Heavy baryons in the Chiral Quark-Soliton Model

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Excited QCD, October 24-28,2022, Giardini-Naxos, Sicilly

in collaboration with
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K.-C. Kim (Incheon Univ.)
G.-S. Yang (Soongsil University, Seoul)
M. Kucab (JU)

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Eur.Phys.J. C78 (2018) 690
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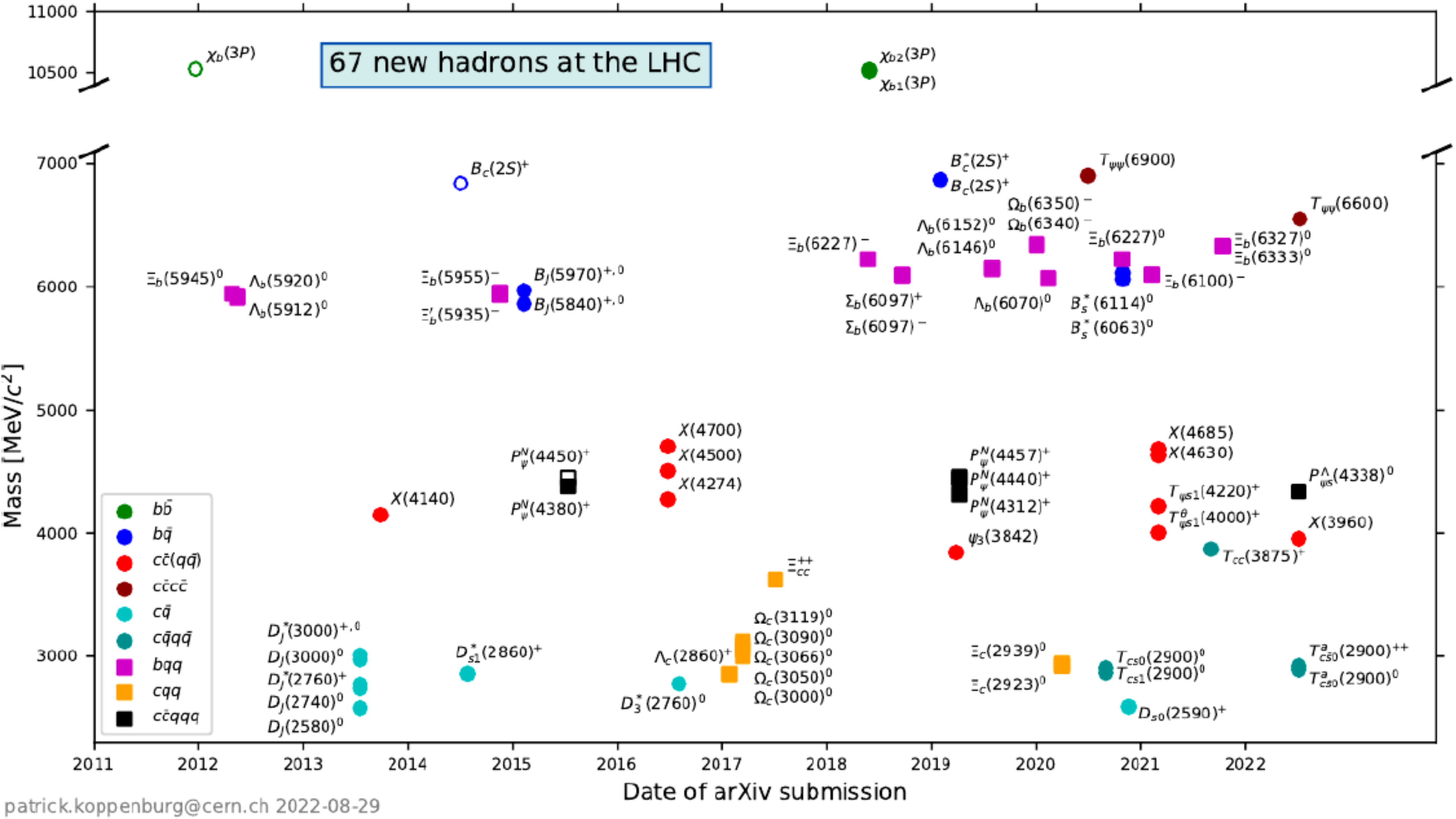
Phys. Rev. D105 (2022) 094004
arXiv:2208.088602 [hep-ph]
in preparation

On August 25, 2021 Maxim Polyakov passed away prematurely

Overture

Spectroscopy at the LHC

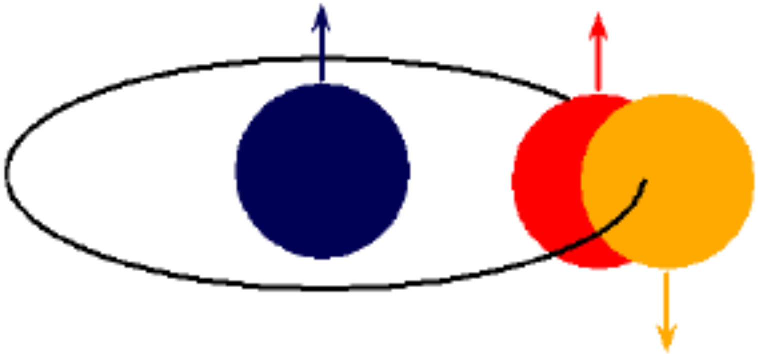


patrick.koppenburg@cern.ch 2022-08-29

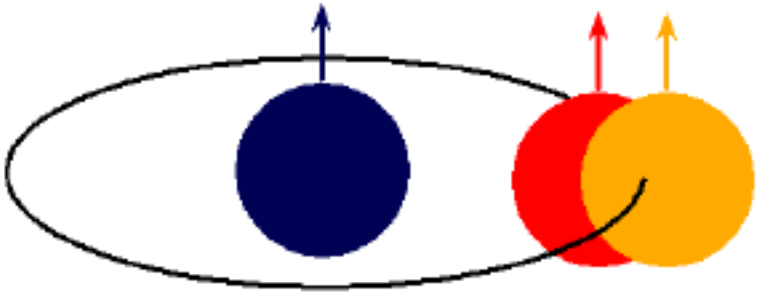
W. Wiślicki, PTF meeting in Katowice, October 2022

- **2017** LHCb five Ω_c^0 states confirmed by Belle in 2018
- **2018** LHCb $\Xi_b(6227)$ and $\Sigma_b(6097)$ and Λ_b at 6146 and 6152
- **2020** LHCb four Ω_b^- states (problem!)
- **2020** LHCb $\Lambda_b^0(6072)$ and $\Xi_b^0(6227)$
- **2021** LHCb two Ξ_b^0 at 6327 and 6333
- **2021** CMS $\Xi_b^-(6100)$

Classification by SU(3) q.n.



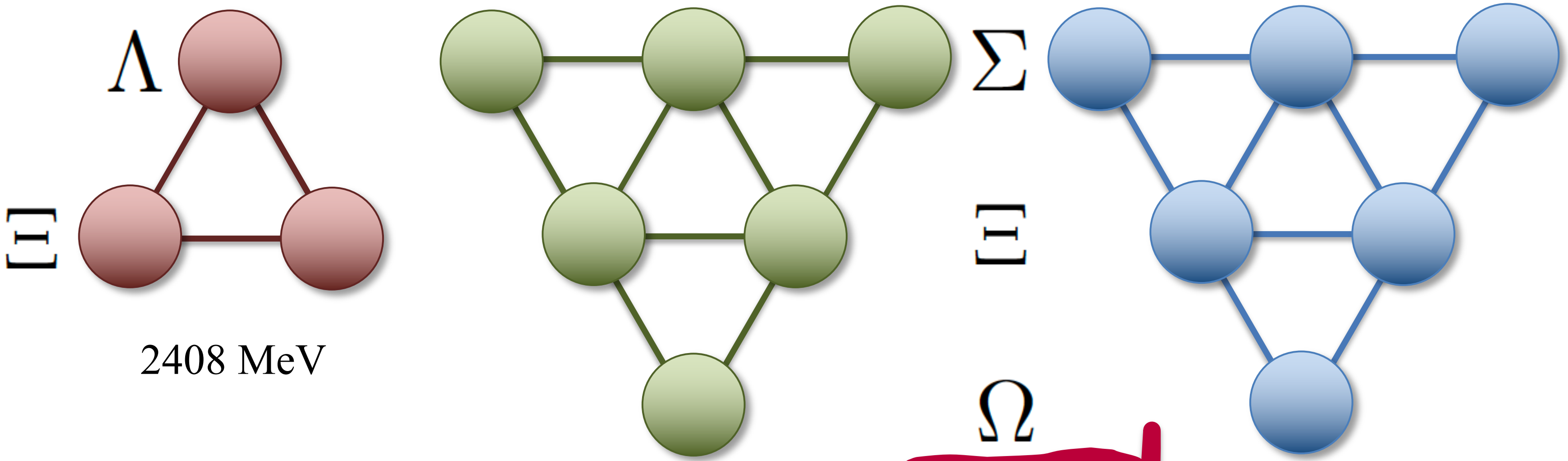
light quarks have spin 0
SU(3) $\overline{\text{triplet}}$, total spin 1/2



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

Charm baryon ground states

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



2408 MeV

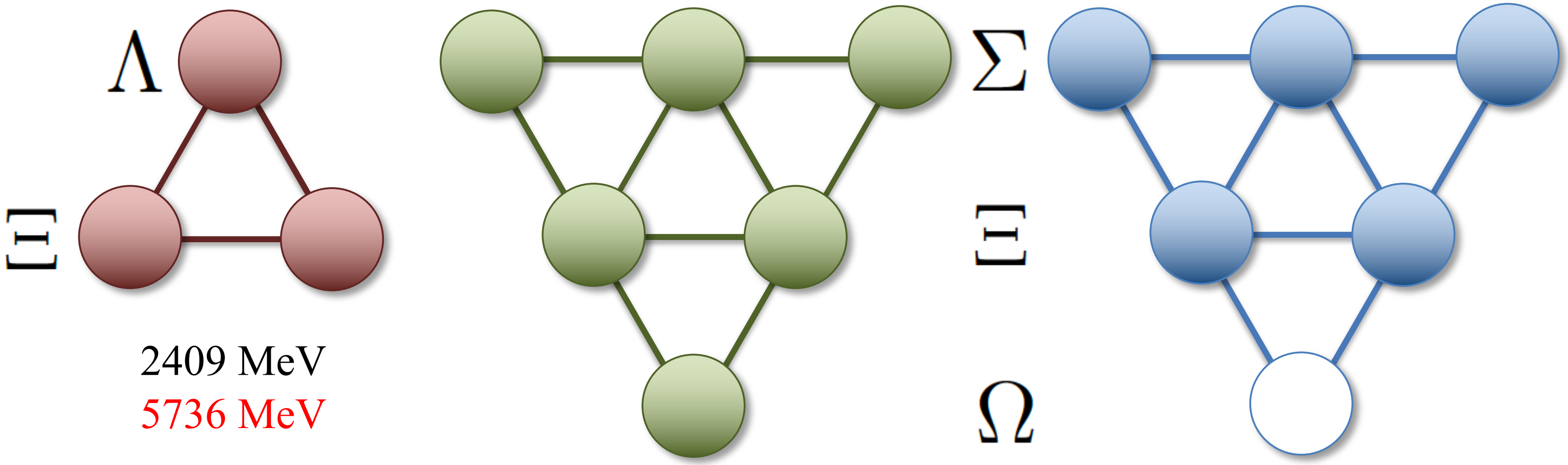
2535 MeV

69 MeV

2602 MeV

Charm and Bottom ground states

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



2409 MeV
5736 MeV

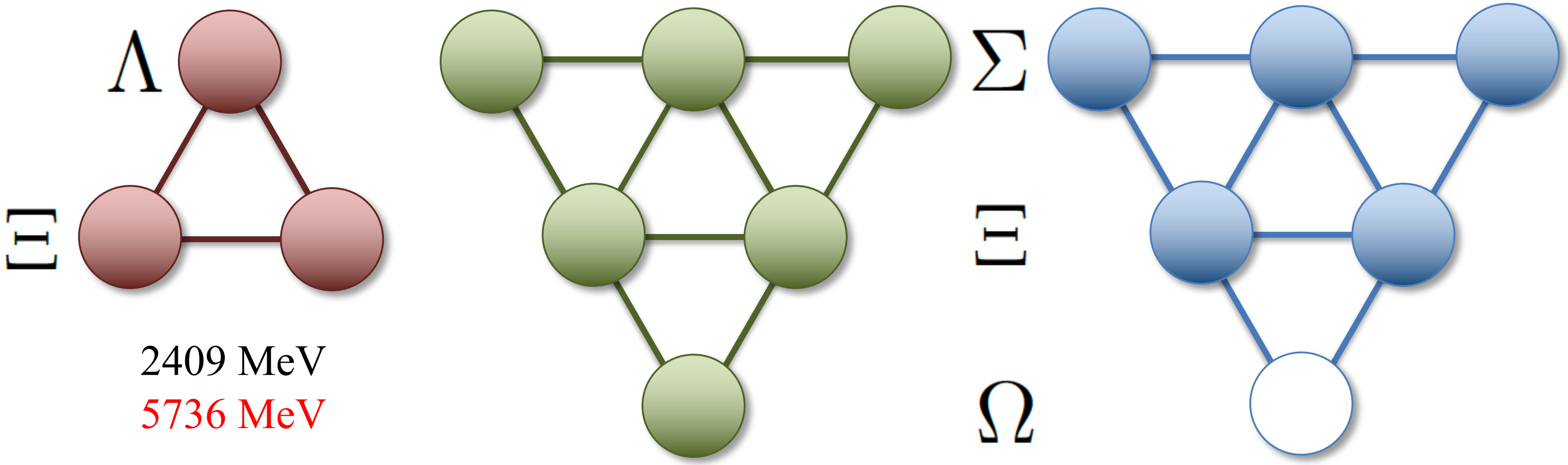
2535 MeV
5893 MeV

69 MeV
20 MeV

2602 MeV
5913 MeV

Charm and Bottom ground states

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



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Fully confirmed experimentally (except for Ω_b^*)

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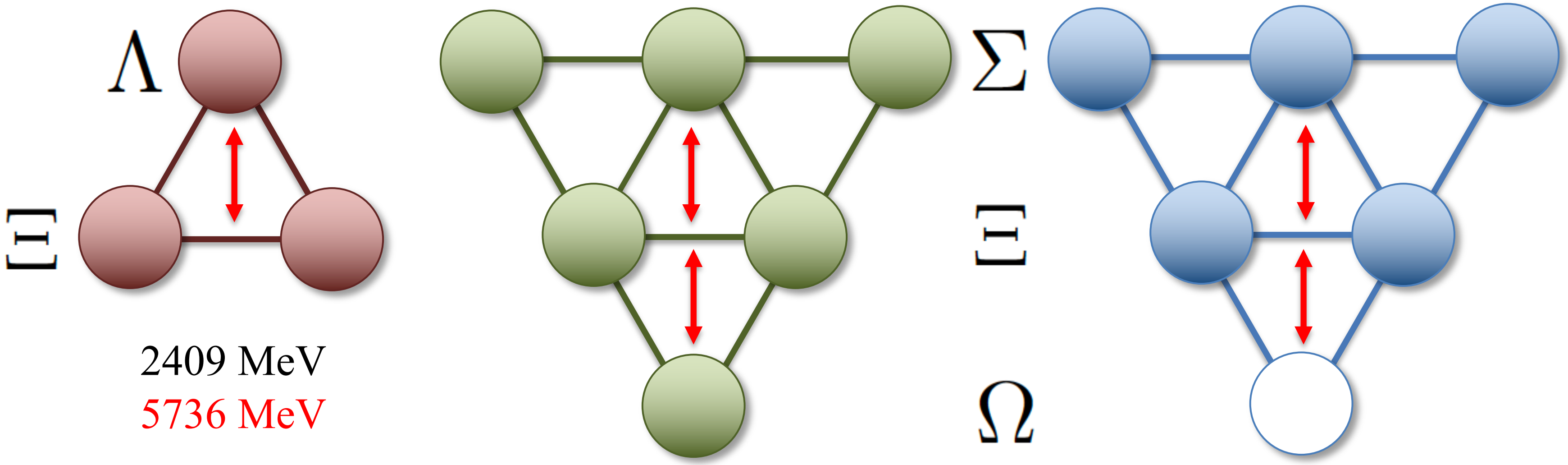

2409 MeV
5736 MeV

$$\boxed{\begin{aligned}\delta_{\bar{3}} &= 180\ \text{MeV}\\ \delta_{6} &= 121\ \text{MeV}\end{aligned}}$$

2535 MeV
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69 MeV
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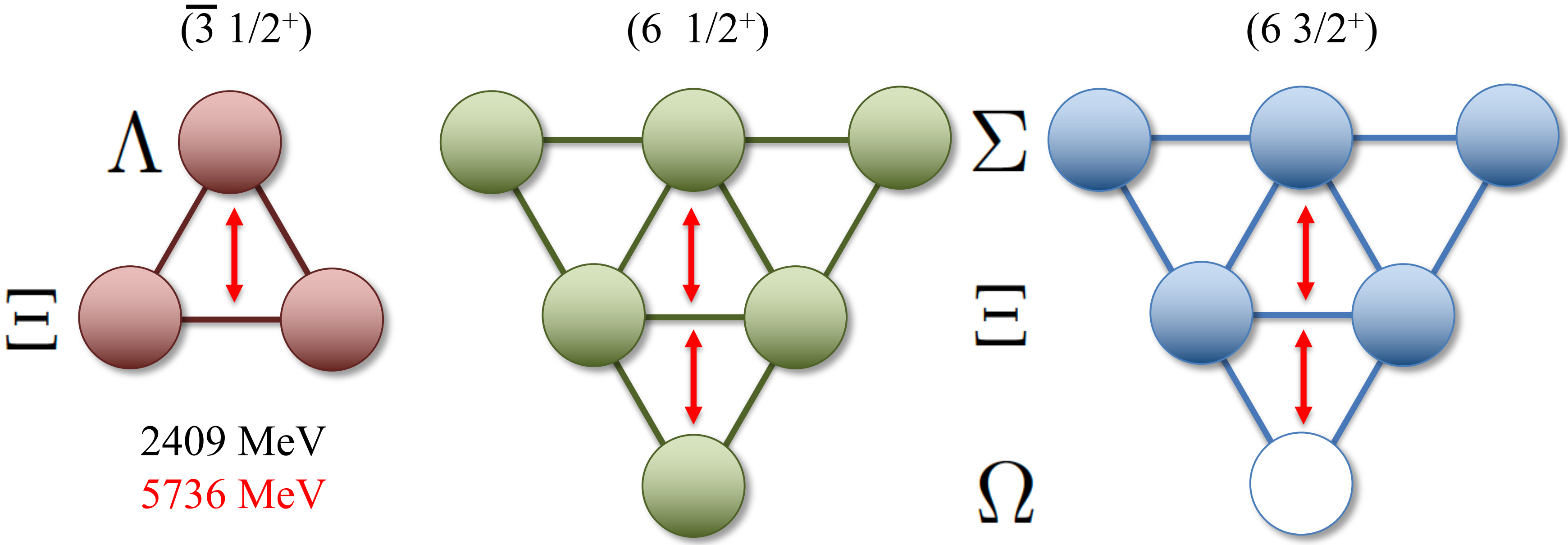
Fully confirmed experimentally (except for Ω_b^*)
SU(3) symmetry (both for c and b sector!)

Charm and Bottom ground states



2409 MeV
5736 MeV

$$\delta_{\bar{\mathbf{3}}} = 180 \text{ MeV}$$
$$\delta_{\mathbf{6}} = 121 \text{ MeV}$$

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69 MeV
20 MeV

2602 MeV
5913 MeV

Fully confirmed experimentally (except for Ω_b^*)

SU(3) symmetry (both for c and b sector!)

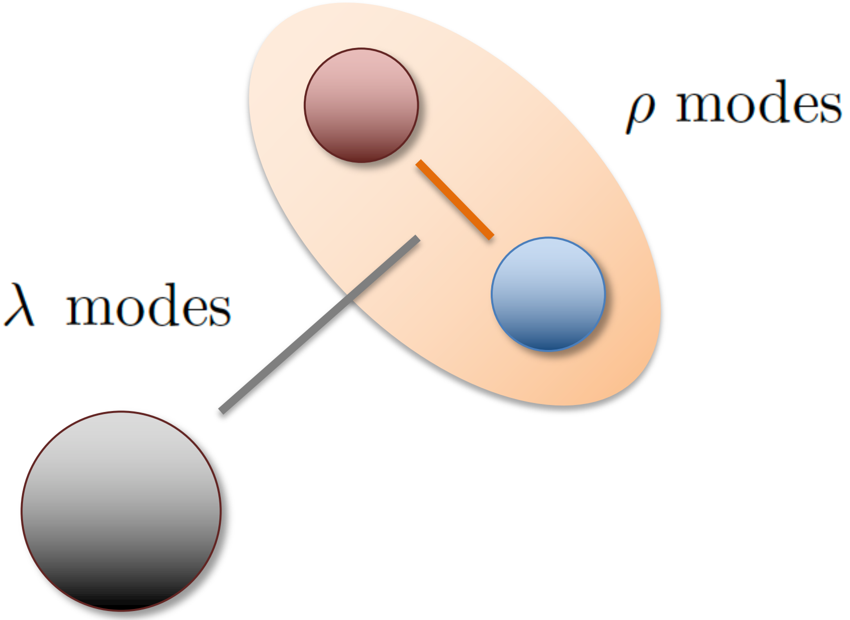
Hyperfine splittings $\sim \dfrac{1}{m_Q}$

PDG:

$$\frac{m_c}{m_b} = 0.3$$

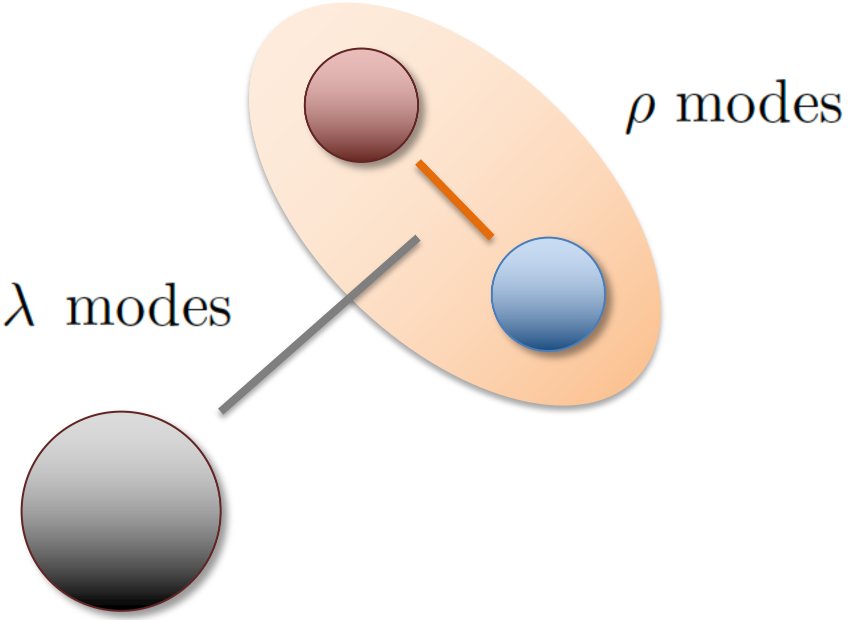
Excited QCD

Exited states in QM models



In both cases breathing and rotational modes contribute leading to a plethora of possible states.

Exited states in QM models



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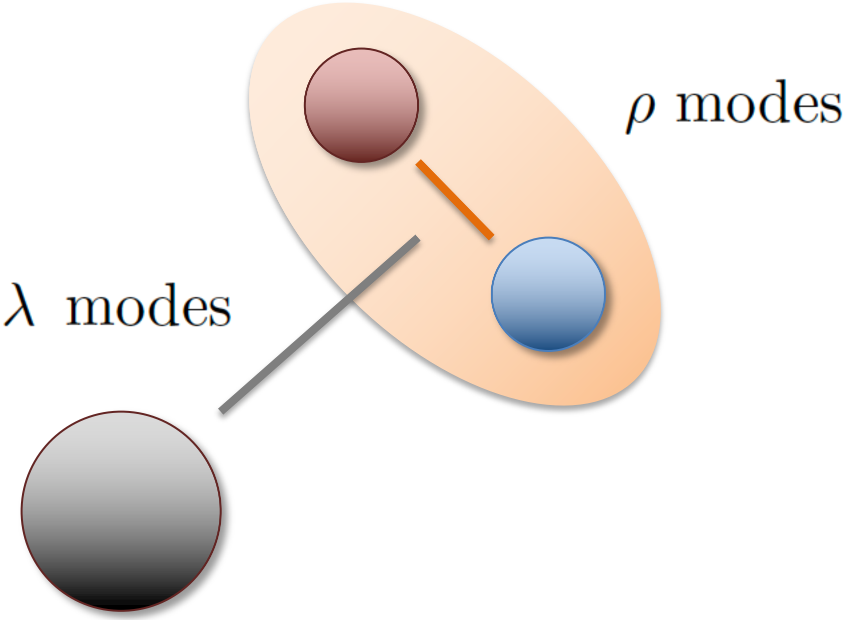
Some organizing principle would be usefull

Exited states in QM models

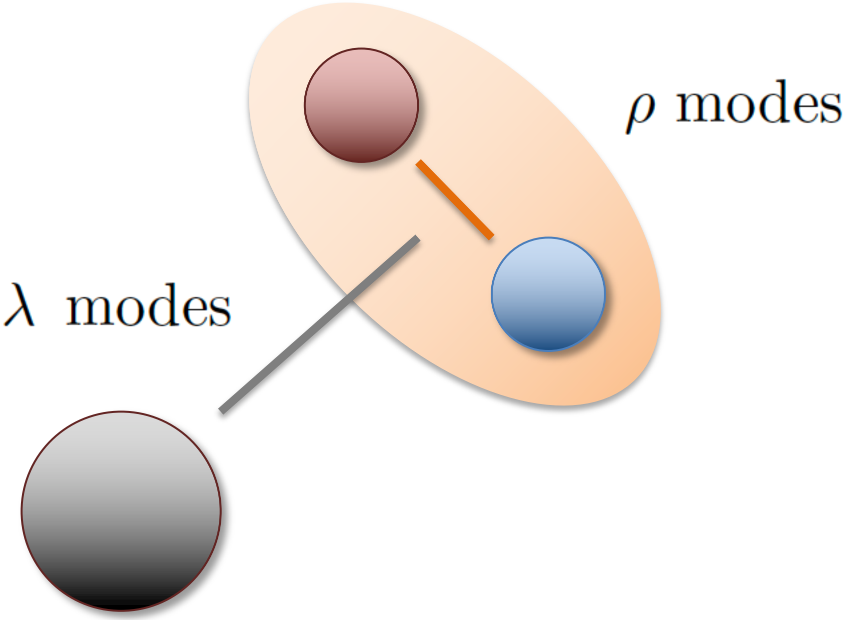


In both cases breathing and rotational modes contribute leading to a plethora of possible states.

Some organizing principle would be usefull

heavy quark symmetry: $1/m_Q$

Exited states in QM models



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Some organizing principle would be usefull

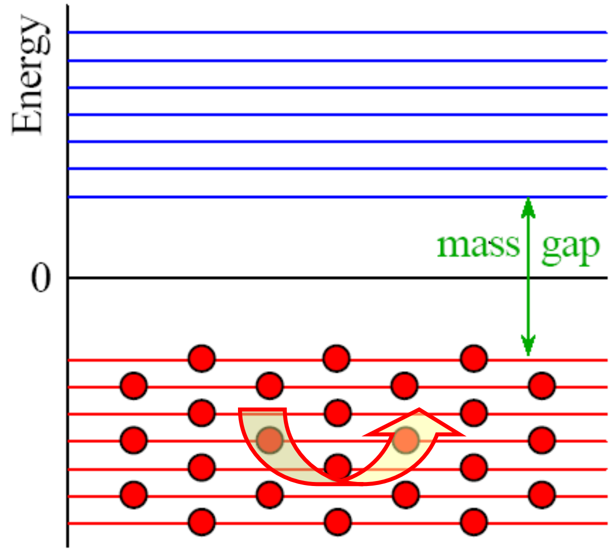
heavy quark symmetry: $1/m_Q$

large N_c → chiral soliton models

Chiral Quark-Soliton Model

Chiral Quark Soliton Model

chiral symmetry breaking:

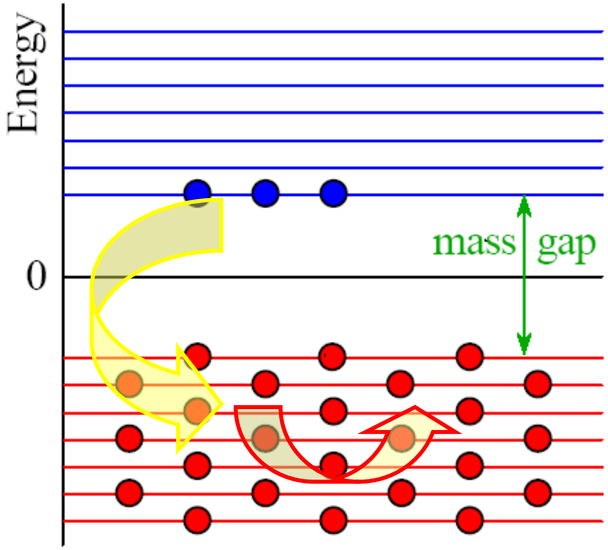


chirally inv. manyquark int.

Chiral Quark Soliton Model

baryon:

adding vlance quarks:

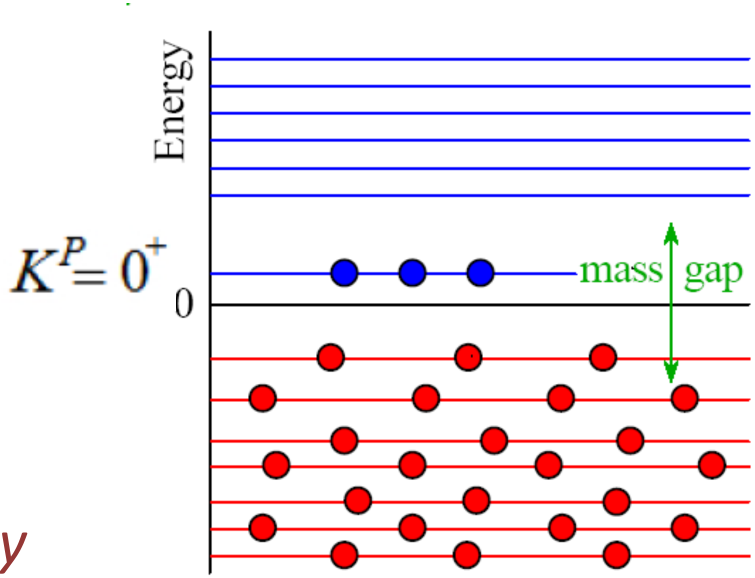


chirally inv. manyquark int.

Chiral Quark Soliton Model

baryon:

"classical" baryon:



due to *hedgehog symmetry* of the mean field only

grand spin

$$K = T + S$$

is a *good* quantum number

chirally inv. manyquark int.

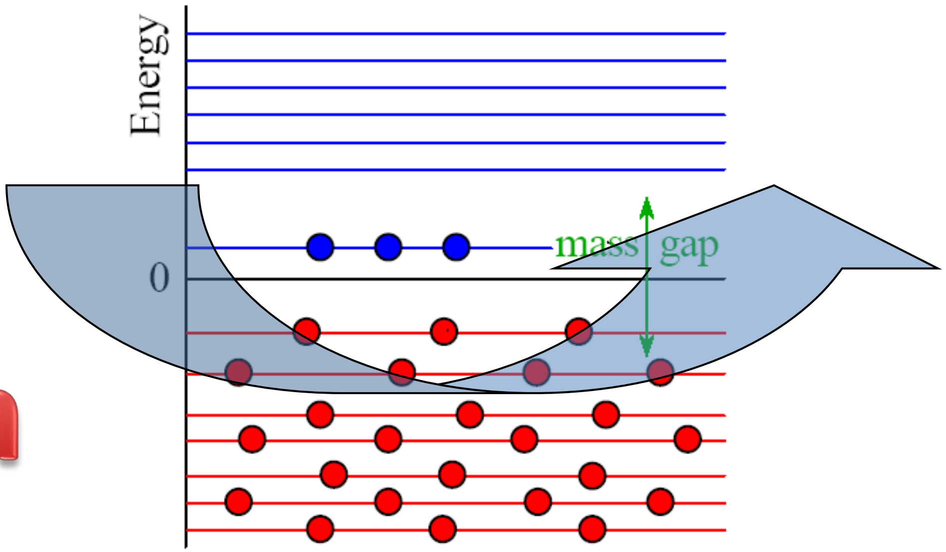
soliton configuration

no quantum numbers except *B*

Chiral Quark Soliton Model

baryon: zero mode quantization

"quantum" baryon:



chirally inv. manyquark int.

soliton configuration
no quantum numbers except *B*

rotation generates flavor and spin

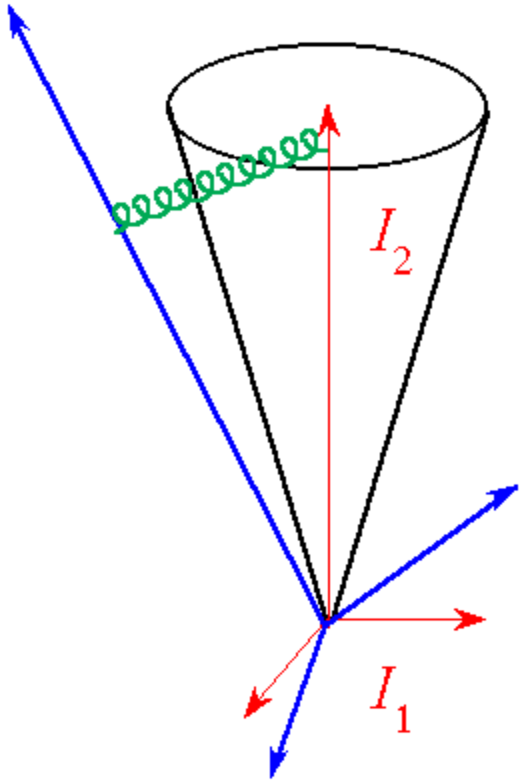
Mass formula

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

constraint: $Y' = \dfrac{N_{\rm val}}{3}$

baryon mass: $\sim N_c$

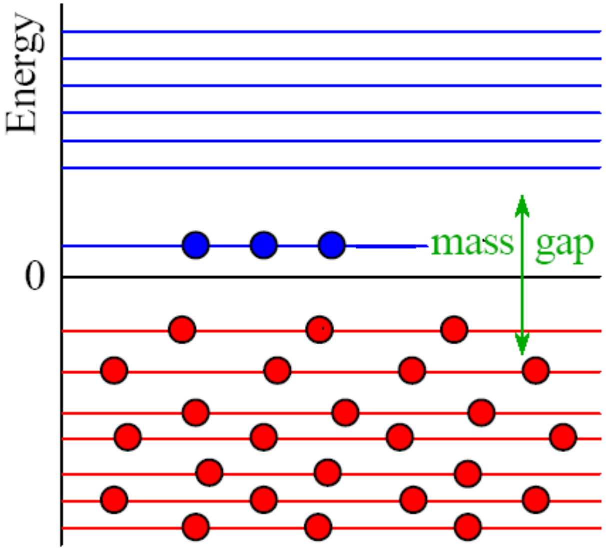
octet-decuplet splitting: $\sim \dfrac{1}{N_c}$



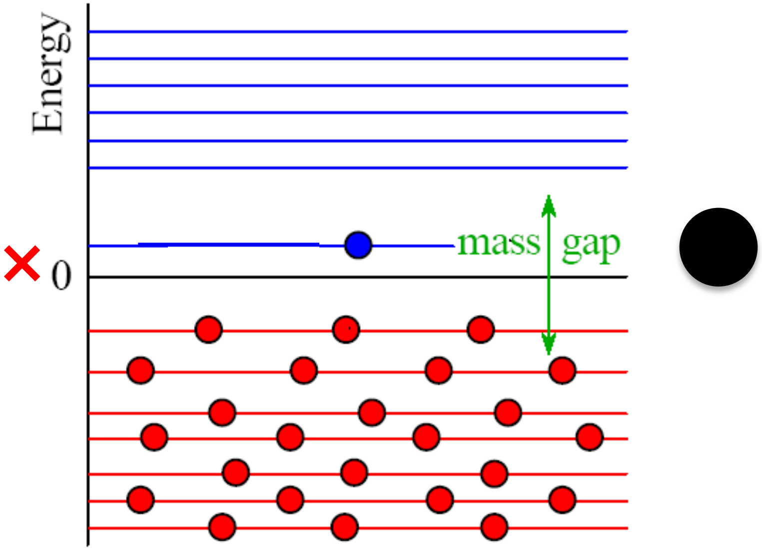
P.O. Mazur, M.A. Nowak, MP, Phys. Lett. 147B (1984) 137
E. Guadagnini, Nucl. Phys. B236 (1984) 35
S. Jain, S.R. Wadia, Nucl. Phys. B258 (1985) 713

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



$(N_c - 1)$ ×



color factorizes!

plus one heavy quark

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

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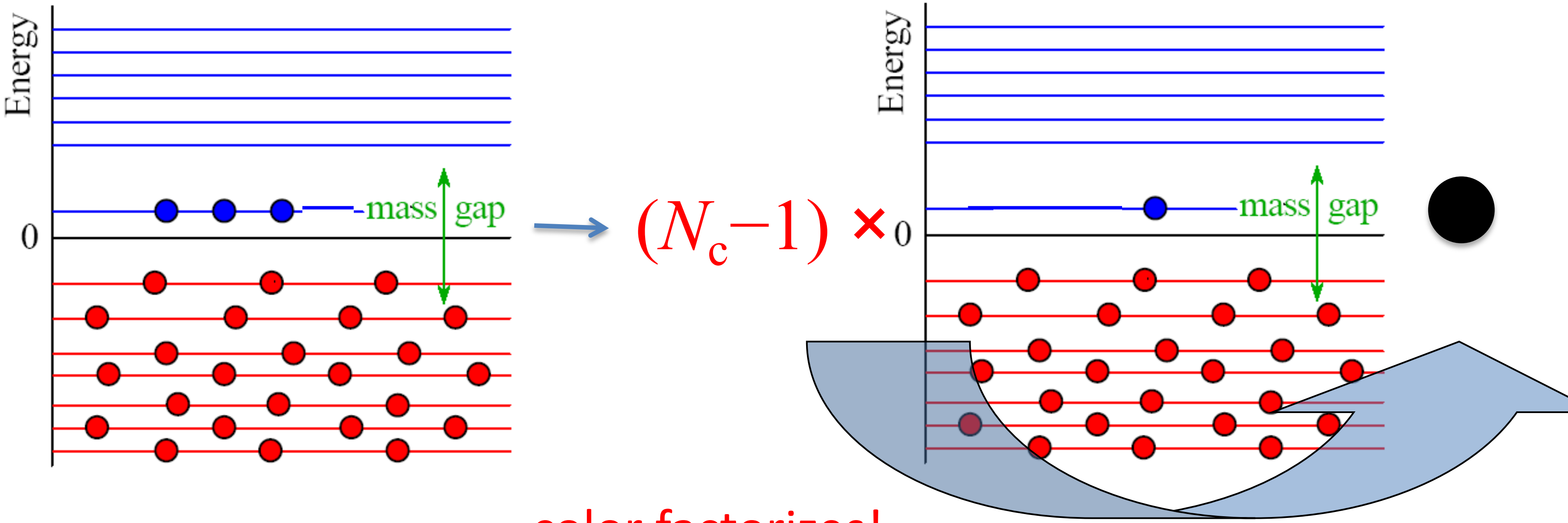


$(N_c - 1) \times$

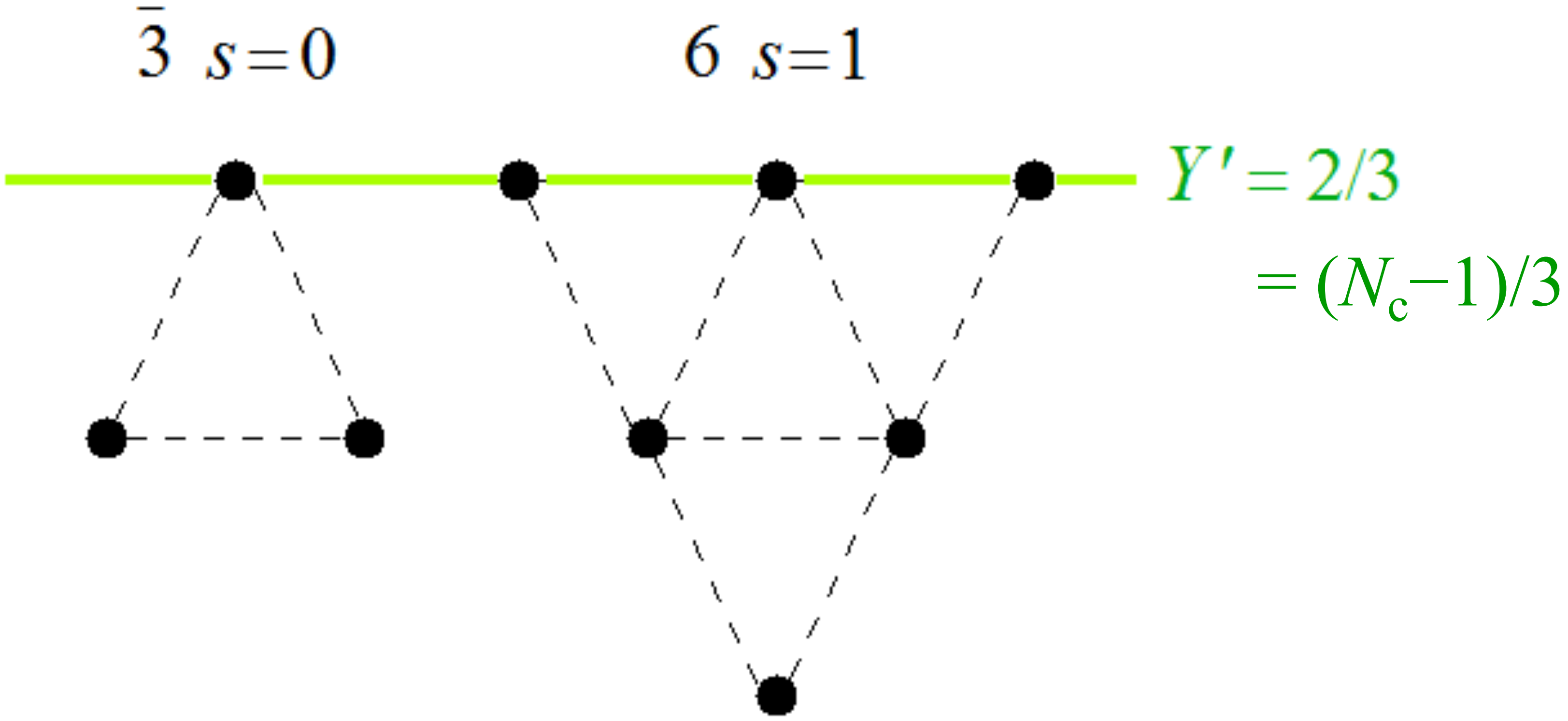
color factorizes!

plus one heavy quark

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

Chiral Quark-Soliton Model ground states

Allowed SU(3) irreps.



Chiral Quark Soliton Model continuation

Need to add:

1) chiral symmetry breaking
2) soliton-h.q. spin interaction

reproduces QM model results (GMO relations)

+

“Gudagnini-like” relation

$$M_{\Omega_Q^*} = 2M_{\Xi'_Q} + M_{\Sigma_Q^*} - 2M_{\Sigma_Q} = 2764.5 \pm 3.1$$

Q = c

Chiral Quark Soliton Model continuation

Need to add:

1) symmetry breaking
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reproduces QM model results (GMO relations)

+

“Gudagnini-like” relation

$$M_{\Omega^*_Q} = 2M_{\Xi'_Q} + M_{\Sigma^*_Q} - 2M_{\Sigma_Q} = 2764.5 \pm 3.1$$

Q = c

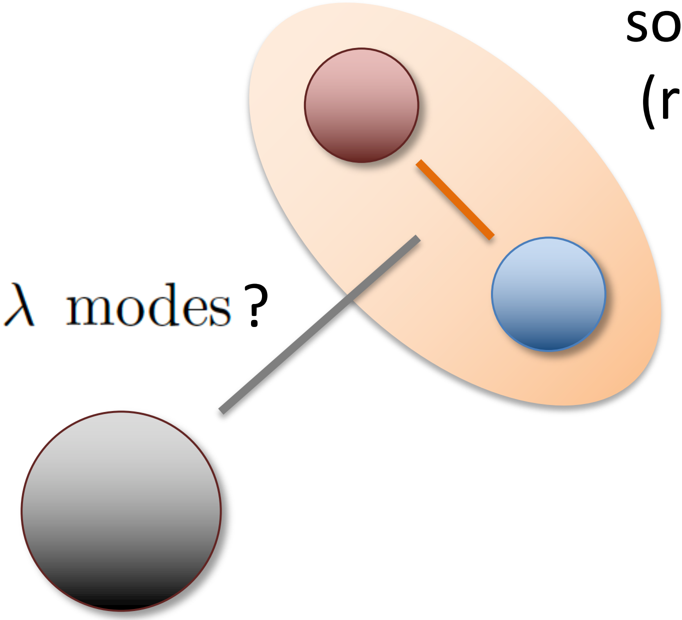
$$M_{\Omega^*_b} = 6076.8 \pm 2.25$$

model independent prediction

G.-S. Yang, H.-Ch. Kim, M.V. Polyakov, MP, Phys.Rev.D 94 (2016) 071502

Excited states in the Chiral Quark-Soliton Model

Excitations



soliton zero modes
(rotations)

$$\sim \frac{1}{N_c}$$

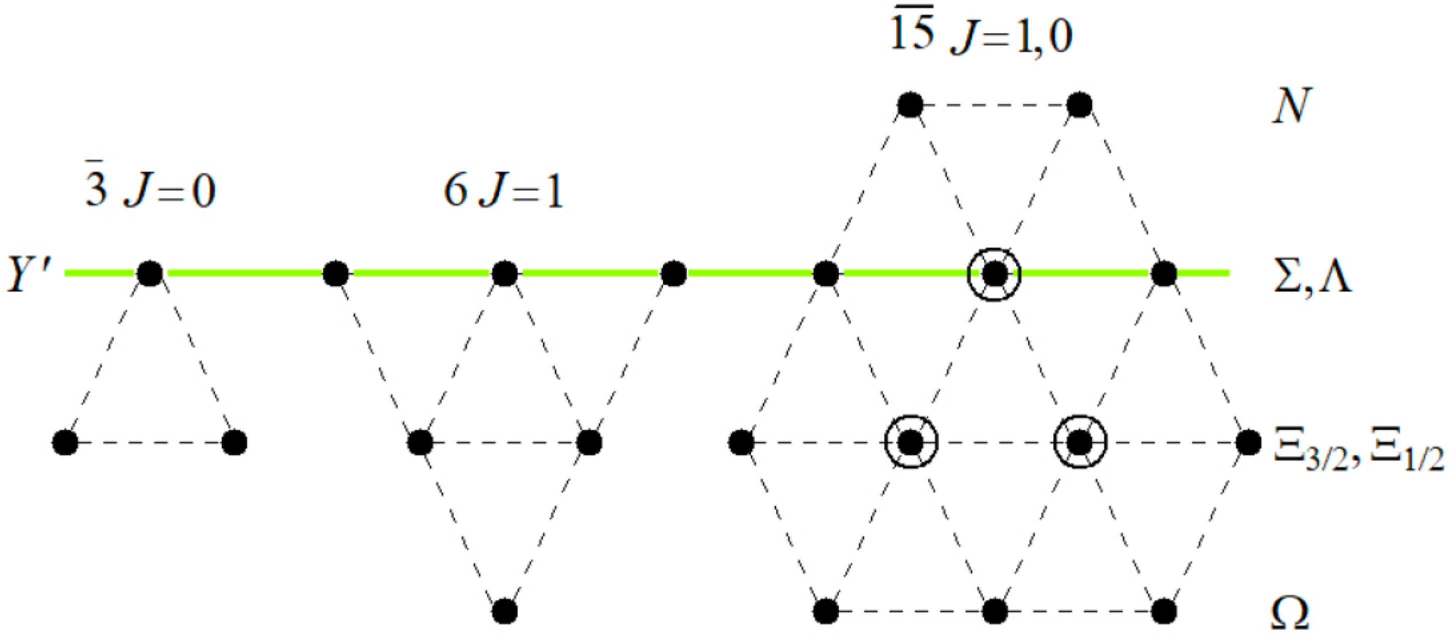
λ modes ?

Suppose we write the Schrödinger equation for λ modes.
Reduced mass $\mu \sim N_c$
Excitations depend on the potential used

$$\Delta_\lambda E \sim \mu \ (\text{Coulomb}), \quad \sim 1 \ (\log), \quad \sim \mu^{-1/3} \ (\text{linear})$$

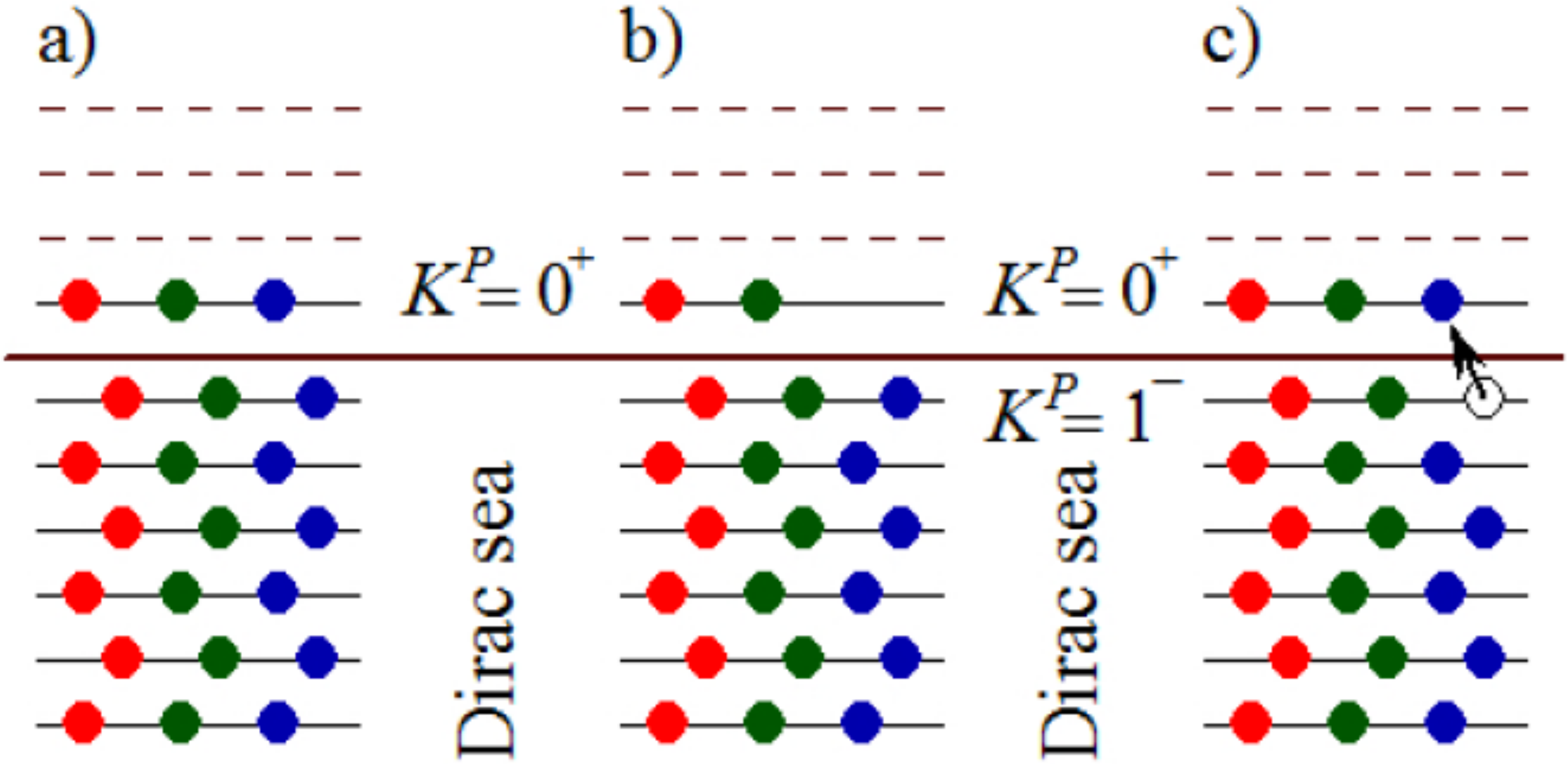
Positive parity

Higher SU(3) representations



Three exotic (pentaquark) multiplets
spin 0 soliton is heavier than spin 1

Negative parity

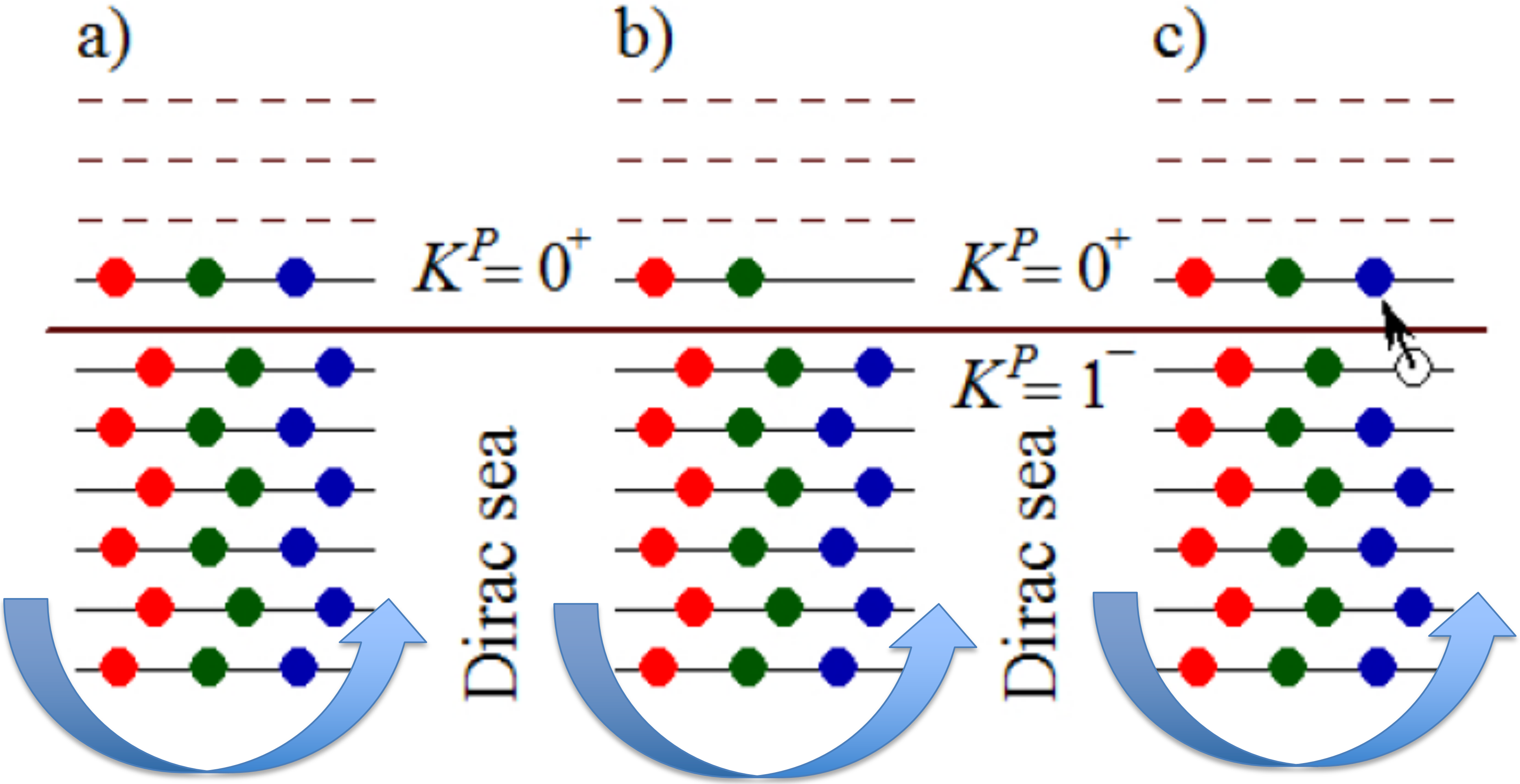


Negative parity

octet and decuplet

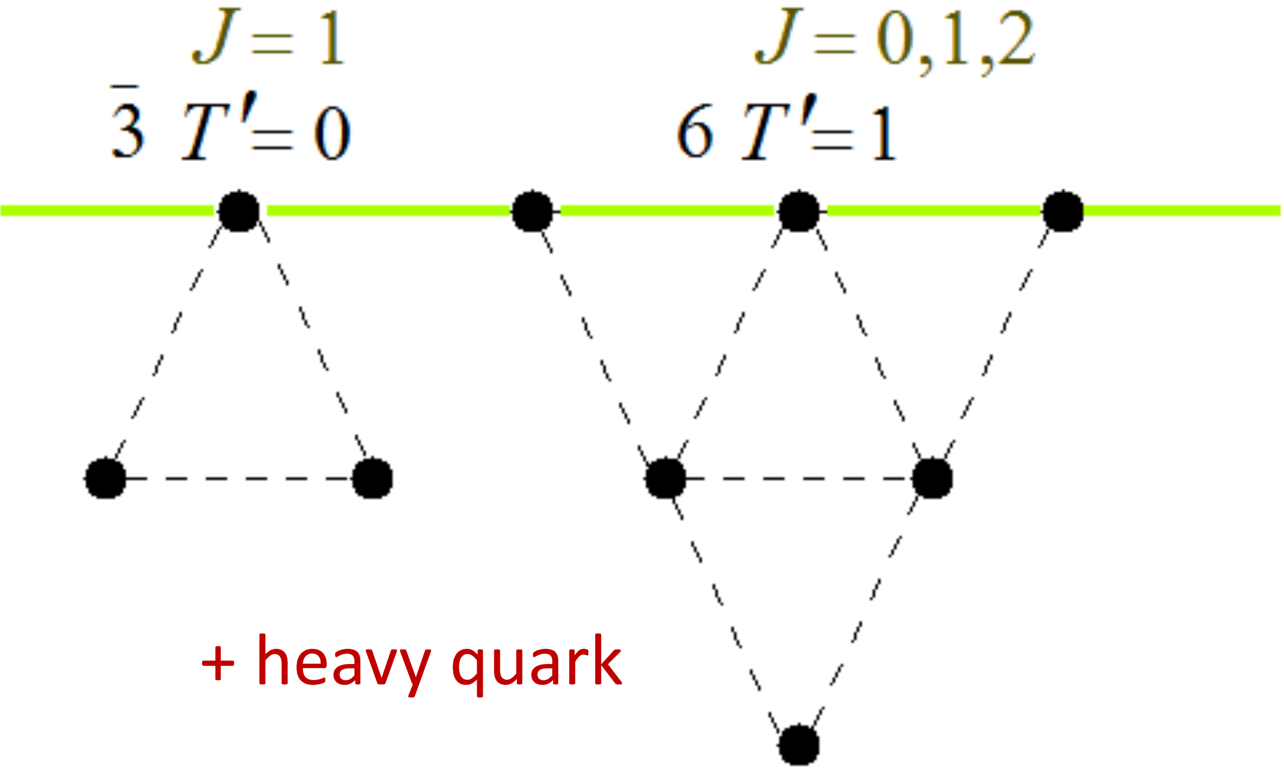
antitriplet and sextet

antitriplet and sextet



One *K*=1 quark excited solitons

$$T' + J = K = 1$$



$J = 1$

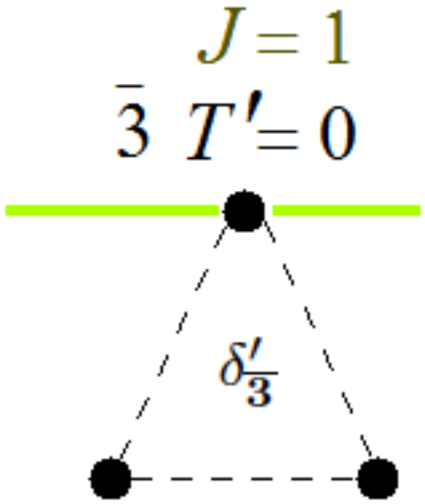
$\bar{3}\ T' = 0$

$J = 0,1,2$

$6\ T' = 1$

+ heavy quark

3bar excited *P*=– heavy baryons

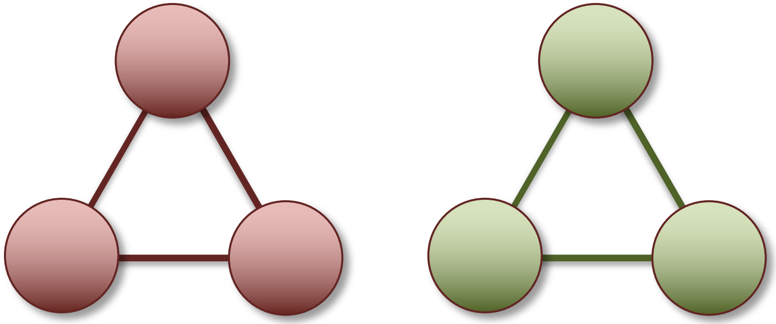


$$M'^{\overline{\mathbf{3}}}_{Q\,Y} = \mathcal{M}'_{Q\,\overline{\mathbf{3}}} + \delta_{\overline{\mathbf{3}}}Y + \frac{\kappa'}{m_Q}\begin{cases} -2/3 & \text{for} \quad S=1/2 \\ +1/3 & \text{for} \quad S=3/2 \end{cases}$$

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

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

3bar excited *P*=– heavy baryons



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

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

$\Lambda_c(2592)$

198 MeV

$\Xi_c(2790)$

$\Lambda_c(2628)$

190 MeV

$\Xi_c(2818)$

$$\frac{\kappa'}{m_c} = 28 \div 36\ \text{MeV}$$

3bar excited *P*=– heavy baryons

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

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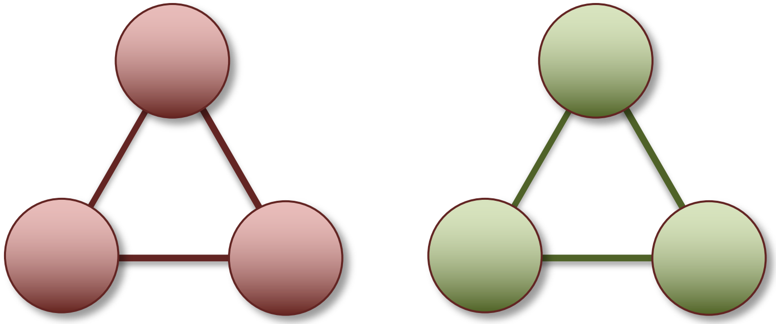


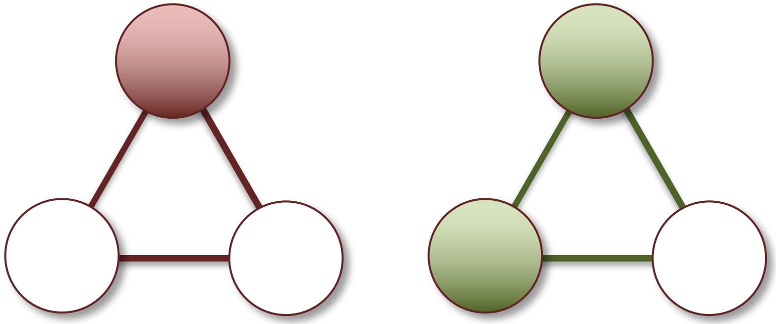
$\Lambda_c(2628)$

190 MeV

$\Xi_c(2818)$

$$\frac{\kappa'}{m_c} = 28 \div 36 \text{ MeV}$$

$\Lambda_b(5915)$



$\Lambda_b(5920)$

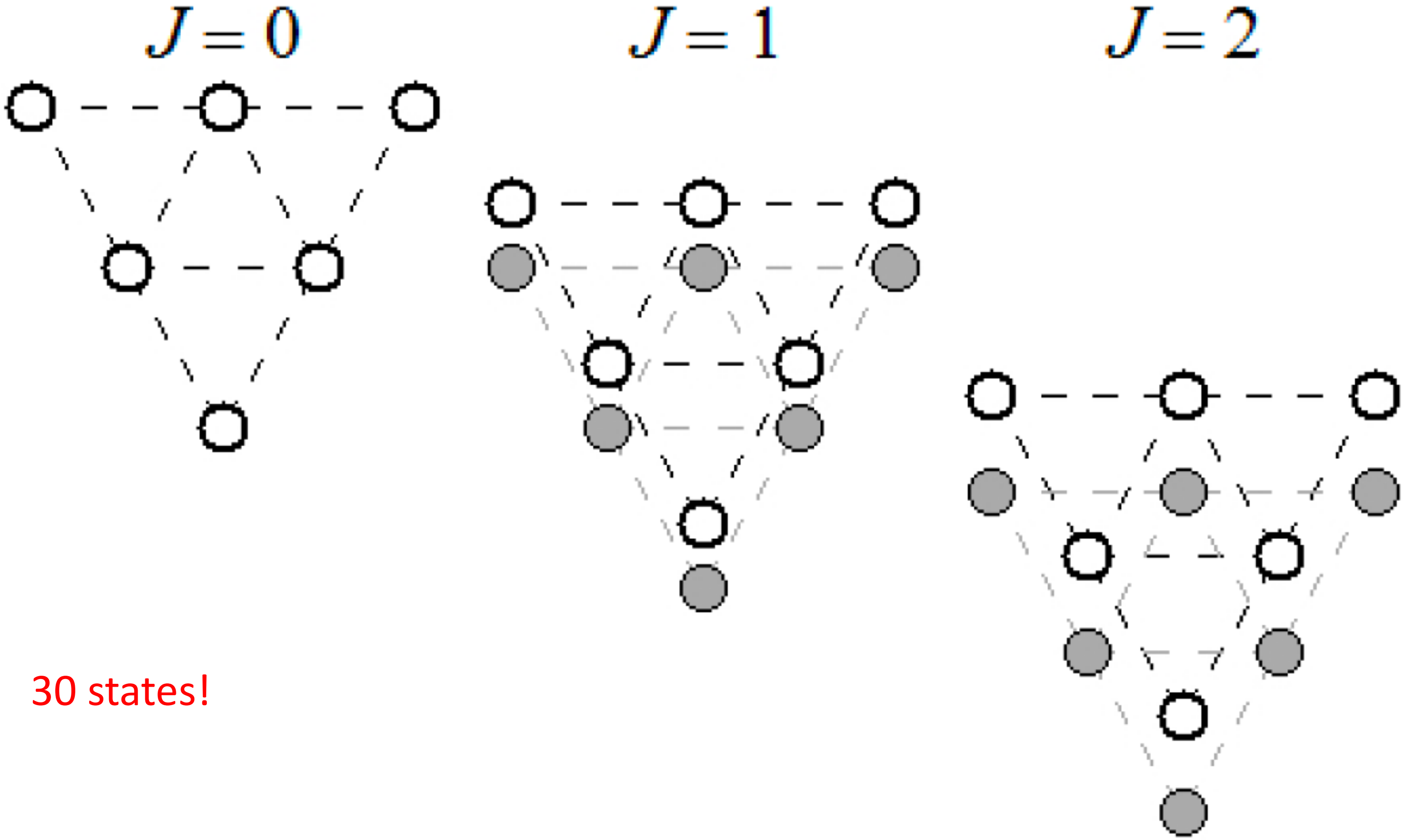
180 MeV

$\Xi_b(6100)$

$$\frac{\kappa'}{m_b} = 8 \text{ MeV}$$

h.f splitting ratio: $\sim m_c/m_b$

sextet excited *P*=– heavy baryons



30 states!

sextet excited *P*=– heavy baryons

$$M'^{\mathbf{6}\,J=0}_{Q\,Y} = \mathcal{M}'_{\mathbf{6}\,Q} - 2\frac{a_1}{I'_1} + \left(\delta_{\mathbf{6}} - \frac{3}{10}\delta\right) Y,$$

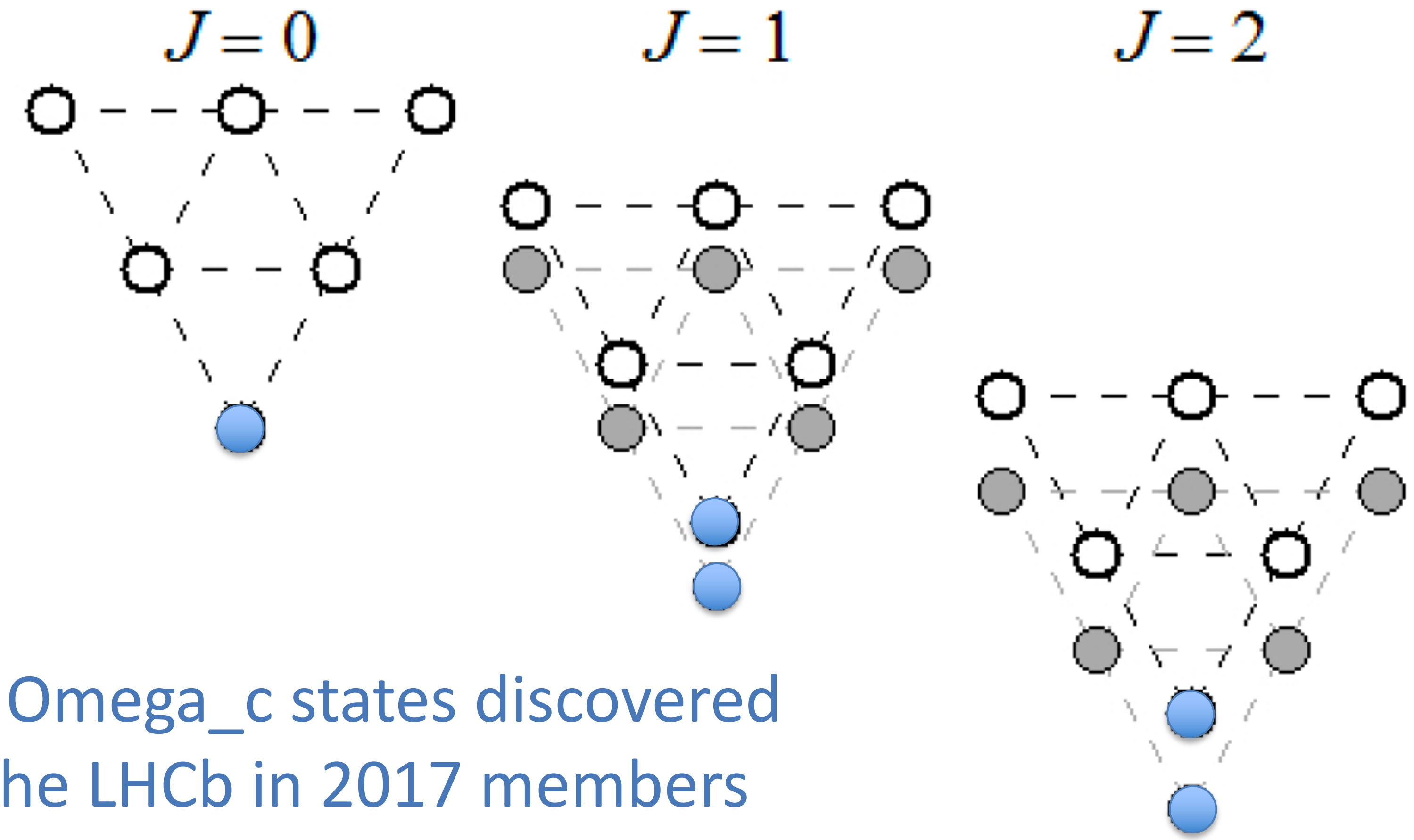
$$M'^{\mathbf{6}\,J=1}_{Q\,Y} = \mathcal{M}'_{\mathbf{6}\,Q} - \frac{a_1}{I'_1} + \left(\delta_{\mathbf{6}} - \frac{3}{20}\delta\right) Y + \frac{\kappa'}{m_Q}\begin{cases} -2/3 & \text{for} \quad S = 1/2 \\ +1/3 & \text{for} \quad S = 3/2 \end{cases}$$

$$M'^{\mathbf{6}\,J=2}_{Q\,Y} = \mathcal{M}'_{\mathbf{6}\,Q} + \frac{a_1}{I'_1} + \left(\delta_{\mathbf{6}} + \frac{3}{20}\delta\right) Y + \frac{\kappa'}{m_Q}\begin{cases} -1 & \text{for} \quad S = 3/2 \\ +2/3 & \text{for} \quad S = 5/2 \end{cases}$$

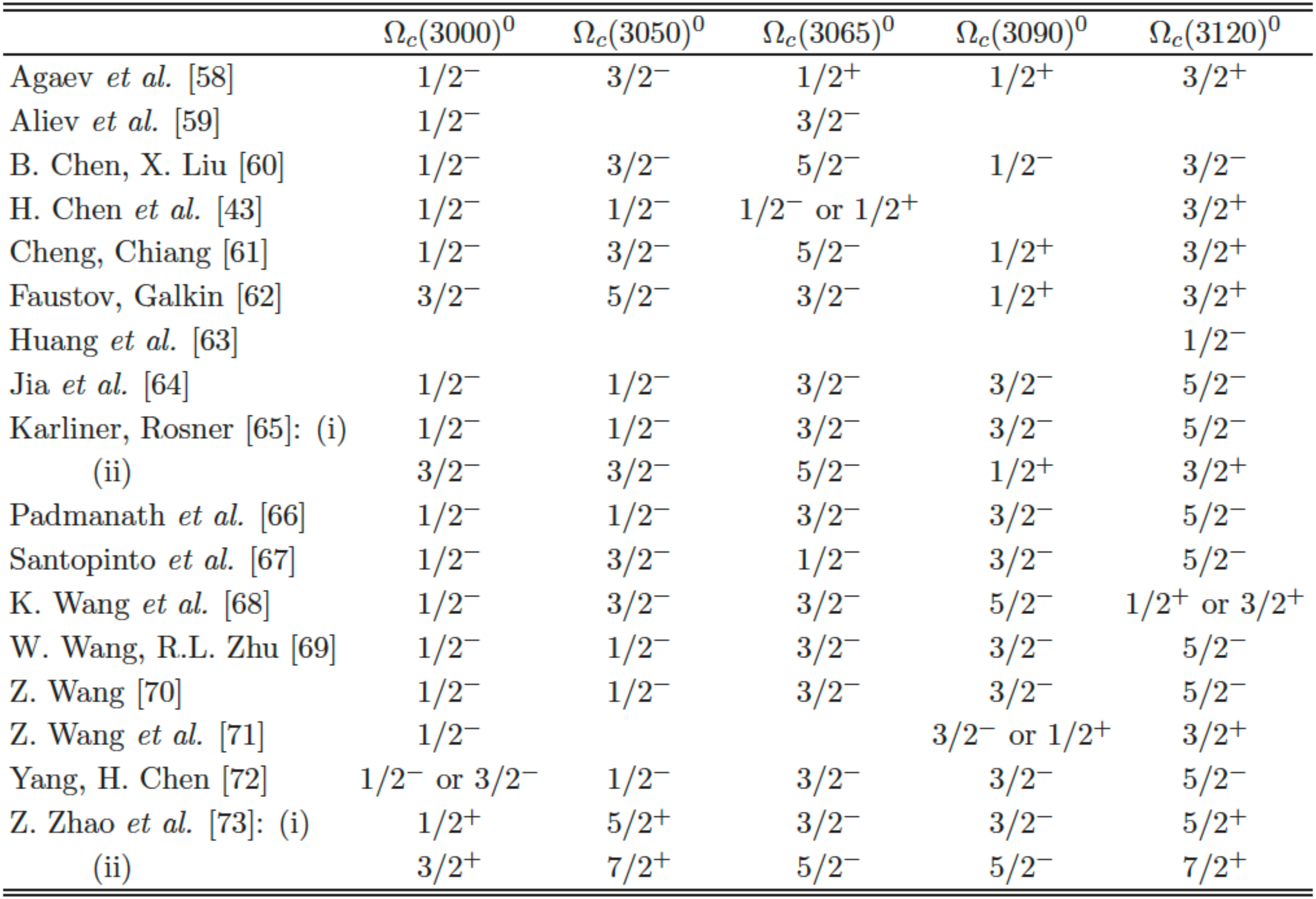
Splittings and average multiplet masses depend on *J*
three new parameters

$\frac{\kappa'}{m_Q}$ known from antitriplet

sextet excited *P*=– heavy baryons



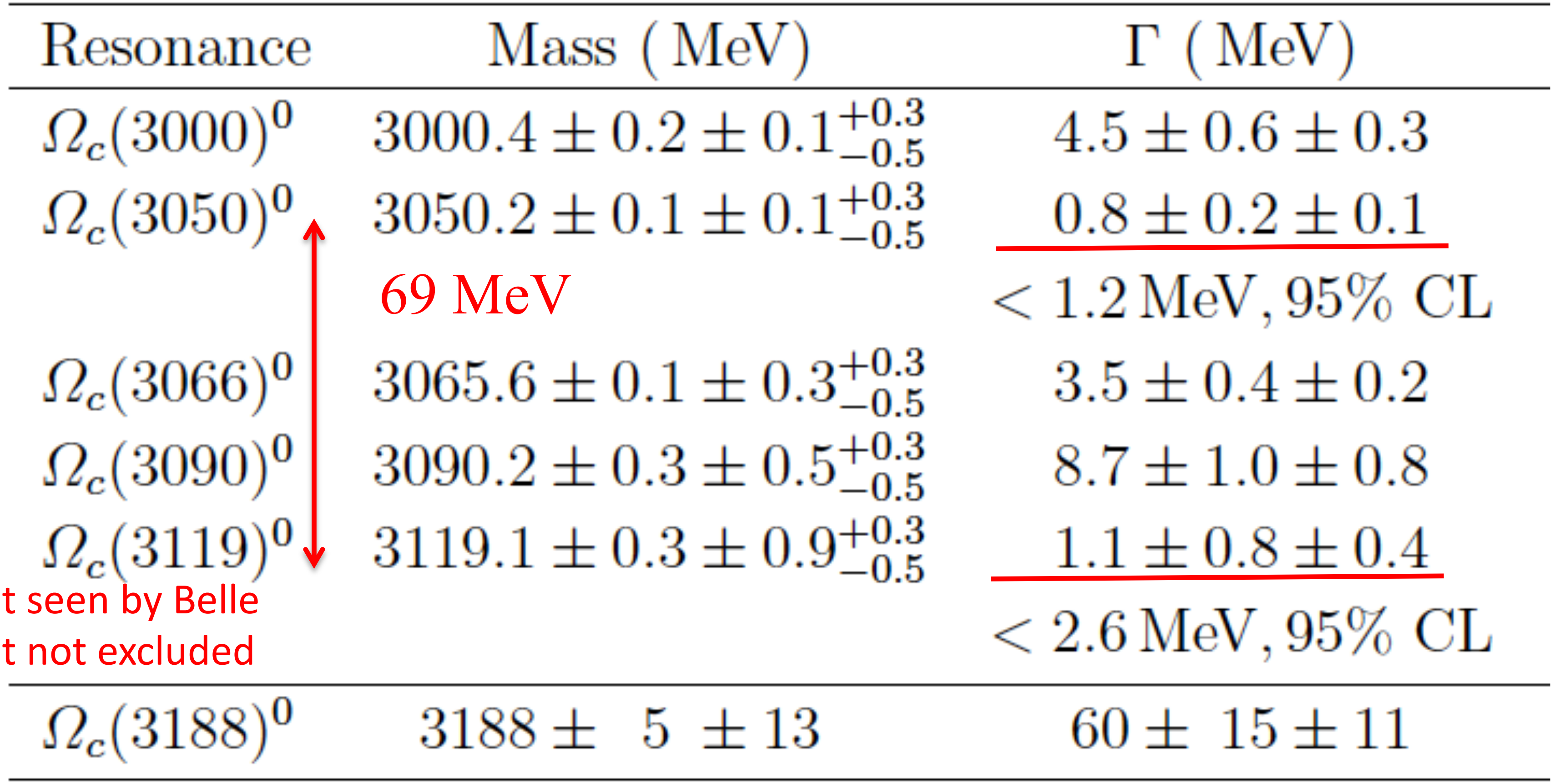
Are Omega_c states discovered by the LHCb in 2017 members of SU(3) sextets?



	$\Omega_c(3000)^0$	$\Omega_c(3050)^0$	$\Omega_c(3065)^0$	$\Omega_c(3090)^0$	$\Omega_c(3120)^0$
Agaev *et al.* [58]	$1/2^-$	$3/2^-$	$1/2^+$	$1/2^+$	$3/2^+$
Aliev *et al.* [59]	$1/2^-$		$3/2^-$		
B. Chen, X. Liu [60]	$1/2^-$	$3/2^-$	$5/2^-$	$1/2^-$	$3/2^-$
H. Chen *et al.* [43]	$1/2^-$	$1/2^-$	$1/2^-$ or $1/2^+$		$3/2^+$
Cheng, Chiang [61]	$1/2^-$	$3/2^-$	$5/2^-$	$1/2^+$	$3/2^+$
Faustov, Galkin [62]	$3/2^-$	$5/2^-$	$3/2^-$	$1/2^+$	$3/2^+$
Huang *et al.* [63]					$1/2^-$
Jia *et al.* [64]	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
Karliner, Rosner [65]: (i)	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
(ii)	$3/2^-$	$3/2^-$	$5/2^-$	$1/2^+$	$3/2^+$
Padmanath *et al.* [66]	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
Santopinto *et al.* [67]	$1/2^-$	$3/2^-$	$1/2^-$	$3/2^-$	$5/2^-$
K. Wang *et al.* [68]	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$	$1/2^+$ or $3/2^+$
W. Wang, R.L. Zhu [69]	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
Z. Wang [70]	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
Z. Wang *et al.* [71]	$1/2^-$			$3/2^-$ or $1/2^+$	$3/2^+$
Yang, H. Chen [72]	$1/2^-$ or $3/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
Z. Zhao *et al.* [73]: (i)	$1/2^+$	$5/2^+$	$3/2^-$	$3/2^-$	$5/2^+$
(ii)	$3/2^+$	$7/2^+$	$5/2^-$	$5/2^-$	$7/2^+$

Hai-Yang Cheng, Chin. J. Phys. 78 (2022) 324-362

LHCb Omegas



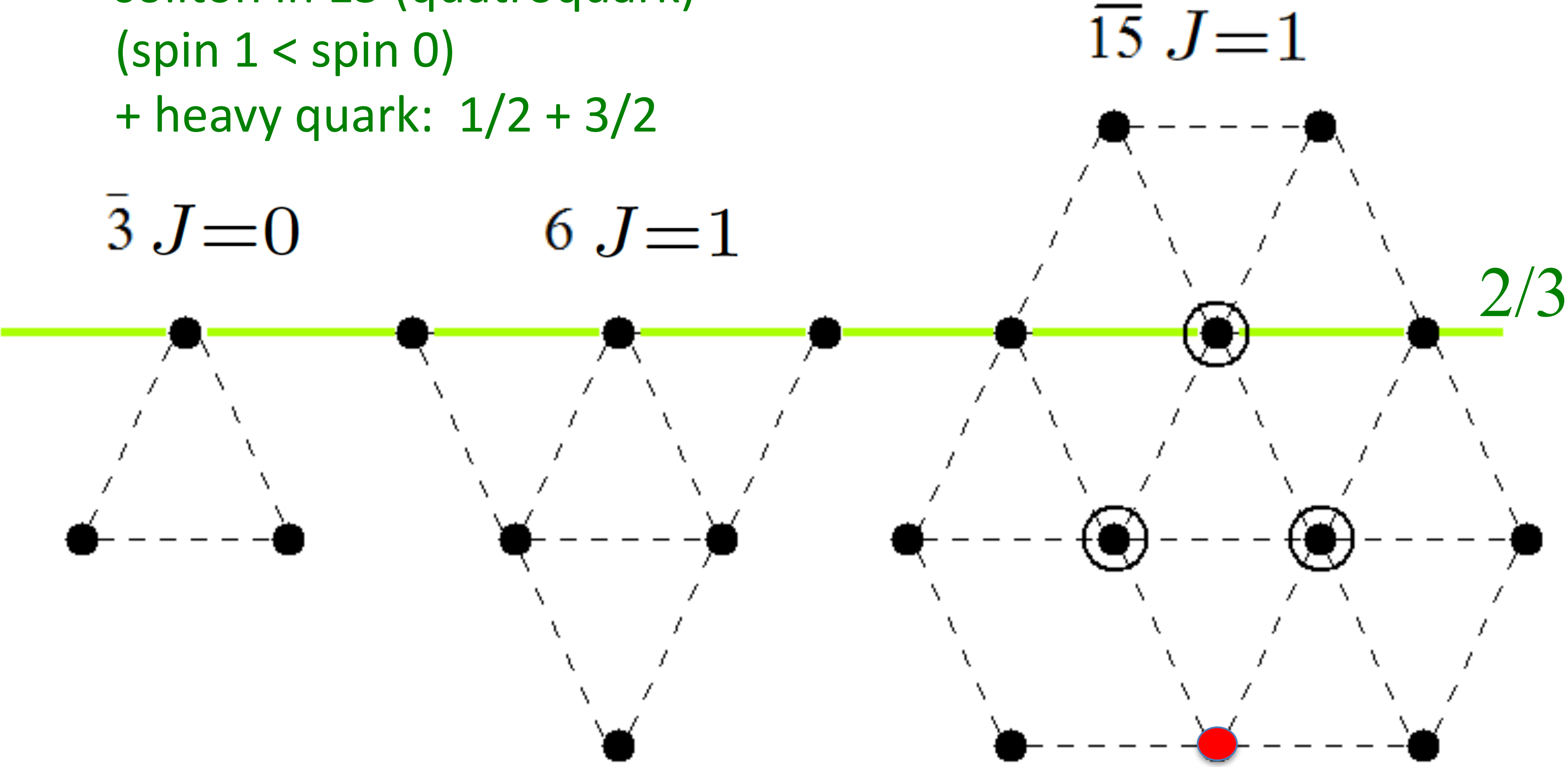
Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
	69 MeV	$< 1.2\,\mathrm{MeV}, 95\%\ \mathrm{CL}$
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5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

not seen by Belle
but not excluded

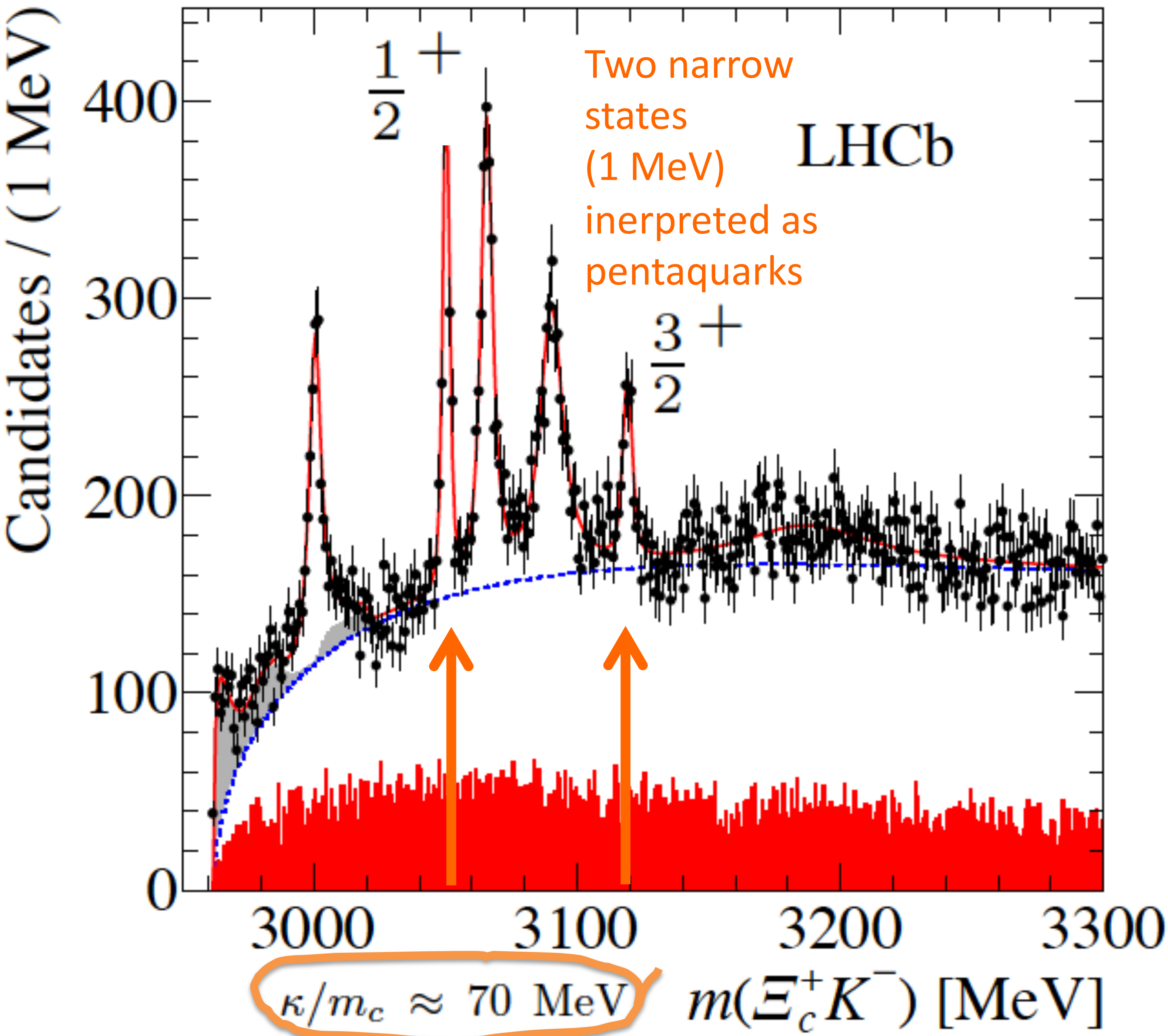
as in the ground state sextet! → $\overline{15}$

LHCb Omegas

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]



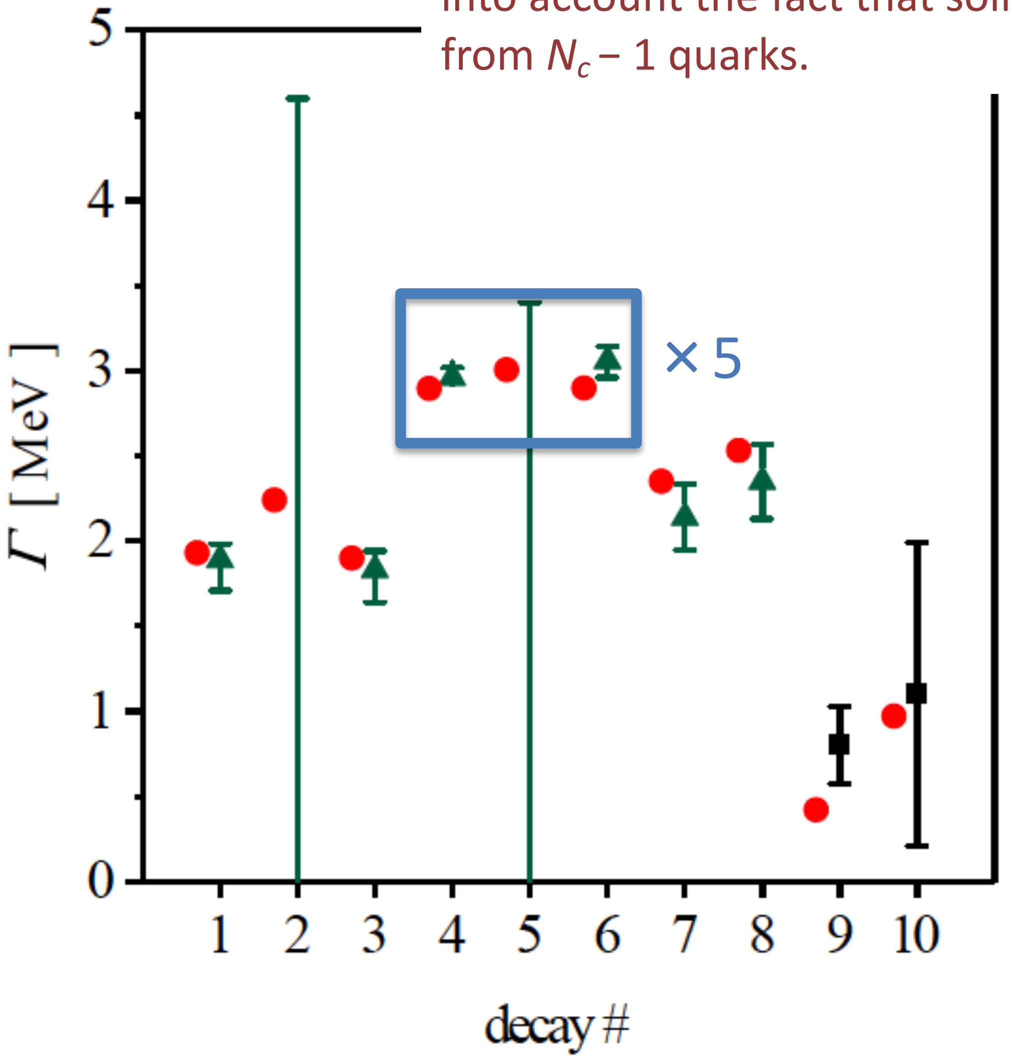
Two narrow states (1 MeV) inerpreted as pentaquarks

$\kappa/m_c \approx 70$ MeV

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

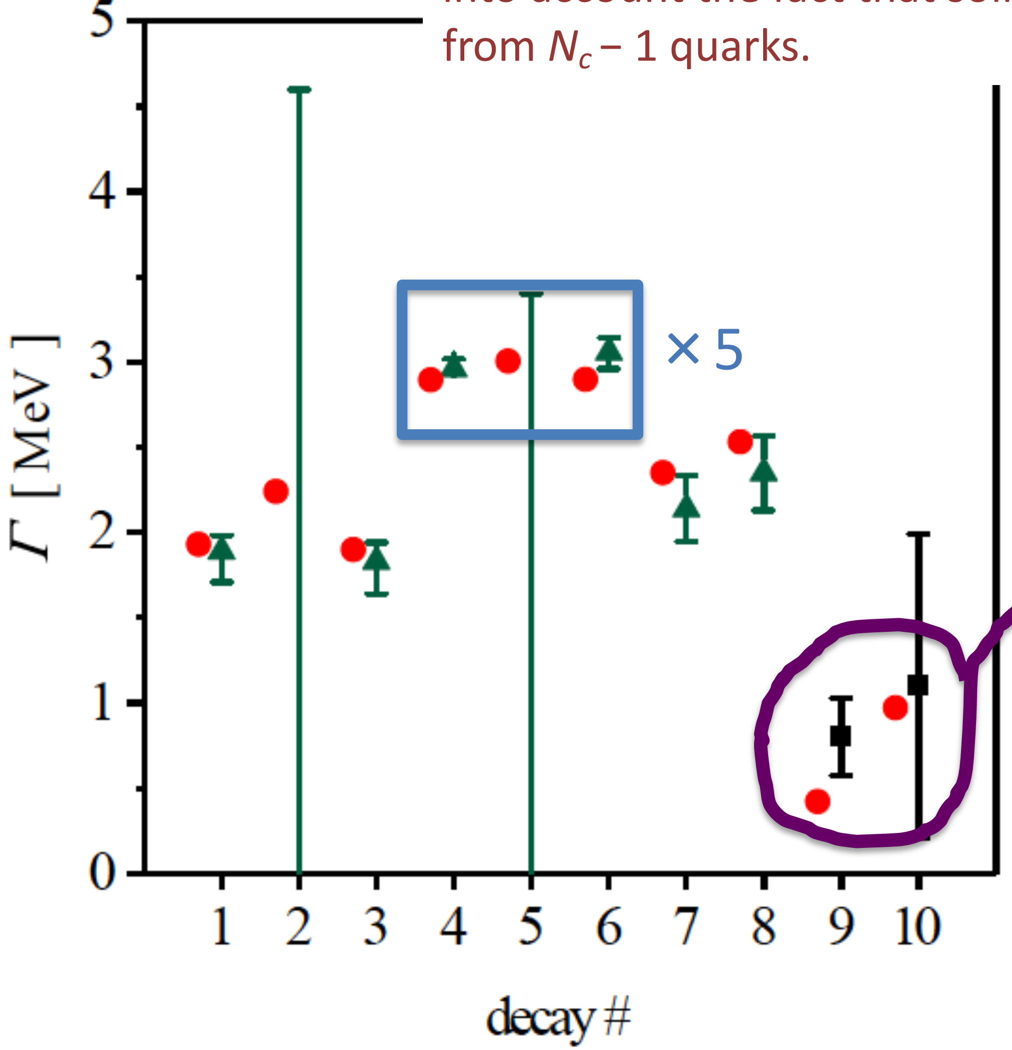
with one adjustable parameter that takes into account the fact that soliton is built up from $N_c - 1$ quarks.



Charm decay widths

1. $\Sigma_c^{++}(1/2) \to \Lambda_c^{+} + \pi^{+}$
2. $\Sigma_c^{+}(1/2) \to \Lambda_c^{+} + \pi^{0}$
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. $\Xi_c^{+}(3/2) \to \Xi_c + \pi$
8. $\Xi_c^{0}(3/2) \to \Xi_c + \pi$
9. $\Omega_c^{0}(1/2)$ – total
10. $\Omega_c^{0}(3/2)$ – total

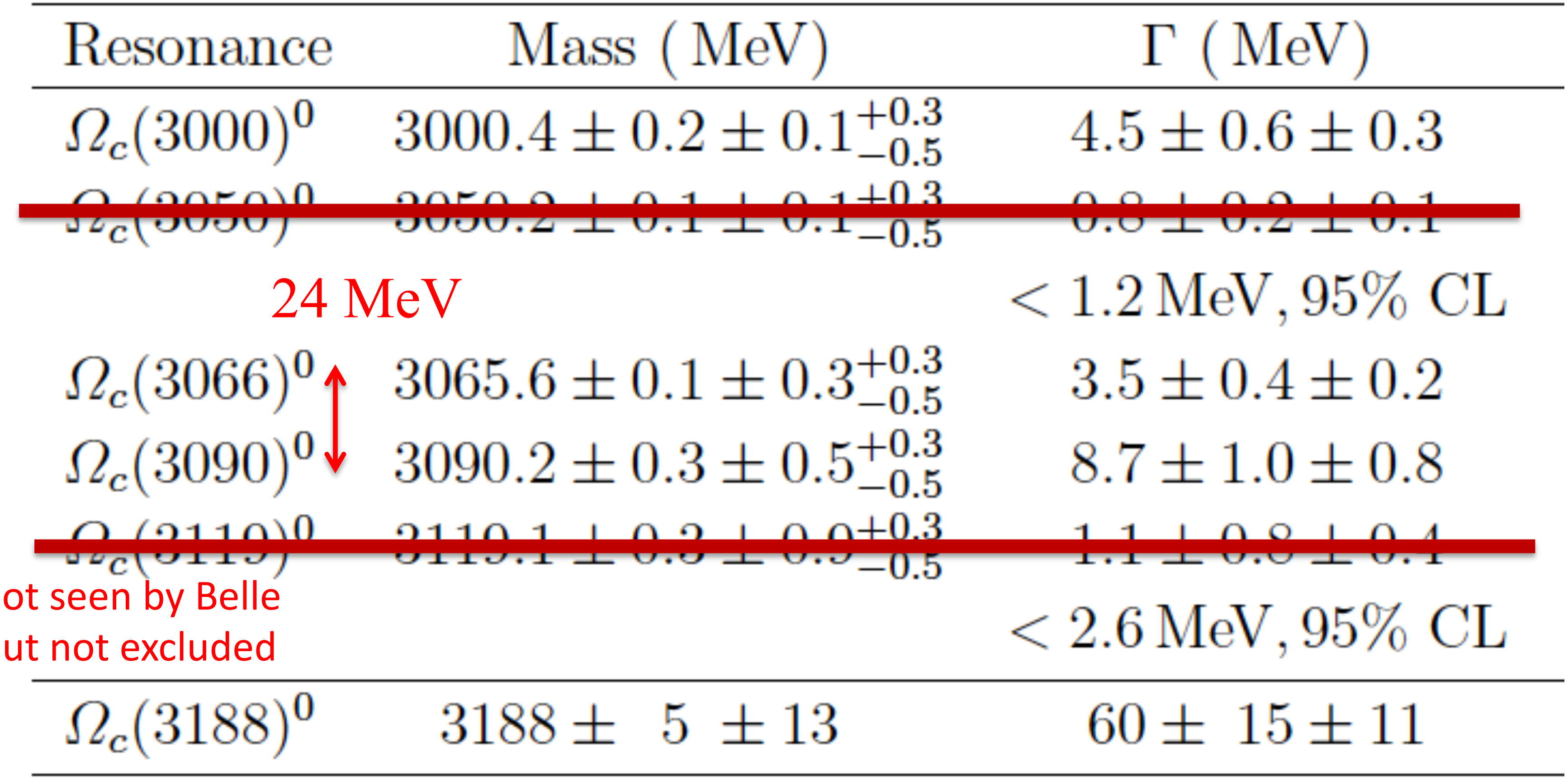
with one adjustable parameter that takes into account the fact that soliton is built up from $N_c - 1$ quarks.



numerical coincidence?

or there is a good reason

LHCb Omegas

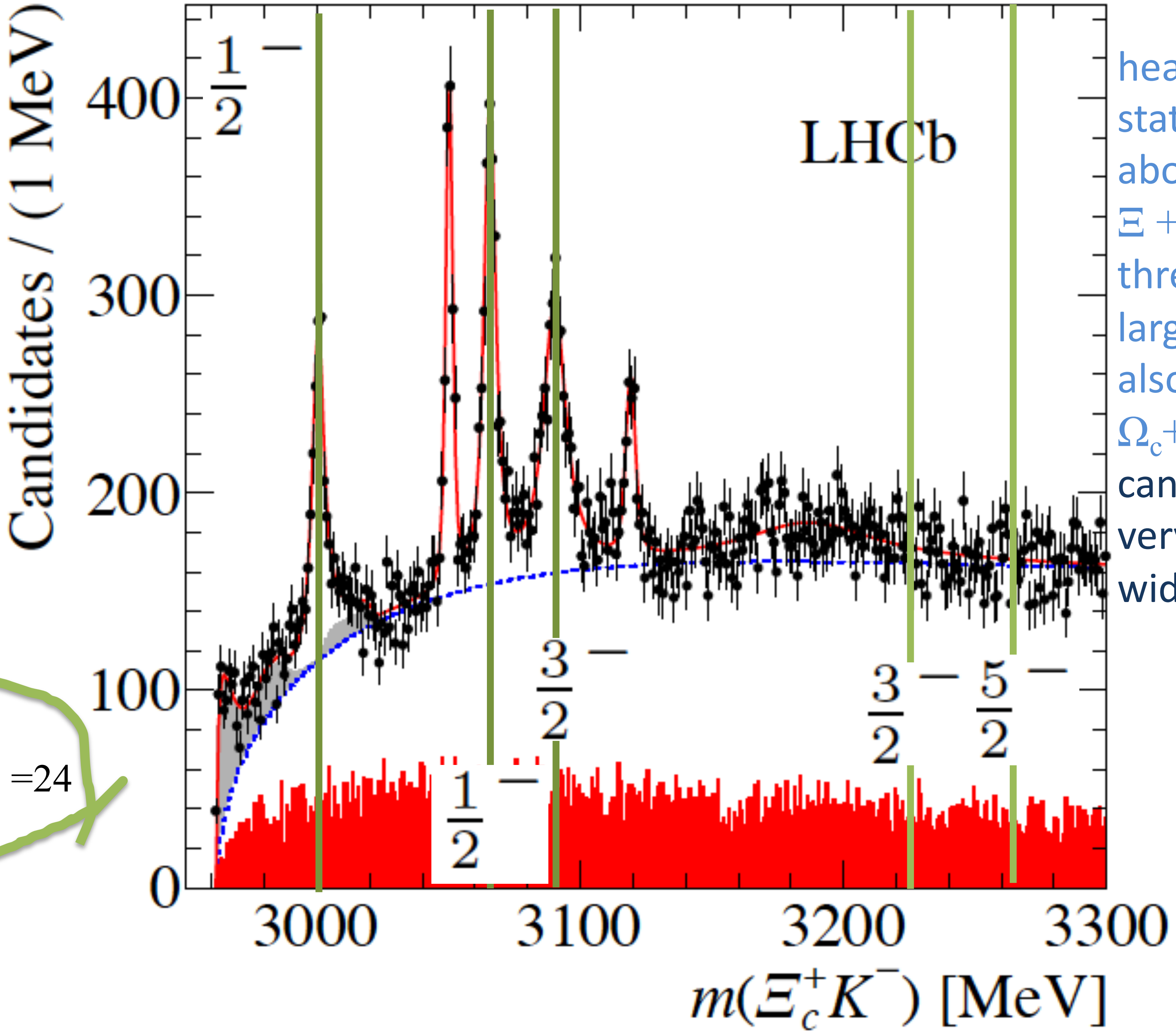


Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
~~$\Omega_c(3050)^0$~~	~~$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$~~	~~$0.8 \pm 0.2 \pm 0.1$~~
		$< 1.2\,\mathrm{MeV}, 95\%\ \mathrm{CL}$
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$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

24 MeV

not seen by Belle
but not excluded

Recall that h.f. splitting for negative parity 3bar was 28 – 36 MeV

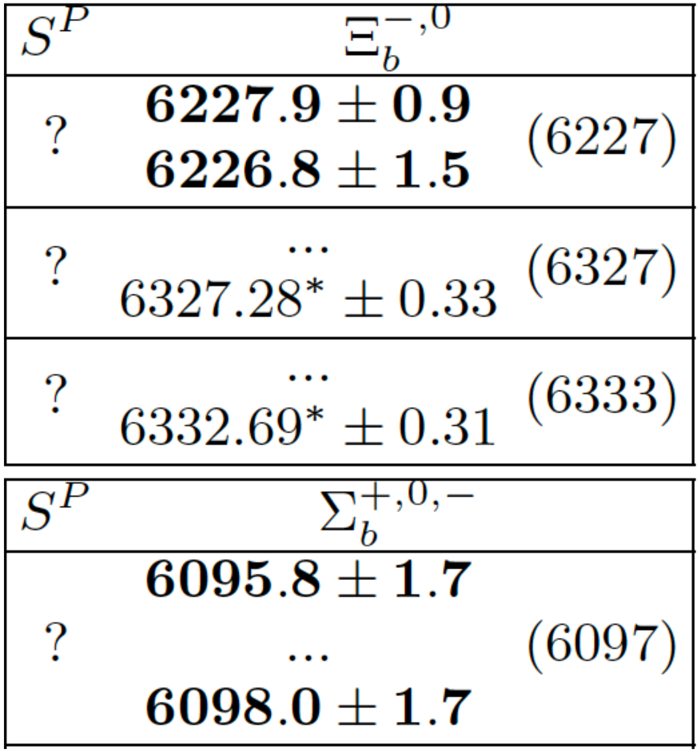


heavy states above $\Xi + D$ threshold, large p.s. also to $\Omega_c + \pi$, can be very wide

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

Possible scenarios for remaining sextet states

Use also beaty hadrons (unknown SU(3) assignement) as input:



S^P	$\Xi_b^{-,0}$	
?	$\mathbf{6227.9 \pm 0.9}$ $\mathbf{6226.8 \pm 1.5}$	(6227)
?	$\ldots$ $6327.28^* \pm 0.33$	(6327)
?	$\ldots$ $6332.69^* \pm 0.31$	(6333)

S^P	$\Sigma_b^{+,0,-}$	
?	$\mathbf{6095.8 \pm 1.7}$ $\ldots$ $\mathbf{6098.0 \pm 1.7}$	(6097)

states with * are from LHCb Phys.Rev.D 103 (2021) 1, 012004

Possible scenario

J	S	Σ_b	Ξ_b	Ω_b	Σ_c	Ξ_c	Ω_c
0	1/2	**6097**	6238	6378	2719	2859	**3000**
1	1/2	6198	**6327**	6457	2807	2937	**3066**
	3/2	6204	**6333**	6462	2831	2961	**3090**
2	3/2	6406	6512	6619	3009	3115	3222
	5/2	6415	6521	6628	3049	3155	3262

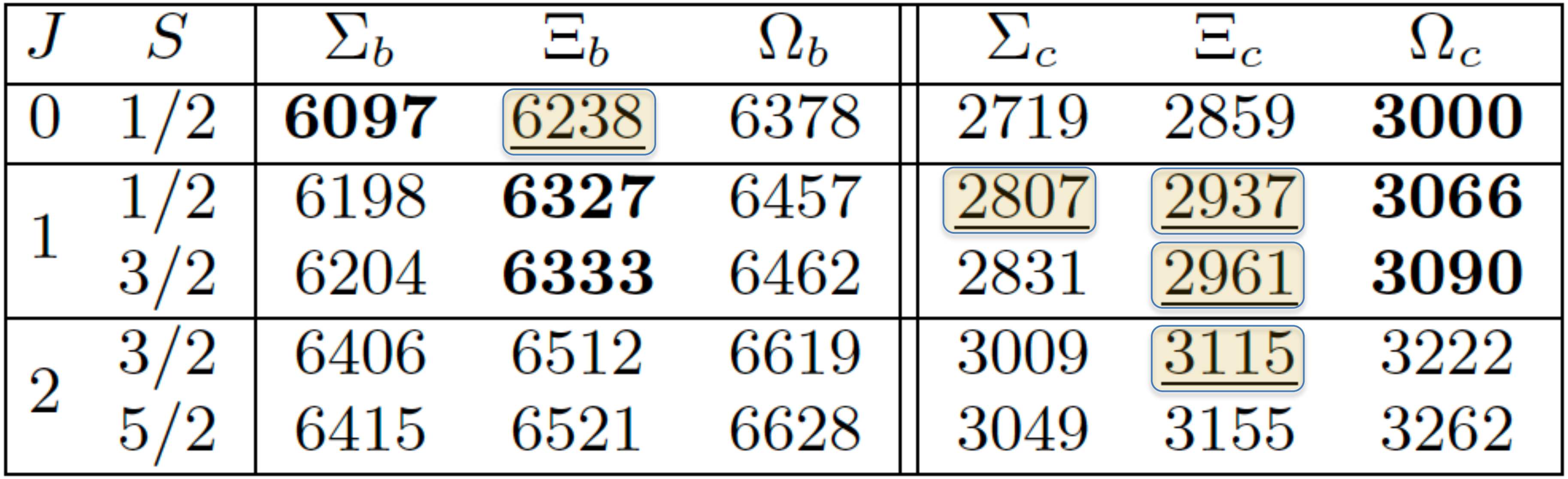
$$\Sigma_c(2800) = \Sigma_c^{1/2^-}(\mathbf{6}', J = 1)\,,$$

$$\Xi_c(2940) = \Xi_c^{1/2^-}(\mathbf{6}', J = 1)\,,$$

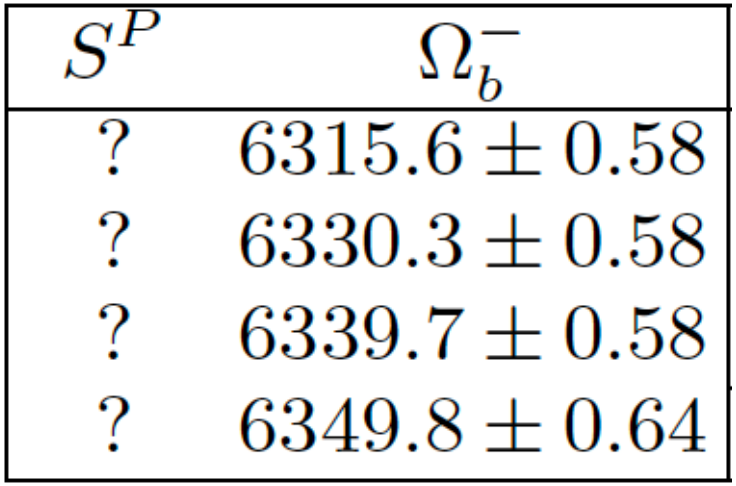
$$\Xi_c(2966) = \Xi_c^{3/2^-}(\mathbf{6}', J = 1)\,,$$

$$\Xi_c(3123) = \Xi_c^{3/2^-}(\mathbf{6}', J = 2)\,.$$

Problem



J	S	Σ_b	Ξ_b	Ω_b	Σ_c	Ξ_c	Ω_c
0	1/2	**6097**	6238	6378	2719	2859	**3000**
1	1/2	6198	**6327**	6457	2807	2937	**3066**
	3/2	6204	**6333**	6462	2831	2961	**3090**
2	3/2	6406	6512	6619	3009	3115	3222
	5/2	6415	6521	6628	3049	3155	3262

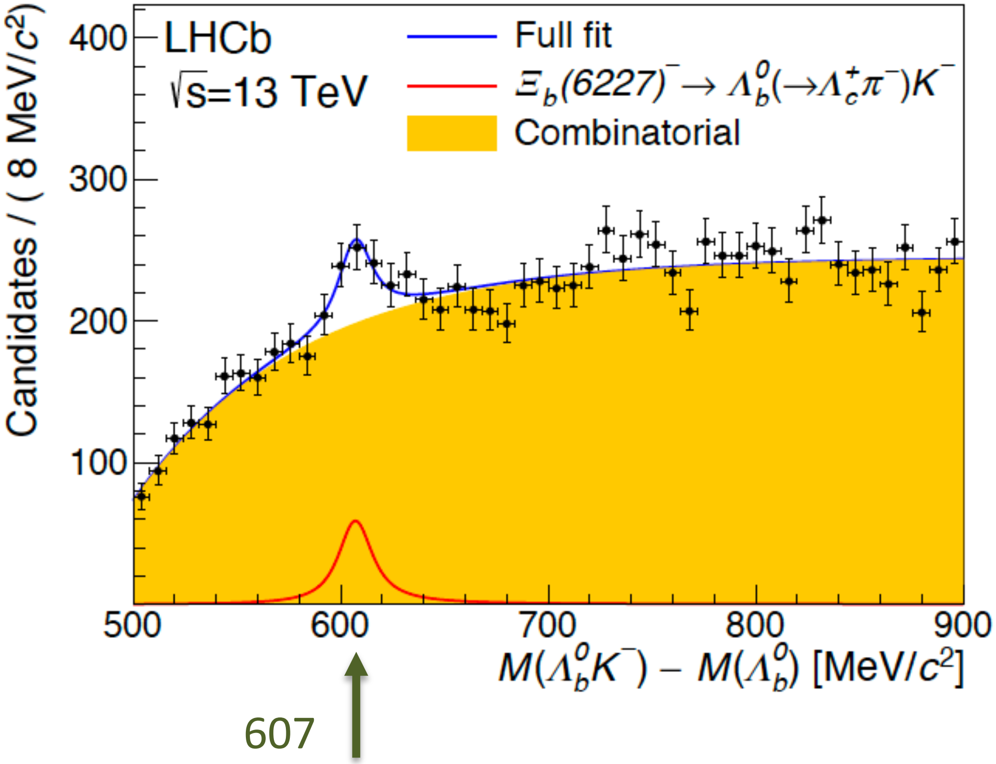


S^P	Ω_b^-
?	6315.6 ± 0.58
?	6330.3 ± 0.58
?	6339.7 ± 0.58
?	6349.8 ± 0.64

Not listed in PDG summary, too dense if compared with the charm sector

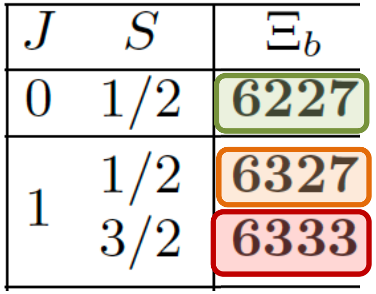
Decays

J	S	Ξ_b
0	1/2	6227
1	1/2	6327
	3/2	6333

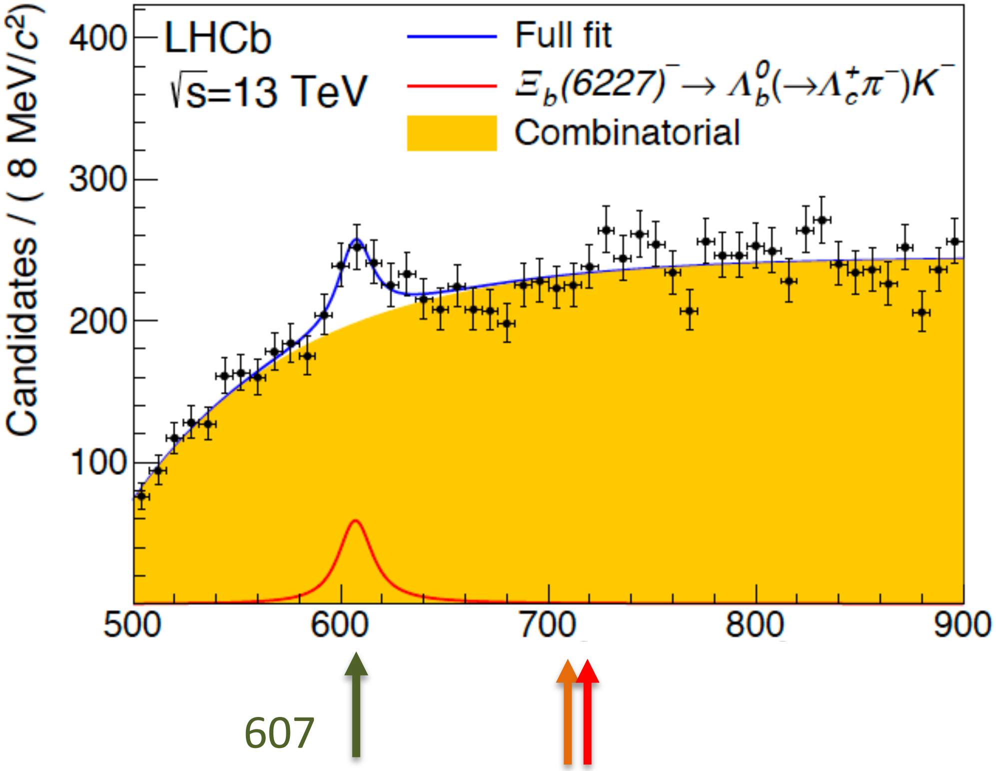


607

Missing states?

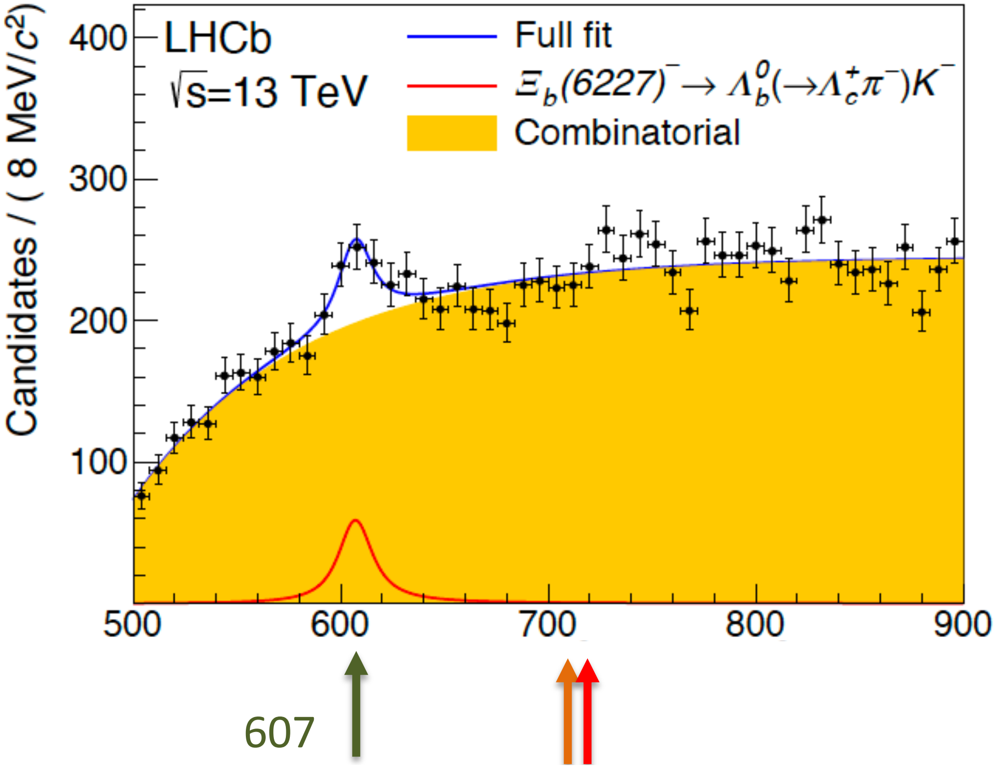


J	S	Ξ_b
0	1/2	6227
1	1/2	6327
	3/2	6333



Decays

J	S	Ξ_b
0	1/2	6227
1	1/2	6327
	3/2	6333

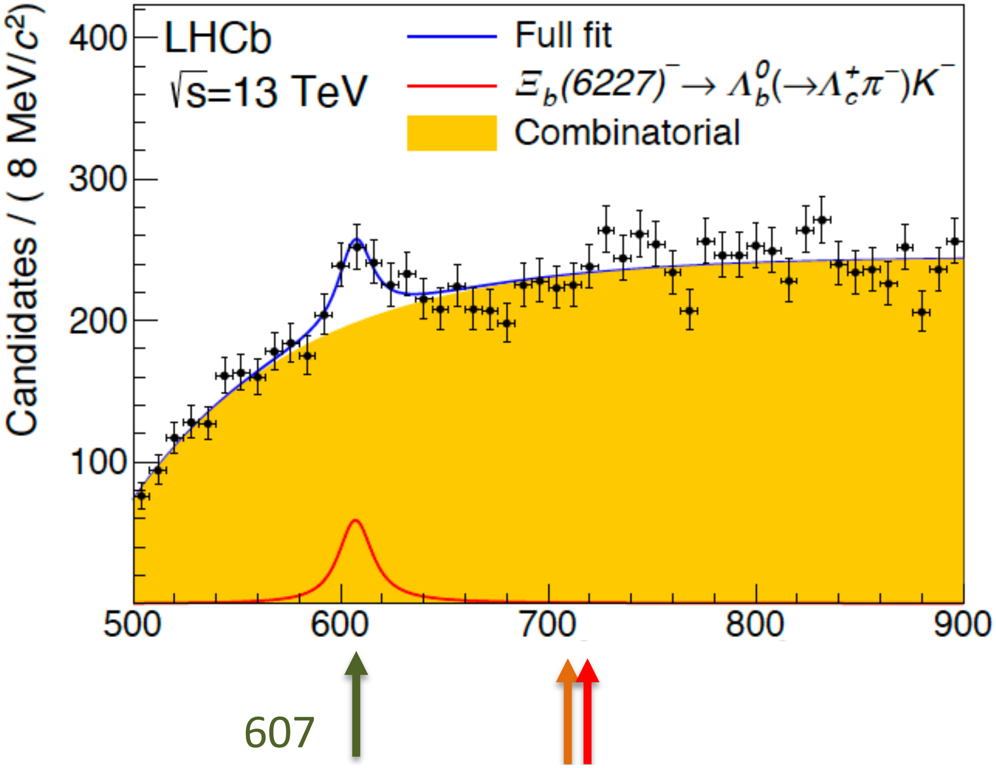


	$\overline{\mathbf{3}}(J^P=0^+)$	$\mathbf{6}(J^P=1^+)$	$\overline{\mathbf{3}}'(J^P=1^-)$
$\overline{\mathbf{3}}'(J^P=1^-)$	$1/m_Q$	S	–
$\mathbf{6}'(J^P=0^-)$	S	$1/m_Q$	P
$\mathbf{6}'(J^P=1^-)$	$1/m_Q$	S	P
$\mathbf{6}'(J^P=2^-)$	D	D	P

Decays

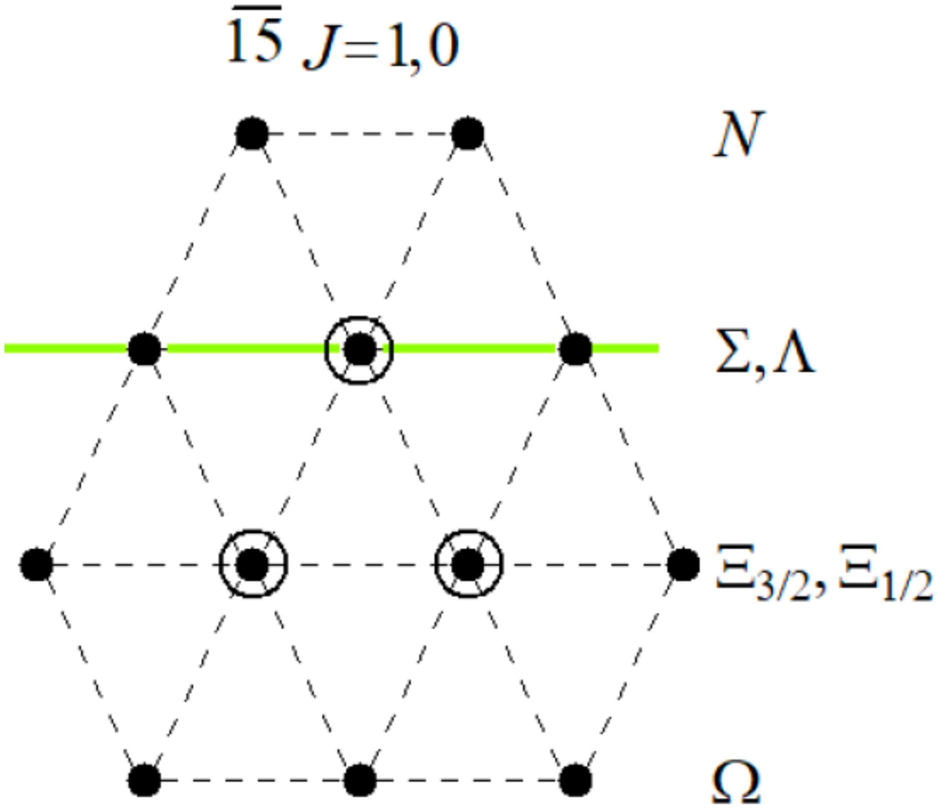
J	S	Ξ_b
0	1/2	**6227**
1	1/2	**6327**
	3/2	**6333**

$\Xi_b(6327)$ and $\Xi_b(6333)$ have been found in 3-body decays to $\Lambda_b^0 K^- \pi^+$



	$\overline{\mathbf{3}}(J^P=0^+)$	$\mathbf{6}(J^P=1^+)$	$\overline{\mathbf{3}}'(J^P=1^-)$
$\overline{\mathbf{3}}'(J^P=1^-)$	$1/m_Q$	S	–
$\mathbf{6}'(J^P=0^-)$	S	$1/m_Q$	P
$\mathbf{6}'(J^P=1^-)$	$1/m_Q$	S	P
$\mathbf{6}'(J^P=2^-)$	D	D	P

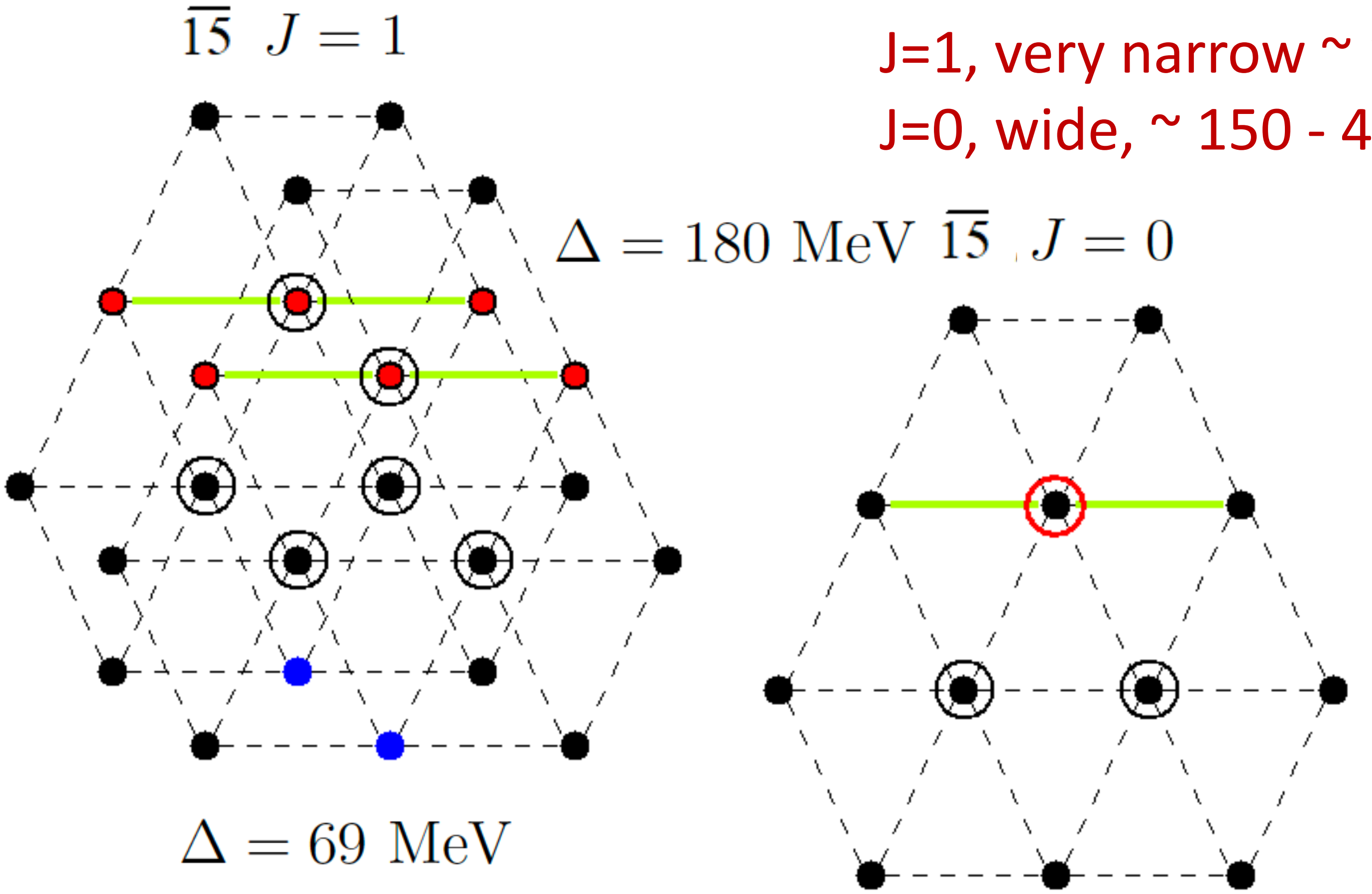
Exotica



Exotica

Three exotic multiplets:

J=1, very narrow ~ 1 MeV
J=0, wide, ~ 150 - 400 MeV



Exotica

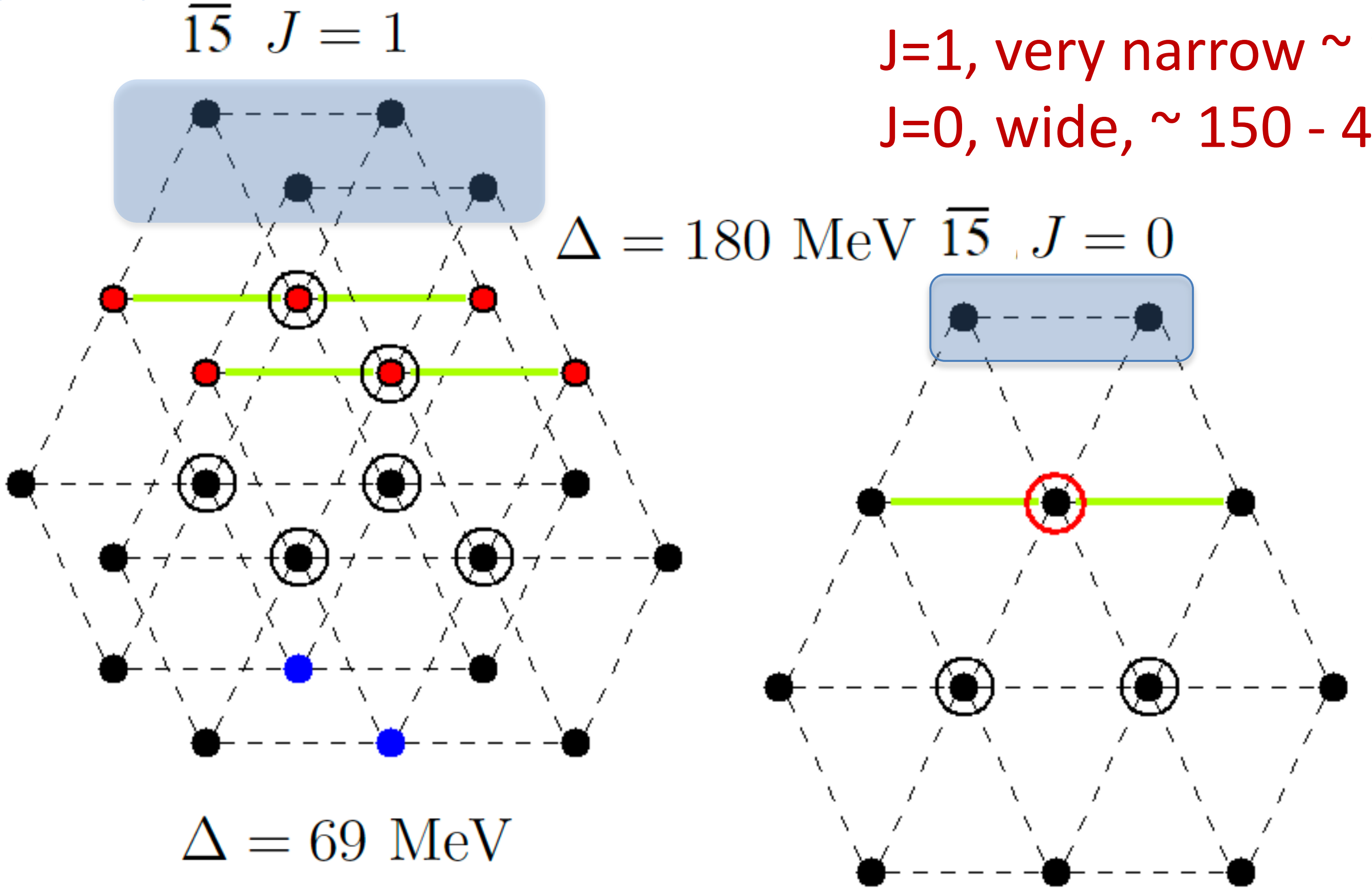
Three exotic multiplets:

J=1, very narrow ~ 1 MeV

J=0, wide, ~ 150 - 400 MeV

Stable!

decaying weakly



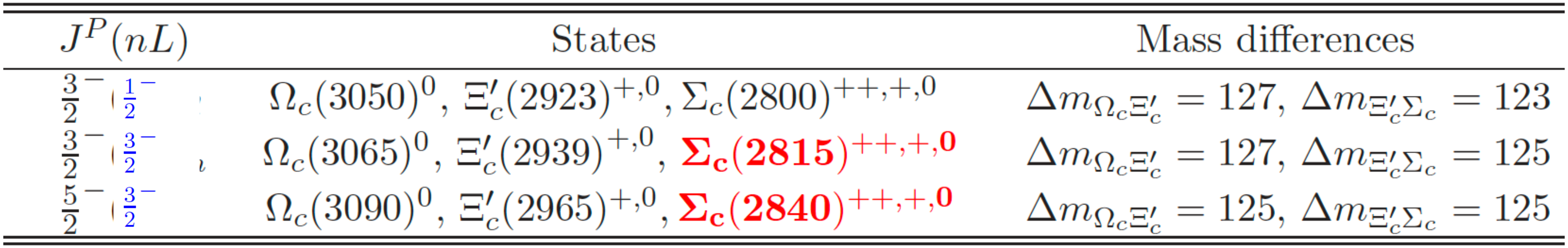
Thank You

Backup slides

Alternative assignements of 6

H. Y. Cheng, Chin. J. Phys. 78, 324-362 (2022)

R. Bijker at al. Phys.Rev.D 105 (2022) 7, 074029



$J^P(nL)$	States	Mass differences
$\frac{3}{2}^-$ ($\frac{1}{2}^-$	$\Omega_c(3050)^0$, $\Xi'_c(2923)^{+,0}$, $\Sigma_c(2800)^{++,+,0}$	$\Delta m_{\Omega_c\Xi'_c} = 127$, $\Delta m_{\Xi'_c\Sigma_c} = 123$
$\frac{3}{2}^-$ ($\frac{3}{2}^-$	$\Omega_c(3065)^0$, $\Xi'_c(2939)^{+,0}$, $\mathbf{\Sigma_c(2815)^{++,+,0}}$	$\Delta m_{\Omega_c\Xi'_c} = 127$, $\Delta m_{\Xi'_c\Sigma_c} = 125$
$\frac{5}{2}^-$ ($\frac{3}{2}^-$	$\Omega_c(3090)^0$, $\Xi'_c(2965)^{+,0}$, $\mathbf{\Sigma_c(2840)^{++,+,0}}$	$\Delta m_{\Omega_c\Xi'_c} = 125$, $\Delta m_{\Xi'_c\Sigma_c} = 125$

Alternative assignements of 6

H. Y. Cheng, Chin. J. Phys. 78, 324-362 (2022)

R. Bijker at al. Phys.Rev.D 105 (2022) 7, 074029

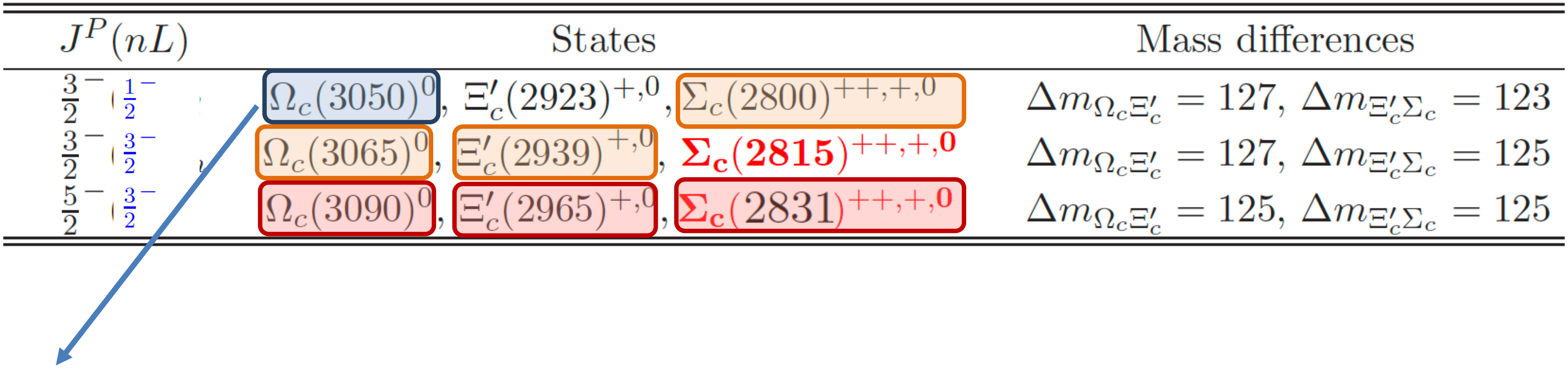
$J^P(nL)$	States	Mass differences
$\frac{3}{2}^-$ ($\frac{1}{2}^-$	$\Omega_c(3050)^0$, $\Xi_c'(2923)^{+,0}$, $\Sigma_c(2800)^{++,+,0}$	$\Delta m_{\Omega_c\Xi_c'} = 127$, $\Delta m_{\Xi_c'\Sigma_c} = 123$
$\frac{3}{2}^-$ ($\frac{3}{2}^-$	$\Omega_c(3065)^0$, $\Xi_c'(2939)^{+,0}$, $\boldsymbol{\Sigma_c(2815)^{++,+,0}}$	$\Delta m_{\Omega_c\Xi_c'} = 127$, $\Delta m_{\Xi_c'\Sigma_c} = 125$
$\frac{5}{2}^-$ ($\frac{3}{2}^-$	$\Omega_c(3090)^0$, $\Xi_c'(2965)^{+,0}$, $\boldsymbol{\Sigma_c(2840)^{++,+,0}}$	$\Delta m_{\Omega_c\Xi_c'} = 125$, $\Delta m_{\Xi_c'\Sigma_c} = 125$

$$M'^{\,\mathbf{6}\,J=0}_{Q\,Y} = \mathcal{M}'_{\mathbf{6}Q} - 2\frac{a_1}{I_1'} + \left(\delta_{\mathbf{6}} - \frac{3}{10}\delta\right)Y,$$

$$M'^{\,\mathbf{6}\,J=1}_{Q\,Y} = \mathcal{M}'_{\mathbf{6}Q} - \frac{a_1}{I_1'} + \left(\delta_{\mathbf{6}} - \frac{3}{20}\delta\right)Y + \frac{\kappa'}{m_Q}\begin{cases} -2/3 & \text{for} \quad S = 1/2 \\ +1/3 & \text{for} \quad S = 3/2 \end{cases}$$

$$M'^{\,\mathbf{6}\,J=2}_{Q\,Y} = \mathcal{M}'_{\mathbf{6}Q} + \frac{a_1}{I_1'} + \left(\delta_{\mathbf{6}} + \frac{3}{20}\delta\right)Y + \frac{\kappa'}{m_Q}\begin{cases} -1 & \text{for} \quad S = 3/2 \\ +2/3 & \text{for} \quad S = 5/2 \end{cases}$$

Assignements of 6

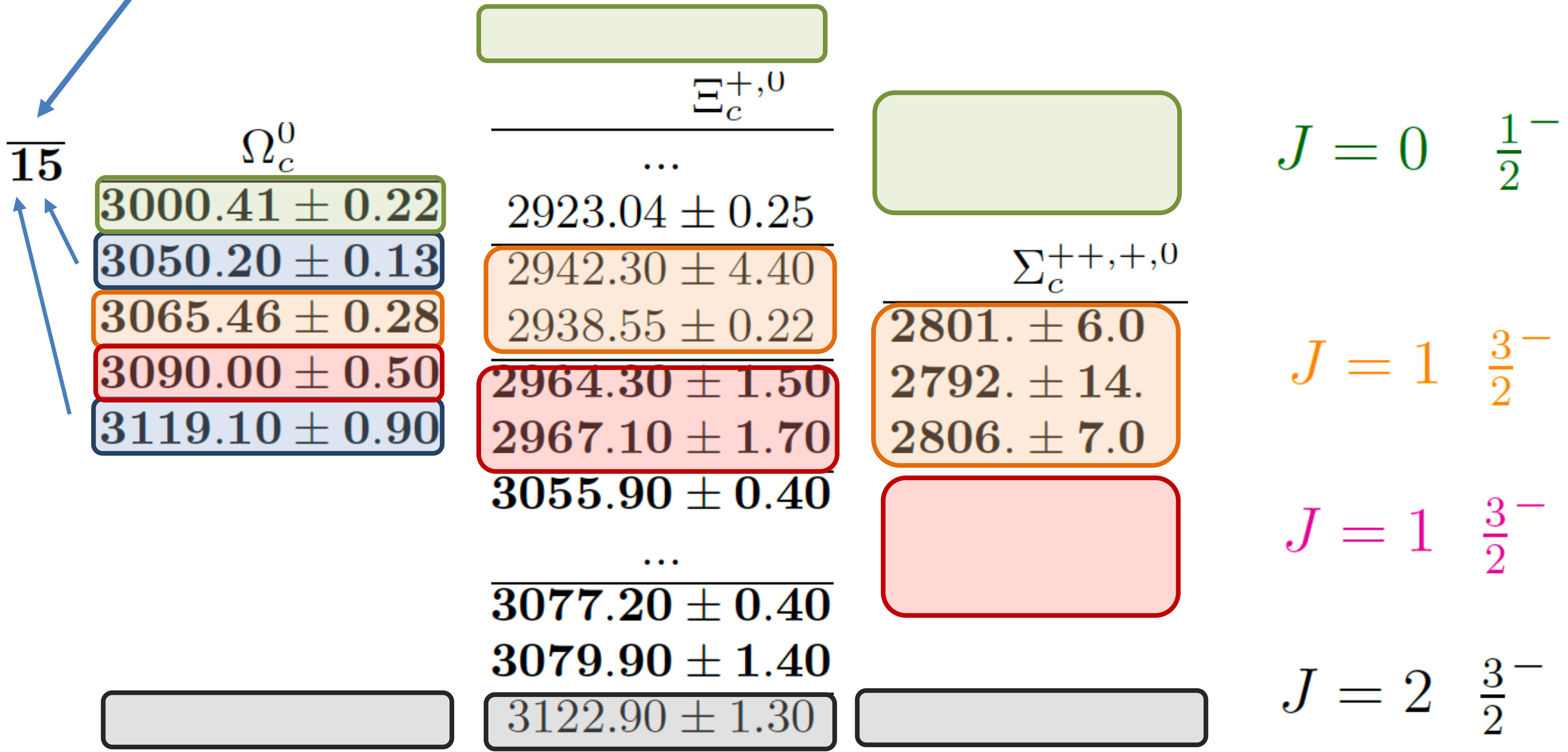


$J^P(nL)$	States	Mass differences
$\frac{3}{2}^{-}$ ($\frac{1}{2}^{-}$	$\Omega_c(3050)^0$, $\Xi'_c(2923)^{+,0}$, $\Sigma_c(2800)^{++,+,0}$	$\Delta m_{\Omega_c\Xi'_c} = 127$, $\Delta m_{\Xi'_c\Sigma_c} = 123$
$\frac{3}{2}^{-}$ ($\frac{3}{2}^{-}$	$\Omega_c(3065)^0$, $\Xi'_c(2939)^{+,0}$, $\mathbf{\Sigma_c(2815)^{++,+,0}}$	$\Delta m_{\Omega_c\Xi'_c} = 127$, $\Delta m_{\Xi'_c\Sigma_c} = 125$
$\frac{5}{2}^{-}$ ($\frac{3}{2}^{-}$	$\Omega_c(3090)^0$, $\Xi'_c(2965)^{+,0}$, $\Sigma_c(2831)^{++,+,0}$	$\Delta m_{\Omega_c\Xi'_c} = 125$, $\Delta m_{\Xi'_c\Sigma_c} = 125$

$\overline{\mathbf{15}}$

Assignements of 6

$J^P(nL)$	States	Mass differences
$\frac{3}{2}^{-}$ ($\frac{1}{2}^{-}$	$\Omega_c(3050)^0$, $\Xi_c'(2923)^{+,0}$, $\Sigma_c(2800)^{++,+,0}$	$\Delta m_{\Omega_c \Xi_c'} = 127$, $\Delta m_{\Xi_c' \Sigma_c} = 123$
$\frac{3}{2}^{-}$ ($\frac{3}{2}^{-}$	$\Omega_c(3065)^0$, $\Xi_c'(2939)^{+,0}$, $\mathbf{\Sigma_c(2815)^{++,+,0}}$	$\Delta m_{\Omega_c \Xi_c'} = 127$, $\Delta m_{\Xi_c' \Sigma_c} = 125$
$\frac{5}{2}^{-}$ ($\frac{3}{2}^{-}$	$\Omega_c(3090)^0$, $\Xi_c'(2965)^{+,0}$, $\mathbf{\Sigma_c(2831)^{++,+,0}}$	$\Delta m_{\Omega_c \Xi_c'} = 125$, $\Delta m_{\Xi_c' \Sigma_c} = 125$



$\overline{\mathbf{15}}$

Ω_c^0

$\mathbf{3000.41 \pm 0.22}$

$\mathbf{3050.20 \pm 0.13}$

$\mathbf{3065.46 \pm 0.28}$

$\mathbf{3090.00 \pm 0.50}$

$\mathbf{3119.10 \pm 0.90}$

$\Xi_c^{+,0}$

...

2923.04 ± 0.25

2942.30 ± 4.40

2938.55 ± 0.22

$\mathbf{2964.30 \pm 1.50}$

$\mathbf{2967.10 \pm 1.70}$

$\mathbf{3055.90 \pm 0.40}$

...

$\mathbf{3077.20 \pm 0.40}$

$\mathbf{3079.90 \pm 1.40}$

3122.90 ± 1.30

$\Sigma_c^{++,+,0}$

$\mathbf{2801. \pm 6.0}$

$\mathbf{2792. \pm 14.}$

$\mathbf{2806. \pm 7.0}$

$J = 0$ $\frac{1}{2}^{-}$

$J = 1$ $\frac{3}{2}^{-}$

$J = 1$ $\frac{3}{2}^{-}$

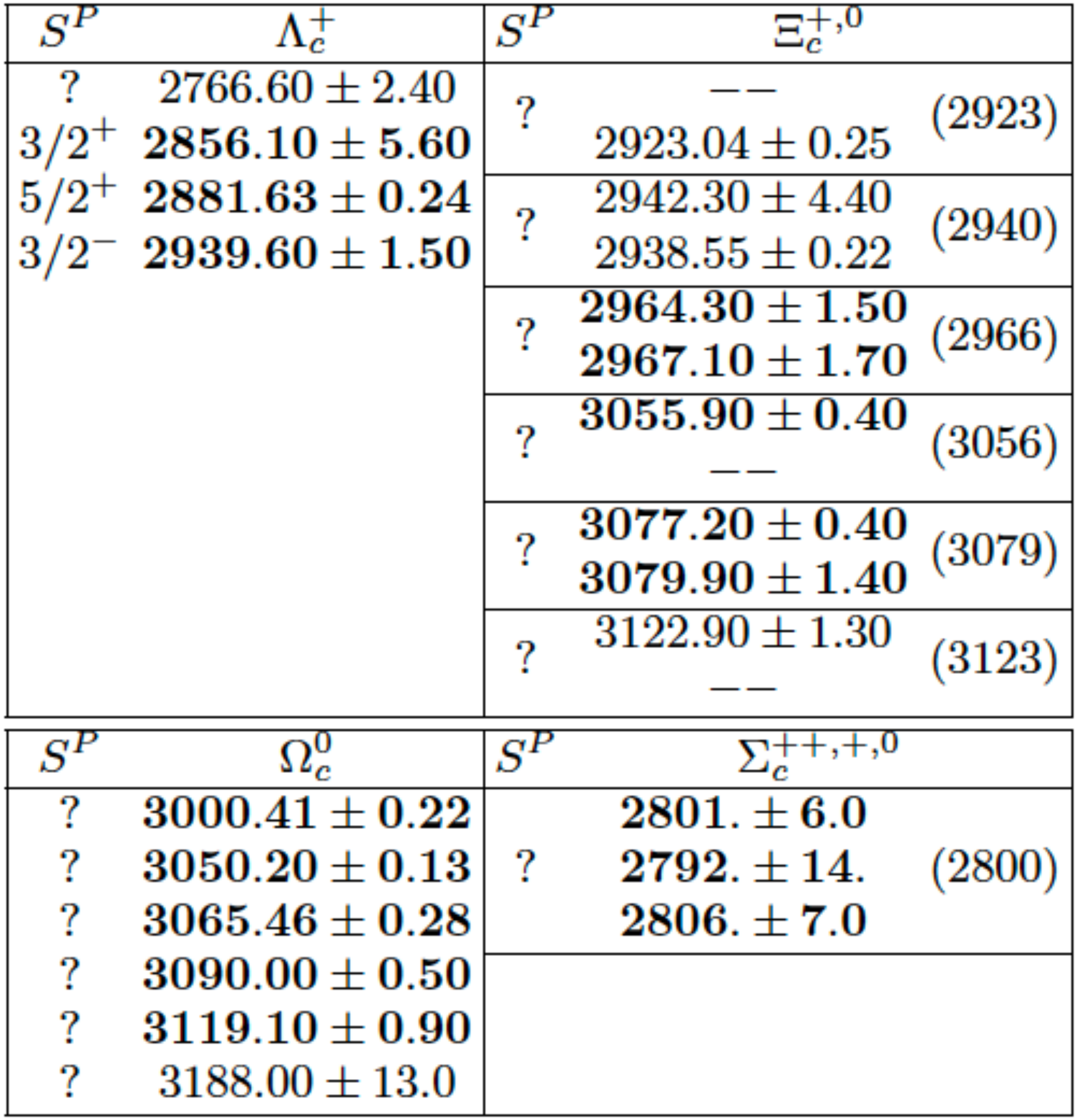
$J = 2$ $\frac{3}{2}^{-}$

only excited antitriplet

excited antitriplet or sextet

only sextet

only sextet



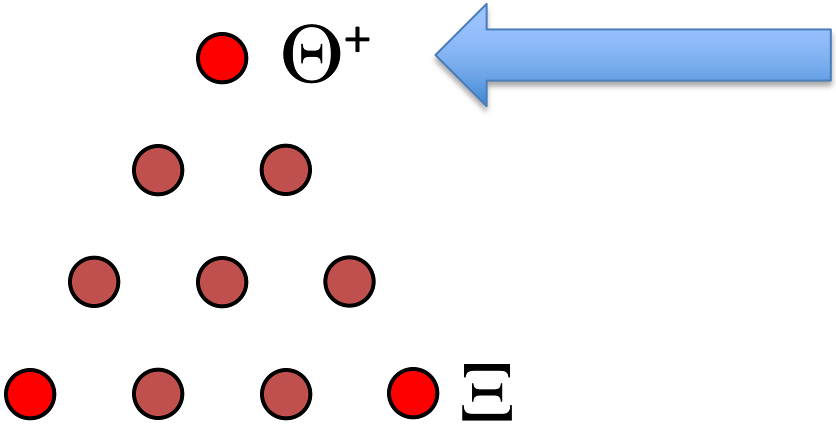
S^P	Λ_c^+	S^P	$\Xi_c^{+,0}$	
?	2766.60 ± 2.40	?	$--$	(2923)
$3/2^+$	**2856.10 ± 5.60**		2923.04 ± 0.25	
$5/2^+$	**2881.63 ± 0.24**	?	2942.30 ± 4.40	(2940)
$3/2^-$	**2939.60 ± 1.50**		2938.55 ± 0.22	
		?	**2964.30 ± 1.50**	(2966)
			2967.10 ± 1.70	
		?	**3055.90 ± 0.40**	(3056)
			$--$	
		?	**3077.20 ± 0.40**	(3079)
			3079.90 ± 1.40	
		?	3122.90 ± 1.30	(3123)
			$--$	

S^P	Ω_c^0	S^P	$\Sigma_c^{++,+,0}$	
?	**3000.41 ± 0.22**	?	**$2801. \pm 6.0$**	(2800)
?	**3050.20 ± 0.13**		**$2792. \pm 14.$**	
?	**3065.46 ± 0.28**		**$2806. \pm 7.0$**	
?	**3090.00 ± 0.50**			
?	**3119.10 ± 0.90**			
?	3188.00 ± 13.0			

TABLE V. Charm baryons with unknown SU(3) assignment.

Suplementary material

What is the experimental status of light pentaquarks today?



July 2003

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

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

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

Physics team goes where no quark has gone before

Quarks

Five alive!

An odd, new subatomic

"pentaquark", has been

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

HIGH-ENERGY PHYSICS

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

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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.

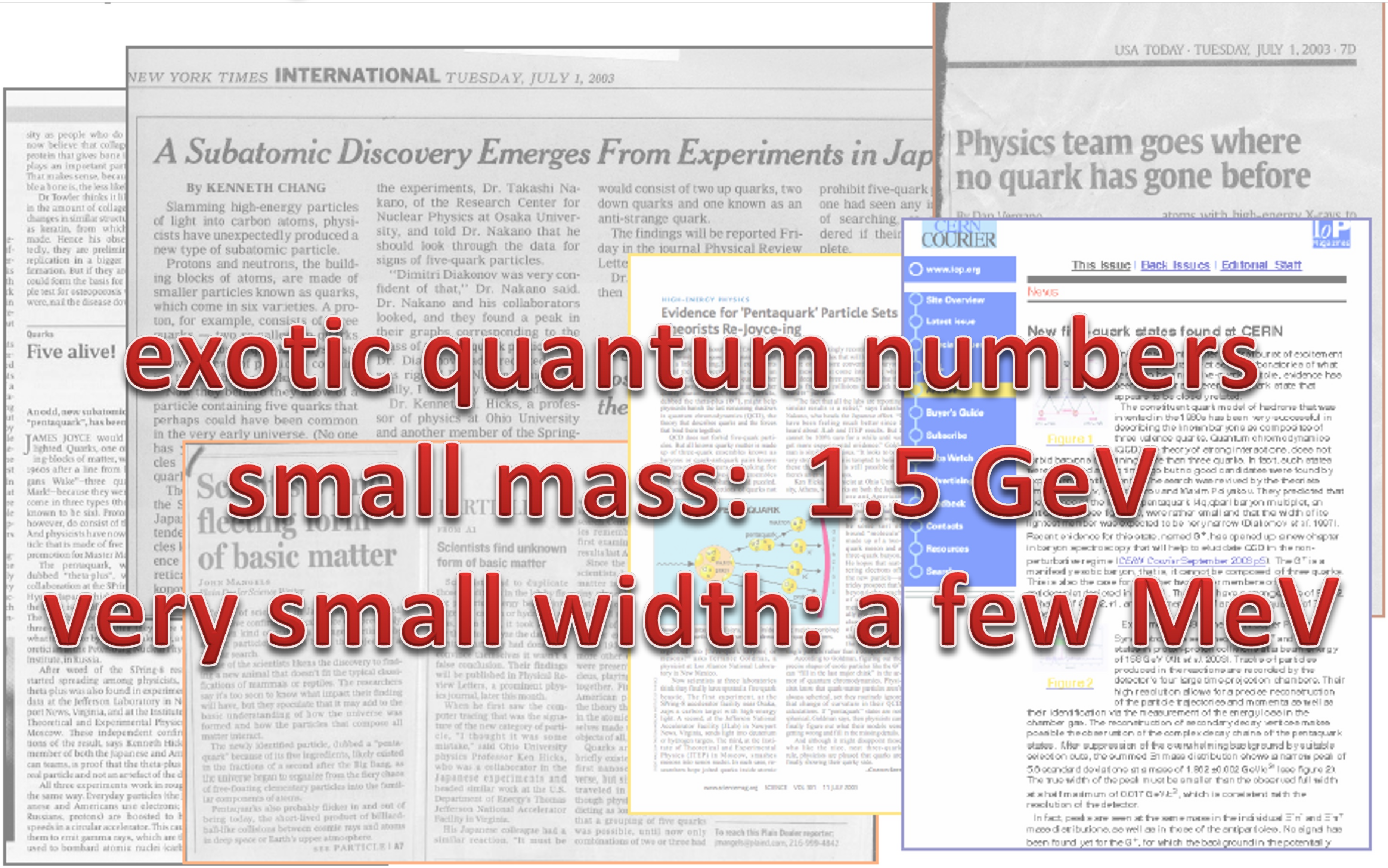
The constituent quark model of hadrons that was invented in the 1960s has been very successful in describing the known baryons as composites of three valence quarks. Quantum chromodynamics (QCD), the theory of strong interactions, does not forbid baryons containing more than three quarks. In fact, such 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 (4q,qbar) 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 a 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

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.

particle containing five quarks that perhaps could have been common in the very early universe.

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

Dr. Kenneth 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

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

Physics team goes where no quark has gone before

Quarks

Five alive!

of basic matter

of the scientists liken 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

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HIGH-ENERGY PHYSICS

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

www.sciencemag.org SCIENCE VOL 301 11 JULY 2003

CERN COURIER

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News

New five-quark states found at CERN

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.

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.

Figure 1

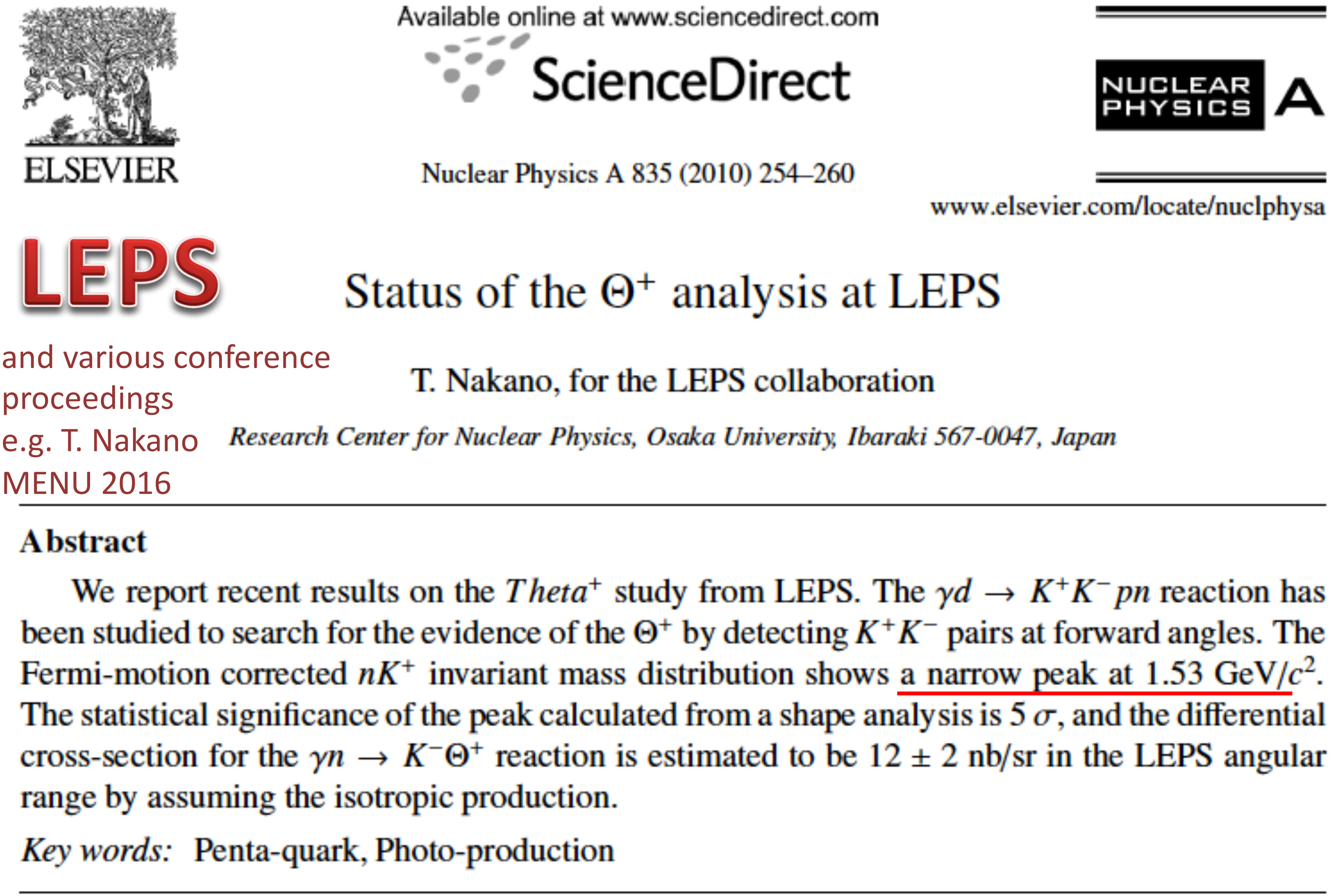
Figure 2

After suppression of the overwhelming background by suitable selection cuts, the summed Ξπ mass distribution shows a narrow peak of 5.6 standard deviations at a mass of 1.862 ±0.002 GeV/c² (see figure 2). The true width of the peak must be smaller than the observed full width at a half maximum of 0.017 GeV/c², which is consistent with the resolution of the detector.

exotic quantum numbers
small mass: 1.5 GeV
very small width: a few MeV

LEPS

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



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Status of the Θ^+ analysis at LEPS

T. Nakano, for the LEPS collaboration

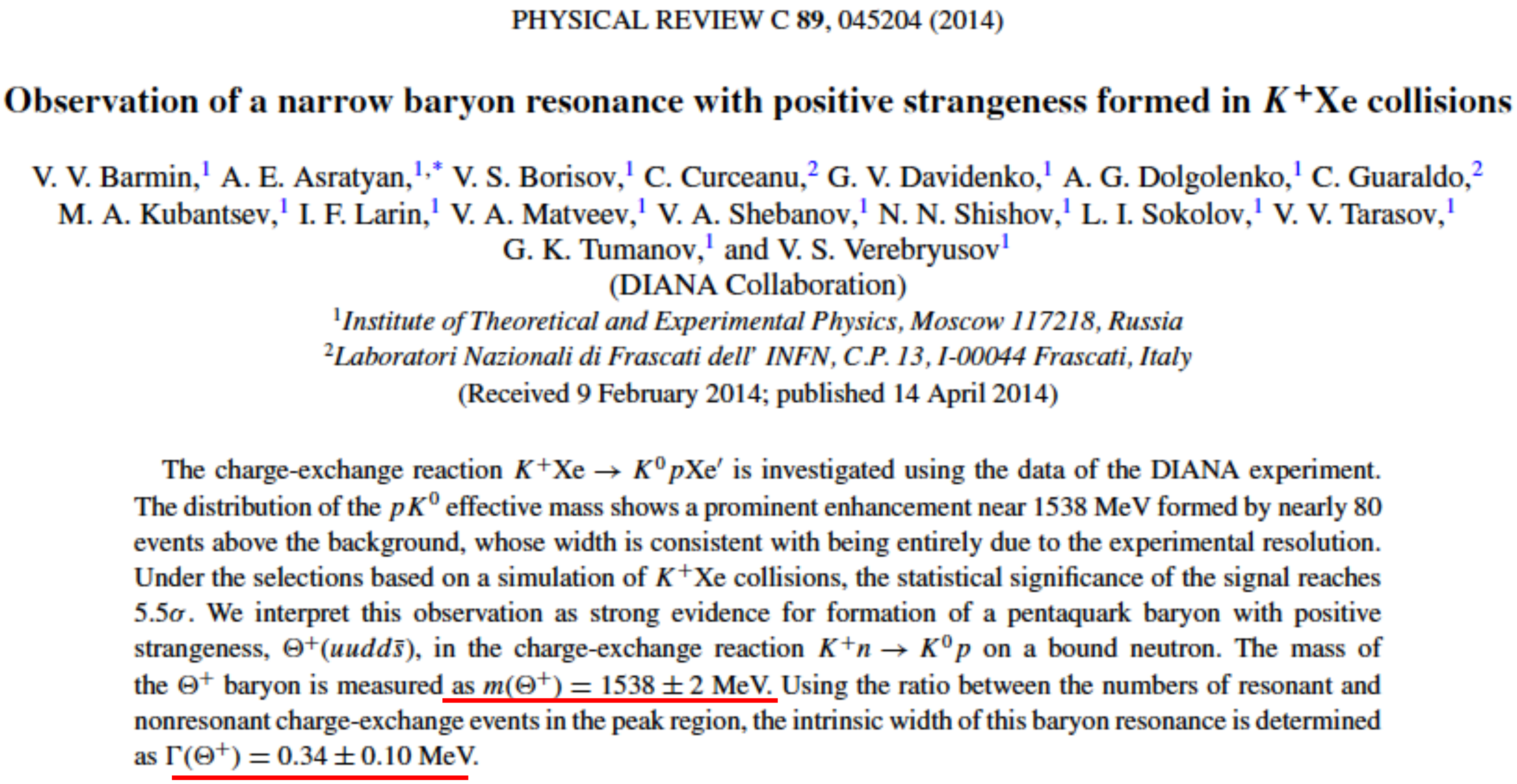
Research Center for Nuclear Physics, Osaka University, Ibaraki 567-0047, Japan

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

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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]
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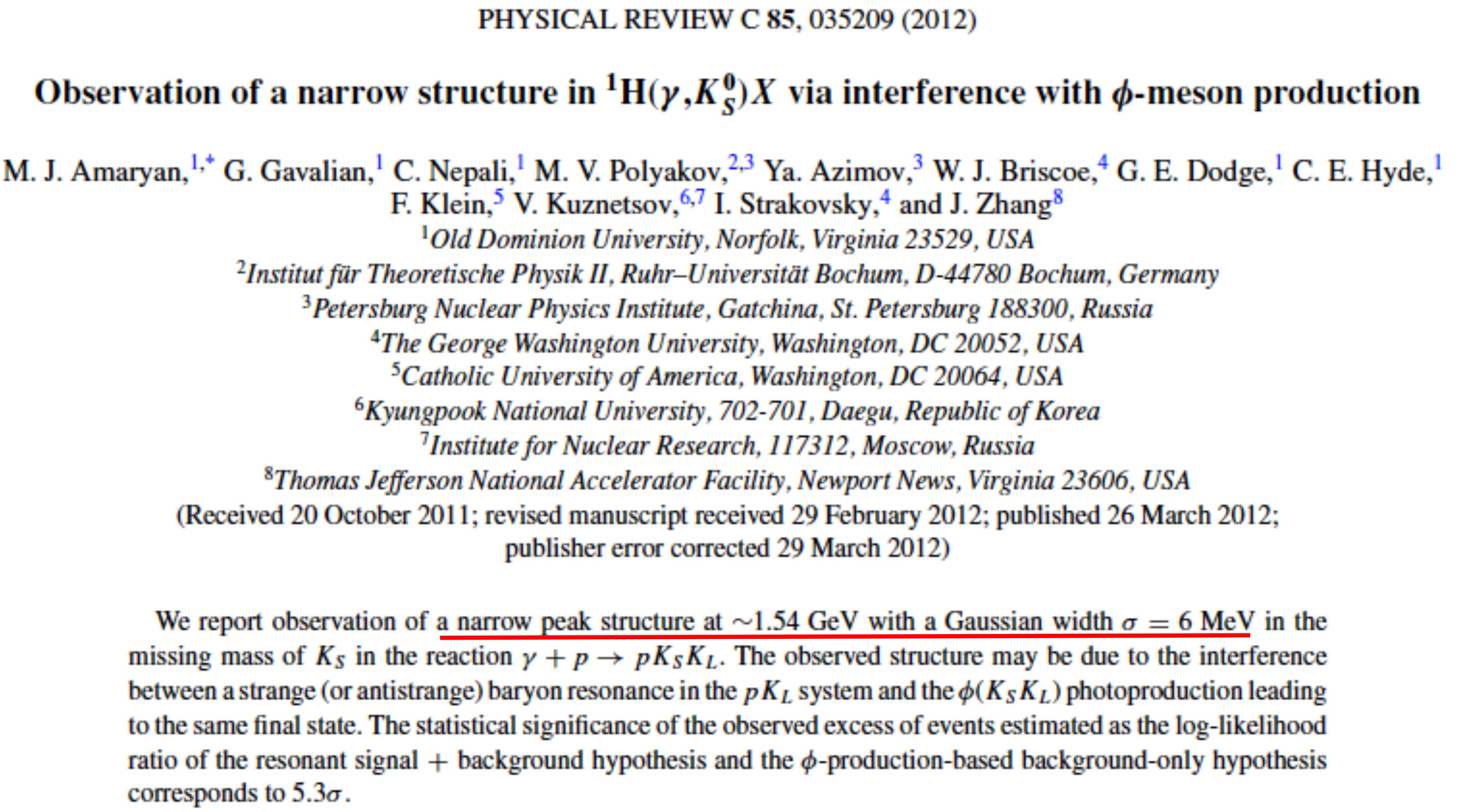
(Received 9 February 2014; published 14 April 2014)

The charge-exchange reaction $K^+\text{Xe} \to K^0 p\text{Xe}'$ 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 $^1\mathrm{H}(\gamma, K^0_S)X$ via interference with ϕ-meson production

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F. Klein,[5] V. Kuznetsov,[6,7] I. Strakovsky,[4] and J. Zhang[8]
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(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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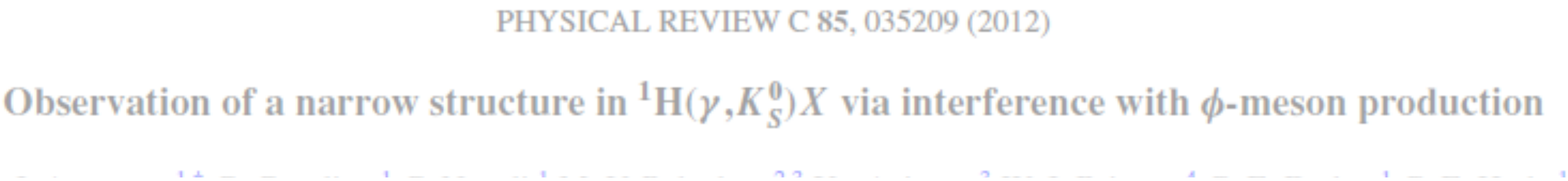
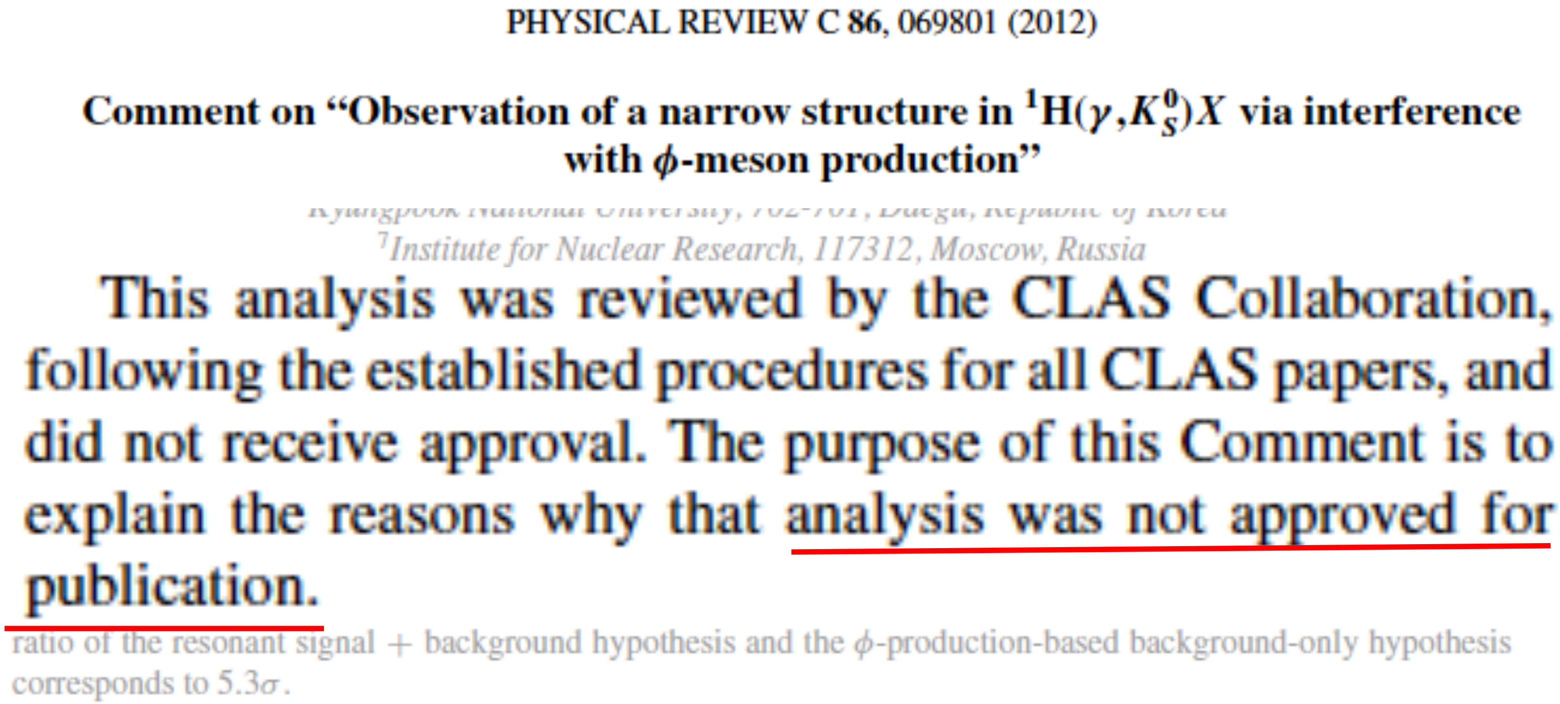


PHYSICAL REVIEW C 85, 035209 (2012)

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



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"

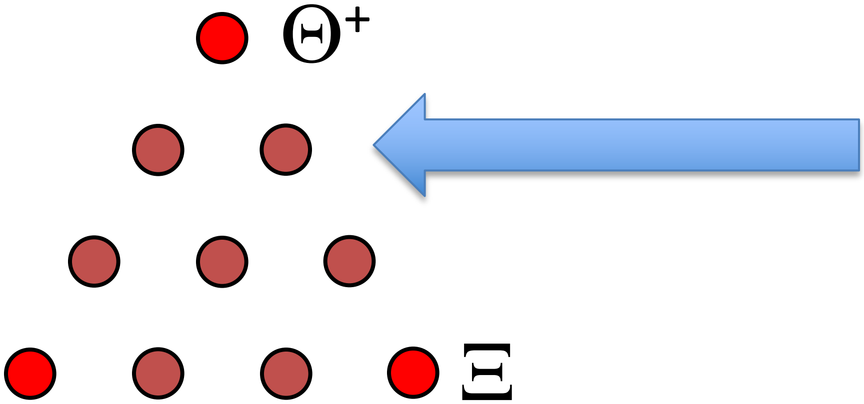
Kyungpook National University, 702-701, Daegu, Republic of Korea

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

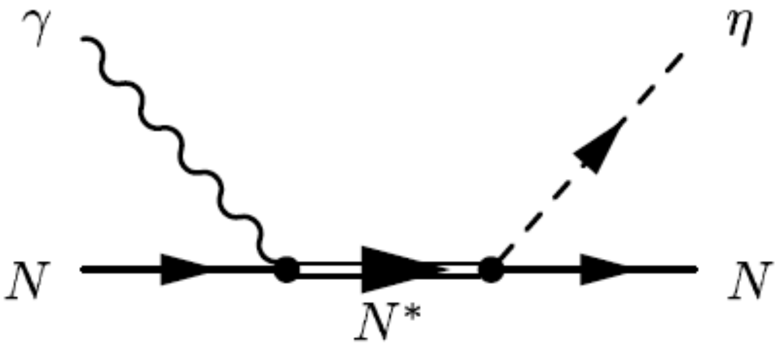
This analysis was reviewed by the CLAS Collaboration, following the established procedures for all CLAS papers, and did not receive approval. The purpose of this Comment is to explain the reasons why that analysis was not approved for publication.

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

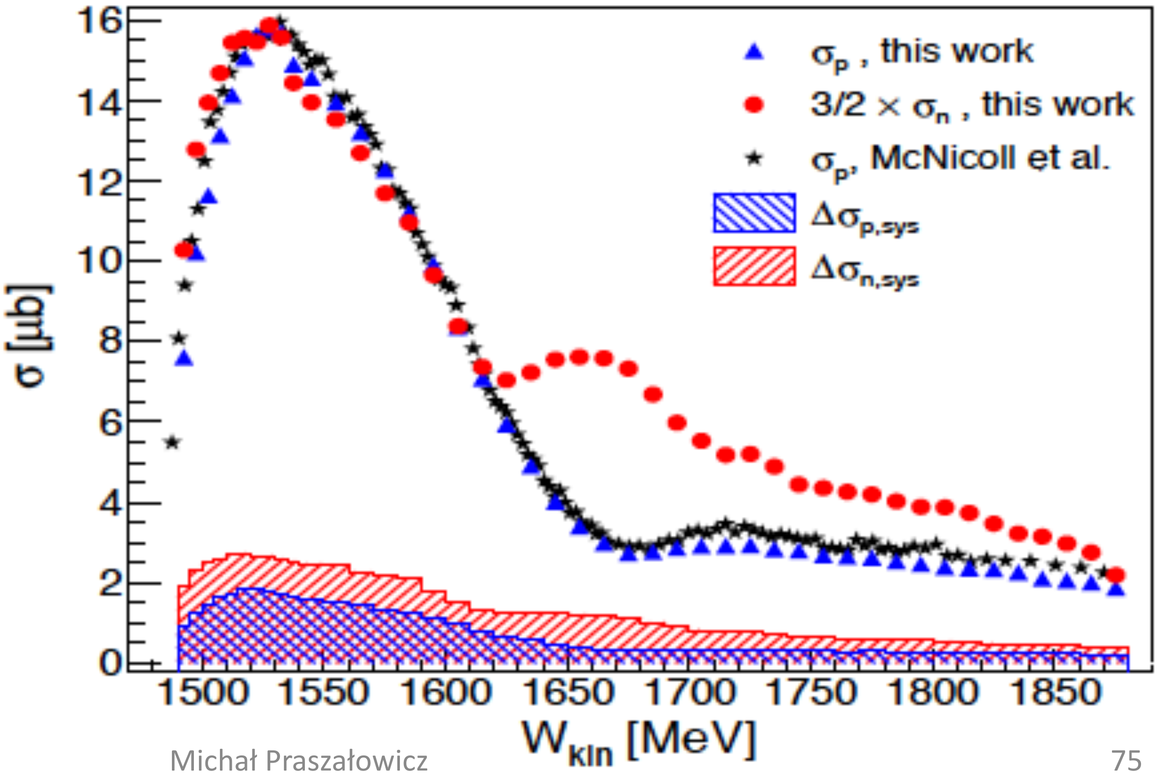
What is the experimental status of light pentaquarks today?



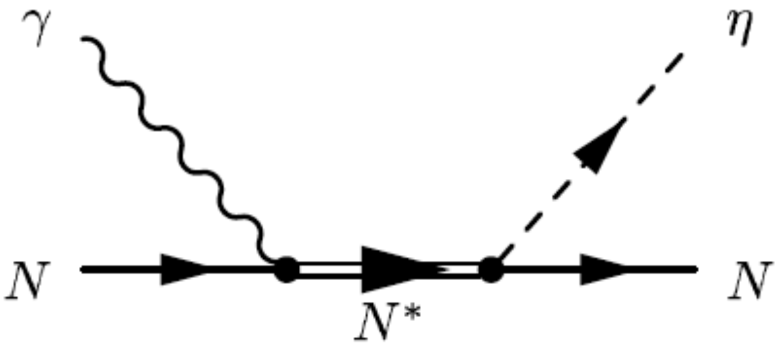
Pentanucleon?



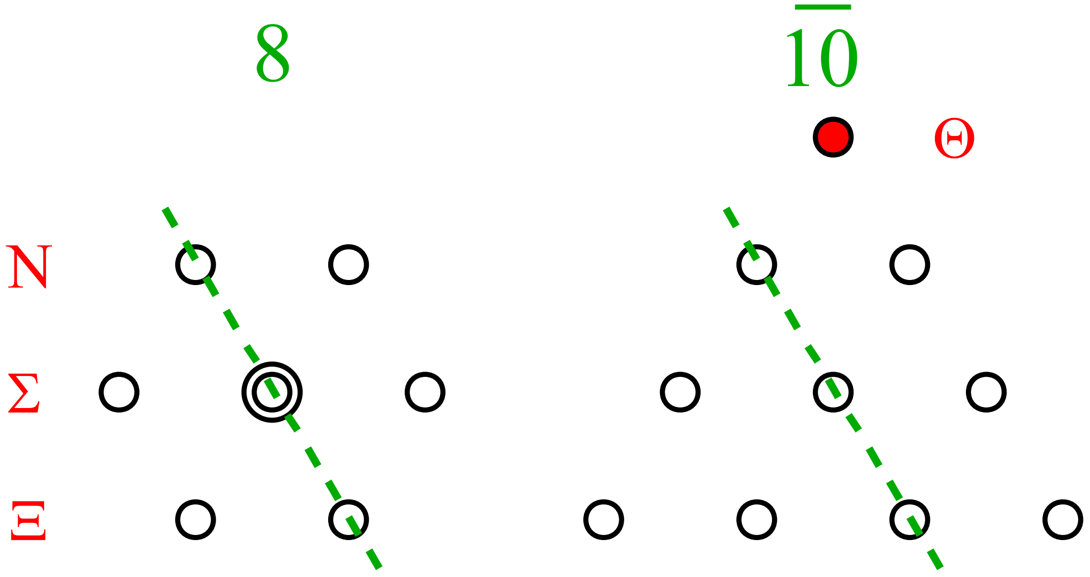
D. Werthmuller et al. [A2 Collaboration]
Phys. Rev. Lett. 111 (2013) 23, 232001
Eur. Phys. J. A 49 (2013) 154
Phys. Rev. Rev. C 90 (2014) 015205



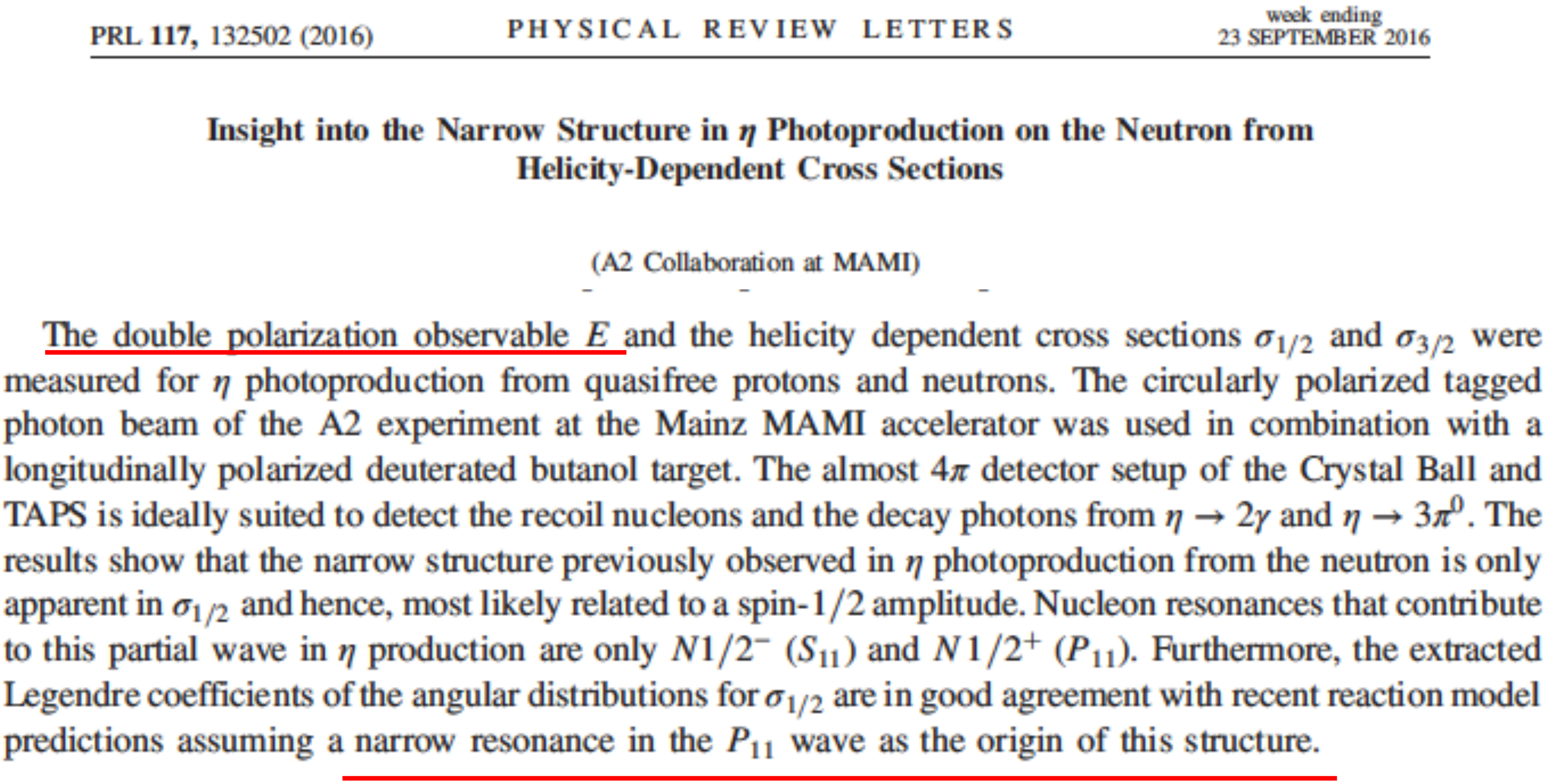
Pentanucleon?



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.