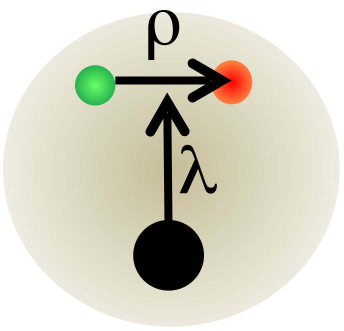
Charmed baryons and their interactions

Atsushi Hosaka
RCNP, Osaka University

Workshop Heavy flavor and CP violation
at Lanzhou, July 22-25, 2015

With Noumi, Shirotori, Kim, Sadato,
Yoshida, Oka, Hiyama, Nagahiro, Yasui



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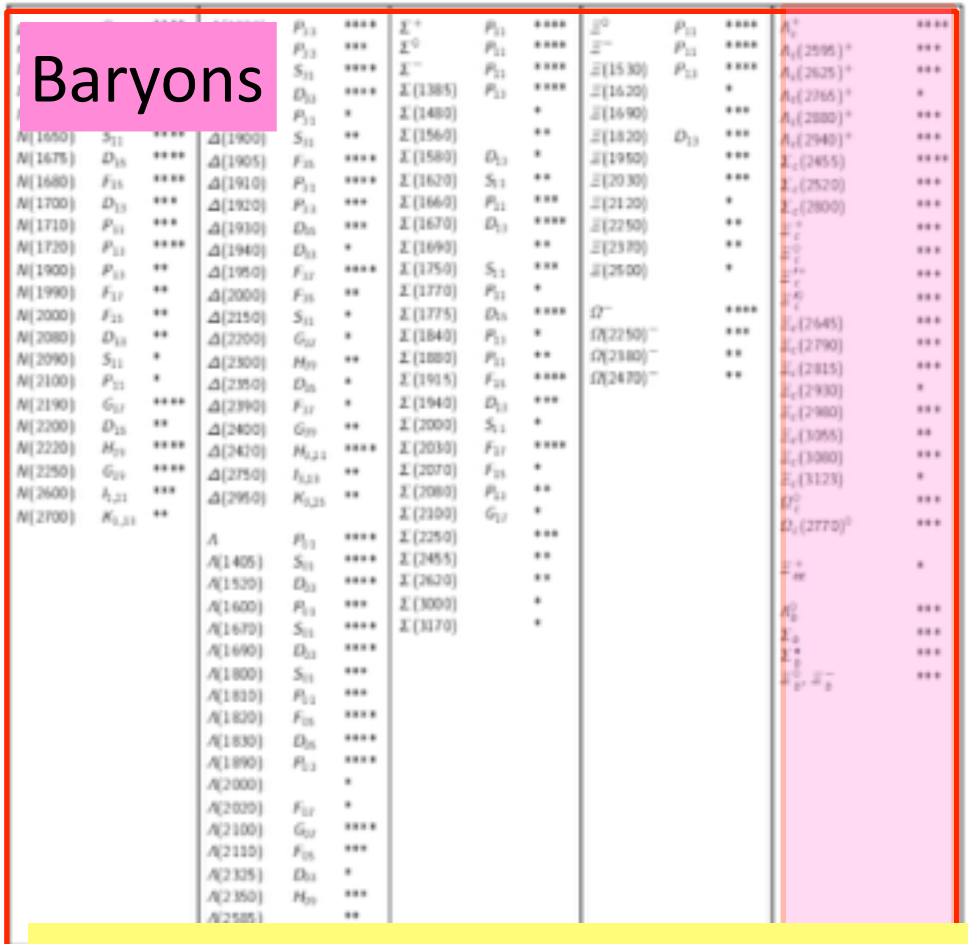
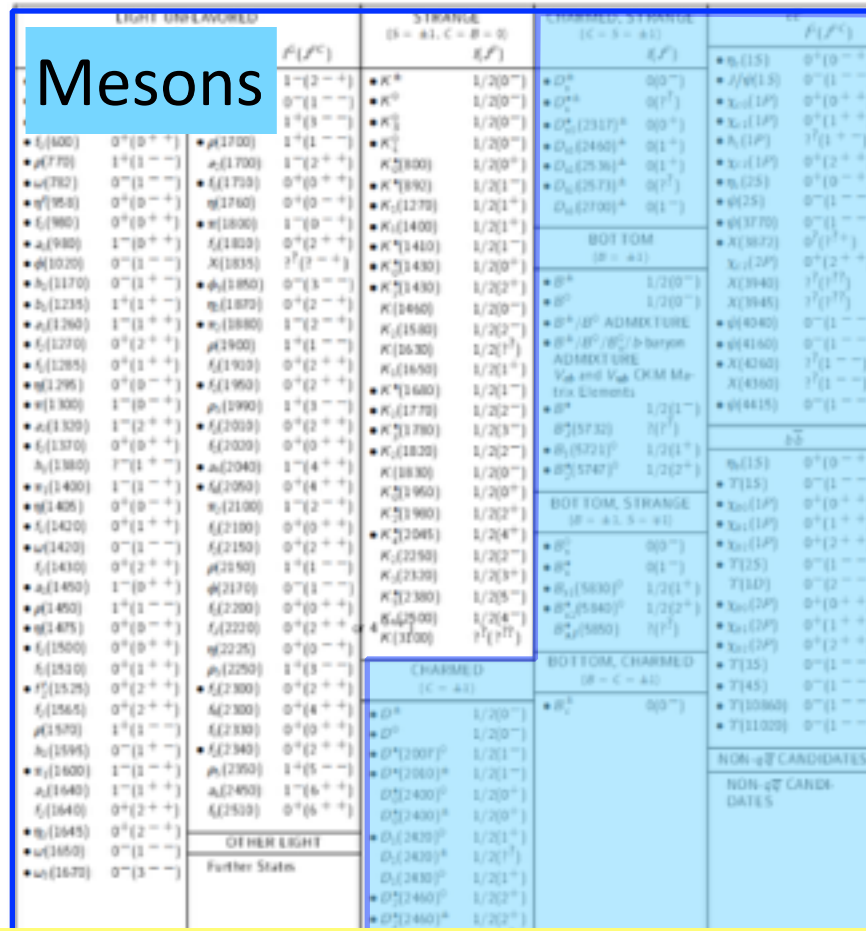
1. Introduction
2. Structure: *How* ***ρλ modes*** *appear in the spectrum*
3. Productions

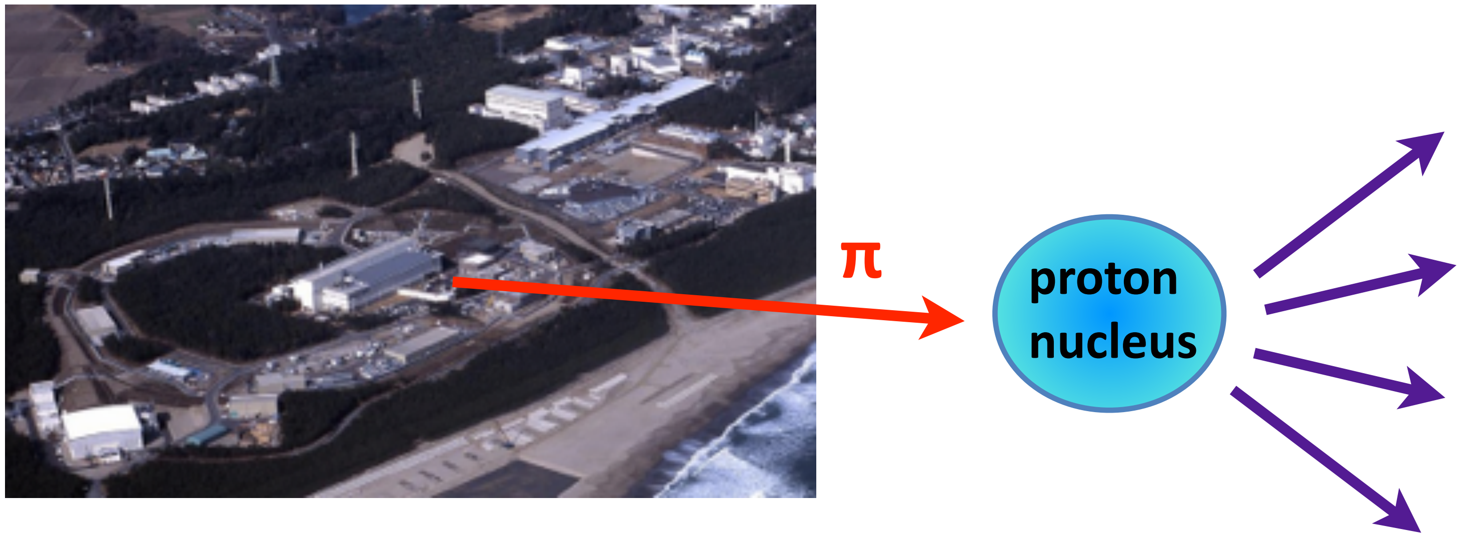
1. Introduction Particle data book (PDG)





- Most baryons are light flavored qqq, mesons as $q\bar{q}$
- Can we see more heavy baryons, exotics?
- How multiquarks of new exotics behave?

J-PARC **50 GeV proton —> 30 GeV pion beam**



Physics of charm hadrons

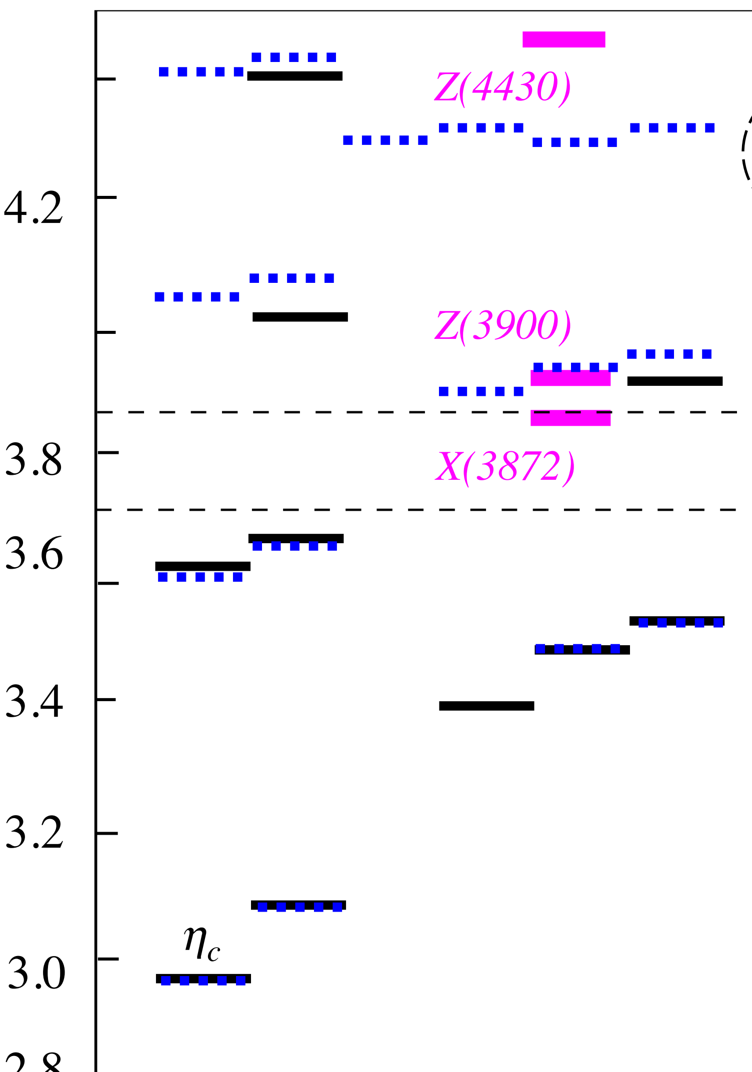
- Primarily single charm baryons, excited states
- Hidden charm baryons, pentaquark
- D, D* mesons and excited states
- Charmed nuclei

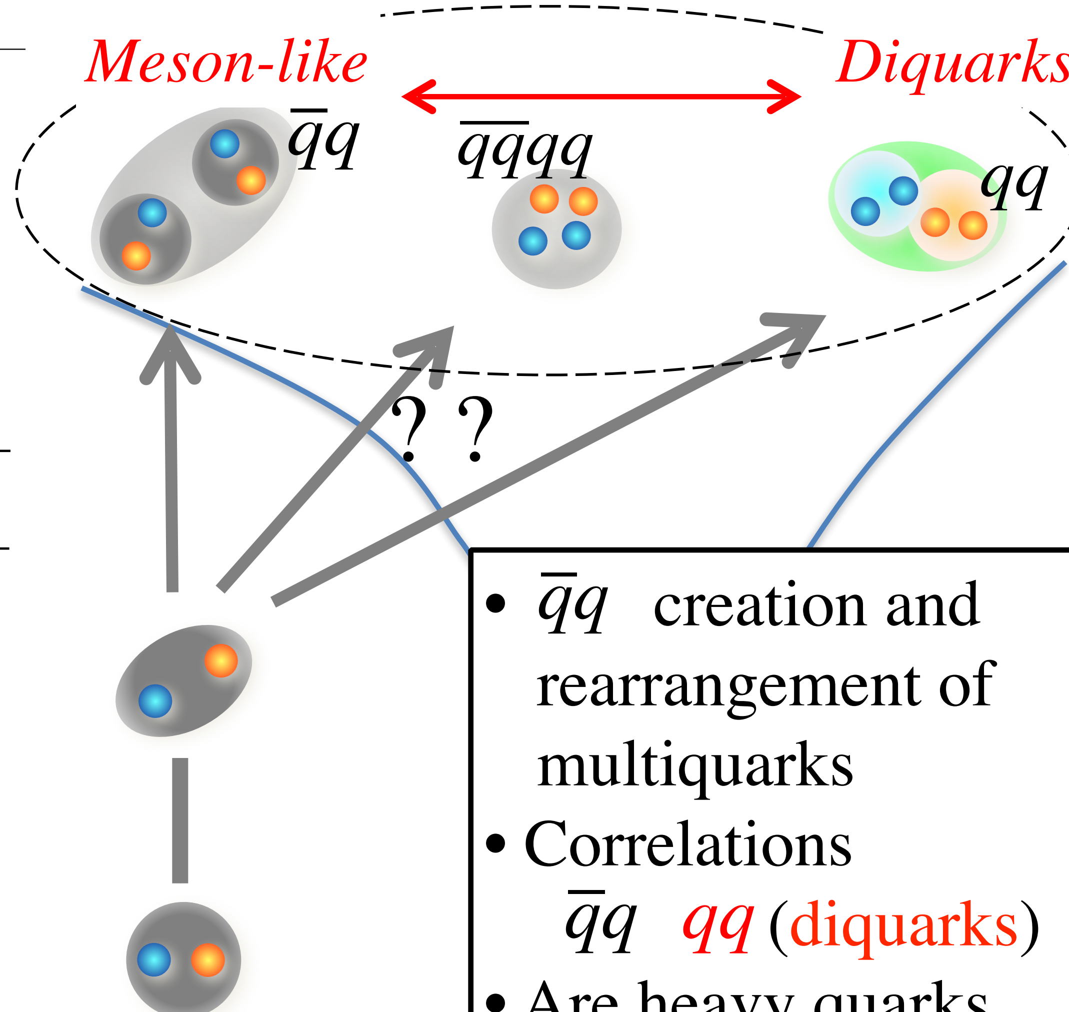
Proposal approved and physics discussions are going

- What we can learn from charmed baryons
  Qqq: the simplest system with qq

- How much they are produced,
  in particular, excited states

Correlations in multiquarks





- $\bar{q}q$ creation and rearrangement of multiquarks
- Correlations
  $\bar{q}q$ qq (diquarks)
- Are heavy quarks useful to know it?

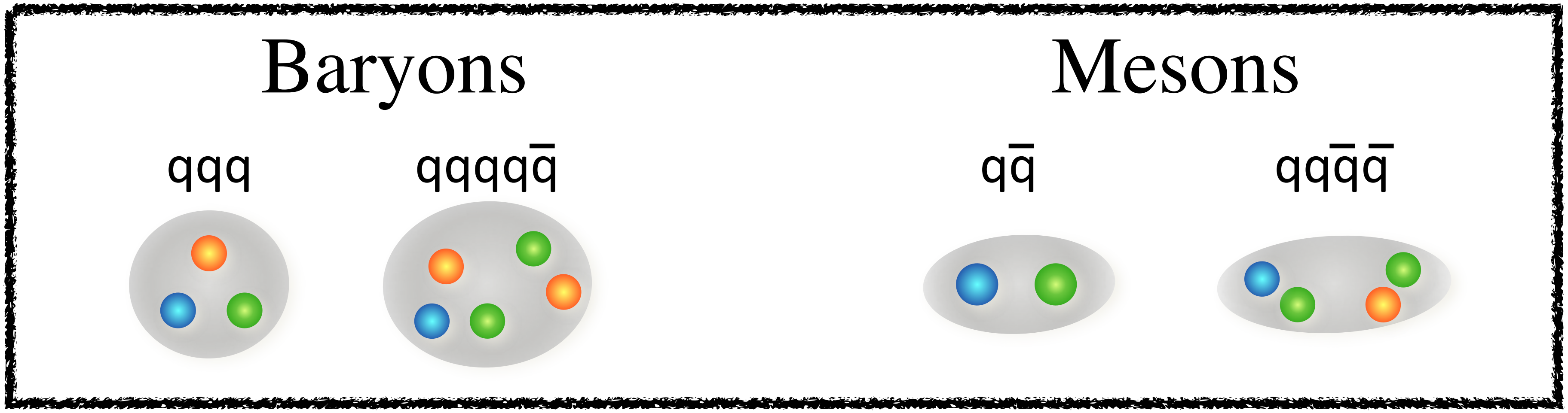
Recent interests are triggered by **Exotic hadrons**

A SCHEMATIC MODEL OF BARYONS AND MESONS

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the represen-

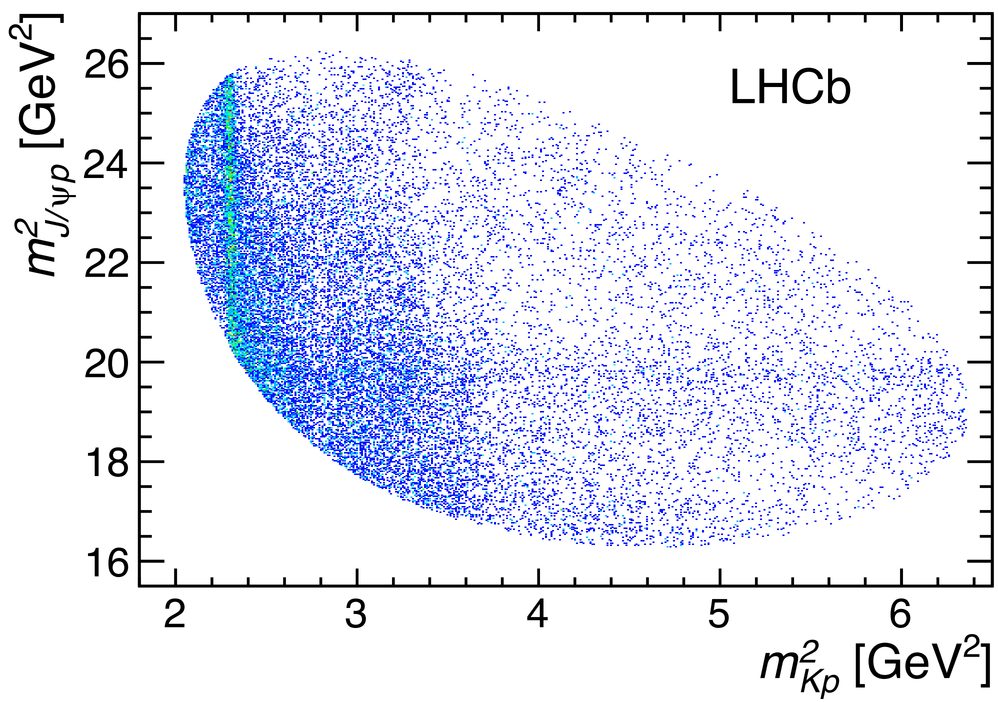


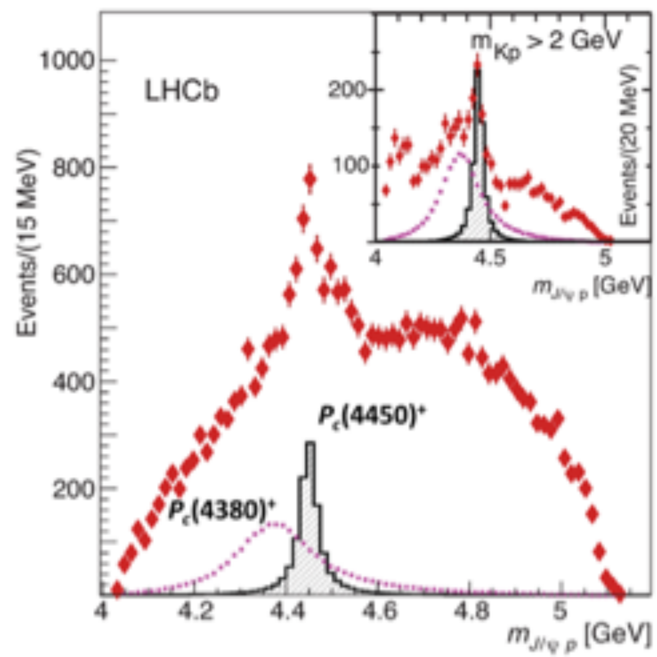
LHCb found Pentaquarks

http://arxiv.org/abs/1507.03414

7-8 TeV pp collision —> Λ_b

$$\Lambda_b \longrightarrow J/\psi, p, K^-$$





- What we can learn from charmed baryons
  Qqq: the simplest system with qq

- How much they are produced,
  in particular, excited states

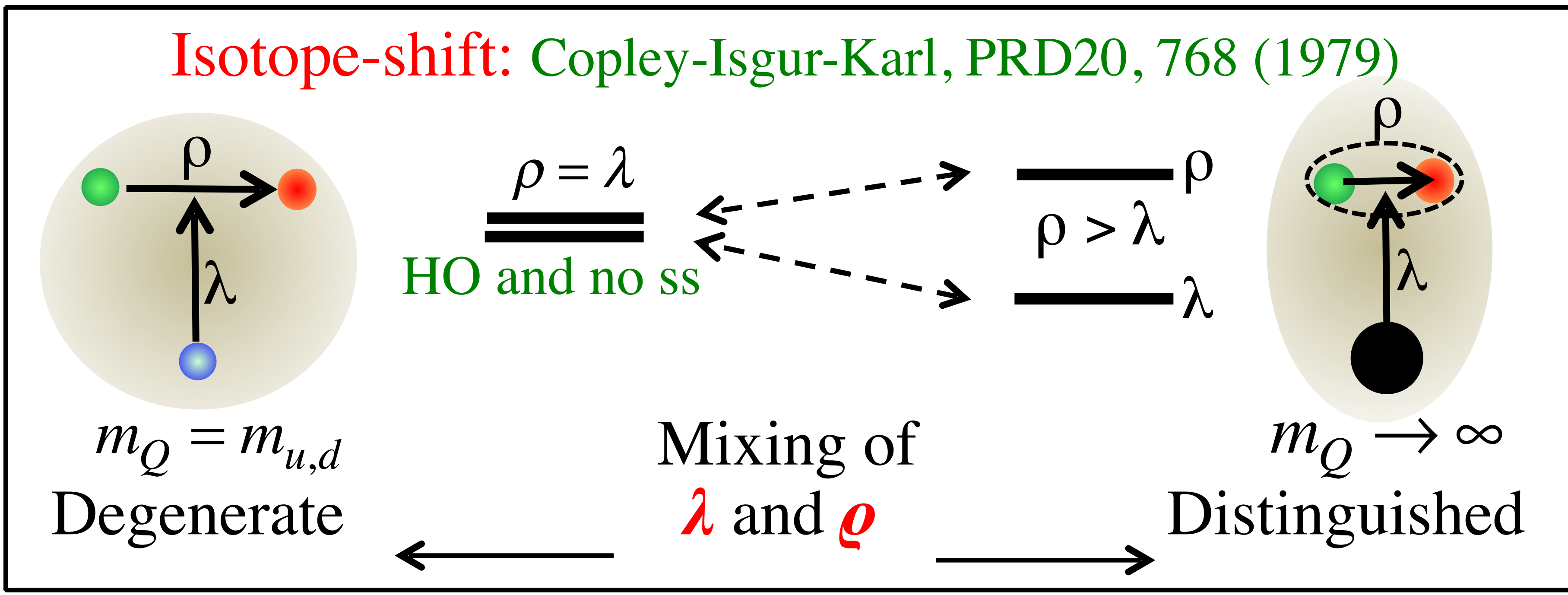
2. Structure
3. Productions $\pi + N \longrightarrow D^* + \Lambda^*$

2. Structure: *what do we expect to study?*

A heavy quark distinguish the fundamental modes

λ and ***ρ***

Place to look at ***qq*** dynamics



Spectrum and WF's as M_Q is varied

Roberts-Pervin, IJMPA, 23, 2817 (2008)

Yoshida, Sadato, Hiyama, Oka, Hosaka

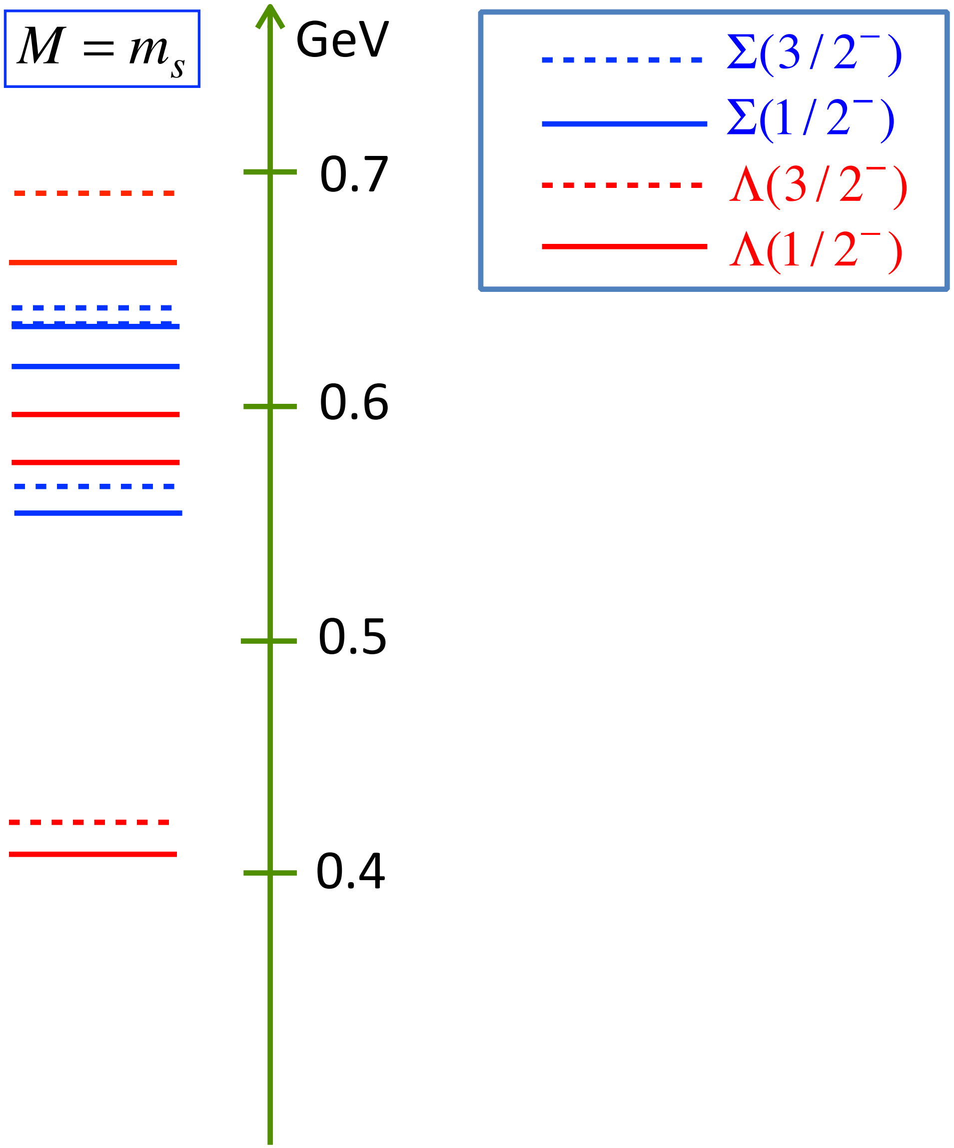
- Model Hamiltonian

$$H = \frac{p_1^2}{2m_q} + \frac{p_2^2}{2m_q} + \frac{p_3^2}{2M_Q} - \frac{P^2}{2M_{tot}}$$

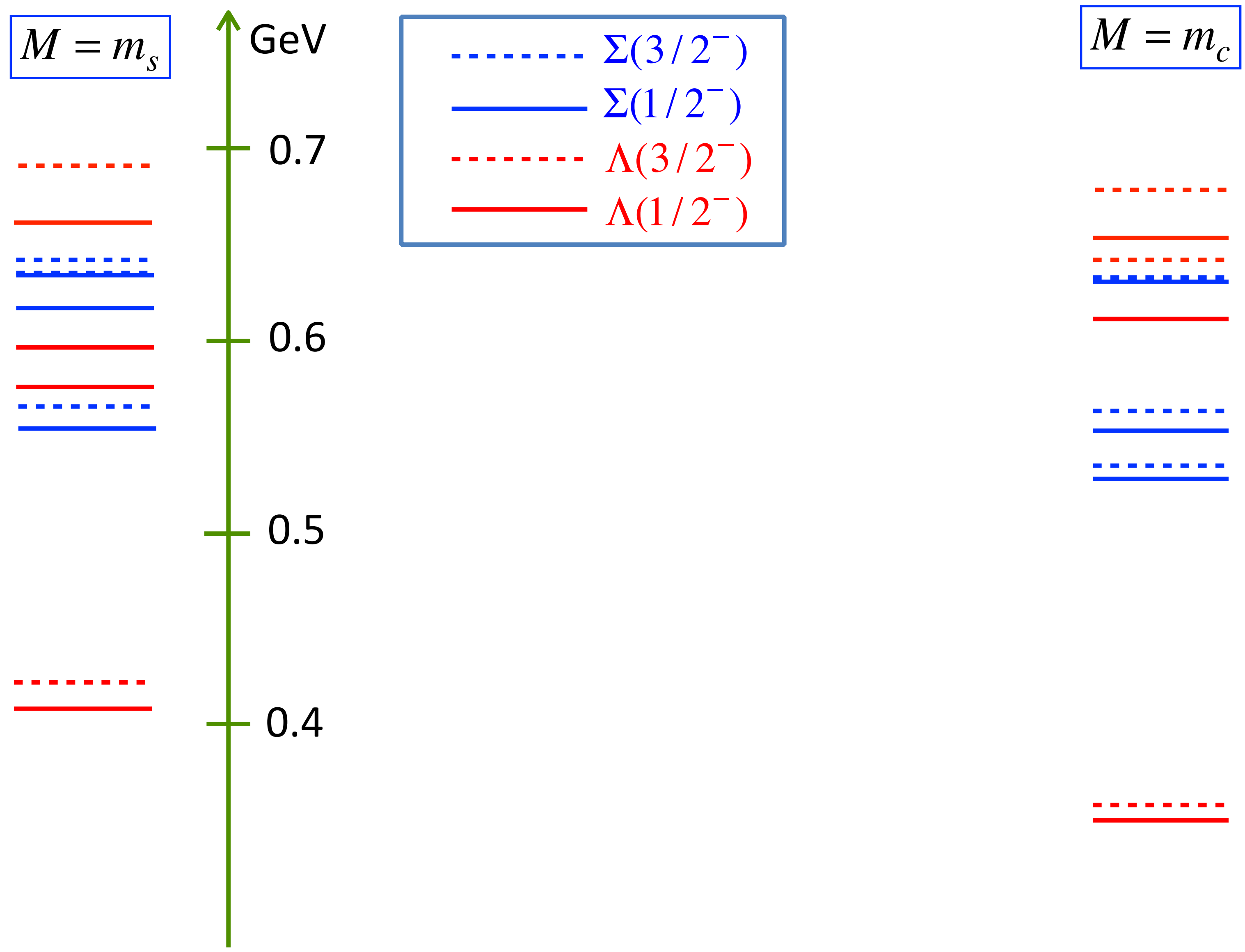
$$+ V_{conf}(HO) + V_{spin-spin}(Color - magnetic) + \dots$$

- Solved by the Gaussian expansion method

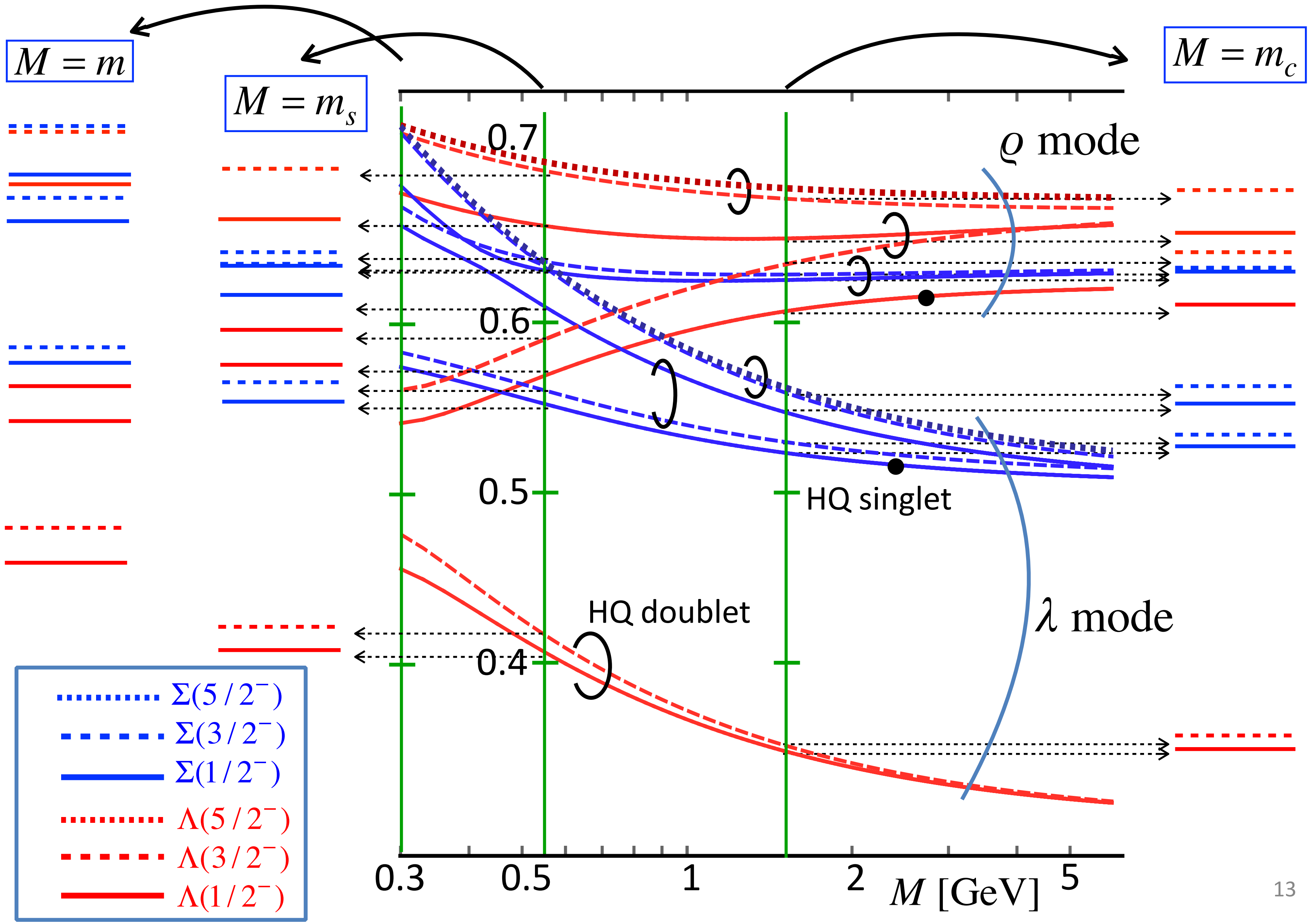
Negative parity states — p-wave excitations - 1/2⁻, 3/2⁻



Negative parity states — p-wave excitations - $1/2^-$, $3/2^-$



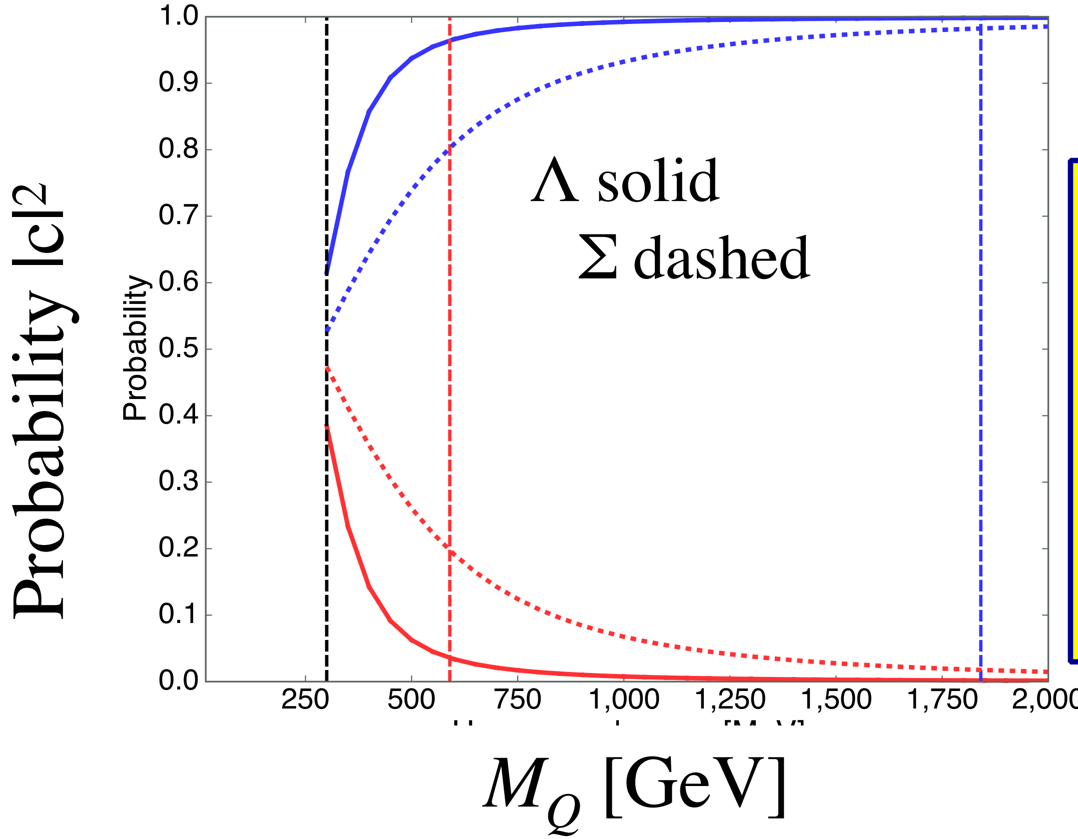
Negative parity states — p-wave excitations - 1/2⁻, 3/2⁻



Wave function

Mixing of $\Lambda(\text{phys}) = c_\lambda \Lambda(^2\lambda) + c_\rho \Lambda(^2\rho)$

e.g. λ-mode dominant state: How much the other mode mixes?



Λ_c^* is almost pure ***λ*** mode
➔
Reflect more ***qq*** nature

SU(3) ⟷ Heavy quark

Intermediate summary

- Heavy quark spectroscopy will give more information on constituents
- Isotope shift may resolve two diquark modes

  collective and *internal*
- Λ baryons may have more chance to see the two modes separately
- HQ singlet, doublet are also useful
- Systematic study from strange to heavy is useful

3. Productions

$\pi + N \rightarrow D^* + \Lambda_c$ reactions

Cross sections (Y_c/Y_s) and Ratios (Y_c^*/Y_c)

Strategy:

Forward peak (high energy) → t-channel dominant

Next figure

We look at:

(1) Absolute values

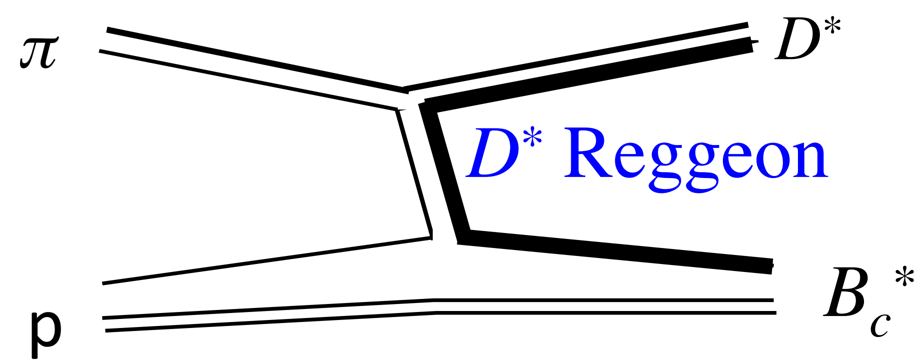
by (Λ_c/Λ_s) by the Regge model, ***K*, D* Vector-Reggeon***

(2) Ratios of B_c^*(λ modes) / B_c

by a one step process of *Qd* picture for λ-mode

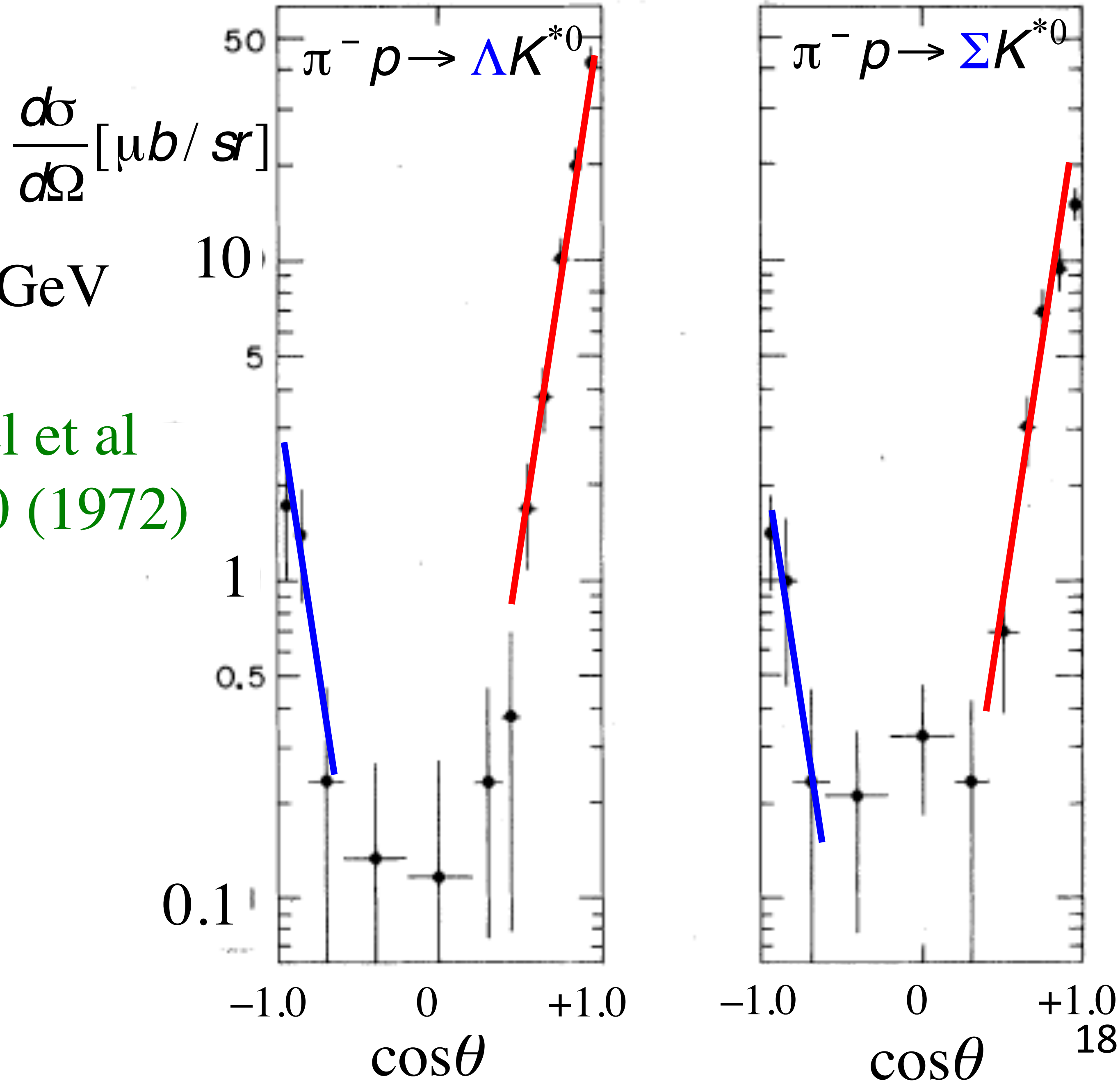
Pion-induced reaction

$\pi + p \rightarrow D^* + B_c^*$



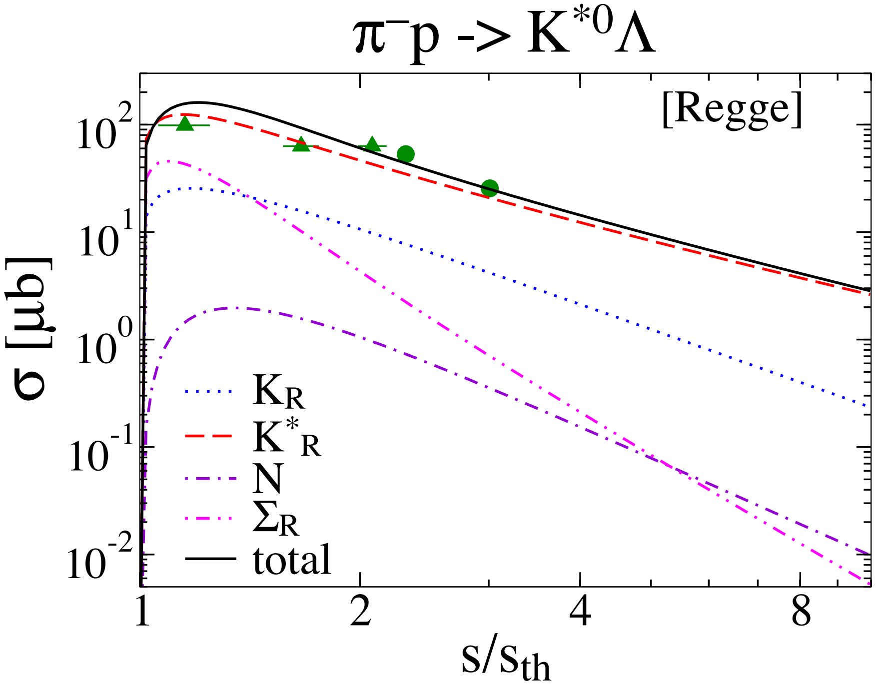
$p_{\pi,\,\mathrm{Lab}} = 4.5$ GeV

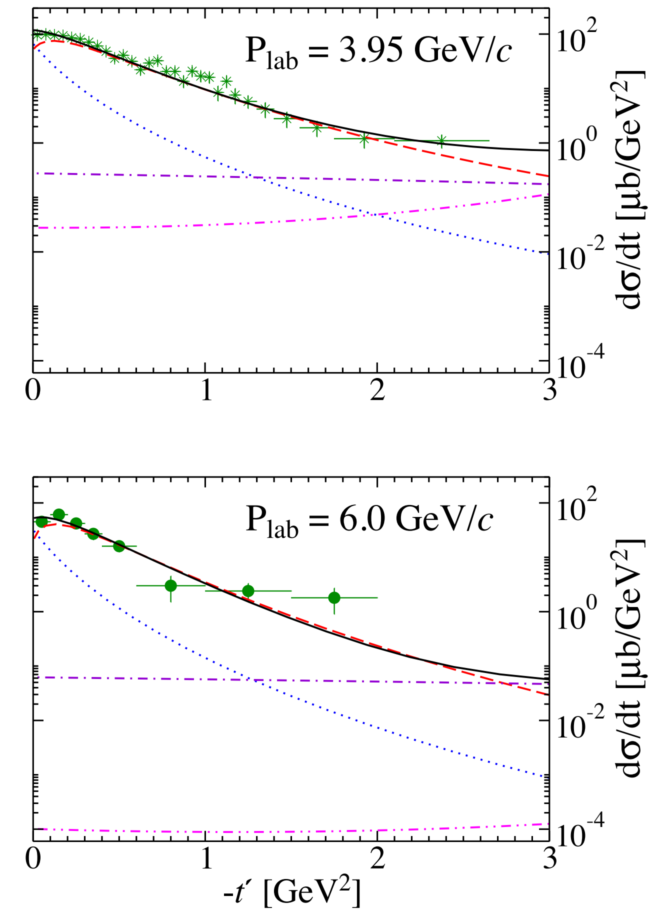
D.J. Krennel et al
PRD6, 1220 (1972)



Vector Reggeon dominance

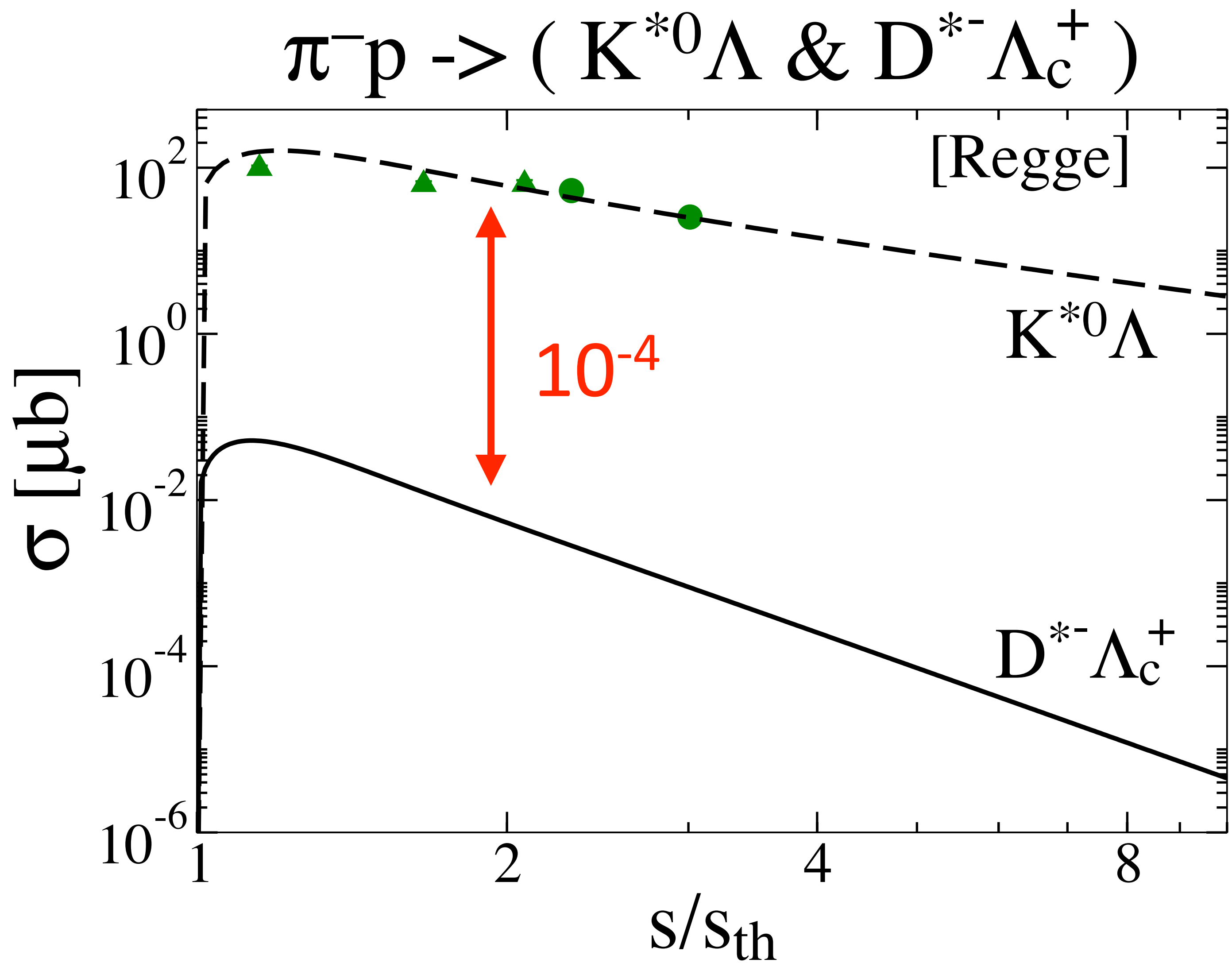
Sang-Ho Kim, in preparation





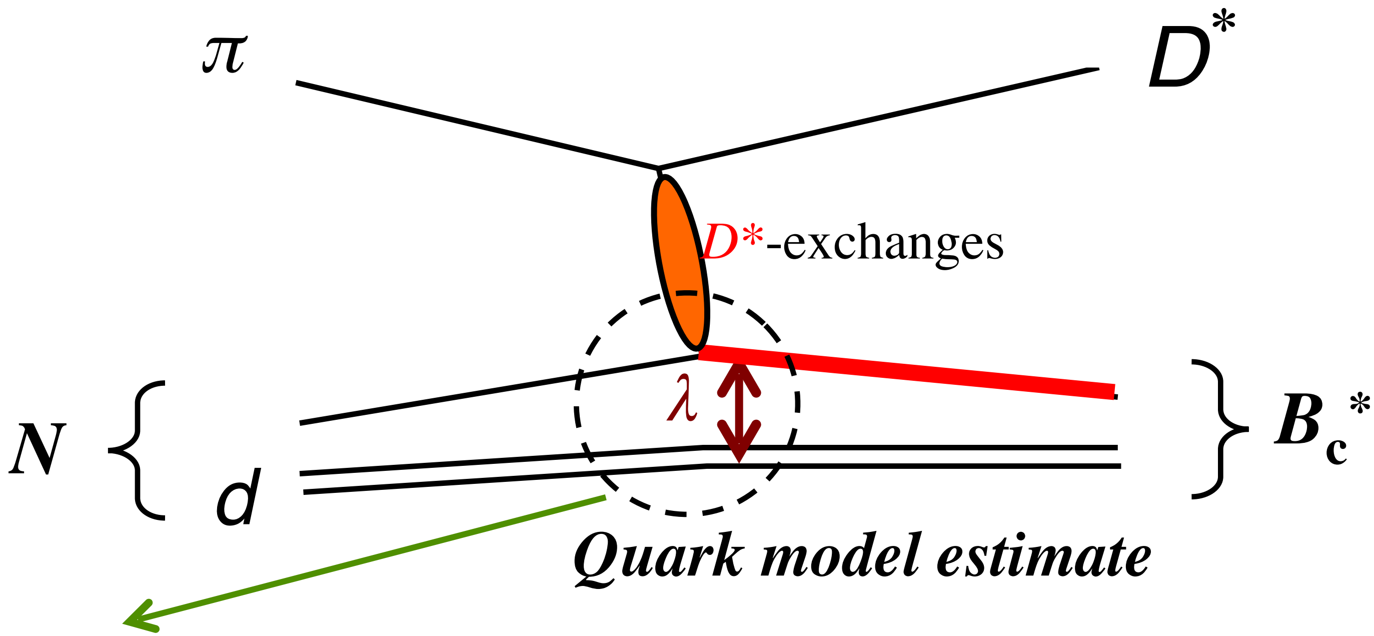
- Angular dependence prefers vector-Reggeon
- Energy dependence seems
- There is some discrepancy in the very forward region

D* meson productions



Relative rates of (B_c^*/B_c)

One step process for Qd λ-mode



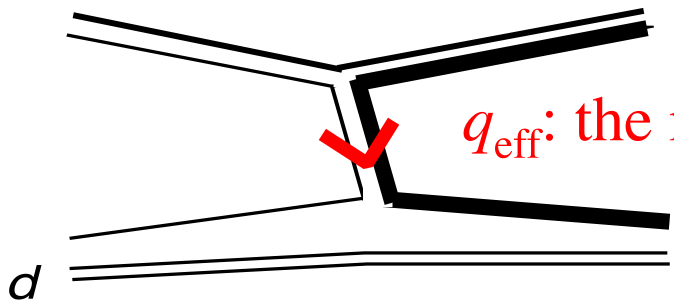
$$t_{fi} \sim \vec{k}_\pi \times \vec{e} \cdot \vec{J}_{fi}$$

$$\sim \left\langle B_c^* \middle| \vec{e}_\perp \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}} \middle| N \right\rangle = \text{(Geometric)} \times \text{(Dynamic)}$$

D ~ Transverse*

CG coefficients

Dynamical part ~ radial integral



q_{eff}: the momentum transfer ~ Large

GS $\langle B_c(\text{S-wave})|\vec{e}_\perp \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}}|N(\text{S-wave})\rangle_{radial} \sim 1 \times \exp\left(-\frac{q_{eff}^2}{4A^2}\right)$

Excited states

$$\langle B_c(P\text{-wave})|\vec{e}_\perp \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}}|N(\text{S-wave})\rangle_{radial} \sim \left(\frac{q_{eff}}{A}\right)^1 \times \exp\left(-\frac{q_{eff}^2}{4A^2}\right)$$

$$\langle B_c(D\text{-wave})|\vec{e}_\perp \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}}|N(\text{S-wave})\rangle_{radial} \sim \left(\frac{q_{eff}}{A}\right)^2 \times \exp\left(-\frac{q_{eff}^2}{4A^2}\right)$$

Transitions to excited states are not suppressed

Results

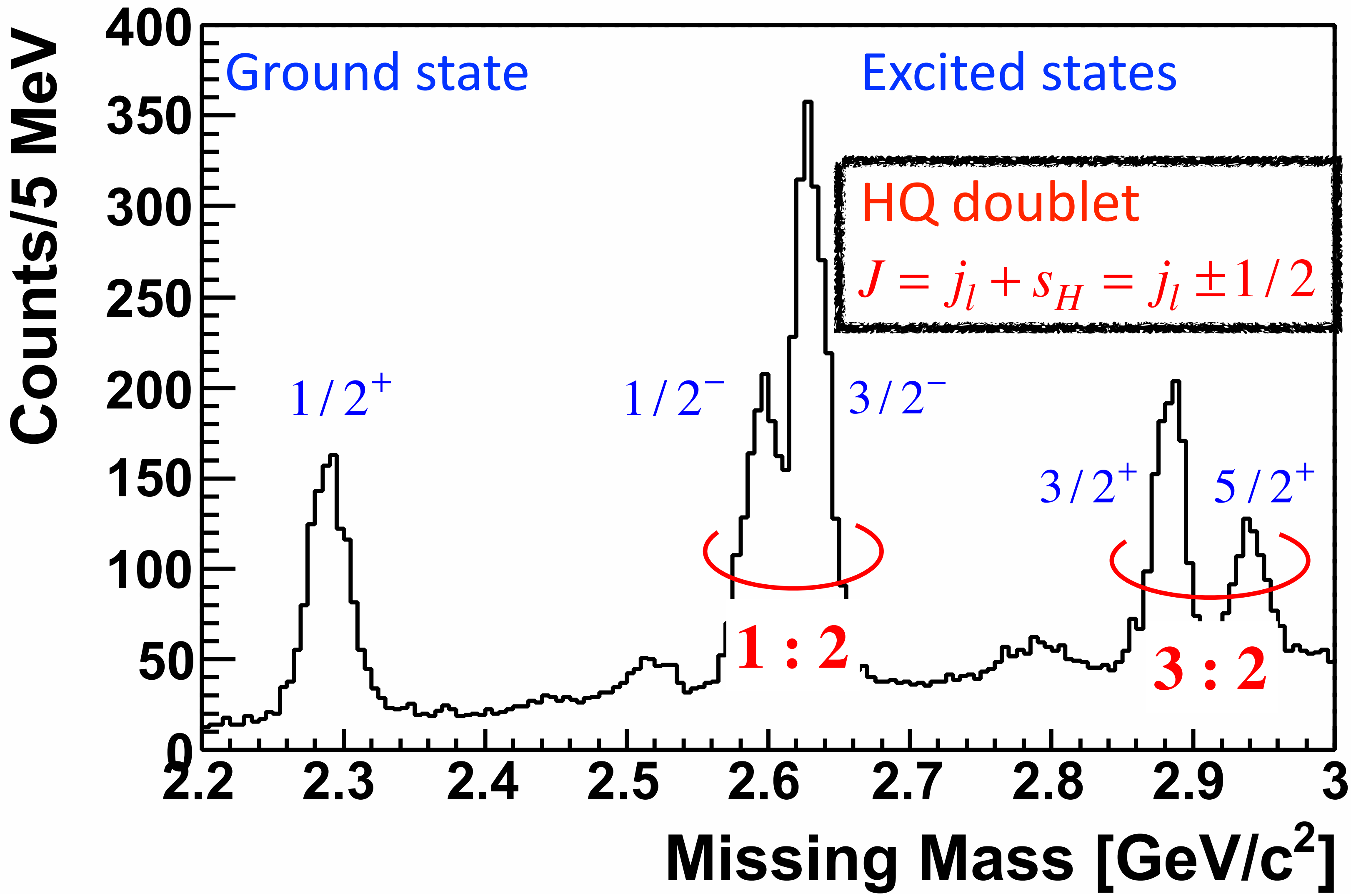
Charm $k_{\pi}^{CM} = 2.71$ [GeV] , $k_{\pi}^{Lab} = 16$ [GeV]

$l=0$	$\Lambda_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{3}{2}^+)$					
	1.00	0.02	0.16					
$l=1$	$\Lambda_c(\frac{1}{2}^-)$	$\Lambda_c(\frac{3}{2}^-)$	$\Sigma_c(\frac{1}{2}^-)$	$\Sigma_c(\frac{3}{2}^-)$	$\Sigma_c'(\frac{1}{2}^-)$	$\Sigma_c'(\frac{3}{2}^-)$	$\Sigma_c'(\frac{5}{2}^-)$	
	0.90	1.70	0.02	0.03	0.04	0.19	0.18	
$l=2$	$\Lambda_c(\frac{3}{2}^+)$	$\Lambda_c(\frac{5}{2}^+ -)$	$\Sigma_c(\frac{3}{2}^+)$	$\Sigma_c(\frac{5}{2}^+)$	$\Sigma_c'(\frac{1}{2}^+)$	$\Sigma_c'(\frac{3}{2}^+)$	$\Sigma_c'(\frac{5}{2}^+)$	$\Sigma_c'(\frac{5}{2}^+)$
	0.50	0.88	0.02	0.02	0.01	0.03	0.07	0.07

Strange $k_{\pi}^{CM} = 1.59$ [GeV], $k_{\pi}^{Lab} = 5.8$ [GeV]

$l=0$	$\Lambda(\frac{1}{2}^+)$	$\Sigma(\frac{1}{2}^+)$	$\Sigma(\frac{3}{2}^+)$					
	1.00	0.067	0.44					
$l=1$	$\Lambda(\frac{1}{2}^-)$	$\Lambda(\frac{3}{2}^-)$	$\Sigma(\frac{1}{2}^-)$	$\Sigma(\frac{3}{2}^-)$	$\Sigma'(\frac{1}{2}^-)$	$\Sigma'(\frac{3}{2}^-)$	$\Sigma'(\frac{5}{2}^-)$	
	0.11	0.23	0.007	0.01	0.01	0.07	0.067	
$l=2$	$\Lambda(\frac{3}{2}^+)$	$\Lambda_c(\frac{5}{2}^+ -)$	$\Sigma(\frac{3}{2}^+)$	$\Sigma(\frac{5}{2}^+)$	$\Sigma'(\frac{1}{2}^+)$	$\Sigma'(\frac{3}{2}^+)$	$\Sigma'(\frac{5}{2}^+)$	$\Sigma'(\frac{5}{2}^+)$
	0.13	0.20	0.007	0.01	0.004	0.02	0.038	0.04

Expected charm production spectrum



Summary

- **Charmed baryons**

  New platform to study quark dynamics

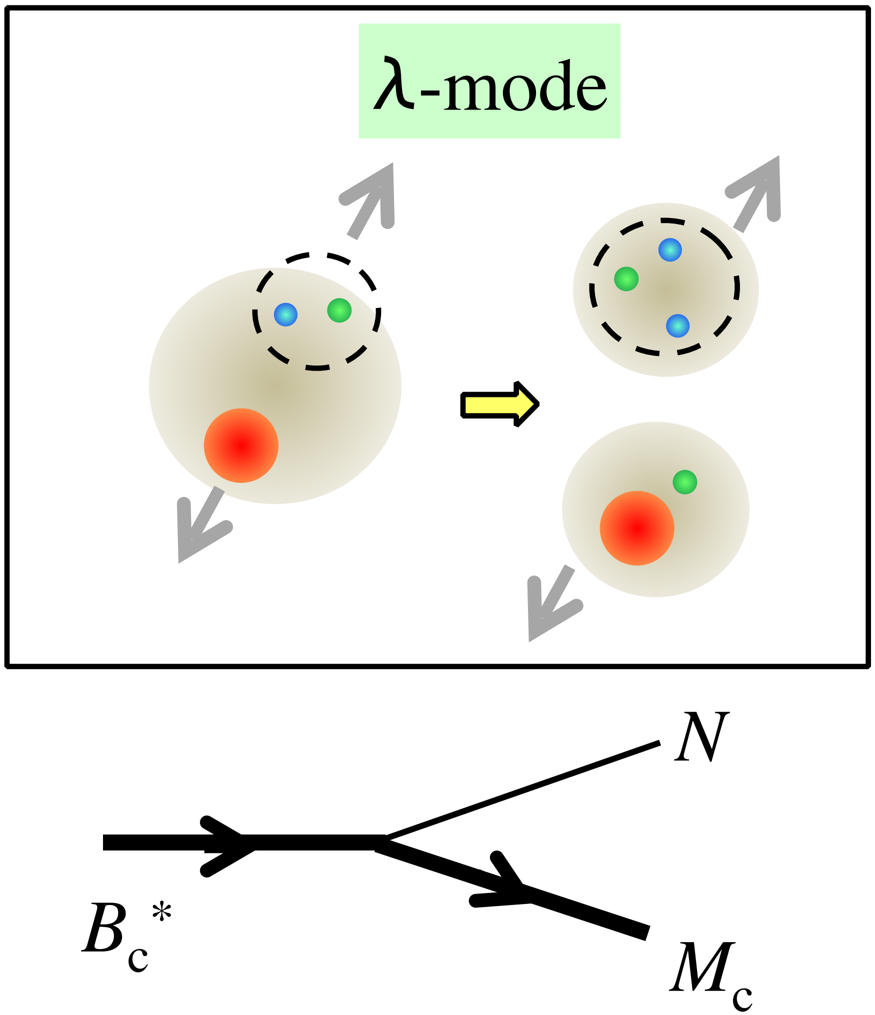
- **J-PARC** plans to study them

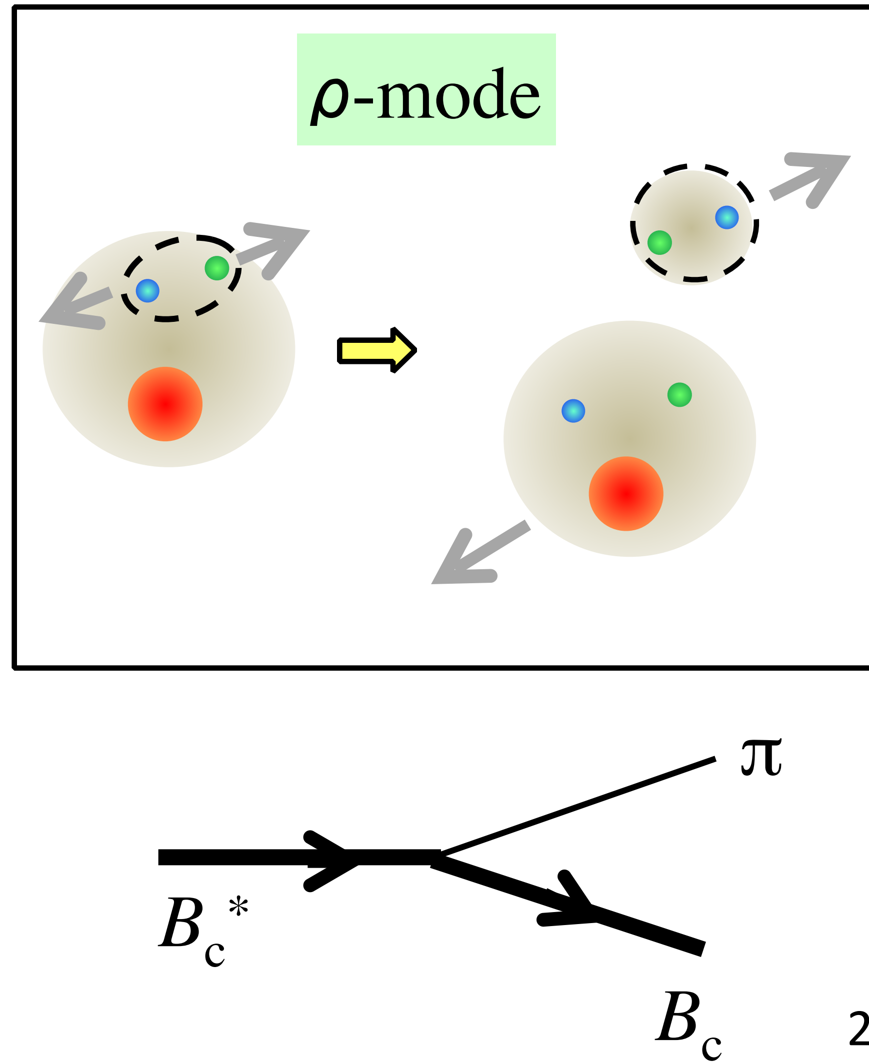
- Production rate: Charm/Strangeness: 10^{-4} or less
- **Abundant excited states**

- **Decays** are also helpful to know the structure

  We are currently working for details

4. Decays

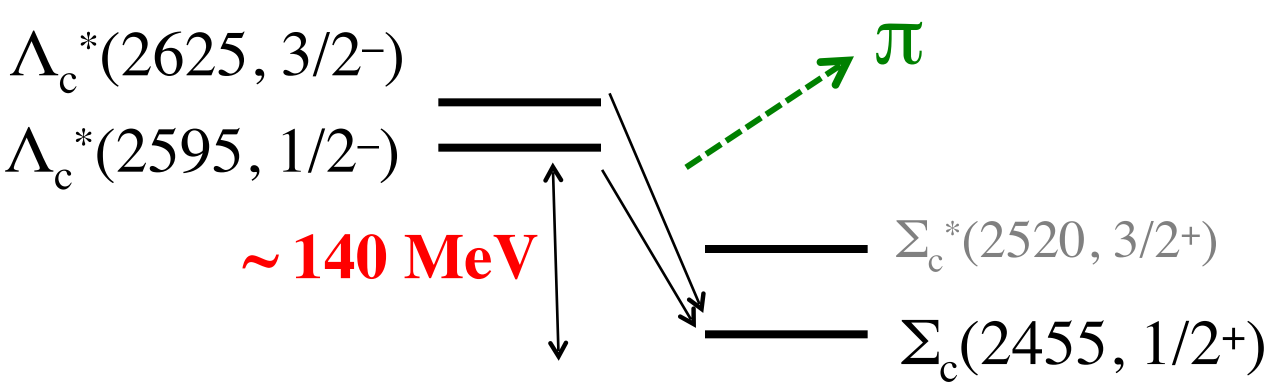




Pion emission – quark model --on going

Things to be looked at:

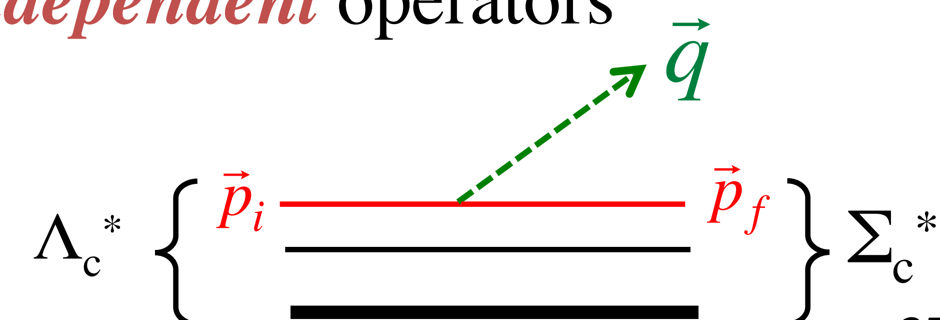
- Pion emission ~ **very near the threshold**



Place to look at the ***two independent*** operators

$$\bar{q}\gamma_5 q\phi_\pi, \ \bar{q}\gamma^\mu\gamma_5 q\partial_\mu\phi_\pi$$

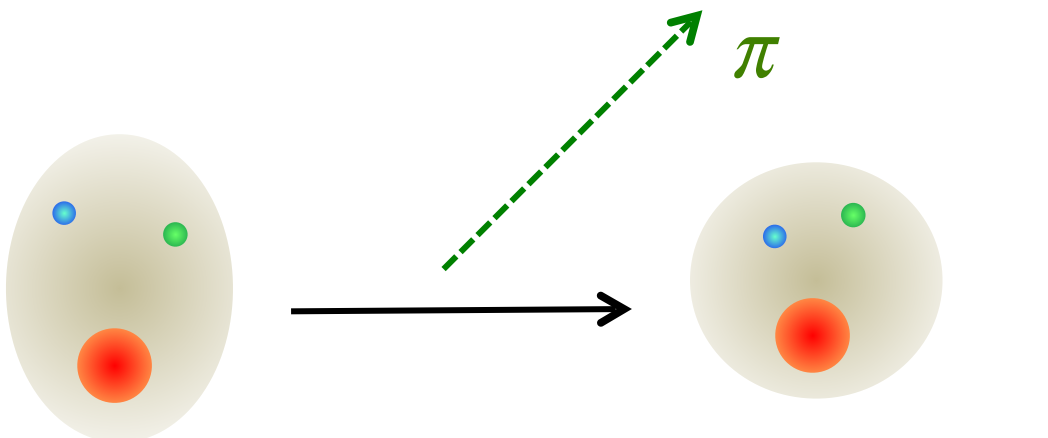
$$\vec{\sigma}\cdot\vec{p}_i, \ \vec{\sigma}\cdot\vec{p}_f \ (\vec{\sigma}\cdot\vec{q})$$



Possible selection rules

ϱ-modes

Decays of baryons = of diquarks

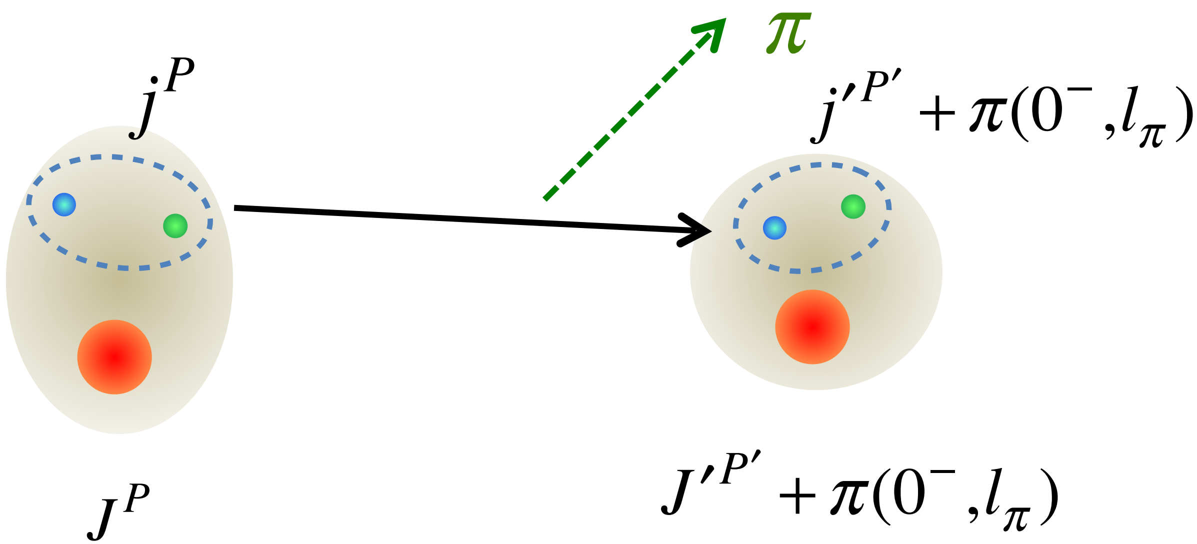


J^P $\quad J'^{P'} + \pi(0^-, l_\pi)$

Possible selection rules

ϱ-modes

Decays of baryons = of diquarks



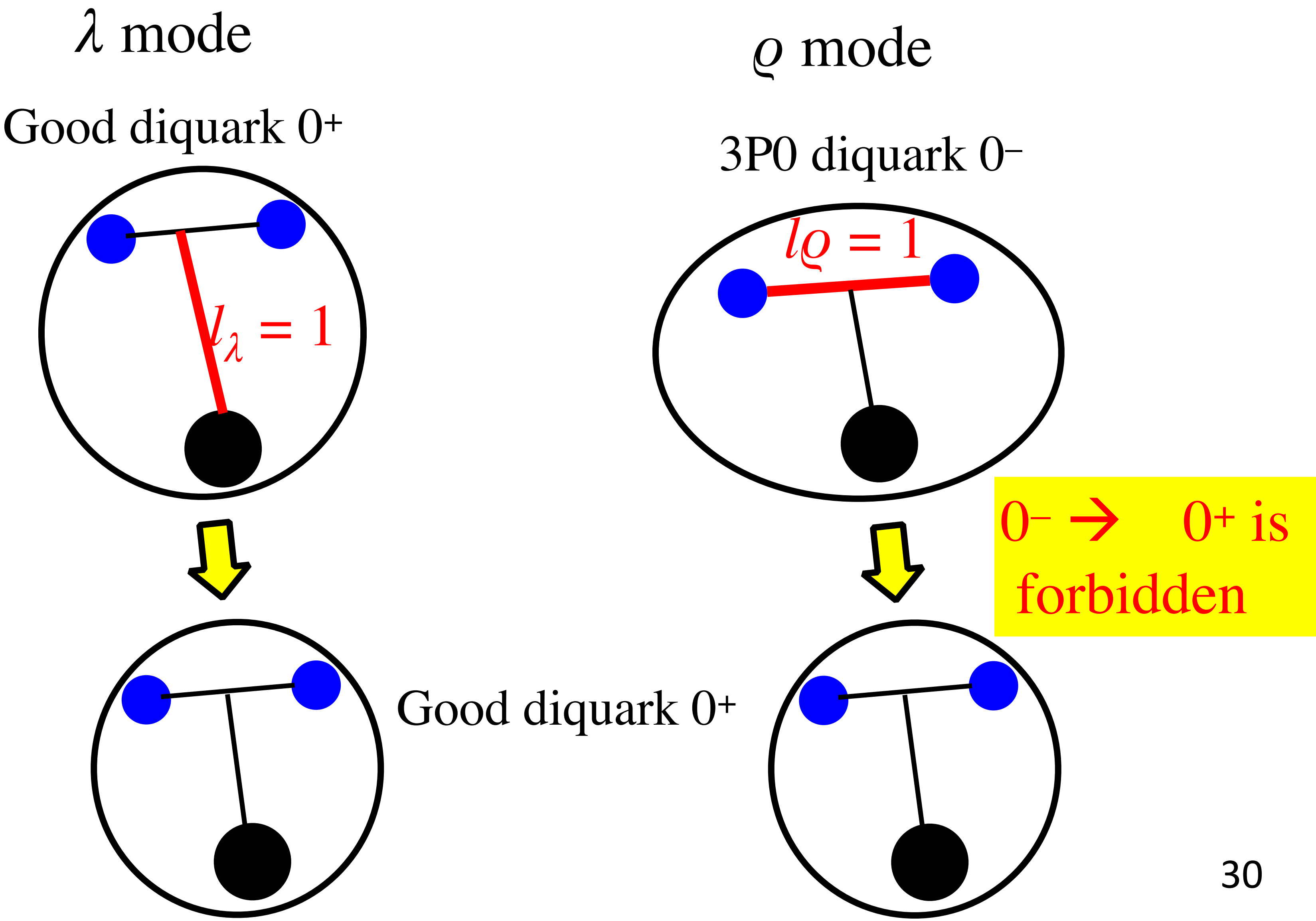
Two conditions must be satisfied for baryons and for diquarks

$$\Lambda_c(1/2^-, \rho) \rightarrow \Sigma_c(1/2^+, GS) + \pi$$

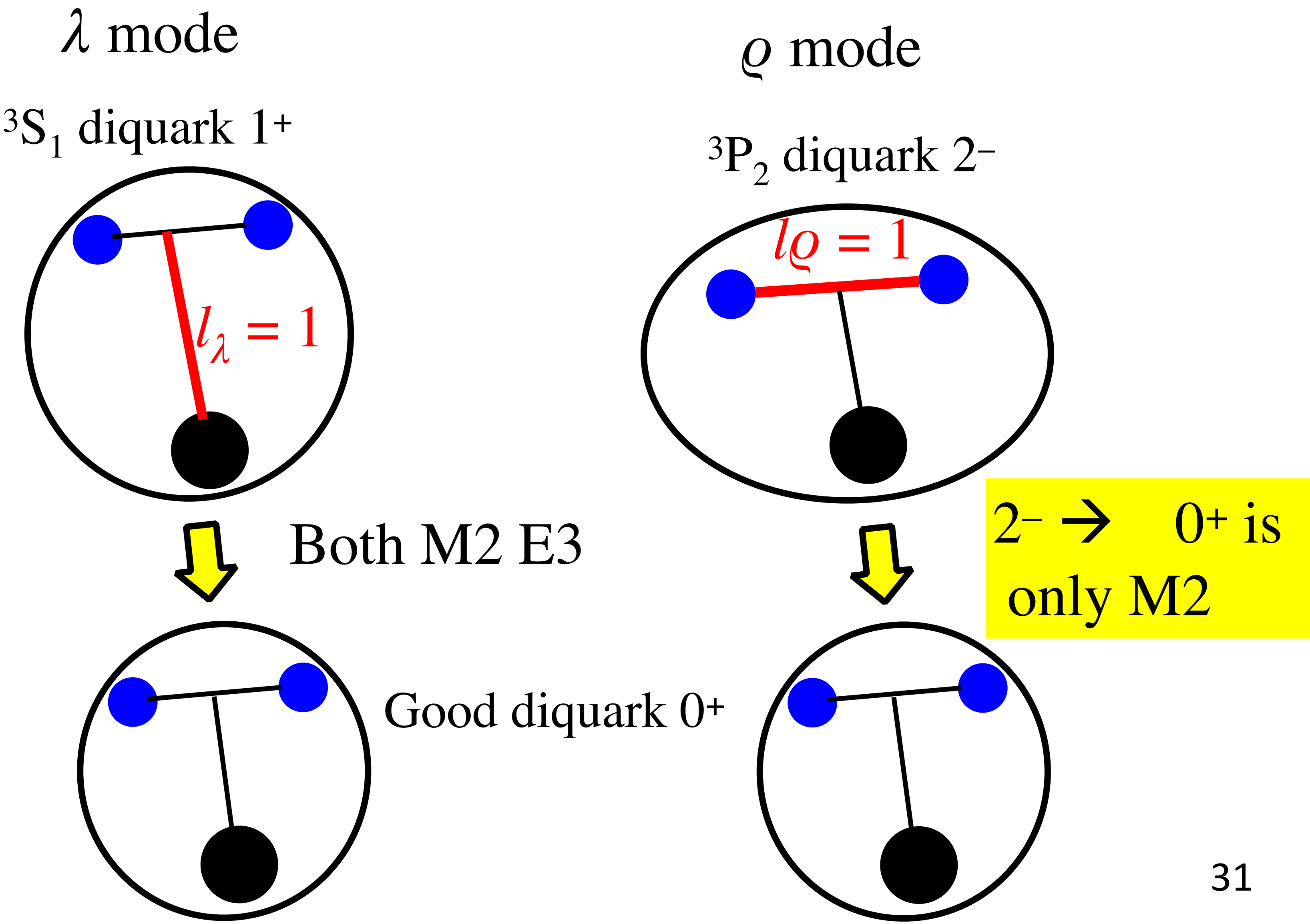
$$d(^3P_0) \rightarrow d(^3S_1) + \pi$$

is not allowed

Radiative decay: $1/2^- \rightarrow 1/2^+$ E1



Radiative decay: $5/2^- \rightarrow 1/2^+$ M2, E3



Aoki Hatsuda Ishii, Phys.Rev.Lett. 99 (2007) 022001

- HAL QCD data are consistent with the quark Pauli effects.

T. Inoue et al., (HAL QCD) PTP 124, 591 (2010)

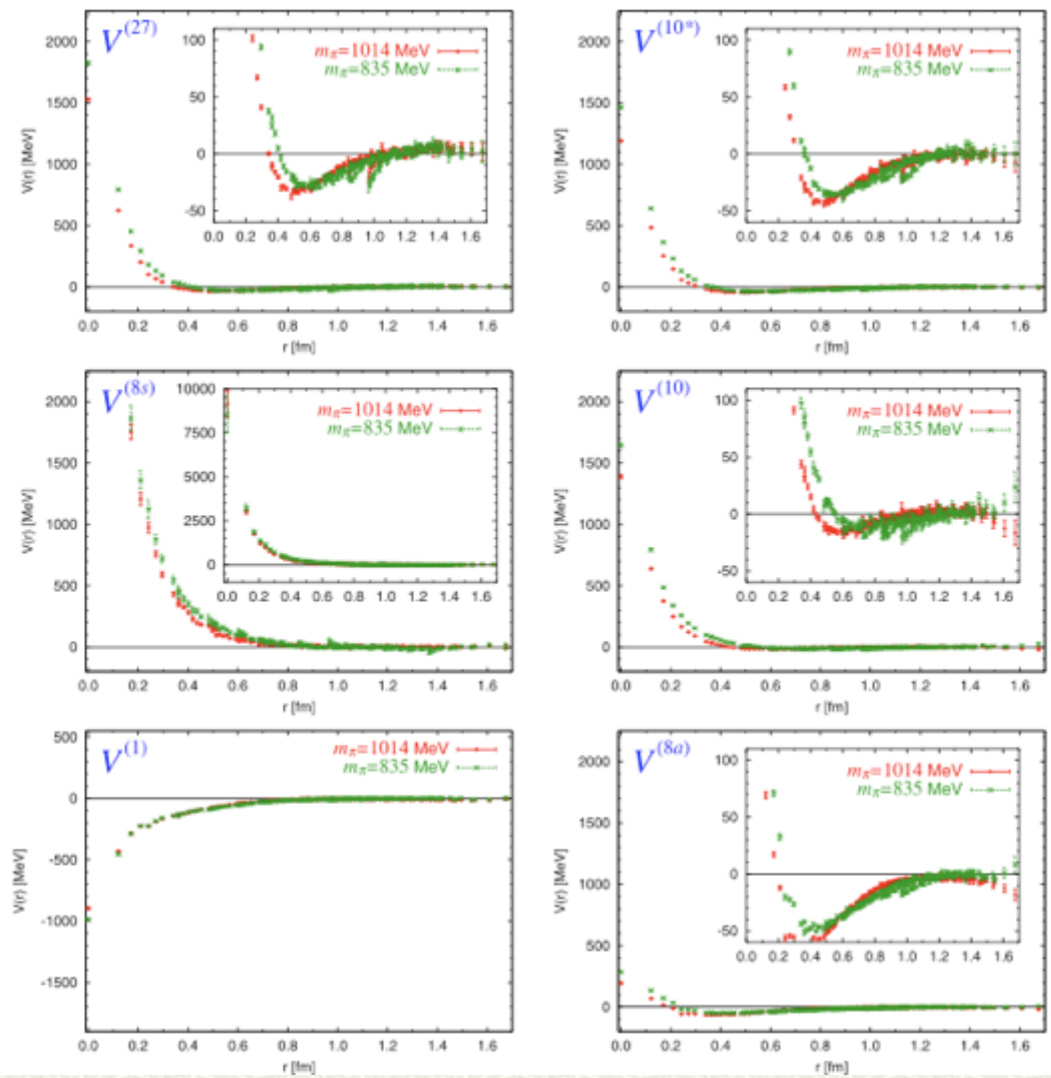
S=0

1	[33]
8_s	[51]
27	[33], [51]

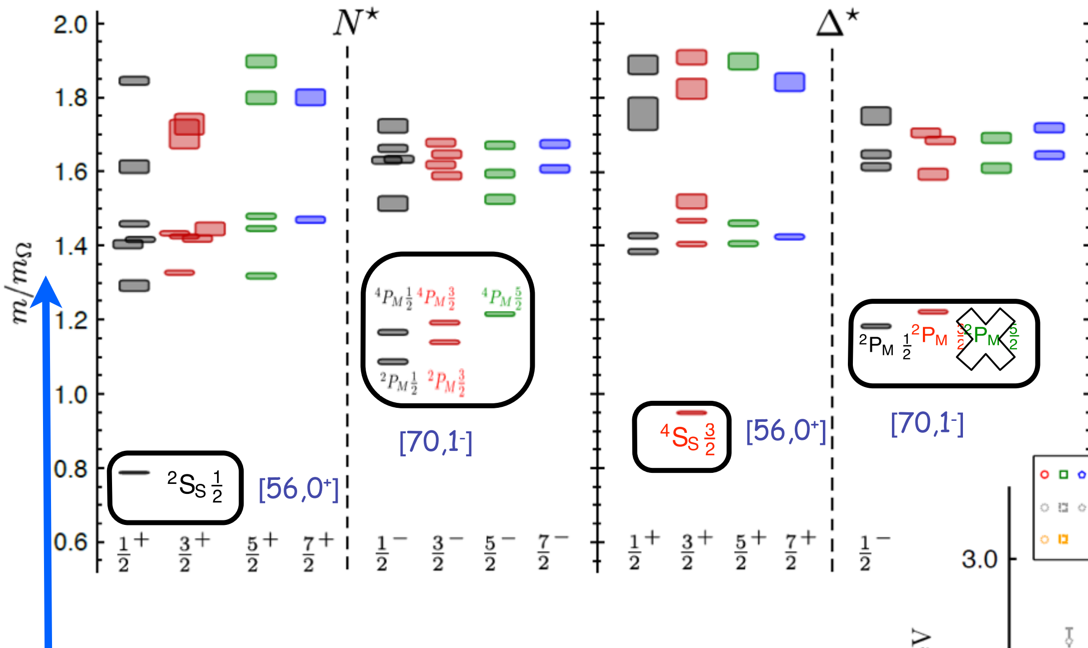
S=1

8_a	[33], [51]
10	[33], [51]
10*	[33], [51]

Classification of SU(6) quark model



Baryon spectrum from the lattice,
David Richard, Talk at YITP, HHIQCD, Feb. 2015

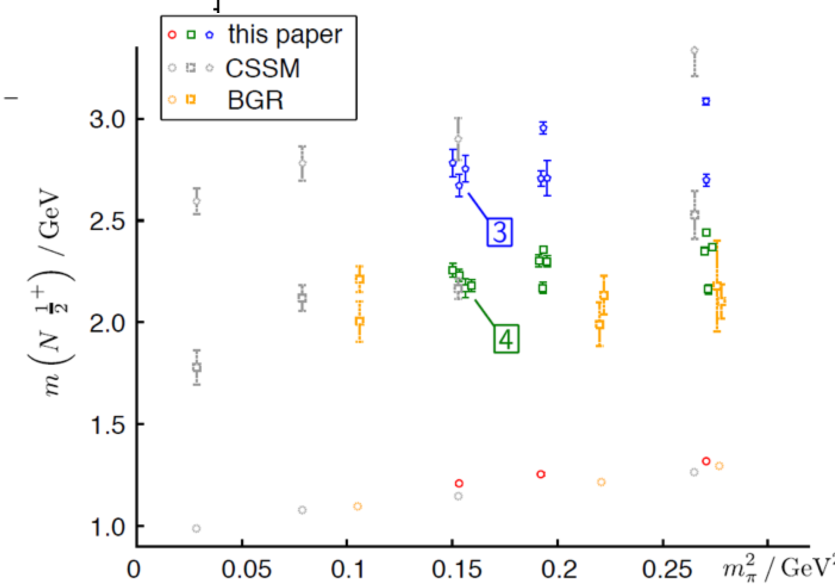


Broad features of SU(6)xO(3) symmetry.

Counting of states consistent with NR quark model.

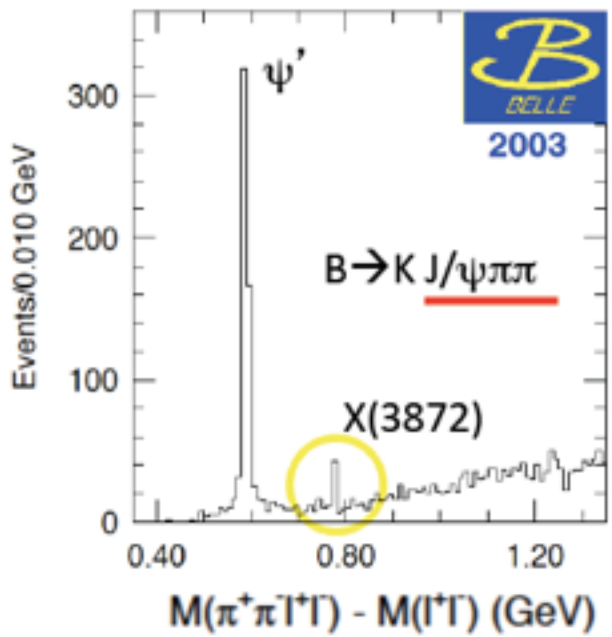
$[70, 0^+], [56, 2^+], [70, 2^+], [20, 1^+]$

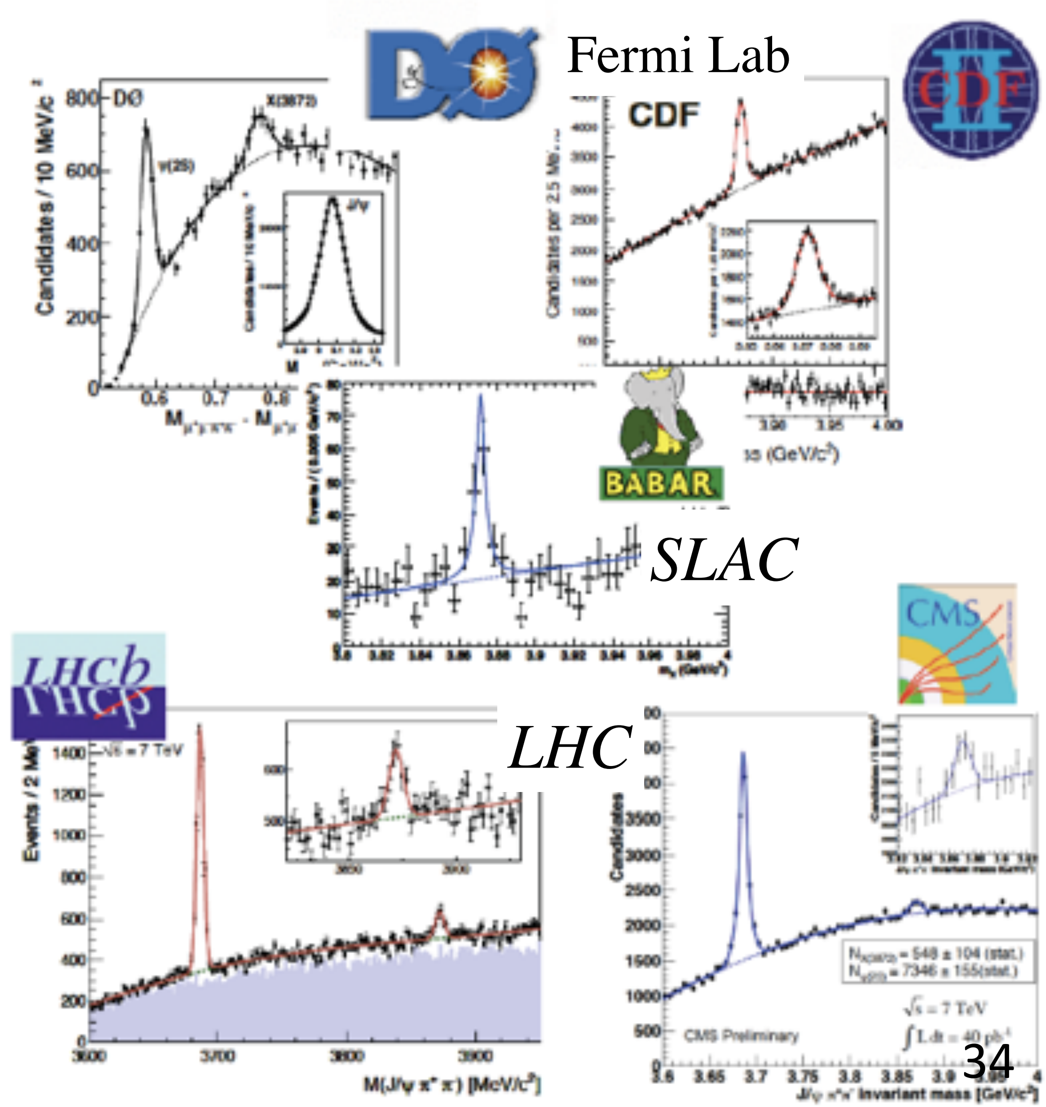
N $^{1/2+}$ sector: need for complete basis to faithfully extract states

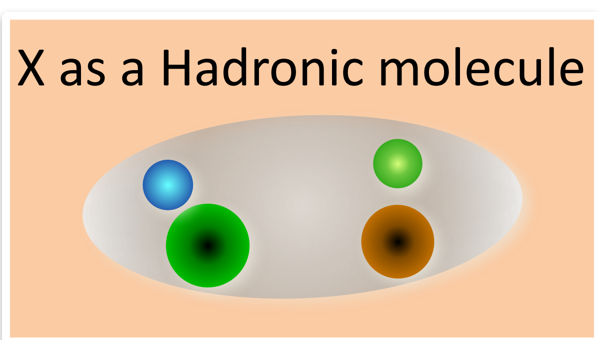


X (3872)

Discovery by Belle in 2003, followed by D0, CDF, BaBar. BES







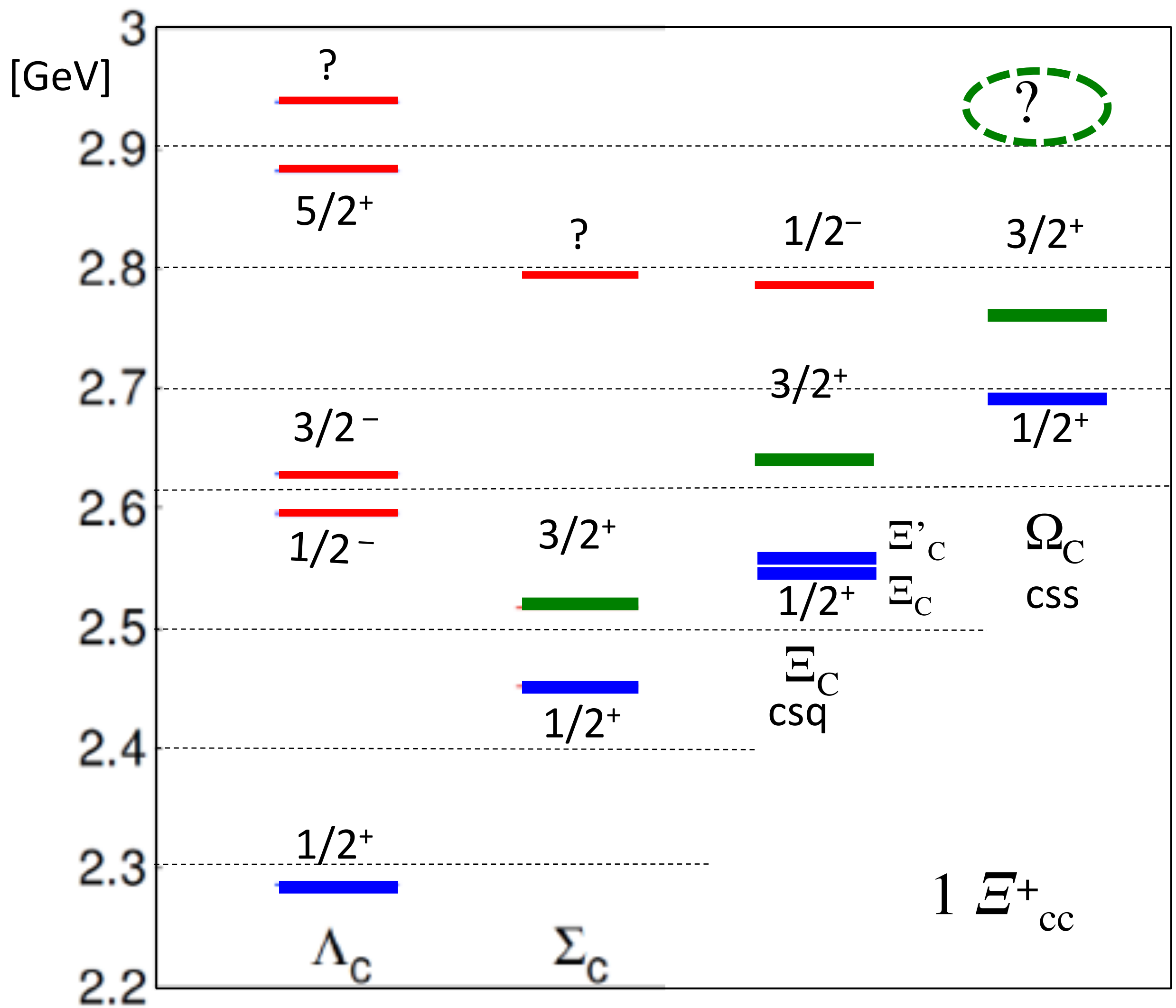
What motivate us

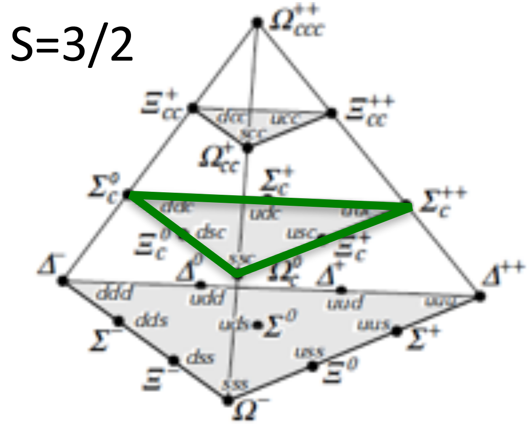
- **Quark model** seem to work
- **Multiquark configurations** have been found

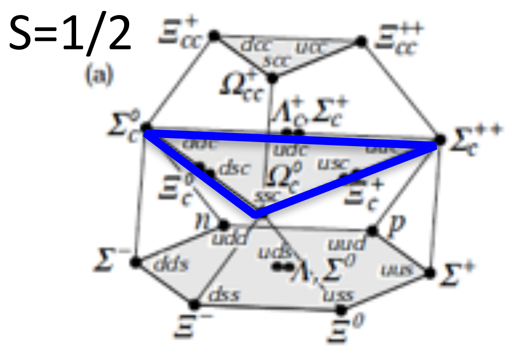
- How are they behave, and what are the **essential degrees of freedom** for hadrons?

- ***Charmed baryons Qqq*** are useful to study
- ***qq,*** yet another possible constituent
  Difficult to study because of colorful and confined nature

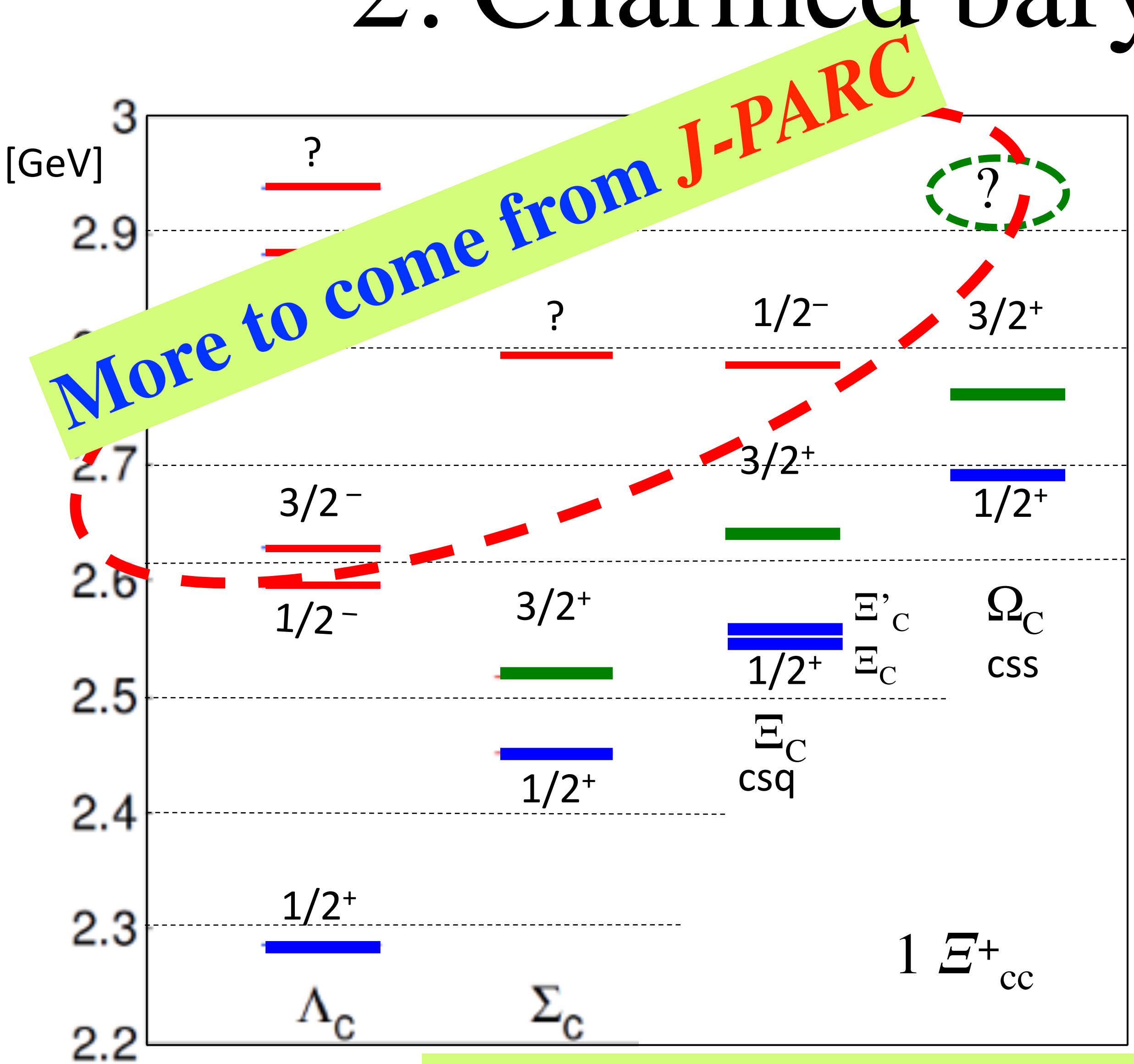
2. Charmed baryons

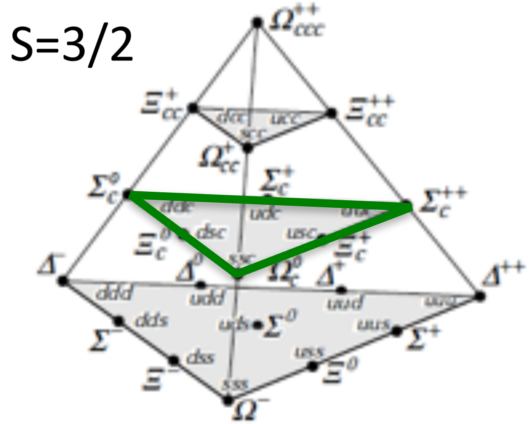


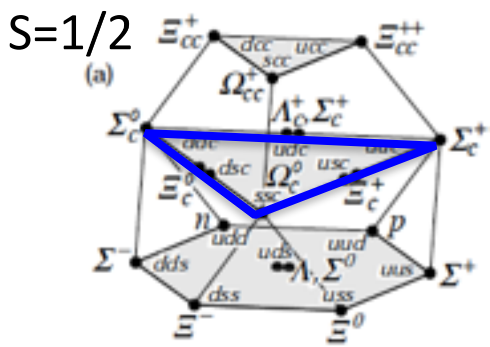




2. Charmed baryons







From *Qqq* to *qq* dynamics

Negative parity states — p-wave excitations - $1/2^-$, $3/2^-$