Study of Roper-like resonances

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Recent progress in hadron physics
September, 2021

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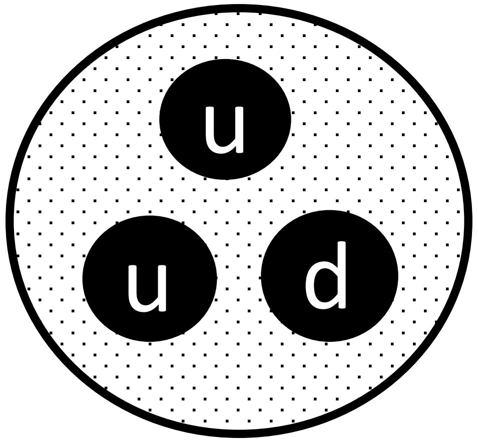
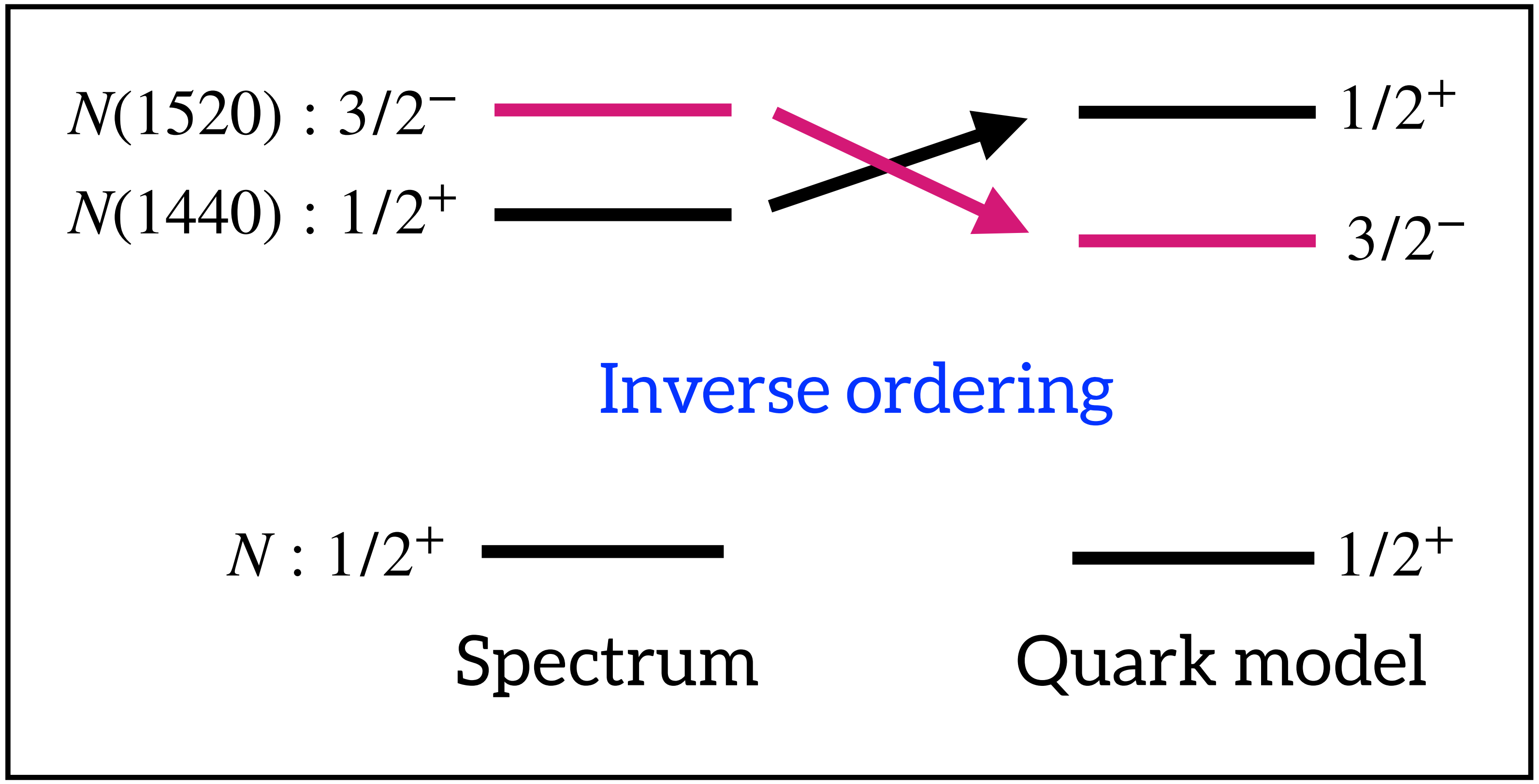
Part 1

Roper resonance and its analogous states

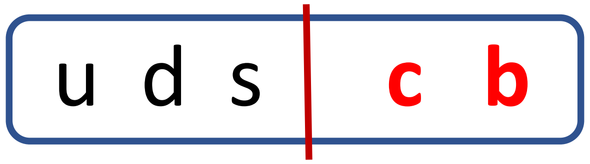
Roper resonance

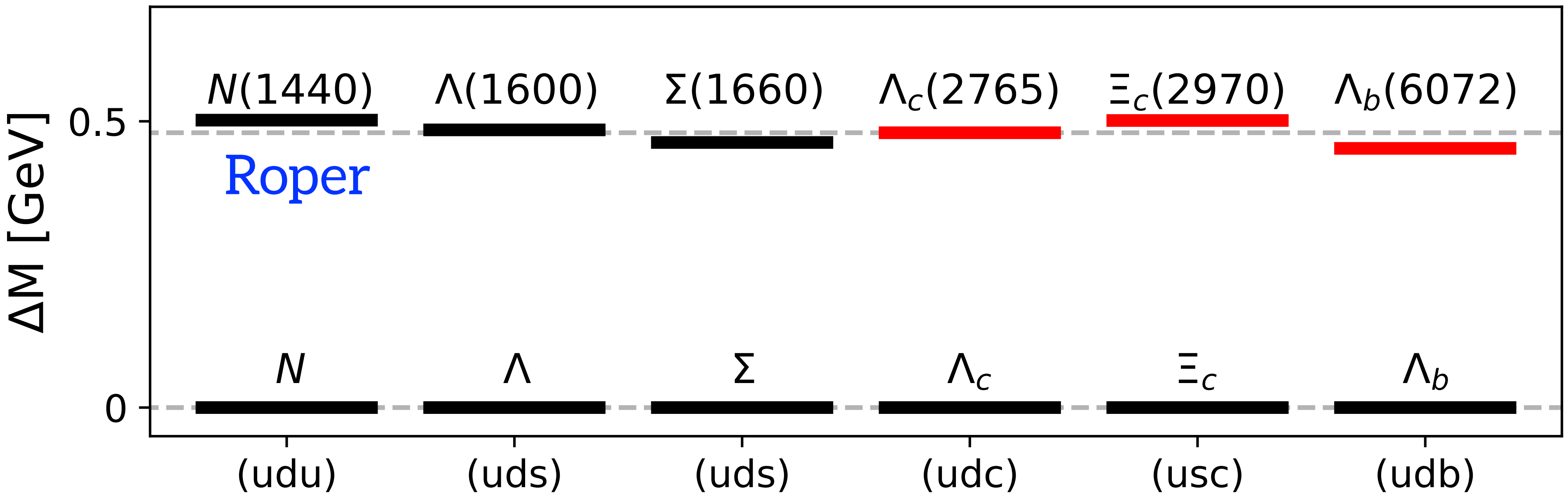


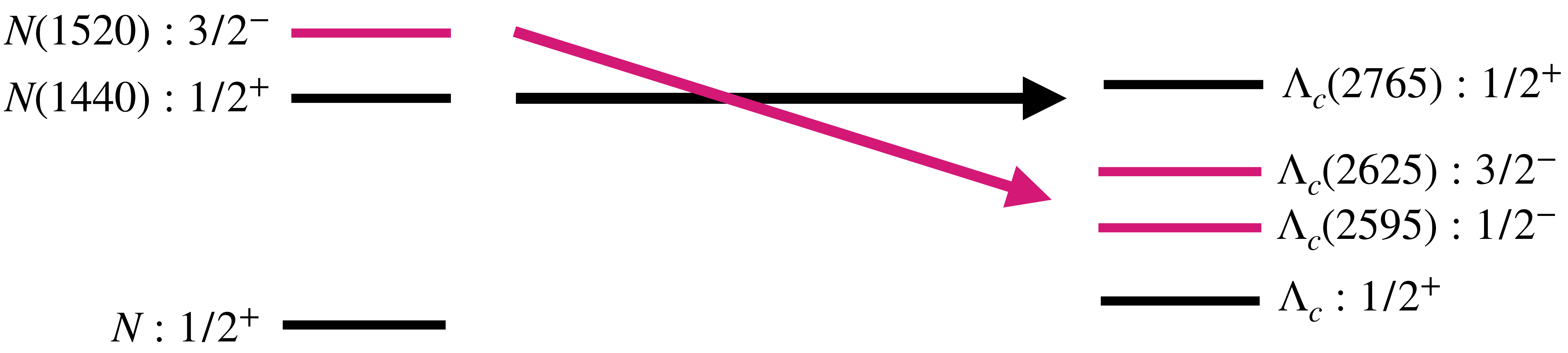
- In PDG –> $N(1440)$
- Discovered by **L. D. Roper** in 1963 (almost 60 years).
- A radial excitation of nucleon with $J^P = 1/2^+$.
- Incompatible with the quark model.
- Interpretation: quark core + meson cloud?



Roper-like resonances







Similarities —> hints to their structures

Status of Roper-like heavy baryons

$\Lambda_c(2765)$

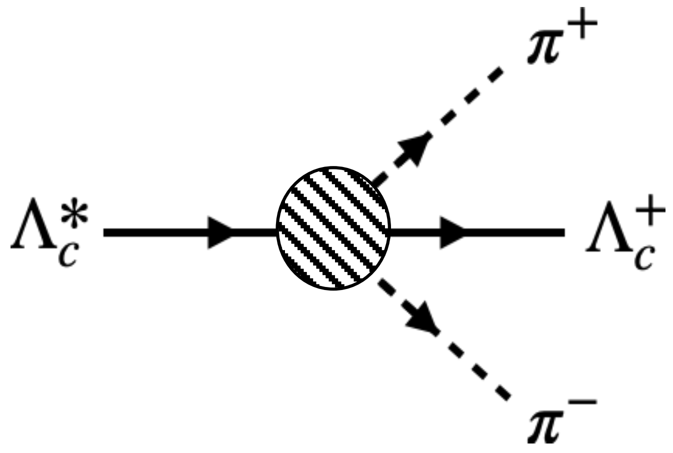
- PDG: 1 star.
- J^P is not determined.
- Mostly decays into $\Lambda_c\pi\pi$

$\Xi_c(2970)$

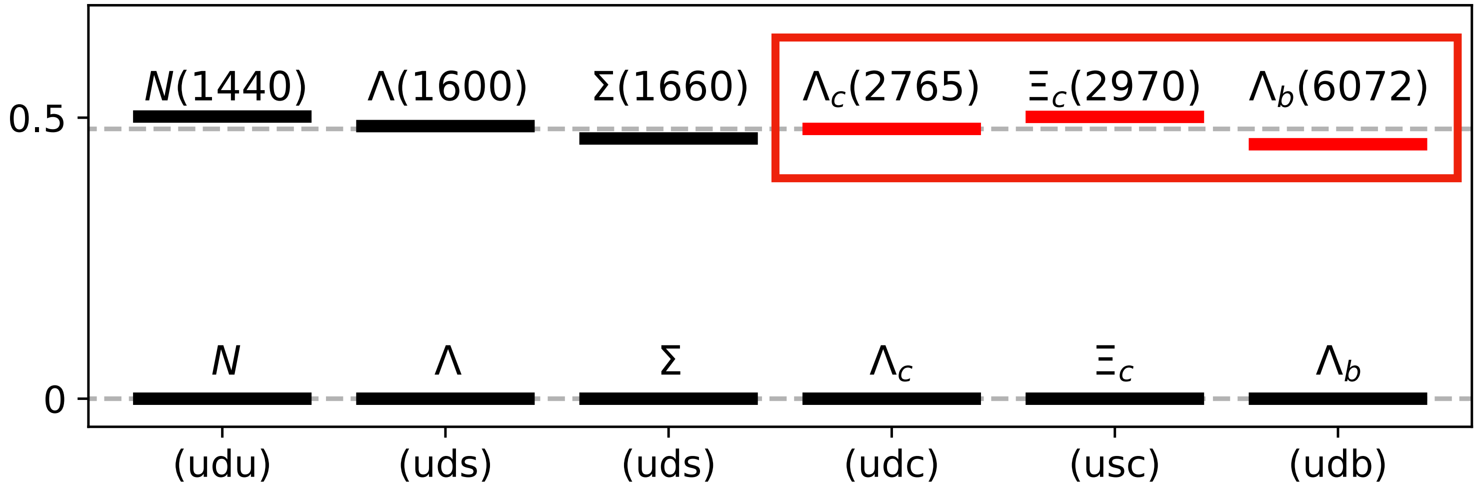
- PDG: 3 star.
- $J^P = 1/2^+$ —> Belle 2021.

$\Lambda_b(6072)$

- Newly observed —> by LHCb 2020
- $\Gamma = 72$ MeV



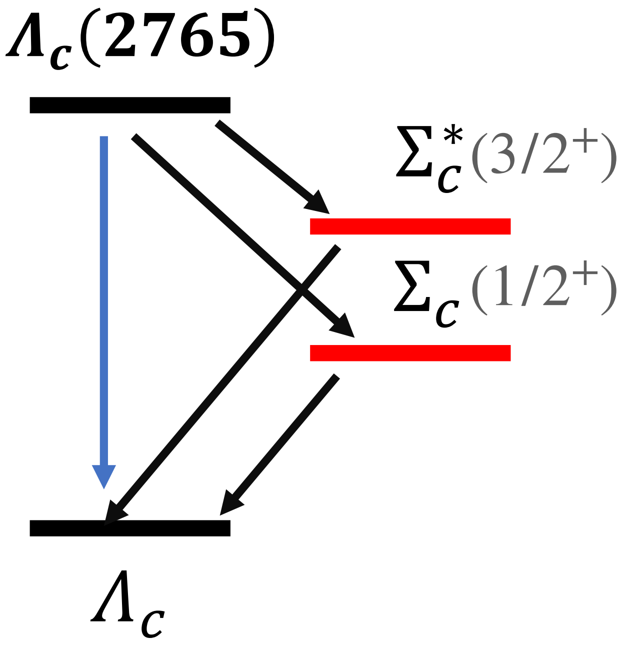
Three-body decays
—> determine spin-parity.

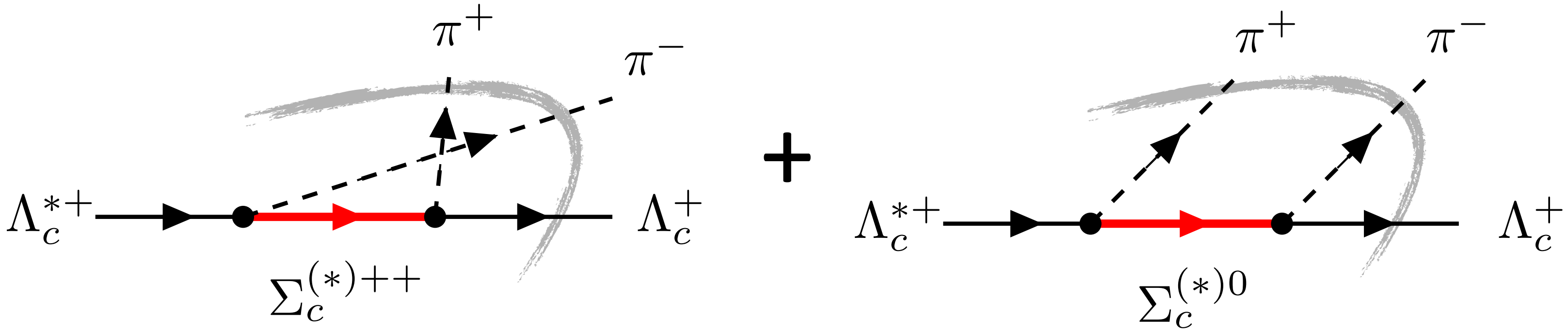


We expect Ξ_b resonance will be reported soon by LHCb.

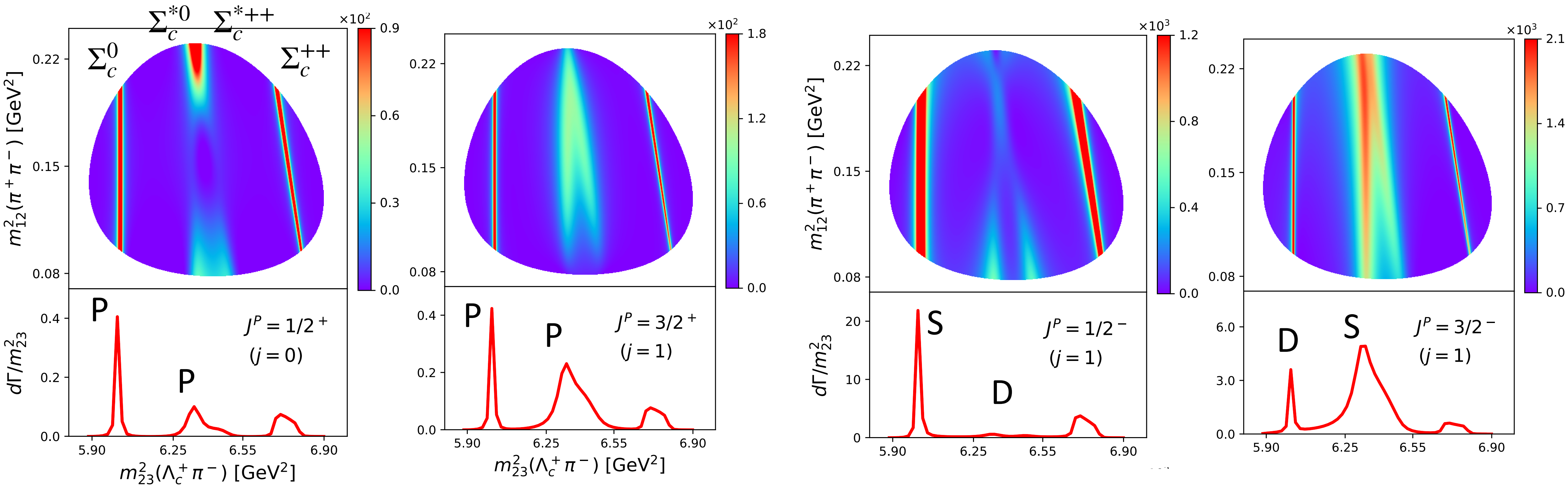
Three-body decay

$\Lambda_c(2765)$



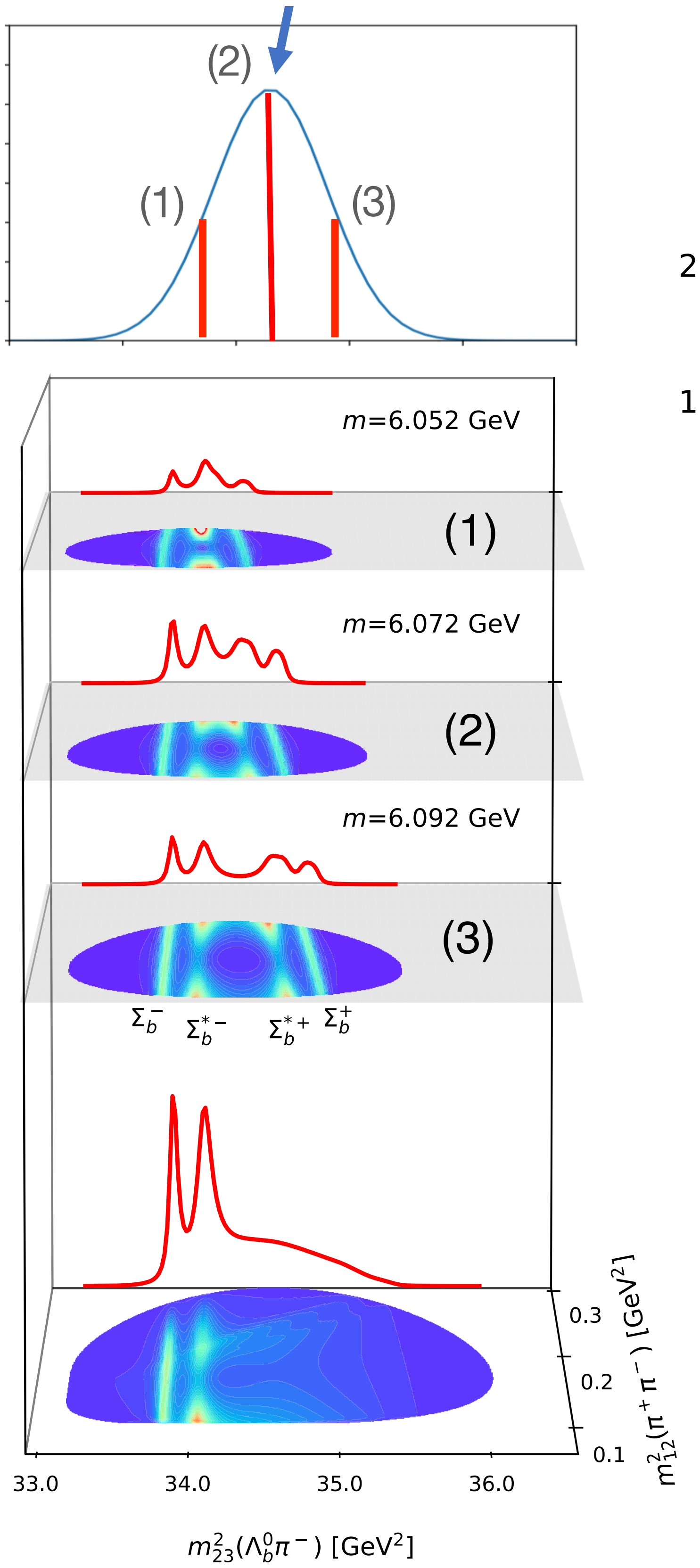


Sequential process going through $\Sigma_c^{(*)}$ resonances.

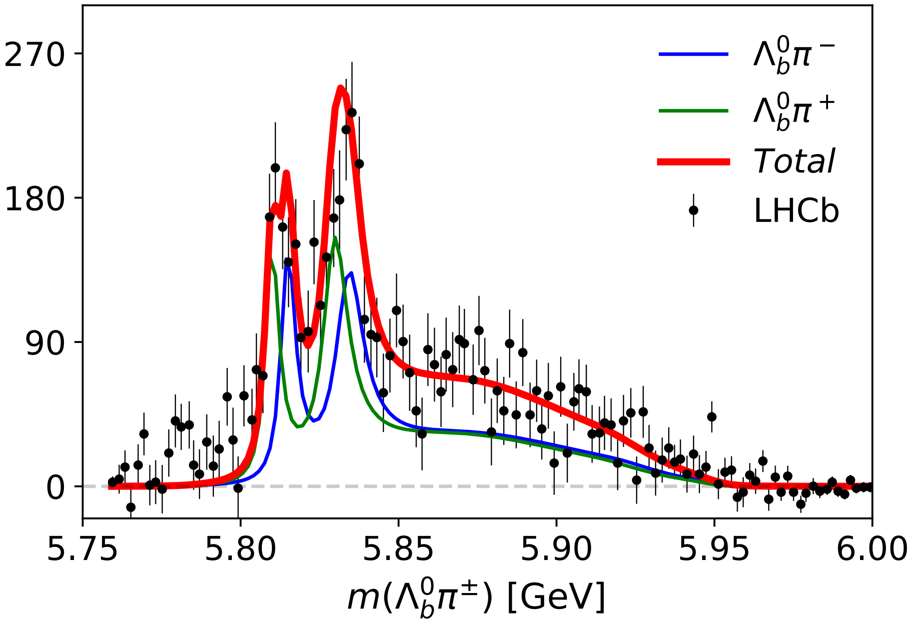


PRD101, 094023 (2020)

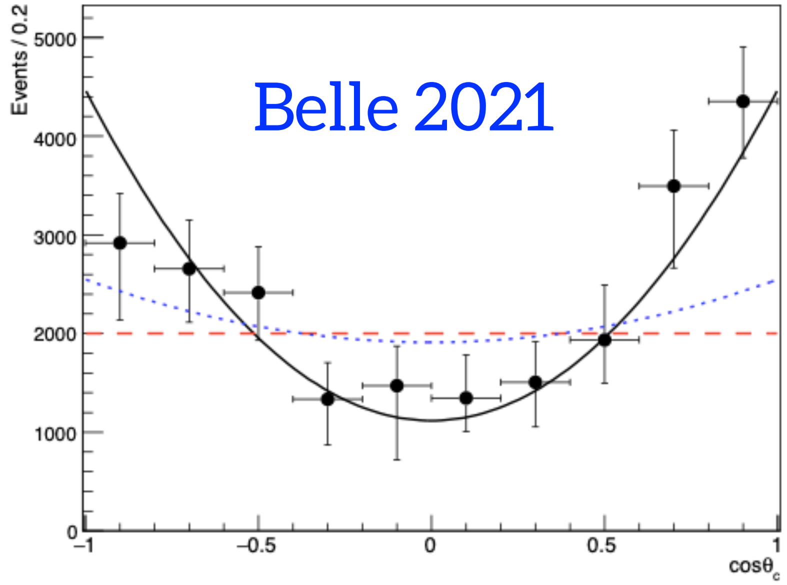
Spin-parity $1/2^+$



$\boxed{\Lambda_b(6072)}$



$\boxed{\Xi_c(2970)}$



- They most likely belong to Roper's family.
  —> Invariant mass distribution
  —> Ratio of decay width
  —> Angular correlation

PRD101, 111502 (R) (2020)

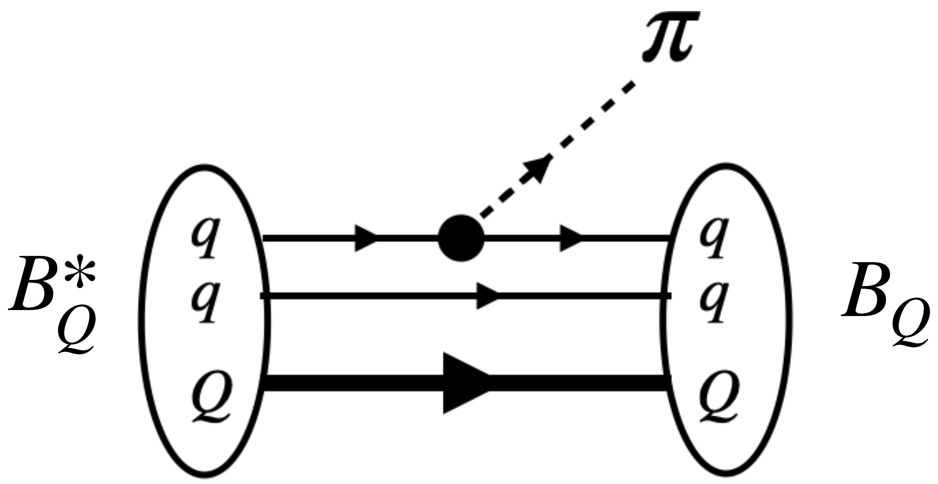
Question?

- Similarities among the Roper-like resonances.
  —> Accidental ? Universal behavior?
- Is the N(1440) rather special to the others?
  —> Pion cloud? What about Ω ?
- Radial excitation of heavy baryon
  —> Why so broad?
- 3-body decay is dominated by sequential process.
  The σ meson (direct) process is insignificant.
  —> hint to the internal structure?
- Nonrelativistic quark model
  —> Predict a narrow width (Problem!)
  —> Relativistic effect? Exotics?
- What about the other system?
  —> We're looking into it.

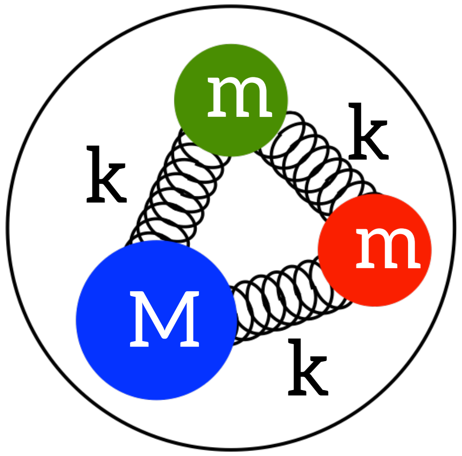
Part 2

Quark model & relativistic effect

Heavy baryon decay in Quark model



Two-body decay



Baryon wave function

Quark-meson interaction

$$\mathcal{T} = \left\langle \pi \; {}_{\Lambda_c} \middle| \mathcal{L}_{\pi qq} \middle| \; {}_{\Lambda_c^*} \right\rangle$$

$$\mathcal{L}_{\pi qq} = \frac{g_A^q}{2f_\pi} \bar{q}\gamma^\mu \gamma_5 \vec{\tau} q \cdot \partial_\mu \vec{\pi}$$

non-relativistic expansion

Leading terms up to 1/m

$$H_{NR} = g\left[\boldsymbol{\sigma}\cdot\boldsymbol{q} - \frac{\omega_\pi}{2m}\boldsymbol{\sigma}\cdot(\boldsymbol{p}_i + \boldsymbol{p}_f)\right]$$

PRD95, 014023 (2017)

Relativistic correction

- FWT transformation gives a correction order by order

$$H = \underbrace{H(1/m^0) + H(1/m)}_{\text{NR}} + \underbrace{H(1/m^2)}_{\text{RC}} + \ldots \qquad H = \beta m + \mathcal{O} + \mathcal{E},$$

Remove large-small component (odd operator).

- Quark-meson interaction

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

- Leading term up to $1/m$

$$H_{NR} = g\left[\boldsymbol{\sigma}\cdot\boldsymbol{q} - \frac{\omega_\pi}{2m}\boldsymbol{\sigma}\cdot(\boldsymbol{p}_i+\boldsymbol{p}_f)\right]$$

The same as obtained by non-rel reduction.

- The correction up to $1/m^2$

$$H_{RC} = \frac{g}{8m^2}\left[m_\pi^2\boldsymbol{\sigma}\cdot\boldsymbol{q} - 2\boldsymbol{\sigma}\cdot(\boldsymbol{p}_i+\boldsymbol{p}_f)\times(\boldsymbol{q}\times\boldsymbol{p}_i)\right]$$

E. M. —> spin-orbit coupling

important term ~ P^2

Ground state: $\Sigma_c \to \Lambda_c \pi$

Ground state	NR	NR + RC	Exp.
$\Sigma_c(2455) : 1/2^+$	4.27 - 4.34	0.35 - 1.95	1.89 MeV
$\Sigma_c(2520) : 3/2^+$	29.8 - 31.4	2.70 - 14.1	14.78 MeV
	2 x	reduced	

- Suppression of g_A^q coupling constant.
- The overlap of the wave functions is unity in wave-length limit.

$$\underbrace{\left\langle \Lambda_c \middle| 1 \middle| \Sigma_c \right\rangle \propto 1}_{\text{large}} \qquad \underbrace{\left\langle \Lambda_c \middle| p_i \middle| \Sigma_c \right\rangle \propto q}_{\text{small}} \qquad \underbrace{\left\langle \Lambda_c \middle| p_i^2 \middle| \Sigma_c \right\rangle \propto a^2}_{\text{large}}$$

- The relativistic correction has opposite sign.

$$H_{NR} = g\left[\boldsymbol{\sigma}\cdot\boldsymbol{q} + \frac{\omega_\pi}{2m}\left(\boldsymbol{\sigma}\cdot\boldsymbol{q} - 2\boldsymbol{\sigma}\cdot\boldsymbol{p}_i\right)\right], \qquad H_{RC} = \frac{g}{8m^2}\left[m_\pi^2\boldsymbol{\sigma}\cdot\boldsymbol{q} + 2\boldsymbol{\sigma}\ \cdot(\boldsymbol{q} - 2\boldsymbol{p}_i)\times(\boldsymbol{q}\times\boldsymbol{p}_i)\right],$$

Negative parity state: $\Lambda_c^* \to \Sigma_c \pi$

Negative parity state	NR	NR + RC	Exp.
$\Lambda_c(2595) : 1/2^-$	1.35 - 3.16	1.36 - 3.20	2.6 MeV
$\Lambda_c(2625) : 3/2^-$	0.15 - 0.33	0.09 - 0.26	< 0.97 MeV

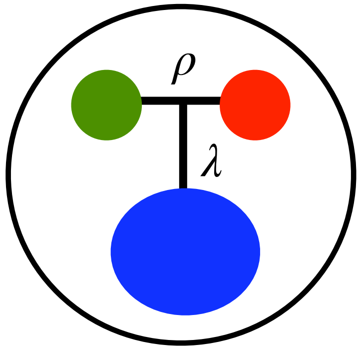
- In this case, the momentum is almost zero.
- The dominant term is $(\sigma \cdot p_i)$ term.

$$\langle \Sigma_c | \, 1 \, | \Lambda_c \rangle \propto q \qquad \langle \Sigma_c | \, p_i \, | \Lambda_c \rangle \propto a \qquad \langle \Sigma_c | \, p_i^2 \, | \Lambda_c \rangle \propto q \; a^2$$

small dominant small

- The dominance of the S-wave decay.
- The relativistic correction is rather small.

Roper-like state: $\Lambda_c^* \to \Sigma_c^{(*)}\pi$



Roper-like state	NR	NR + RC	Exp.
$\Lambda_c(2765) : 1/2^+, \lambda\lambda$	2 - 5	11 - 49	73 MeV
$\Lambda_c(3136) : 1/2^+, \rho\rho$	11 - 123	314 - 1799	

- The overlap is orthogonal in the long-wavelength limit.

$$\langle \Sigma_c | \, 1 \, | \Lambda_c \rangle \propto q^2 \qquad \langle \Sigma_c | \, p_i \, | \Lambda_c \rangle \propto q \qquad \langle \Sigma_c | \, p_i^2 \, | \Lambda_c \rangle \propto a^2$$

negligible small large

- The leading order is somehow suppressed.
- The relativistic correction is essential.

PRD**103**, 094003 (2021)

Some remarks

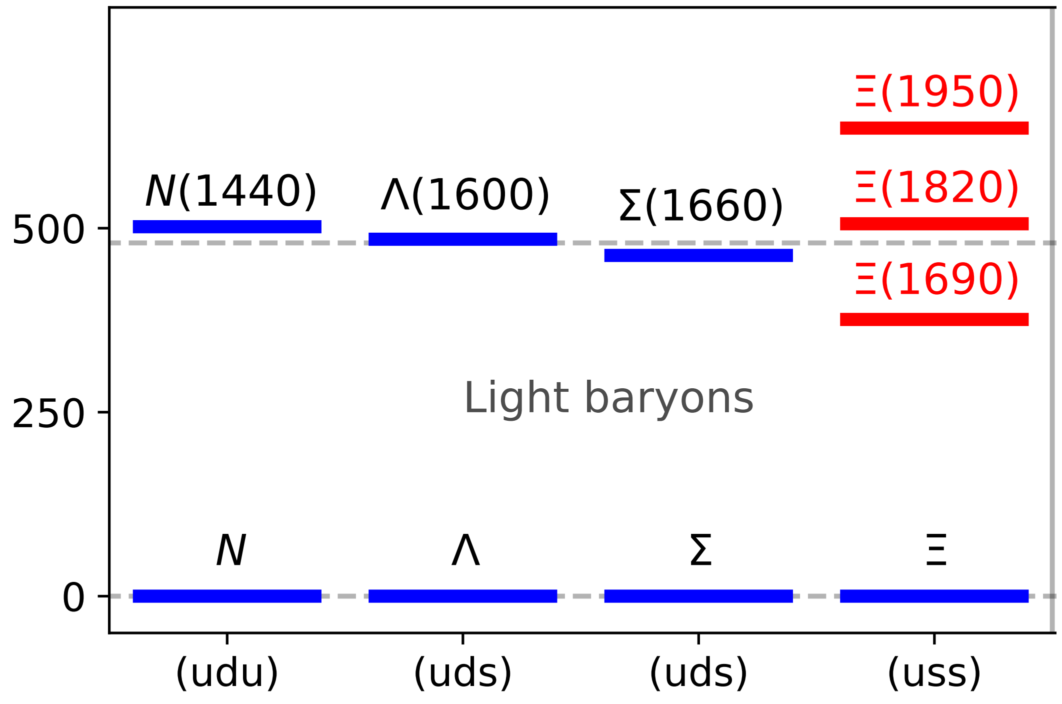
- The Roper-like heavy baryon
—> Quark model state?
- A problem of narrow width
—> Cured by the relativistic correction.
- Role of relativistic correction
—> not important for negative parity state
—> Essential especially for Roper-like state.
- How about fully relativistic quark model?
—> Light-front quark model.
- What about other baryons or mesons?
—> It's interesting to study them as well.

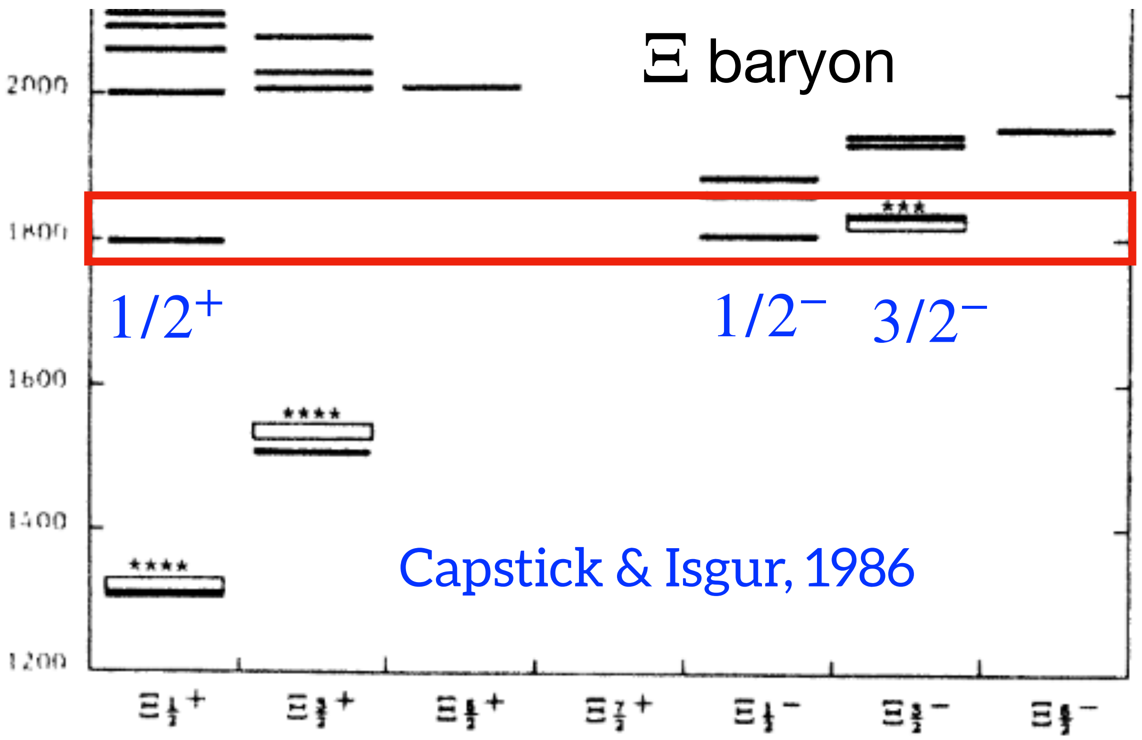
apctp

Part 3

Finding the missing Roper-like resonances

Roper-like strange baryons



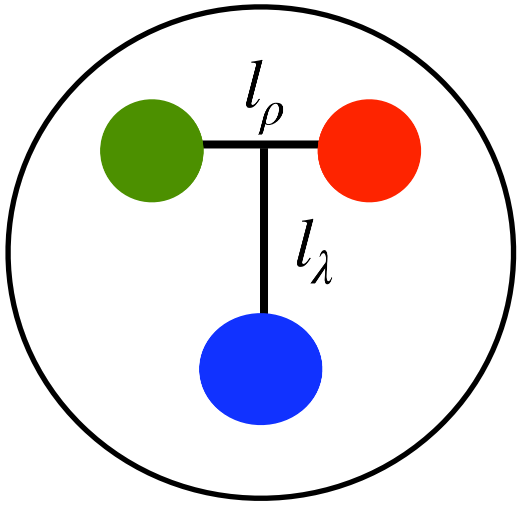


Capstick & Isgur, 1986

- We expect the Roper-like strange baryons lie around ΔM ~ 500 MeV.
- However, they are not yet identified in experiment.
- Here, we study their decay properties in the quark model.

Strange baryon decay in quark model

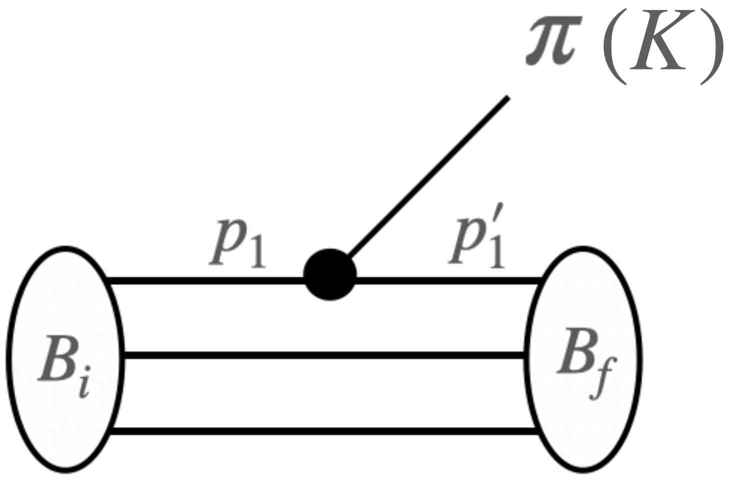
Wave function



Gaussian-type (harmonic oscillator)
The λ and ρ modes are mixed.
We average the mass of strange and light quarks.
Parameter k & m -> the baryon core's radius.

$$\mathbf{6}\otimes\mathbf{6}\otimes\mathbf{6}=\mathbf{56}_S\oplus\mathbf{70}_M\oplus\mathbf{70}_M\oplus\mathbf{20}_A,$$

Quark-meson Interaction FWT



$$H=\underbrace{H(1/m^0)+H(1/m)}_{\text{NR}}+\underbrace{H(1/m^2)}_{\text{RC}}+\dots$$

$$H_{NR}=g\left[\boldsymbol{\sigma}\cdot\boldsymbol{q}-\frac{\omega_\pi}{2m}\boldsymbol{\sigma}\cdot(\boldsymbol{p}_i+\boldsymbol{p}_f)\right]$$

$$H_{RC}=\frac{g}{8m^2}\left[m_\pi^2\boldsymbol{\sigma}\cdot\boldsymbol{q}-2\boldsymbol{\sigma}\cdot(\boldsymbol{p}_i+\boldsymbol{p}_f)\times(\boldsymbol{q}\times\boldsymbol{p}_i)\right]$$

$\Xi(1530),\ 3/2^+$

$\Gamma_{\rm exp} = 9.1 \pm 0.5$ MeV

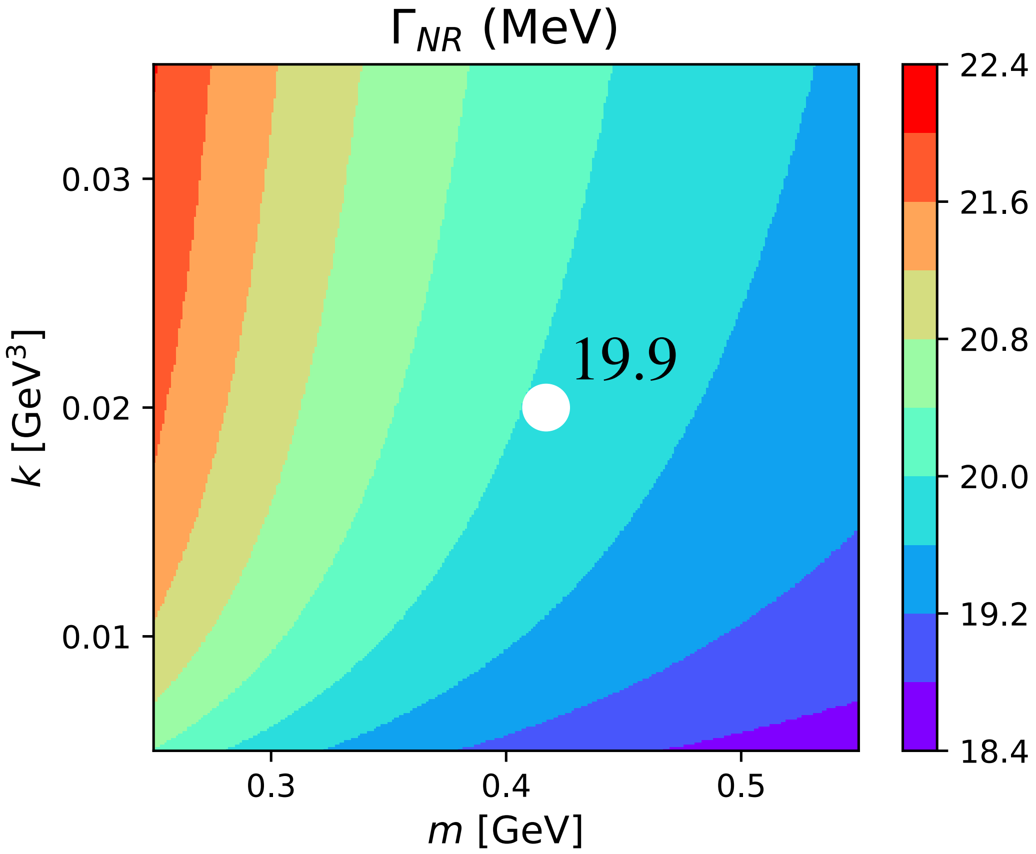
$\Xi(1530),\ 3/2^+$

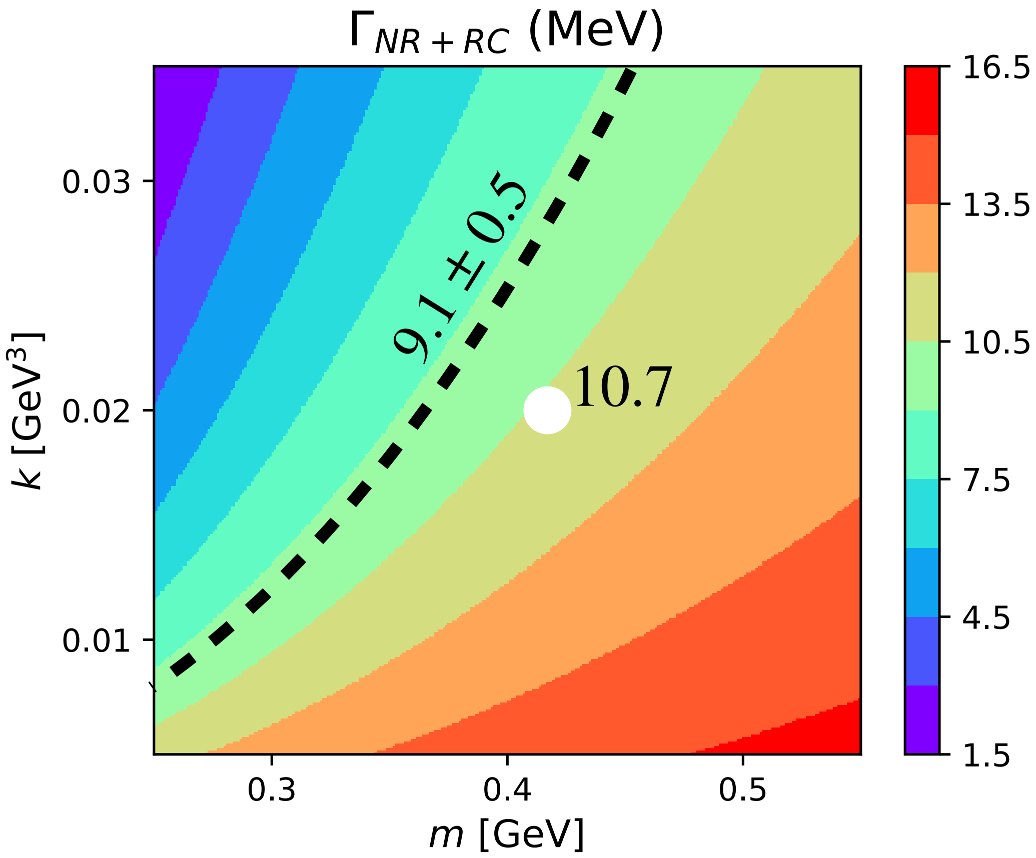
$\Xi(1690),\ ?^?$

$\Xi(1820),\ 3/2^-$

$\Xi(1950),\ ?^?$

- NR over predicts the data by a factor of two.
- With RC, the quark model can explain the data.
- This decay is similar to Σ_c^* decay.





$\Xi(1690)$, $?^?$

$$\Gamma_{\rm exp} < 30\ \text{MeV}$$

		$\Xi\pi$	$\Xi^*\pi$	ΛK	ΣK	Sum
$\lvert 70,{}^{2}10,1,1,1/2^-\rangle$	NR NR+RC	2.0 2.7	0.002 0.002	4.1 4.3	0.6 0.6	6.7 7.6
$\lvert 70,{}^{2}8,1,1,1/2^-\rangle$	NR NR+RC	2.0 2.7	0.002 0.002	16.4 17.3	9.4 9.4	27.9 29.5
$\lvert 70,{}^{4}8,1,1,1/2^-\rangle$	NR NR+RC	32.3 42.8	0.0006 0.0004	16.4 17.3	2.4 2.4	51.1 62.5
$\lvert 56,{}^{2}8,1,1,3/2^-\rangle$	NR NR+RC	0.3 0.2	1.0 1.1	0.2 0.2	~0 ~0	1.8 1.6
$\lvert 56,{}^{2}8,2,0,1/2^+\rangle$	NR NR+RC	0.2 2.3	0.02 0.3	0.4 1.3	0.02 0.1	0.7 3.9

$$R^{\Sigma^+K^-}_{\Lambda^0\bar{K}^0} = 0.50$$

$$R^{\Xi\pi}_{\Sigma\bar{K}} < 0.09$$

$$R^{\Xi^*\pi}_{\Sigma\bar{K}} < 0.06$$

The most suitable state: 1/2-, Not possible to assign it as 1/2+

$\Xi(1620)$

$$\Gamma_{\rm exp} = 40 \pm 15\ \text{MeV}$$

		$\Xi\pi$	ΛK	Sum
$\lvert 70,{}^{4}8,1,1,1/2^-\rangle$	NR NR+RC	24 29	6 6	30 35

Only the 1/2- state that have a sizable width.

Exp status of $\Xi(1820)$

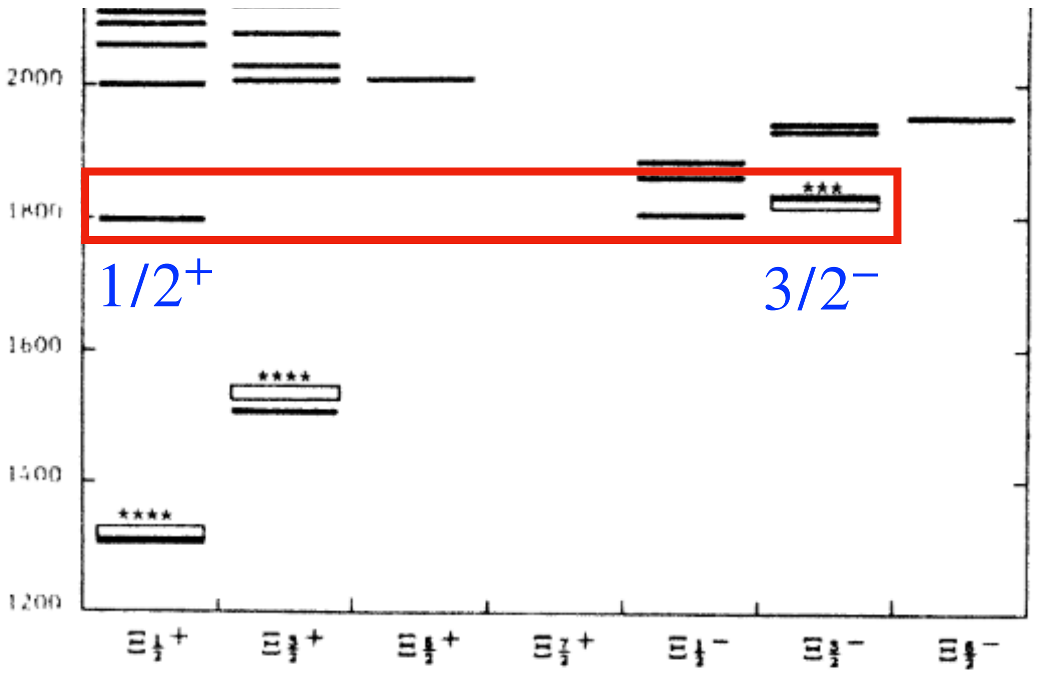
$$\Gamma_{\text{pdg}} = 24 \ \pm 5 \text{ MeV}$$

LHCb, 2021	$\Gamma = 36 \ \pm 4 \text{ MeV}$
BES III, 2020	$\Gamma = 17 \ \pm 15 \text{ MeV}$
BES III, 2015	$\Gamma = 54.4 \ \pm 15.7 \text{ MeV}$
Biagi, 1987	$\Gamma = 24.6 \pm 5.3 \text{ MeV}$
Biagi, 1981	$\Gamma = 72 \pm 20 \text{ MeV}$
Briefel, 1976	$\Gamma = 99 \pm 57 \text{ MeV}$
Gay, 1976	$\Gamma = 21 \pm 7 \text{ MeV}$
Apsel, 1970	$\Gamma = 64 \ \pm 23 \text{ MeV}$

Some experiments –> $J^P = 3/2^-$.

Hypothesis:

other nearby resonance?



Inconsistencies among the data

$\Xi(1820)$ in the quark model

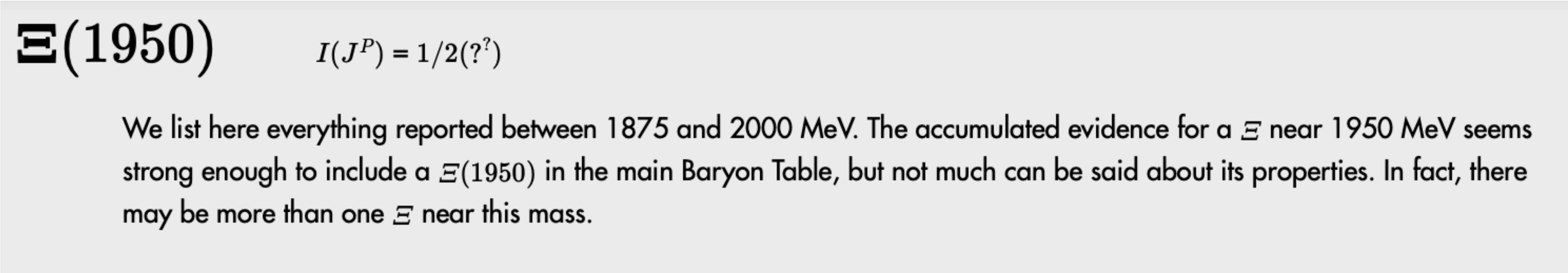
			$\Xi\pi$	$\Xi^*\pi$	ΛK	ΣK	Sum
$1/2^-$	$\lvert 70,{}^28,1,1,1/2^-\rangle$	NR	2.5	0.7	18.3	75.3	96.7
		NR+RC	3.9	0.5	21.5	83.1	109
	$\lvert 70,{}^48,1,1,1/2^-\rangle$	NR	39.3	0.2	18.3	18.8	76.6
		NR+RC	62.4	0.1	21.5	20.8	105
	$\lvert 70,{}^210,1,1,1/2^-\rangle$	NR	2.5	0.7	4.6	4.7	12.4
		NR+RC	3.9	0.5	5.4	5.2	14.9
$3/2^-$	$\lvert 70,{}^28,1,1,3/2^-\rangle$	NR	1.2	6.2	2.6	3.8	13.8
		NR+RC	0.8	7.2	2.4	3.5	13.9
	$\lvert 70,{}^48,1,1,3/2^-\rangle$	NR	1.9	4.8	0.3	0.1	7.1
		NR+RC	1.3	6.5	0.2	0.1	8.1
	$\lvert 70,{}^210,1,1,3/2^-\rangle$	NR	1.2	6.2	0.7	0.2	8.2
		NR+RC	0.8	7.2	0.6	0.2	8.8
$1/2^+$	$\lvert 56,{}^28,1,1,1/2^+\rangle$	NR	0.3	0.9	0.9	17.2	19.3
		NR+RC	4.5	8.8	3.9	64.1	81.2

RC —> Large (for 1/2+), but small (for 1/2-,3/2-)

$3/2^-$ —> small (Γ~14) & dominant $\Xi^*\pi$

$1/2^+$ —> large (Γ~80) & dominant ΣK

$\Xi(1950)$

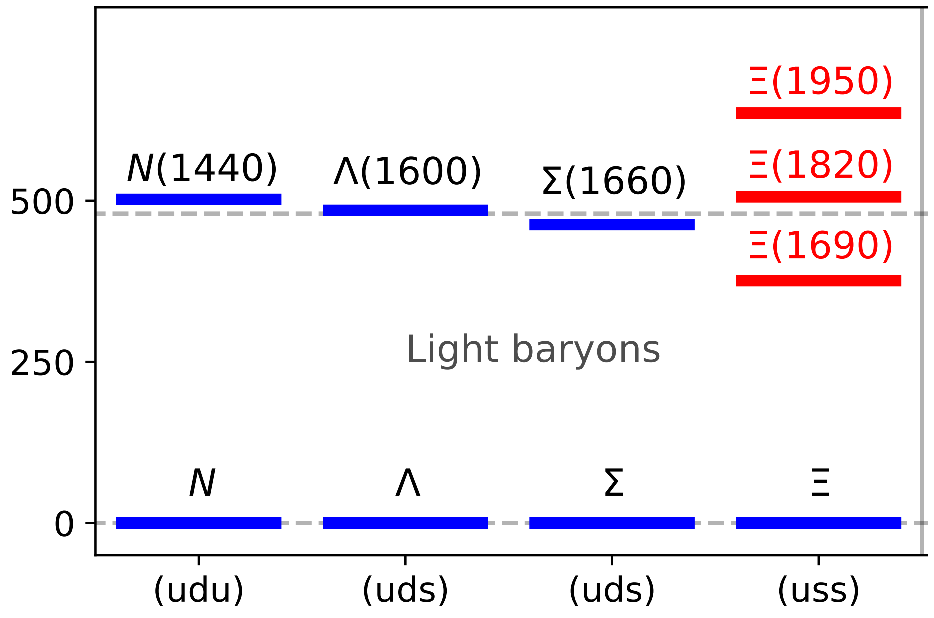


$\Xi(1950)$ $I(J^P) = 1/2(?^?)$

We list here everything reported between 1875 and 2000 MeV. The accumulated evidence for a Ξ near 1950 MeV seems strong enough to include a $\Xi(1950)$ in the main Baryon Table, but not much can be said about its properties. In fact, there may be more than one Ξ near this mass.

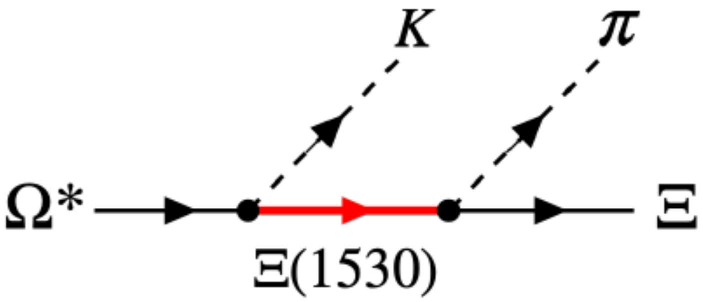
		$\Xi\pi$	$\Xi^*\pi$	ΛK	ΣK	$\Sigma^* K$	Sum
$\lvert 56,{}^28,2,0,1/2^+\rangle$	NR	0.2	2.5	0.7	23	3.1	29
	NR+RC	6.0	26	4.9	117	15	169

$$\Gamma_{\rm exp} = 60 \pm 20 \ \text{MeV}$$



- The predicted width is quite large for $1/2^+$ as compared to data.
- ΔM ~ 636 MeV seems also larger than expected.
- Not suitable with $1/2^+$.

Intermezzo: $\Omega(2012)$

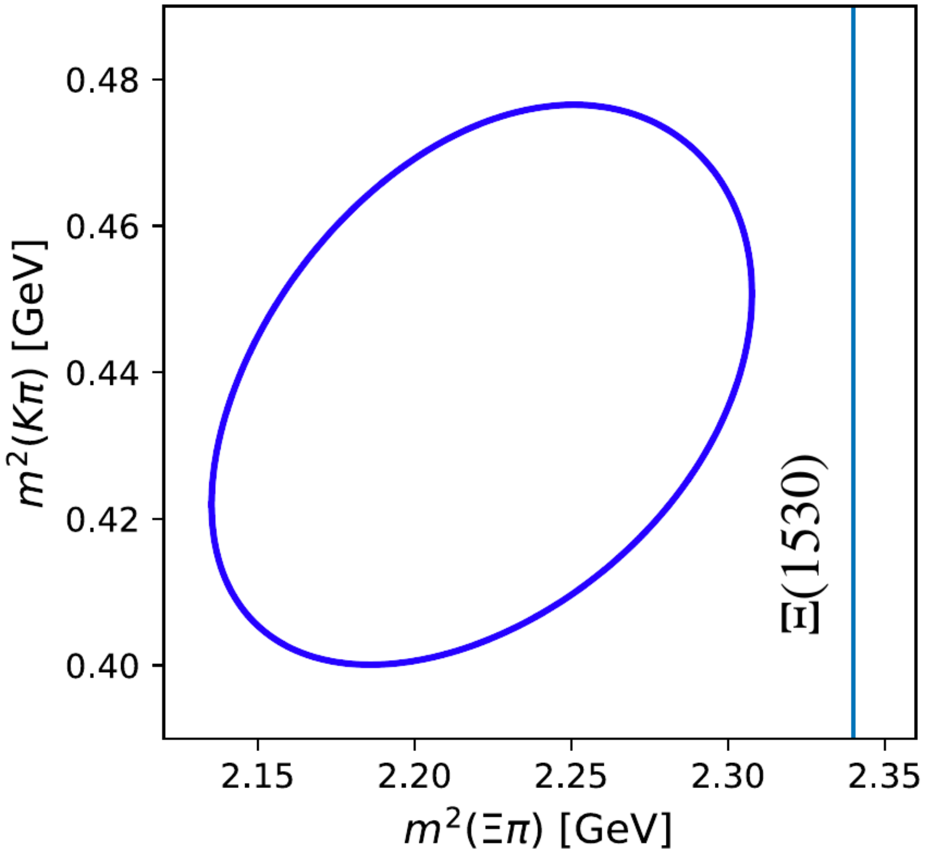


- Discovered by Belle in 2018.
- Relatively narrow state.
- Likely to be $3/2^-$ in the quark model.
- Recently, Belle measure its 3-body decay.

$$[R^{\Xi\pi\bar{K}}_{\Xi\bar{K}}]_{\rm exp} < 11.9\%.$$

State	Channel	$\Gamma_{\rm NR}$	$\Gamma_{\rm NR+RC}$	$\Gamma_{\rm exp}$
$\Omega(2012)$	$\Xi\bar{K}$	2.63	2.41	
	$\Xi\bar{K}\pi$	0.09	0.11	
	sum	2.72	2.52	$6.4^{+3.0}_{-2.6}$

$$[R^{\Xi\pi\bar{K}}_{\Xi\bar{K}}]_{\rm QM} = 4.5\%,$$



Some remarks

- Opportunity to study strange baryon in J-PARC.
  —> Roper-like Ξ and Ω resonances.
  —> Establishing negative parity states.

- Signature of the Roper-like Ξ resonance.
  —> Large width & dominant $\Sigma\bar{K}$ channel.

- Identifying overlapping resonances: $1/2^+$ and $3/2^-$.
  —> How to distinguish them in J-PARC experiment?

- $\Omega(2012)$: quark model, molecular state, or what?
  —> In QM, it is an orbital excitation with $3/2^-$.
  —> Need to find its LS partner

Final part

Summary & outlook

Summary & Outlook

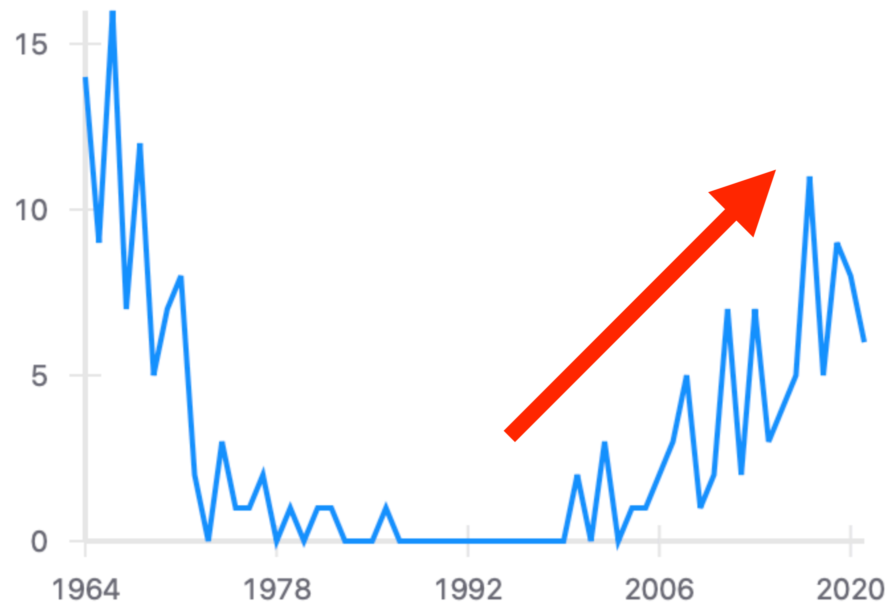
- We recently study Roper-like resonances.
  —> Similarity: mass & decay property
  —> Three-body decay —> spin-parity

- Roper-like resonances in the quark model.
  —> Narrow width problem
  —> Inclusion of relativistic correction
  —> Relativistic quark model -> LFQM

- Finding the missing Roper-like resonances.
  —> Strange baryons in the quark model
  —> Production in J-PARC

- Studying other system.
  —> Heavy-light meson (D meson, B meson, etc)

Citations per year

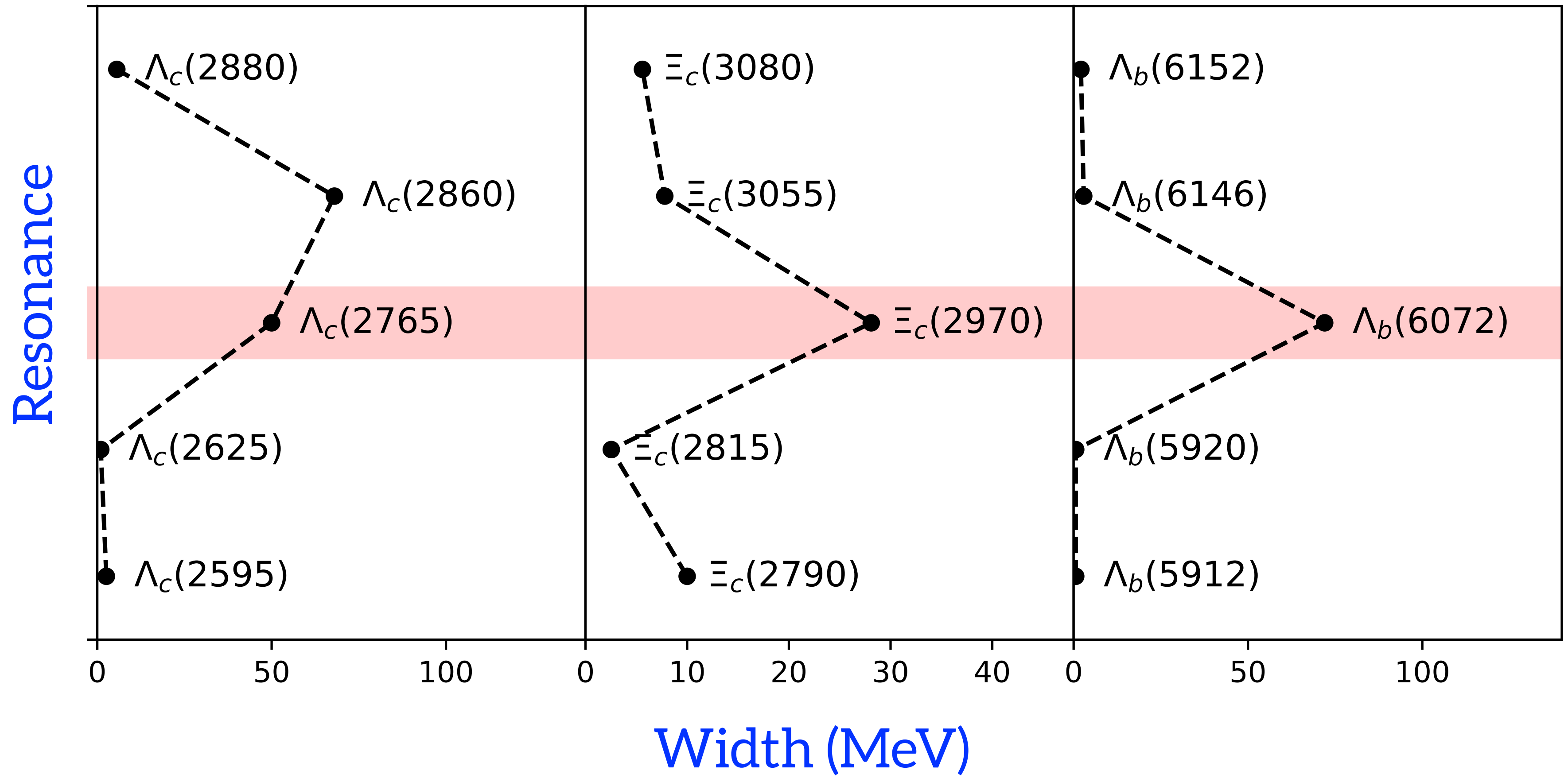


Discovery of Roper resonance

Thank you for your attention

Email: ahmad.jafar.arifi@apctp.org
Web: https://ajarifi.github.io

Decay widths: Why are they so broad?

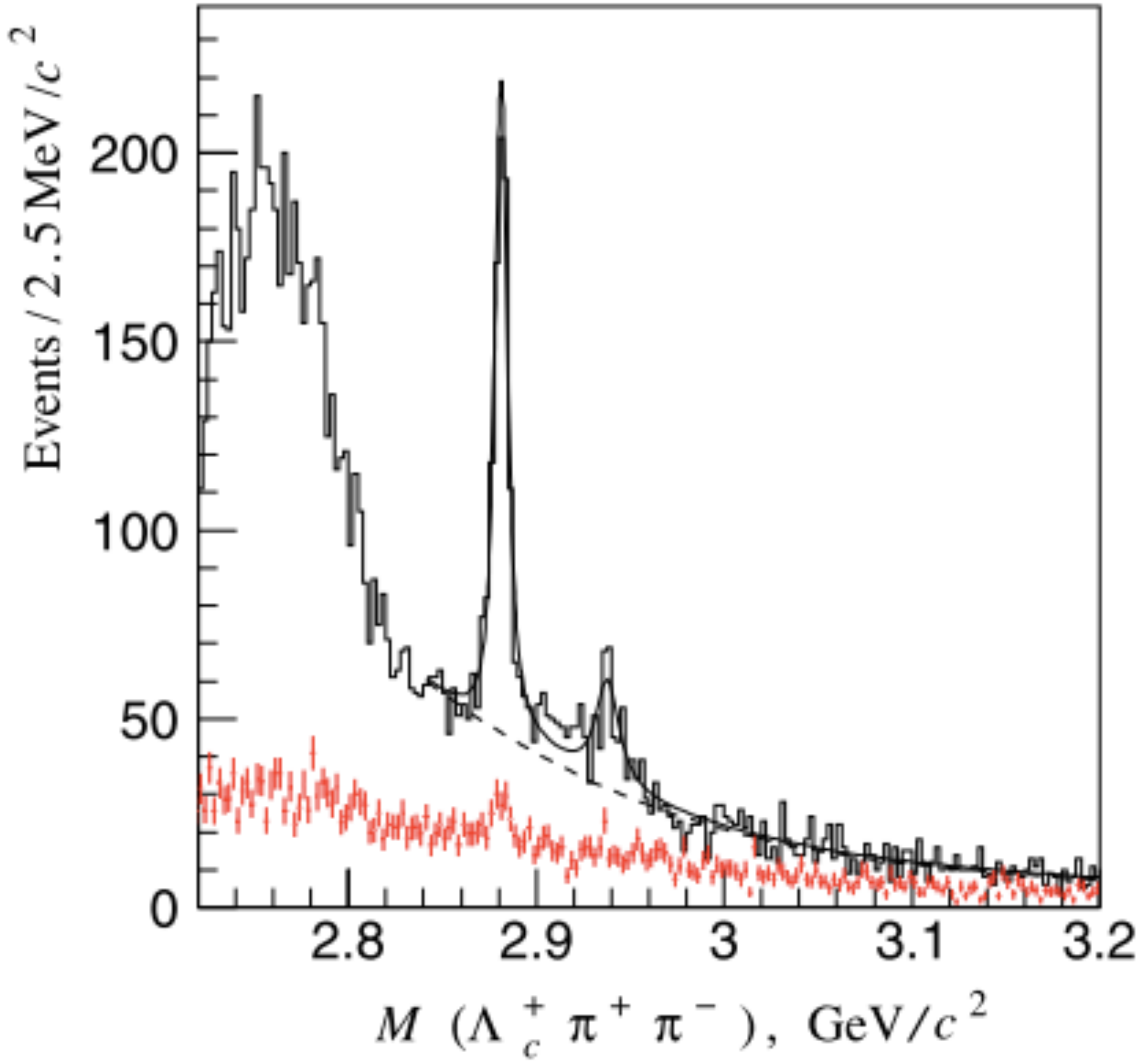


Quark model:

- narrow width
  (Orthogonality of w.f.)
- Relativistic corr.
  FWT transformation.
- The importance of
  $1/m^2$ term.

Roper-like state	NR	NR + RC	Exp.
$\Lambda_c(2765) : 1/2^+, \lambda\lambda$	2 - 5	11 - 49	73 MeV

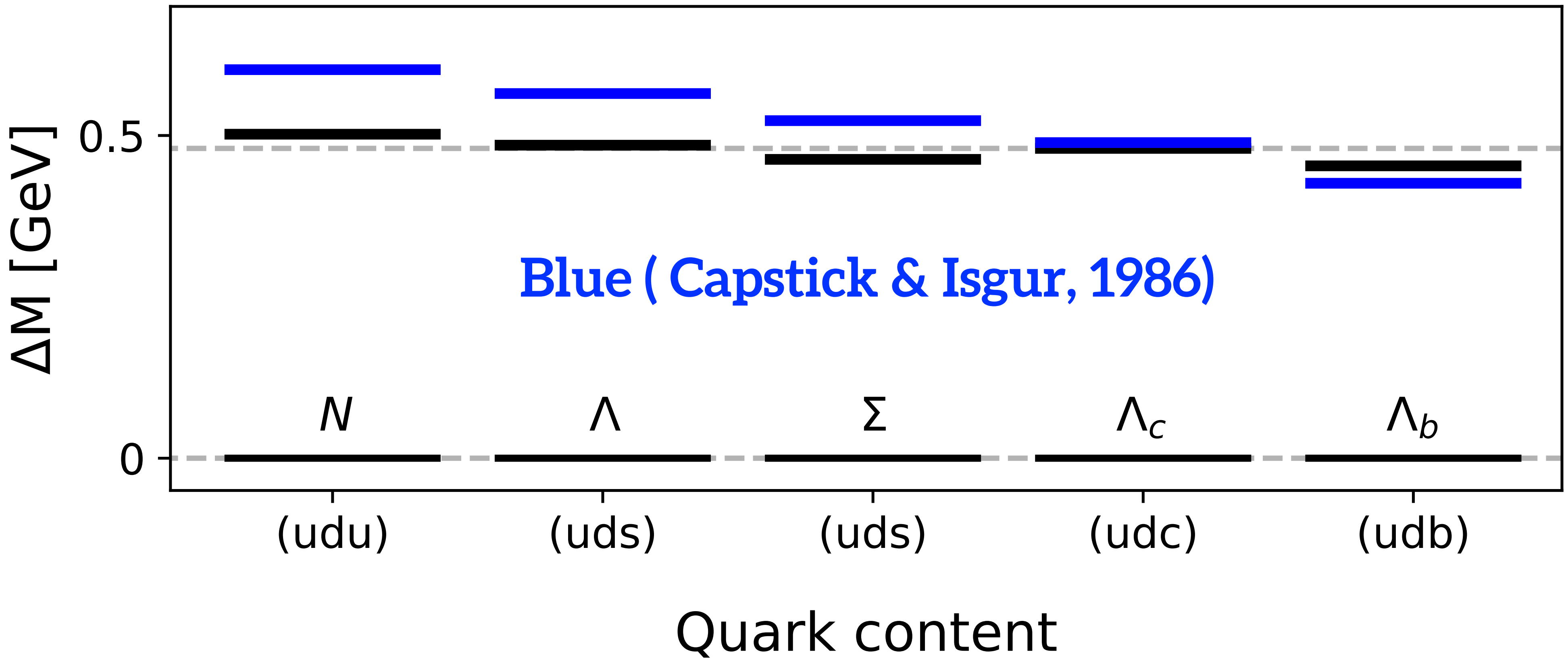
Suppression of nonresonant contribution



Experimental constraints on the spin and parity of $\Lambda_c(2880)$.

Belle. PRL98 262001 (2007)

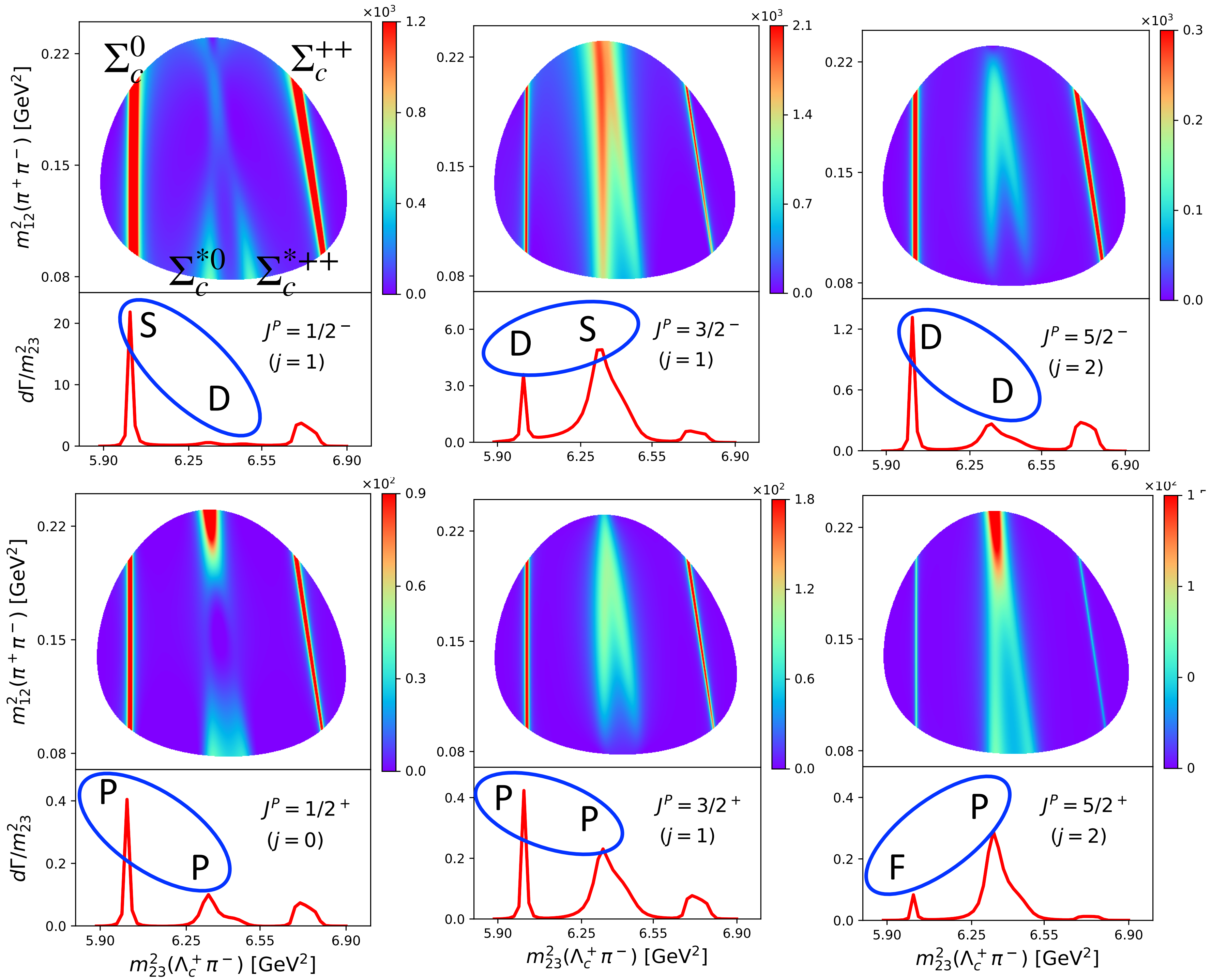
Comparison with the quark model



Quark model

- The mass has decreasing behaviors.
- lowering behavior of λ mode.
- heavy baryons have better agreements.

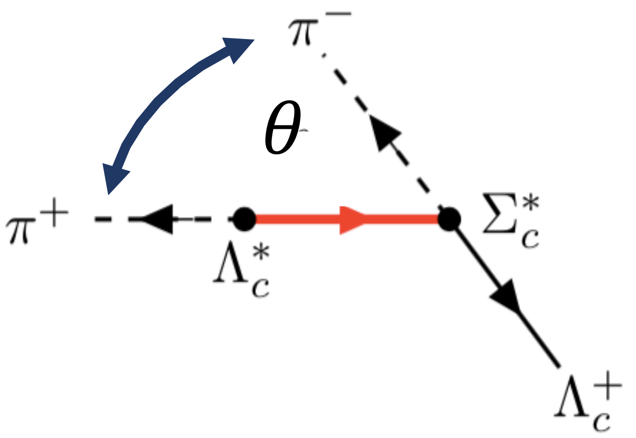
Dalitz plot: $\Lambda_c^*(2765)$ decay



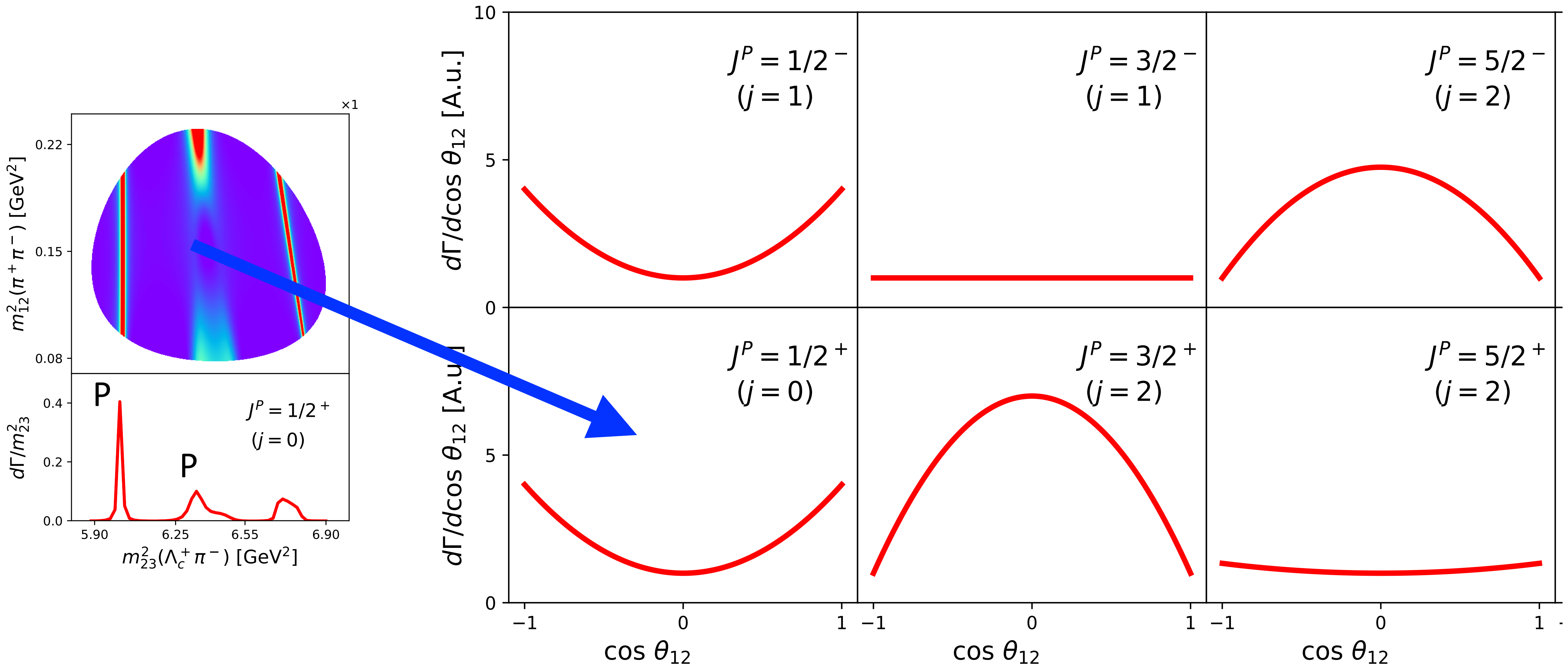
Ratio

$$R = \frac{\Gamma(\Lambda_c^* \to \Sigma_c^* \pi)}{\Gamma(\Lambda_c^* \to \Sigma_c \pi)}$$

Angular correlation



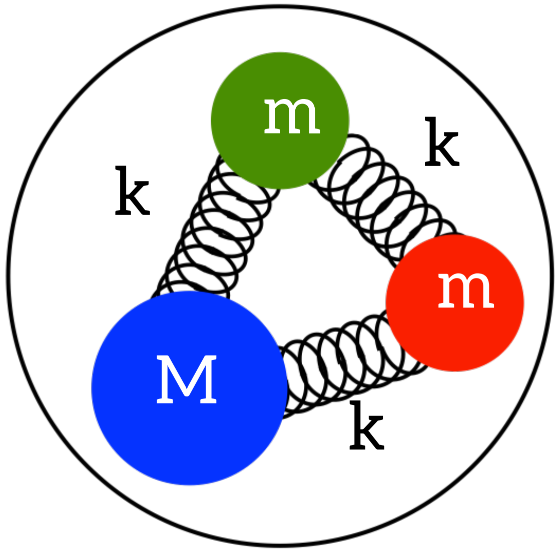
Angular correlation: $\Sigma_c^*(3/2^+)$ band

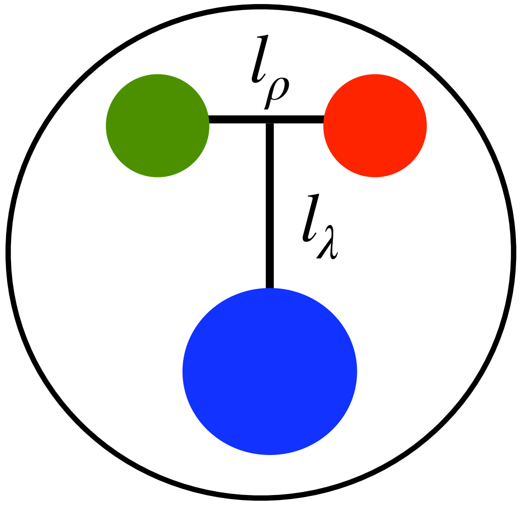


$$W(\theta) \propto |A_{1/2}|^2\, \underbrace{(1 + 3\cos^2\theta)}_{\text{Valley}} + |A_{3/2}|^2\, \underbrace{3\sin^2\theta}_{\text{Hill}}$$

$$\tilde{R} = \frac{|A_{3/2}|^2}{|A_{1/2}|^2}$$

Wave function of heavy baryon





Harmonic Oscillator potential

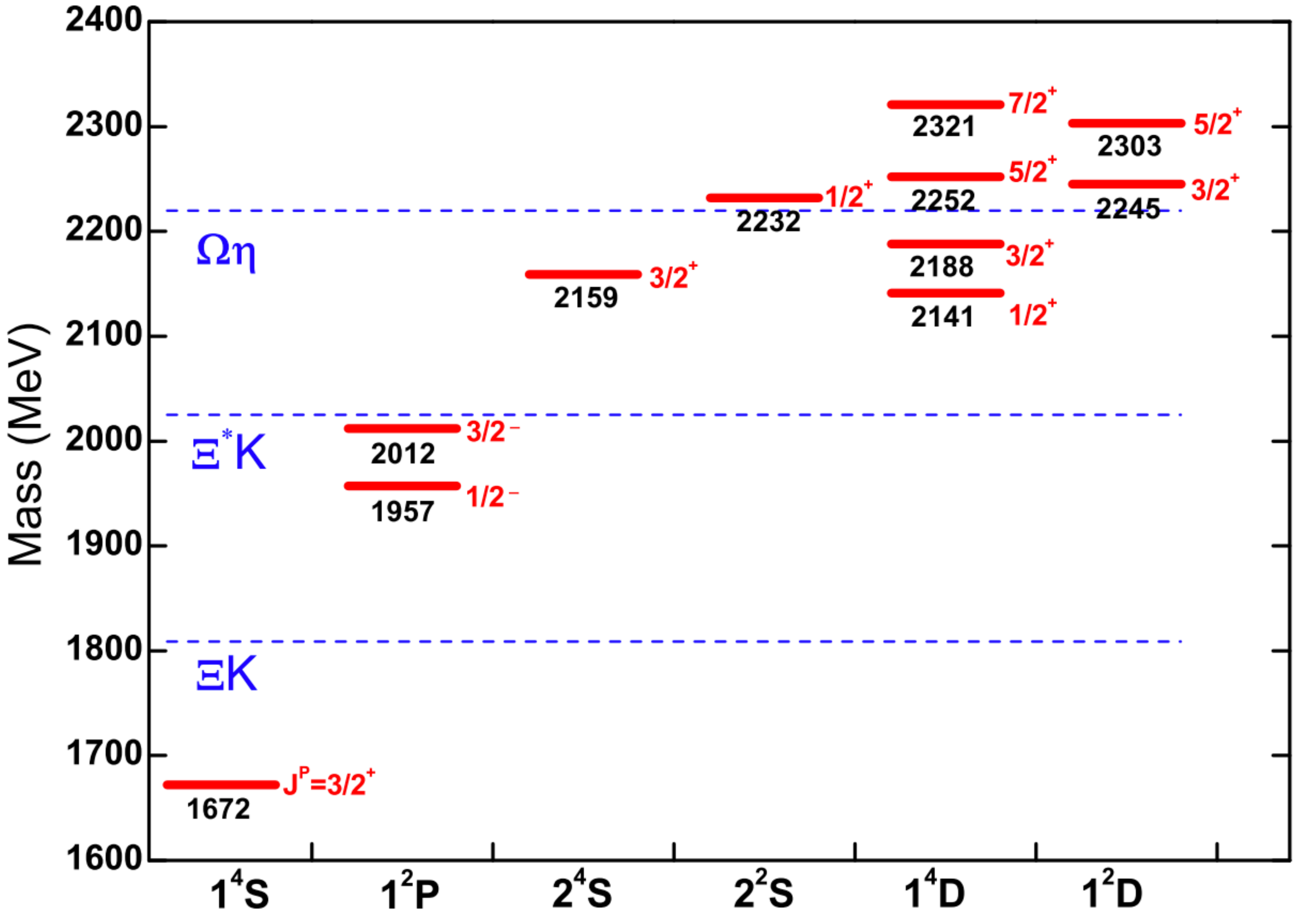
M = 1.50 GeV
m = 0.35 GeV
k = 0.03 GeV^3

⇨ $\omega_\lambda = 350\ \text{MeV}$

$$Y_c = \underbrace{\left[\left[\overset{\text{Orbital}}{\psi_{l_\lambda}(\overrightarrow{\lambda})\psi_{l_\rho}(\overrightarrow{\rho})}, d\right]^j, \overset{\text{Spin}}{s_c}\right]^J \psi_{flavor}}_{\text{Symmetric}}\ \underbrace{\psi_{color}}_{\text{Anti-Symmetric}} \qquad J = j + s_Q$$

Nagahiro, *et. al.* PRD95 014023 (2017)

Ω spectrum



We will focus on these 3 states:

1 doublet of P-wave state

1 Roper-like state

Ω(1957)

Ω(2012)

Ω(2159)

Phys. Rev. D **101**, 016002 (2020)