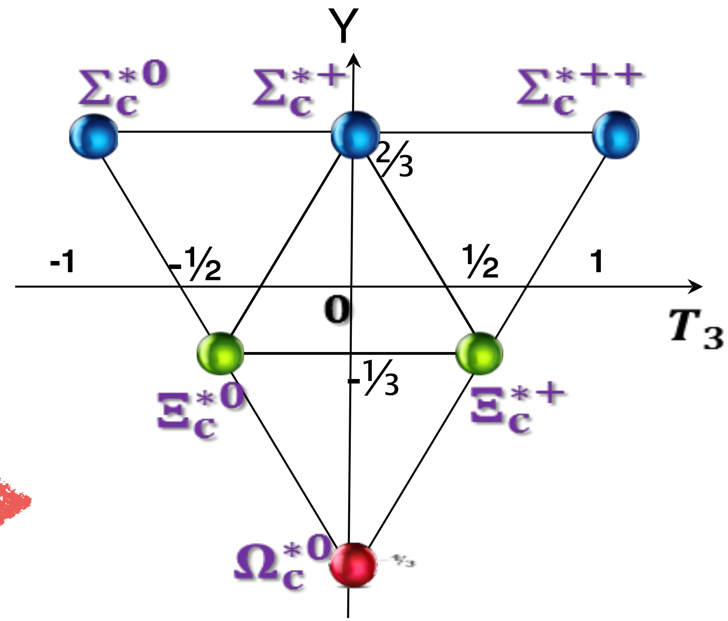
Hyperfine mass splittings



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



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

Hyperfine splitting between different spin states

$$H_{LQ} = \frac{2}{3}\frac{\kappa}{m_Q M_{\rm sol}}\mathbf{S}_{\rm L}\cdot\mathbf{S}_Q = \frac{2}{3}\frac{\varkappa}{m_Q}\mathbf{S}_{\rm L}\cdot\mathbf{S}_Q$$

The ratio can be determined by the center values of the sextet masses

Expressions for the masses

$$\frac{\varkappa}{m_c} = (68.1 \pm 1.1)\,\mathrm{MeV}$$
$$\frac{\varkappa}{m_b} = (20.3 \pm 1.0)\,\mathrm{MeV}$$

$\mathcal{R}_J$	B_Q	T	Y	M_{B_Q}
$\overline{\mathbf{3}}_{1/2}$	Λ_Q	0	$\frac{2}{3}$	$\frac{2}{3}\delta_{\overline{\mathbf{3}}} + M^Q_{\overline{\mathbf{3}}}$
	Ξ_Q	$\frac{1}{2}$	$-\frac{1}{3}$	$-\frac{1}{3}\delta_{\overline{\mathbf{3}}} + M^Q_{\overline{\mathbf{3}}}$
$\mathbf{6}_{1/2}$	Σ_Q	1	$\frac{2}{3}$	$\frac{2}{3}\delta_{\mathbf{6}} - 2\varkappa/3m_Q + M^Q_{\mathbf{6}}$
	Ξ'_Q	$\frac{1}{2}$	$-\frac{1}{3}$	$-\frac{1}{3}\delta_{\mathbf{6}} - 2\varkappa/3m_Q + M^Q_{\mathbf{6}}$
	Ω_Q	0	$-\frac{4}{3}$	$-\frac{4}{3}\delta_{\mathbf{6}} - 2\varkappa/3m_Q + M^Q_{\mathbf{6}}$
$\mathbf{6}_{3/2}$	Σ^*_Q	1	$\frac{2}{3}$	$\frac{2}{3}\delta_{\mathbf{6}} + \varkappa/3m_Q + M^Q_{\mathbf{6}}$
	Ξ^*_Q	$\frac{1}{2}$	$-\frac{1}{3}$	$-\frac{1}{3}\delta_{\mathbf{6}} + \varkappa/3m_Q + M^Q_{\mathbf{6}}$
	Ω^*_Q	0	$-\frac{4}{3}$	$-\frac{4}{3}\delta_{\mathbf{6}} + \varkappa/3m_Q + M^Q_{\mathbf{6}}$

Gh.S. Yang, HChK, M. Polyakov, M. Praszalowicz, arXiv:1607.07089
To appear in Phys. Rev. D as a rapid comm in Nov. (2016).

Results for the charmed baryon masses

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

$$\xi_c = (M_{\rm th}^{B_c} - M_{\rm exp}^{B_c})/M_{\rm exp}^{B_c}$$

Gh.S. Yang, HChK, M. Polyakov, M. Praszalowicz, arXiv:1607.07089
To appear in Phys. Rev. D as a rapid comm in Nov. (2016).

Results for the bottom baryon masses

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

Prediction from the present work

$$\xi_b = (M_{\rm th}^{B_b} - M_{\rm exp}^{B_b})/M_{\rm exp}^{B_b}$$

Gh.S. Yang, HChK, M. Polyakov, M. Praszalowicz, arXiv:1607.07089
To appear in Phys. Rev. D as a rapid comm in Nov. (2016).

Summary & Outlook

Summary

- We aimed at investigating the masses of heavy baryons, based on pion mean fields.
- The light quarks govern heavy-baryon systems, while a heavy quark plays a role of a mere static color source.
- Nc-1 valence light quarks produce the pion mean field, in which the light quarks and a heavy quark are bound.
- We introduce a phenomenological spin-spin interaction that accounts for hyperfine mass splittings.

What we can predict in the next

- Doubly charmed (bottom) heavy baryons:

  Nc-2 light-quark system

  $$QQ\boxed{q}$$

  ↓

  Qualiton

- A tetraquark system: $\bar{Q}\bar{Q}qq \to (\bar{Q}\bar{Q})\boxed{(qq)}$

  ↓

  A kind of diquark colored soliton

What we can predict in the next

- Strong decays of heavy baryons
- Magnetic moments of heavy baryons
- Strong axial-vector coupling constants
- Vector coupling constants
- Form factors and GPDs

What we need is to compute three-point correlation functions within the present method:

$$\langle B_Q(\mathcal{R}_1)|\mathcal{O}^{\mathcal{R}}|B'_Q(\mathcal{R}_2)\rangle$$

Though this be madness,
yet there is method in it.

Hamlet Act 2, Scene 2

Thank you very much!