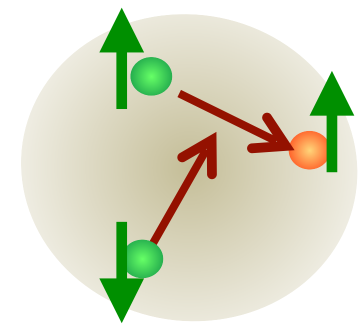
Heavy baryons (*conventional resonances*)
— Theory —

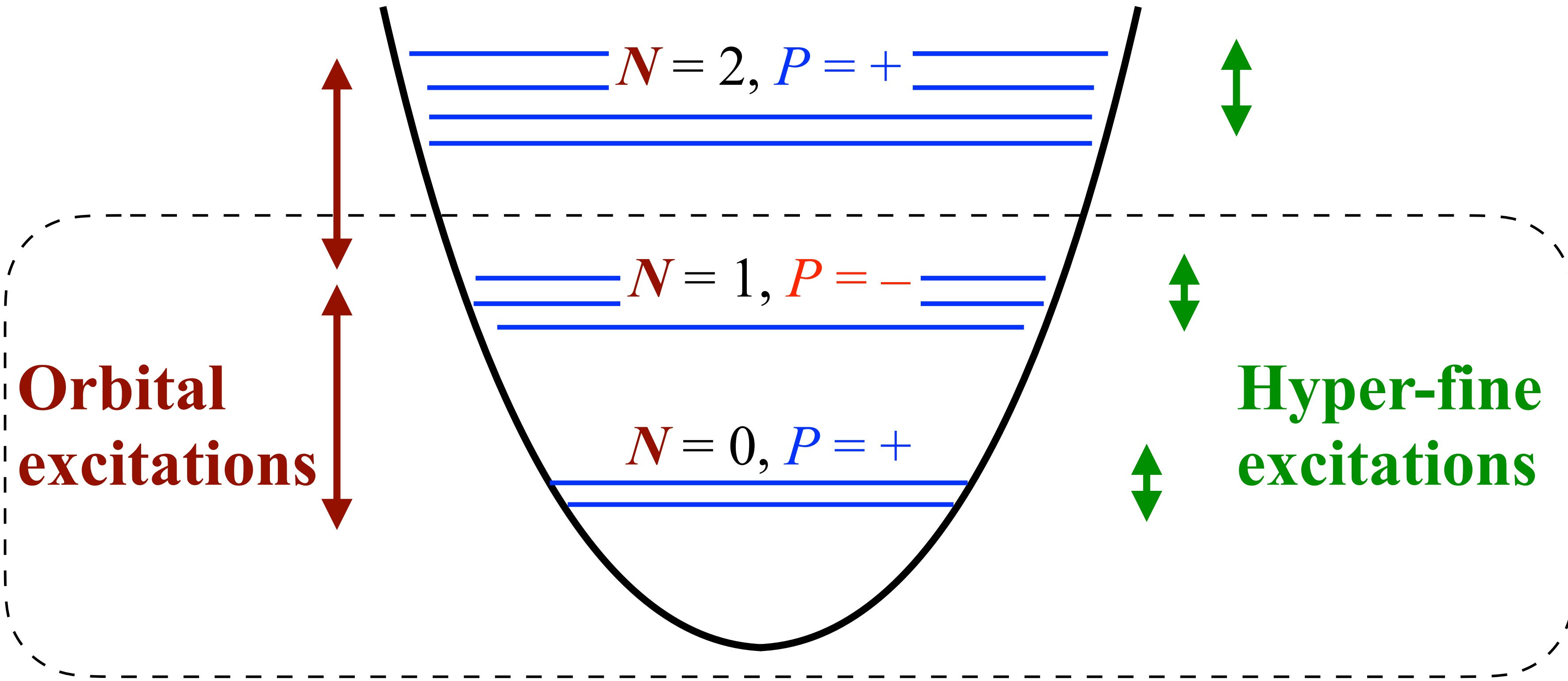
Atsushi Hosaka
RCNP, Osaka University
ASRC, Japan Atomic Energy Agency
SnowMass21, Sept. 23, 2020, Online

- qqQ baryons split the λ and ρ modes
- Masses and decay properties
- Some discussions on Roper siblings
- P_c as a threshold phenomena

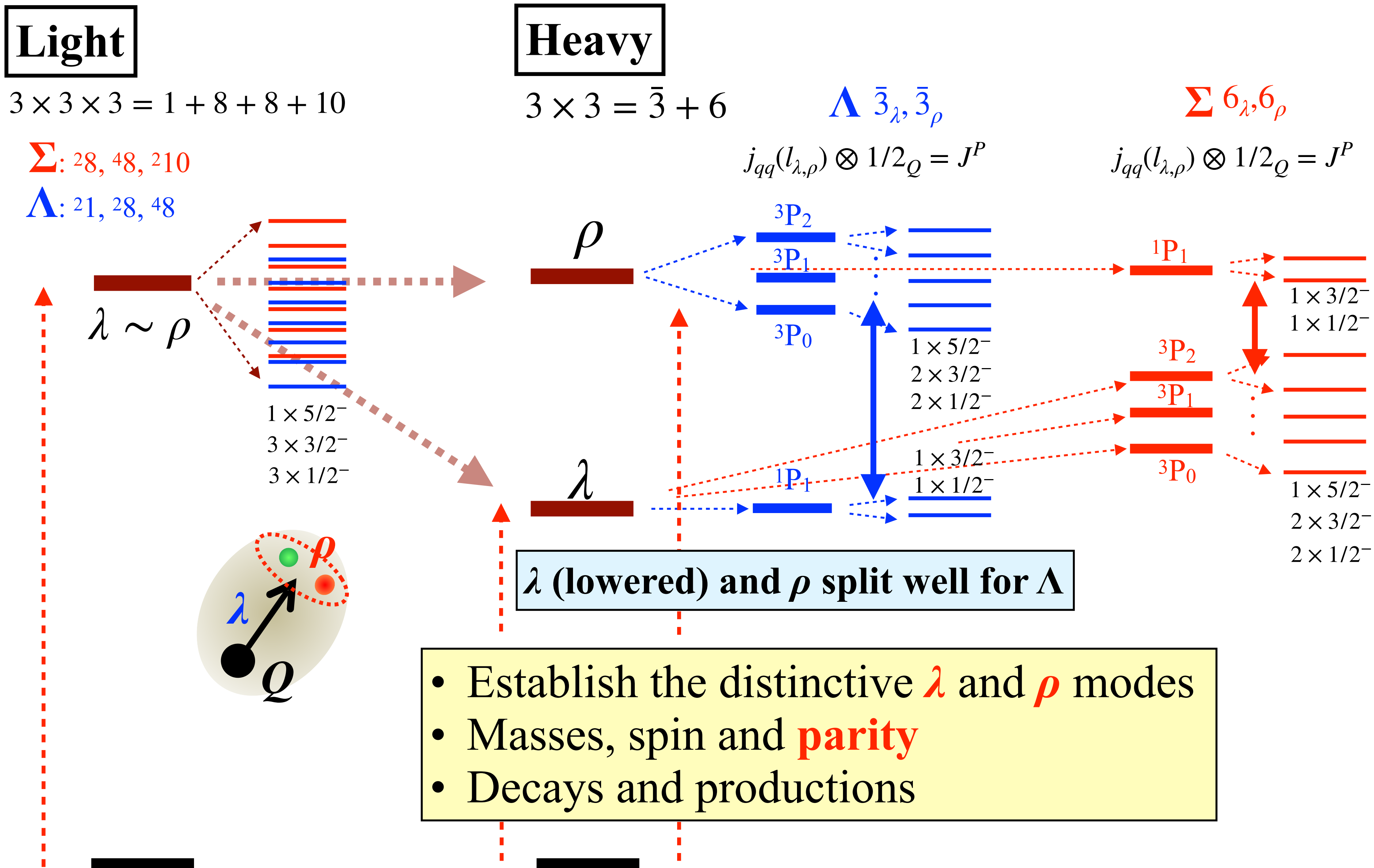
Baryon spectrum

Explain various baryon resonances
in simple words → Classify the excitation modes



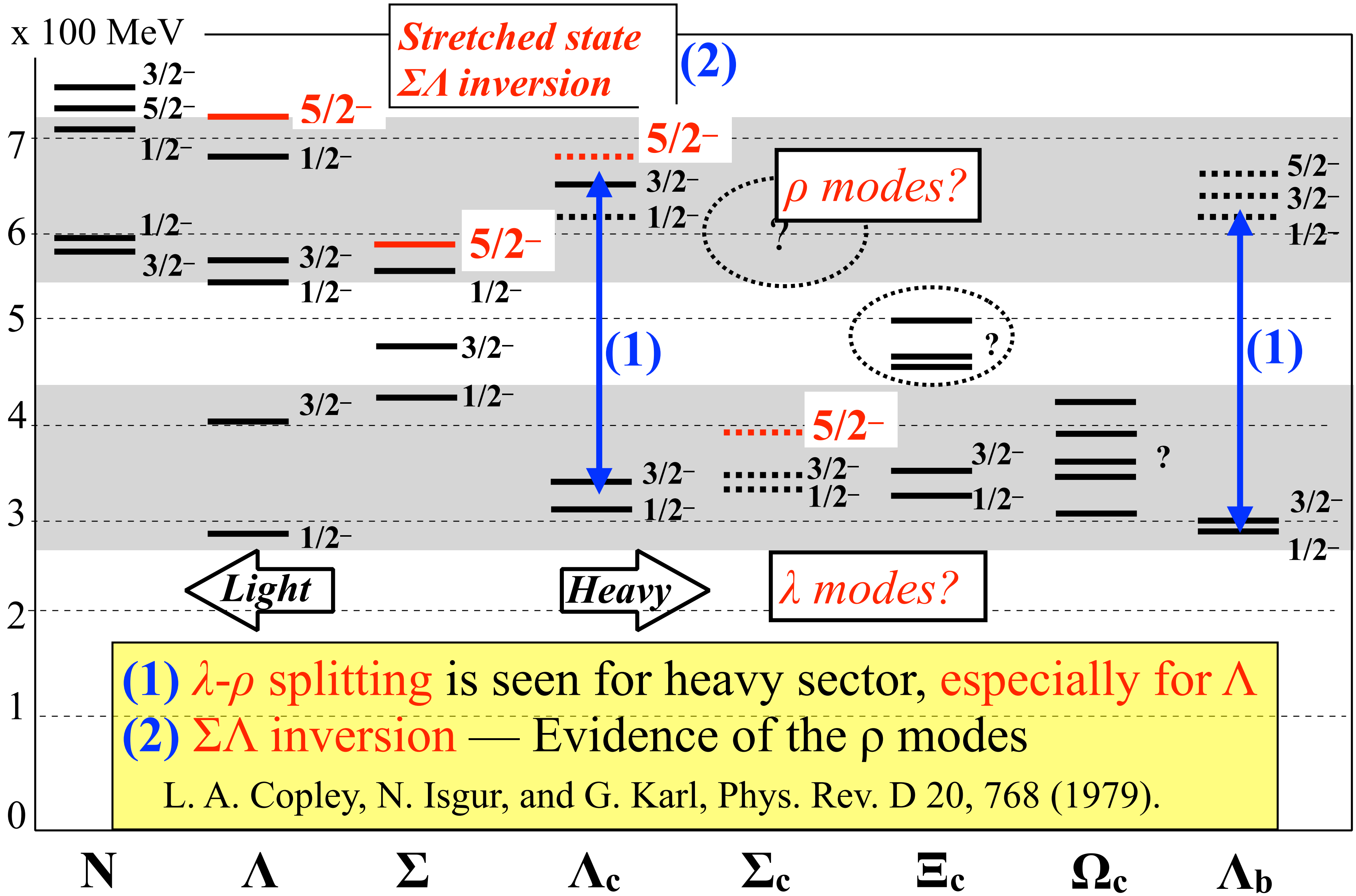


Spectrum — light vs heavy (detail)



- Establish the distinctive λ and ρ modes
- Masses, spin and **parity**
- Decays and productions

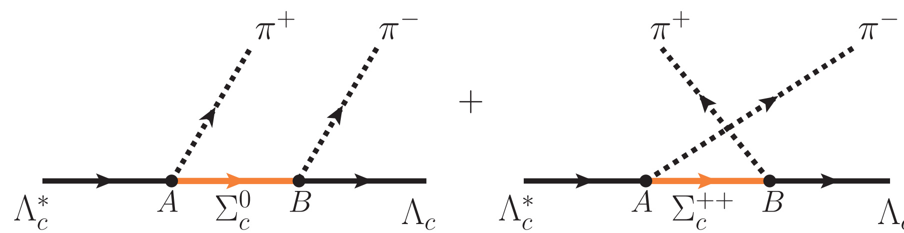
Baryon spectrum (negative parity)



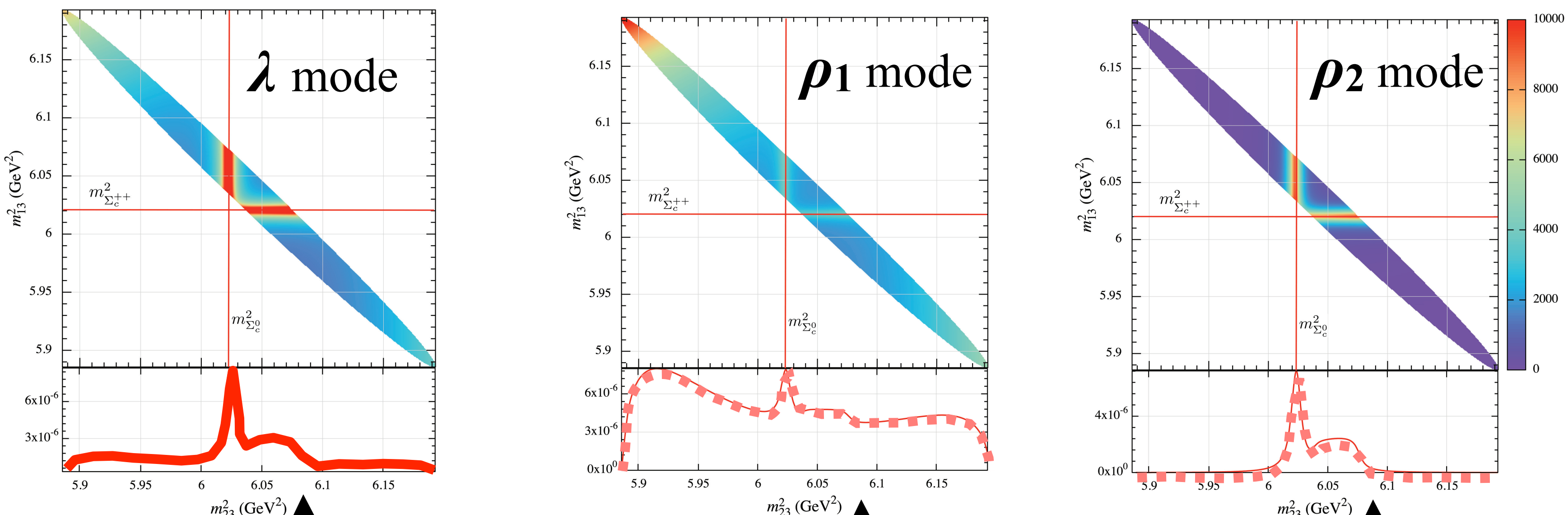
Decays

Ex. of $\Lambda_c(2620)\ 3/2^- \to \Lambda_{gs}\pi\pi$

$\Delta E(2620) \sim 330$ MeV supports the λ mode



Three-body Dalitz analysis



***R* = 0.61** **0.91** **0.00**

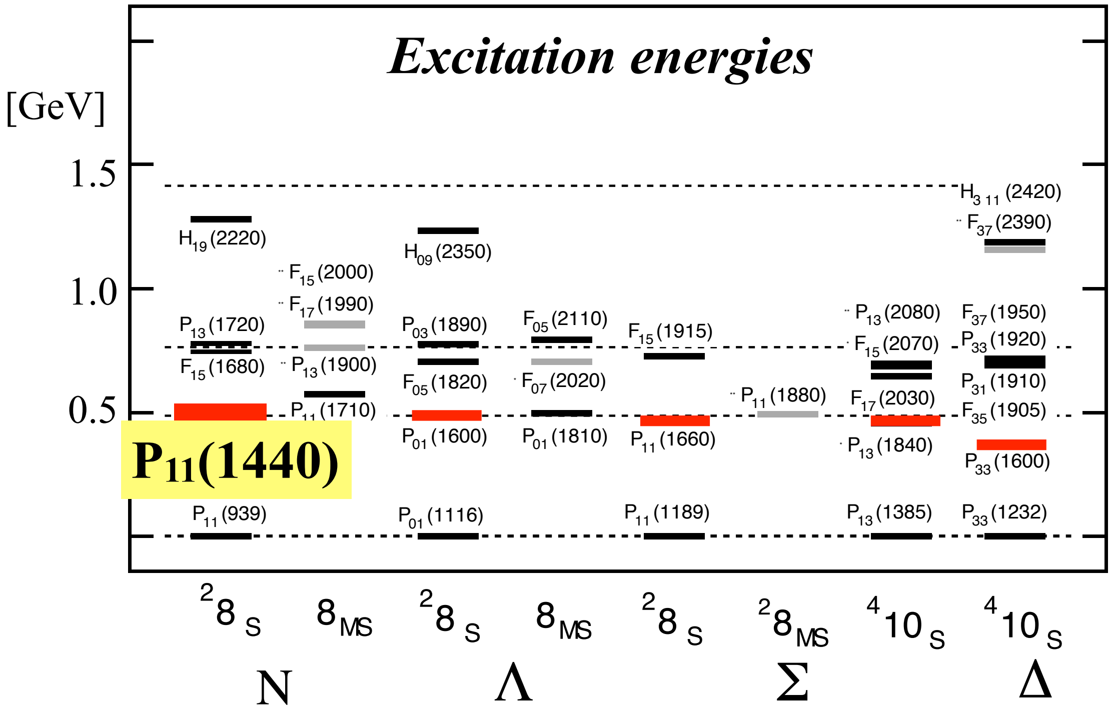
$$R = \frac{\Gamma(\Lambda_c^* \to \Lambda_c \pi^+\pi^-(\text{non-resonant}))}{\Gamma(\Lambda_c^* \to \Lambda_c \pi^+\pi^-(\text{total}))}$$

$\sim 0.54 \pm 0.14$ * **prefers λ mode**

H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B 6 441 317, 227 (1993).

Roper siblings in various flavors ?

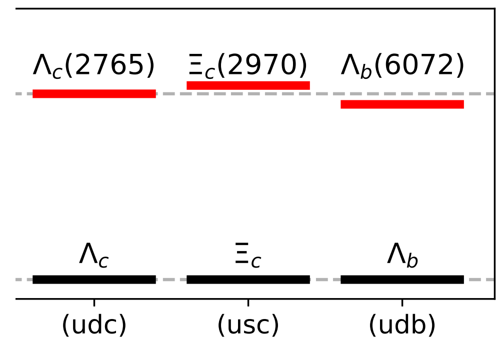
Takayama, Hosaka and Toki
Prog.Theor.Phys. 101 (1999) 1271-1283



Arifi, Nagahiro, Hosaka and Tanida
Phys.Rev.D 101 (2020) 11, 111502,
e-Print: 2004.07423 [hep-ph]

LHCb, JHEP 06 (2020) 136

$\Lambda_c(2765)$, $\Xi_c(2970)$, $\Lambda_b(6072)$



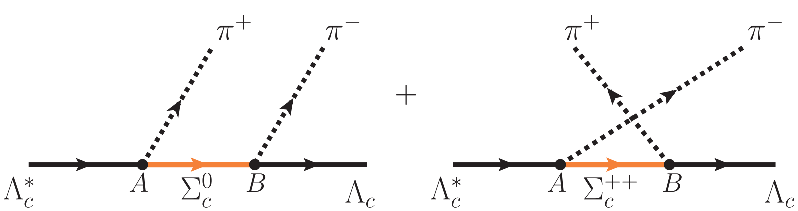
Similarities

$\Delta M \sim 500$ MeV

$\Gamma \sim 50 - 100$ MeV

$J^P \sim 1/2^+$?

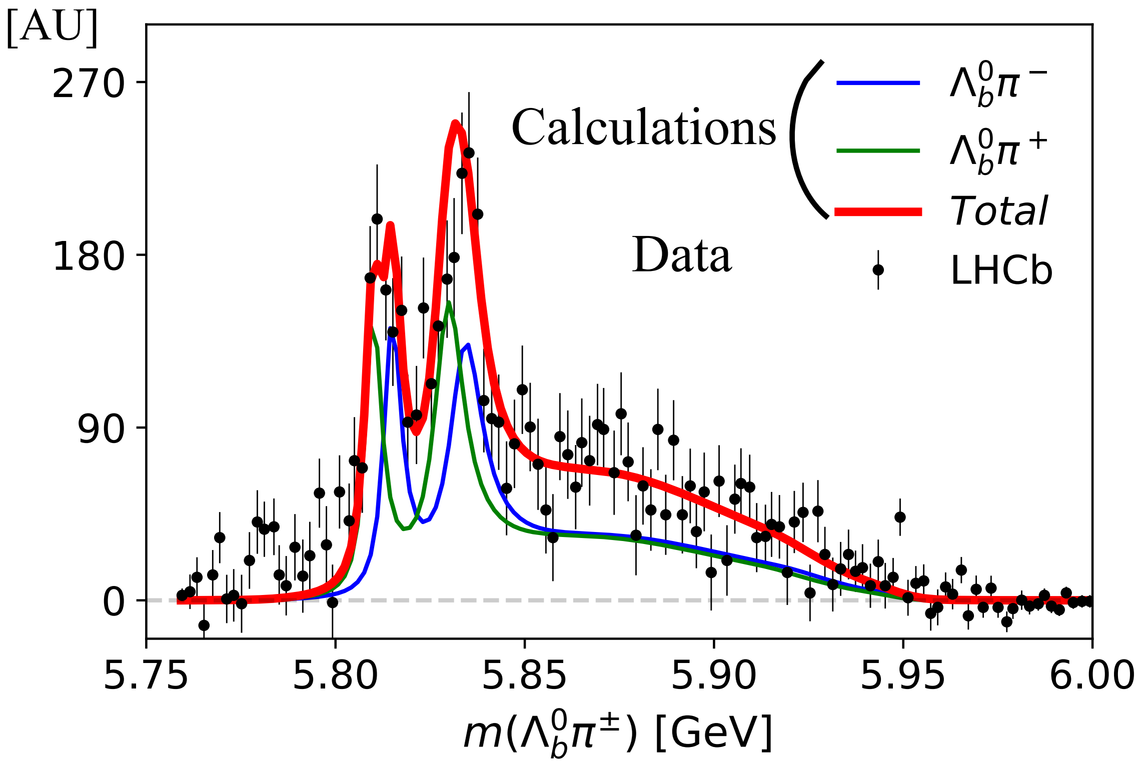
Mostly 2π decays



Describes well

LHCb, JHEP 06 (2020) 136, arXiv:2002.05112 [hep-ex]
Arifi, Arifi, Nagahiro, Hosaka and Tanida, Phys.Rev.D 101 (2020) 11, 111502

$$\Lambda_b(6072) \to \Lambda_b + \pi + \pi$$



Line shape is explained by the HQ symmetry ~ quark model shares
→ suggesting to study in the **quark model**

Conventional description with a heavy quark

(1) Masses - lowering of λ modes

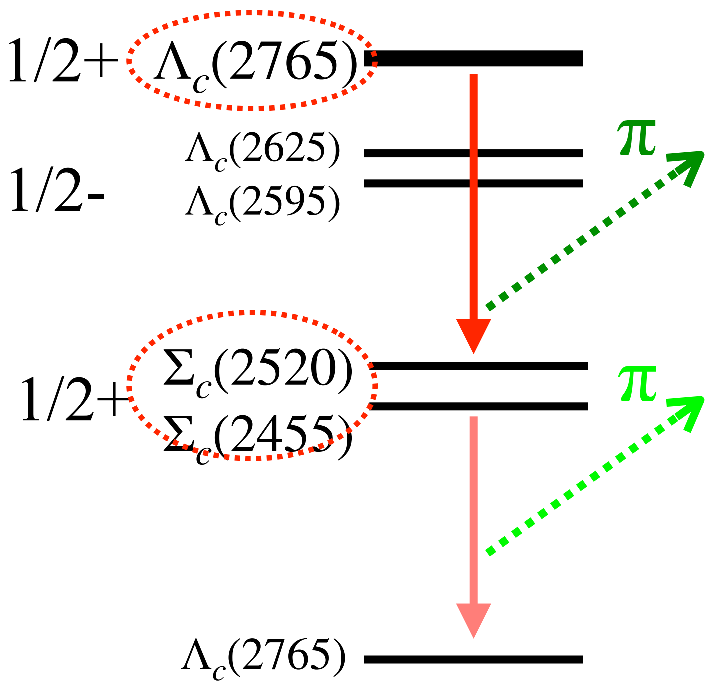
		Λ_c EXP (Model)	Λ_b EXP (Model)	Ξ_c EXP (Model)
$N = 2$	$1/2^+$	2765 (2857)	6072 (6153)	2970 (2924)
~ 200 MeV				
$N = 1$	$3/2^-$	2625 (2630)	5920 (5939)	2815 (2783)
	$1/2^-$	2595 (2628)	5912 (5938)	2790 (2773)
~ 300 MeV		***λ mode dominant***		
$N = 0$	$1/2^+$	2286 (2285)	5620 (5618)	2467 (2466)

→ Consistent

Yoshida et al, Phys.Rev.D 92 (2015) 11, 114029
Roberts and Pervin, Int.J.Mod.Phys.A 23 (2008) 2817-2860

(2) Decays (Pion emission)

Focus on Λ_c baryons



Width Γ in MeV

	EXP	Model
$\Lambda_c(2765)$	50-70	3 [1]
$\Lambda_c(2625)$	< 0.97	0.3 [2]
$\Lambda_c(2595)$	2.6	2.2 [1]
$\Sigma_c(2520)$	15	31 [1]
$\Sigma_c(2455)$	1.9	4.3 [1]

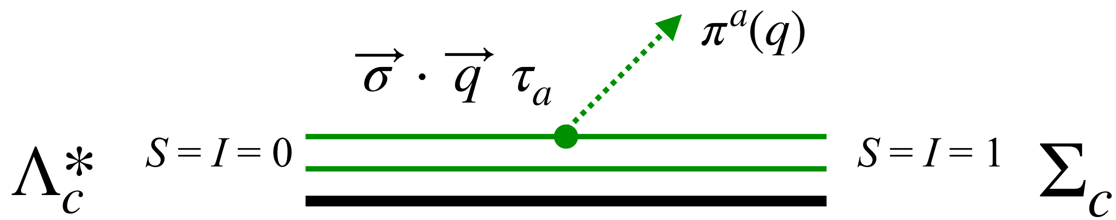
[1] Nagahiro et al, PRD95, 014023 (2017)
[2] Arifi et al, PRD95, 114018 (2017)

Using the leading terms of $\mathscr{L}_{\pi qq} = \frac{g_A^q}{2f_\pi}\bar{q}\gamma_\mu\gamma_5 q\vec{\tau}q \cdot \partial^\mu \vec{\pi}$

The total width is too small

Assuming $\Lambda_c(2765)$ to be of $J^P = 1/2^+$

- The pion transition is forbidden to the leading order



$$A \sim (\text{Spin} - \text{isospin part}) \times \langle \Sigma_c(\text{orbital}) | e^{i\vec{q}\cdot\vec{x}} | \Lambda_c^*(\text{orbital}) \rangle \to 0!$$

$n = 0$ $\quad n = 1$

Suppressed ~ orthogonality of Σ_c and Λ_c^*

- Similar case is known for the EM transition

Kubota, Ohta, Phys.Lett.B 65 (1976) 374-376

Higher order in $1/m$ ~ relativistic corrections

Table 1

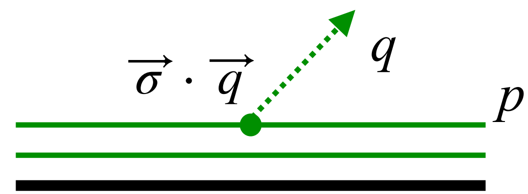
Photoelectric matrix elements A^{NR} calculated using a simple nonrelativistic model and relativistic corrections A^{RC}. The experimental data are taken from table IV.1. at p. 160 of ref. [1]. Units for these amplitudes are 10^{-3} GeV$^{-1/2}$.

State	Multiplet	λ N	A^{NR}	$A^{RC} \times \frac{M_q}{\mu k}\sqrt{\frac{2k}{4\pi}}\left(2-\frac{1}{g}\right)^{-1}$	A^{RC}	$A^{NR} + A^{RC}$	A^{exp}
$P_{11}(1470)$	$^2 8_{1/2}[56,0^+]_2$	$\frac{1}{2}\begin{bmatrix} p \\ n \end{bmatrix}$	26 −17	$\begin{bmatrix} 3 \\ -2 \end{bmatrix} \times R_{00}^{s*}/3\sqrt{2}$	−31 21	−5 4	−74 ± 15 34 ± 35

Relativistic corrections

Foldy–Wouthuysen-Tani transformation $\sim 1/m$ expansion

$$\mathscr{L}_{\pi qq} = \frac{g_A^q}{2f_\pi}\bar{q}\gamma_\mu\gamma_5 q\vec{\tau}q \cdot \partial^\mu \vec{\pi}$$



$$\sim (\sigma q) + \frac{\omega}{2m}((\sigma q) - 2(\sigma p))$$

Previous calculations

$$-\frac{1}{8m^2}\left[(\sigma q)q^2 + 2(\sigma q)(qp) - 2(\sigma p)q^2 + \underline{4(\sigma q)p^2 - 4(\sigma p)(pq)}\right]$$

Generate unsuppressed terms

$$+\frac{\omega^2}{8m^2}(\sigma q)$$

$$(ab) = \vec{a} \cdot \vec{b}, \quad \omega = \sqrt{m_\pi^2 + \vec{q}^{\,2}}$$

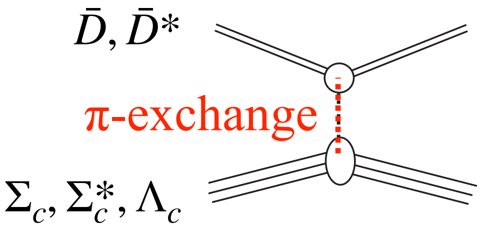
p: internal quark momentum

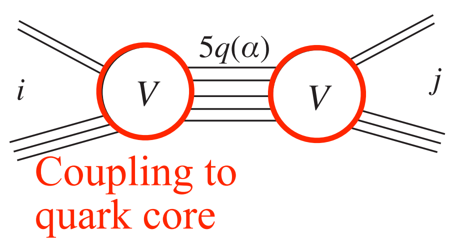
Preliminary Γ's

	EXP	Model (NR)	+ Corrections
$\Lambda_c(2765)$	50-70	3 [1]	~ 25
$\Lambda_c(2625)$	< 0.97	0.3 [2]	~ 0.3
$\Lambda_c(2595)$	2.6	2.2 [1]	~ 2.2
$\Sigma_c(2520)$	15	31 [1]	~ 10
$\Sigma_c(2455)$	1.9	4.3 [1]	~ 1.3

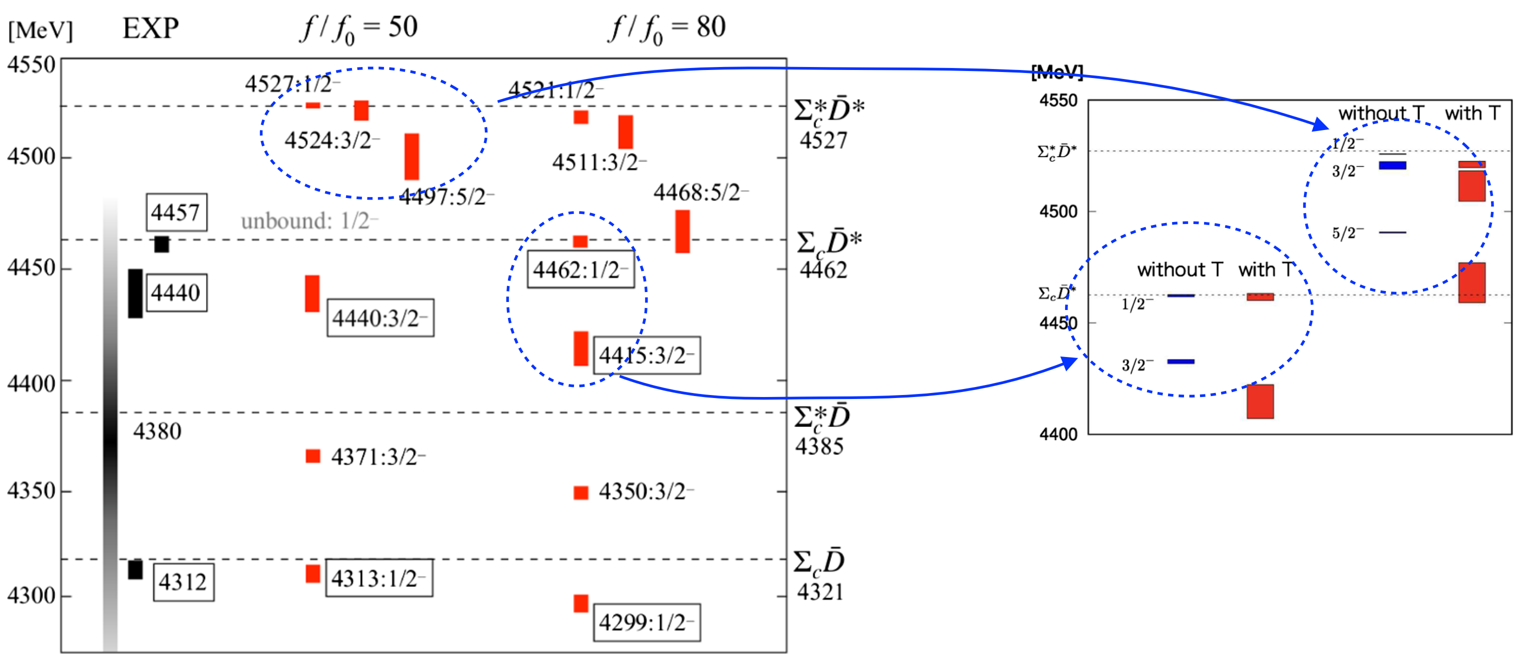
P_c - Nucleon resonance above the $c\bar{c}$ threshold ~ $uudc\bar{c}$

A couple channel model with MB and 5q core





Yamaguchi, Hosaka, Santopinto et al
Phys.Rev. D96 (2017), 114031,
Phys.Rev.D 101 (2020) 9, 091502



- One parameter fit explains the three states as molecules: masses and decay widths
- OPEP and quark core couplings are important to form hadronic molecules

Summary and prospects

(1) The ***λ*** and ***ρ*** modes should be further established, especially ***ρ modes***.

λ mode: ***diquark*** motion, ***ρ*** mode: ***diquark*** excitation.

(2) ***Roper siblings with HQ*** seem to be explained by the QM.

as supplemented by ***relativistic corrections***.

Their similarities in a wide range of flavors must be understood.

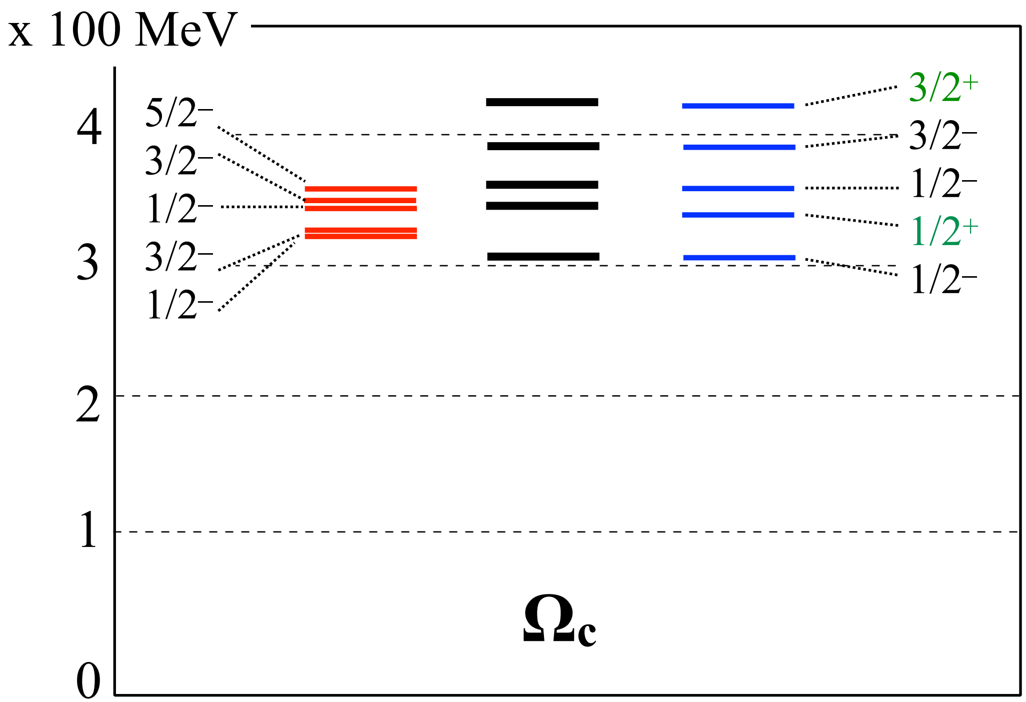
Stiffness/compressibility of the smallest matter.

(3) ***Pc,*** the ***nucleon excited states*** is a molecular like.

The nucleon shows with ***completely different structure*** by energy.

Analogous to ***^{12}C ground state*** and the ***Hoyle state of α cluster.***

Ω_c: Two opposite models



Quark model: Yoshida et al, Phys.Rev.D 92 (2015) 11, 114029

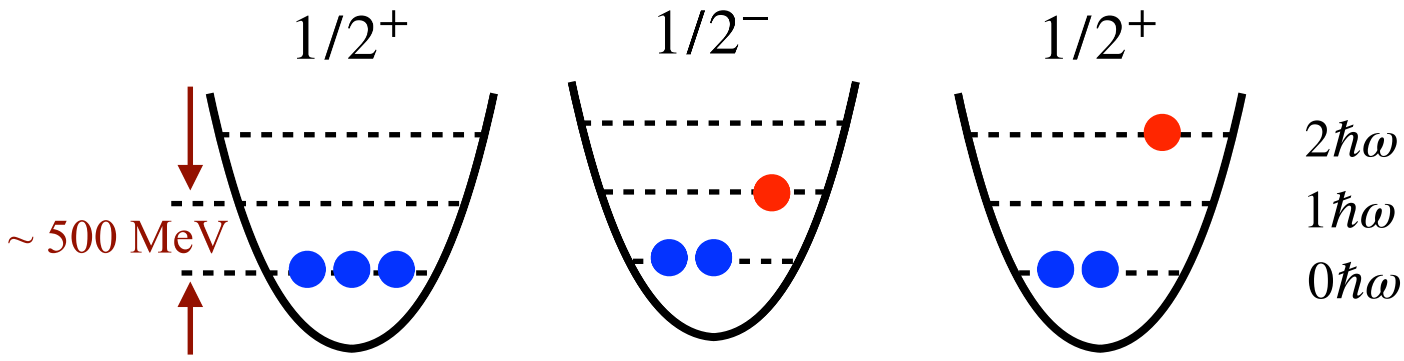
Five states appear as λ modes ~ agrees with the QM but splittings are too narrow

Chiral soliton: Kim, Polyakov, Praszałowicz, Phys.Rev.D 96 (2017) 1, 014009

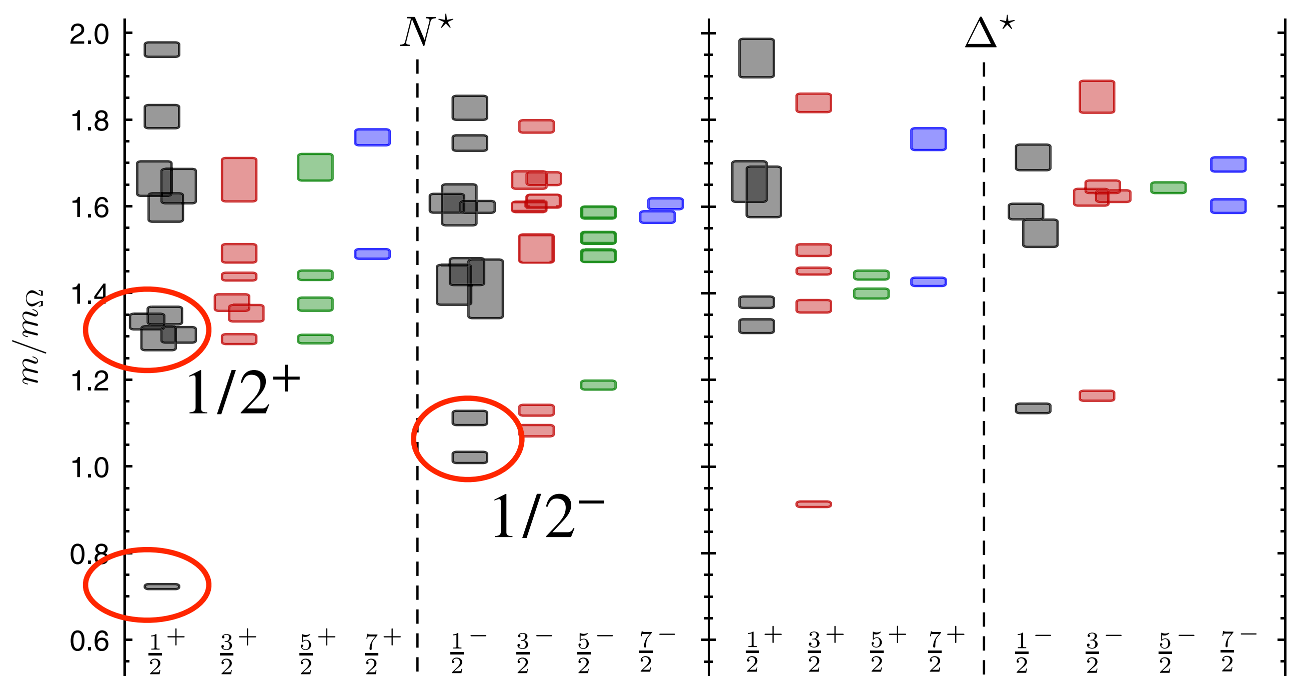
Chiral interaction lowers positive parity states

Determination of parity is important

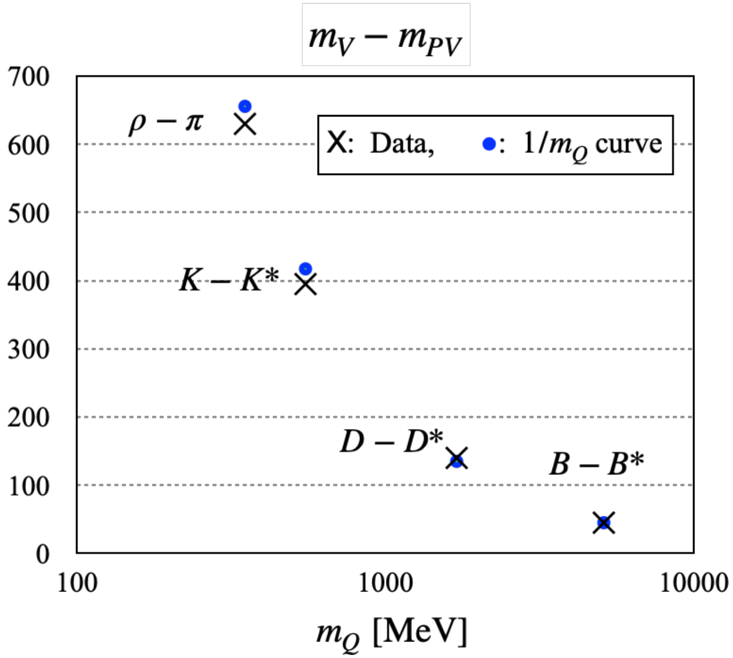
Standard quark model

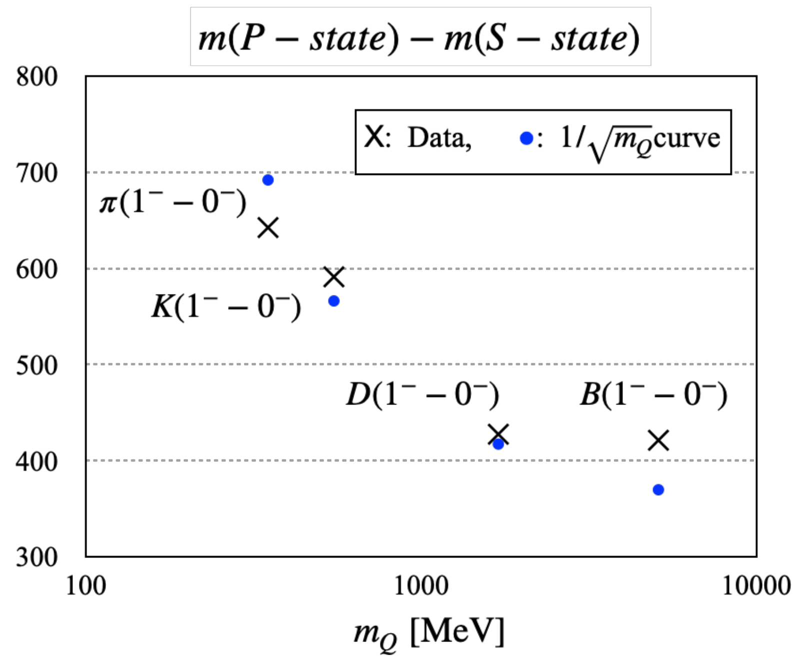


Lattice data



$$m_N/m_\Omega = 940/1672 \sim 0.56$$


$m_V - m_{PV}$
700
600
500
400
300
200
100
0
100
1000
10000
m_Q [MeV]
$\rho - \pi$
$K - K^*$
$D - D^*$
$B - B^*$
X: Data, ●: $1/m_Q$ curve


$m(P-state) - m(S-state)$
800
700
600
500
400
300
100
1000
10000
m_Q [MeV]
$\pi(1^- - 0^-)$
$K(1^- - 0^-)$
$D(1^- - 0^-)$
$B(1^- - 0^-)$
X: Data, ●: $1/\sqrt{m_Q}$curve

"Quantum Field Theory", Itzykson and Zuber, McGraw-Hill, 1980, p71

....

$1/m^2$ terms

$$H''' = \beta\left[m + \frac{(\mathbf{p} - e\mathbf{A})^2}{2m} - \frac{(\mathbf{p})^4}{8m^3}\right] + eA^0 - \frac{e}{2m}\beta\boldsymbol{\sigma}\cdot\mathbf{B}$$
$$+\left(-\frac{ie}{8m^2}\boldsymbol{\sigma}\cdot\operatorname{curl}\mathbf{E} - \underline{\frac{e}{4m^2}\boldsymbol{\sigma}\cdot\mathbf{E}\times\mathbf{p}}\right) - \frac{e}{8m^2}\operatorname{div}\mathbf{E} \qquad \text{(2-82)}$$

The interpretation of the various terms deserves some comments. The term in the bracket is the expansion (to the required order) of $[(\mathbf{p} - e\mathbf{A})^2 + m^2]^{1/2}$. The second term eA^0 is the electrostatic energy of a point-like charge, whereas the third one represents the energy of a magnetic dipole for $g = 2$. The term inside parentheses may be seen to correspond to a spin-orbit (s.o.) interaction. Indeed, for a static spherically symmetric potential, curl $\mathbf{E} = 0$ and $\mathbf{E} = -\nabla A^0$. Therefore

$$\boldsymbol{\sigma}\cdot(\mathbf{E}\times\mathbf{p}) = -\frac{1}{r}\frac{dA^0}{dr}\boldsymbol{\sigma}\cdot(\mathbf{r}\times\mathbf{p}) = -\frac{1}{r}\frac{dA^0}{dr}\boldsymbol{\sigma}\cdot\mathbf{L}$$

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