Unified description of baryons in a mean-field approach

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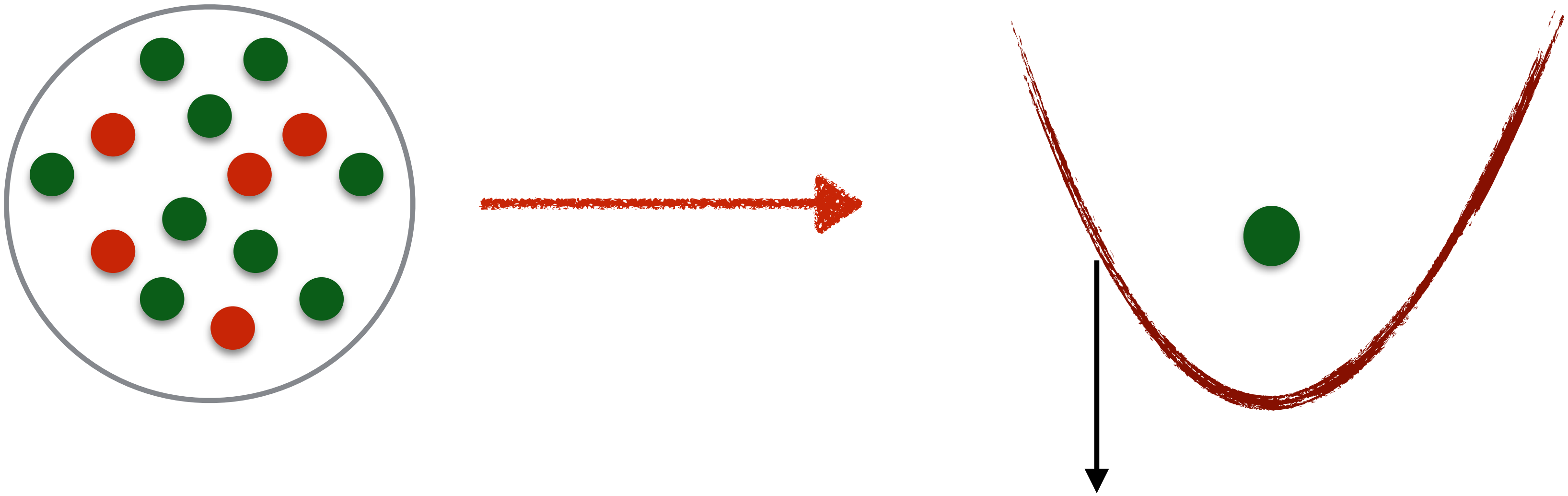
Content

- Introduction to mean-field approaches
- **Light** Baryons: Chiral symmetry
- **Heavy** Baryons: +Heavy-quark symmetry
- **Exotic** Baryons: Pentaquarks
- **Excited** Baryons & Confinement: required for a theory beyond the mean-field theory
- Outlook

Mean-Field Approximation

Simple picture of a mean-field approximation



Mean-field potential that is produced by all other particles.

- Nuclear shell models
- Ginzburg-Landau theory for superconductivity
- Quark potential models for baryons

Mean-Field Approximation

More theoretically defined mean fields

Given action, $S[\phi]$

$$\left.\frac{\delta S}{\delta \phi}\right|_{\phi=\phi_0} = 0$$: Solution of this saddle-point equation ϕ_0

Key point: Ignore the quantum fluctuation.

→ How we can understand the structure of baryons, based on this mean field approach.
This is the subject of the present talk.

Baryon in mean fields

* A baryon can be viewed as a state of Nc quarks bound by mesonic **mean fields** (E. Witten, NPB, 1979 & 1983).

Its mass is proportional to *Nc*, while its width is of order *O(1)*.

→ Mesons are weakly interacting (Quantum fluctuations are suppressed by 1/Nc: *O(1/Nc)*.

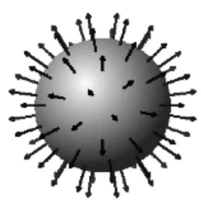
Meson mean-field approach (Chiral Quark-Soliton Model)

* Baryons as a state of Nc quarks bound by mesonic mean fields.

$$S_{\mathrm{eff}} = -N_c \mathrm{Tr}\ln\left(-i\partial_\mu + S(\boldsymbol{r}) + P(\boldsymbol{r})i\gamma_5 + V_\mu(\boldsymbol{r})\gamma_\mu + A_\mu(\boldsymbol{r})\gamma_\mu\gamma_5 + T_{\mu\nu}(\boldsymbol{r})\sigma_\mu + i\hat{m}\right)$$

* Key point: Hedgehog Ansatz

$$\pi^a(\boldsymbol{r}) = \begin{cases} n^a F(r),\, n^a = x^a/r, & a = 1,\, 2,\, 3 \\ 0, & a = 4,\, 5,\, 6,\, 7,\, 8. \end{cases}$$



hedgehog

→ It breaks spontaneously $\mathrm{SU(3)}_{\mathrm{flavor}} \otimes \mathrm{O(3)}_{\mathrm{space}} \to \mathrm{SU(2)}_{\mathrm{isospin+space}}$

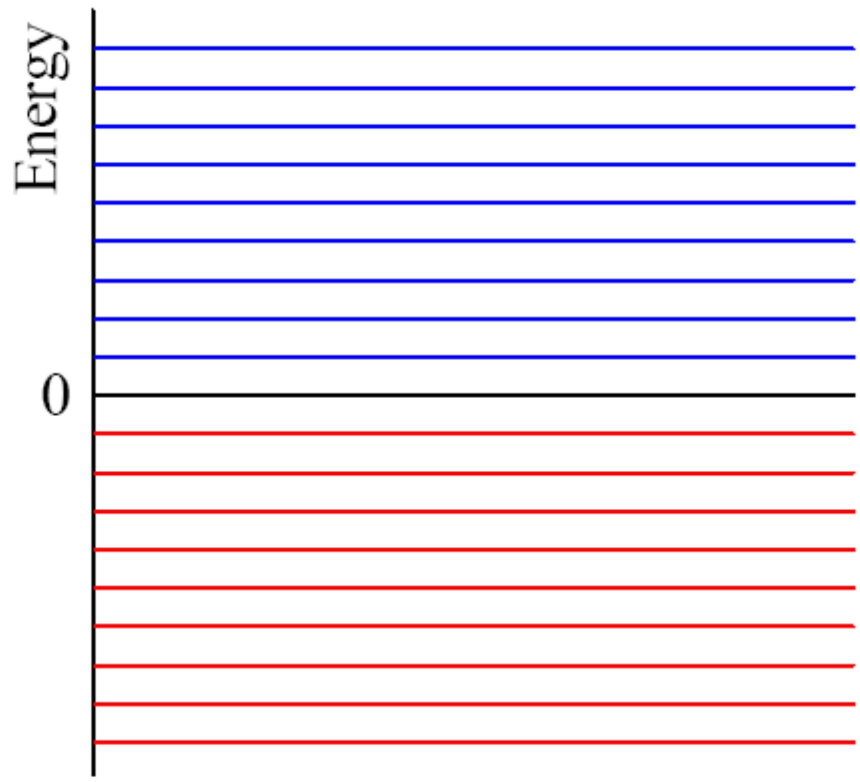
→ 12 profile functions are only allowed.

Diakonov, Petrov, Vladimirov, PRD 88, 074030 (2013)

Chiral quark-soliton picture

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

Chiral quark-soliton picture



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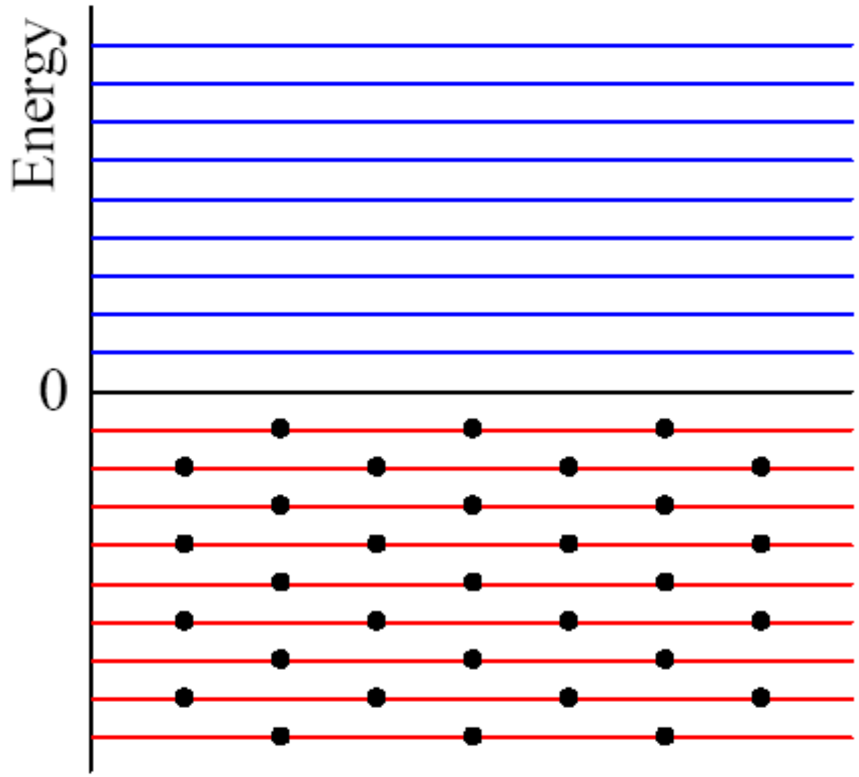

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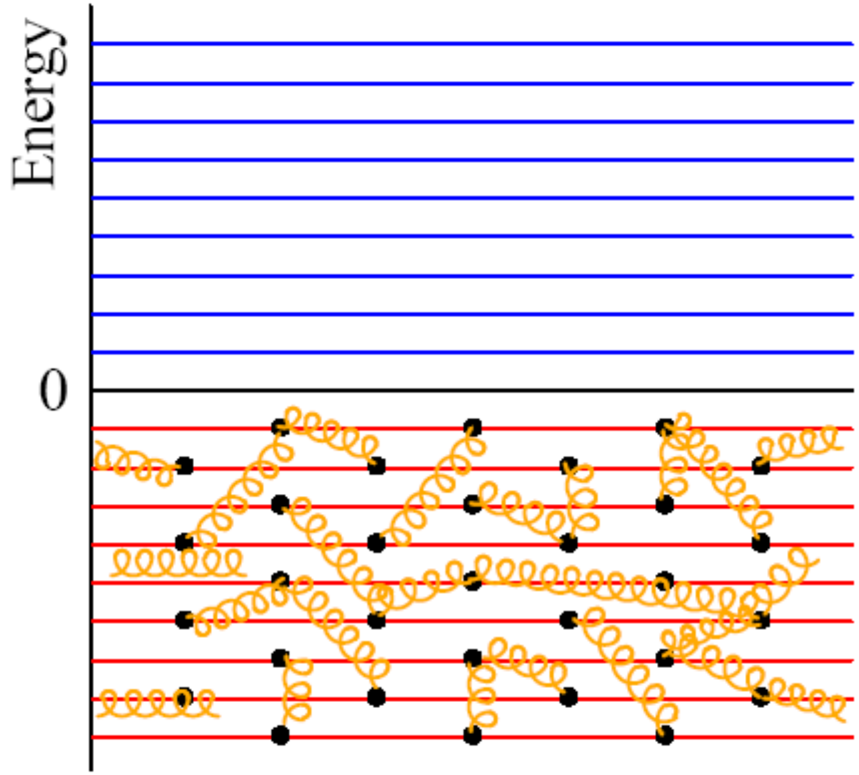

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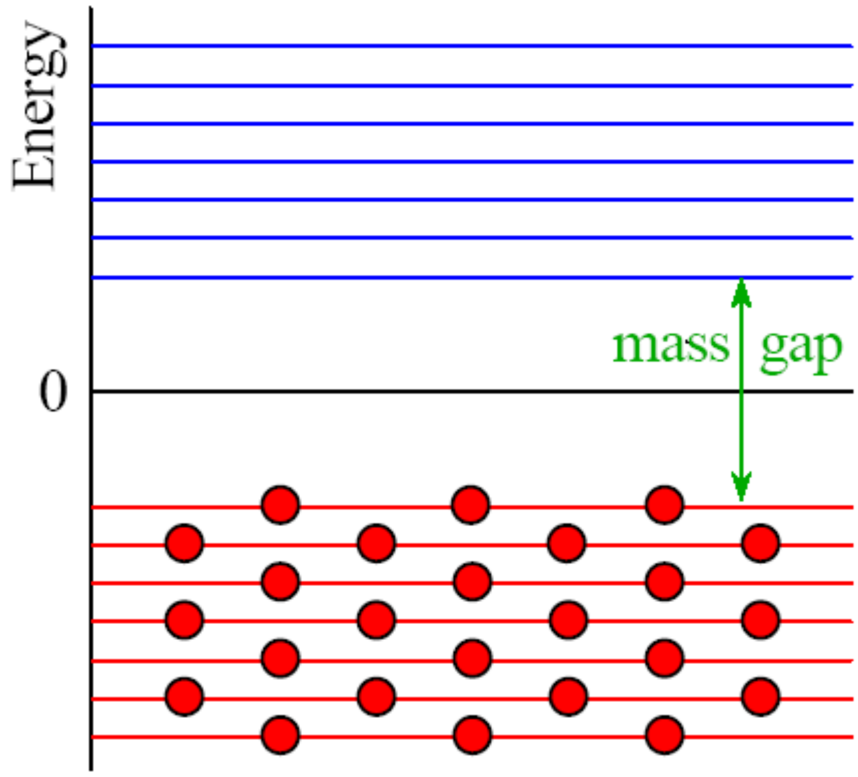

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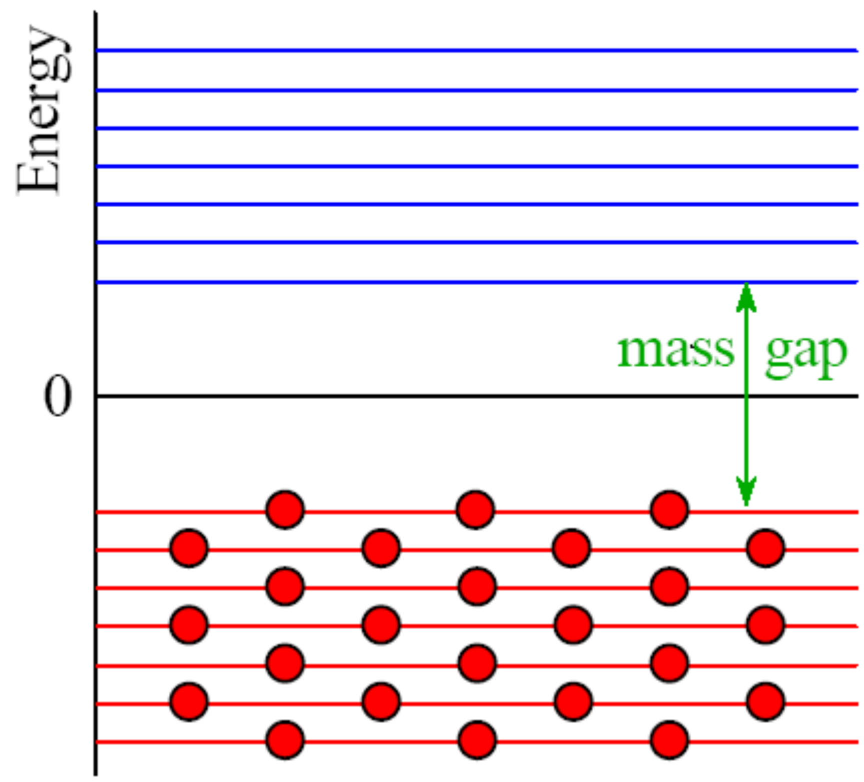

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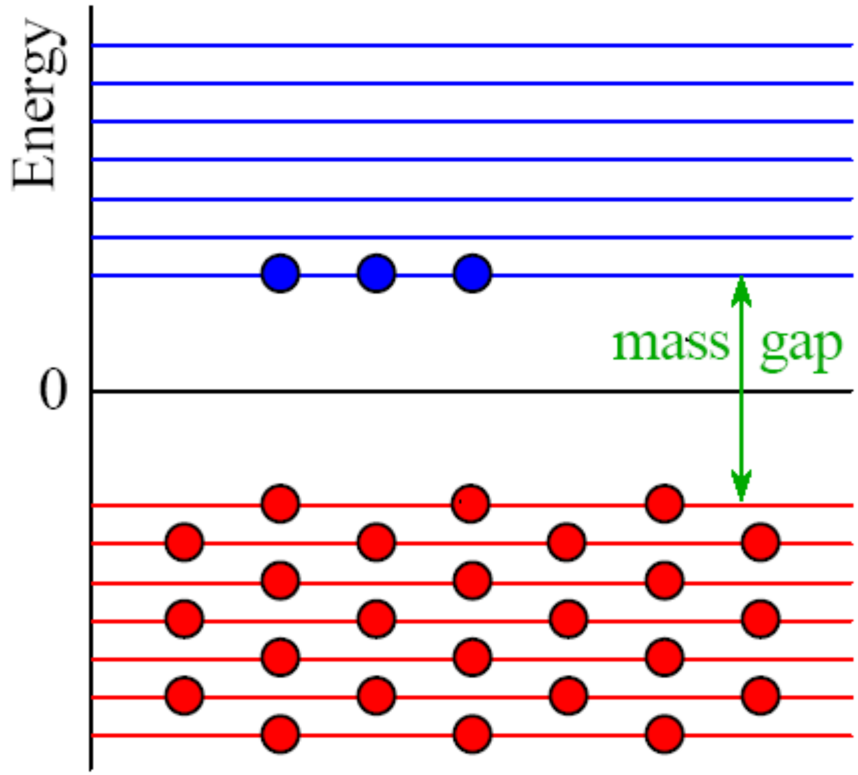

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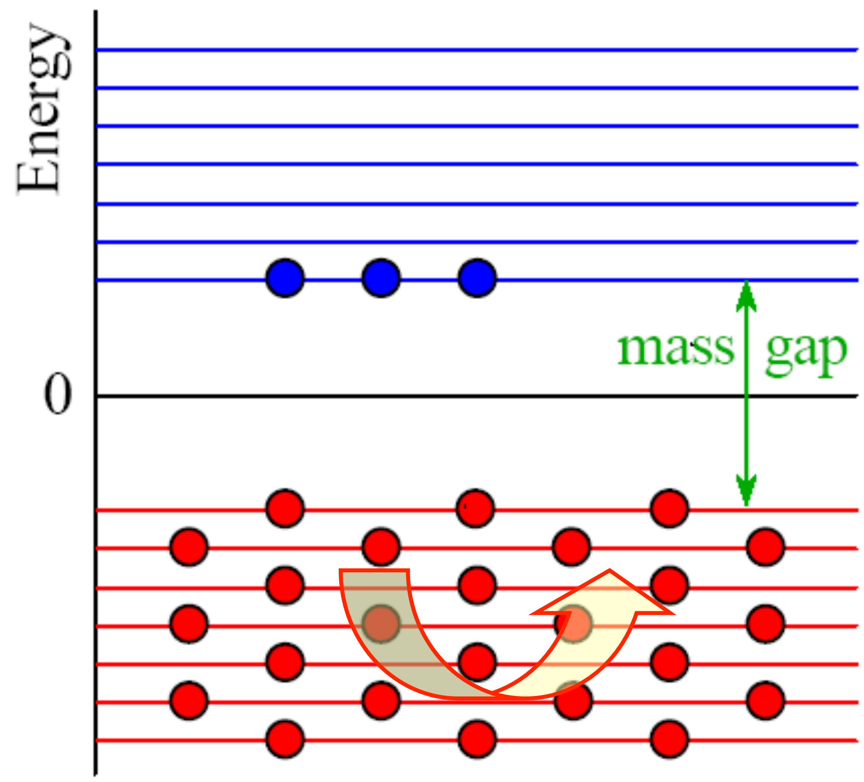

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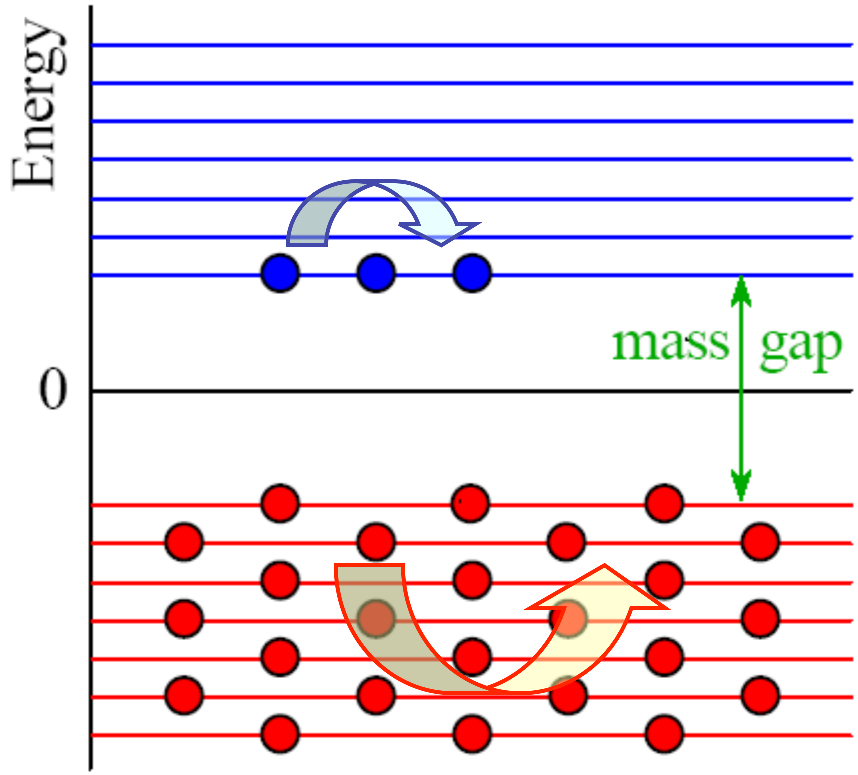

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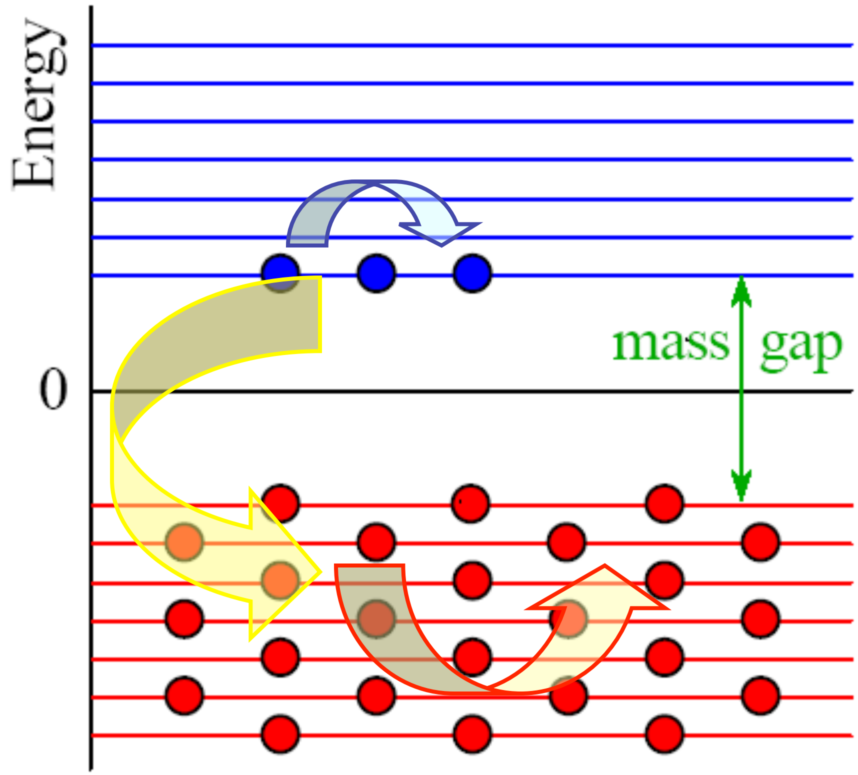

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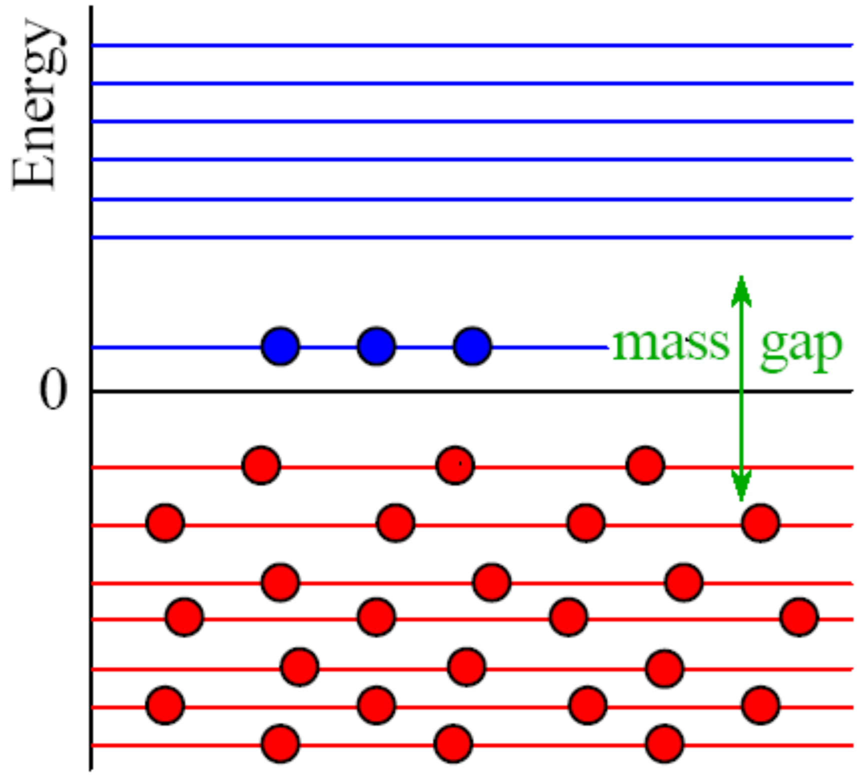
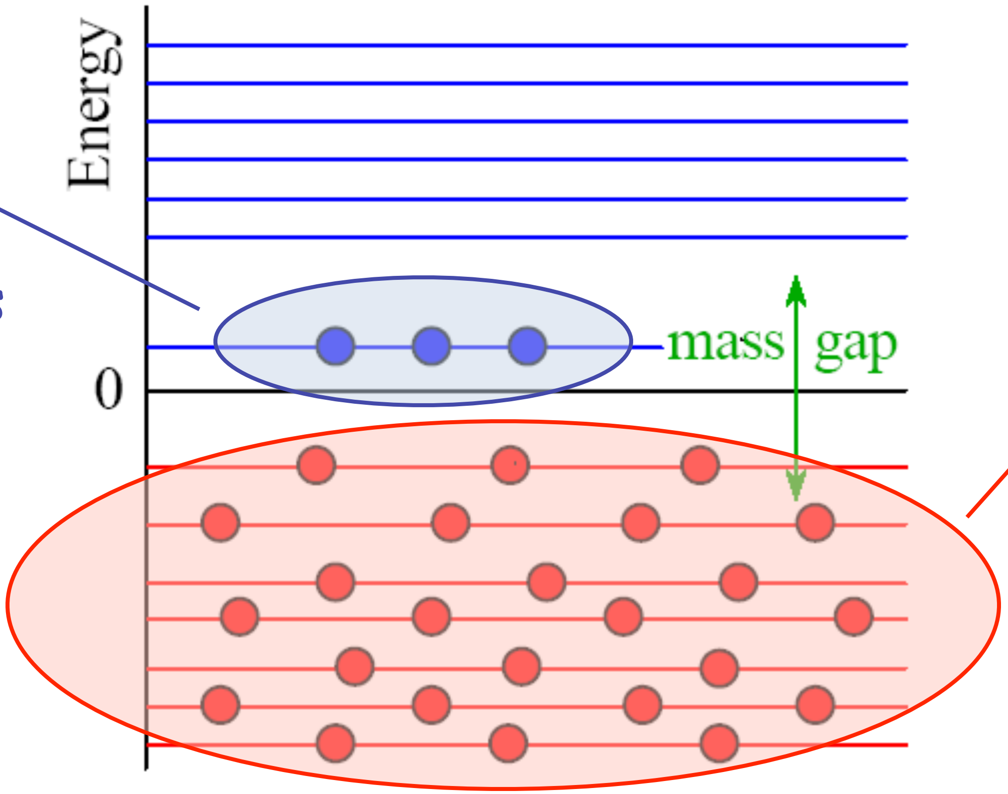


HChK et al. Prog. Part. Nucl. Phys. Vol.95, (1995)

Chiral quark-soliton picture

valence
level:

energy
decreases



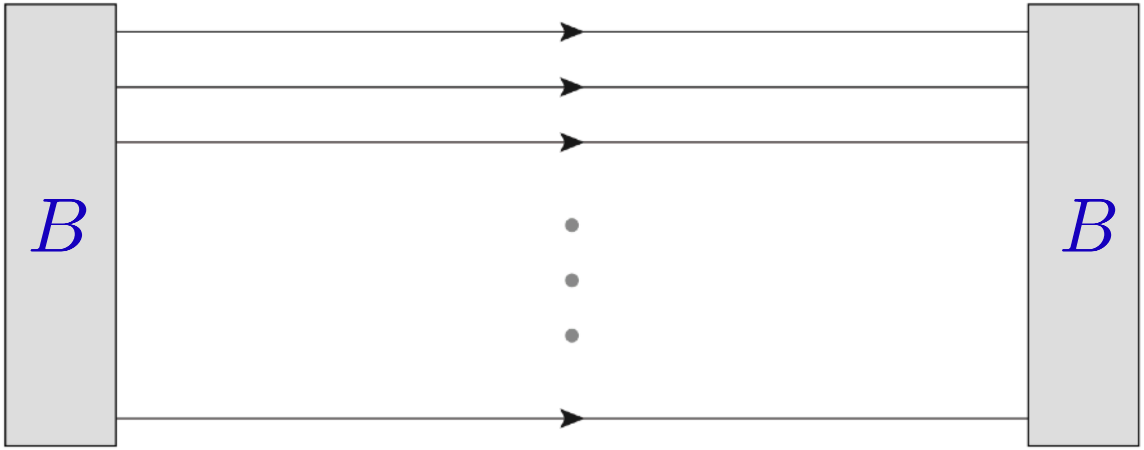
sea
levels:

energy
increases

system is stabilized

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

Light baryons in mean fields

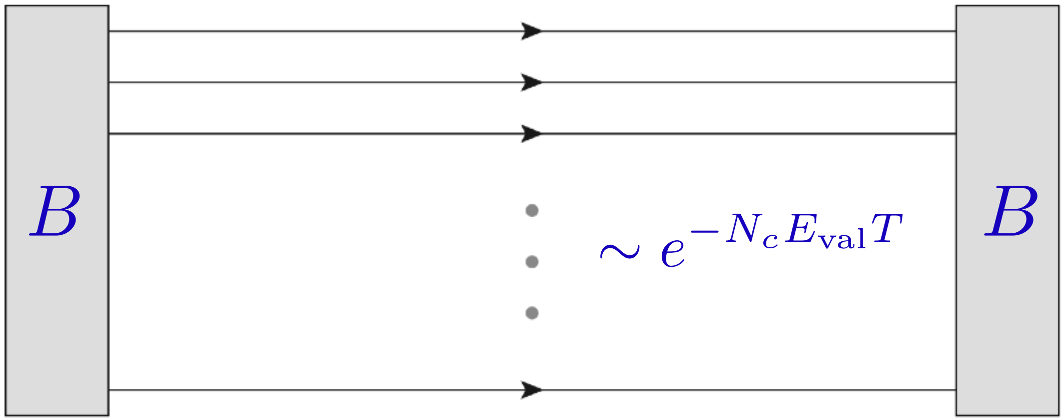


$$\langle J_B J_B^\dagger \rangle_0 \sim e^{-N_c E_{\rm val} T}$$

Presence of Nc quarks will polarize the vacuum or create mean fields.

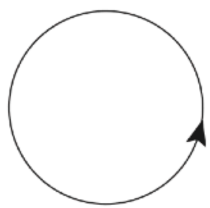
Nc valence quarks $\longrightarrow$ Vacuum polarization or meson mean fields

Light baryons in mean fields



$$\sim e^{-N_c E_{\rm val} T}$$

$$E_{\rm cl} = N_c E_{\rm val} + E_{\rm sea}$$



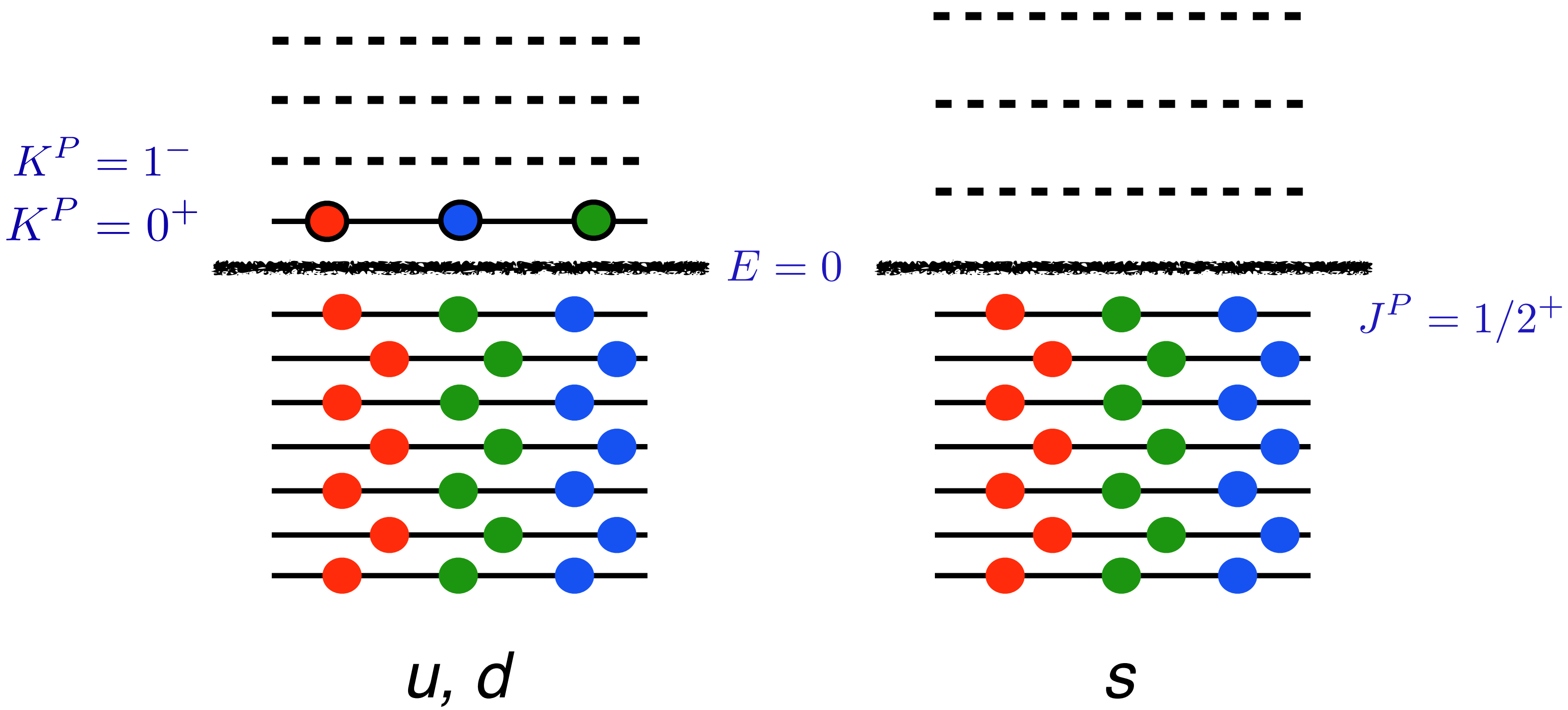
$$\sim e^{-E_{\rm sea} T}$$

Classical Nucleon mass is described by the Nc valence quark energy and sea-quark energy.

$$\frac{\delta E_{cl}}{\delta U} = 0 \longrightarrow M_{\rm cl} \longrightarrow P(r)$$

P(r): Soliton profile function
or Soliton field

Light baryons in mean fields



- u,d quark levels are classified by the grand spin K^P.
- s quark levels are classified by the grand spin J^P.

Grand spin: $\boldsymbol{K} = \boldsymbol{J} + \boldsymbol{T}$

$$\boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S}$$

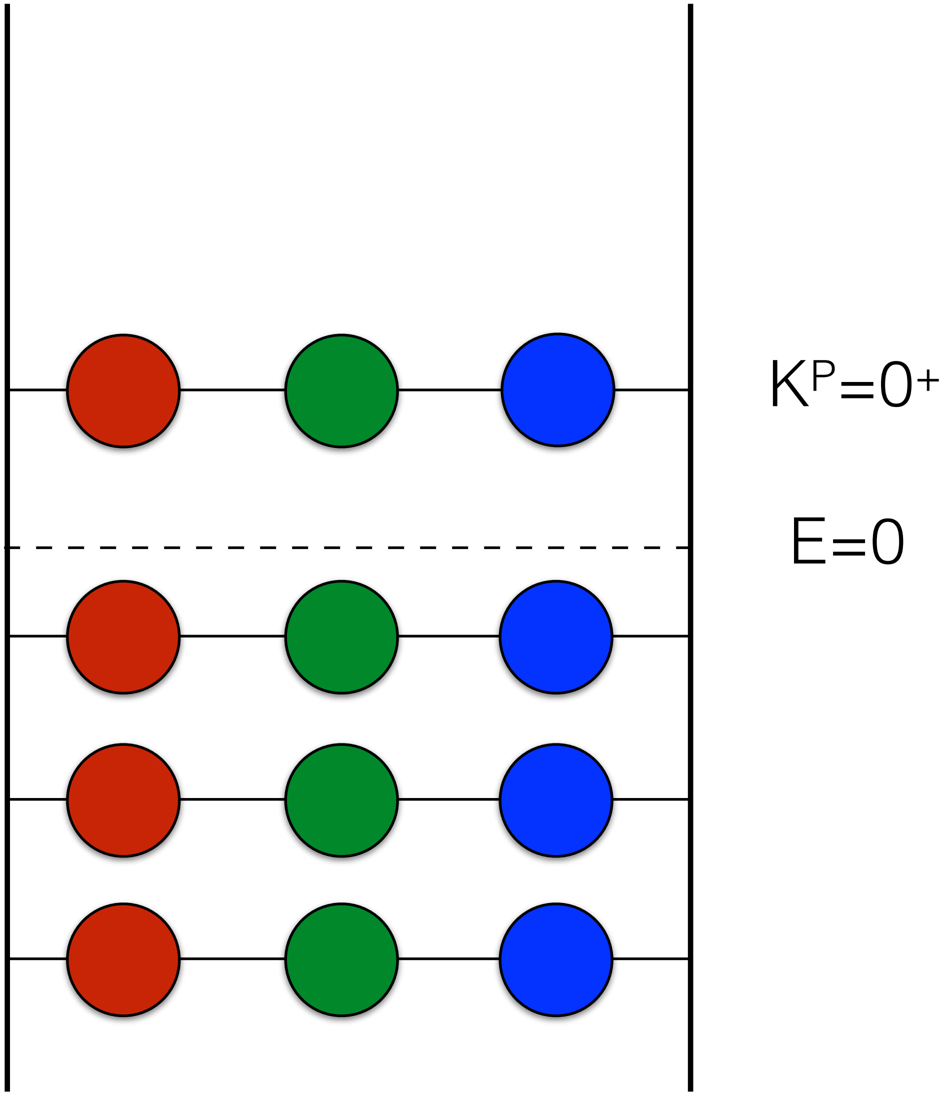
Lowest-lying light baryons

$$\boldsymbol{K} = \boldsymbol{J} + \boldsymbol{T} = \mathbf{0}, \quad T_8 = \frac{N_c}{2\sqrt{3}}$$

Right hypercharge

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

- Nc quark gives the baryon number in the XQSM.



Ground state

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

Collective Quantization

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

Witten's embedding

Collective (Zero-mode) quantization

$$\boxed{\begin{aligned} U(\boldsymbol{x},t) &= R(t)U_c(\boldsymbol{x}-\boldsymbol{Z}(t))R^\dagger(t) \\ \int DU[\cdots] &\rightarrow \int DAD\boldsymbol{Z}[\cdots] \end{aligned}}$$

$$\Rightarrow \quad \mathcal{L} = -M_{sol} + \frac{I_1}{2}\sum_{i=1}^{3}{\Omega_i}^2 + \frac{I_2}{2}\sum_{i=4}^{7}{\Omega_i}^2 + \frac{N_c}{2\sqrt{3}}\Omega_8$$

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

Collective Hamiltonian

Collective rotational Hamiltonian

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

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

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.

Success of the XQSM in the light baryon sector

- Connection to QCD via the instanton vacuum (natural scale) $\rho \approx 600\,\mathrm{MeV}$
- The mass splittings of the lowest-lying hyperons
- **All different types of baryon form factors**
- Parton distribution amplitudes (u-d asymmetry, transversity)
- Quasi-parton distribution amplitudes
- GPDs

Two different directions for further development

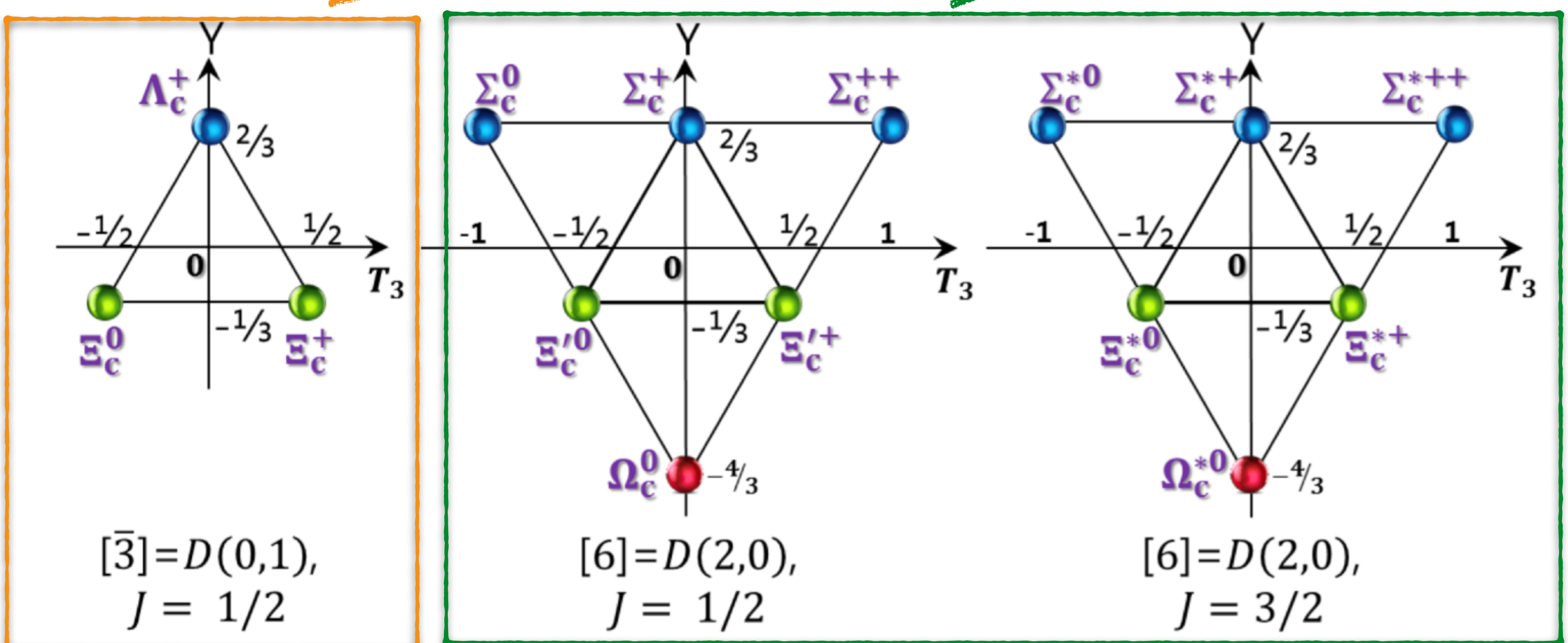
Heavy baryon sector

Excited baryon sector

Singly heavy baryons in SU(3)

- 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.

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



Heavy baryons

* Valence quarks are bound by the meson mean fields.
* Light quarks govern a heavy-light quark system.
* Heavy quarks can be simply viewed as **static color sources.**

$$\boldsymbol{K} = \boldsymbol{J} + \boldsymbol{T} = 0, \quad T_8 = \frac{N_c - 1}{2\sqrt{3}}$$ Ground-state heavy baryons

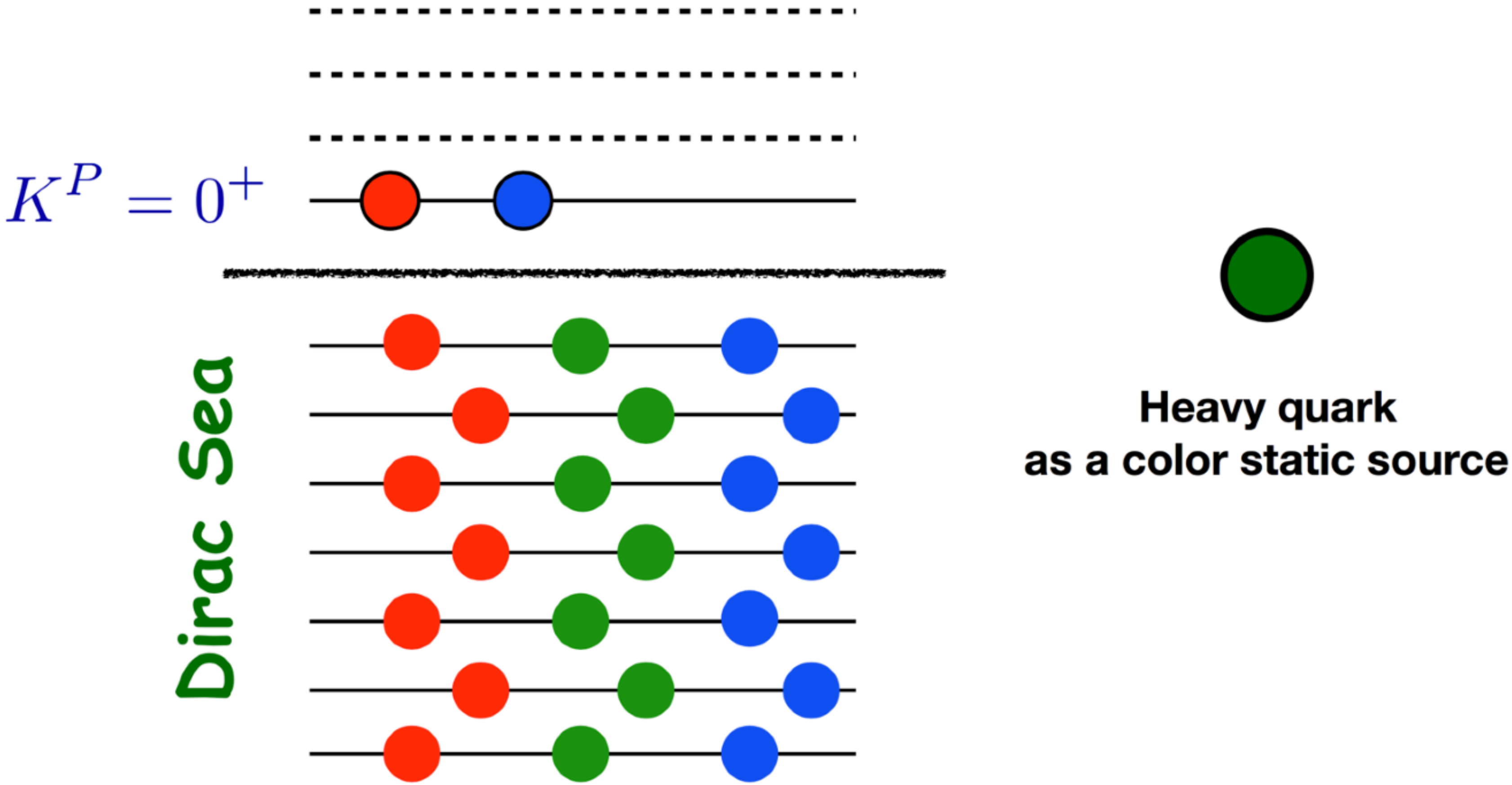
Right hypercharge $$Y' = \frac{N_c - 1}{3}$$

A heavy quark: Static color source to make a heavy baryon color singlet.

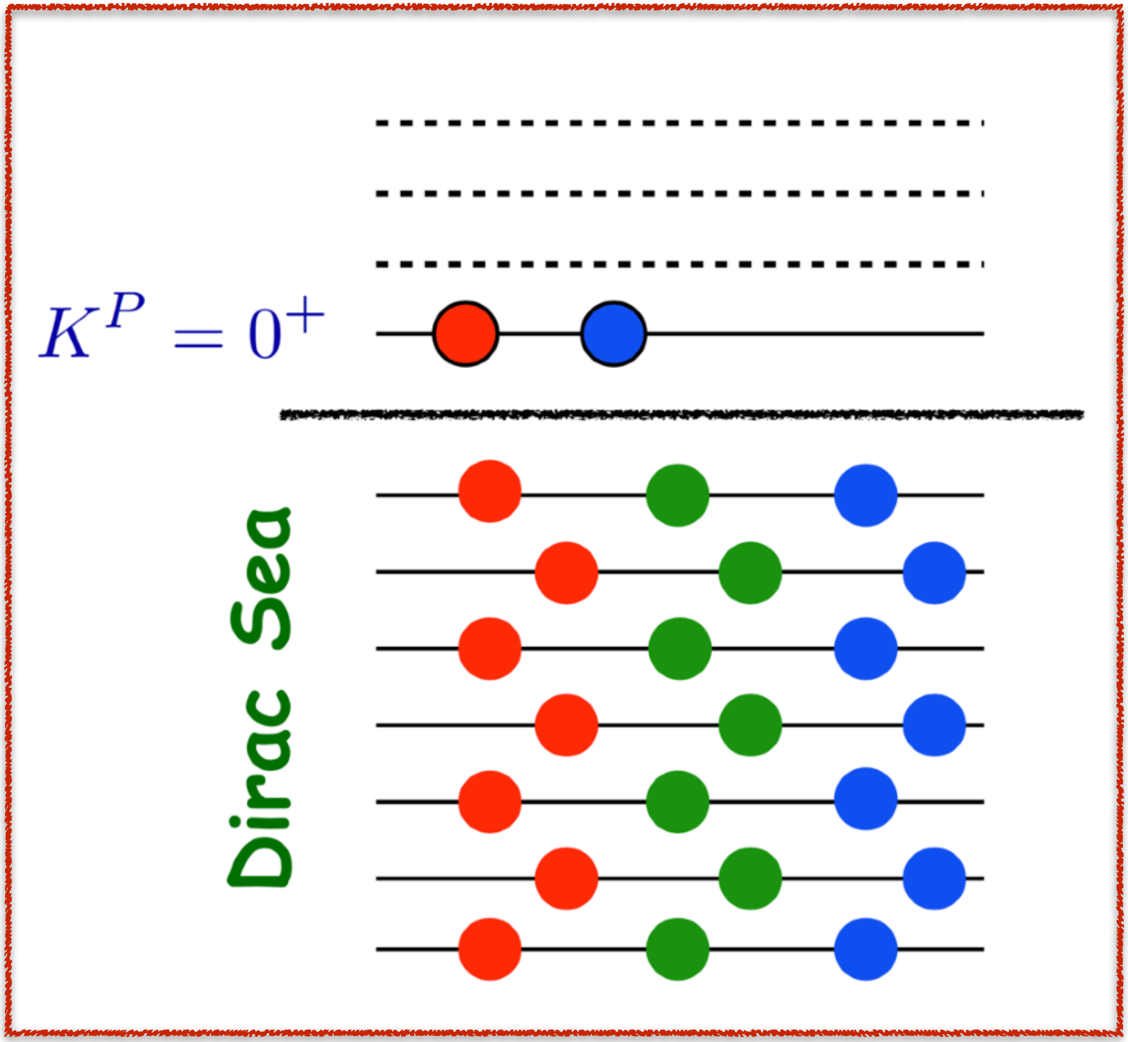
D. Diakonov, arXiv:1003.2157 [hep-ph].

Gh.S. Yang, HChK, M. Polyakov, M. Praszalowicz, PRD **94**, 071501(R) (2016)

Heavy baryons



Heavy baryons



Nc-1 light quarks govern a singly heavy baryon.

Heavy baryons

Nc-1 quarks represent heavy-baryon spectra.

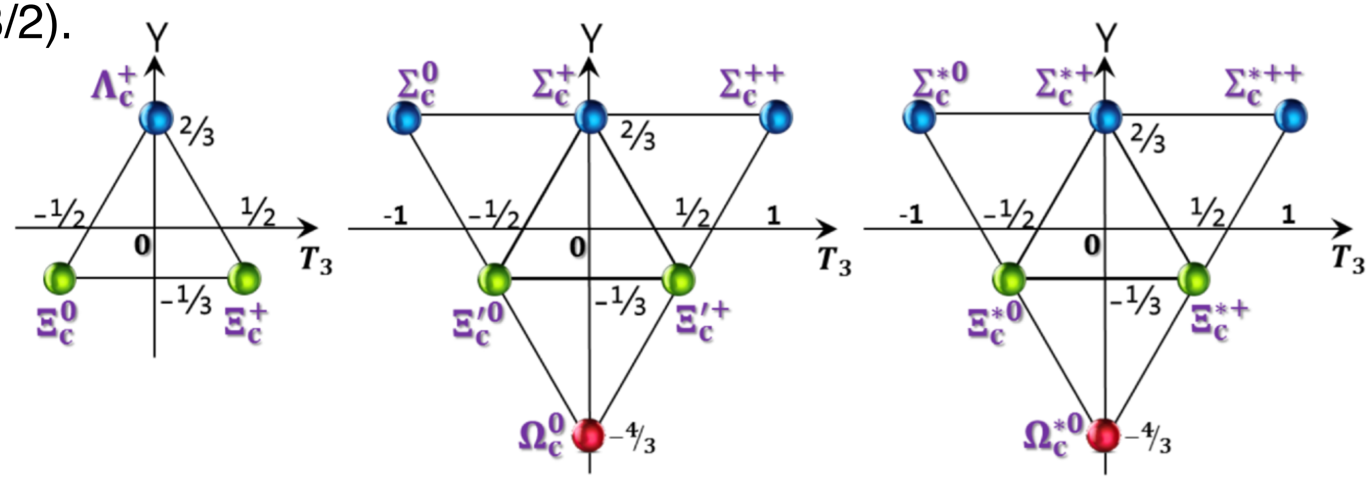
$$Y' = \frac{N_c - 1}{3}$$

Grand spin: $K = 0 \to T = J$

- The lowest rotationally excited states $\mathbf{3} \times \mathbf{3} = \overline{\mathbf{3}} + \mathbf{6}$

✱ T=0 for a anti-triplet: J=0 for it. Combining a charm quark with spin 1/2, we have one anti-triplet.

✱ T=1 for a sextet: J=1. We have two sextets with a charm quark. (1/2, 3/2).



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

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

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

$Y' = 2/3$

SU(3) symmetry breaking

- The collective Hamiltonian for SU(3) symmetry breaking

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

In the light-quark sector, we have fixed already these dynamical parameters as

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

SU(3) symmetry breaking

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In the light-quark sector, we have fixed already these dynamical parameters as

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

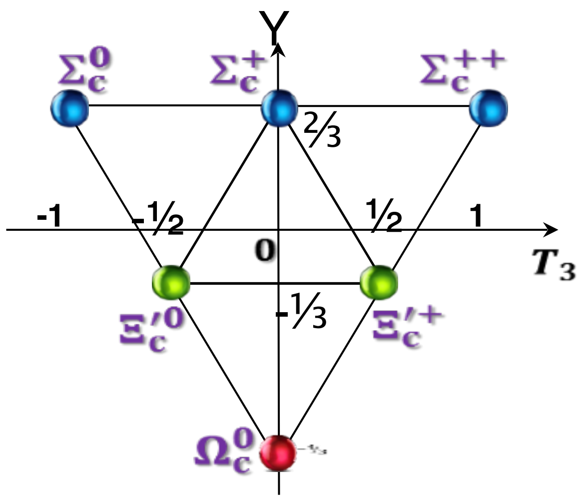
$$\beta = -\frac{m_s K_2}{I_2} = -(140.04 \pm 3.20)\,\mathrm{MeV}$$

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

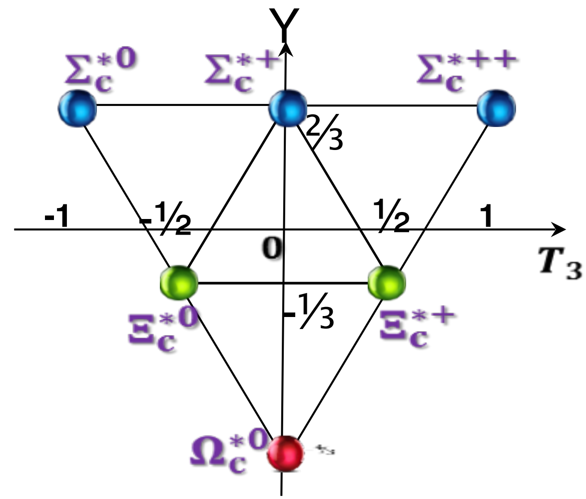
$$\alpha \to \bar{\alpha} = \frac{N_c - 1}{N_c}\alpha$$

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

Hyperfine mass splittings (only new parameter)



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



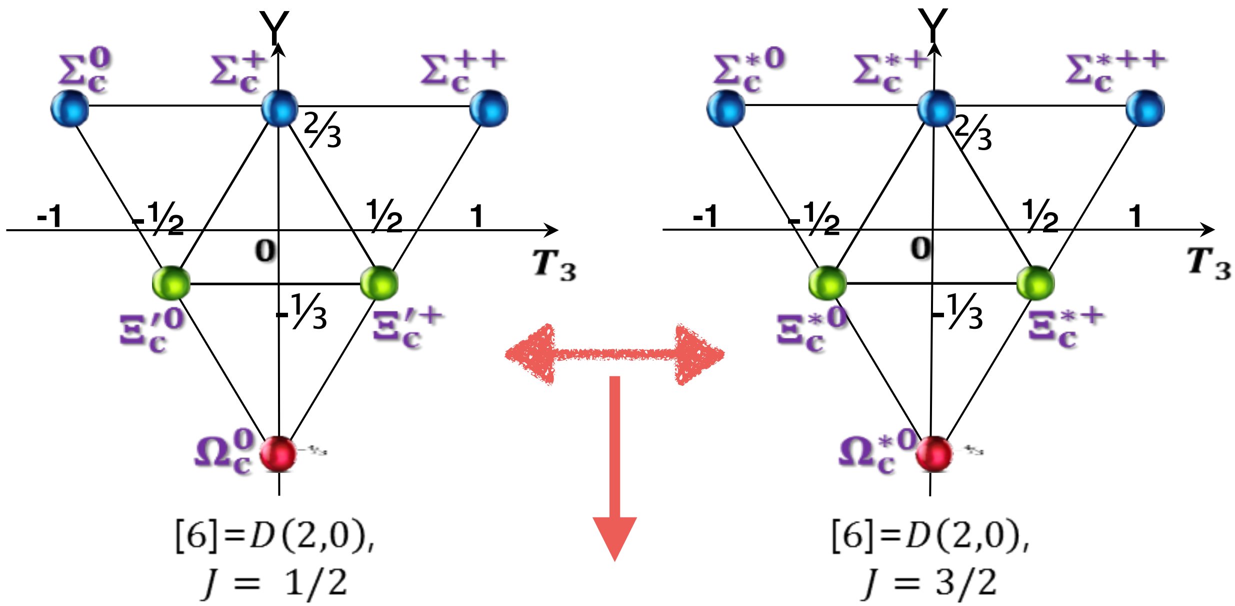
$[6]=D(2,0)$,
$J = 3/2$

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

Remind you that all the parameters are the same as in the light baryon sector except for the hyperfine interaction.

Gh.S. Yang, HChK, M. Polyakov, M. Praszalowicz, PRD **94**, 071501(R) (2016)

Hyperfine mass splittings (only new parameter)



Hyperfine splitting between different spin states

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

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

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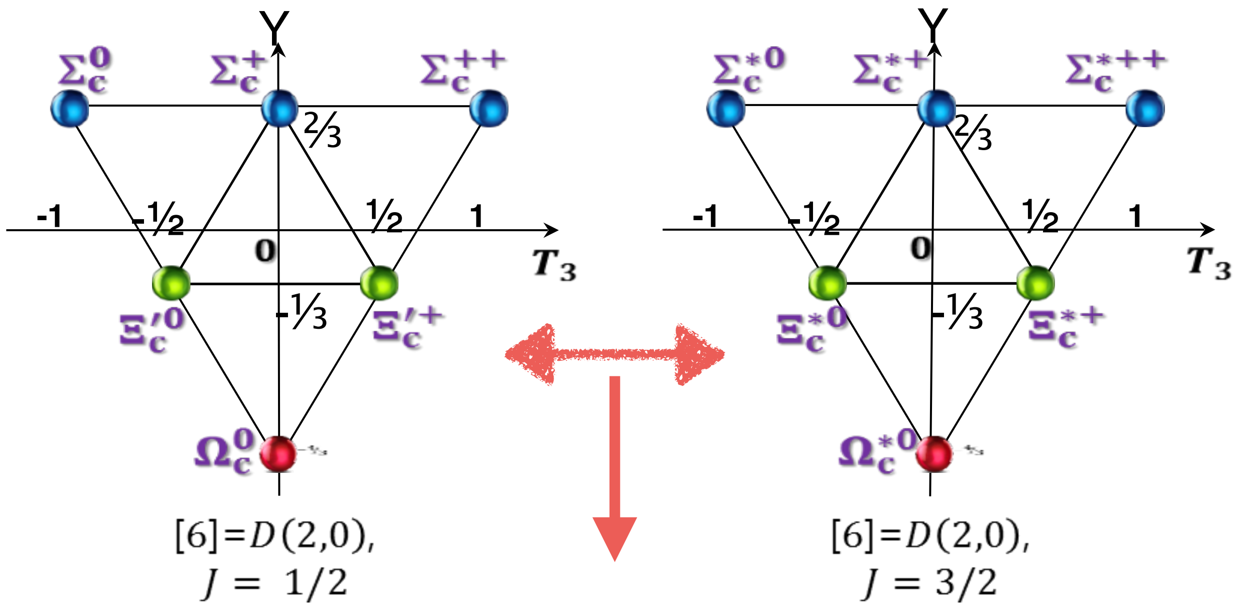

Hyperfine splitting between different spin states

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

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

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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

The results are in remarkable agreement with the experimental data.

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

Gh.S. Yang, HChK, M. Polyakov, M. Praszalowicz, PRD **94**, 071501(R) (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	$-$	$-$

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

Gh.S. Yang, HChK, M. Polyakov, M. Praszalowicz, PRD **94**, 071501(R) (2016)

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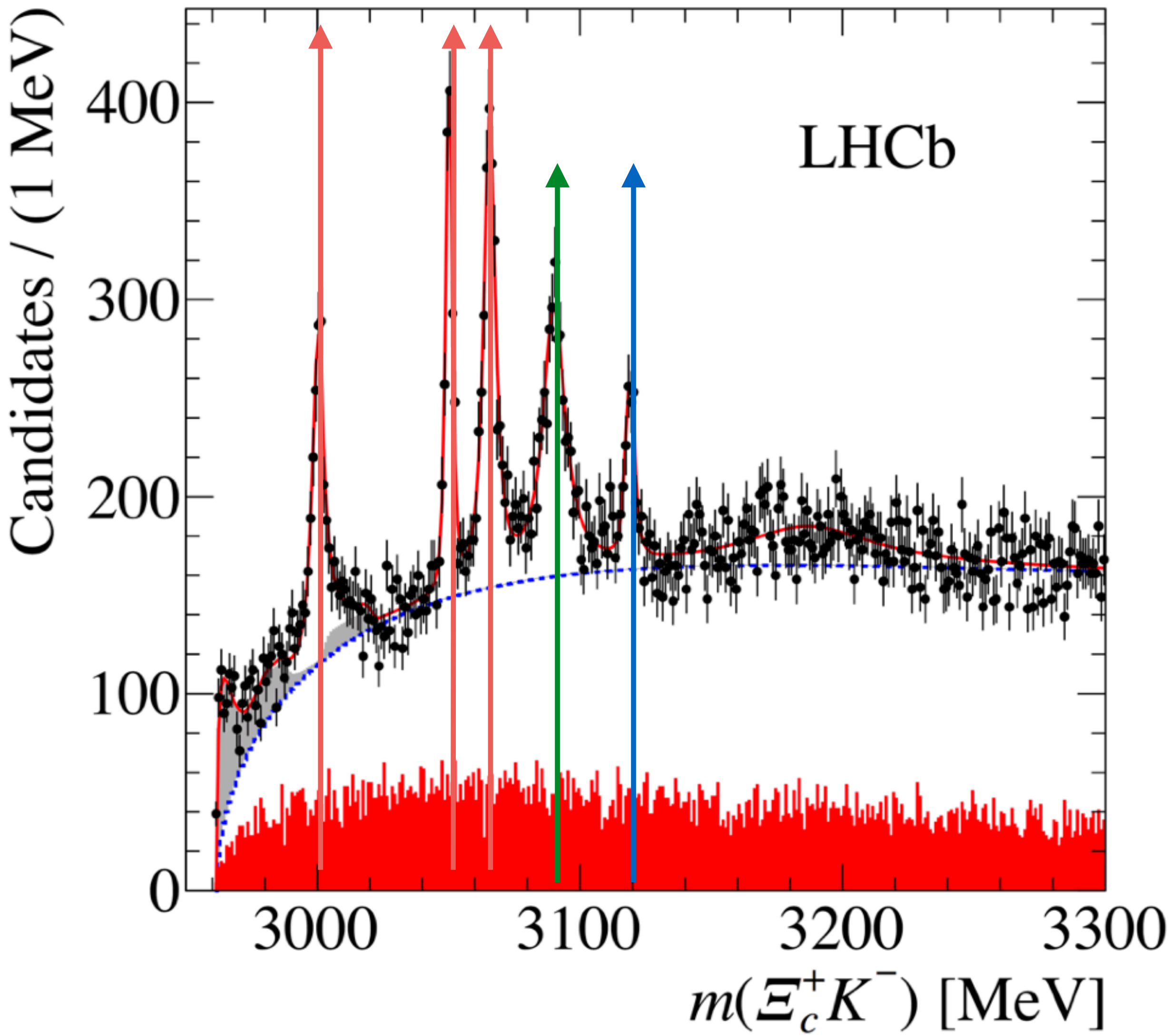
Prediction from the present work

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

Gh.S. Yang, HChK, M. Polyakov, M. Praszalowicz, PRD **94**, 071501(R) (2016)

LHCb Findings: New five Omega_cs

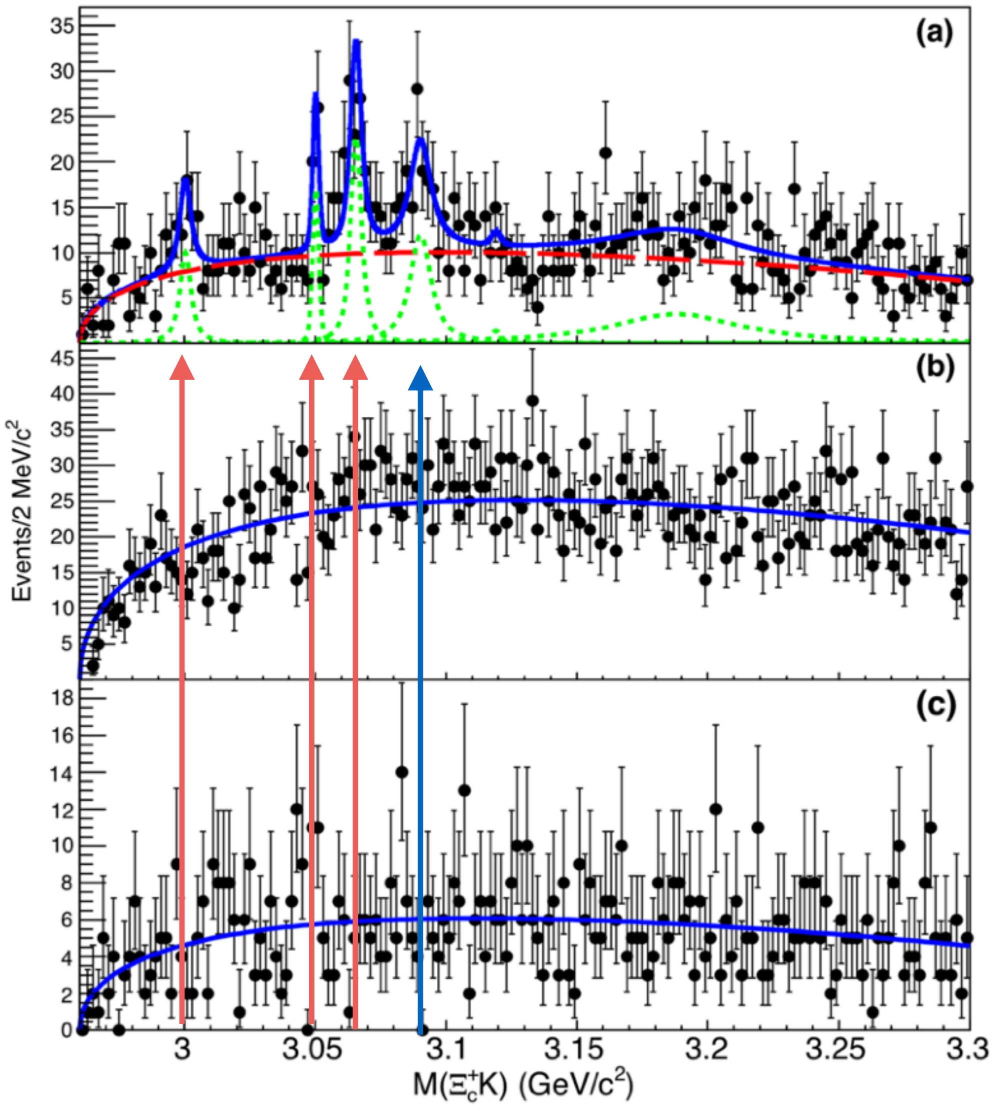


Refer to
Yangxi Zhang's talk

Five Ω_cs were announced by LHCb Coll.

LHCb Collaboration, PRL 118 (2017) 182001

Belle Findings: Four Omega_cs confirmed



Four Ω_cs were confirmed by Belle Coll.

Refer to Masayuki Niiyama’s talk

Belle Collaboration, hep-ex 1711.07927

LHCb Findings: New five Omega_cs

The Widths are rather small, even if we consider the fact that heavy baryons have smaller widths than light ones.

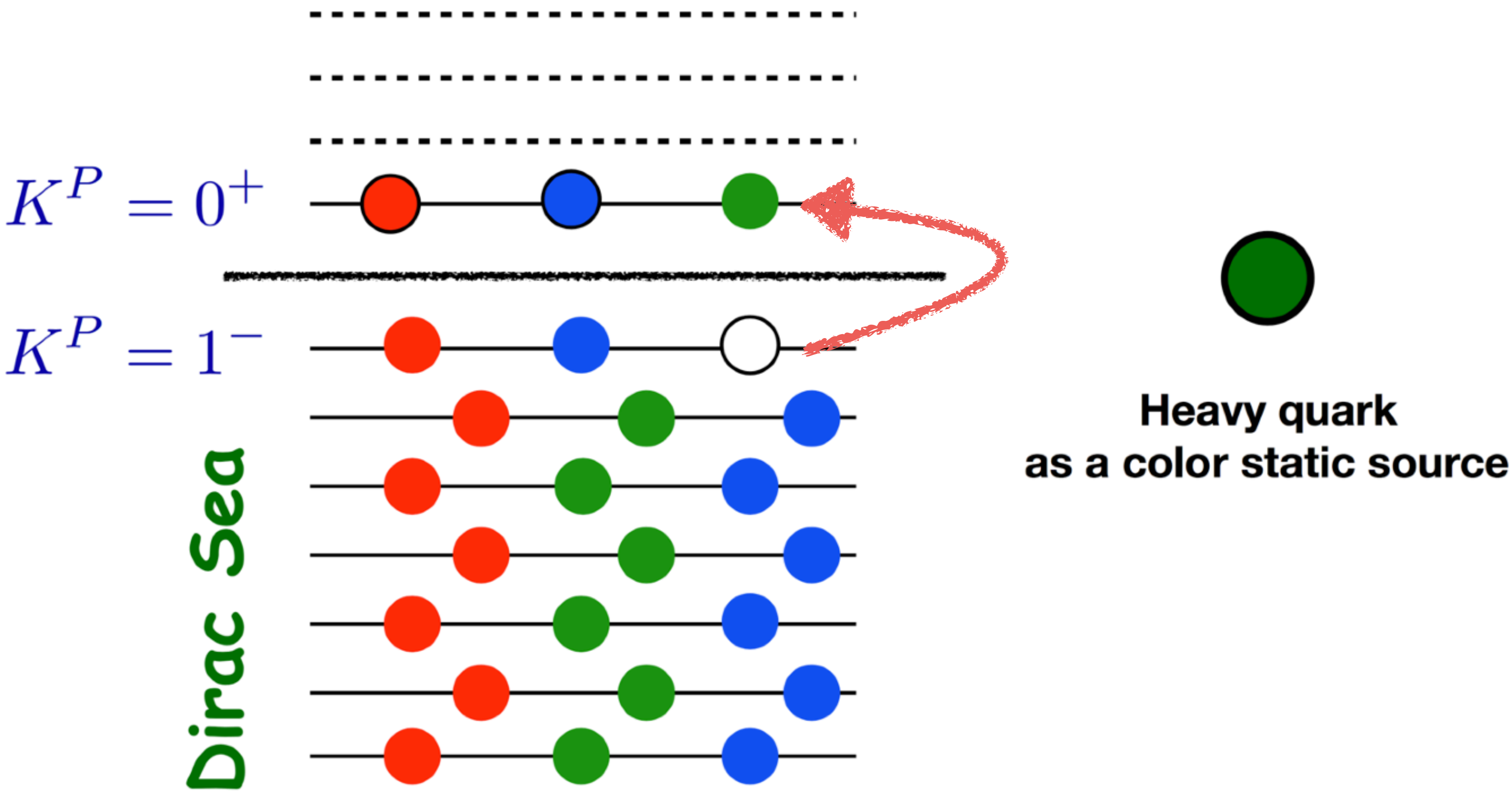
Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2\,\mathrm{MeV}, 95\%\ \mathrm{CL}$		
$\Omega_c(3066)^0$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

LHCb Collaboration, 2007

Ω_c Excited State Yield Significance	3000 37.7 ± 11.0 3.9σ	3050 28.2 ± 7.7 4.6σ	3066 81.7 ± 13.9 7.2σ	3090 86.6 ± 17.4 5.7σ	3119 3.6 ± 6.9 0.4σ	3188 135.2 ± 43.0 2.4σ
LHCb Mass	$3000.4 \pm 0.2 \pm 0.1$	$3050.2 \pm 0.1 \pm 0.1$	$3065.5 \pm 0.1 \pm 0.3$	$3090.2 \pm 0.3 \pm 0.5$	$3119 \pm 0.3 \pm 0.9$	$3188 \pm 5 \pm 13$
Belle Mass (with fixed Γ)	$3000.7 \pm 1.0 \pm 0.2$	$3050.2 \pm 0.4 \pm 0.2$	$3064.9 \pm 0.6 \pm 0.2$	$3089.3 \pm 1.2 \pm 0.2$	-	$3199 \pm 9 \pm 4$

Belle Collaboration, hep-ex 1711.07927

Excited anti-triplets and sextets



$K = J + T \neq 0$

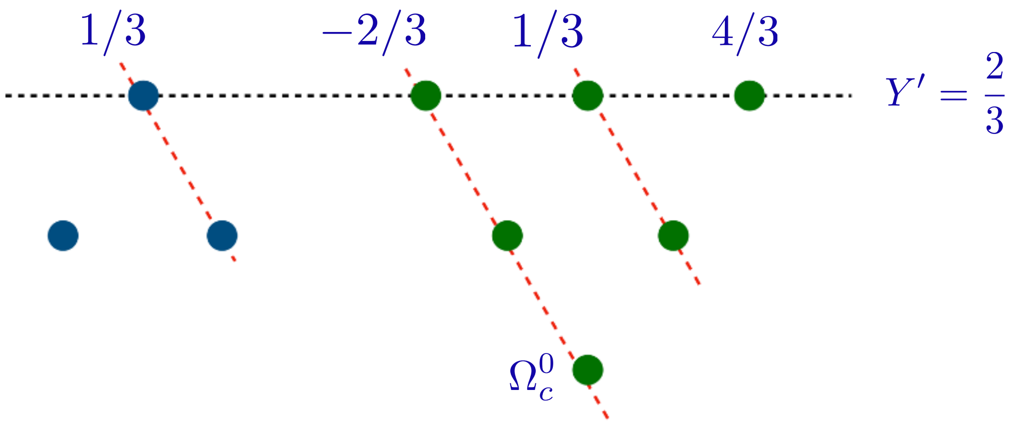
$J = |T - K|, \cdots |T + K|$

HChK, M. V. Polyakov, M. Praszalowicz, PRD **96**, 014009 (2017)

Excited anti-triplets and sextets

Grand spin: $K^p = 1^-$

- Quantization of excited baryons yield **two** anti-triplet and FIVE sextets.



$$\boldsymbol{K = J + T = 1}$$

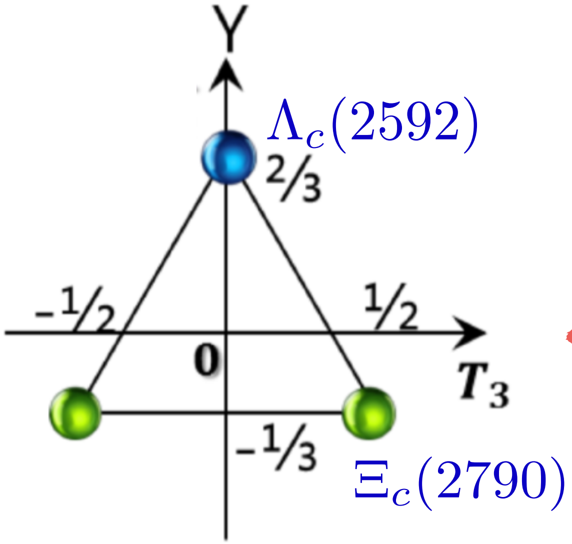
$$J = |T - K|, \cdots |T + K|$$

- **T=0** for a anti-triplet: J=1 for it. Combining a charm quark with spin 1/2, we have two anti-triplets.
- **T=1** for a sextet: J=0,1,2 for 6. We have five sextets with a charm quark. (1/2), (1/2, 3/2), and (3/2, 5/2)!

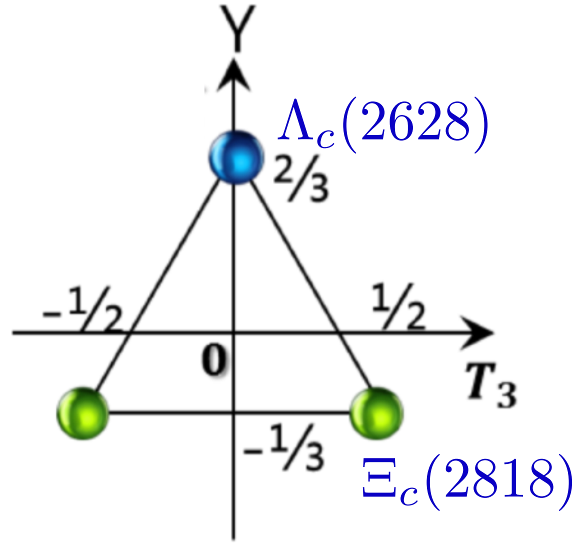
HChK, M. V. Polyakov, M. Praszalowicz, PRD **96**, 014009 (2017)

Hyperfine splittings for excited anti-triplets

- Candidates for excited anti-triplets



$J^p = 1/2^-$

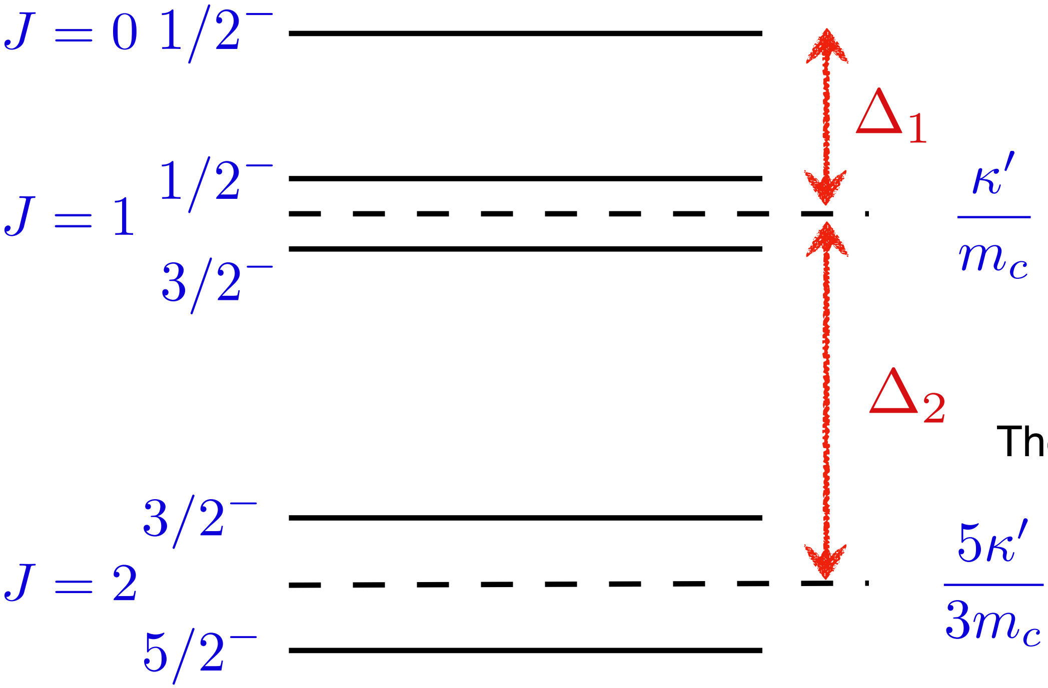


$J^p = 3/2^-$

$$\boxed{\frac{\kappa'}{m_c} \approx 30\,\mathrm{MeV}}$$

HChK, M. V. Polyakov, M. Praszalowicz, PRD **96**, 014009 (2017)

Hyperfine splittings for excited sextets



$$\Delta_1 = \frac{a_1}{I_1} + \frac{3}{20}\delta$$

$$\boxed{\Delta_2 = 2\Delta_1}$$

The robust relation from mean-field approach

- The mean-field approach (XQSM) predicts **five excited sextet states**!
- The splitting between J=1 and J=2 is twice as large as that between J=0 and J=1.($\Delta_2 = 2\Delta_1$)

HChK, M. V. Polyakov, M. Praszalowicz, PRD **96**, 014009 (2017)

Scenario I

Assertion: Five Ω_c^*s belong to excited sextets.

J	S^P	M [MeV]	κ'/m_c [MeV]	Δ_J [MeV]
0	$\frac{1}{2}^-$	3000	–	–
1	$\frac{1}{2}^-$	3050	16	61
	$\frac{3}{2}^-$	3066		
2	$\frac{3}{2}^-$	3090	17	47
	$\frac{5}{2}^-$	3119		

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$$\frac{\kappa'}{m_c} = 30\,\mathrm{MeV}$$

The HF splittings are very much **deviated** from what we have determined from the excited anti-triplet.

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$\Delta_2 = 2\Delta_1$

This relation is badly broken.

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The HF splittings are very much **deviated** from what we have determined from the excited anti-triplet.

Scenario II

Assertion: **Three** Ω_c^*s belong to excited sextets, whereas **two** Ω_c^*s with smaller widths are the members of the anti-15plet.

J	S^P	M [MeV]	κ'/m_c [MeV]	Δ_J [MeV]
0	$\frac{1}{2}^-$	3000	–	–
1	$\frac{1}{2}^-$	3066	24	82
	$\frac{3}{2}^-$	3090		
2	$\frac{3}{2}^-$	*3222*	input	input
	$\frac{5}{2}^-$	*3262*	24	164

What about other two Ω_c^* s?

- We assume that Omega(3050) and Omega(3119) belong to the **third** rotational excitation of the ground states: They will be then **pentaquarks**!

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This relation is satisfied.

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This relation is satisfied.

Bump structure above 3.2 GeV in the data

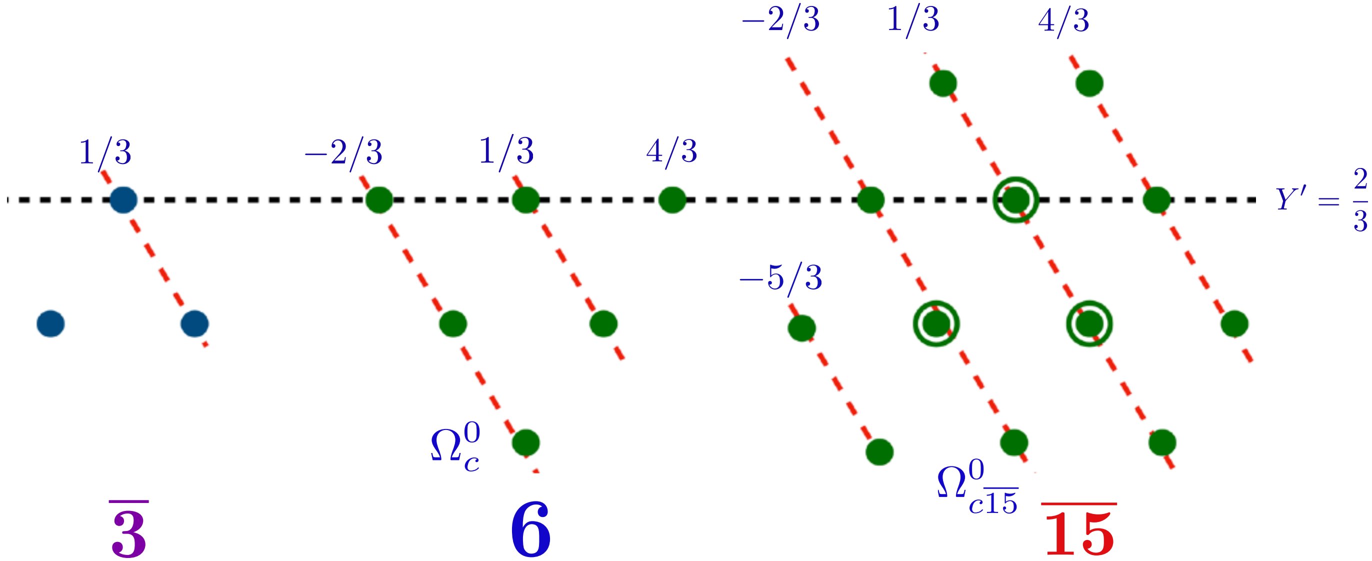
$\kappa'/m_c \approx 30\,\mathrm{MeV}$

What about other two Ω_c^* s?

- We assume that Omega(3050) and Omega(3119) belong to the **third** rotational excitation of the ground states: They will be then **pentaquarks**!

Anti-15plet

* In the heavy-quark sector, we have yet the third representation, i.e. the anti-15plet.



For the anti-15plet

$T = 1 \to J = 1$ Combined with a charm quark: $1 \otimes \frac{1}{2} = \frac{1}{2} \oplus \frac{3}{2} \in \overline{\mathbf{15}}$

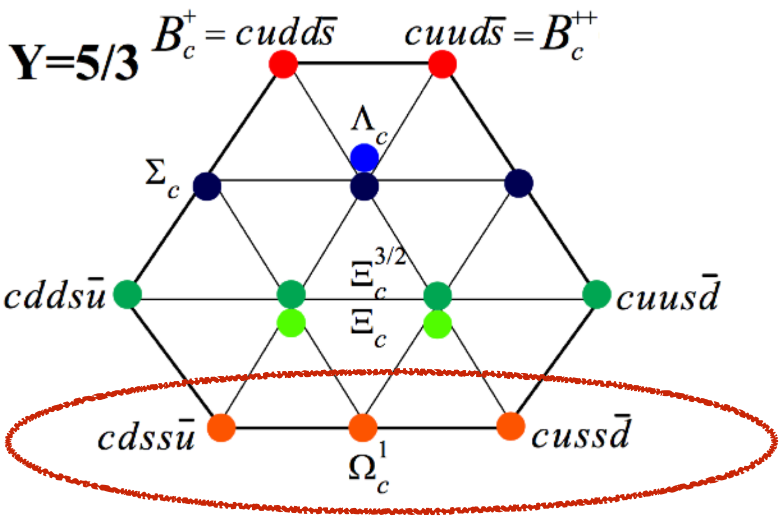
In the limit of infinitely heavy quark mass, 1/2 & 3/2 are degenerate, which will be lifted by a hyperfine interaction.

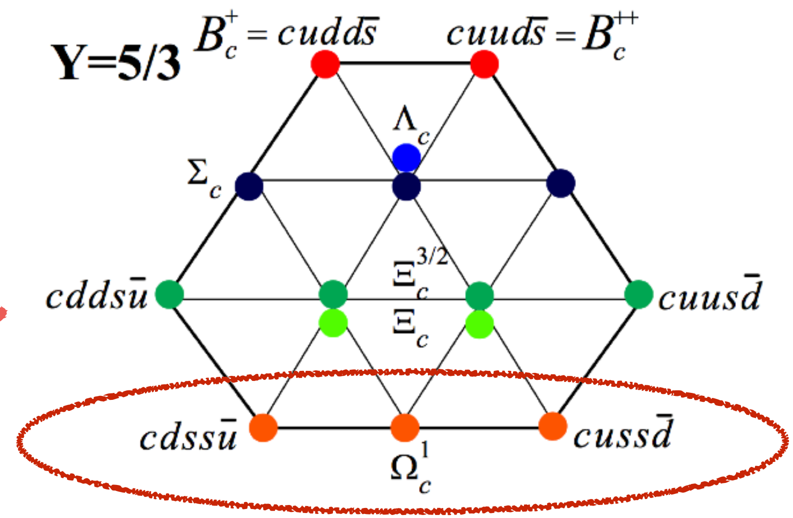
$\Omega_c(3050)1/2^+ \quad \Omega_c(3119)3/2^+$: $M_{\Omega_c(3/2^+)} - M_{\Omega_c(1/2^+)} \simeq 69\,\mathrm{MeV}\,!$

$\frac{\kappa}{m_c} = (68.1 \pm 1.1)\,\mathrm{MeV}$ in **excellent agreement** with the ground-state value!

Anti-15plet

- Exotic anti-15plet naturally arises from the XQSM.



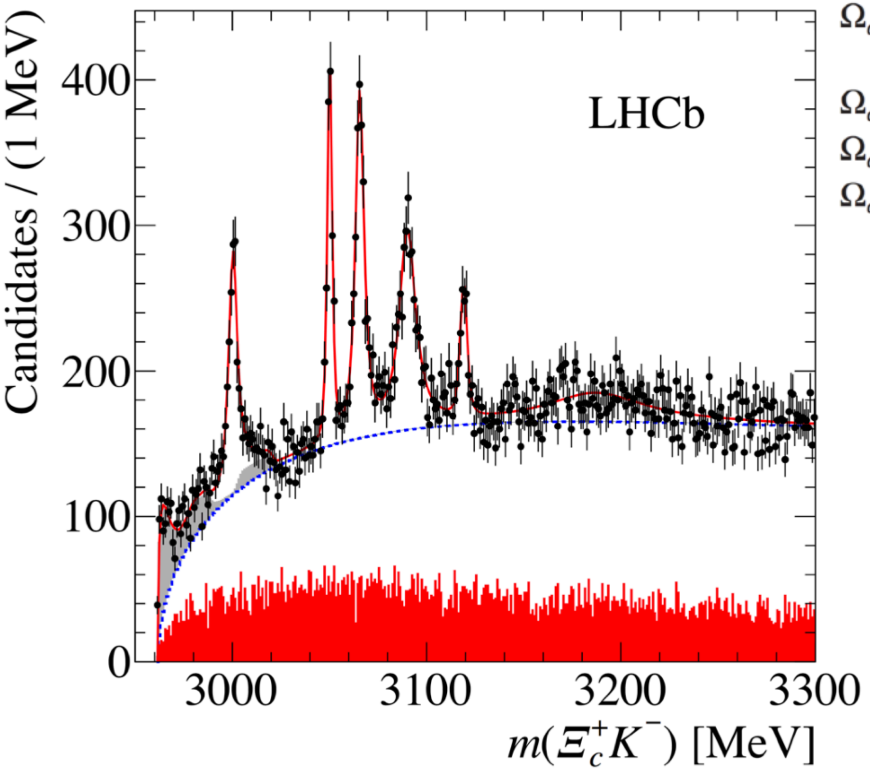


$J = 1/2$ $\qquad \dfrac{\kappa}{m_c} = (68.1 \pm 1.1)\,\mathrm{MeV}$ $\qquad J = 3/2$

- All parameters were fixed in the light baryon sector except for the hyperfine interaction.
- Considering almost all theoretical uncertainties, we get the following: $\mathcal{M}_{\Omega_c} = (3140 - 3370)\,\mathrm{MeV}$

Interpretation of the LHCb data

In the present picture



Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$ <1.2 MeV, 95% C.L.
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$

J	S^P	M [MeV]	κ'/m_c [MeV]	Δ_J [MeV]
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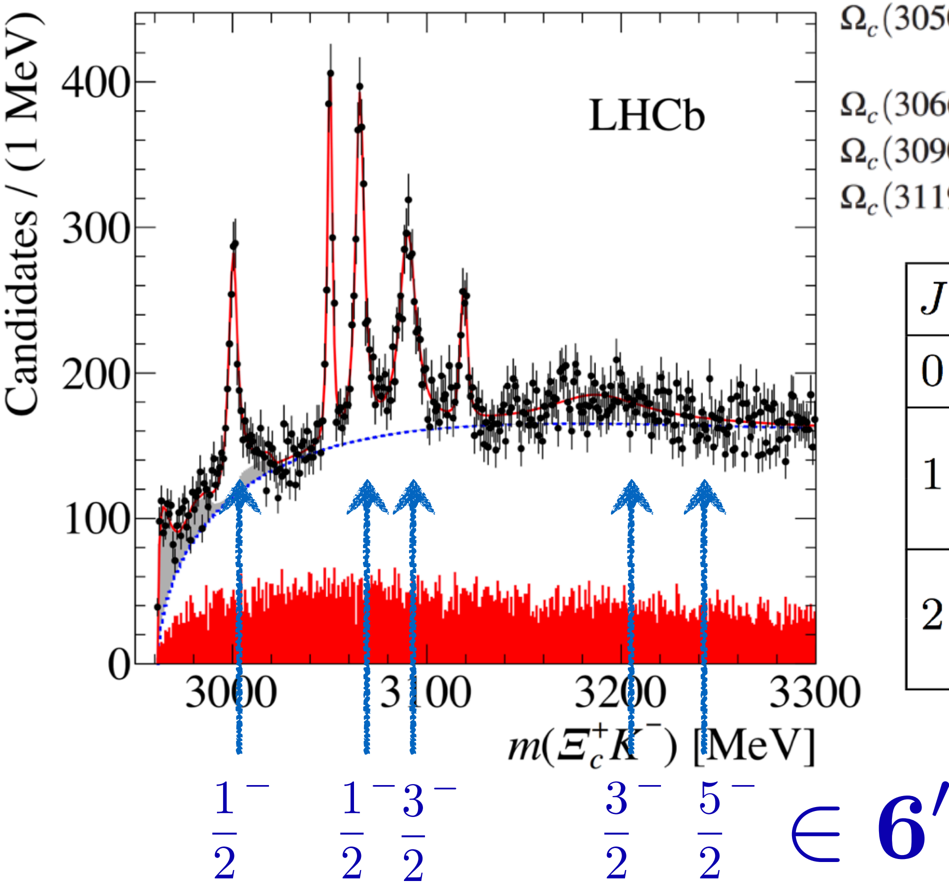

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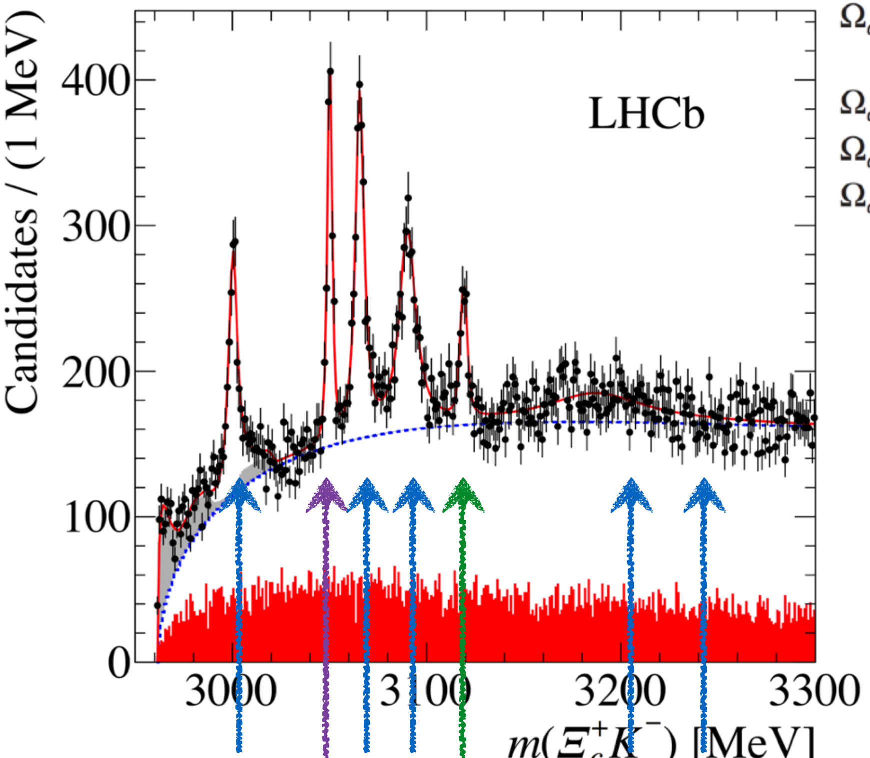

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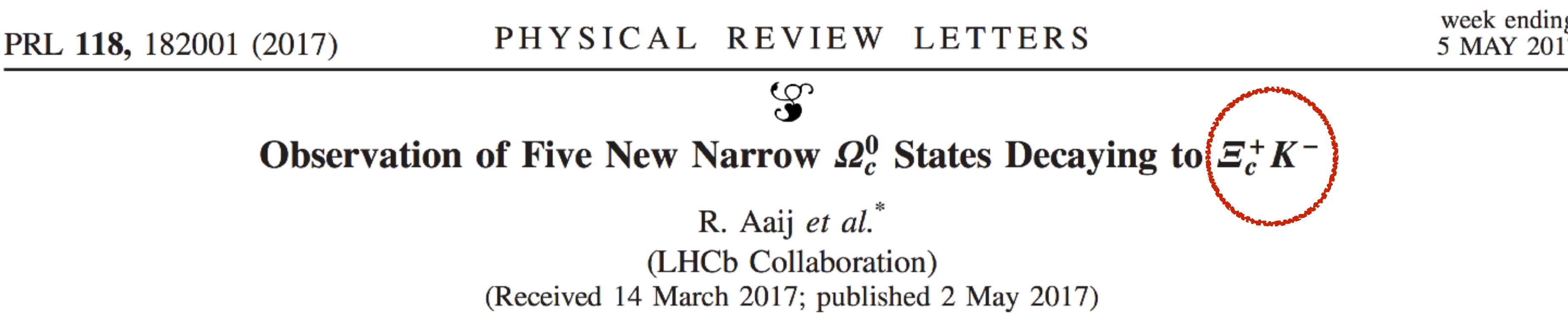
$\frac{1}{2}^-$ $\frac{1}{2}^-$ $\frac{3}{2}^-$ $\frac{3}{2}^-$ $\frac{5}{2}^-$ $\in \mathbf{6'}$

$\frac{1}{2}^+$ $\frac{3}{2}^+$ $\in \overline{\mathbf{15}}$ $\Omega_c(3050)$ & $\Omega_c(3119)$

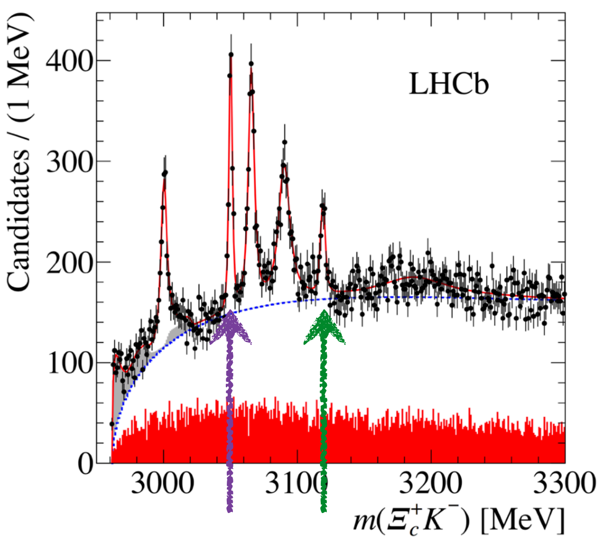
How can one falsify the present idea?


PRL **118,** 182001 (2017) PHYSICAL REVIEW LETTERS week ending 5 MAY 2017

Observation of Five New Narrow Ω_c^0 States Decaying to $\Xi_c^+ K^-$

R. Aaij *et al.**
(LHCb Collaboration)
(Received 14 March 2017; published 2 May 2017)

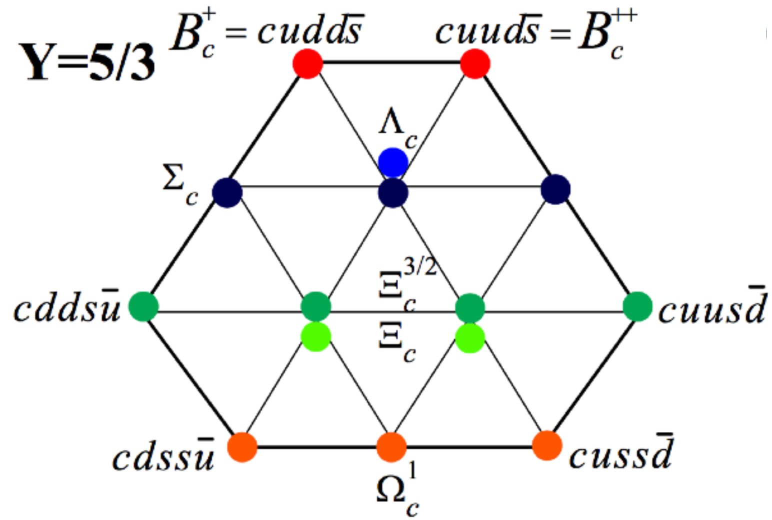
- Anti-15plet consists of **three** Omega_cs (Isovector baryons).
- The same peaks with the same strength can be found not only in the $\Xi_c^+ K^-$ channel but also in $\Xi_c^+ K^0$ and $\Xi_c^0 K^-$.



$\Omega_c(3050)$ & $\Omega_c(3119)$

LHCb Findings: New five Omega_cs

	Y	T	$S^P = \frac{1}{2}^+$	$S^P = \frac{3}{2}^+$
B_c	$\frac{5}{3}$	$\frac{1}{2}$	2685	2754
Σ_c	$\frac{2}{3}$	1	2808	2877
Λ_c	$\frac{2}{3}$	0	2806	2875
Ξ_c	$-\frac{1}{3}$	$\frac{1}{2}$	2928	2997
$\Xi_c^{3/2}$	$-\frac{1}{3}$	$\frac{3}{2}$	2931	3000
Ω_c	$-\frac{4}{3}$	1	3050	3119



Bc baryons will decay weakly, if they exist.
So, they should be stable.

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

Decay widths of Ω_cs

- Collective operator for the strong vertices in SU(3) symmetric case

$$\mathcal{O}_\varphi = \frac{3}{M_1+M_2}\sum_{i=1,2,3}\left[G_0 D^{(8)}_{\varphi\, i} - G_1\, d_{ibc}D^{(8)}_{\varphi\, b}\hat{S}_c - G_2\frac{1}{\sqrt{3}}D^{(8)}_{\varphi\, 8}\hat{S}_i\right]p_i$$

- Decay widths

$$\Gamma_{B_1\to B_2+\varphi} = \frac{1}{2\pi}\overline{\langle B_2\,|\mathcal{O}_\varphi|\,B_1\rangle^2}\frac{M_2}{M_1}p$$

$$G_0 = -\frac{M+M'}{6f_\varphi}a_1$$

$$G_{1,2} = \frac{M+M'}{6f_\varphi}a_{2,3}$$

a_1	a_2	a_3
-3.509 ± 0.011	3.437 ± 0.028	0.604 ± 0.030

G. Yang and HChK, PRC **92**, 035206 (2015)

No additional free parameter!

$$f_\pi = 93\,\mathrm{MeV}, \quad f_K = 1.2 f_\pi$$

- These parameters a_i have been determined by the hyperon semileptonic decays.

HChK, Polyakov, Praszalowicz, Yang, PRD, D96, 094021 (2017).

Decay widths of Ω_cs

- Decay widths of the **charm** baryon sextet

No additional free parameter!

#	decay	this work	exp.
1	$\Sigma_c^{++}(\mathbf{6}_1, 1/2) \to \Lambda_c^+(\overline{\mathbf{3}}_0, 1/2) + \pi^+$	1.93	$1.89^{+0.09}_{-0.18}$
2	$\Sigma_c^{+}(\mathbf{6}_1, 1/2) \to \Lambda_c^+(\overline{\mathbf{3}}_0, 1/2) + \pi^0$	2.24	< 4.6
3	$\Sigma_c^{0}(\mathbf{6}_1, 1/2) \to \Lambda_c^+(\overline{\mathbf{3}}_0, 1/2) + \pi^-$	1.90	$1.83^{+0.11}_{-0.19}$
4	$\Sigma_c^{++}(\mathbf{6}_1, 3/2) \to \Lambda_c^+(\overline{\mathbf{3}}_0, 1/2) + \pi^+$	14.47	$14.78^{+0.30}_{-0.19}$
5	$\Sigma_c^{+}(\mathbf{6}_1, 3/2) \to \Lambda_c^+(\overline{\mathbf{3}}_0, 1/2) + \pi^0$	15.02	< 17
6	$\Sigma_c^{0}(\mathbf{6}_1, 3/2) \to \Lambda_c^+(\overline{\mathbf{3}}_0, 1/2) + \pi^-$	14.49	$15.3^{+0.4}_{-0.5}$
7	$\Xi_c^{+}(\mathbf{6}_1, 3/2) \to \Xi_c(\overline{\mathbf{3}}_0, 1/2) + \pi$	2.35	2.14 ± 0.19
8	$\Xi_c^{0}(\mathbf{6}_1, 3/2) \to \Xi_c(\overline{\mathbf{3}}_0, 1/2) + \pi$	2.53	2.35 ± 0.22

Experimental data are taken from the PDG Book.

HChK, Polyakov, Praszalowicz, Yang, PRD, D96, 094021 (2017).

Decay widths of Ω_cs

- Decay widths of the **bottom** baryon sextet

No additional free parameter!

#	decay	this work	exp.
1	$\Sigma_b^+(\mathbf{6}_1, 1/2) \to \Lambda_b^0(\overline{\mathbf{3}}_0, 1/2) + \pi^+$	6.12	$9.7^{+4.0}_{-3.0}$
2	$\Sigma_b^-(\mathbf{6}_1, 1/2) \to \Lambda_b^0(\overline{\mathbf{3}}_0, 1/2) + \pi^-$	6.12	$4.9^{+3.3}_{-2.4}$
3	$\Xi_b'(\mathbf{6}_1, 1/2) \to \Xi_c(\overline{\mathbf{3}}_0, 1/2) + \pi$	0.07	< 0.08
4	$\Sigma_b^+(\mathbf{6}_1, 3/2) \to \Lambda_b^0(\overline{\mathbf{3}}_0, 1/2) + \pi^+$	10.96	11.5 ± 2.8
5	$\Sigma_b^-(\mathbf{6}_1, 3/2) \to \Lambda_c^0(\overline{\mathbf{3}}_0, 1/2) + \pi^-$	11.77	7.5 ± 2.3
6	$\Xi_b^0(\mathbf{6}_1, 3/2) \to \Xi_b(\overline{\mathbf{3}}_0, 1/2) + \pi$	0.80	0.90 ± 0.18
7	$\Xi_b^-(\mathbf{6}_1, 3/2) \to \Xi_b(\overline{\mathbf{3}}_0, 1/2) + \pi$	1.28	1.65 ± 0.33

Experimental data are taken from the PDG Book.

HChK, Polyakov, Praszalowicz, Yang, PRD, D96, 094021 (2017).

Decay widths of Ω_cs

- Decay widths of the **charm** baryon antidecapentaplet

No additional free parameter!

#	decay	this work	exp.
	$\Omega_c(\overline{\mathbf{15}}_1, 1/2) \to \Xi_c(\overline{\mathbf{3}}_0, 1/2) + K$	0.339	–
	$\Omega_c(\overline{\mathbf{15}}_1, 1/2) \to \Omega_c(\mathbf{6}_1, 1/2) + \pi$	0.097	–
	$\Omega_c(\overline{\mathbf{15}}_1, 1/2) \to \Omega_c(\mathbf{6}_1, 3/2) + \pi$	0.045	–
9	total	0.48	$0.8 \pm 0.2 \pm 0.1$

Experimental data are taken from the LHCb measurement.

- Note that the widths of Omega_cs are rather small!

HChK, Polyakov, Praszalowicz, Yang, PRD, D96, 094021 (2017).

Decay widths of Ω_cs

- Decay widths of the **charm** baryon antidecapentaplet

No additional free parameter!

#	decay	this work	exp.
	$\Omega_c(\overline{\mathbf{15}}_1, 3/2) \to \Xi_c(\overline{\mathbf{3}}_0, 1/2) + K$	0.848	$-$
	$\Omega_c(\overline{\mathbf{15}}_1, 3/2) \to \Xi_c(\mathbf{6}_1, 1/2) + K$	0.009	$-$
	$\Omega_c(\overline{\mathbf{15}}_1, 3/2) \to \Omega_c(\mathbf{6}_1, 1/2) + \pi$	0.169	$-$
	$\Omega_c(\overline{\mathbf{15}}_1, 3/2) \to \Omega_c(\mathbf{6}_1, 3/2) + \pi$	0.096	$-$
10	total	1.12	$1.1 \pm 0.8 \pm 0.4$

Experimental data are taken from the LHCb measurement.

- Note that the widths of Omega_cs are rather small!

HChK, Polyakov, Praszalowicz, Yang, PRD, D96, 094021 (2017).

Summary

- We have aimed in this talk at how to interpret the newly found five Omega_cs by the LHCb within a mean-filed approach (Witten).

- The meson mean fields describe well both the lowest-lying singly heavy baryons and the excited anti-triplet.

- We have predicted **Five** excited sextet and **Two** members in the anti-15plet.

Suggestions to the LHCb & Belle Collaborations

- *Can you perform the PWAs to determine the quantum numbers of Omega_c's?*

- *Can you scan channels $\Xi_c^+ K^0$ and $\Xi_c^0 K^-$ in the range of the invariant masses between 3050 MeV and 3119 MeV to find isovector Omega_cs?*

Extended XQSM: toward excited baryons

Physics for excited baryons

- Confinement & Chiral symmetry with its spontaneous breaking
- Relativistic Quantum field theory should be used for excited baryons ($q\bar{q}$ excitations).
- Vector, Axial-vector, and tensor mean fields for higher-lying excited states
- Question: How can one incorporate them to describe excited baryons?

Puzzles in excited baryon spectra

- Missing Resonances: Too many resonances were predicted. Additional symmetries?
- Mass orderings: N*(1440) & N*(1535), N*(1520)(3/2-) & N*(1535)(1/2-)
- Broad widths: Large coupling constants.
- Question: How can one resolve these puzzles?

Extended effective chiral action

- **How to incorporate quark confinement**

$$S_{\mathrm{eff}} = -N_c \mathrm{Trlog}\left[i\partial\!\!\!/ + i\hat{m} + iM(r)U^{\gamma_5}\right]$$

[D. Diakonov, V. Petrov, and A. Vladimirov, Phys. Rev. D 88, 074030 (2013)]

Extended effective chiral action

- **How to incorporate quark confinement**

$$S_{\rm eff} = -N_c \mathrm{Trlog}\left[i\partial\!\!\!/ + i\hat{m} + \boxed{iM(r)U^{\gamma_5}}\right]$$

$$M(r)U^{\gamma_5}(r) = S(r)\left[\cos P(r) + i\gamma_5 \tau\cdot\mathbf{n}\sin P(r)\right]$$

[D. Diakonov, V. Petrov, and A. Vladimirov, Phys. Rev. D 88, 074030 (2013)]

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$S(r)$ Confining background (mean) field

$P(r)$ Pion background (mean) field

[D. Diakonov, V. Petrov, and A. Vladimirov, Phys. Rev. D 88, 074030 (2013)]

Extended effective chiral action

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$S(r)$ Confining background (mean) field

$P(r)$ Pion background (mean) field

The confining and pion fields are non-linearly coupled within **hedgehog Ansatz**.

[D. Diakonov, V. Petrov, and A. Vladimirov, Phys. Rev. D 88, 074030 (2013)]

Hedgehog symmetry and mean field

Collective (Zero-mode) quantisation

$$U_0 = \begin{bmatrix} e^{i\vec{n}\cdot\vec{\tau}P(r)} & 0 \\ 0 & 1 \end{bmatrix} \quad \mathrm{SU}(3)_{\mathrm{f}} \otimes \mathrm{O}(3)_{\mathrm{space}} \to \mathrm{SU}(2)_{\mathrm{iso+space}}$$

- Breaking of this higher symmetry will reduce the number of baryon states!
- We keep the zero-mode quantization for the moment.
- For excited states, meson loops should come into play. (**beyond the zero modes, beyond mean-field apprx.**)
- Vector and axial-vector, and tensor mean fields should be considered! **(Future works)**

Confining background field

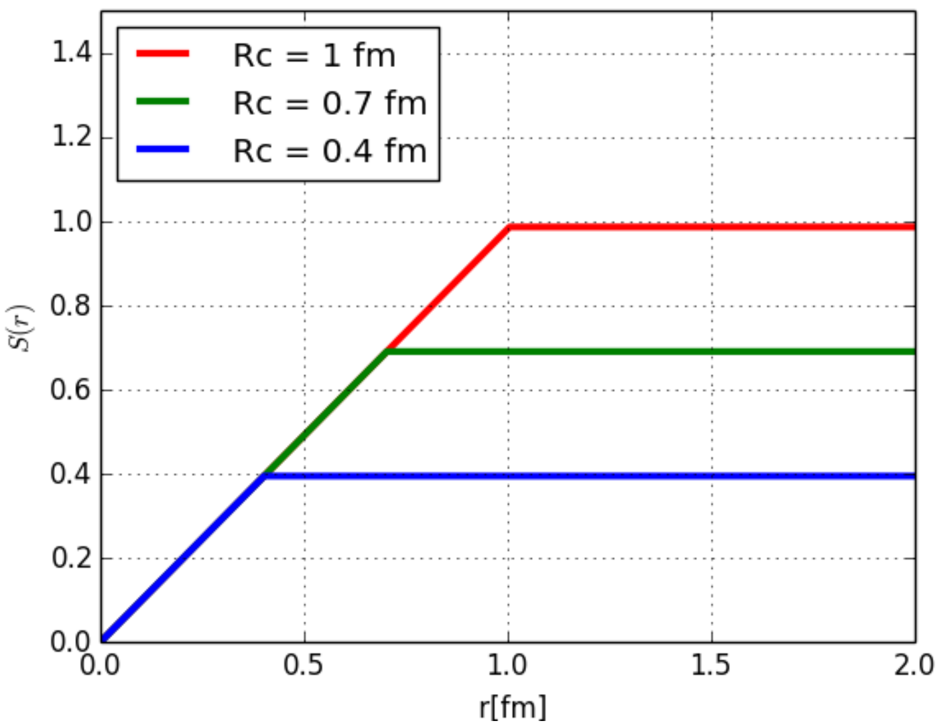
Critical distance

$$\sigma R_c \approx M, \quad \lim_{r\to\infty} S(r) = M$$

σ = (0.44 GeV)^2

We need to saturate S(r) to avoid a divergence

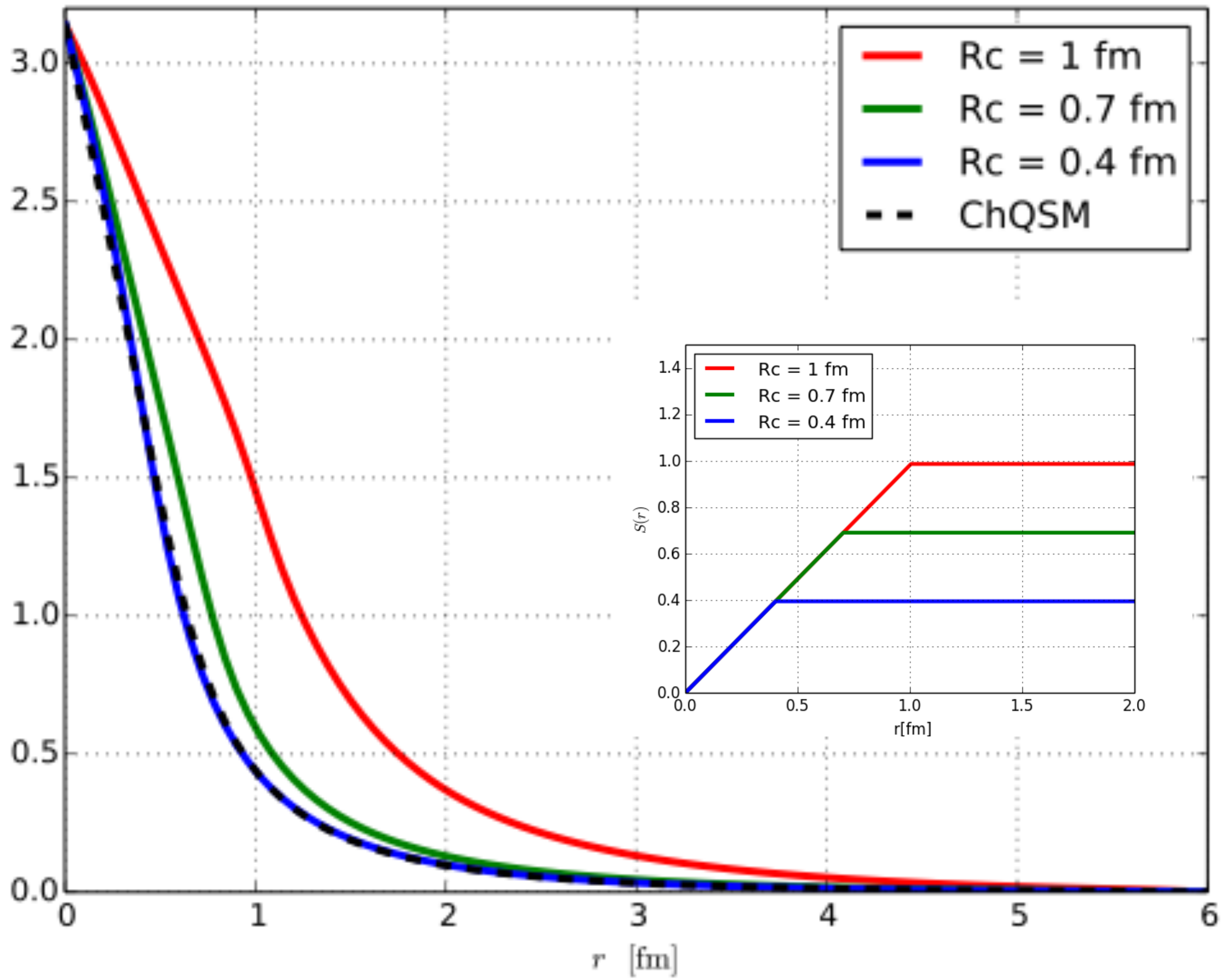
$$S(r) = \sigma r\, \theta(R_c - r) + \sigma R_c\, \theta(r - R_c)$$



This is plausible, since the string should be broken into creating mesons.

HD Son & HChK, in preparation

Self-consistent pion background field



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Classical Nucleon mass

[MeV]	Valence	Sea	Total
ChQSM M = 420 MeV	589	707	1296
Rc = 0.4 fm	701	557	1258
Rc = 0.7 fm	269	916	1185
Rc = 1.0 fm	x	916	916

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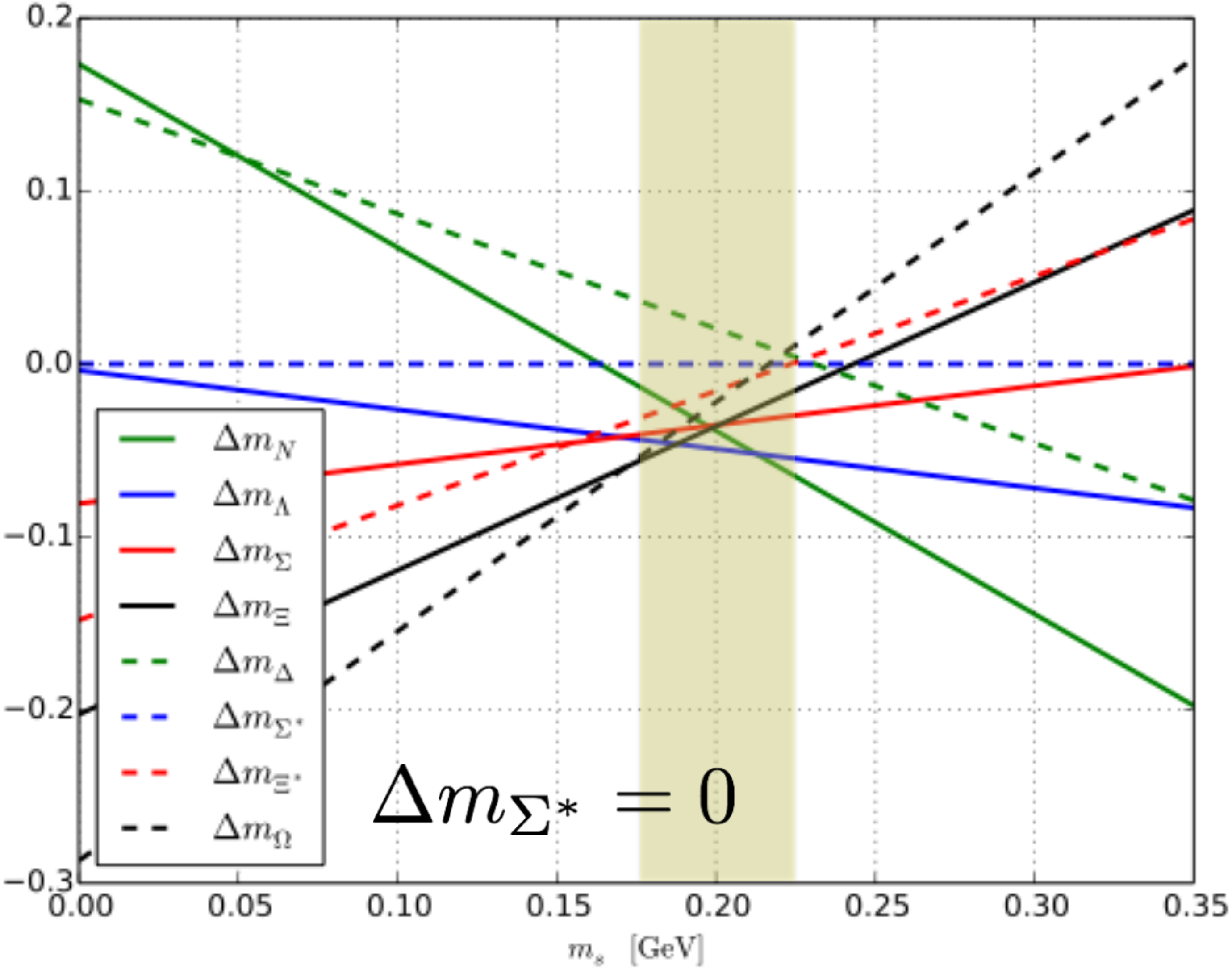
Hyperon mass splitting to the first order of m_s



Original XQSM

— octet

- - decuplet

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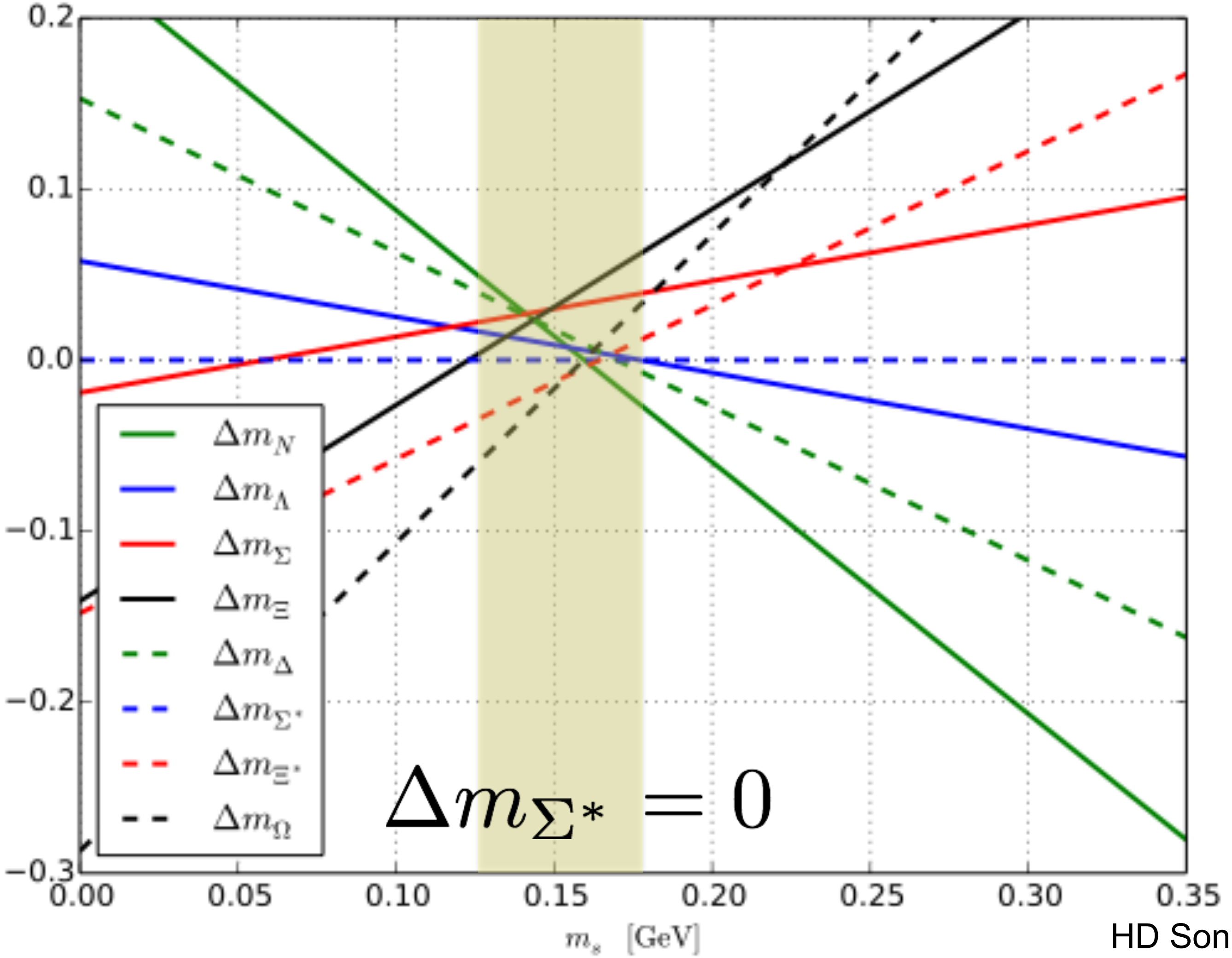
Hyperon mass splitting to the first order of m_s

Rc = 0.42 fm: — octet - - decuplet

Large σ-term → smaller strange quark mass



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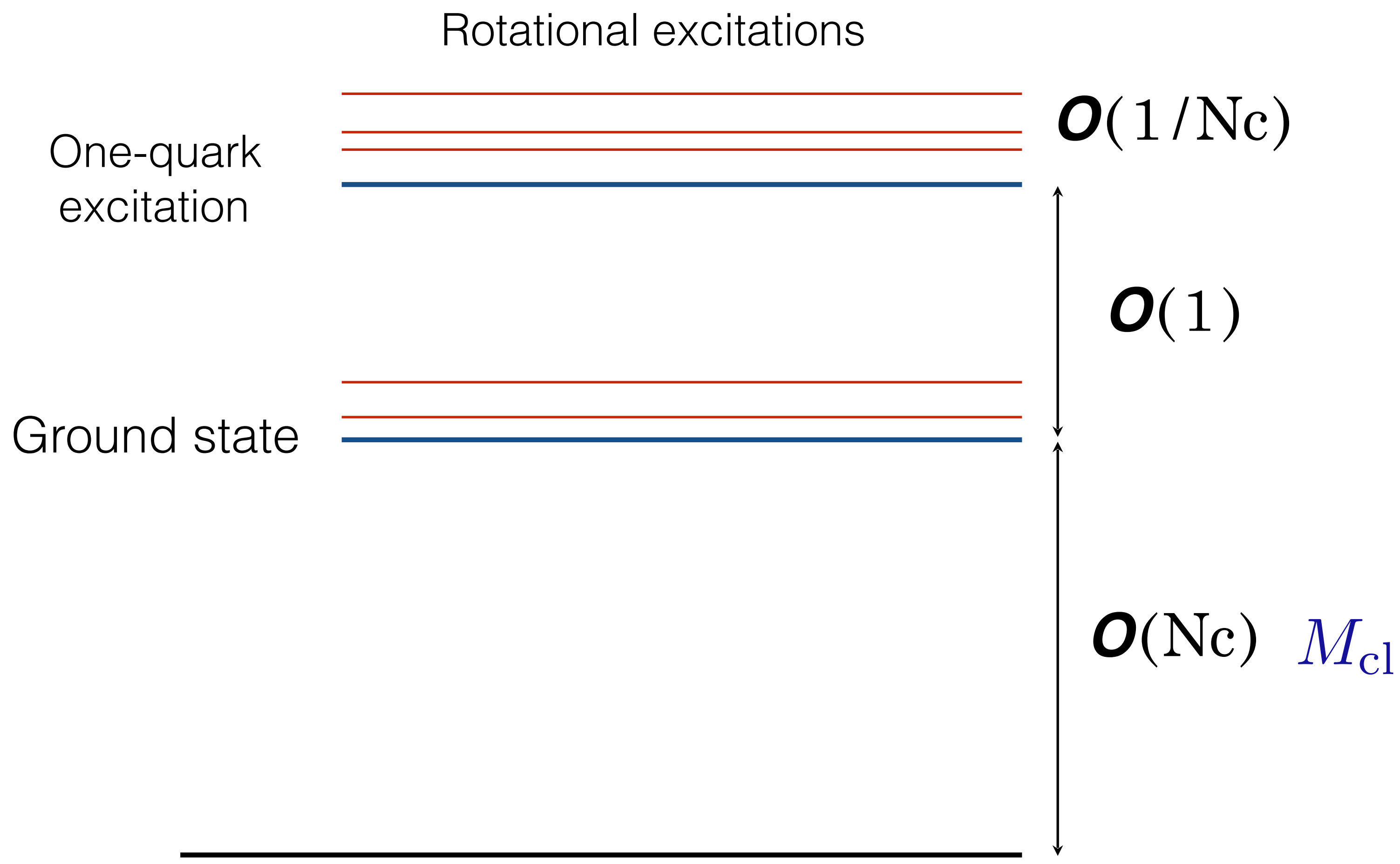
Excited valence quark

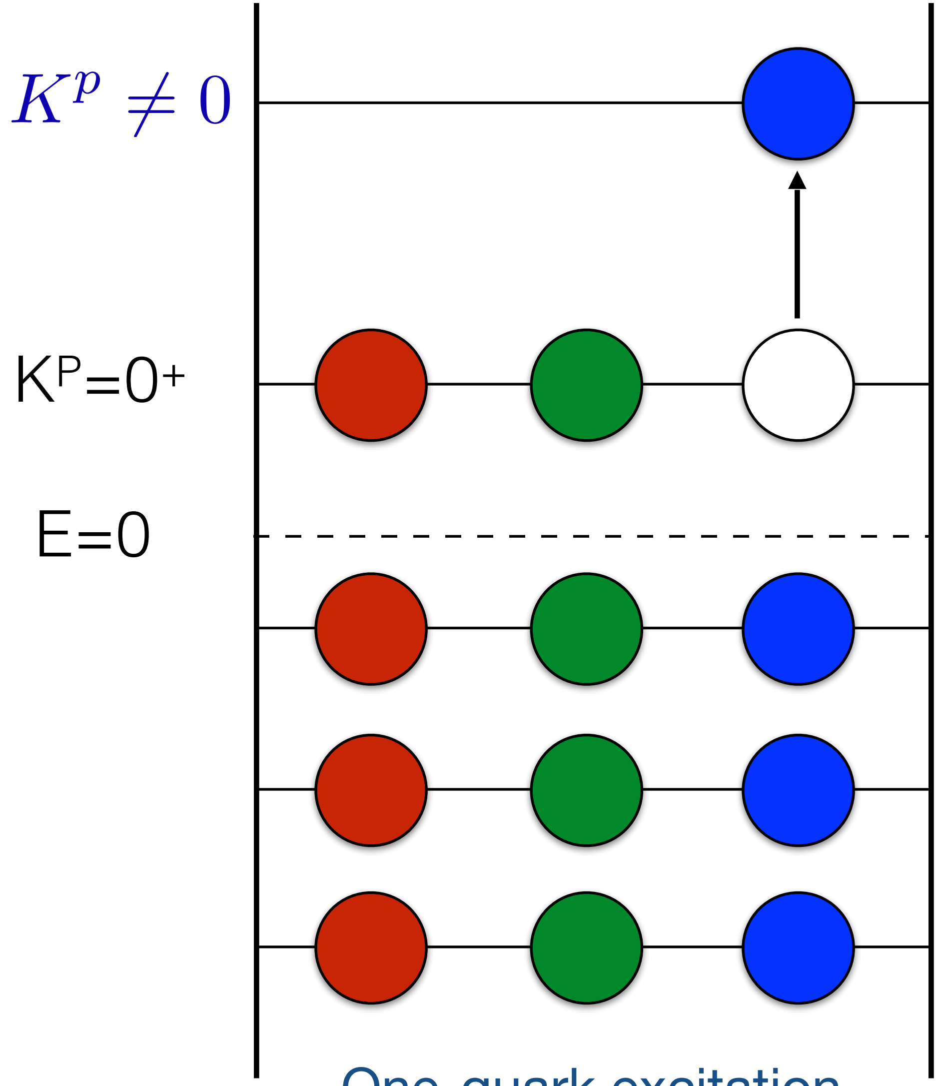
Schematic picture at large N_c



Excited valence quark for 8(J^P=1/2$^+$)

$$\boldsymbol{K} = \boldsymbol{J} + \boldsymbol{T},$$

$$Y' = \frac{N_c}{3} = \frac{2}{\sqrt{3}} T_8$$

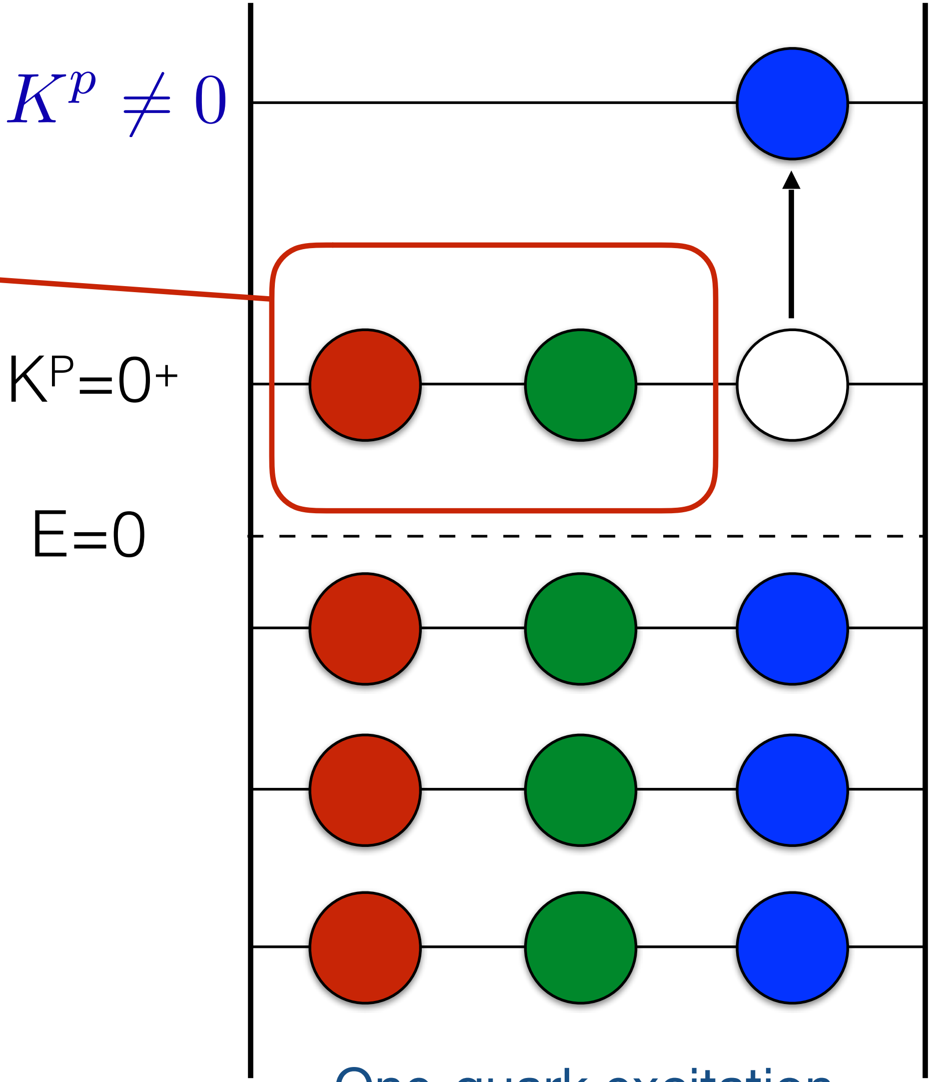


One-quark excitation from the valence level

Collective Hamiltonian for excited baryons

$$H = H_{\rm cl} + H_K + H_{\rm m}$$

$$M_{\rm cl} = (N_c - 1)E_{\rm val} + E_{\rm sea}$$



One-quark excitation
from the valence level

Collective Hamiltonian for excited baryons

$$H = H_{\rm cl} + H_K + H_{\rm m}$$

$$H_K = \frac{1}{2I_2}\sum_{a=4}^{7} T_a^2 + \frac{(\boldsymbol{T} - a_K \boldsymbol{K})^2}{2I_1}$$

$$H_m = \alpha D_{88}^{(8)}(R) + \beta Y + \frac{1}{\sqrt{3}}\gamma \sum_{i=1}^{3} D_{8i}^{(8)}(R) T_i + \frac{1}{\sqrt{3}}\delta_K \sum_{i=1}^{3} D_{8i}^{(8)}(R) K_i$$

$$\delta_K = \frac{2m_s}{3}\left(d_K - \frac{K_1}{I_1} a_K\right)$$

Wave functions for excited baryons

$$\Psi_K(R,S,\chi) = \sqrt{\frac{\dim(R)(2J+1)}{2K+1}} \sum_{TT_3J_3} C_{TT_3JJ_3}^{KK_3} D_{Y'T'T_3',YTT_3}(R^\dagger) D_{J_3'J_3}(S^\dagger)\chi_{K_3}$$

Collective Hamiltonian for excited baryons

$$H = H_{\mathrm{cl}} + H_K + H_{\mathrm{m}}$$

$$\boldsymbol{T} = \boldsymbol{K} - \boldsymbol{J}$$

$$H_K = \frac{1}{2I_2}\sum_{a=4}^{7} T_a^2 + \frac{(\boldsymbol{T} - a_K \boxed{\boldsymbol{K})^2}}{2I_1}$$

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Excited valence quark for 8(J^P=1/2$^+$)

K=0+ → K=0+ : No contribution from χ_K

	Y	Mass	Candidates	Status	I(J^P)	Δ_{calc}	Δ_{exp}
N	1	**1458**	1440	****	1/2(1/2$^+$)	190	220
Λ	0	**1648**	1660	***	0(1/2$^+$)	102	
Σ	0	**1750**	1660	****	1(1/2$^+$)	139	
Ξ	-1	**1889**	1690	*	1/2(?$^?$)		

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Ξ	-1	1889	1690	*	1/2(?$^?$)		

HD Son & HChK, in preparation

Excited valence quark for 8($J^P=3/2^+$)

K=0+ → K=0+ : No contribution from χ_K

	Y	Mass	Candidates	Status	$I(J^P)$	Δ_{calc}	Δ_{exp}
Δ	1	**1826**	1600	****	$3/2(3/2^+)$		
Σ	0	**1977**	1660	*	$1(3/2^+)$	**151**	
Ξ	-1	**2128**	1950	***	$1/2(?^?)$	**151**	
Ω	-2	**2280**	2250	***	$0(?^?)$	**151**	

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Parameters for the baryons with negative parity

c_K, a_K, and d_K

	$\Delta E(0+\rightarrow 1-)$ [MeV]	c_k	a_K	d_K
ChQSM (M=420MeV)	240	0.377	0.217	0.213
R_C=0.42 fm	163	0.391	0.207	0.201
R_C=0.44 fm	249	0.398	0.202	0.198
R_C=0.46 fm	337	0.407	0.195	0.193
Diakonov *et al*	468		0.336	

HD Son & HChK, in preparation

Excited valence quark for 8(J^P=1/2$^-$)

K=0+ → K=1-

	Y	Mass[MeV]	Candidates	Status	I(J^P)	Δ_{calc}	Δ_{exp}
N	1	**1408**	1535	****	1/2(1/2$^-$)	**145**	**135**
Λ	0	**1553**	1670	****	0(1/2$^-$)	**92**	
Σ	0	**1645**				**99**	
Ξ	-1	**1744**	?	?	?		

HD Son & HChK, in preparation

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Λ	0	**1553**	1670	****	0(1/2$^-$)	**92**	
Σ	0	**1645**				**99**	
Ξ	-1	**1744**	?	?	?		

HD Son & HChK, in preparation

Excited valence quark for 8(J^P=3/2$^-$)

K=0+ → K=1-

	Y	Mass[MeV]	Candidates	Status	I(J^P)	Δ_{calc}	Δ_{exp}
N	1	**1432**	1520	****	1/2(3/2$^-$)		
						170	**170**
Λ	0	**1602**	1690	****	0(3/2$^-$)		
						103	**-20**
Σ	0	**1705**	1670	****	1(3/2$^-$)		
						119	**150**
Ξ	-1	**1824**	1820	***	1/2(3/2$^-$)		

HD Son & HChK, in preparation

Excited valence quark for 8(J^P=3/2$^-$)

K=0+ → K=1-

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N	1	**1432**	1520	****	1/2(3/2$^-$)	**170**	**170**
Λ	0	**1602**	1690	****	0(3/2$^-$)	**103**	**-20**
Σ	0	**1705**	1670	****	1(3/2$^-$)	**119**	**150**
Ξ	-1	**1824**	1820	***	1/2(3/2$^-$)		

HD Son & HChK, in preparation

Excited valence quark for 10(J^P=1/2$^-$)

K=0+ → K=1-

	Y	Mass[MeV]	Candidates	Status	I(J^P)	Δ_{calc}	Δ_{exp}
Δ	1	**1669**	1620	****	3/2(1/2$^-$)	**139**	**130**
Σ*	0	**1808**	1750	***	1(1/2$^-$)	**139**	
Ξ*	-1	**1947**	1900	?	?	**139**	
Ω	-2	**2085**	2050	?	?		

Predictions by V. Petrov

HD Son & HChK, in preparation

Excited valence quark for 10($J^P=3/2^-$)

K=0+ → K=1-

	Y	Mass[MeV]	Candidates	Status	I(J^P)	Δ_{calc}	Δ_{exp}
Δ	1	**1726**	1700	****	3/2($3/2^-$)		
Σ*	0	**1862**	1850	?	?	**136**	
Ξ*	-1	**1999**	2000	?	?	**136**	
Ω	-2	**2135**	2150	?	?	**136**	

Predictions by V. Petrov

HD Son & HChK, in preparation

What is missing in this approach?

- Meson-loop corrections (1/Nc): So far, the approach is just like a mean-field approach. We have to go beyond mean-field approx.: RPA-like meson-loop contributions.

- qqbar excitations more than pions: vector, Axial-vector, and tensor mean fields and meson loops for higher-lying excited states

→ They will be future works: To build up a realistic model of describing excited baryons

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

Hamlet Act 2, Scene 2

Thank you very much!