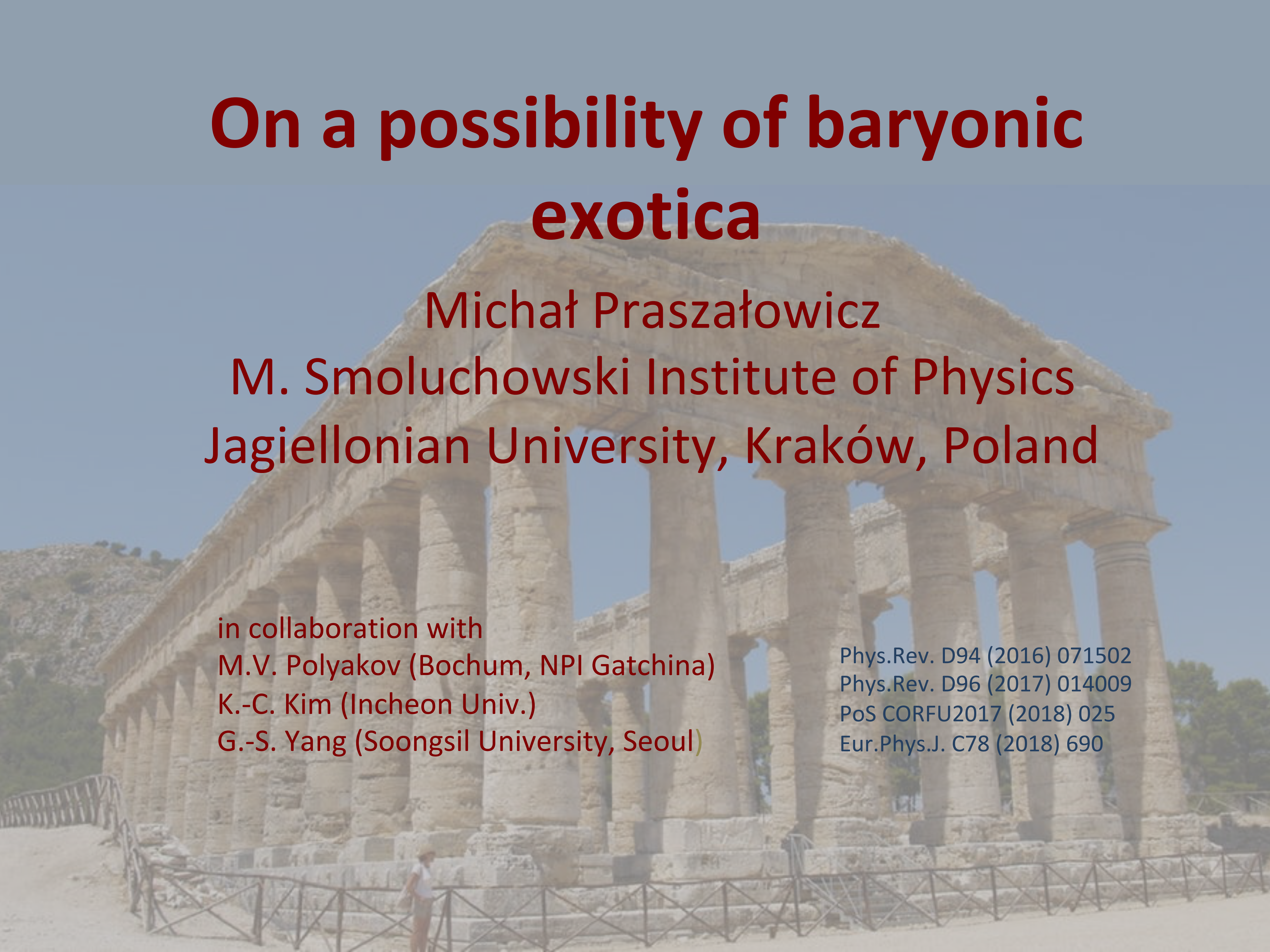

On a possibility of baryonic exotica

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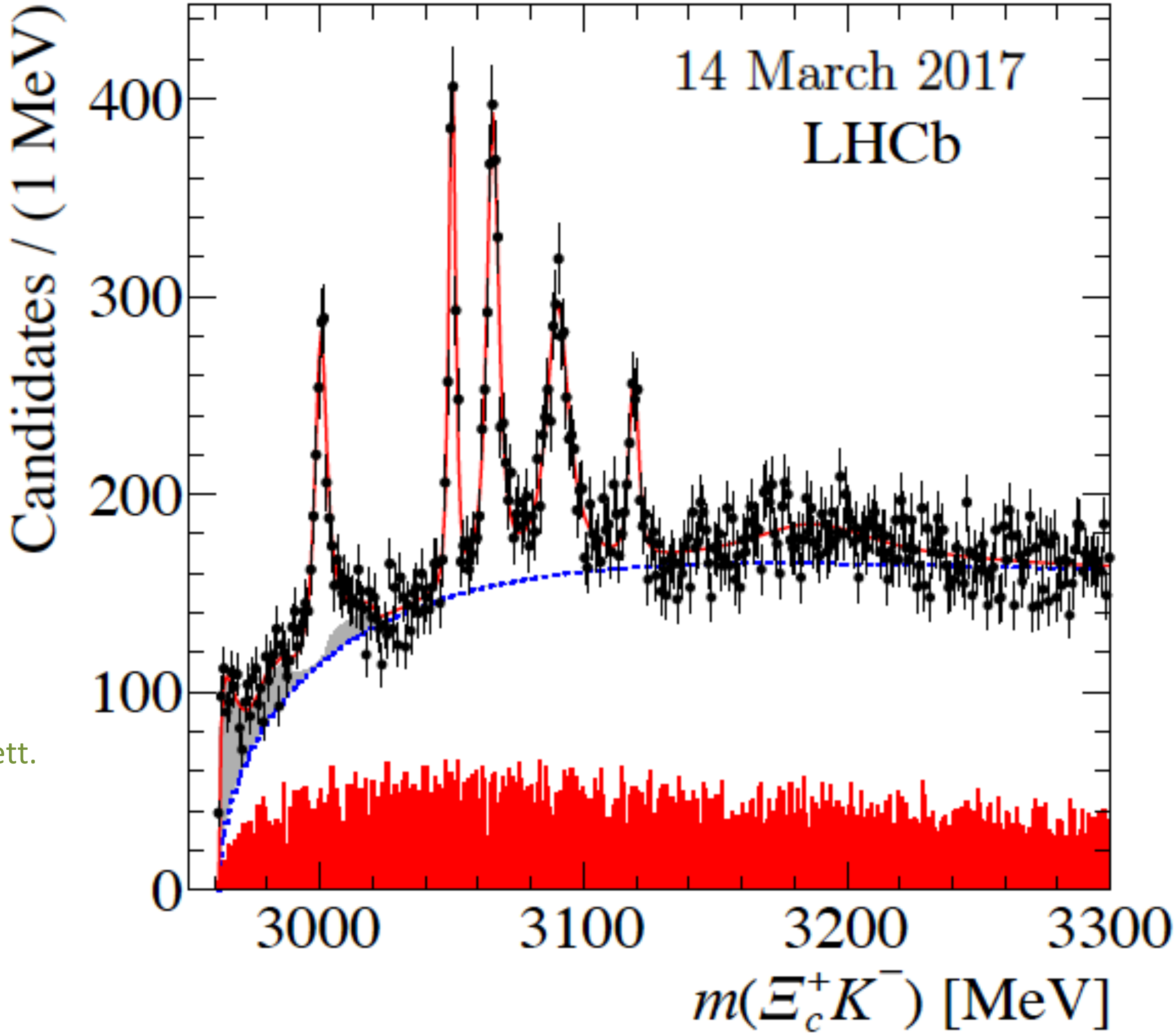
in collaboration with
M.V. Polyakov (Bochum, NPI Gatchina)
K.-C. Kim (Incheon Univ.)
G.-S. Yang (Soongsil University, Seoul)

Phys.Rev. D94 (2016) 071502
Phys.Rev. D96 (2017) 014009
PoS CORFU2017 (2018) 025
Eur.Phys.J. C78 (2018) 690

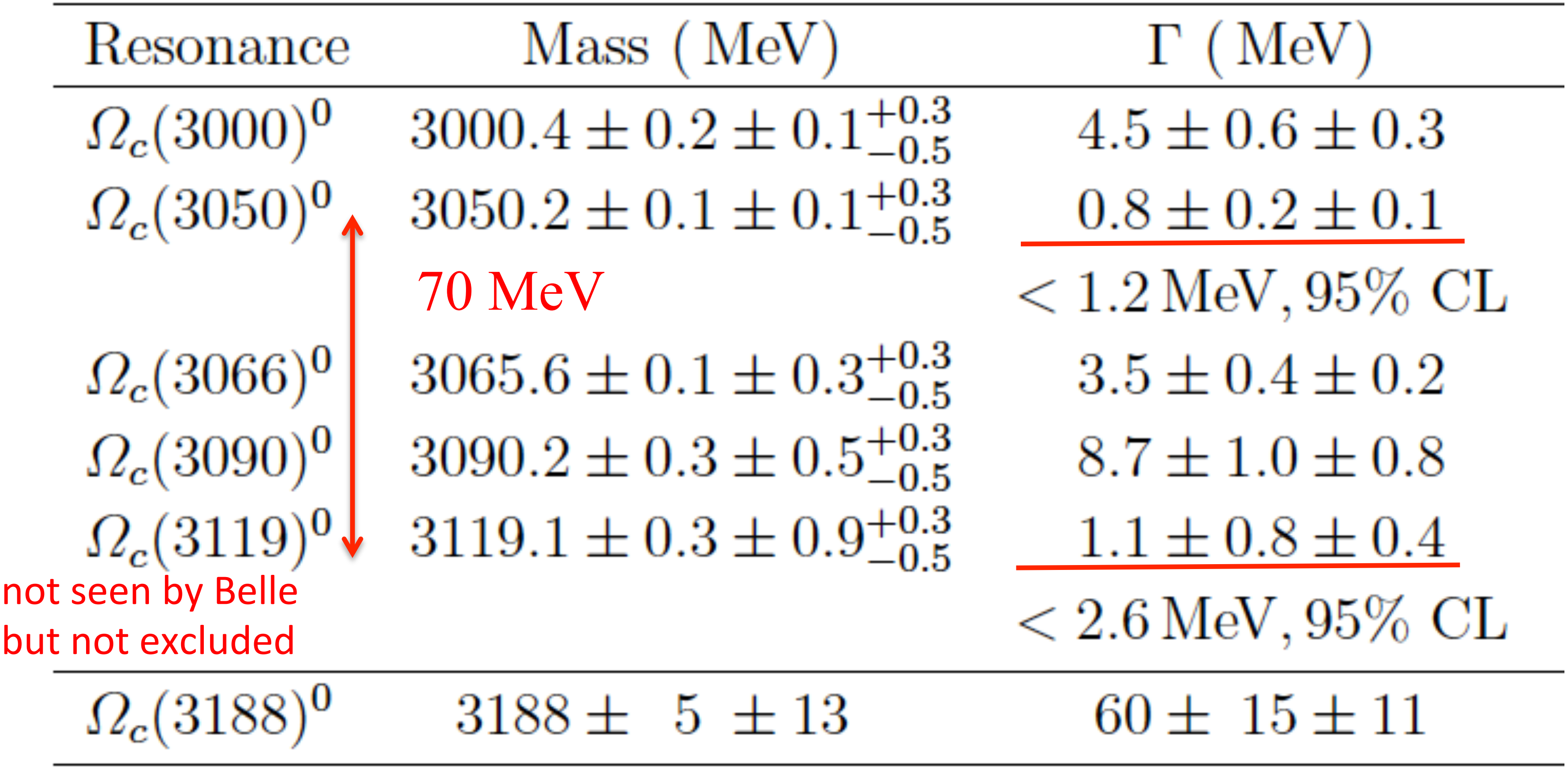
Motivation

Motivation: 5 narrow Ω_c's



LHCb, Phys. Rev. Lett.
118 (2017) 182001
Belle, Phys. Rev. D
97 (2018) 051102

Motivation: 5 narrow Ω_c's



Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$ $< 1.2\,\mathrm{MeV}, 95\%$ CL
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$ $< 2.6\,\mathrm{MeV}, 95\%$ CL
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$

70 MeV

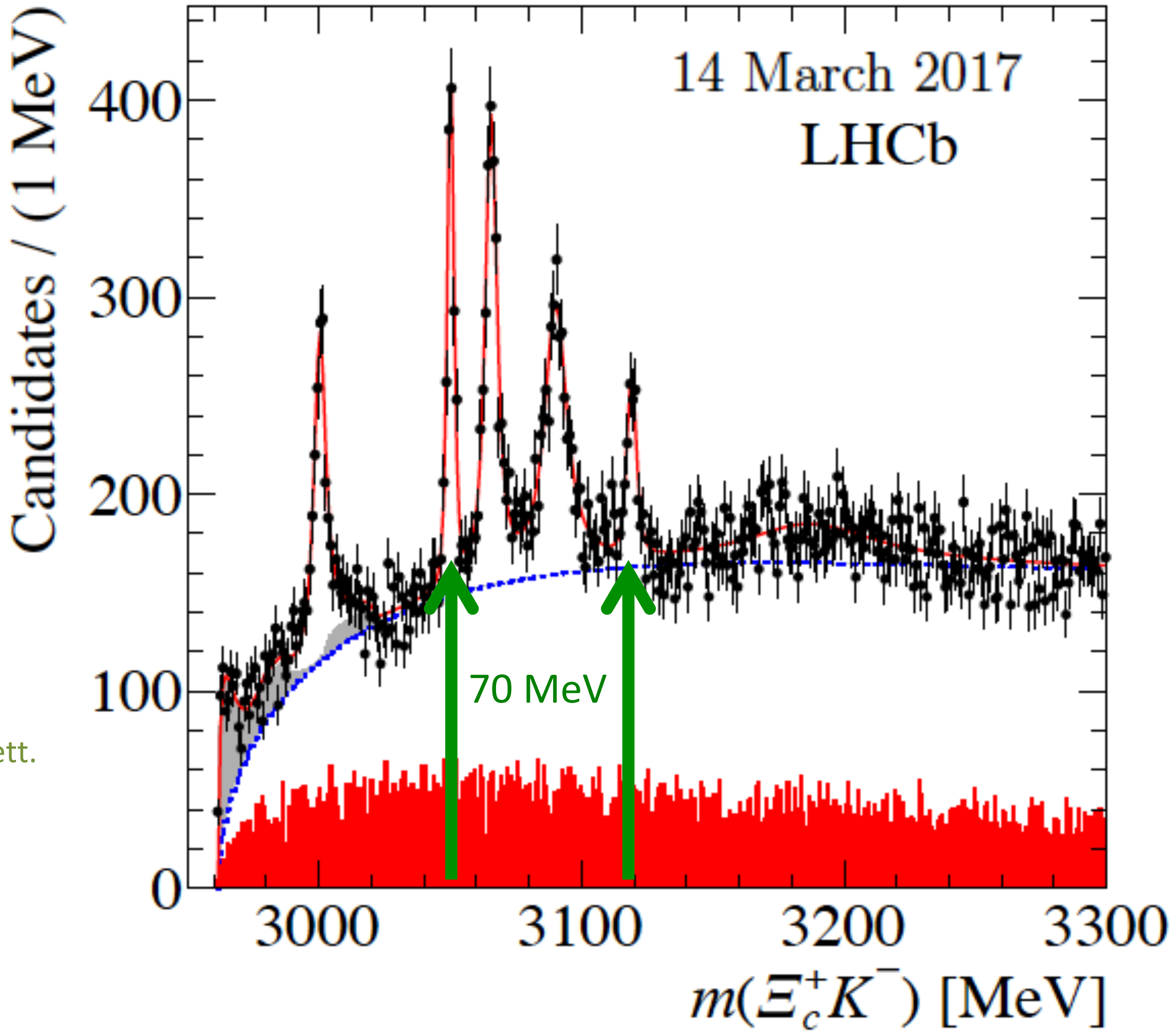
not seen by Belle
but not excluded

Motivation: 5 narrow Ω_c's

Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$\underline{0.8 \pm 0.2 \pm 0.1}$
	70 MeV	$< 1.2\,\text{MeV}, 95\%\ \text{CL}$
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$\underline{1.1 \pm 0.8 \pm 0.4}$
not seen by Belle but not excluded		$< 2.6\,\text{MeV}, 95\%\ \text{CL}$
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$

$$\Delta \to \pi N \;\; p_\pi = 225\ \text{MeV}, \quad \Omega_c^*(3050) \to K\Xi_c \;\; p_K = 274\ \text{MeV}$$

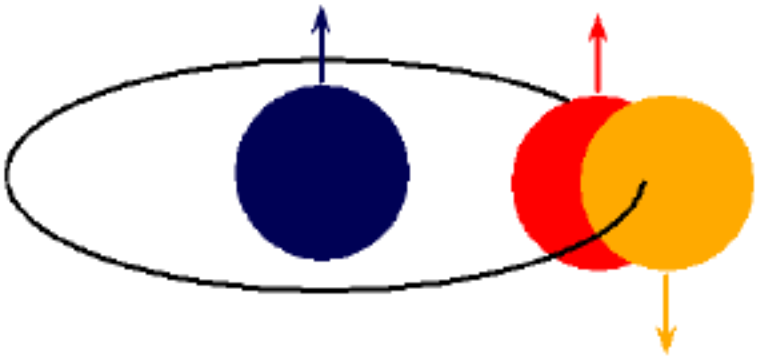
Motivation: 5 narrow Ω_c's



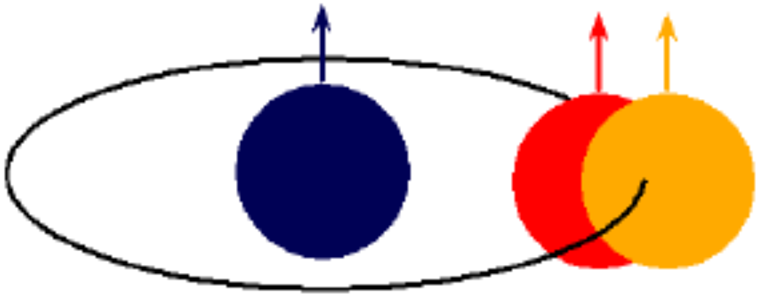
LHCb, Phys. Rev. Lett. 118 (2017) 182001
Belle, Phys. Rev. D 97 (2018) 051102

Reminder

Classification by SU(3) q.n.



light quarks have spin 0
SU(3) triplet, total spin 1/2



light quarks have spin 1
SU(3) sextet, total spin
1/2 and 3/2, hyperfine split

Heavy baryon ground states

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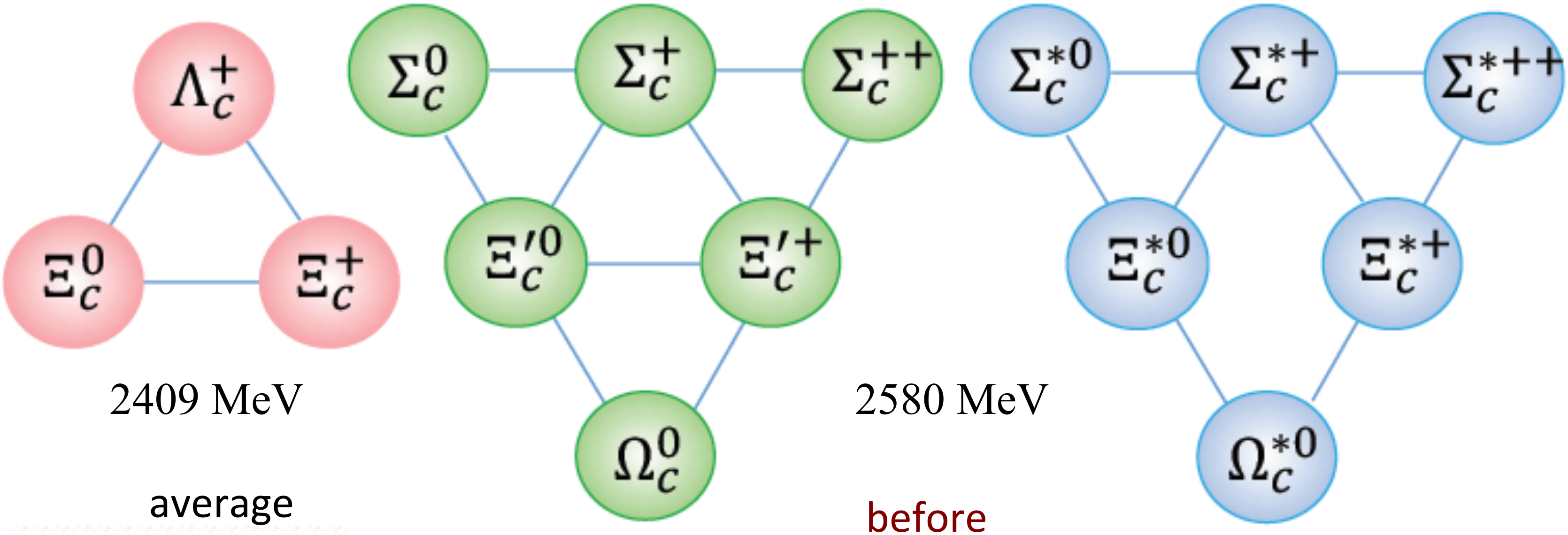
$(\overline{3}\ 1/2^+)$ $(6\ \ 1/2^+)$ $(6\ 3/2^+)$



2409 MeV

2580 MeV

average
multiplet
masses

2535 MeV

before
hf splitting
70 MeV

2602 MeV

$s = 0$ diquark $+\ s = 1/2$ HQ $\qquad$ $s = 1$ diquark $+\ s = 1/2$ HQ

Heavy baryon ground states

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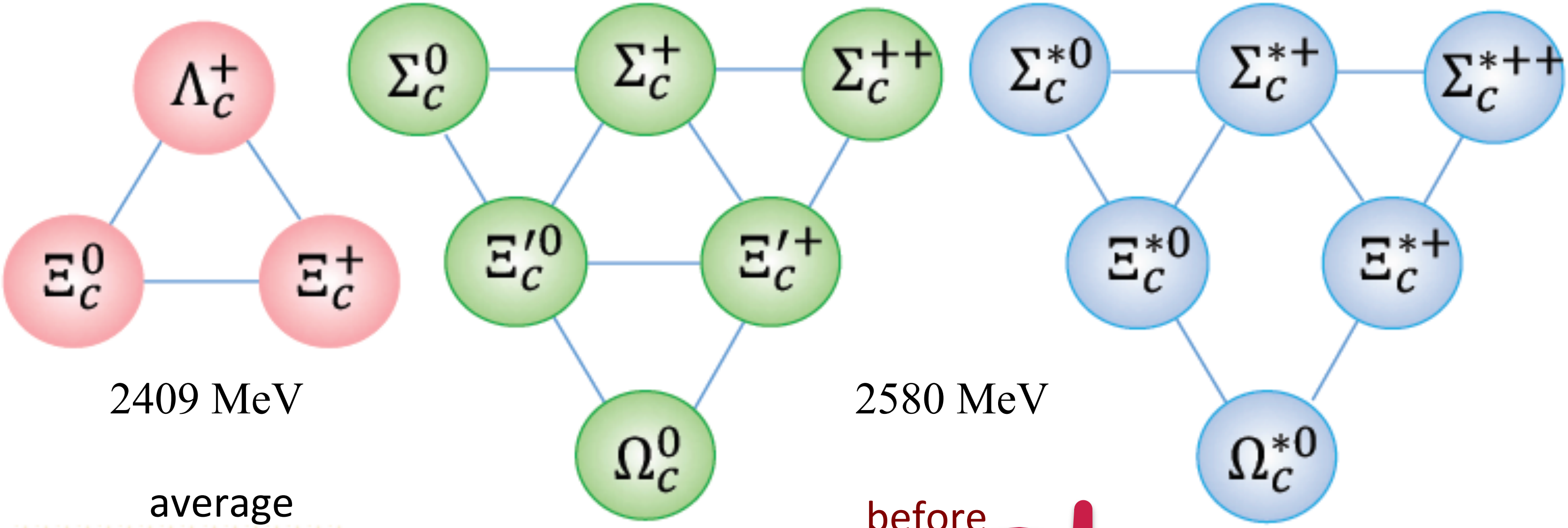
($\bar{3}$ 1/2$^+$) (6 1/2$^+$) (6 3/2$^+$)



2409 MeV

2580 MeV

average
multiplet
masses

before
hf splitting
70 MeV

2535 MeV

2602 MeV

$s = 0$ diquark + $s = 1/2$ HQ

$s = 1$ diquark + $s = 1/2$ HQ

Heavy baryon ground states

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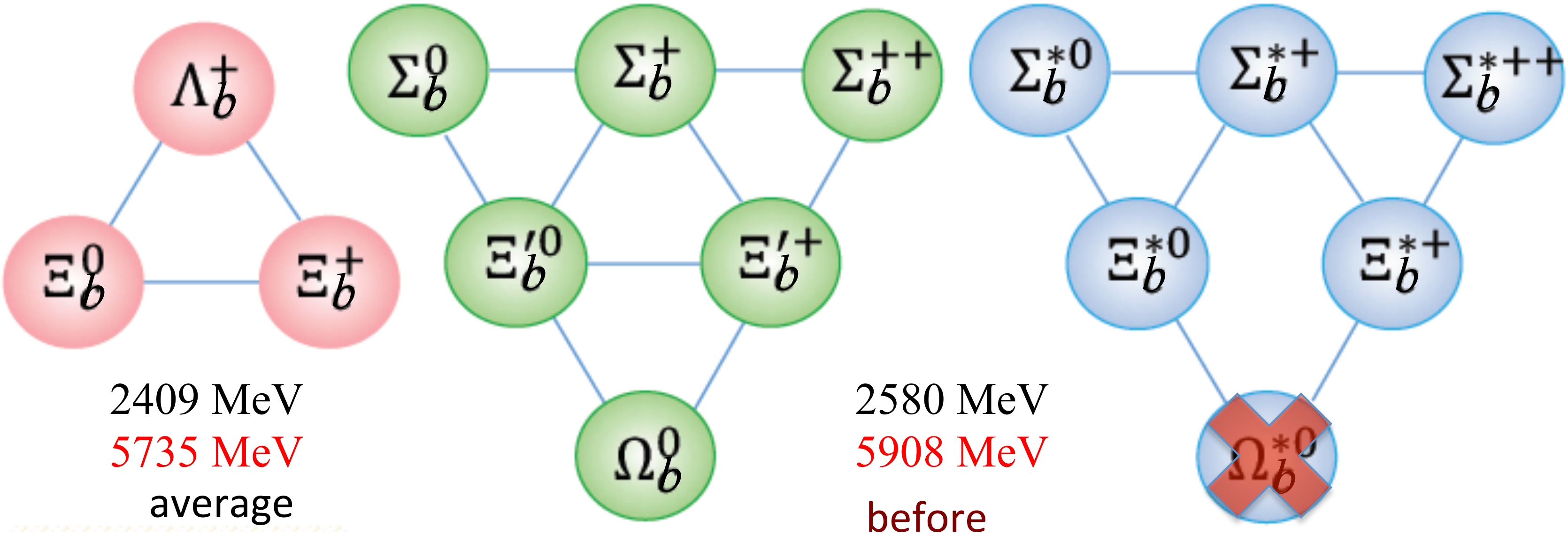
$(\bar{3}\ 1/2^+)$ $(6\ \ 1/2^+)$ $(6\ 3/2^+)$



2409 MeV
5735 MeV
average
multiplet
masses

2535 MeV
5893 MeV

2580 MeV
5908 MeV
before
hf splitting
70 MeV
20 MeV

2602 MeV
5913 MeV

same for the bottom

Heavy baryon ground states

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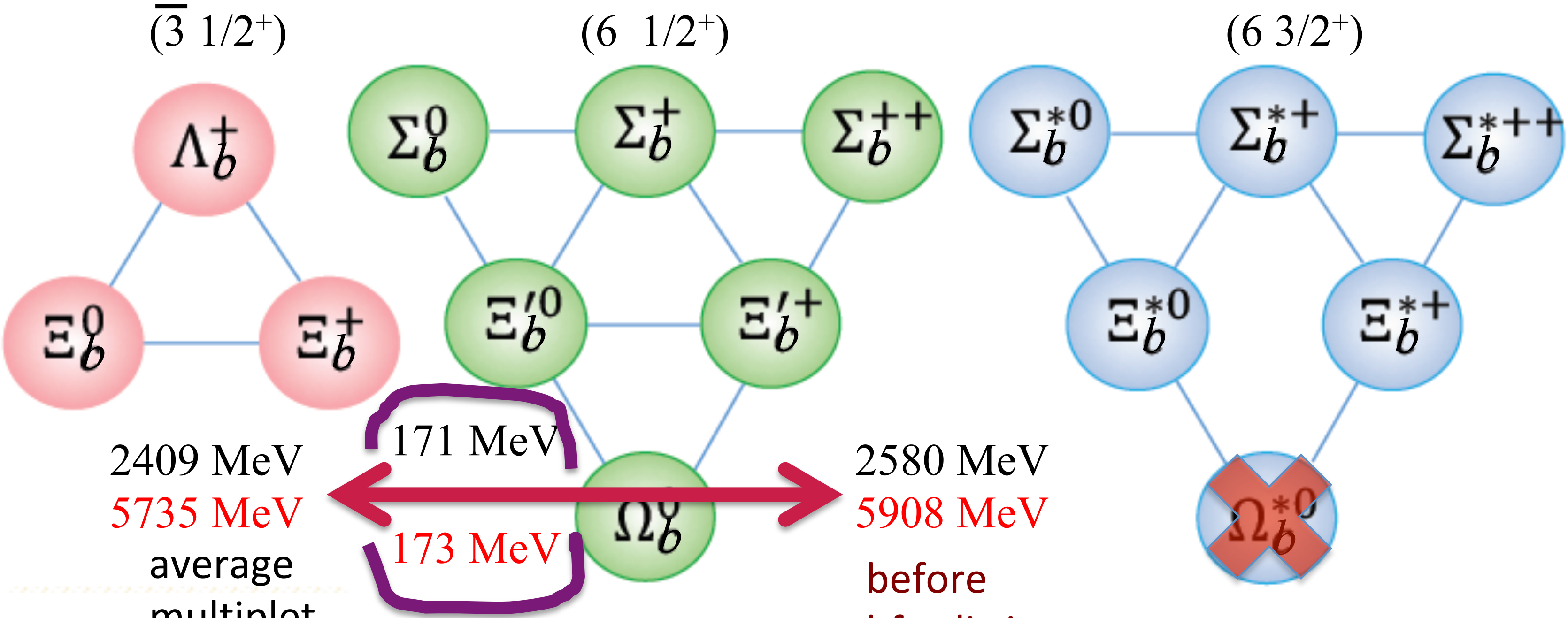


2409 MeV
5735 MeV
average
multiplet
masses

171 MeV
173 MeV

2580 MeV
5908 MeV
before
hf splitting

2535 MeV
5893 MeV

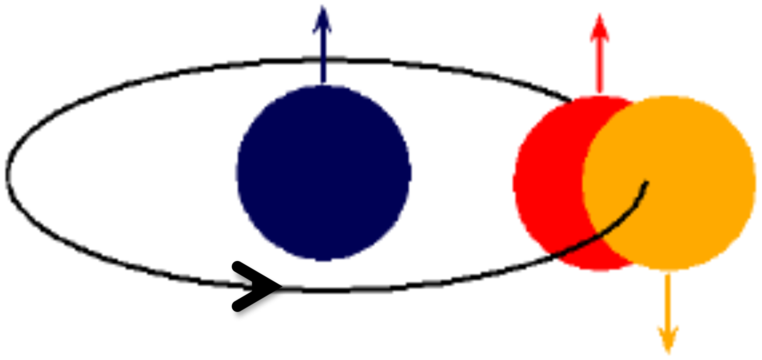
70 MeV
20 MeV

2602 MeV
5913 MeV

hf splitting ratio ~ 0.3 ~ m_c/m_b

universality charm vs. bottom

SU(3) classification of excited states



light quarks have spin 0

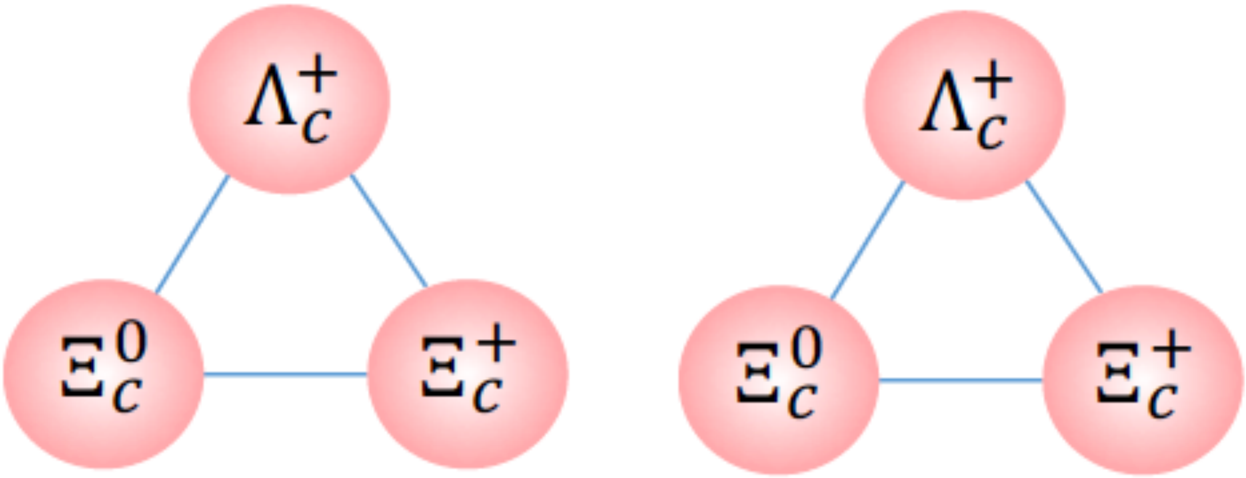
SU(3) triplet

angular momentum 1

1/2 and 3/2 hyperfine split

Heavy baryon excited states

$(\bar{3}\ 1/2^-)$ $(\bar{3}\ 3/2^-)$



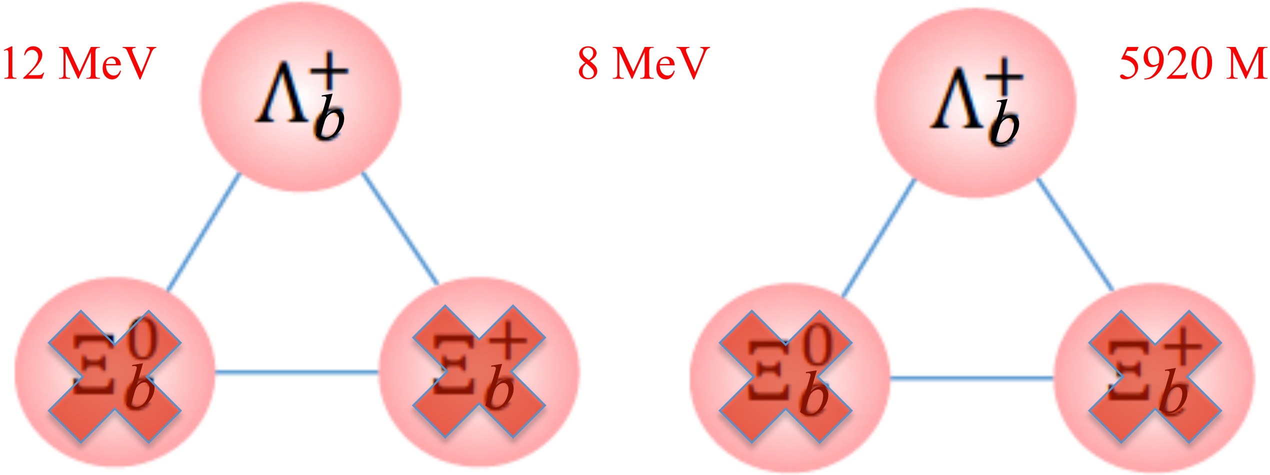
2724 MeV 30 MeV 2754 MeV

$s = 0$ diquark + $s = 1/2$ HQ + $L = 1$

Heavy baryon excited states

$(\bar{3}\ 1/2^-)$ $(\bar{3}\ 3/2^-)$

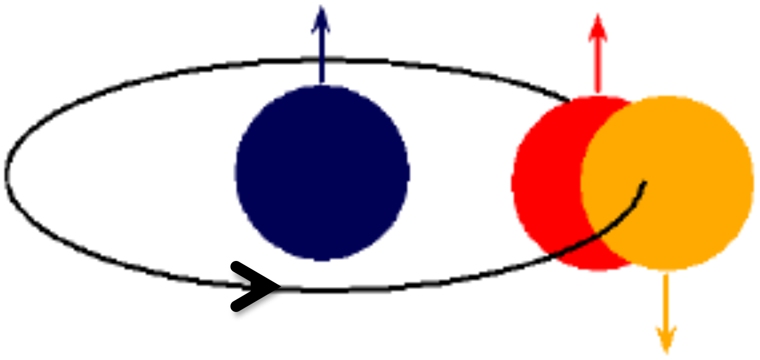
5912 MeV 8 MeV 5920 MeV



2724 MeV 30 MeV 2754 MeV

not much known in the bottom sector

SU(3) classification of excited states

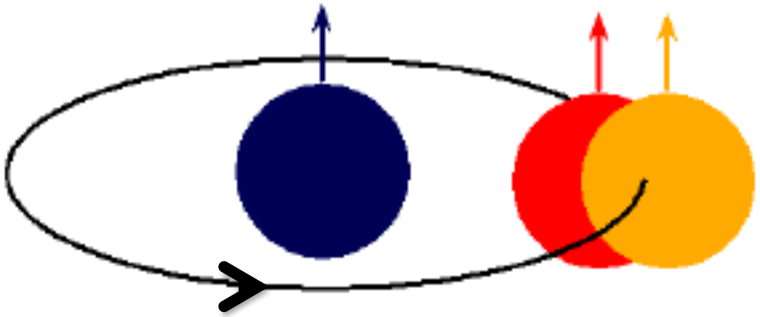


light quarks have spin 0

SU(3) triplet

angular momentum 1

1/2 and 3/2 hyperfine split



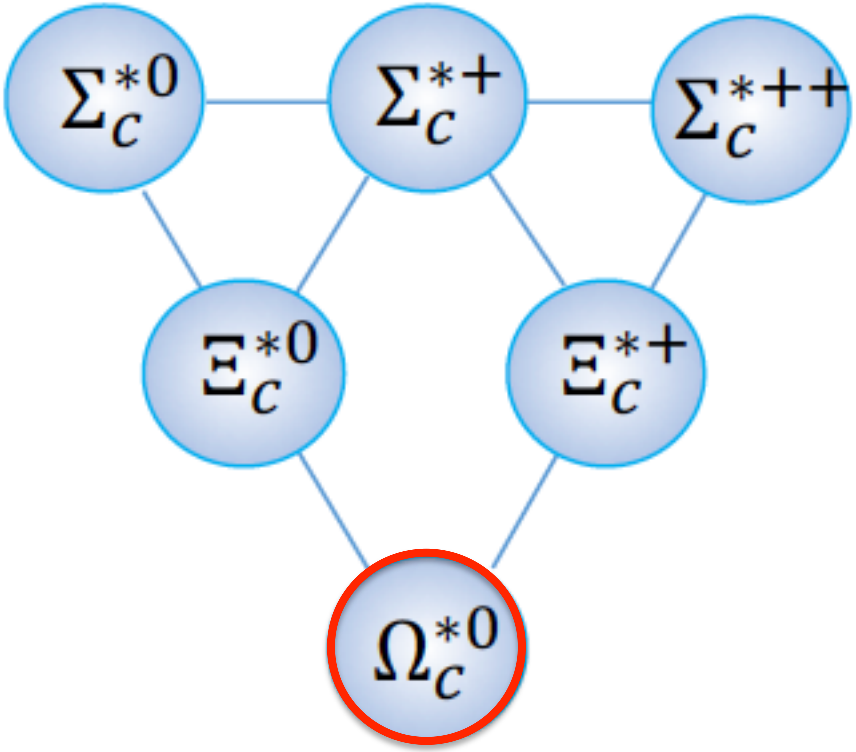
light quarks have spin 1

SU(3) sextet

angular momentum 1

1/2, 1/2, 3/2,
3/2, 5/2 hyperfine split

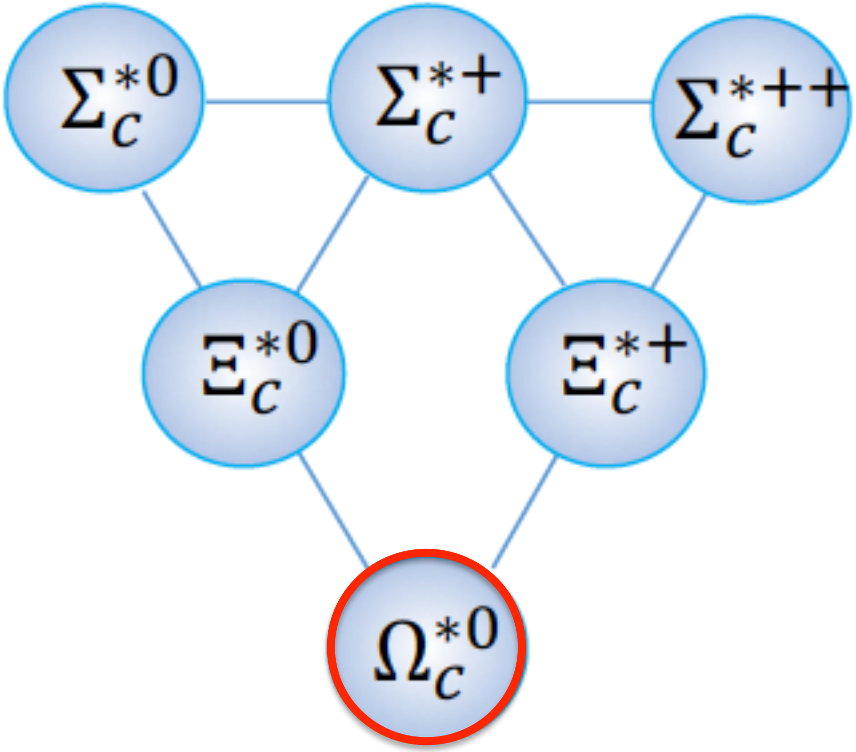
Sextet excitations?



$s = 1$ diquark + $s = 1/2$ HQ + $L = 1$

→ 1/2, 1/2, 3/2, 3/2, 5/2 → 5 states!

Sextet excitations?



however:
one has to fit both
masses
and
widths

$s = 1$ diquark + $s = 1/2$ HQ + $L = 1$

→ 1/2, 1/2, 3/2, 3/2, 5/2 → 5 states!

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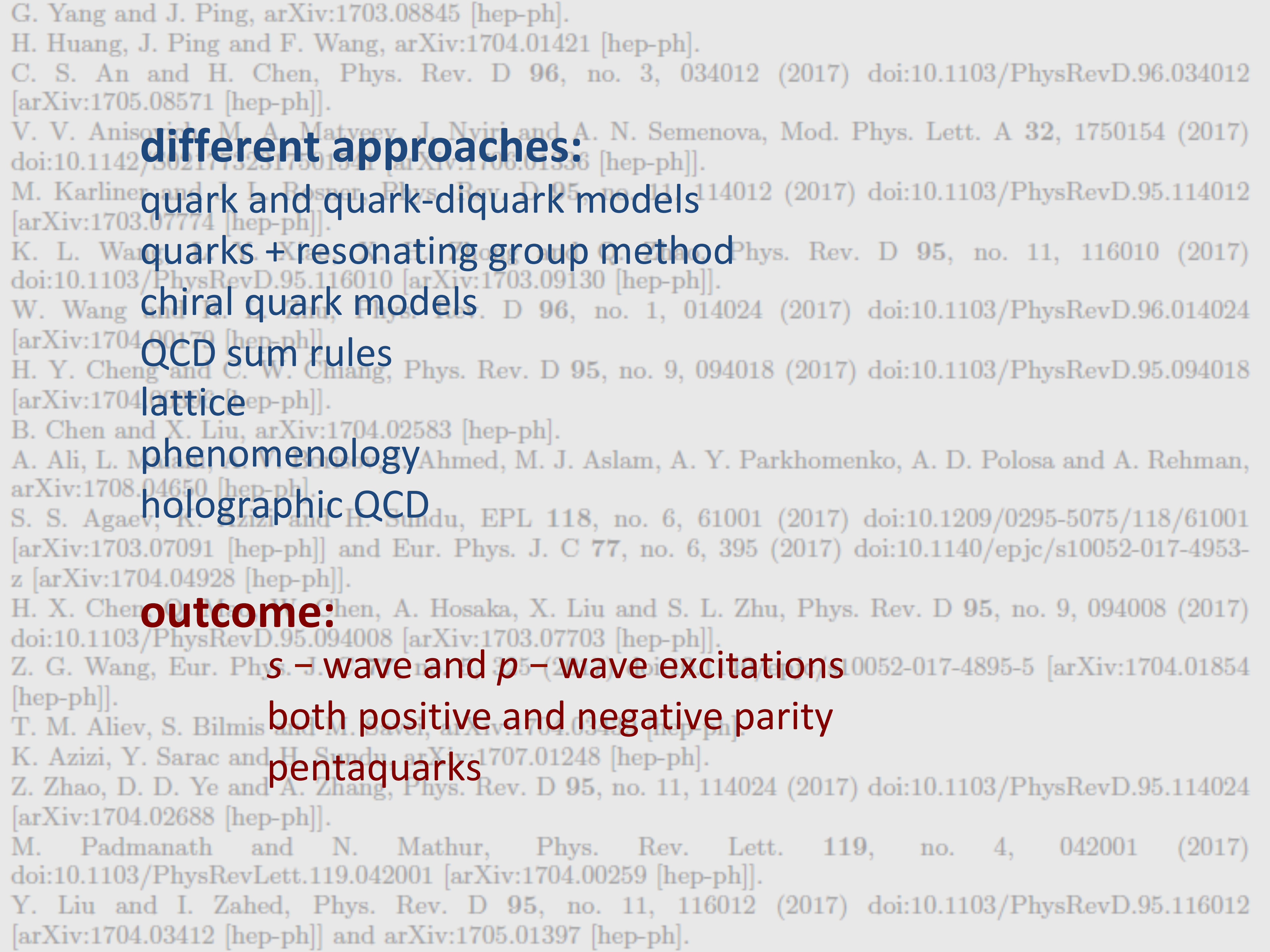
different approaches:

quark and quark-diquark models
quarks + resonating group method
chiral quark models
QCD sum rules
lattice
phenomenology
holographic QCD

outcome:

- s – wave and p – wave excitations
- both positive and negative parity
- pentaquarks



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Chiral Quark-Soliton Model

Why Chiral Quark-Soliton Model?

- Why not?

Why Chiral Quark-Soliton Model?

- ~~Why not?~~
- because it predicts small widths
  for some specific decays

QCD: quarks and gluons

integrate out gluons

many quark nonlocal interactions

Lagrangian chirally symmetric

approximation:

manyq, nonl. → 4q, local

Nambu Jona Lasinio model

spontaneous chiral symmetry breaking

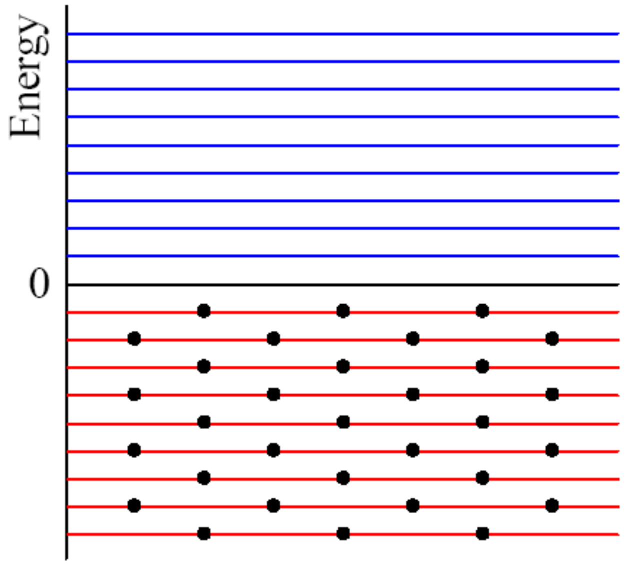
semibosonization:

$q\bar{q}q\bar{q} \longrightarrow q\bar{q}\pi$

Chiral Quark Model

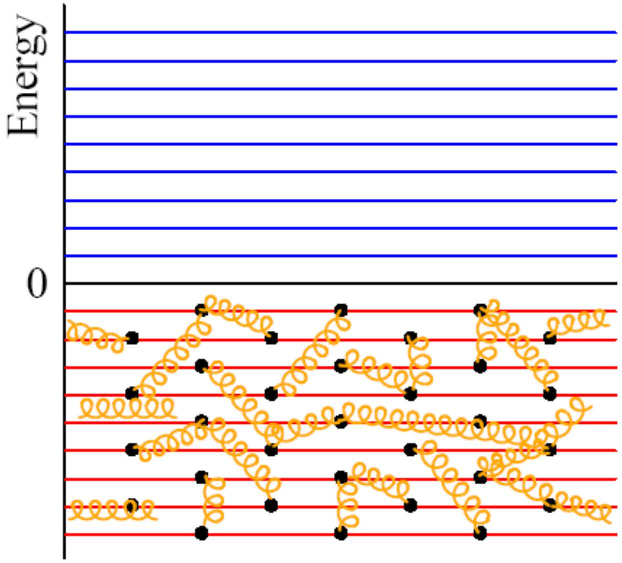
Chiral Quark Soliton Model

QCD vacuum:



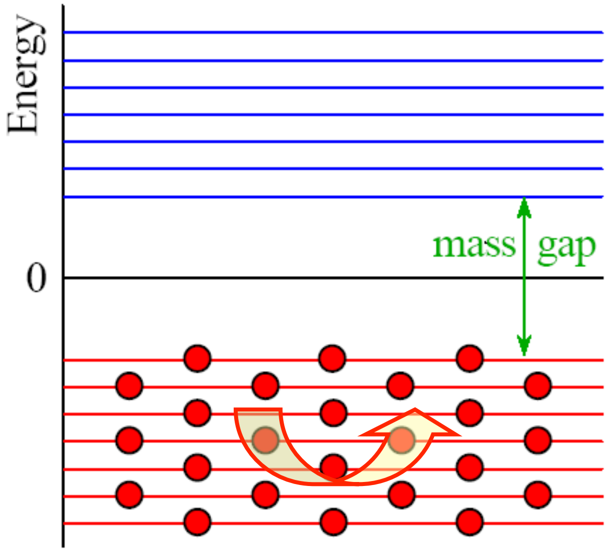
Chiral Quark Soliton Model

QCD vacuum:



Chiral Quark Soliton Model

chiral symmetry breaking:

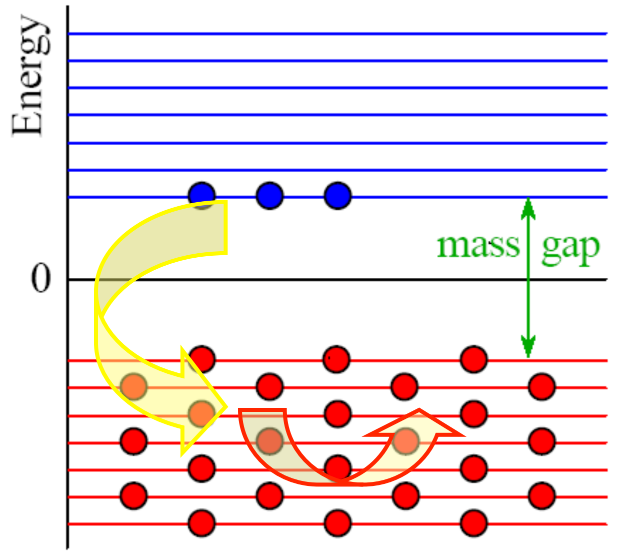


chirally inv. manyquark int.

Chiral Quark Soliton Model

baryon:

adding vlence quarks:



chirally inv. manyquark int.

Chiral Quark Soliton Model

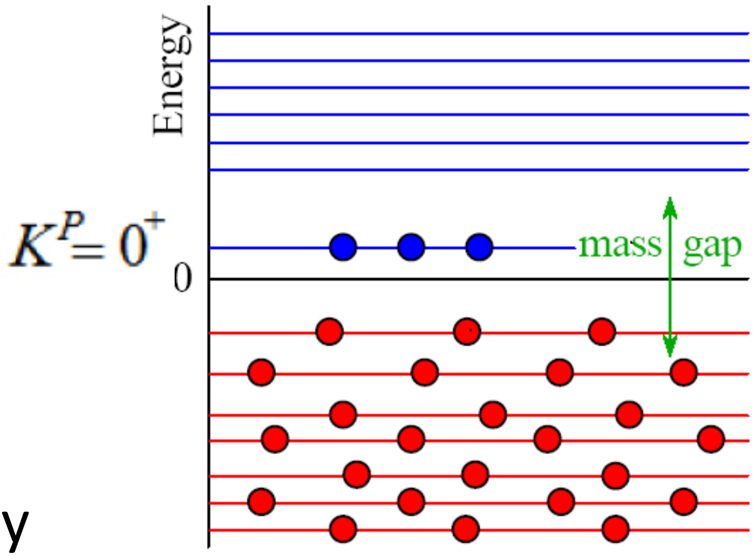
baryon:

due to hedgehog symmetry
of the mean field only
grand spin

$$K = T + S$$

is a *good* quantum number

"classical" baryon:



chirally inv. manyquark int.

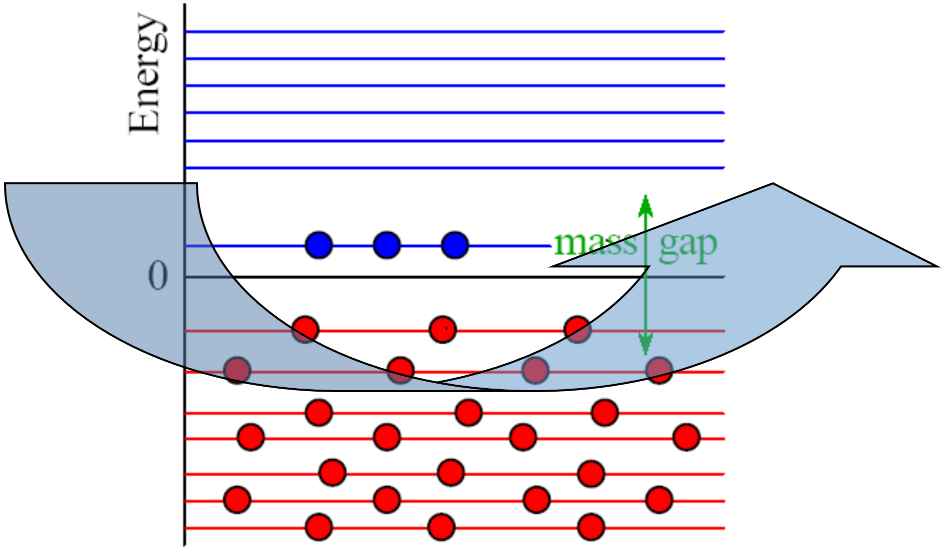
soliton configuration

no quantum numbers except *B*

Chiral Quark Soliton Model

baryon:

“quantum” baryon:



chirally inv. manyquark int.

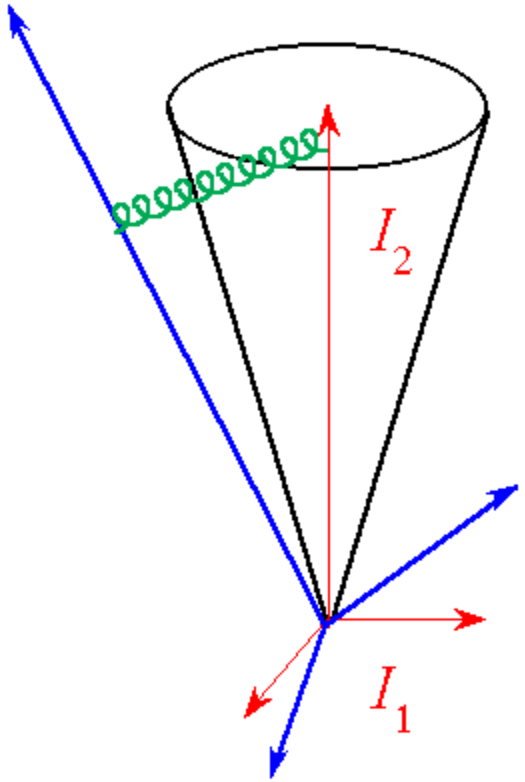
soliton configuration
no quantum numbers except *B*

rotation generates flavor and spin

Mass formula

$\pi_8 = N_c/2\sqrt{3}$

$$H_0 = M_{\rm cl} + \frac{1}{2I_1}S(S+1) + \frac{1}{2I_2}\left(C_2(\mathcal{R}) - S(S+1) - \frac{N_c^2}{12}\right)$$



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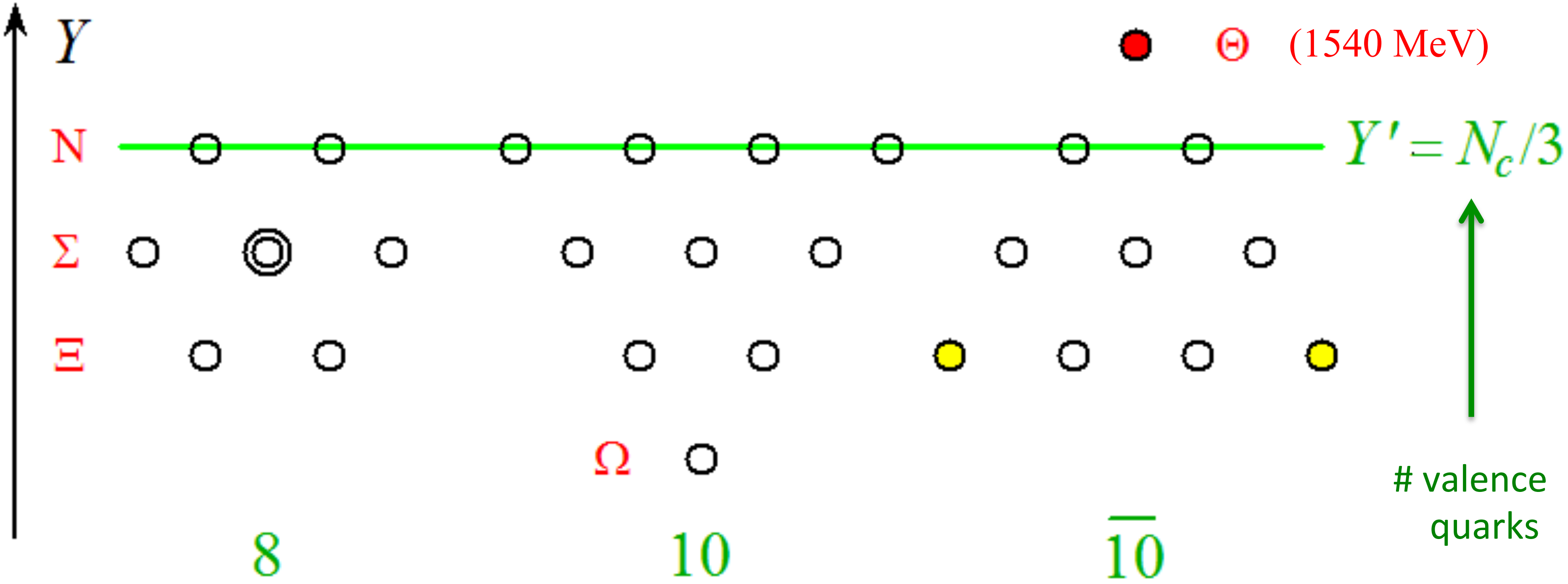
S. Jain, S.R. Wadia, Nucl. Phys. B258 (1985) 713

Allowed states

- allowed SU(3) representations must contain states with hypercharge $Y' = N_c/3$,
- the isospin $\boldsymbol{T}'$ of the states with $Y' = N_c/3$ couples with the soliton spin $\boldsymbol{J}$ to a singlet: $\boldsymbol{T}' + \boldsymbol{J} = 0$.



Ch.V. Christov et al. Prog. Part. Nucl. Phys. 37 (1996) 91

Successful Phenomenology

In a ”model independent” approach
one can get both good fits to the existing data
(including very narrow light pentaquark Θ^+)
one can fix all necessary model parameters:
M, I_1, I_2, α, β, γ − mass splittings …

Ch.V. Christov et al. Prog. Part. Nucl. Phys. 37 (1996) 91

Successful Phenomenology

In a ”model independent” approach
one can get both good fits to the existing data
(including very narrow light pentaquark Θ^+)
one can fix all necessary model parameters:
M, I_1, I_2, α, β, γ – mass splittings …

but also one can recover the NRQM result
in a special limit

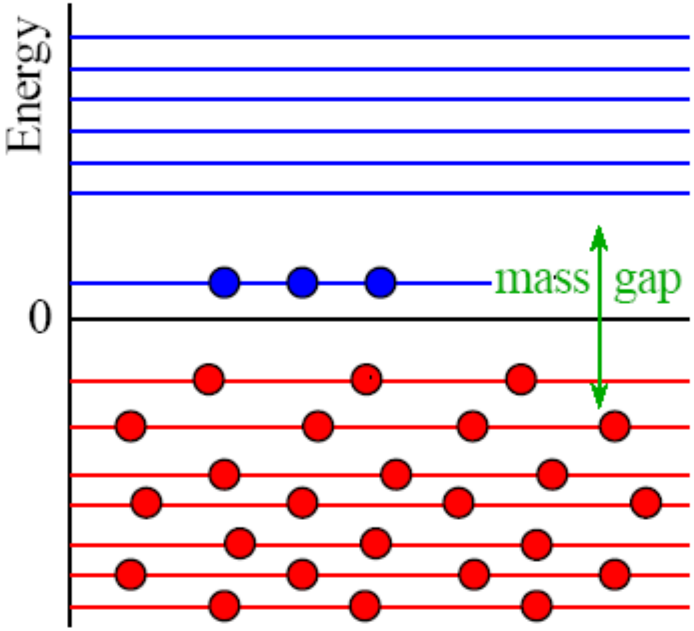
NRQM limit =
= squeezing the soliton to zero size

MP, A. Blotz, K. Goeke Phys. Lett. B354 (1995) 415

NRQM Limit

Diakonov, Petrov, Polyakov, Z.Phys **A359** (97) 305
MP, A.Blotz K.Goeke, Phys.Lett.**B354**:415-422,1995

energy is calculated
with respect to the vacuum:



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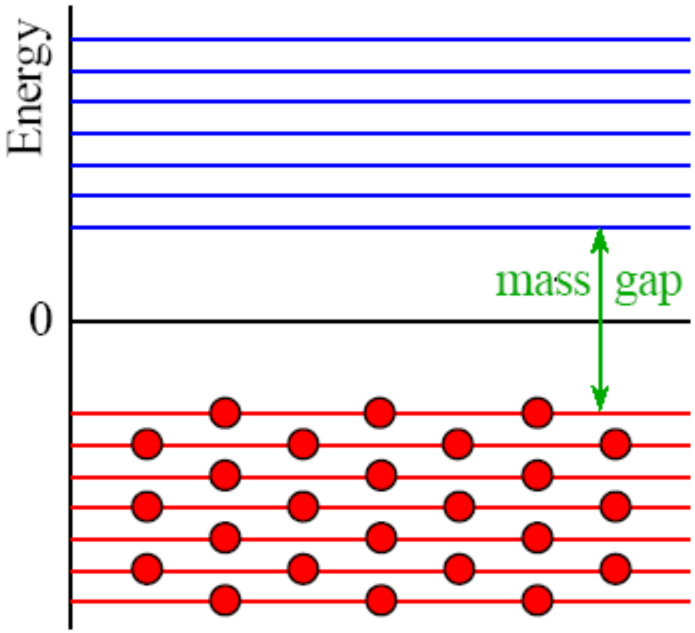
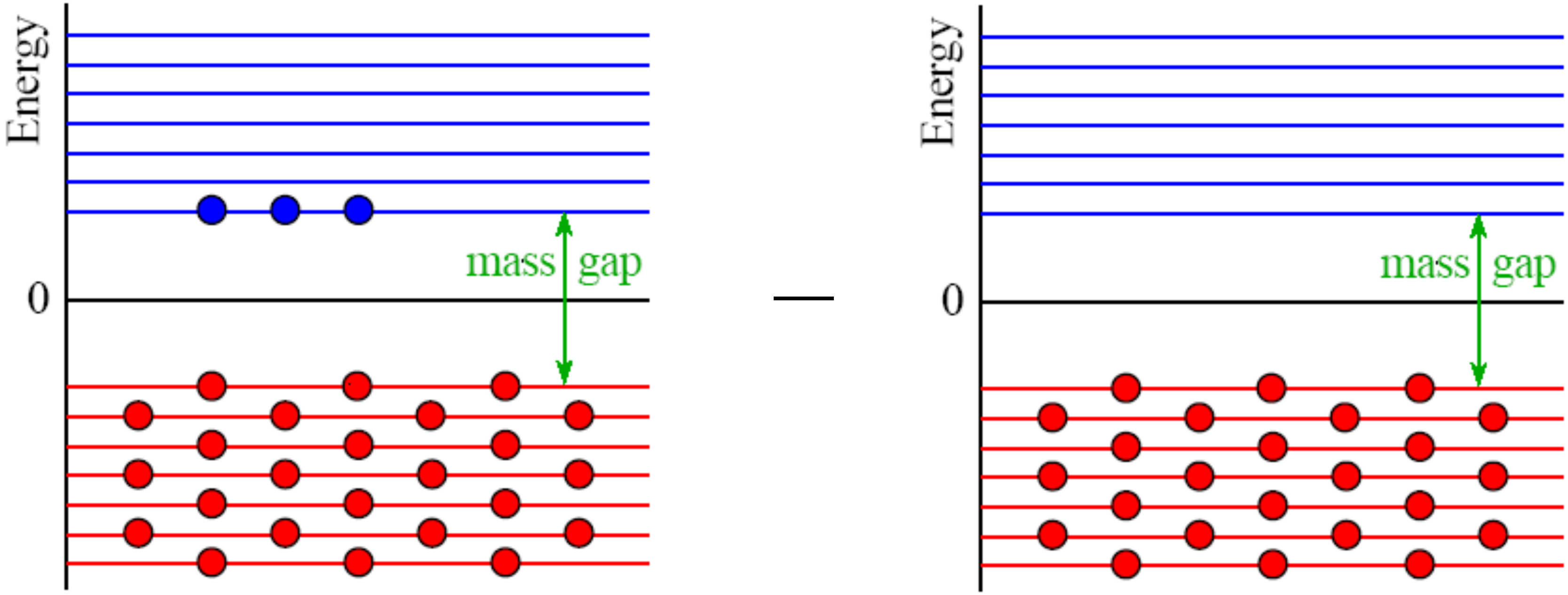


NRQM Limit

Diakonov, Petrov, Polyakov, Z.Phys **A359** (97) 305
MP, A.Blotz K.Goeke, Phys.Lett.**B354**:415-422,1995

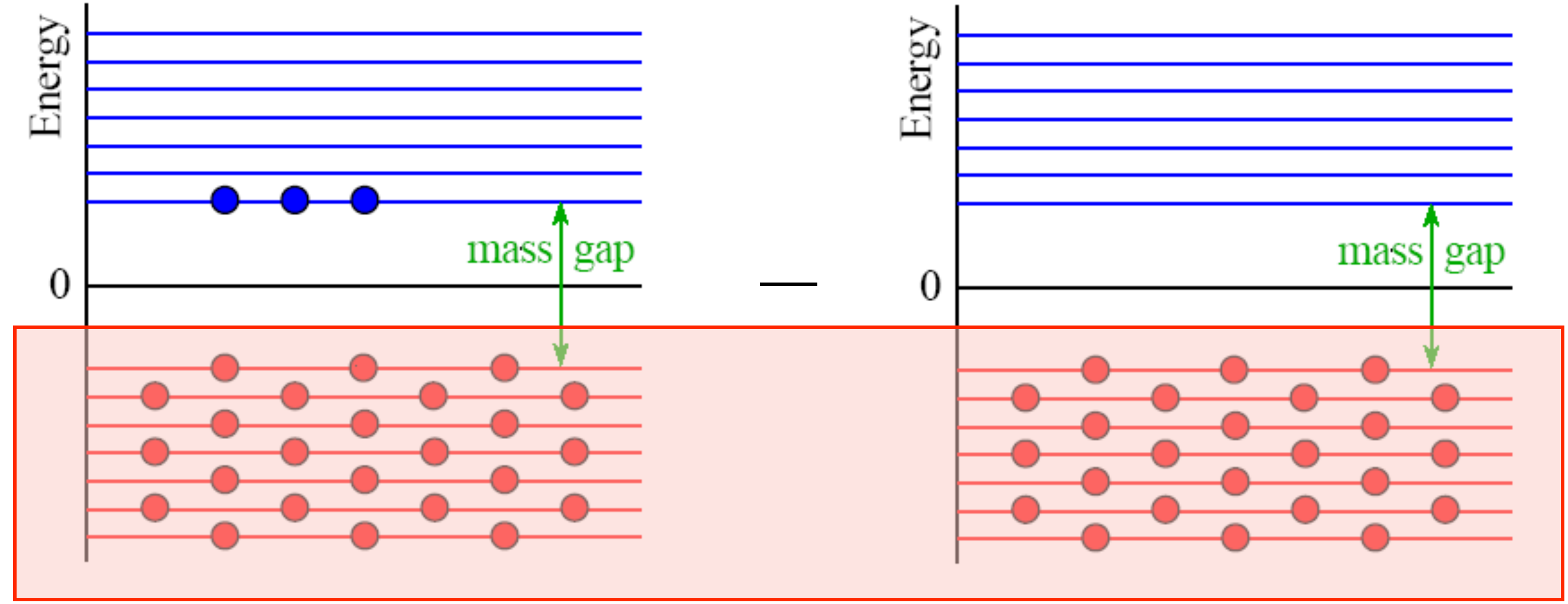
energy is calculated
with respect to the vacuum:



NRQM Limit

Diakonov, Petrov, Polyakov, Z.Phys **A359** (97) 305
MP, A.Blotz K.Goeke, Phys.Lett.**B354**:415-422,1995

energy is calculated
with respect to the vacuum:



in the NRQM limit only valence level contributes

NRQM Limit

$$g_A^{(3)} = \frac{5}{3}, \quad \Delta\Sigma = 1, \quad \frac{\mu_p}{\mu_n} = -\frac{3}{2}$$

Diakonov, Petrov, Polyakov, Z.Phys **A359** (97) 305
MP, A.Blotz K.Goeke, Phys.Lett.**B354**:415-422,1995

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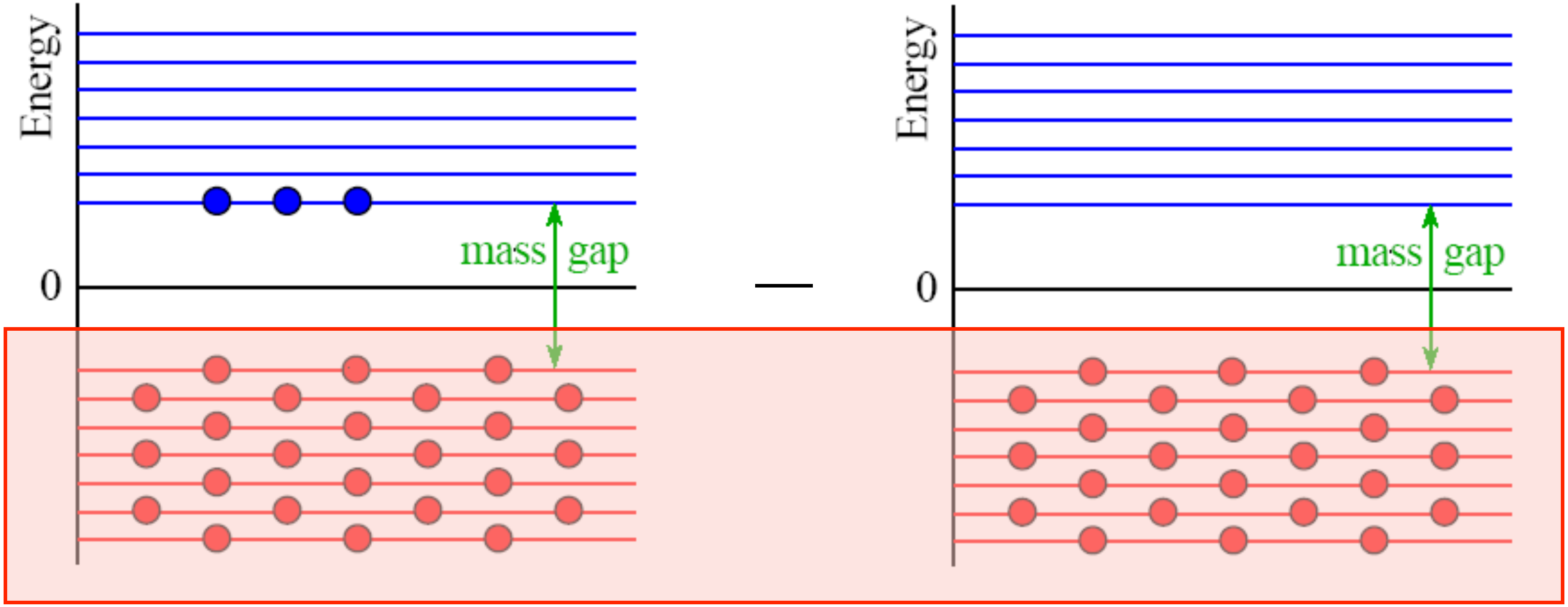

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NRQM Limit

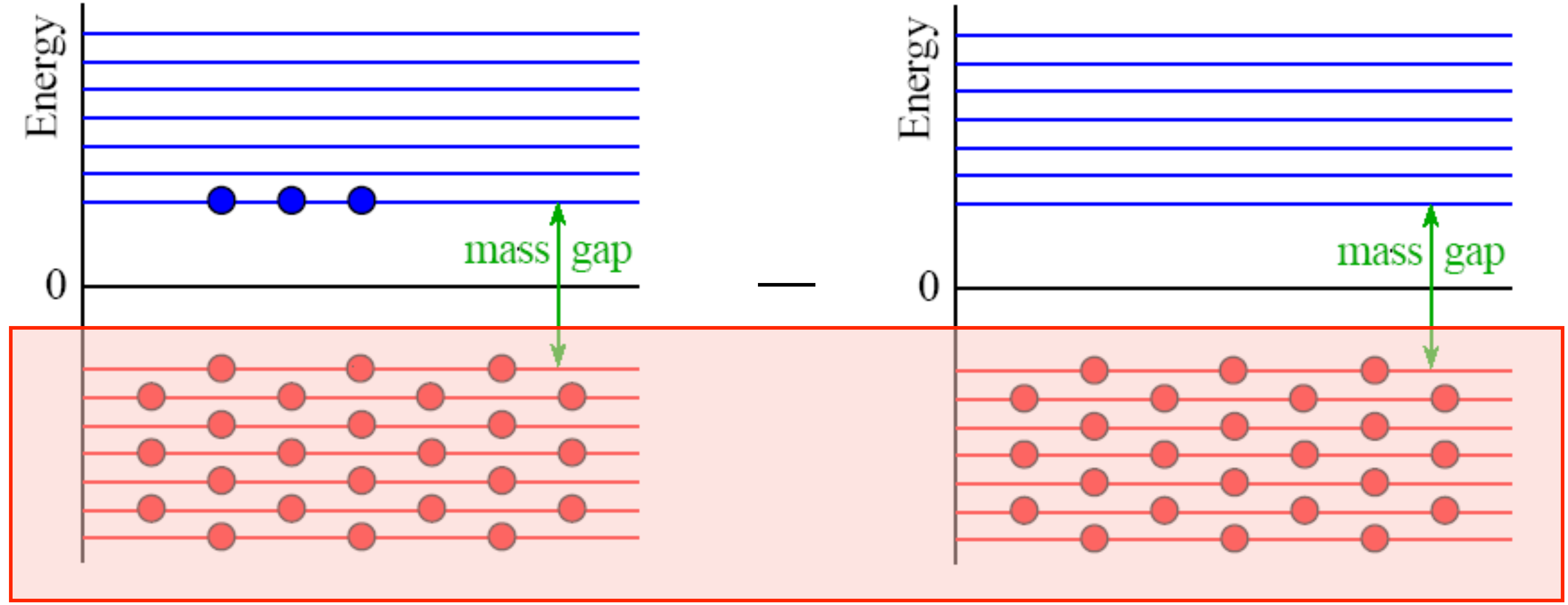
$$g_A^{(3)} = \frac{5}{3}, \quad \Delta\Sigma = 1, \quad \frac{\mu_p}{\mu_n} = -\frac{3}{2}$$

Diakonov, Petrov, Polyakov, Z.Phys **A359** (97) 305
MP, A.Blotz K.Goeke, Phys.Lett.**B354**:415-422,1995

$$\boxed{G_{\overline{10}} = 0}$$

energy is calculated
with respect to the vacuum:

pentaquark width = 0 !

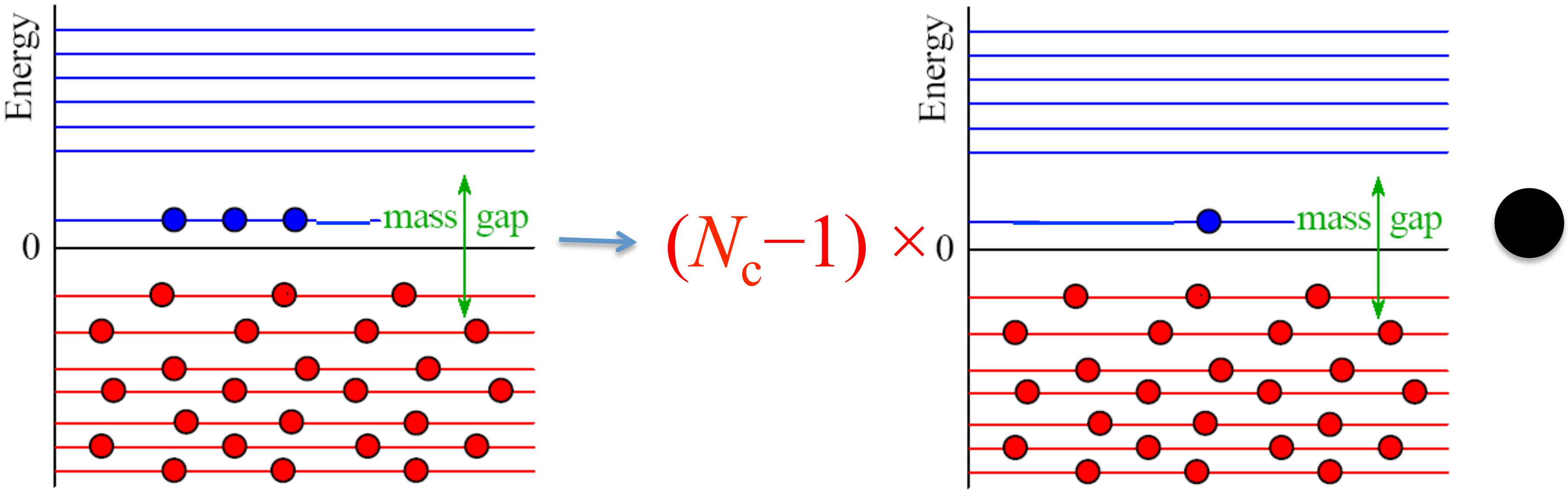


in the NRQM limit only valence level contributes

Heavy baryons in the Chiral Quark-Soliton Model

Soliton with $N_c - 1$ quarks

if N_c is large, $N_c - 1$ is also large and one can use the same mean field arguments



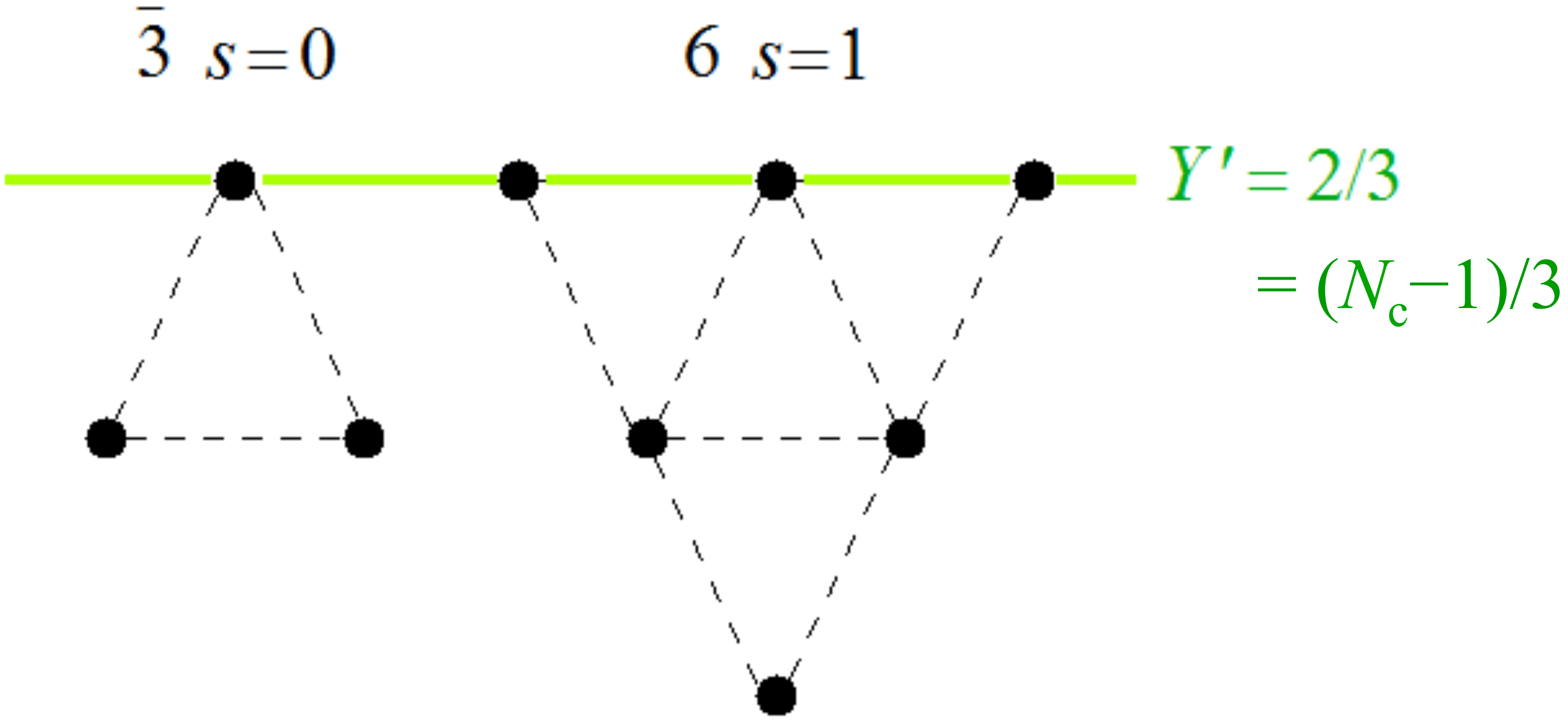
$(N_c-1)\times$

color factorizes!

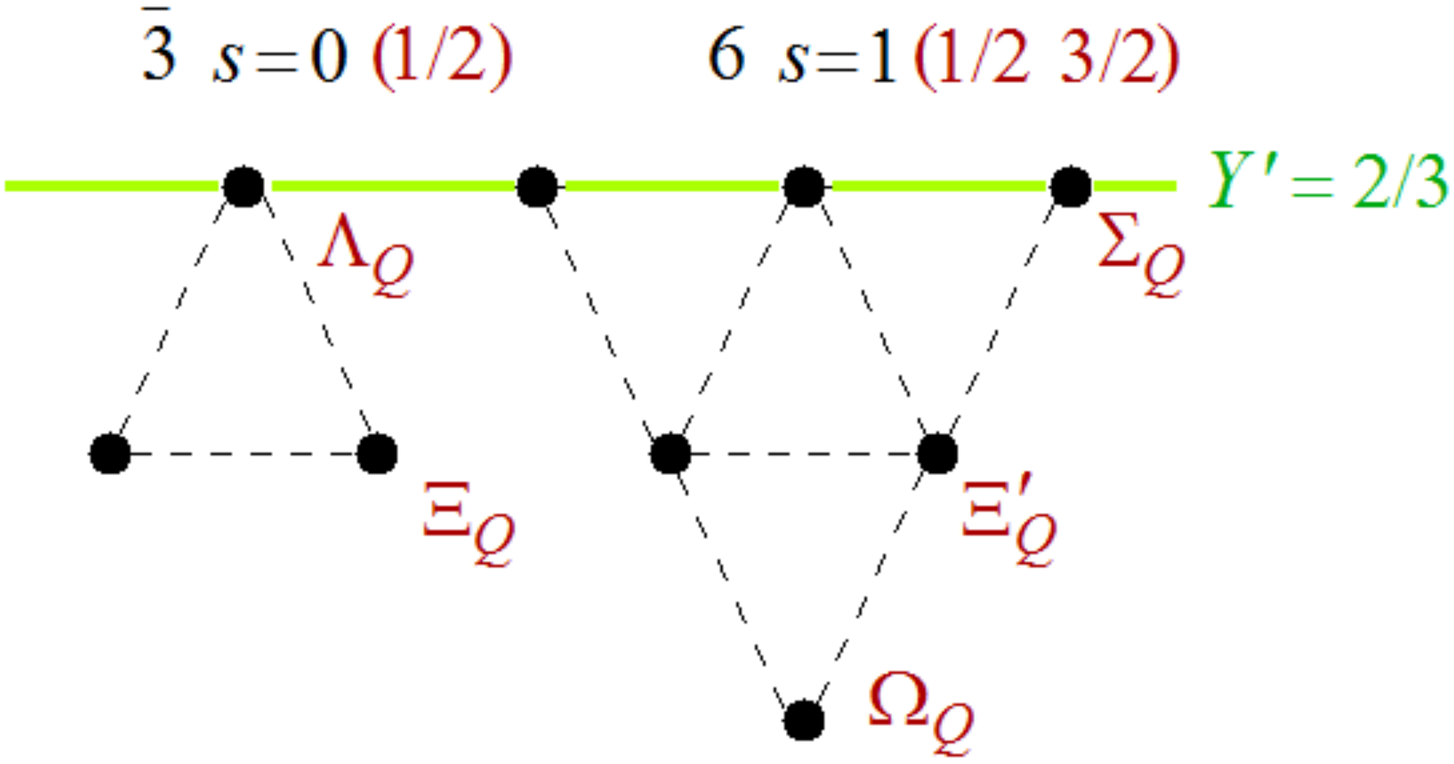
plus one heavy quark

G.S. Yang, H.C. Kim, M.V. Polyakov, MP Phys. Rev. D94 (2016) 071502

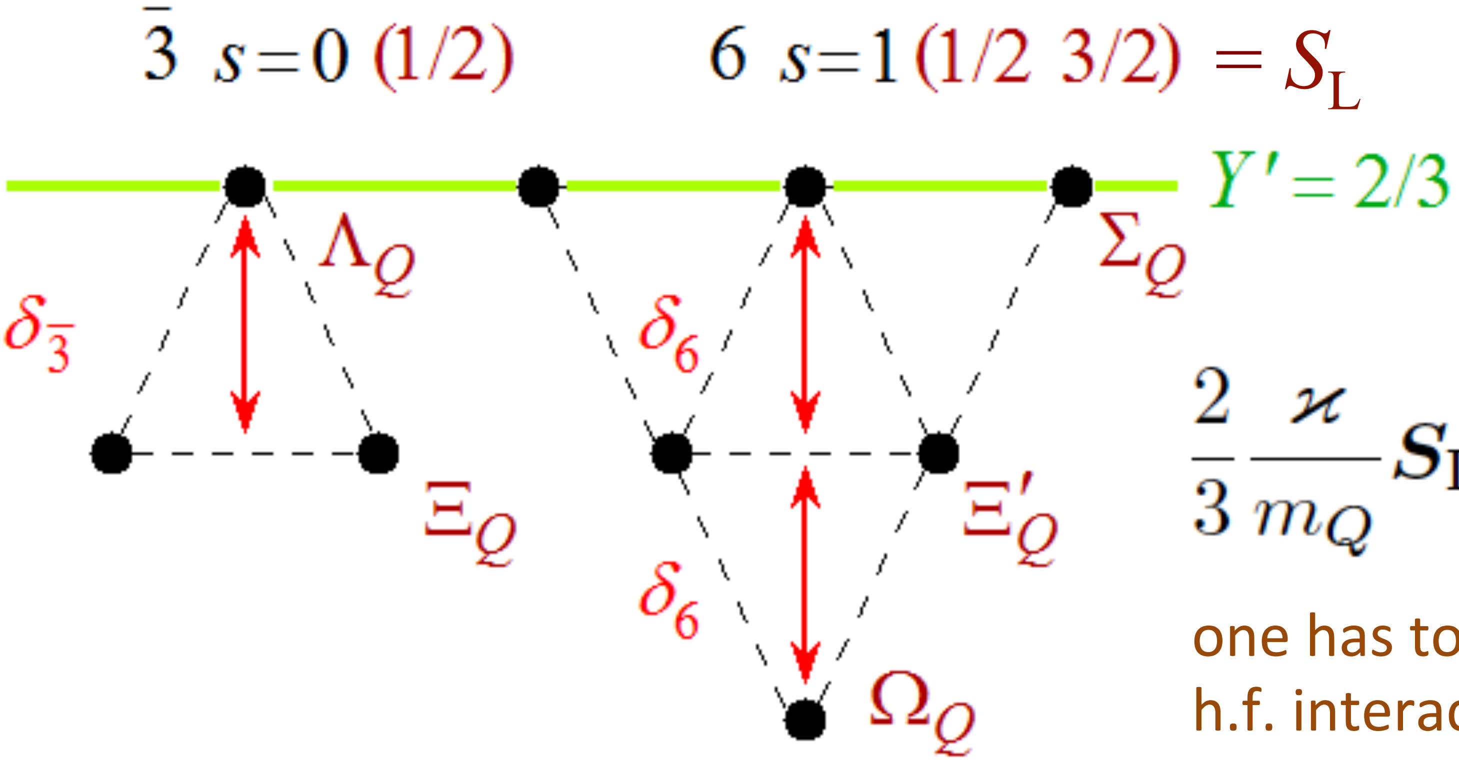
Allowed SU(3) irreps.



Heavy Baryons: soliton + heavy Q



Splittings inside multiplets

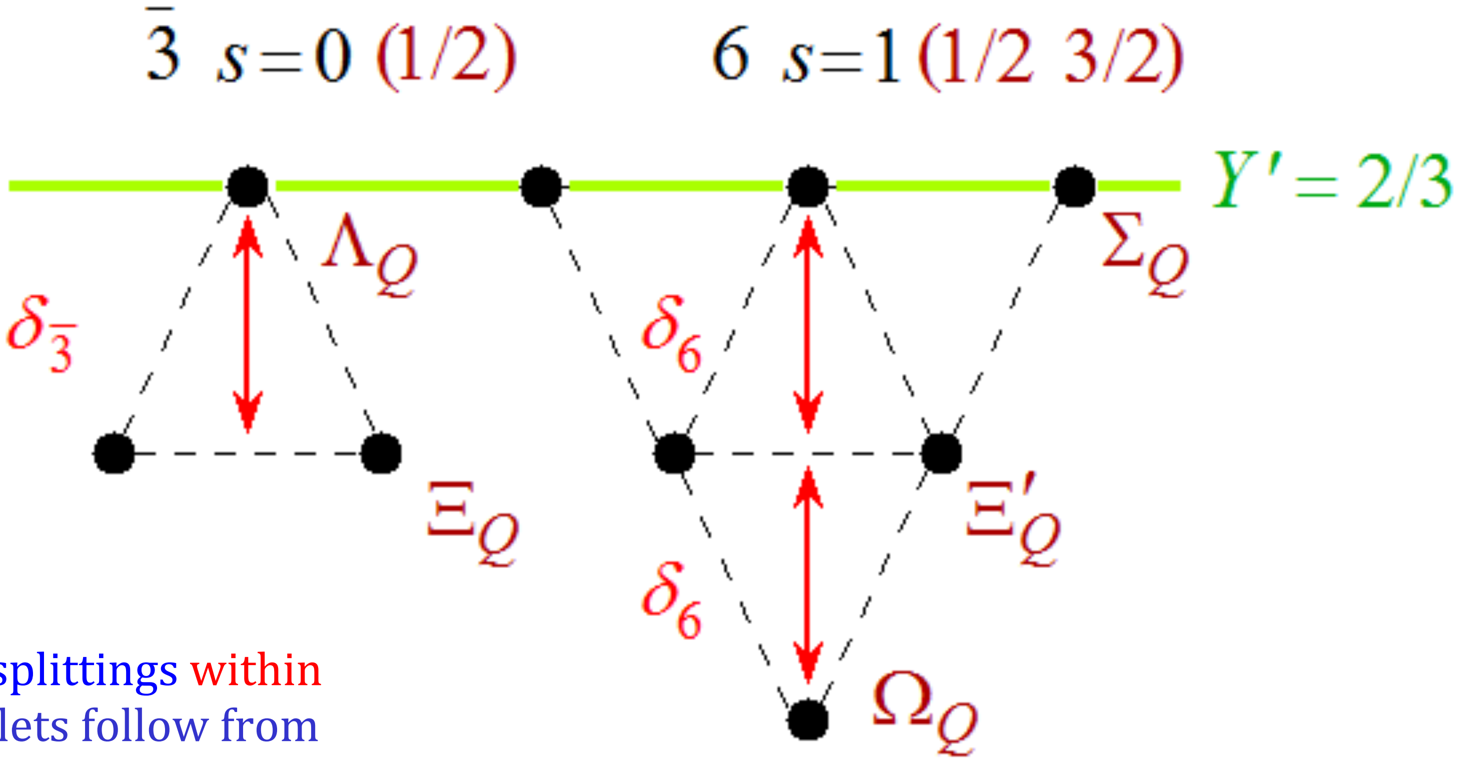


$$\frac{2}{3}\frac{\varkappa}{m_Q}\boldsymbol{S}_{\rm L}\cdot\boldsymbol{S}_Q$$

one has to add
h.f. interaction

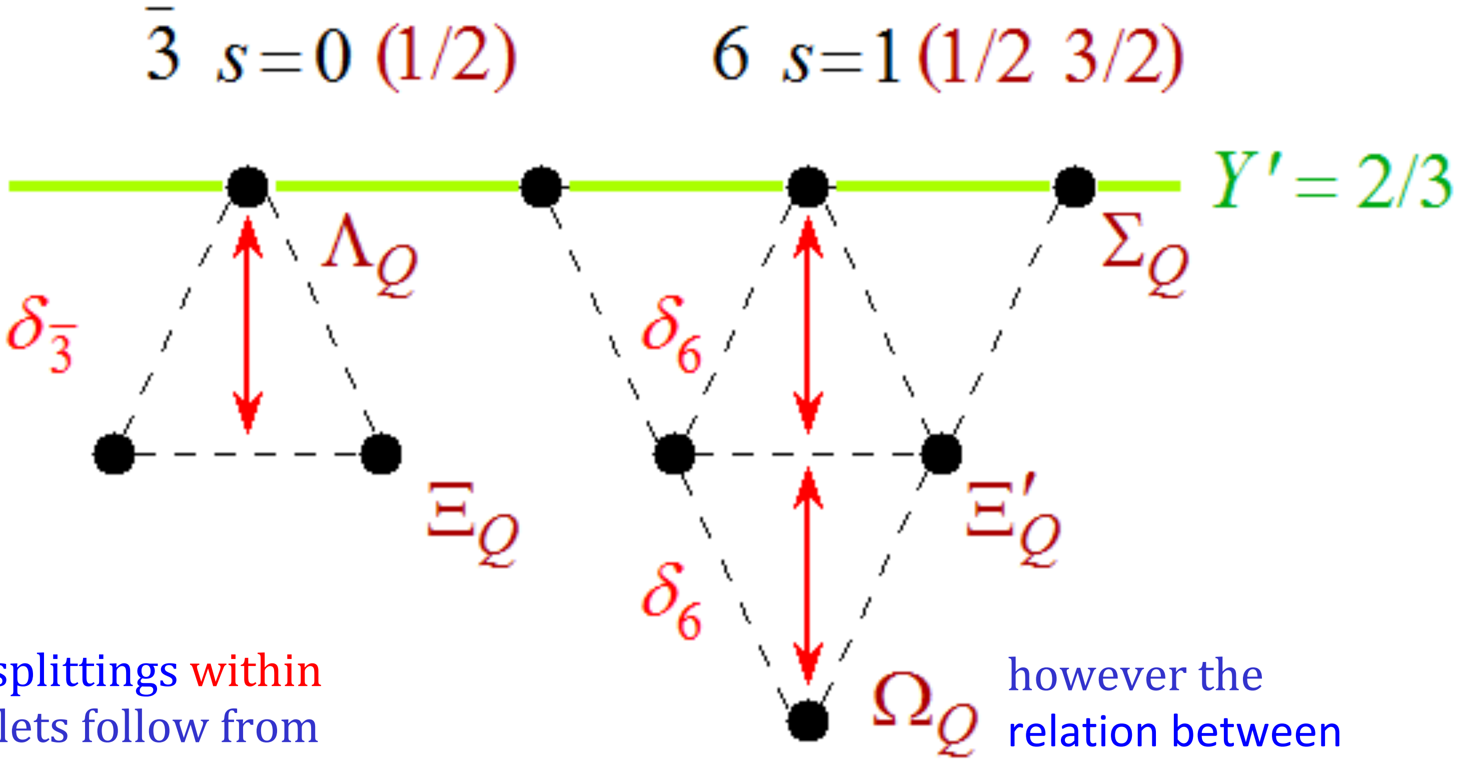
$$\kappa/m_c = 70 \text{ MeV}$$

Splittings inside multiplets



Equal splittings within multiplets follow from Eckhart-Wigner theorem (GMO relations)

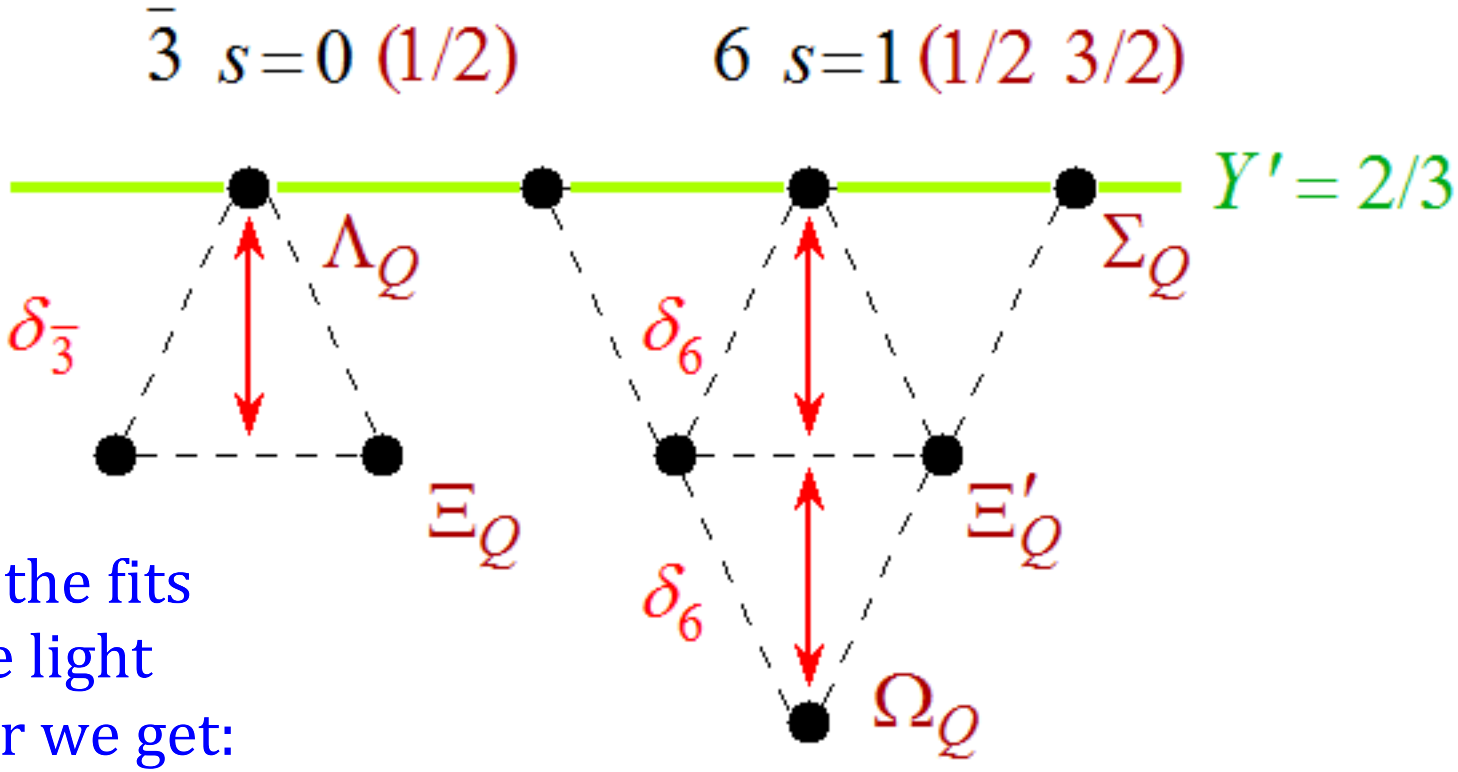
Splittings inside multiplets



Equal splittings within multiplets follow from Eckhart-Wigner theorem (GMO relations)

however the relation between the deltas does not follow from Eckhart-Wigner theorem

Splittings inside multiplets



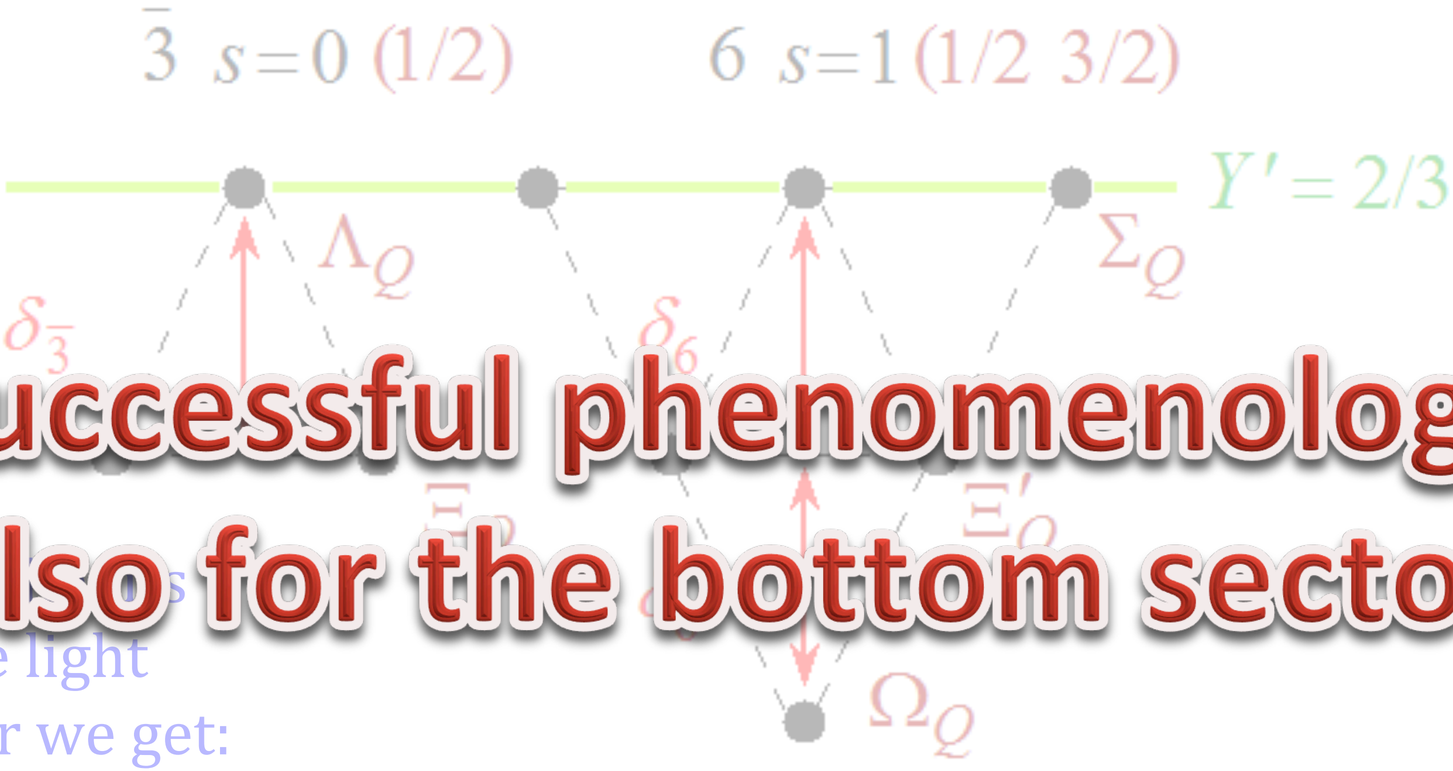
from the fits to the light sector we get:

$$\delta_{\bar{\mathbf{3}}} = \quad 203.8 \pm 3.5 \text{ MeV},$$ (exp.: 178 MeV)

$$\delta_{\mathbf{6}} = \quad 135.2 \pm 3.3 \text{ MeV},$$ (exp.: 121 MeV)

13%

Splittings inside multiplets



Successful phenomenology also for the bottom sector

fro [illegible] s to the light sector we get:

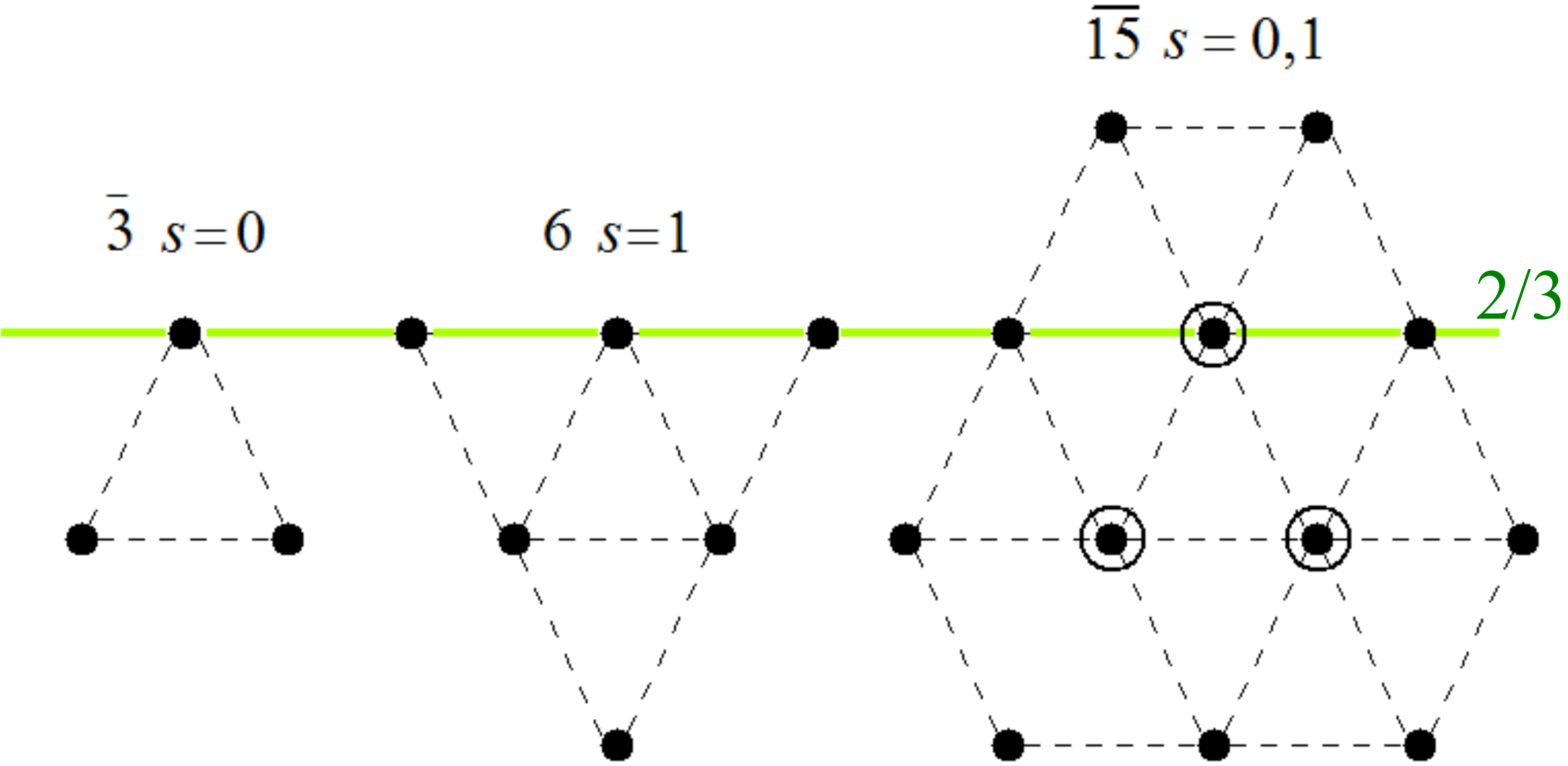
G.S. Yang, H.C. Kim, M.V. Polyakov, MP Phys. Rev. D94 (2016) 071502

$$\delta_{\bar{\mathbf{3}}} = \quad 203.8 \pm 3.5\ \mathrm{MeV}, \quad \text{(exp.: 178 MeV)}$$

$$\delta_{\mathbf{6}} = \quad 135.2 \pm 3.3\ \mathrm{MeV}, \quad \text{(exp.: 121 MeV)}$$

13%

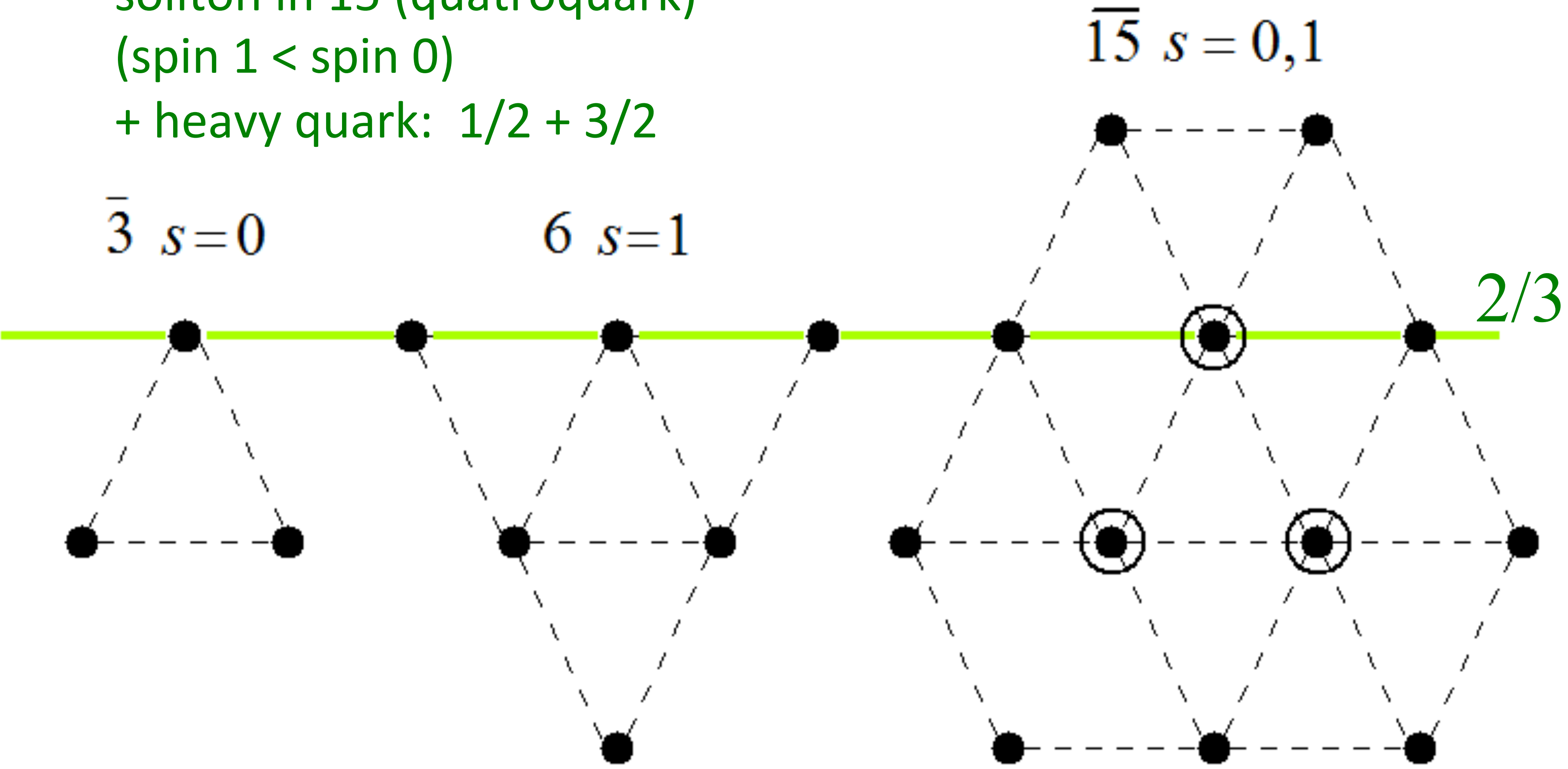
Rotational excitations: heavy pentaquarks



H.C. Kim, M.V. Plyakov, MP arXiv:1704.04082 [hep-ph]

Rotational excitations: heavy pentaquarks

soliton in 15 (quatroquark)
(spin 1 < spin 0)
+ heavy quark: 1/2 + 3/2



H.C. Kim, M.V. Plyakov, MP arXiv:1704.04082 [hep-ph]

Rotational excitations: heavy pentaquarks

soliton in 15 (quatroquark)

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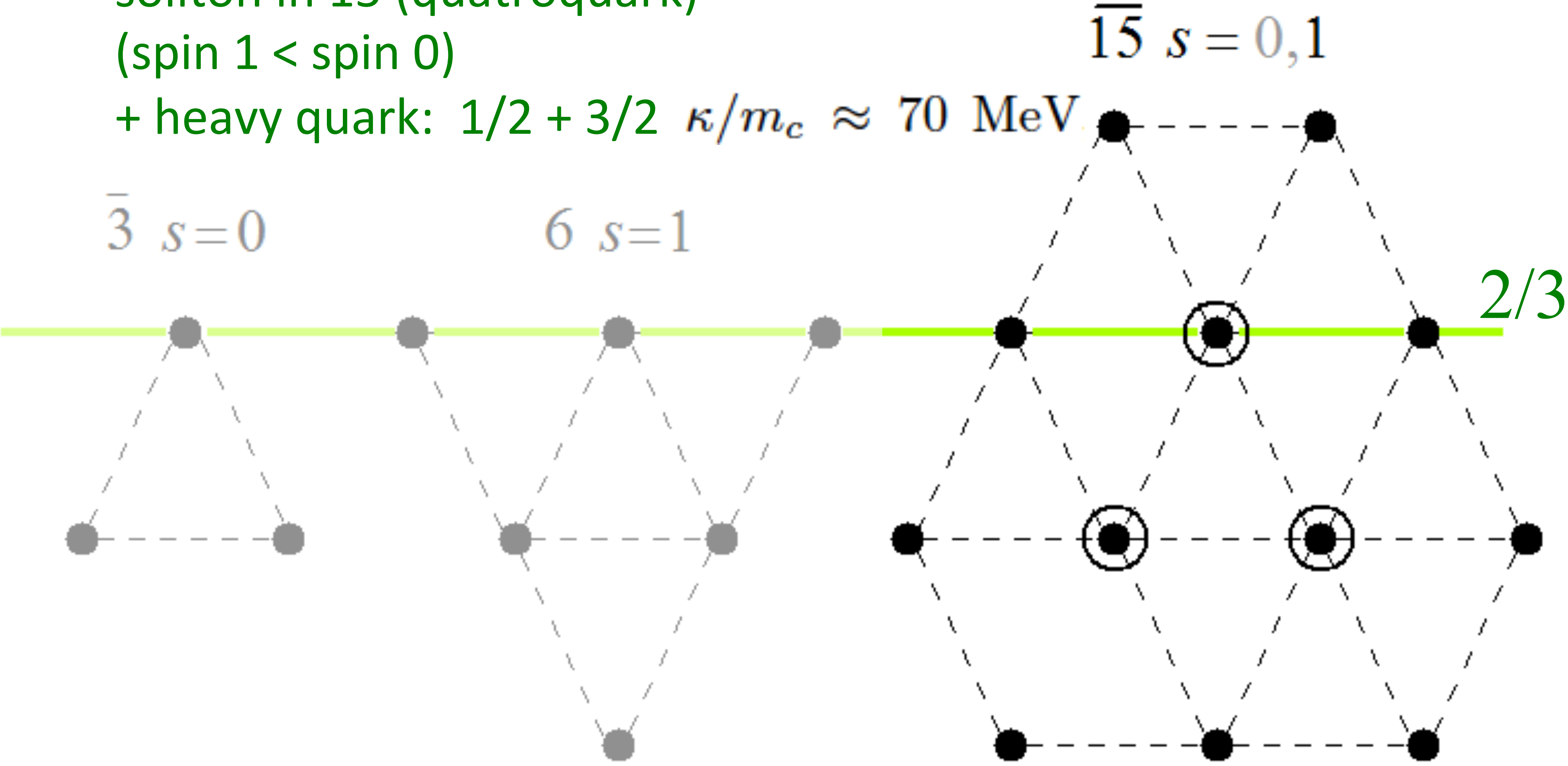
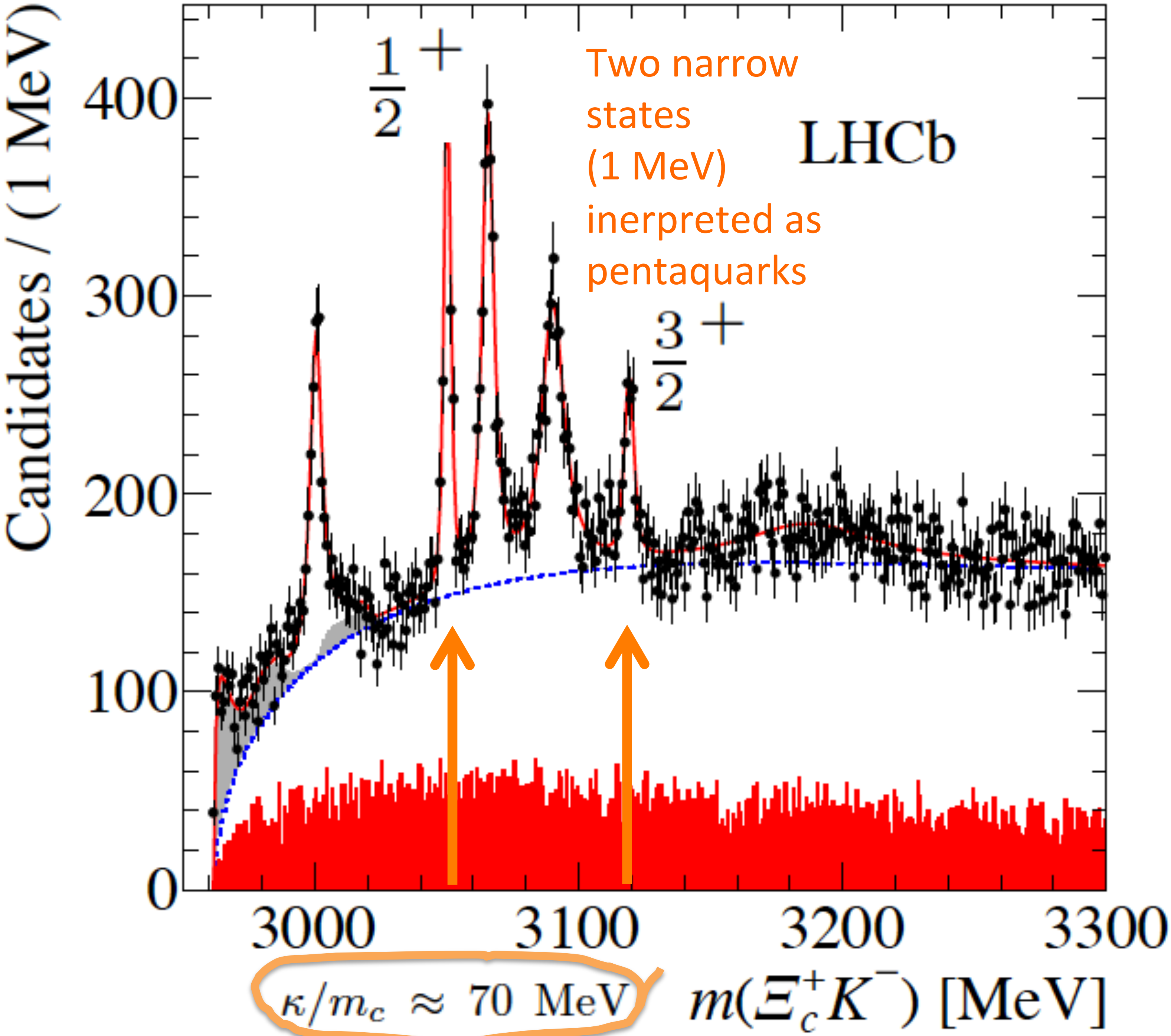


H.C. Kim, M.V. Plyakov, MP arXiv:1704.04082 [hep-ph]



Two narrow states (1 MeV) inerpreted as pentaquarks

$\kappa/m_c \approx 70$ MeV

Decays of positive parity states

axial-vector constants with $X = 3, 8, 0$

$$g^{(B_1\to B_2)} = a_1\langle B_2|D^{(8)}_{X3}|B_1\rangle \; + \; a_2 d_{pq3}\langle B_2|D^{(8)}_{Xp}\,\hat{S}_q|B_1\rangle \; + \; \frac{a_3}{\sqrt{3}}\langle B_2|D^{(8)}_{X8}\,\hat{S}_3|B_1\rangle$$

$a_1 \sim N_c \; a_2 \sim O(1) \;\; a_3 \sim O(1)$ fixed from the data on weak hyperon decays

Goldberger-Treiman relation:

for strong decays $B_1 \to B_2 + \varphi$ use the same operator

H. Y. Cheng and C. K. Chua, Phys. Rev. D 75 (2007) 014006

H. Y. Cheng and C. K. Chua, Phys. Rev. D 92 (2015) 074014

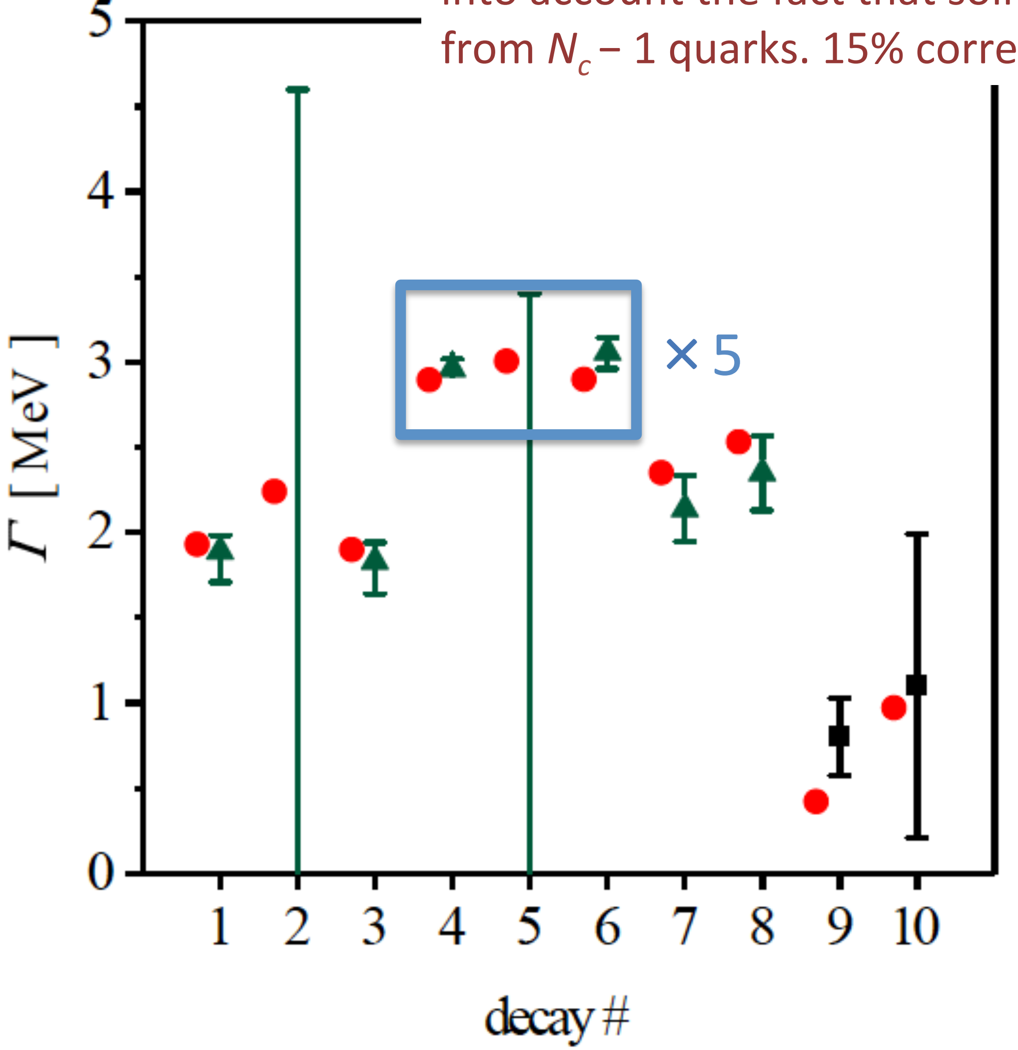
example

$$\Gamma_{\Sigma(\mathbf{6}_1)\to\Lambda(\overline{\mathbf{3}}_0)+\pi} = \frac{1}{72\pi}\frac{p^3}{F_\pi^2}\frac{M_{\Lambda(\overline{\mathbf{3}}_0)}}{M_{\Sigma(\mathbf{6}_1)}}H_{\overline{\mathbf{3}}}^2\frac{3}{8} \qquad H_{\overline{\mathbf{3}}} = -a_1 + \frac{1}{2}a_2$$

Charm decay widths

1. $\Sigma_c^{++}(1/2) \rightarrow \Lambda_c^+ + \pi^+$
2. $\Sigma_c^{+}(1/2) \rightarrow \Lambda_c^+ + \pi^0$
3. $\Sigma_c^{0}(1/2) \rightarrow \Lambda_c^+ + \pi^-$
4. $\Sigma_c^{++}(3/2) \rightarrow \Lambda_c^+ + \pi^+$
5. $\Sigma_c^{+}(3/2) \rightarrow \Lambda_c^+ + \pi^0$
6. $\Sigma_c^{0}(3/2) \rightarrow \Lambda_c^+ + \pi^-$
7. $\Xi_c^{+}(3/2) \rightarrow \Xi_c + \pi$
8. $\Xi_c^{0}(3/2) \rightarrow \Xi_c + \pi$
9. $\Omega_c^{0}(1/2)$ – total
10. $\Omega_c^{0}(3/2)$ – total

with one adjustable parameter that takes into account the fact that soliton is built up from $N_c - 1$ quarks. 15% correction to a_1



Charm decay widths

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1. $\Sigma_c^{++}(1/2) \to \Lambda_c^+ + \pi^+$
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3. $\Sigma_c^{0}(1/2) \to \Lambda_c^+ + \pi^-$
4. $\Sigma_c^{++}(3/2) \to \Lambda_c^+ + \pi^+$
5. $\Sigma_c^{+}(3/2) \to \Lambda_c^+ + \pi^0$
6. $\Sigma_c^{0}(3/2) \to \Lambda_c^+ + \pi^-$
7. $\Xi_c^{+}(3/2) \to \Xi_c + \pi$
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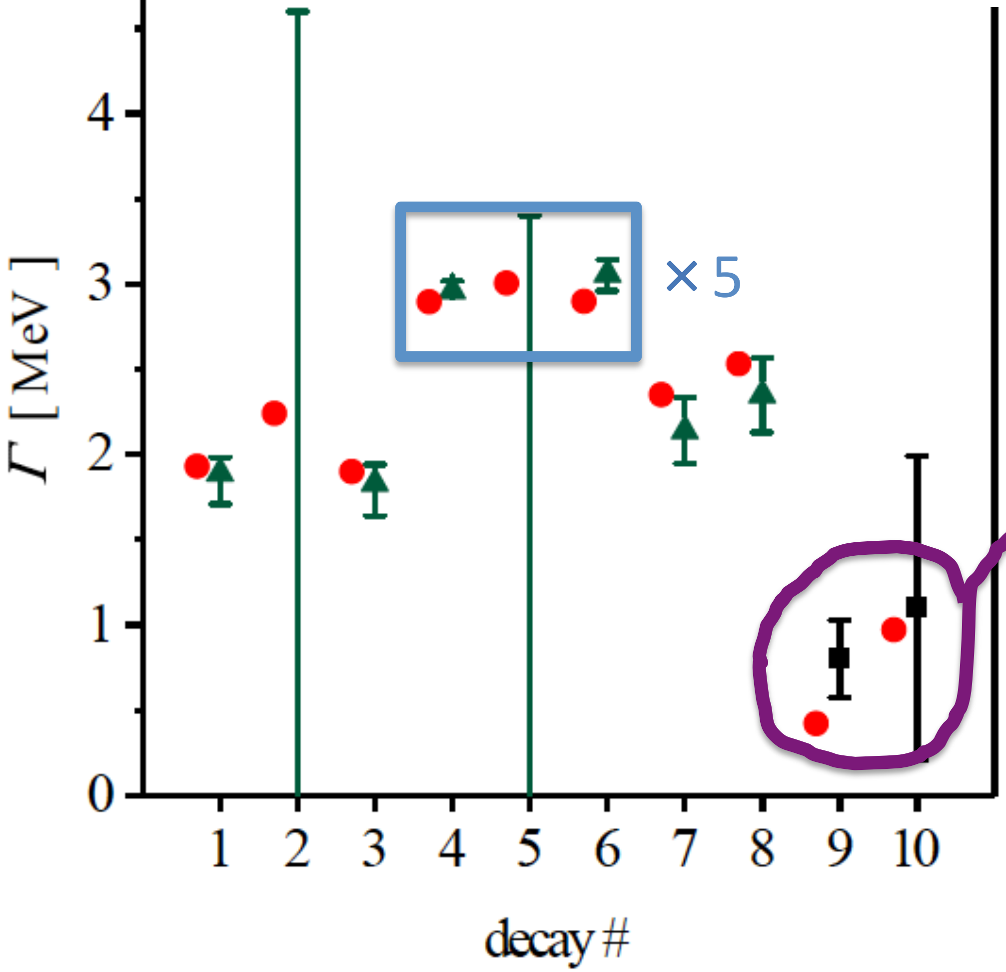
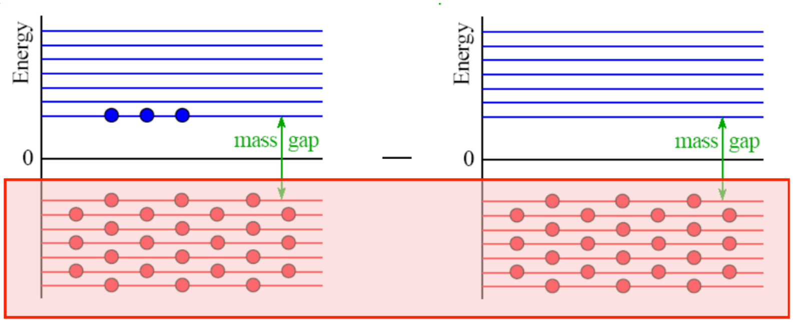


numerical coincidence?

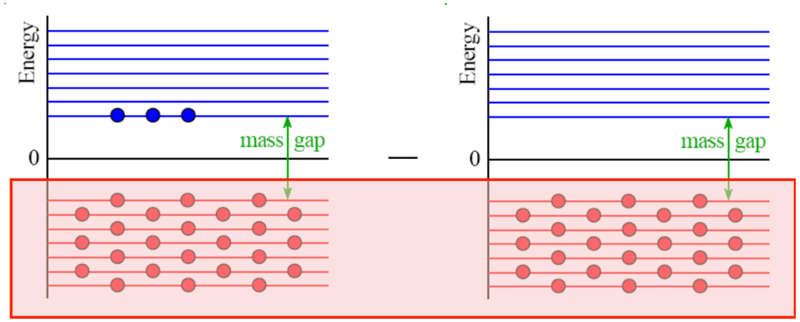
or there is a good reason

Quark Model limit and large N_c



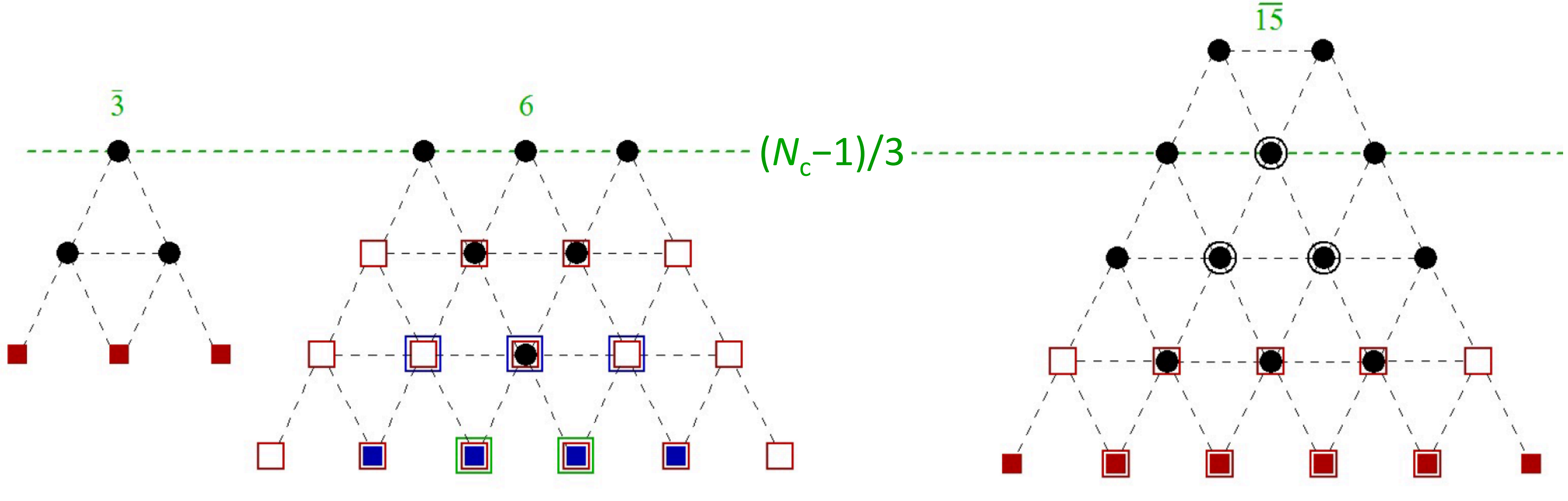
$$-\tilde{a}_1 \overset{\mathrm{QM}}{\to} N_c + 1, \quad a_2 \overset{\mathrm{QM}}{\to} 4, \quad a_3 \overset{\mathrm{QM}}{\to} 2$$

Quark Model limit and large N_c



$$-\tilde{a}_1 \overset{\mathrm{QM}}{\rightarrow} N_c+1,\quad a_2 \overset{\mathrm{QM}}{\rightarrow} 4,\quad a_3 \overset{\mathrm{QM}}{\rightarrow} 2$$

N_c dependent SU(3) representations ⟶ N_c dependent C-G coefficiens



MP Eur.Phys.J. C78 (2018) 690

Decay constants

generically O(N_c)

$$\mathbf{6}_1 \to \overline{\mathbf{3}}_0 \qquad H_{\overline{3}} = -\tilde{a}_1 + \frac{1}{2}a_2,$$

$$\overline{\mathbf{15}}_1 \to \overline{\mathbf{3}}_0 \qquad G_{\overline{3}} = -\tilde{a}_1 - \frac{1}{2}a_2,$$

$$\overline{\mathbf{15}}_1 \to \mathbf{6}_1 \qquad G_6 = -\tilde{a}_1 - \frac{1}{2}a_2 - a_3$$

exotic

MP Eur.Phys.J. C78 (2018) 690

Decay constants

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$$\mathbf{6}_1 \to \overline{\mathbf{3}}_0 \qquad H_{\overline{3}} = -\tilde{a}_1 + \frac{1}{2}a_2,$$

exotic

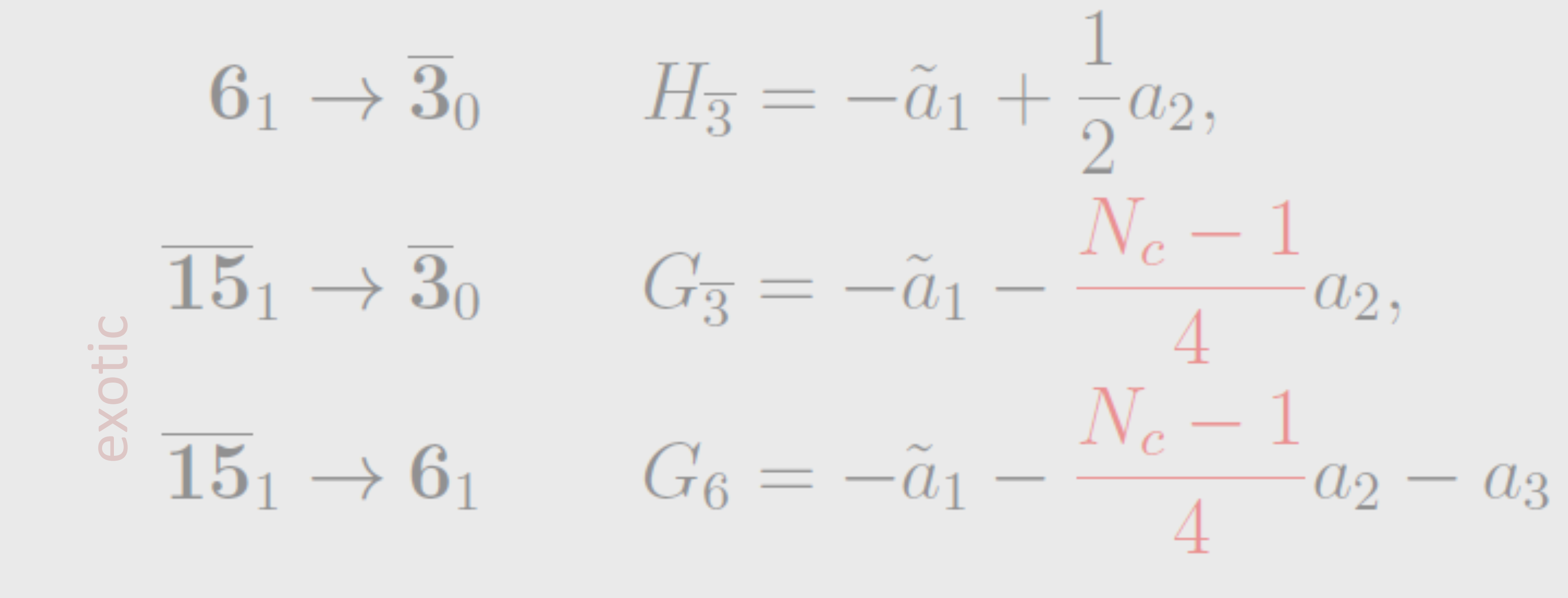
$$\overline{\mathbf{15}}_1 \to \overline{\mathbf{3}}_0 \qquad G_{\overline{3}} = -\tilde{a}_1 - \frac{N_c - 1}{4}a_2,$$

$$\overline{\mathbf{15}}_1 \to \mathbf{6}_1 \qquad G_6 = -\tilde{a}_1 - \frac{N_c - 1}{4}a_2 - a_3$$

MP Eur.Phys.J. C78 (2018) 690

Decay constants in the QM limit

generically O(N_c)



exotic

$$6_1 \to \bar{3}_0 \qquad H_{\bar{3}} = -\tilde{a}_1 + \frac{1}{2}a_2,$$

$$\overline{15}_1 \to \bar{3}_0 \qquad G_{\bar{3}} = -\tilde{a}_1 - \frac{N_c-1}{4}a_2,$$

$$\overline{15}_1 \to 6_1 \qquad G_6 = -\tilde{a}_1 - \frac{N_c-1}{4}a_2 - a_3$$

$$H_{\overline{\mathbf{3}}} \overset{\text{QM}}{\to} N_c + 3, \quad G_{\overline{\mathbf{3}}} \overset{\text{QM}}{\to} 2, \quad G_{\mathbf{6}} \overset{\text{QM}}{\to} 0.$$

MP Eur.Phys.J. C78 (2018) 690

Decay constants in the QM limit

generically O(N_c)

exotic

$$6_1 \to \bar{3}_0 \qquad H_{\bar{3}} = -\tilde{a}_1 + \frac{1}{2} a_2,$$

$$\overline{15}_1 \to \bar{3}_0 \qquad G_{\bar{3}} = -\tilde{a}_1 - \frac{N_c - 1}{4} a_2,$$

$$\overline{15}_1 \to 6_1 \qquad G_6 = -\tilde{a}_1 - \frac{N_c - 1}{4} a_2 - a_3$$

Expectations:
decays of exotica are suppressed

$$H_{\overline{\mathbf{3}}} \overset{\text{QM}}{\to} N_c + 3, \quad \boxed{G_{\overline{\mathbf{3}}} \overset{\text{QM}}{\to} 2, \quad G_{\mathbf{6}} \overset{\text{QM}}{\to} 0.}$$

MP Eur.Phys.J. C78 (2018) 690

Decay widths: large N_c

$$\Gamma_{\Sigma(\mathbf{6}_1)\to\Lambda(\overline{\mathbf{3}}_0)+\pi} \overset{N_c\to\infty}{\to} \frac{1}{N_c^2}$$

$$\Gamma_{\Xi(\mathbf{6}_1)\to\Xi(\overline{\mathbf{3}}_0)+\pi} \overset{N_c\to\infty}{\to} \frac{1}{N_c^2}$$

$$\Gamma_{\Omega(\overline{\mathbf{15}}_1)\to\Xi(\overline{\mathbf{3}}_0)+K} \overset{N_c\to\infty}{\to} \frac{1}{N_c^2}$$

$$\Gamma_{\Omega(\overline{\mathbf{15}}_1)\to\Omega(\mathbf{6}_1)+\pi} \overset{N_c\to\infty}{\to} \frac{1}{N_c}$$

$$\Gamma_{\Omega(\overline{\mathbf{15}}_1)\to\Xi(\mathbf{6}_1)+K} \overset{N_c\to\infty}{\to} \frac{1}{N_c^2}$$

Decay widths: large N_c and QM limit

$$\Gamma_{\Sigma(\mathbf{6}_1)\to\Lambda(\overline{\mathbf{3}}_0)+\pi} \overset{N_c\to\infty}{\to} \frac{1}{N_c^2} \overset{\mathrm{QM}}{\to} \frac{1}{N_c^2},$$

$$\Gamma_{\Xi(\mathbf{6}_1)\to\Xi(\overline{\mathbf{3}}_0)+\pi} \overset{N_c\to\infty}{\to} \frac{1}{N_c^2} \overset{\mathrm{QM}}{\to} \frac{1}{N_c^2},$$

$$\Gamma_{\Omega(\overline{\mathbf{15}}_1)\to\Xi(\overline{\mathbf{3}}_0)+K} \overset{N_c\to\infty}{\to} \frac{1}{N_c^2} \overset{\mathrm{QM}}{\to} \frac{1}{N_c^4},$$

$$\Gamma_{\Omega(\overline{\mathbf{15}}_1)\to\Omega(\mathbf{6}_1)+\pi} \overset{N_c\to\infty}{\to} \frac{1}{N_c} \overset{\mathrm{QM}}{\to} 0,$$

$$\Gamma_{\Omega(\overline{\mathbf{15}}_1)\to\Xi(\mathbf{6}_1)+K} \overset{N_c\to\infty}{\to} \frac{1}{N_c^2} \overset{\mathrm{QM}}{\to} 0.$$

Decay widths

$$\Gamma_{\Sigma(\mathbf{6}_1)\to\Lambda(\overline{\mathbf{3}}_0)+\pi} \overset{N_c\to\infty}{\longrightarrow} \frac{1}{N_c^2} \overset{\mathrm{QM}}{\longrightarrow} \frac{1}{N_c^2},$$

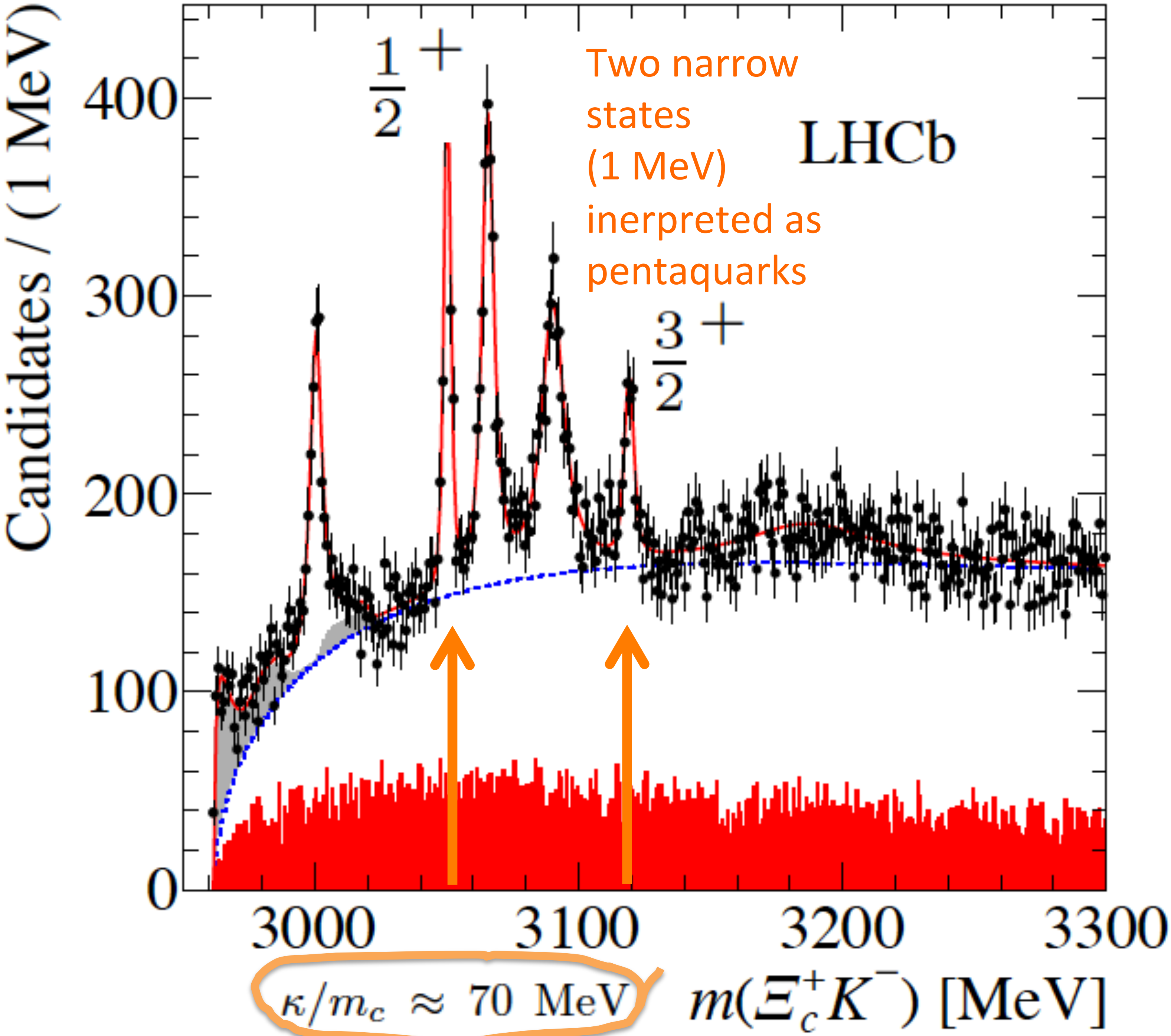
$$\Gamma_{\Xi(\mathbf{6}_1)\to\Xi(\overline{\mathbf{3}}_0)+\pi} \overset{N_c\to\infty}{\longrightarrow} \frac{1}{N_c^2} \overset{\mathrm{QM}}{\longrightarrow} \frac{1}{N_c^2},$$

all decay widths vanish at large $N_{\rm c}$
even without taking QM limit
in contrast to light pentaquarks

$$\Gamma_{\Omega(\overline{\mathbf{15}}_1)\to\Xi(\overline{\mathbf{3}}_0)+K} \overset{N_c\to\infty}{\longrightarrow} \frac{1}{N_c^2} \overset{\mathrm{QM}}{\longrightarrow} \frac{1}{N_c^4},$$

$$\Gamma_{\Omega(\overline{\mathbf{15}}_1)\to\Omega(\mathbf{6}_1)+\pi} \overset{N_c\to\infty}{\longrightarrow} \frac{1}{N_c} \overset{\mathrm{QM}}{\longrightarrow} 0,$$

$$\Gamma_{\Omega(\overline{\mathbf{15}}_1)\to\Xi(\mathbf{6}_1)+K} \overset{N_c\to\infty}{\longrightarrow} \frac{1}{N_c^2} \overset{\mathrm{QM}}{\longrightarrow} 0.$$

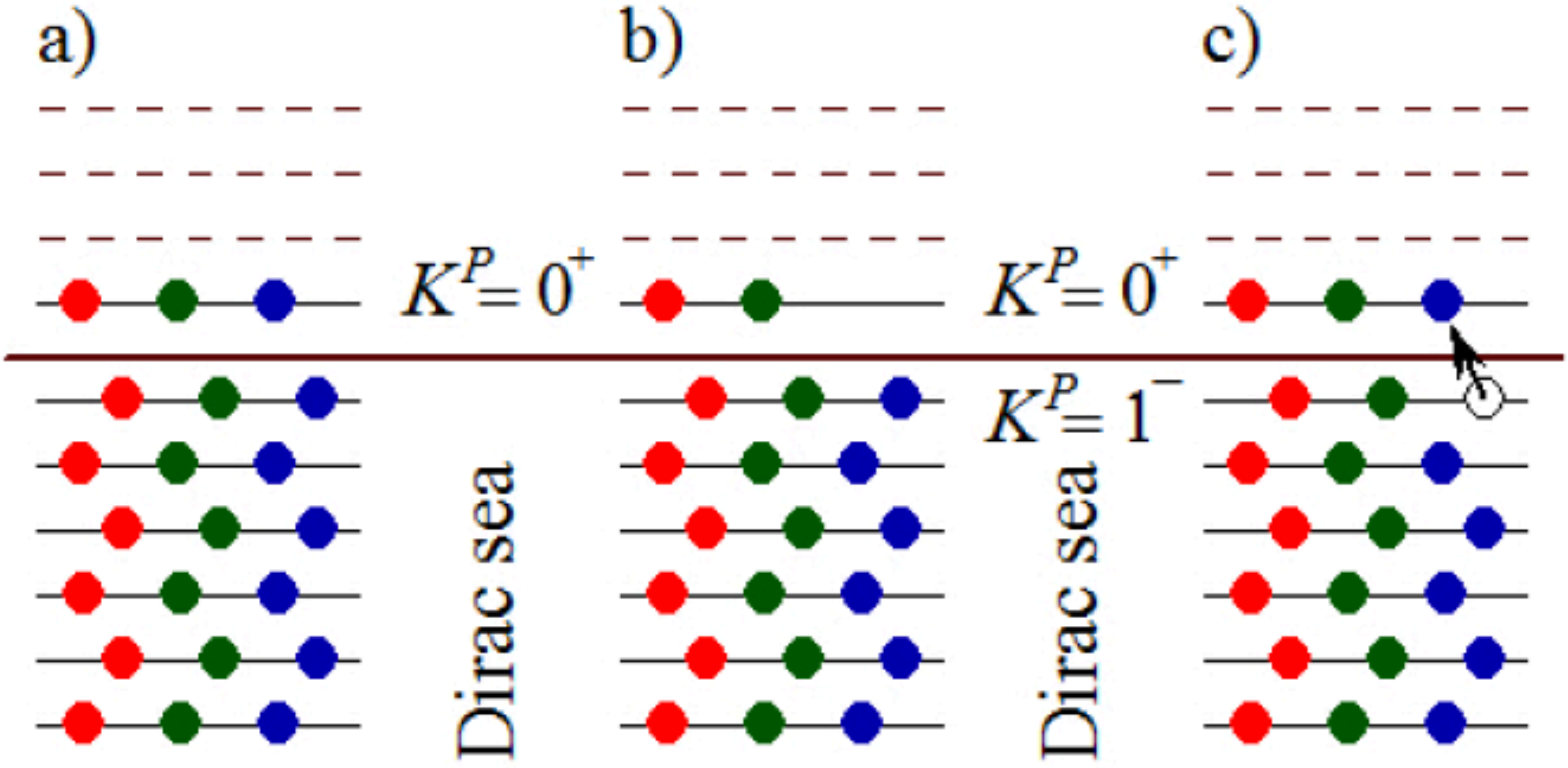


Two narrow states (1 MeV) inerpreted as pentaquarks

$\kappa/m_c \approx 70$ MeV

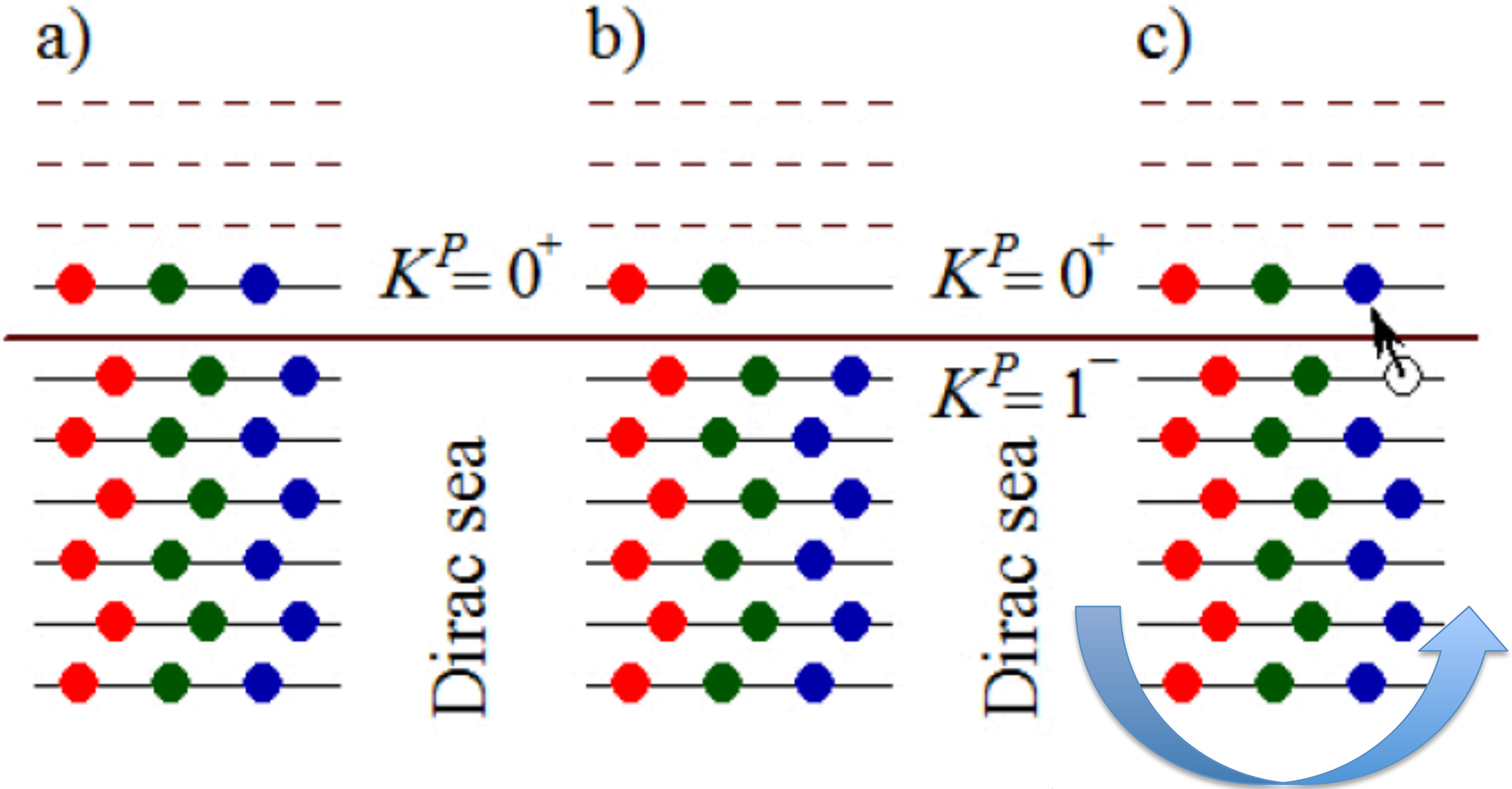
Where are the remaining three states?

Quark excitations: non-exotic heavy baryons



V. Petrov, Acta Phys. Pol. B47 (2016) 59

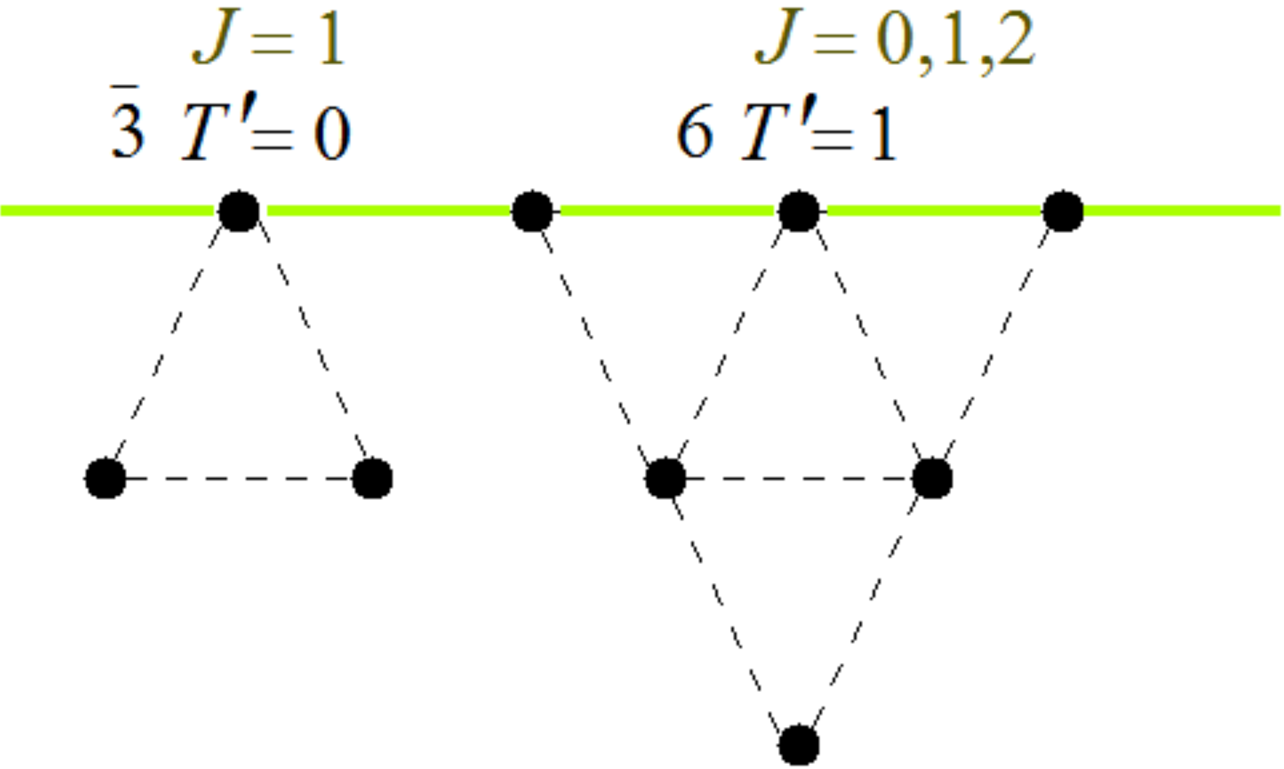
Quark excitations:
non-exotic heavy baryons



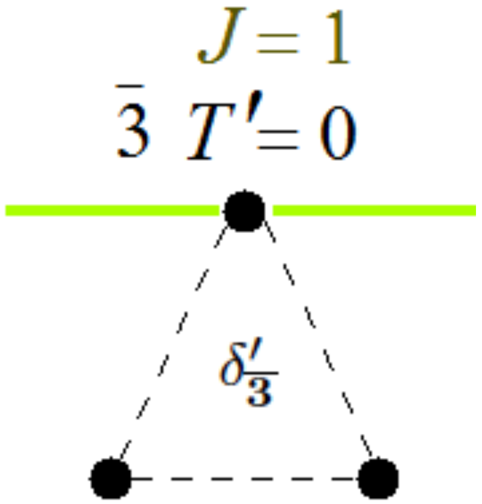
Rotations generate quantum numbers

One *K*=1 quark excited solitons

- the isospin $\boldsymbol{T}'$ of the states with $Y' = (N_c - 1)/3$ couples with the soliton spin $\boldsymbol{J}$ as follows: $\boldsymbol{T}' + \boldsymbol{J} = \boldsymbol{K}$, where $\boldsymbol{K}$ is the grand spin of the excited level.



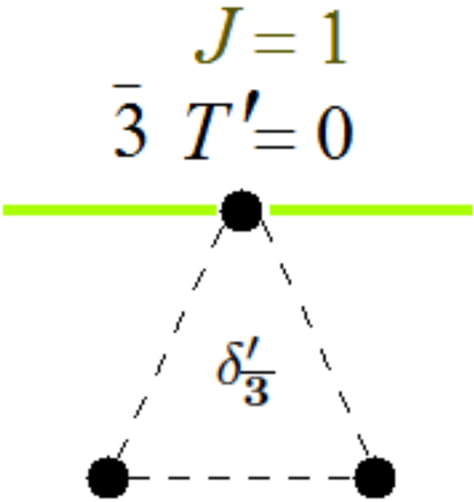
3bar excited *P*=– heavy baryons



add heavy quark
total spin 1/2 and 3/2

$$\delta'_{\bar{\mathbf{3}}} = \delta_{\bar{\mathbf{3}}} = -180\ \mathrm{MeV}$$

3bar excited *P*=– heavy baryons



experimentally:

$\Lambda_c(2592)$	$\Lambda_c(2628)$
198 MeV	190 MeV
$\Xi_c(2790)$	$\Xi_c(2818)$
$(1/2)^-$	$(3/2)^-$

add heavy quark
total spin 1/2 and 3/2

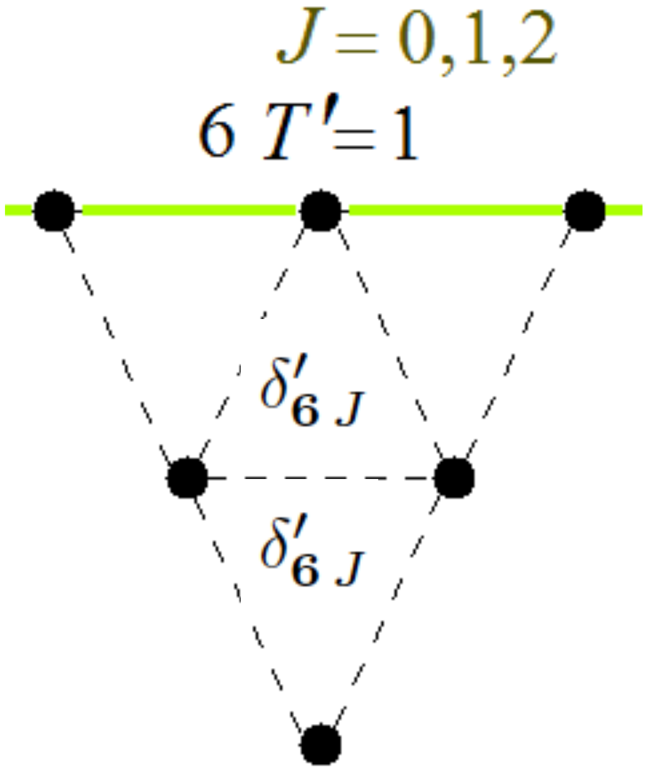
$$\delta'_{\bar{\mathbf{3}}} = \delta_{\bar{\mathbf{3}}} = -180\ \text{MeV}$$

$$\frac{\kappa'}{m_c} = 30\ \text{MeV}$$

$$H_{\text{hf}} = \frac{2}{3}\frac{\kappa}{m_Q}\boldsymbol{J}\cdot\boldsymbol{J}_Q$$

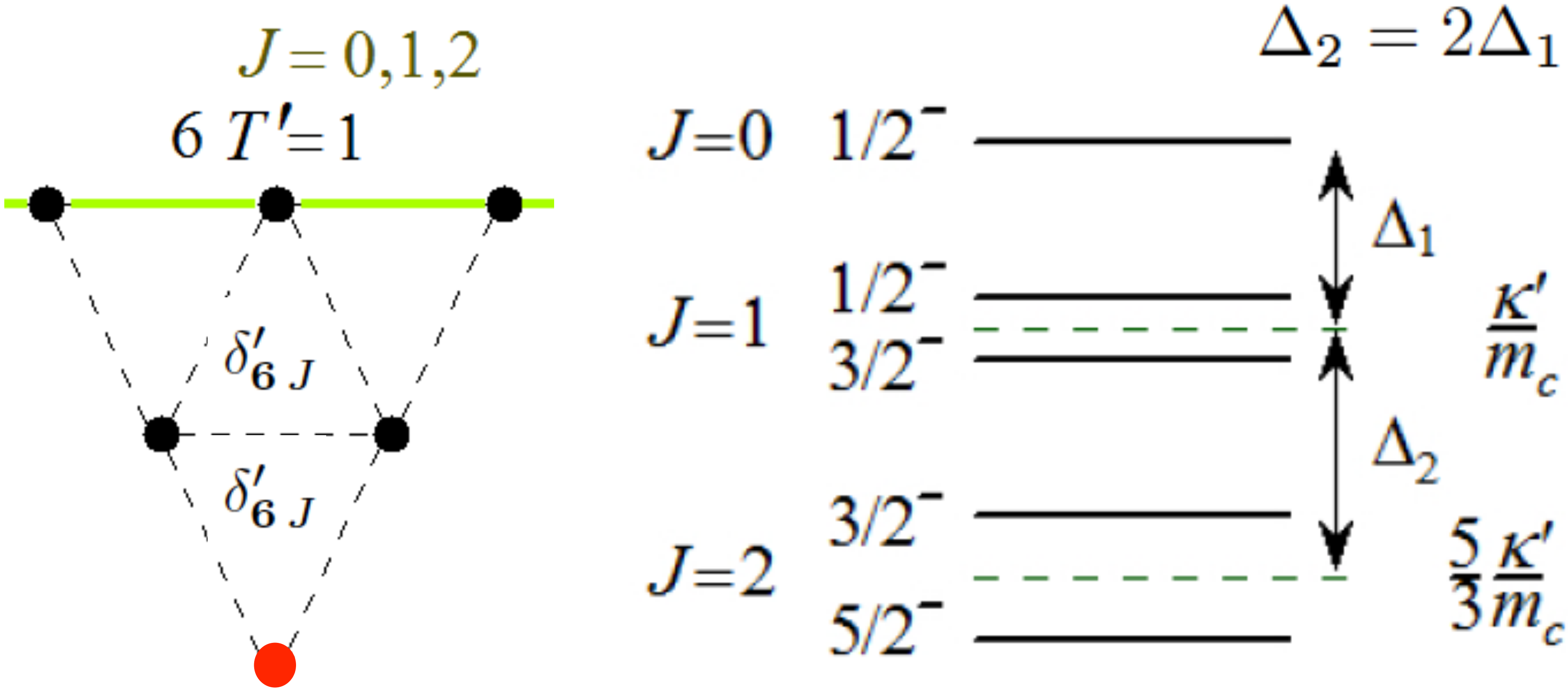
hyprfine splitting different from the ground state

sextet excited *P*=– heavy baryons

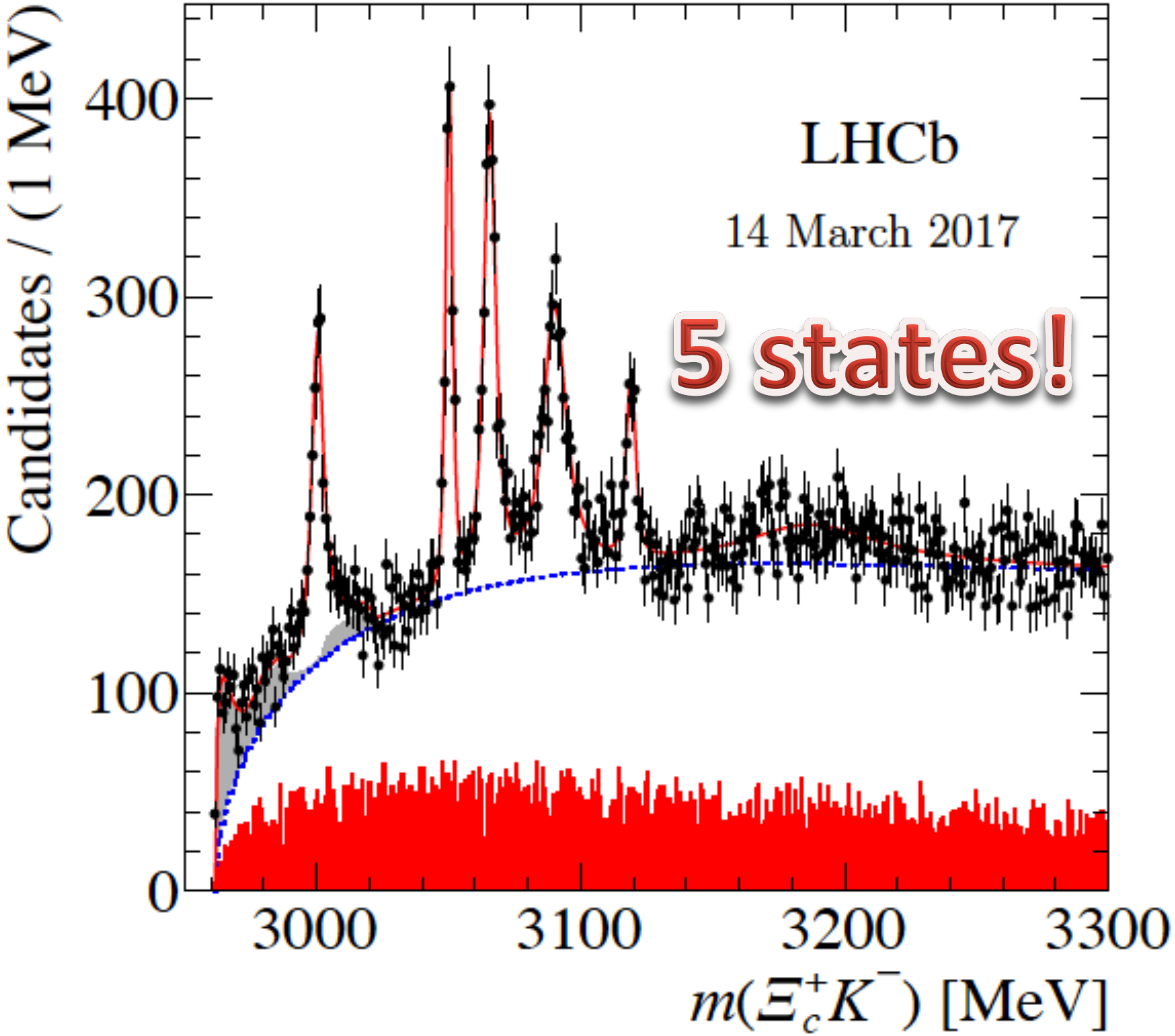


$$\delta'_{\mathbf{6}\,J} = \delta_{\mathbf{6}} - \frac{3}{20}\delta \times \begin{cases} 2 & \text{for} \quad J = 0 \\ 1 & \text{for} \quad J = 1 \\ -1 & \text{for} \quad J = 2 \end{cases}$$

sextet excited *P*=– heavy baryons



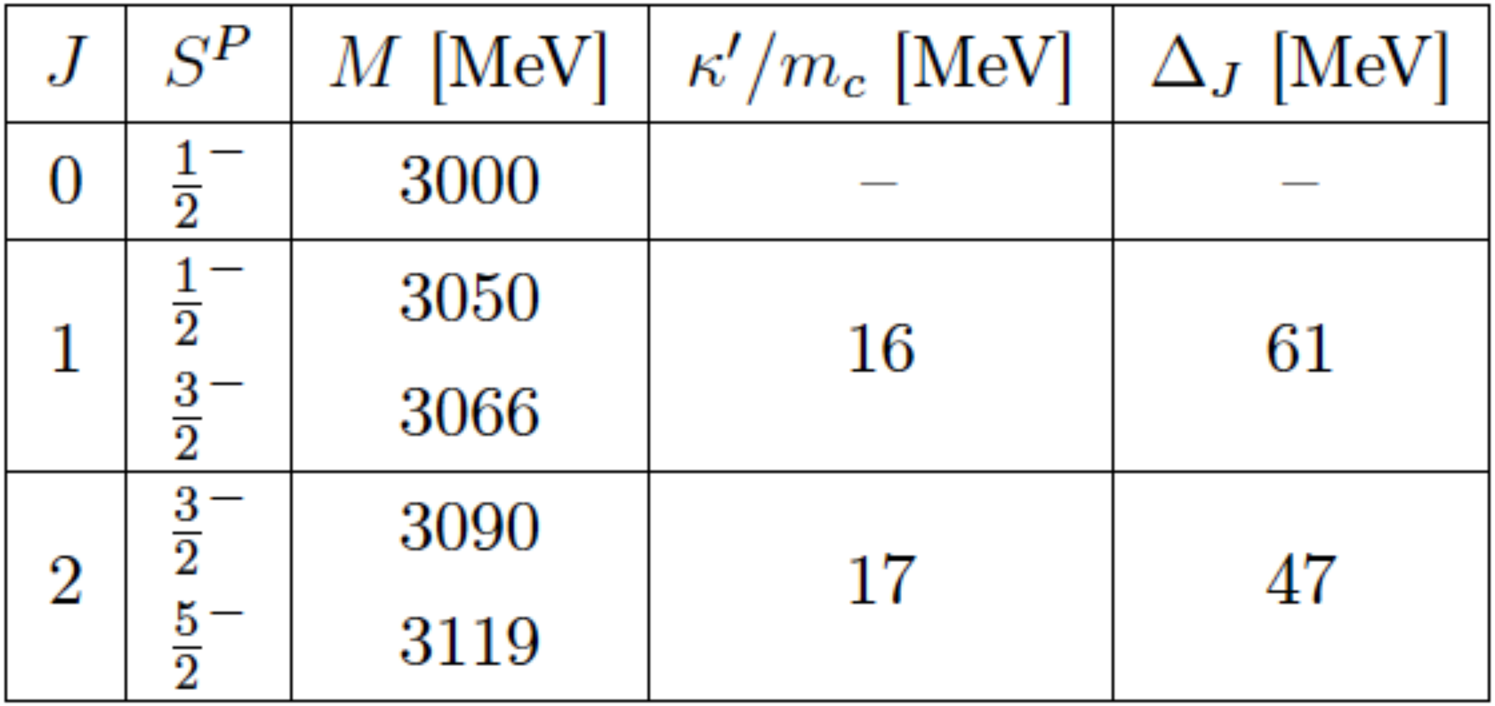
excited Omega_Q spectrum,
5 states



LHCb
14 March 2017
Candidates / (1 MeV)
0
100
200
300
400
3000
3100
3200
3300
$m(\Xi_c^+ K^-)$ [MeV]

5 states!

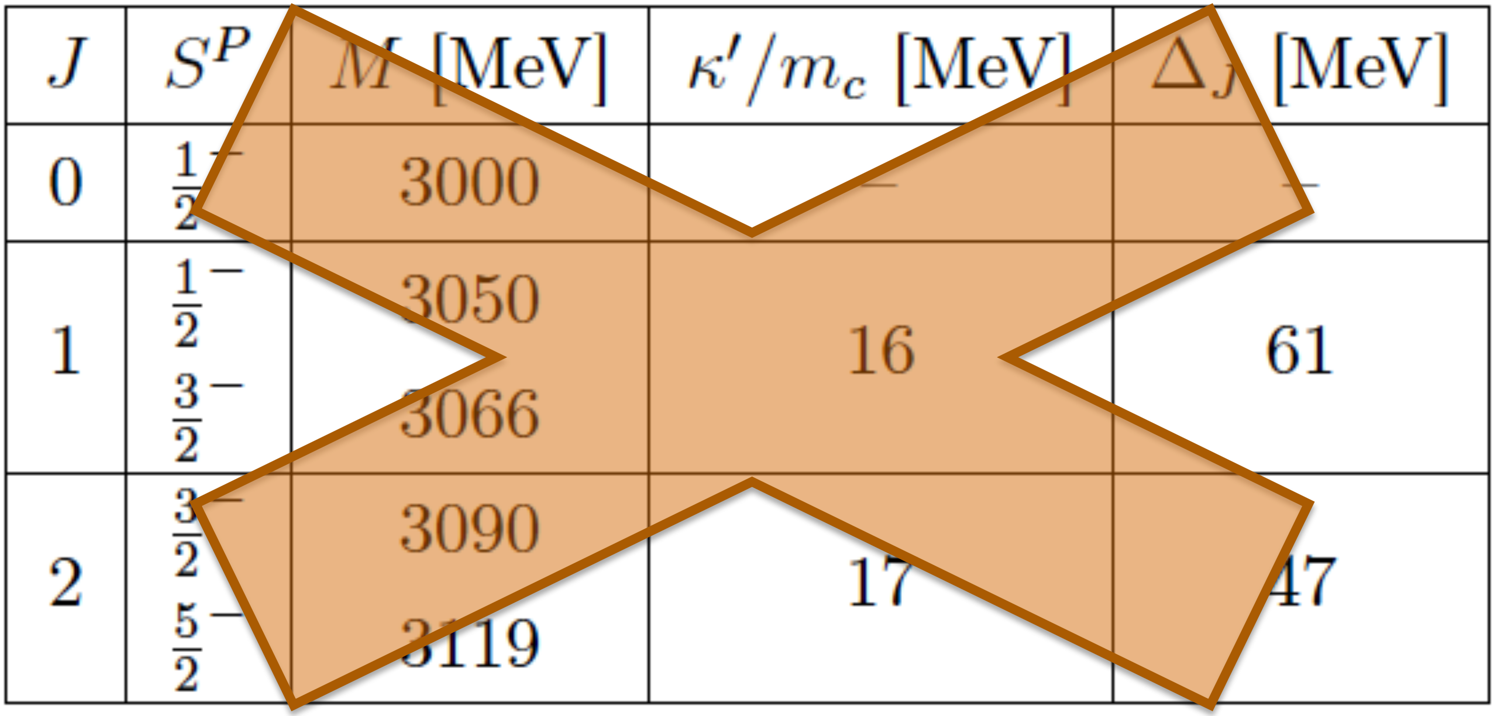
Scenario 1:
all LHCb Omega's are sextet states



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		

violates constraints: $\frac{\kappa'}{m_c} = 30\ \text{MeV}$ $\quad \Delta_2 = 2\Delta_1$

Scenario 1:
all LHCb Omega's are sextet states

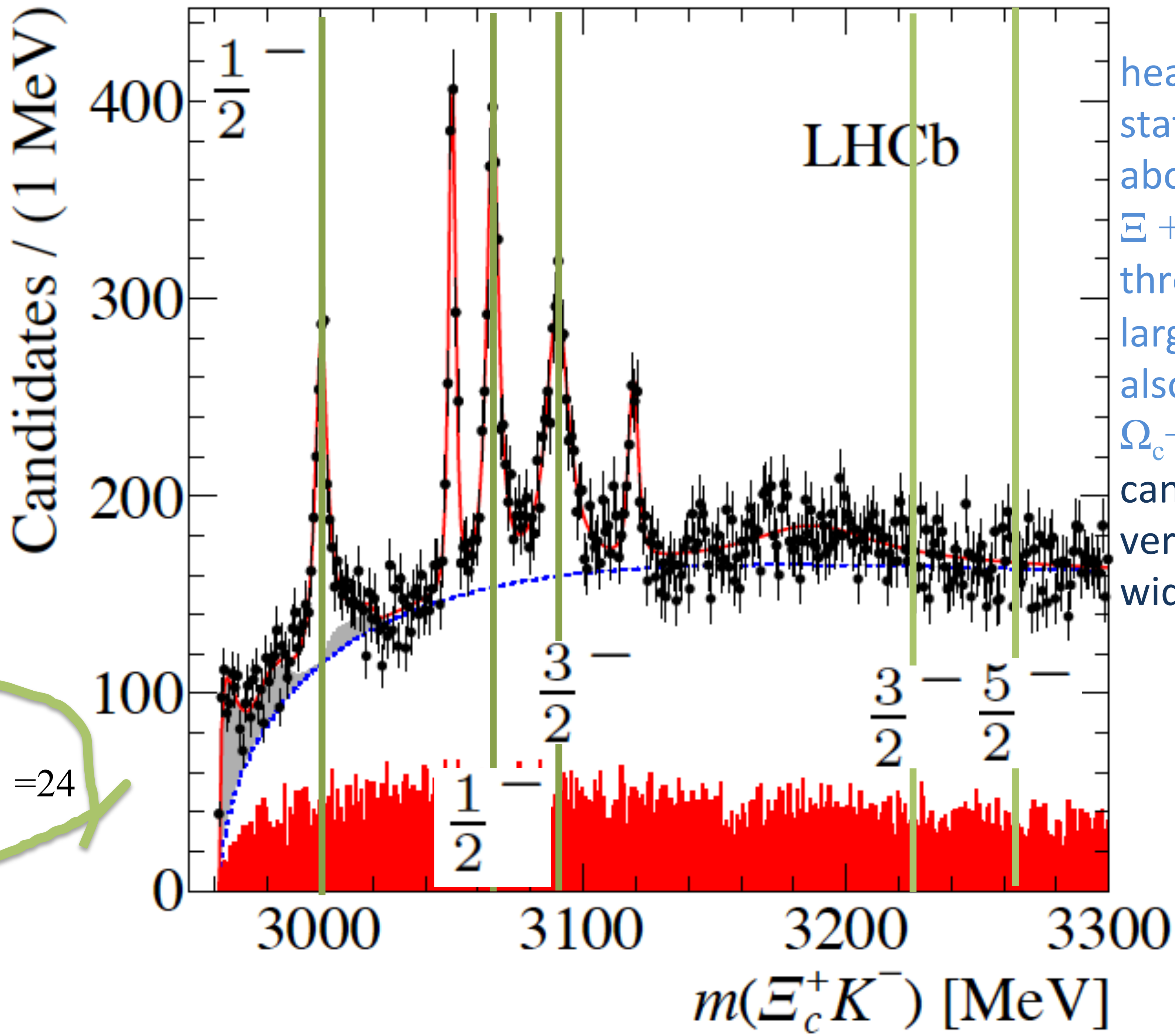


J	S^P	M [MeV]	κ'/m_c [MeV]	Δ_J [MeV]
0	$\frac{1}{2}^-$	3000	–	–
1	$\frac{1}{2}^-$ $\frac{3}{2}^-$	3050 3066	16	61
2	$\frac{3}{2}^-$ $\frac{5}{2}^-$	3090 3119	17	47

violates constraints: $\frac{\kappa'}{m_c} = 30$ MeV $\quad \Delta_2 = 2\Delta_1$

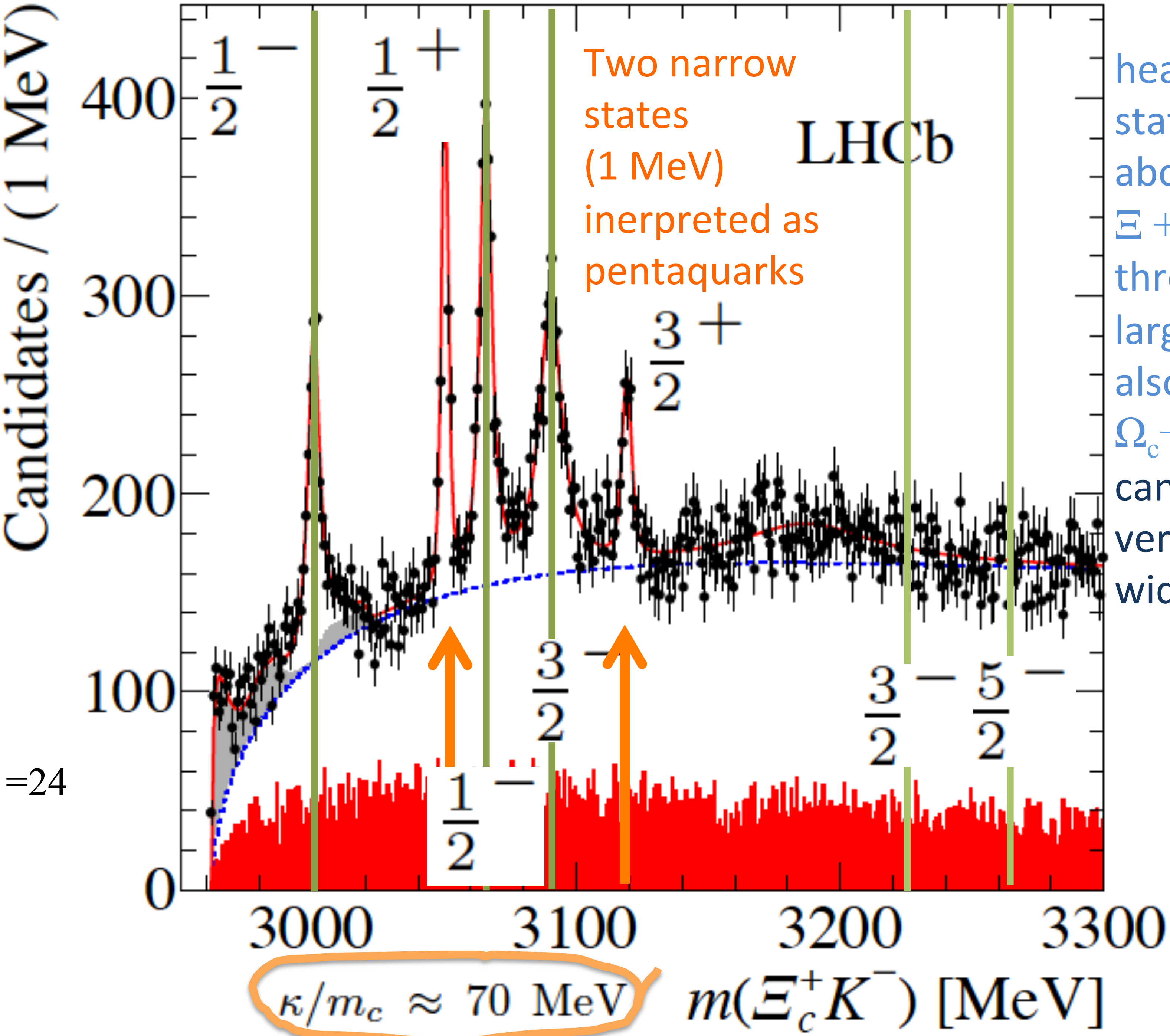
similar problem in the quark models

Scenario 2
force sextet constraints



heavy states above $\Xi + D$ threshold, large p.s. also to $\Omega_c + \pi$, can be very wide

$$\frac{\kappa'}{m_c} = 24$$



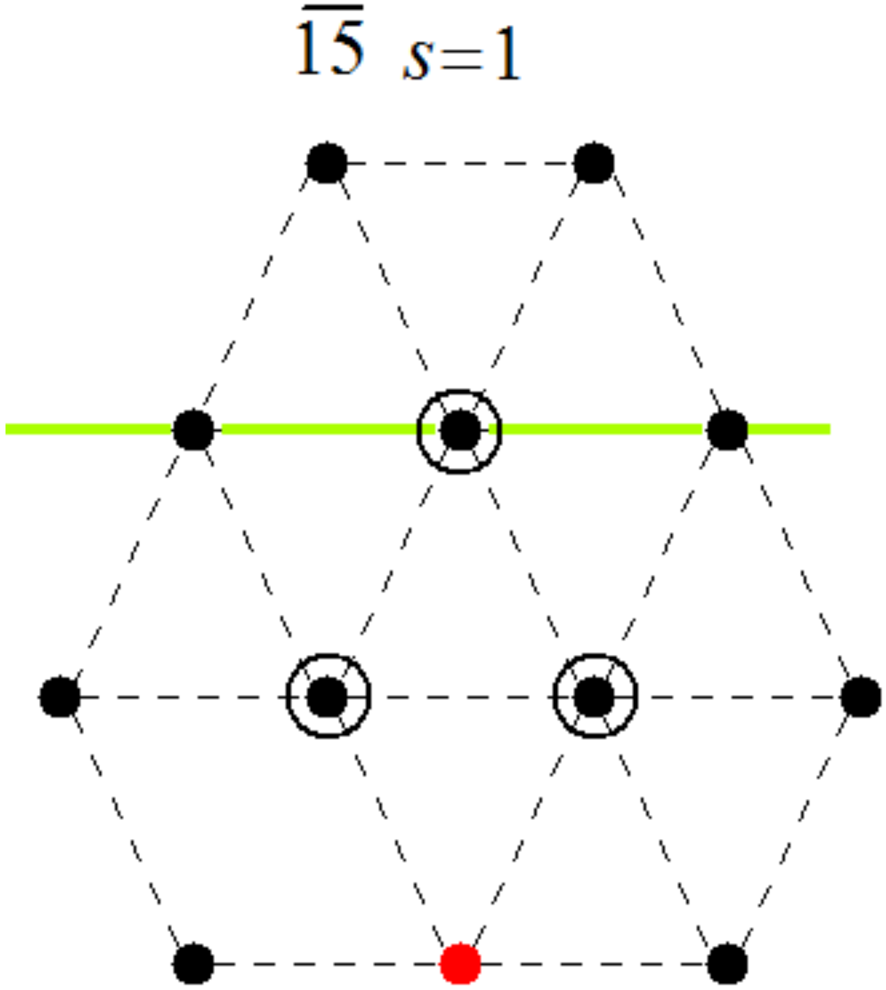
Two narrow states (1 MeV) inerpreted as pentaquarks

heavy states above $\Xi + D$ threshold, large p.s. also to $\Omega_c + \pi$, can be very wide

$\frac{\kappa'}{m_c} = 24$

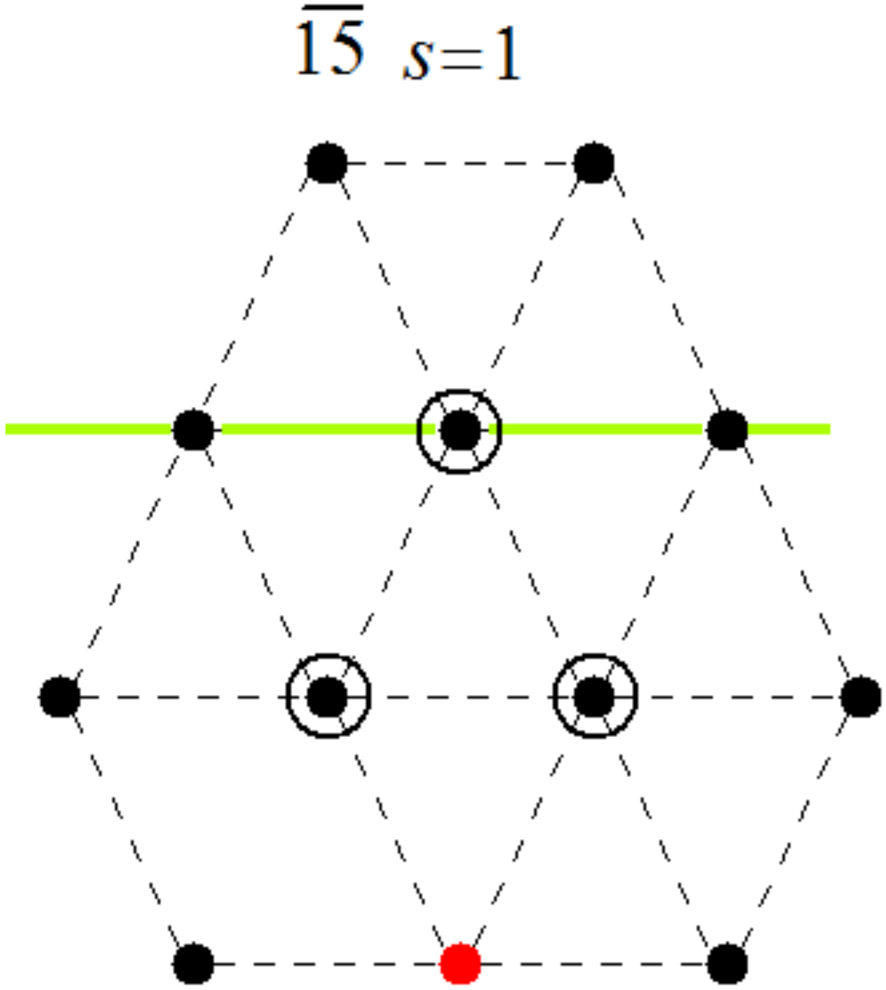
$\kappa / m_c \approx 70$ MeV

Consequences



Omega’s form isospin triplet, easy to check experimentally

Consequences



rich structure -

- many new states,

also in the case of b baryons

Omega's form isospin triplet, easy to check experimentally

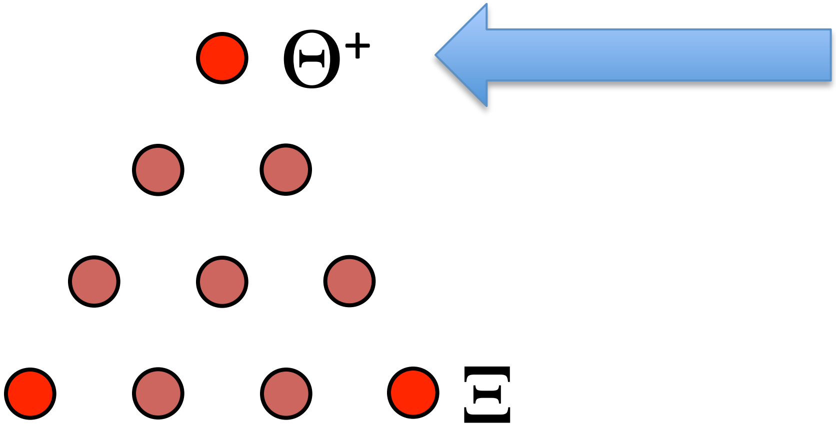
Conclusions

- soliton models **are** quark models
- **successful phenomenology** in the light baryon sector
- in soliton models pentaquarks are **naturally light**
- in QM limit **no decay** of antidecuplet to octet (!)
- heavy baryons can be desribed in terms of **N_c-1 quark soliton**
- two types of excitations:
  - **rotations**: 15-bar (exotic)
  - **quark** excitations (regular)

- mass spectrum **positively tested** against data for both parities
- + parity decay widths **agree** with the data with one free parameter
- **hierarchy** of the couplings in the QM limit
- all widths **vanish** in the large N_c limit
- **two** of the LHCb Omega_c states may be interpreted as **5q**

Thank you

What is the experimental status of light pentaquarks today?



July 2003

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Quarks

Five alive!

An odd, new subatomic
"pentaquark", has been

JAMES JOYCE would
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The pentaquark, w
dubbed "theta-plus", w
collaboration at the SPrin
Hyogo, Japan, which rep
the latest issue of *Physic*
The collaborators foun
three-year old data, after they were
what to look for by Dmitri Diakonov, a
oretician at the Petersburg Nuclear Phy
Institute, in Russia.

After word of the SPring-8 res
started spreading among physicists,
theta-plus was also found in experime
data at the Jefferson Laboratory in N
port News, Virginia, and at the Institute
Theoretical and Experimental Physic
Moscow. These independent confir
tions of the result, says Kenneth Hick
member of both the Japanese and Am
can teams, is proof that the theta-plus
real particle and not an artefact of the d

All three experiments work in roug
the same way. Everyday particles (the J
anese and Americans use electrons;
Russians, protons) are boosted to h
speeds in a circular accelerator. This ca
them to emit gamma rays, which are t
used to bombard atomic nuclei (carb

NEW YORK TIMES **INTERNATIONAL** *TUESDAY, JULY 1, 2003*

A Subatomic Discovery Emerges From Experiments in Jap

By KENNETH CHANG

Slamming high-energy particles of light into carbon atoms, physicists have unexpectedly produced a new type of subatomic particle.

Protons and neutrons, the building blocks of atoms, are made of smaller particles known as quarks, which come in six varieties. A proton, for example, consists of three quarks — two so-called up quarks and one down quark. Physicists know of slews of particles containing two or three quarks.

Now they believe they know of a particle containing five quarks that perhaps could have been common in the very early universe. (No one
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the experiments, Dr. Takashi Nakano, of the Research Center for Nuclear Physics at Osaka University, and told Dr. Nakano that he should look through the data for signs of five-quark particles.

"Dimitri Diakonov was very confident of that," Dr. Nakano said. Dr. Nakano and his collaborators looked, and they found a peak in their graphs corresponding to the mass of the five-quark particle that Dr. Diakonov had predicted. "He was right," Dr. Nakano said. "Actually, I was very surprised."

Dr. Kenneth H. Hicks, a professor of physics at Ohio University and another member of the Spring-

would consist of two up quarks, two down quarks and one known as an anti-strange quark.

The findings will be reported Friday in the journal Physical Review
Lette

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prohibit five-quark
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Scientists find fleeting form of basic matter

John Mangels
Plain Dealer Science Writer

Teams of scientists in Japan and the United States have confirmed the existence of a previously unknown kind of matter, a strange, fleeting subatomic particle that has been the object of a 30-year search.

One of the scientists likens the discovery to finding a new animal that doesn't fit the typical classifications of mammals or reptiles. The researchers say it's too soon to know what impact their finding will have, but they speculate that it may add to the basic understanding of how the universe was formed and how the particles that compose all matter interact.

The newly identified particle, dubbed a "pentaquark" because of its five ingredients, likely existed in the fractions of a second after the Big Bang, as the universe began to organize from the fiery chaos of free-floating elementary particles into the familiar components of atoms.

Pentaquarks also probably flicker in and out of being today, the short-lived product of billiard-ball-like collisions between cosmic rays and atoms in deep space or Earth's upper atmosphere.

SEE PARTICLE | A7

PARTICLE

FROM A1

Scientists find unknown form of basic matter

Scientists had to duplicate those conditions in the lab by firing powerful energy beams into targets of carbon or hydrogen atoms. Even then, it took months for them to analyze the data, recognize what they had done, and convince themselves it wasn't a false conclusion. Their findings will be published in Physical Review Letters, a prominent physics journal, later this month.

When he first saw the computer tracing that was the signature of the new category of particle, "I thought it was some mistake," said Ohio University physics Professor Ken Hicks, who was a collaborator in the Japanese experiments and headed similar work at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility in Virginia.

His Japanese colleague had a similar reaction. "It must be

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HIGH-ENERGY PHYSICS

Evidence for 'Pentaquark' Particle Sets Theorists Re-Joyce-ing

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USA TODAY · TUESDAY, JULY 1, 2003 · 7D

Physics team goes where no quark has gone before

By Dan Vergano

atoms with high-energy X-rays to

CERN COURIER

IoP Magazines

News

New five-quark states found at CERN

Figure 1

Only a few months after the first burst of excitement over the appearance at several laboratories of what seems to be a new five-quark particle, evidence has been found for a different five-quark state that appears to be closely related.

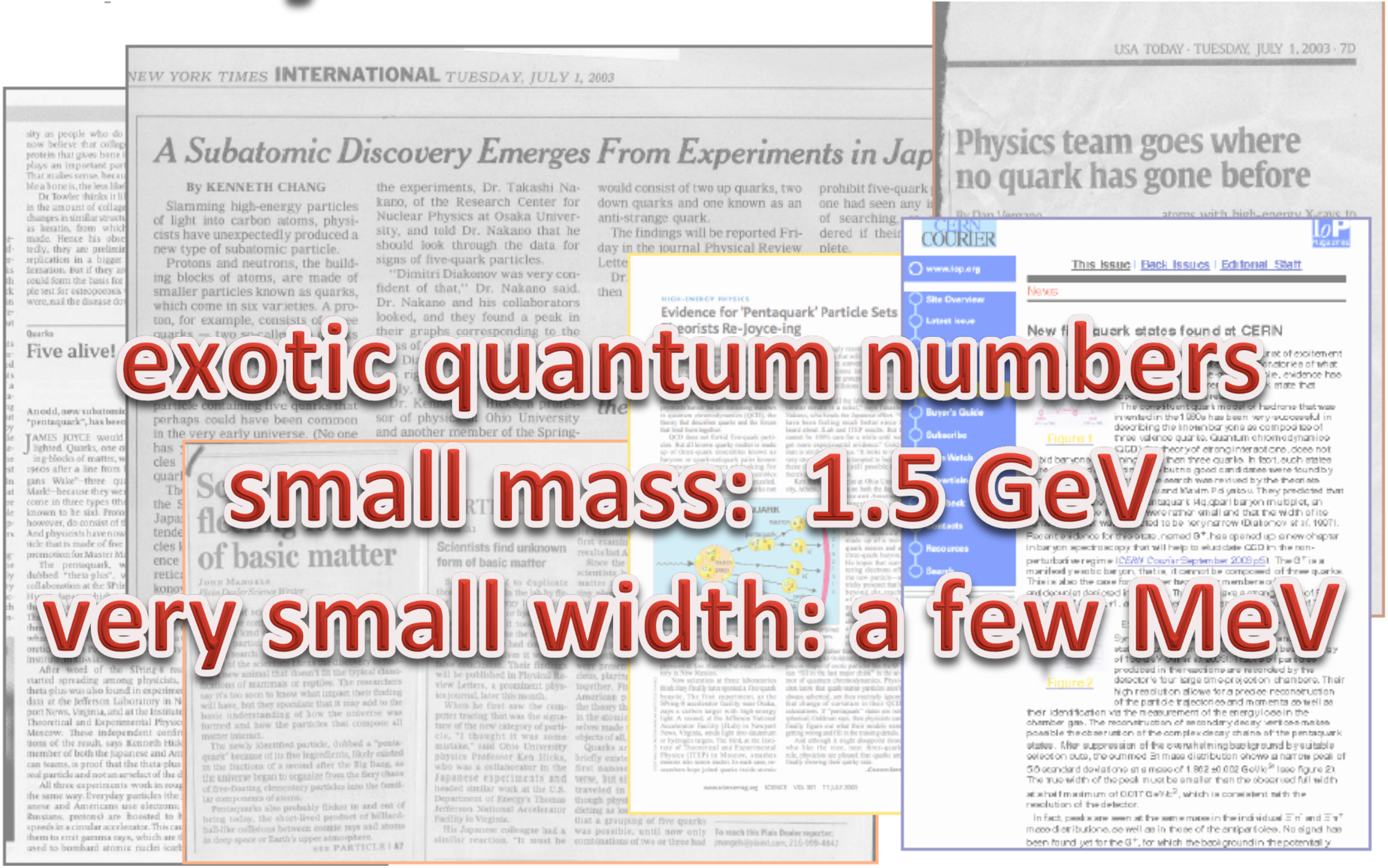
The constituent quark model of hadrons that was invented in the 1960s has been very successful in describing the known baryons as composites of three valence quarks. Quantum chromodynamics (QCD), the theory of strong interactions, does not forbid baryons containing more than three quarks. In fact, such states were proposed a long time ago but no good candidates were found by experiments until recently. The search was revived by the theorists Dmitri Diakonov, Victor Petrov and Maxim Polyakov. They predicted that the masses of the lightest pentaquark ($qqqq\bar{q}$) baryon multiplet, an antidecuplet (see figure 1), were rather small and that the width of its lightest member was expected to be very narrow (Diakonov et al. 1997). Recent evidence for this state, named Θ^+, has opened up a new chapter in baryon spectroscopy that will help to elucidate QCD in the non-perturbative regime (CERN Courier September 2003 p5). The Θ^+ is a manifestly exotic baryon, that is, it cannot be composed of three quarks. This is also the case for the other two corner members of the antidecuplet depicted in figure 1. The latter have a strangeness of $S = -2$, a charge of $Q = -2, +1$, and form members of an isospin quartet of Ξ states.

Figure 2

Experiment NA49 at the CERN Super Proton Synchrotron has searched for the Θ^+ and the Ξ states in proton-proton collisions at a beam energy of 158 GeV (Alt et al. 2003). Tracks of particles produced in the reactions are recorded by the detector's four large time-projection chambers. Their high resolution allows for a precise reconstruction of the particle trajectories and momenta as well as their identification via the measurement of the energy loss in the chamber gas. The reconstruction of secondary decay vertices makes possible the observation of the complex decay chains of the pentaquark states. After suppression of the overwhelming background by suitable selection cuts, the summed $\Xi\pi$ mass distribution shows a narrow peak of 5.6 standard deviations at a mass of 1.862 ± 0.002 GeV/c^2 (see figure 2). The true width of the peak must be smaller than the observed full width at half maximum of 0.017 GeV/c^2, which is consistent with the resolution of the detector.

In fact, peaks are seen at the same mass in the individual $\Xi^-\pi^-$ and $\Xi^-\pi^+$ mass distributions, as well as in those of the antiparticles. No signal has been found yet for the Θ^+, for which the background in the potentially

July 2003



NEW YORK TIMES INTERNATIONAL TUESDAY, JULY 1, 2003

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would consist of two up quarks, two down quarks and one known as an anti-strange quark.

The findings will be reported Friday in the journal Physical Review Lette

USA TODAY · TUESDAY, JULY 1, 2003 · 7D

Physics team goes where no quark has gone before

HIGH-ENERGY PHYSICS

Evidence for 'Pentaquark' Particle Sets Theorists Re-Joyce-ing

CERN COURIER

This Issue | Back Issues | Editorial Staff

News

New five-quark states found at CERN

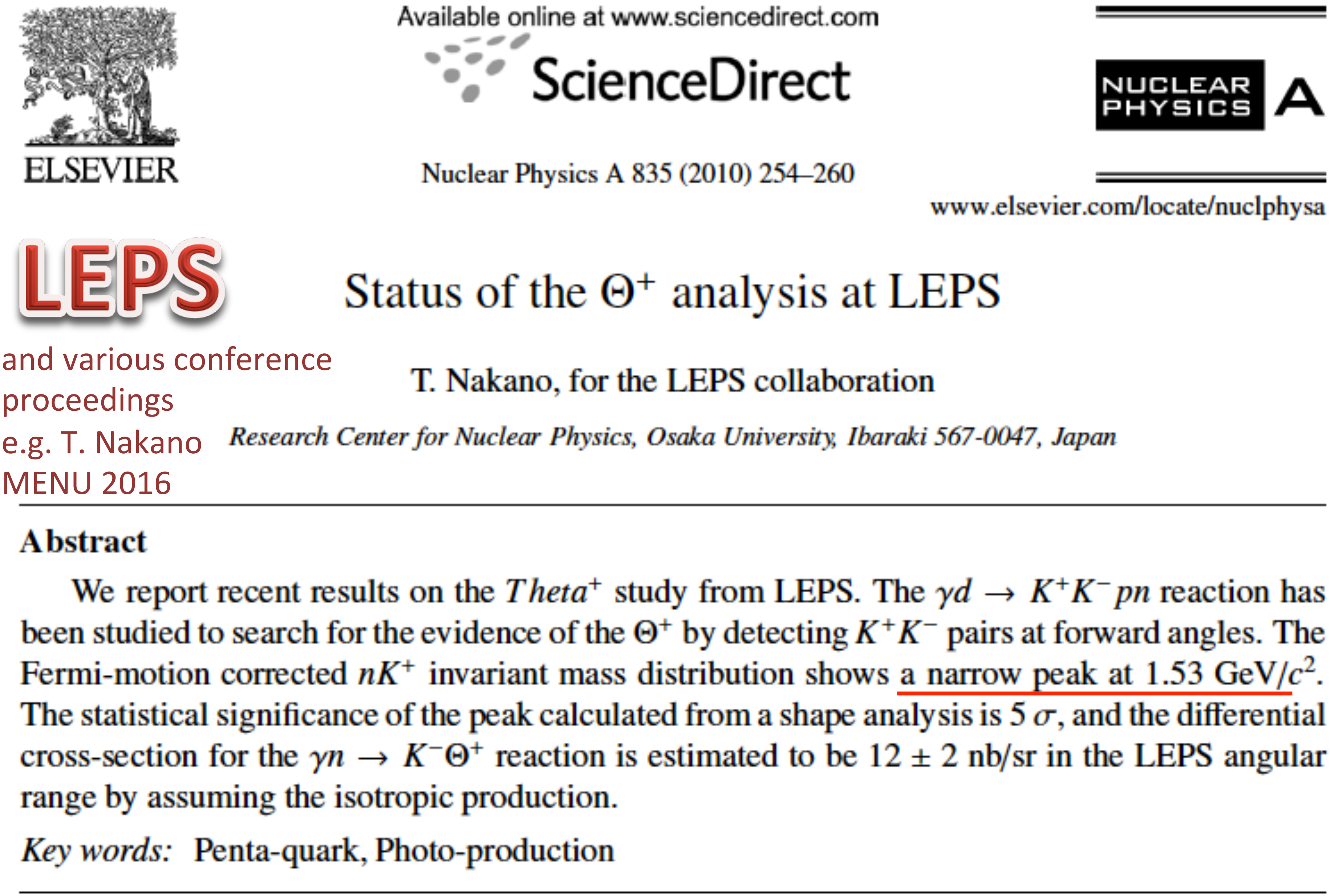
Five alive!

Scientists find unknown form of basic matter

exotic quantum numbers

small mass: 1.5 GeV

very small width: a few MeV



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Nuclear Physics A 835 (2010) 254–260

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LEPS

Status of the Θ^+ analysis at LEPS

and various conference proceedings
e.g. T. Nakano
MENU 2016

T. Nakano, for the LEPS collaboration

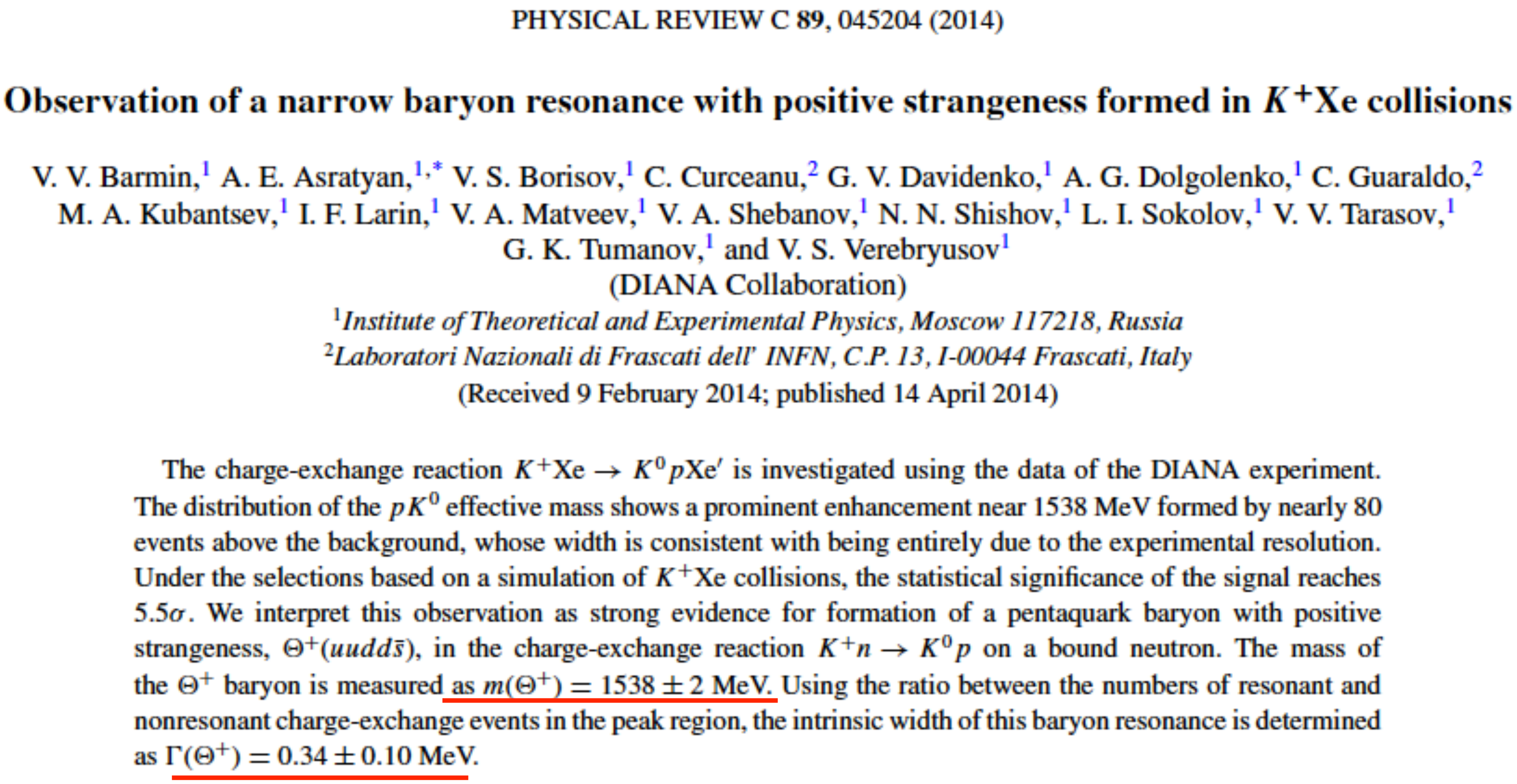
Research Center for Nuclear Physics, Osaka University, Ibaraki 567-0047, Japan

Abstract

We report recent results on the *Theta*$^+$ study from LEPS. The $\gamma d \rightarrow K^+K^-pn$ reaction has been studied to search for the evidence of the Θ^+ by detecting K^+K^- pairs at forward angles. The Fermi-motion corrected nK^+ invariant mass distribution shows a narrow peak at 1.53 GeV/c^2. The statistical significance of the peak calculated from a shape analysis is 5 σ, and the differential cross-section for the $\gamma n \rightarrow K^-\Theta^+$ reaction is estimated to be 12 ± 2 nb/sr in the LEPS angular range by assuming the isotropic production.

Key words: Penta-quark, Photo-production

DIANA



PHYSICAL REVIEW C **89**, 045204 (2014)

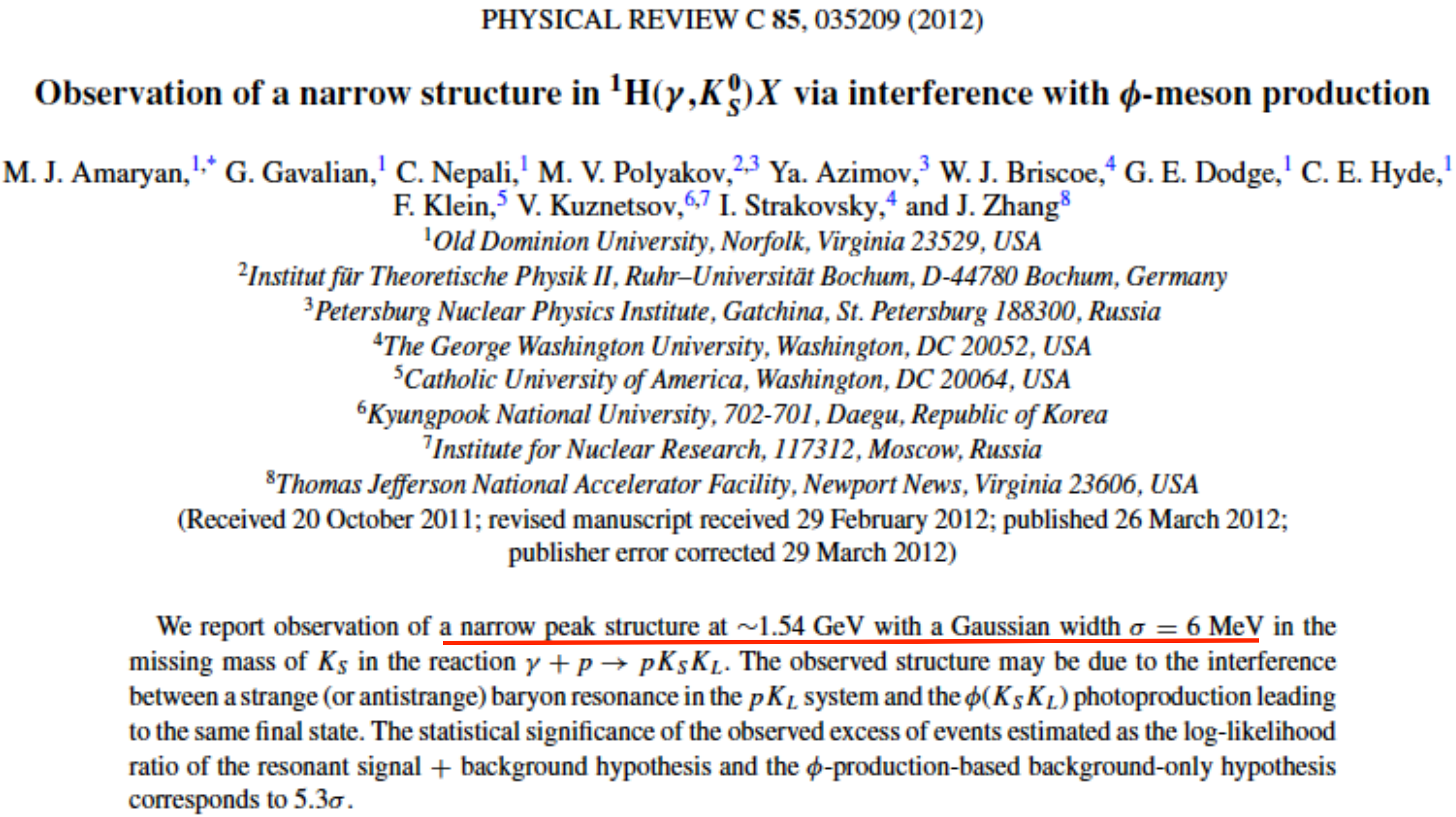
Observation of a narrow baryon resonance with positive strangeness formed in K^+Xe collisions

V. V. Barmin,[1] A. E. Asratyan,[1,*] V. S. Borisov,[1] C. Curceanu,[2] G. V. Davidenko,[1] A. G. Dolgolenko,[1] C. Guaraldo,[2]
M. A. Kubantsev,[1] I. F. Larin,[1] V. A. Matveev,[1] V. A. Shebanov,[1] N. N. Shishov,[1] L. I. Sokolov,[1] V. V. Tarasov,[1]
G. K. Tumanov,[1] and V. S. Verebryusov[1]
(DIANA Collaboration)
[1]*Institute of Theoretical and Experimental Physics, Moscow 117218, Russia*
[2]*Laboratori Nazionali di Frascati dell' INFN, C.P. 13, I-00044 Frascati, Italy*

(Received 9 February 2014; published 14 April 2014)

The charge-exchange reaction $K^+\mathrm{Xe} \to K^0 p\mathrm{Xe}'$ is investigated using the data of the DIANA experiment. The distribution of the pK^0 effective mass shows a prominent enhancement near 1538 MeV formed by nearly 80 events above the background, whose width is consistent with being entirely due to the experimental resolution. Under the selections based on a simulation of K^+Xe collisions, the statistical significance of the signal reaches 5.5σ. We interpret this observation as strong evidence for formation of a pentaquark baryon with positive strangeness, $\Theta^+(uudd\bar{s})$, in the charge-exchange reaction $K^+n \to K^0p$ on a bound neutron. The mass of the Θ^+ baryon is measured as $m(\Theta^+) = 1538 \pm 2$ MeV. Using the ratio between the numbers of resonant and nonresonant charge-exchange events in the peak region, the intrinsic width of this baryon resonance is determined as $\Gamma(\Theta^+) = 0.34 \pm 0.10$ MeV.

dissidents from CLAS



PHYSICAL REVIEW C **85**, 035209 (2012)

Observation of a narrow structure in $^1\mathrm{H}(\gamma,K_S^0)X$ via interference with ϕ-meson production

M. J. Amaryan,[1,*] G. Gavalian,[1] C. Nepali,[1] M. V. Polyakov,[2,3] Ya. Azimov,[3] W. J. Briscoe,[4] G. E. Dodge,[1] C. E. Hyde,[1]
F. Klein,[5] V. Kuznetsov,[6,7] I. Strakovsky,[4] and J. Zhang[8]
[1]*Old Dominion University, Norfolk, Virginia 23529, USA*
[2]*Institut für Theoretische Physik II, Ruhr–Universität Bochum, D-44780 Bochum, Germany*
[3]*Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg 188300, Russia*
[4]*The George Washington University, Washington, DC 20052, USA*
[5]*Catholic University of America, Washington, DC 20064, USA*
[6]*Kyungpook National University, 702-701, Daegu, Republic of Korea*
[7]*Institute for Nuclear Research, 117312, Moscow, Russia*
[8]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*

(Received 20 October 2011; revised manuscript received 29 February 2012; published 26 March 2012;
publisher error corrected 29 March 2012)

We report observation of a narrow peak structure at ~1.54 GeV with a Gaussian width $\sigma = 6$ MeV in the missing mass of K_S in the reaction $\gamma + p \to pK_SK_L$. The observed structure may be due to the interference between a strange (or antistrange) baryon resonance in the pK_L system and the $\phi(K_SK_L)$ photoproduction leading to the same final state. The statistical significance of the observed excess of events estimated as the log-likelihood ratio of the resonant signal + background hypothesis and the ϕ-production-based background-only hypothesis corresponds to 5.3σ.

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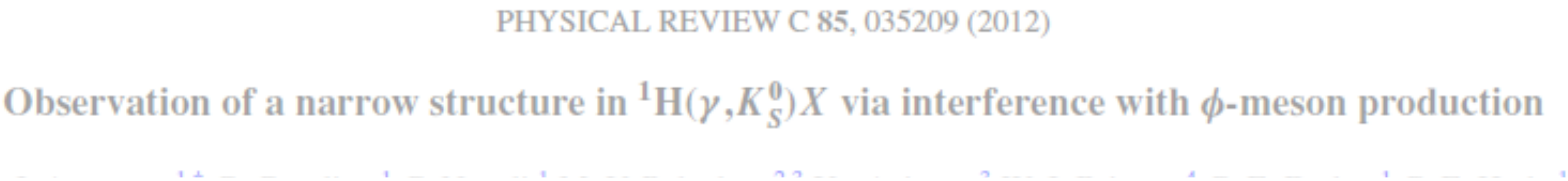

PHYSICAL REVIEW C 85, 035209 (2012)

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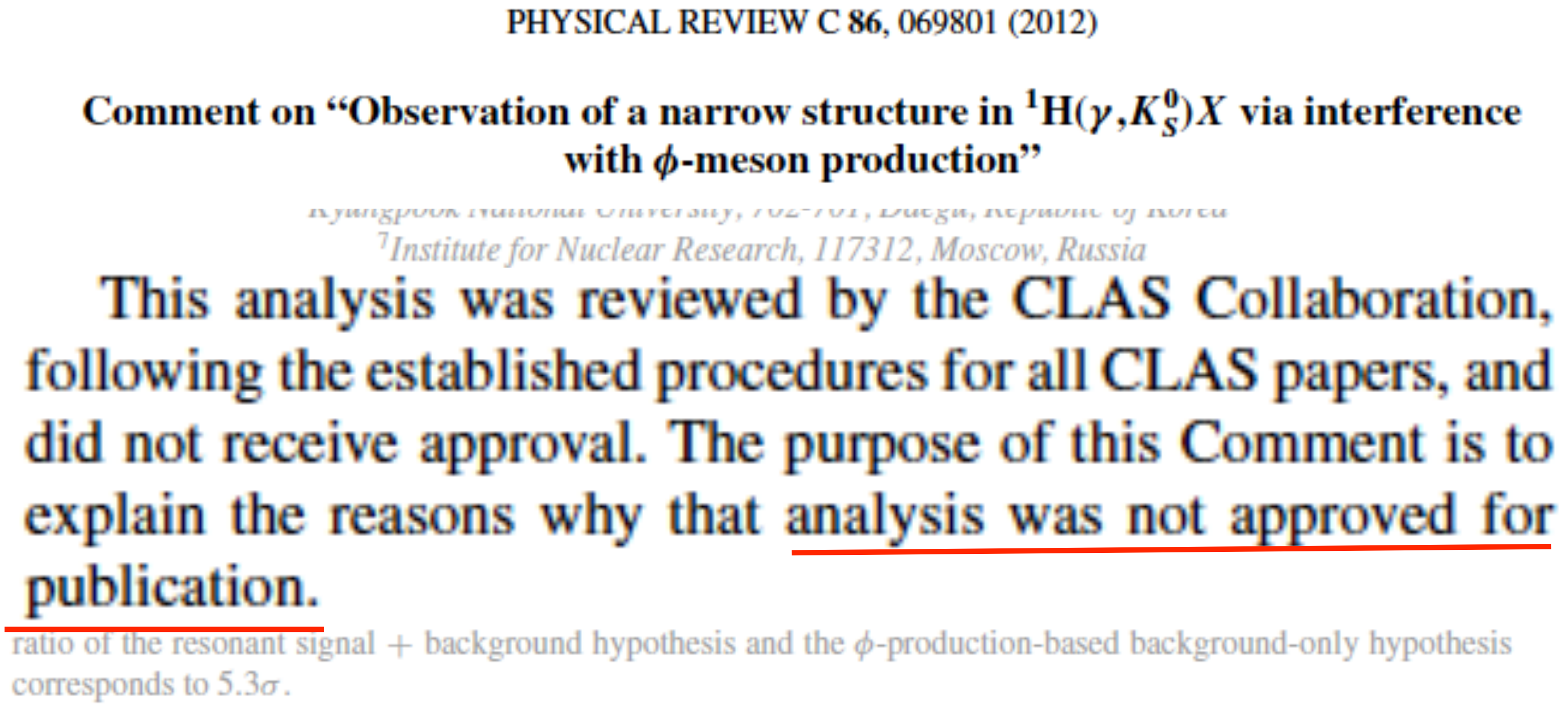


PHYSICAL REVIEW C **86**, 069801 (2012)

Comment on "Observation of a narrow structure in $^1\mathrm{H}(\gamma,K_S^0)X$ via interference with ϕ-meson production"

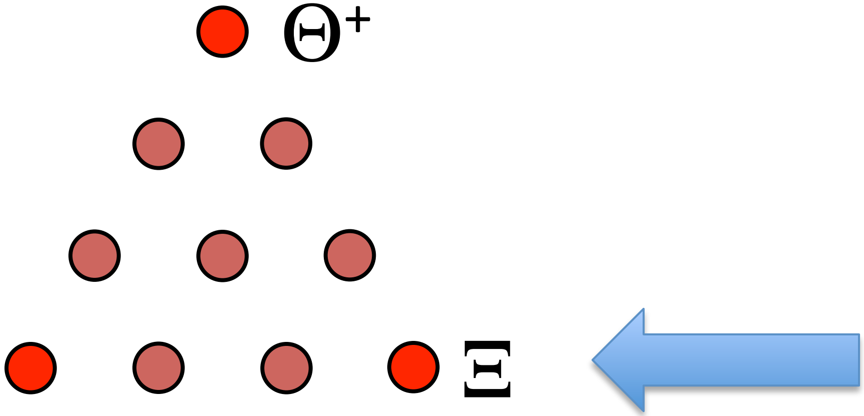
Kyungpook National University, 702-701, Daegu, Republic of Korea

[7]*Institute for Nuclear Research, 117312, Moscow, Russia*

This analysis was reviewed by the CLAS Collaboration, following the established procedures for all CLAS papers, and did not receive approval. The purpose of this Comment is to explain the reasons why that analysis was not approved for publication.

ratio of the resonant signal + background hypothesis and the ϕ-production-based background-only hypothesis corresponds to 5.3σ.

What is the experimental status of light pentaquarks today?



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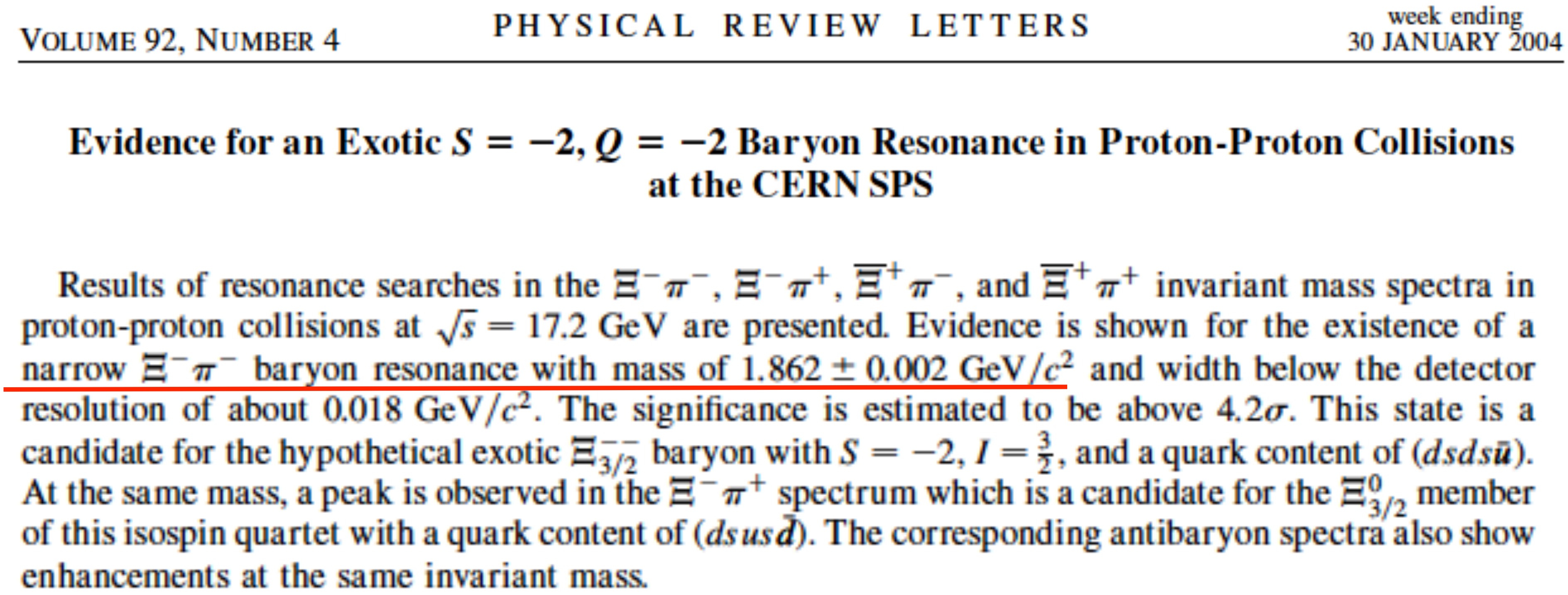
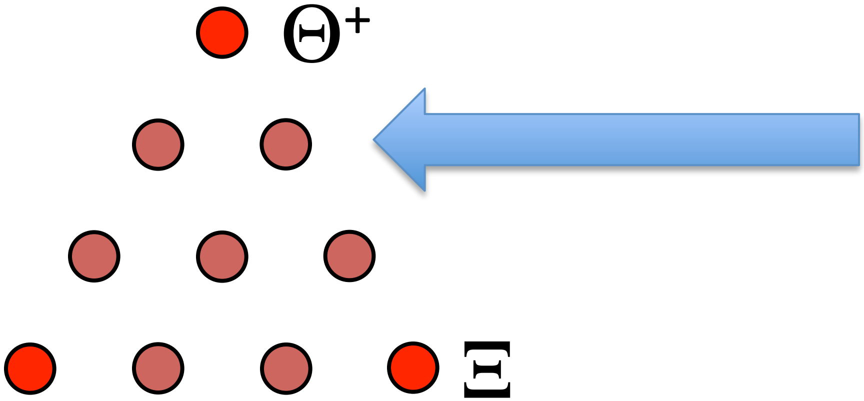


VOLUME 92, NUMBER 4 PHYSICAL REVIEW LETTERS week ending 30 JANUARY 2004

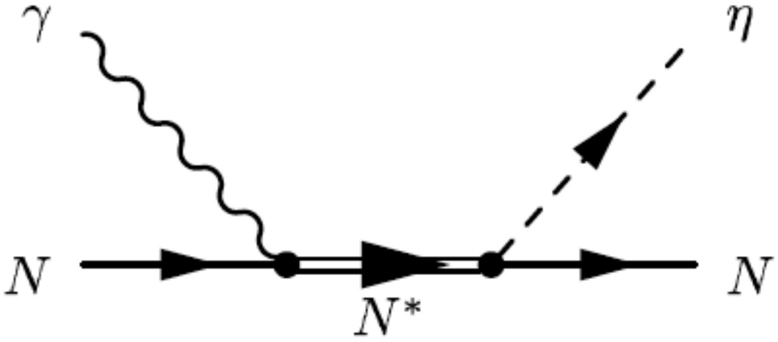
Evidence for an Exotic $S = -2, Q = -2$ Baryon Resonance in Proton-Proton Collisions at the CERN SPS

Results of resonance searches in the $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\overline{\Xi}^+\pi^-$, and $\overline{\Xi}^+\pi^+$ invariant mass spectra in proton-proton collisions at $\sqrt{s} = 17.2$ GeV are presented. Evidence is shown for the existence of a narrow $\Xi^-\pi^-$ baryon resonance with mass of 1.862 ± 0.002 GeV$/c^2$ and width below the detector resolution of about 0.018 GeV$/c^2$. The significance is estimated to be above 4.2σ. This state is a candidate for the hypothetical exotic $\Xi^{--}_{3/2}$ baryon with $S = -2$, $I = \frac{3}{2}$, and a quark content of $(dsds\bar{u})$. At the same mass, a peak is observed in the $\Xi^-\pi^+$ spectrum which is a candidate for the $\Xi^0_{3/2}$ member of this isospin quartet with a quark content of $(dsus\bar{d})$. The corresponding antibaryon spectra also show enhancements at the same invariant mass.

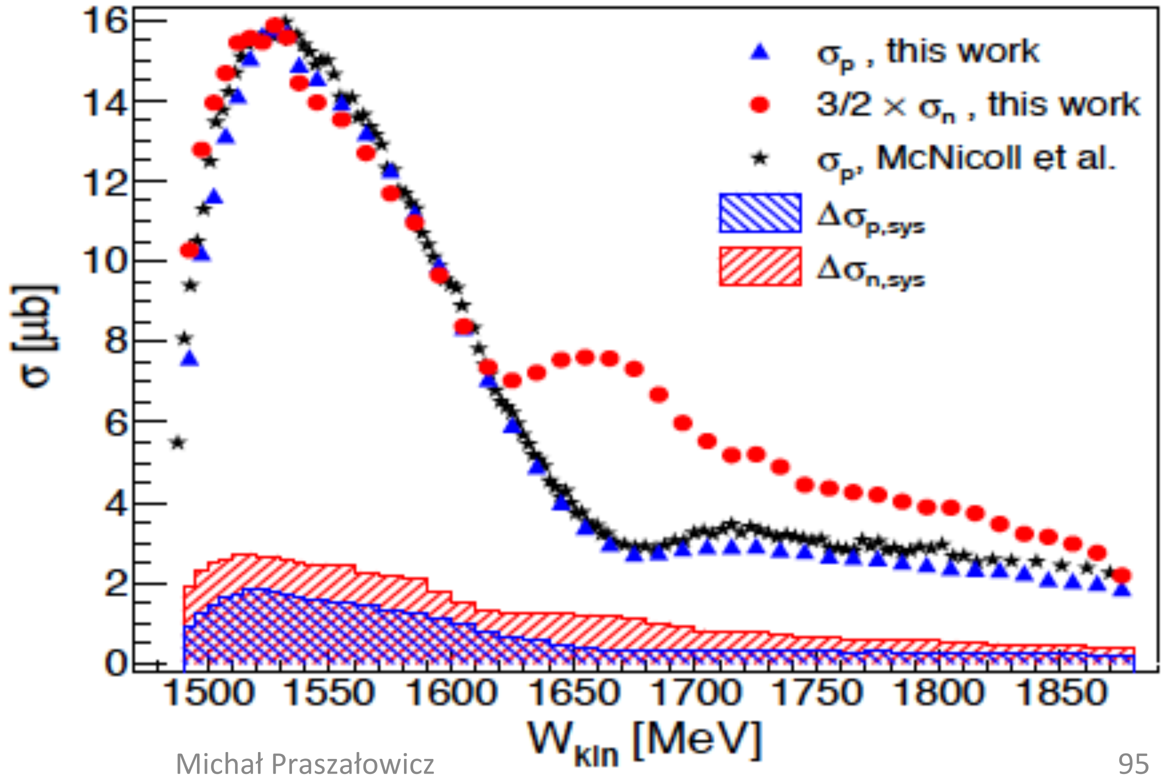
What is the experimental status of light pentaquarks today?



Pentanucleon?



D. Werthmuller et al. [A2 Collaboration]
Phys. Rev. Lett. 111 (2013) 23, 232001
Eur. Phys. J. A 49 (2013) 154
Phys. Rev. Rev. C 90 (2014) 015205



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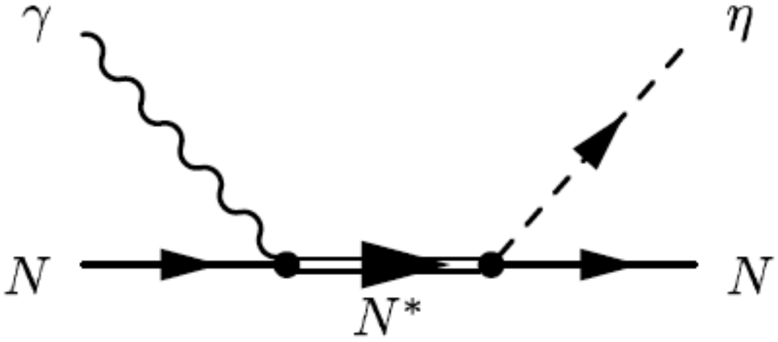
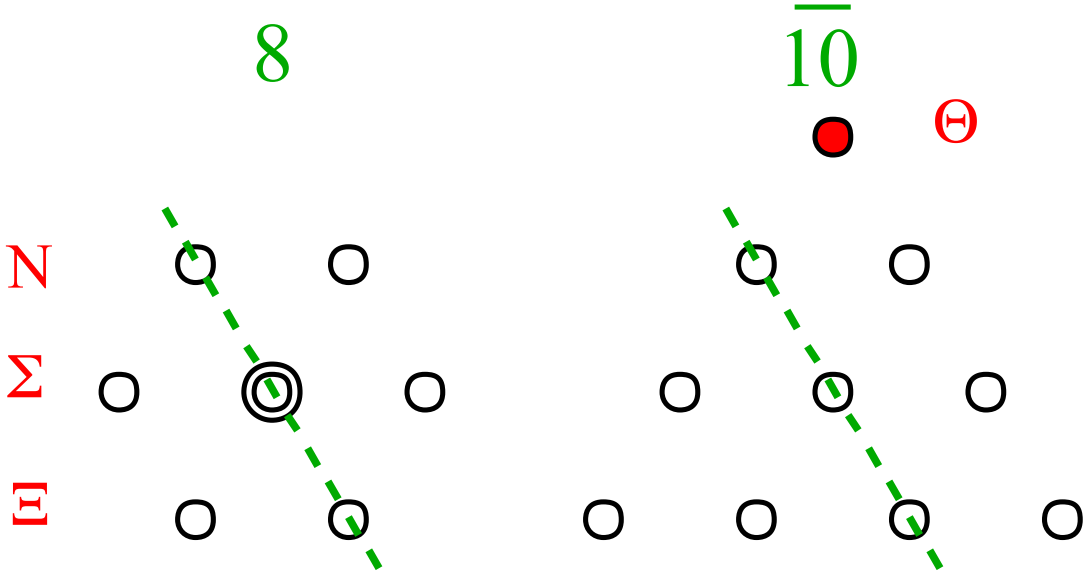


M.V. Polyakov and A. Rathke,
On photoexcitation of baryon anti-decuplet
Eur. Phys. J. A 18 (2003) 691



natural (but not the only one) explanation if N* is a pentaquark

PRL 117, 132502 (2016) PHYSICAL REVIEW LETTERS week ending 23 SEPTEMBER 2016

Insight into the Narrow Structure in η Photoproduction on the Neutron from Helicity-Dependent Cross Sections

(A2 Collaboration at MAMI)

The double polarization observable E and the helicity dependent cross sections $\sigma_{1/2}$ and $\sigma_{3/2}$ were measured for η photoproduction from quasifree protons and neutrons. The circularly polarized tagged photon beam of the A2 experiment at the Mainz MAMI accelerator was used in combination with a longitudinally polarized deuterated butanol target. The almost 4π detector setup of the Crystal Ball and TAPS is ideally suited to detect the recoil nucleons and the decay photons from $\eta \to 2\gamma$ and $\eta \to 3\pi^0$. The results show that the narrow structure previously observed in η photoproduction from the neutron is only apparent in $\sigma_{1/2}$ and hence, most likely related to a spin-$1/2$ amplitude. Nucleon resonances that contribute to this partial wave in η production are only $N1/2^-$ (S_{11}) and $N1/2^+$ (P_{11}). Furthermore, the extracted Legendre coefficients of the angular distributions for $\sigma_{1/2}$ are in good agreement with recent reaction model predictions assuming a narrow resonance in the P_{11} wave as the origin of this structure.