

# Charmed baryons and their interactions

*Baryons with heavy quark(s) may disentangle light quark dynamics*

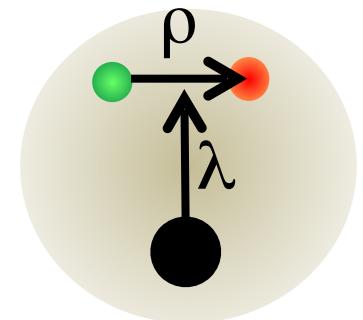
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QCD Exotics at Shandong Univ. Jinan, China

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

## Contents

1. Introduction
2. Structure: *How  $\rho\lambda$  modes appear in the spectrum*
3. Productions
4. Decays



# 1. Introduction

Quark model and EXOTICS: Now 51 years old

## A SCHEMATIC MODEL OF BARYONS AND MESONS

M. GELL-MANN

*California Institute of Technology, Pasadena, California*

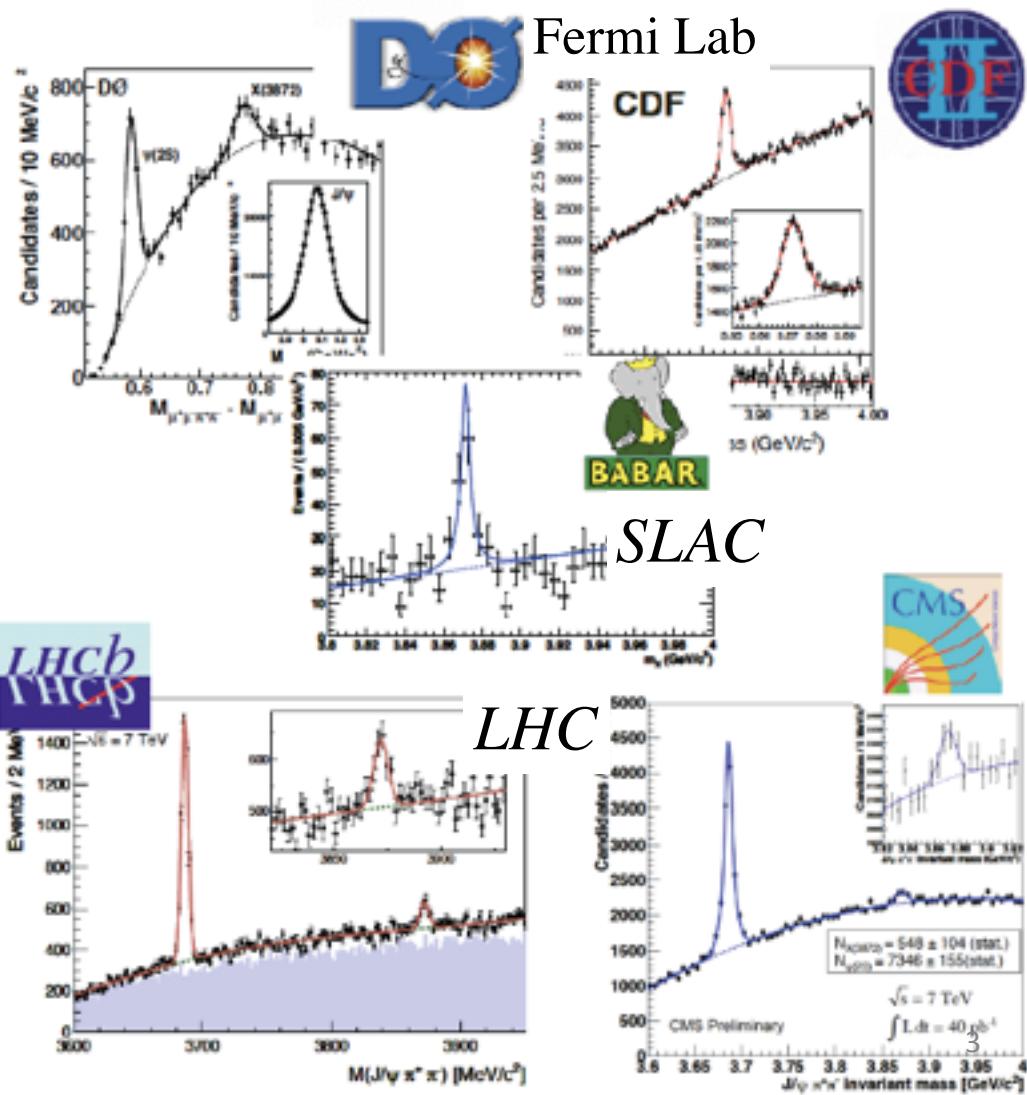
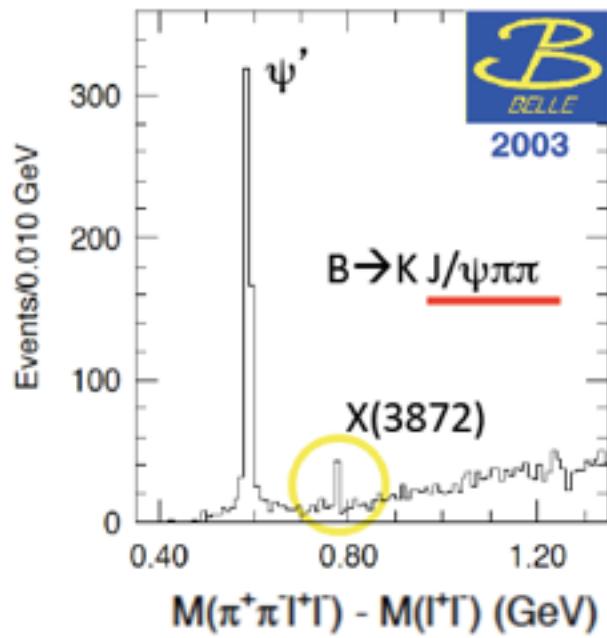
Received 4 January 1964

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 representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration  $(q \bar{q})$  similarly gives just **1** and **8**.

But no colors ~ glues <sup>2</sup>

# X (3872)

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



And more recently  
also by LHCb, CMS

# Quarks bonding differently at LHCb Z+(4430)

<http://www.theguardian.com/science/life-and-physics/2014/apr/13/quarks-bonding-differently-at-lhcb>

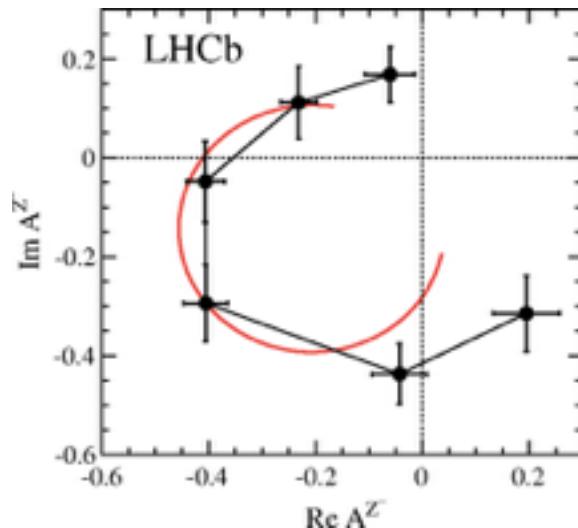
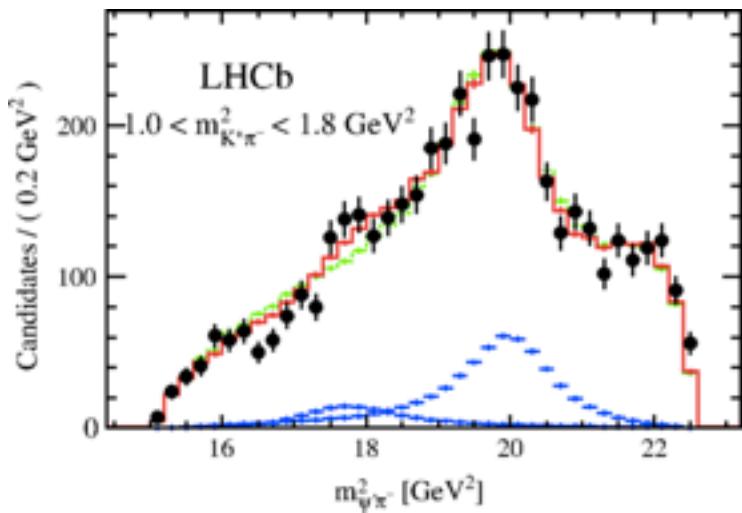


*So until last week there were  
two known types of hadron.*

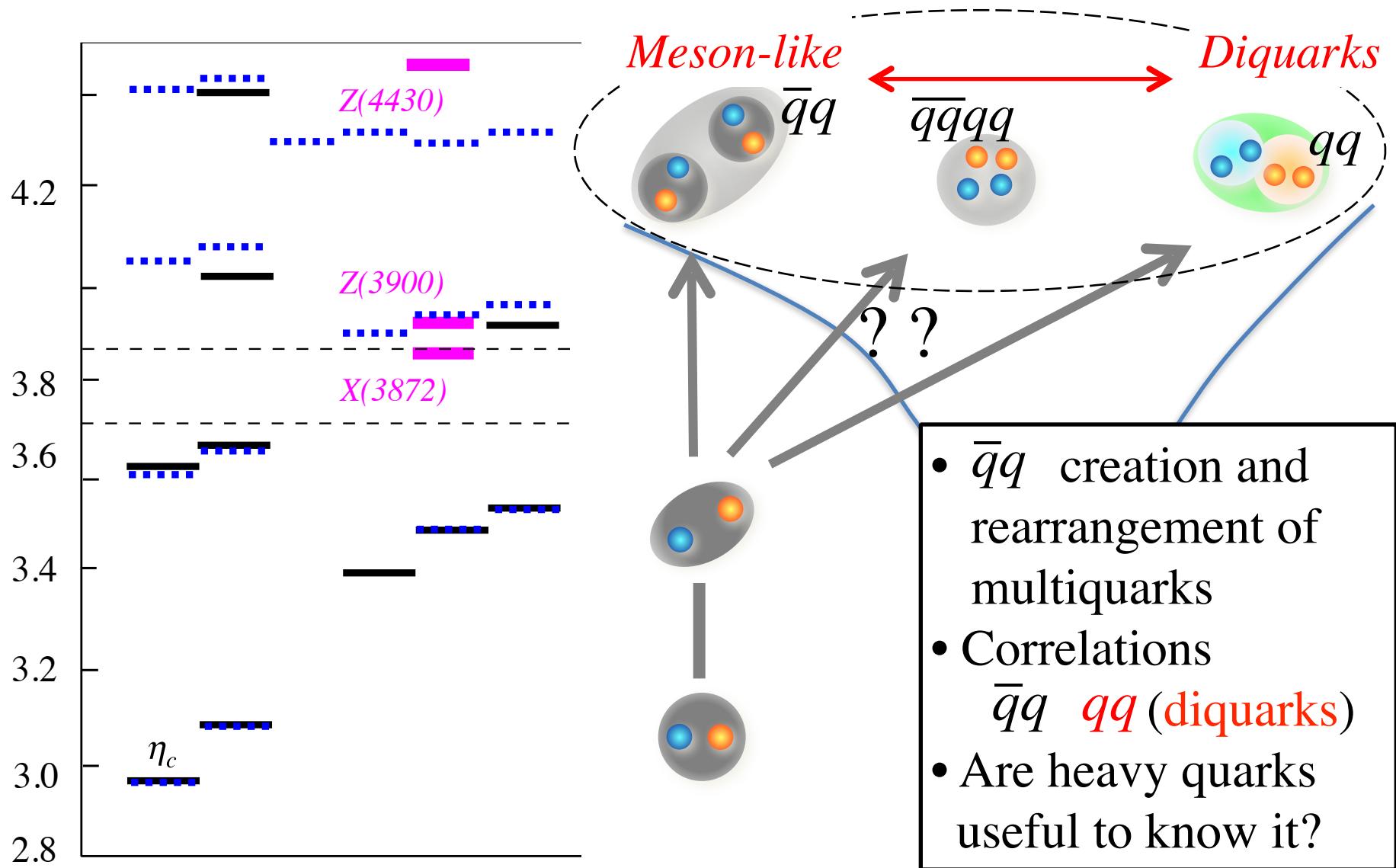
.....

*LHCb has just confirmed what  
data from other experiments  
had already led us to suspect.  
*There is a third way.**

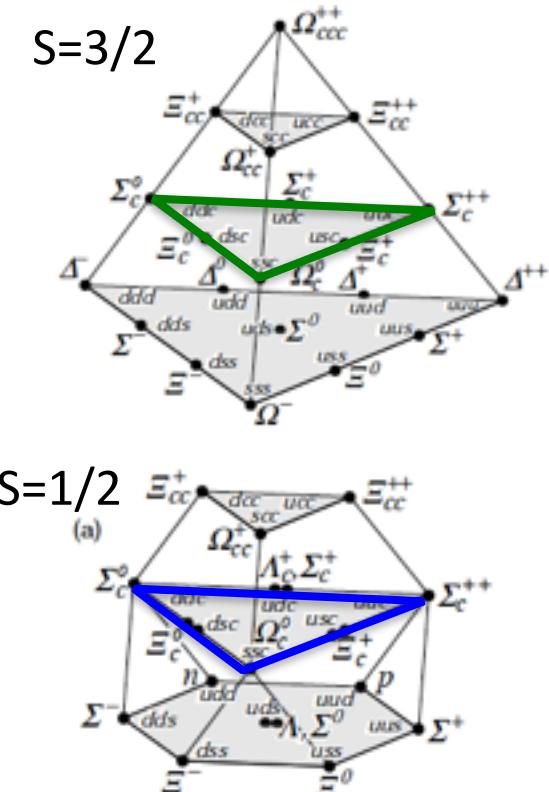
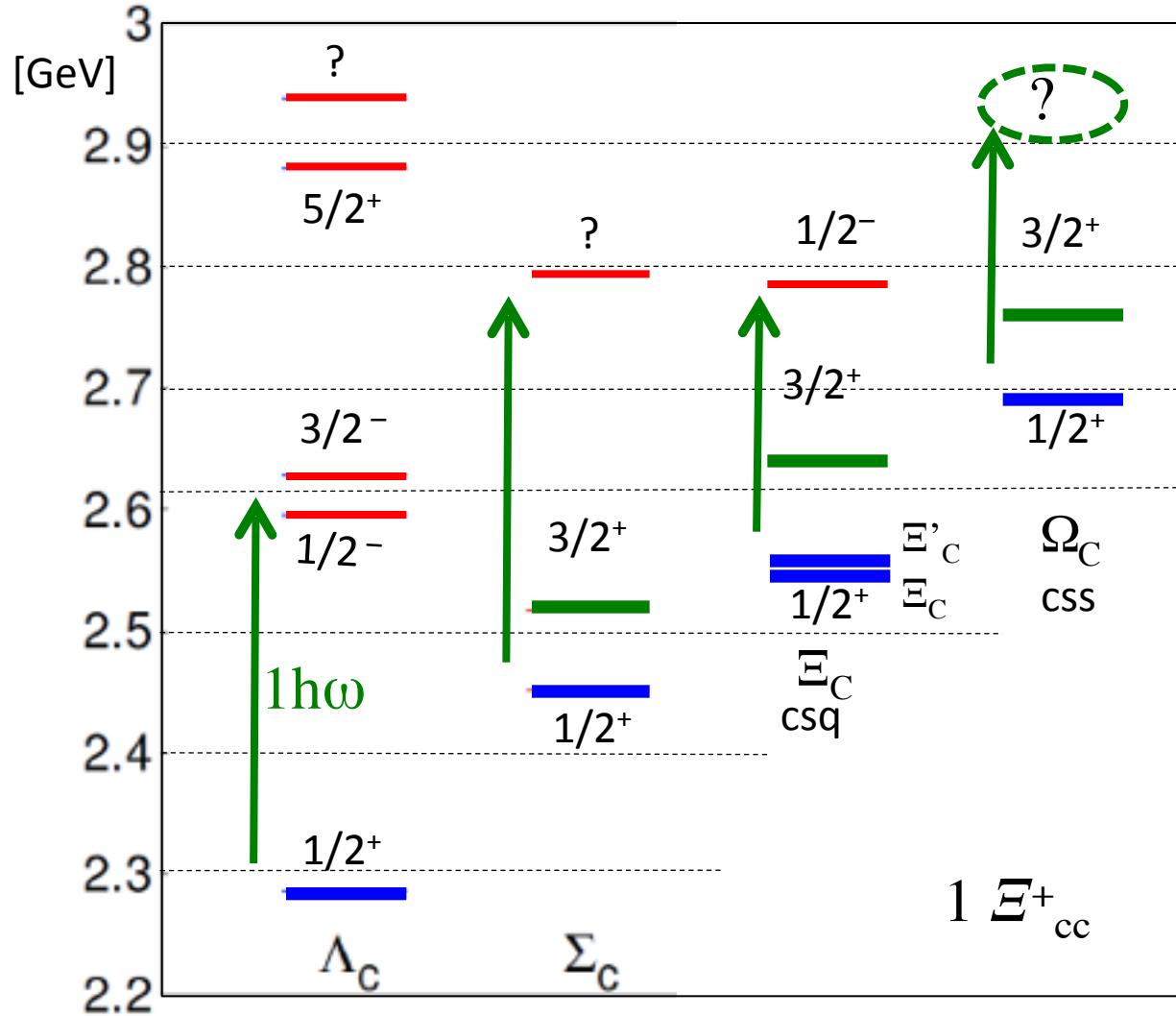
Phys. Rev. Lett. **112**, 222002



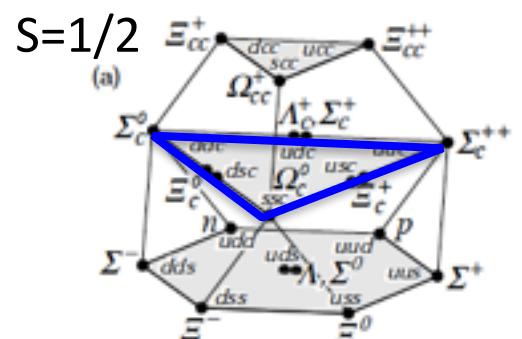
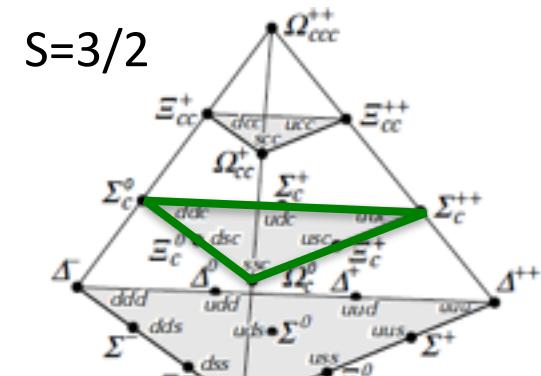
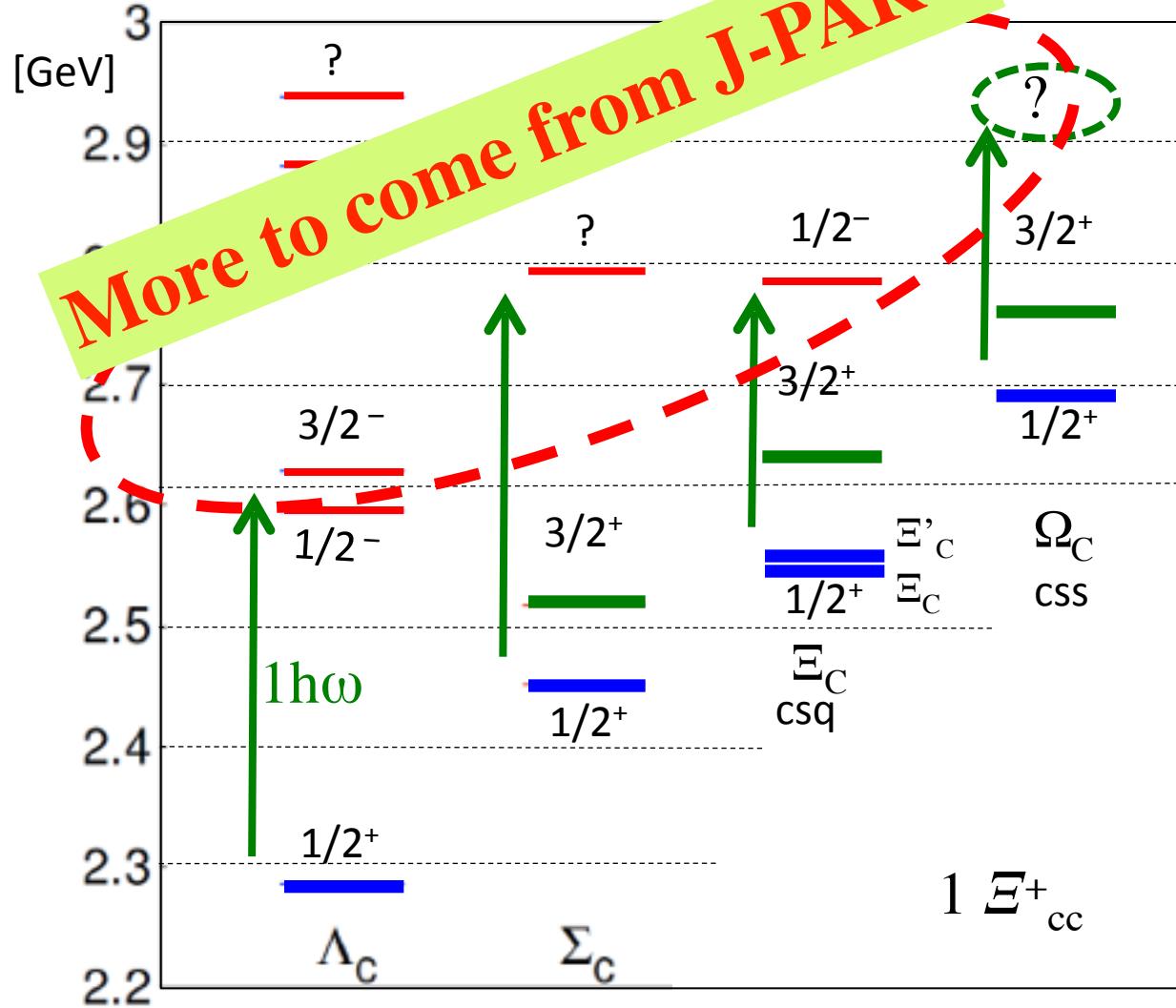
# Near and above the threshold



## 2. Charmed baryons



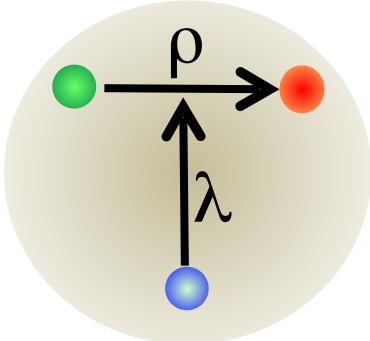
## 2. Charmed baryons



# What do we expect to study?

*A heavy quark* may distinguish  
the fundamental modes  $\lambda$  and  $\rho$   
→ place to look at diquark correlations

Isotope-shift: Copley-Isgur-Karl, PRD20, 768 (1979)

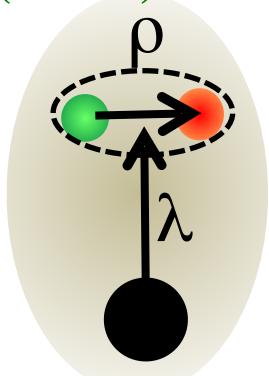


$m_Q = m_{u,d}$   
Degenerate

$$\frac{\rho = \lambda}{\text{HO and no ss}}$$

Mixing of  
 $\lambda$  and  $\rho$

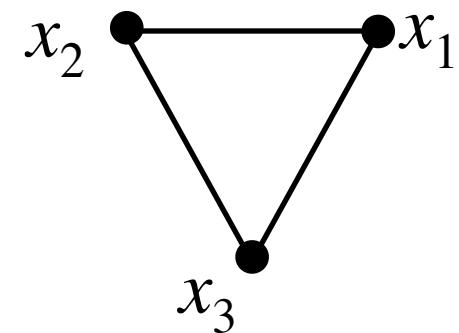
$$\frac{\rho > \lambda}{\lambda}$$



$m_Q \rightarrow \infty$   
Distinguished

# Harmonic oscillator

$$\begin{aligned} H &= \frac{p_1^2}{2m} + \frac{p_2^2}{2m} + \frac{p_3^2}{2M} + \frac{k}{2} \left( (x_1 - x_2)^2 + (x_2 - x_3)^2 + (x_3 - x_1)^2 \right) \\ &= \frac{p_\rho^2}{2m_\rho} + \frac{p_\lambda^2}{2m_\lambda} + \frac{k_\rho \rho^2}{2} + \frac{k_\lambda \lambda^2}{2} \end{aligned}$$



$$m_\rho = \frac{m}{2}, \quad m_\lambda = \frac{2mM}{M + 2m}$$

$$k_\rho = \frac{3}{2}k, \quad k_\lambda = 2k$$

$$\boxed{\omega_\rho = \sqrt{3}\omega \quad > \quad \omega_\lambda = \sqrt{\frac{M+2m}{M}}\omega}$$

# Spectrum and WF's as $M_Q$ is varied

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

Yoshida, Sadato, Hiyama, Oka, Hosaka

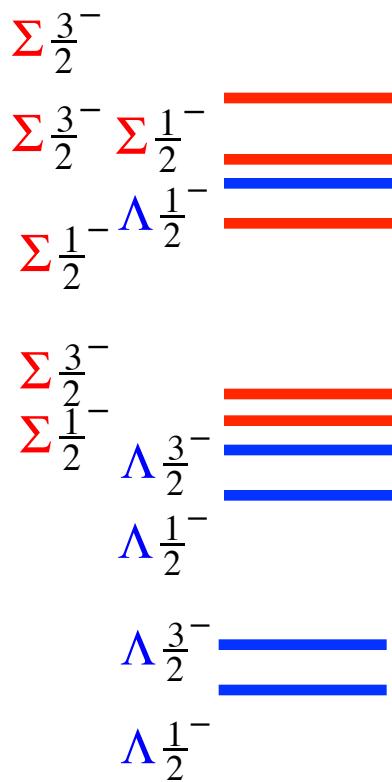
- Model Hamiltonian

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

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

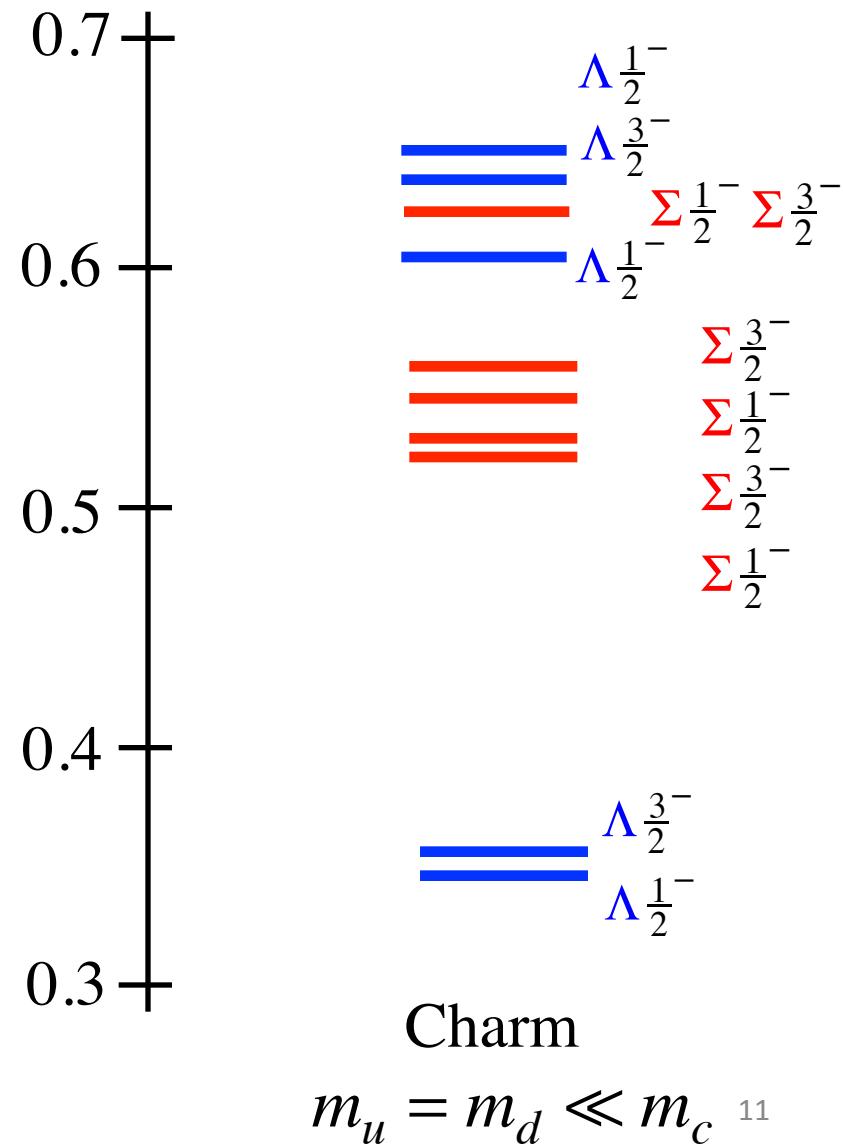
- Solved by the Gaussian expansion method

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

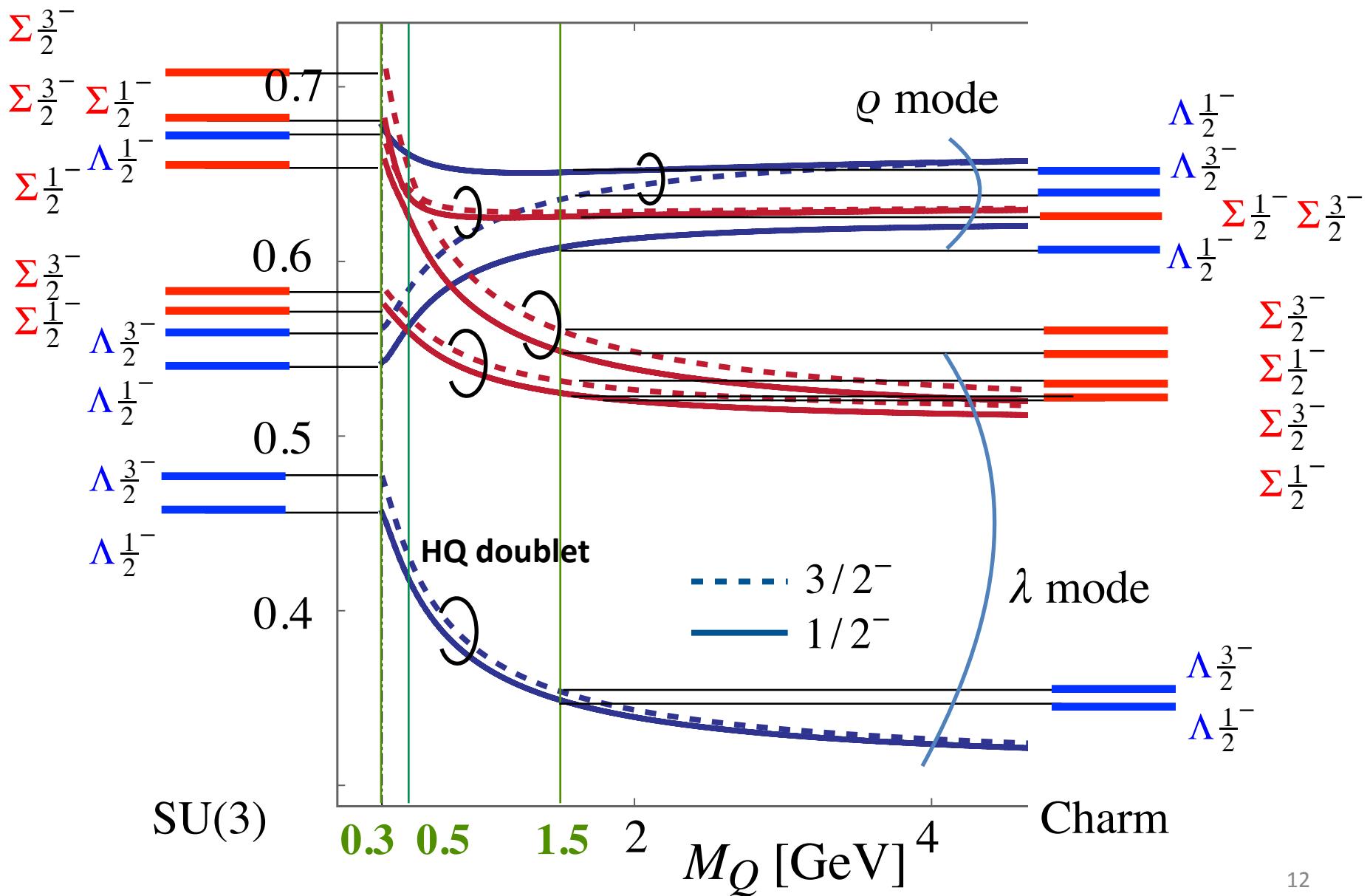


$SU(3)$

$$m_u = m_d = m_s$$



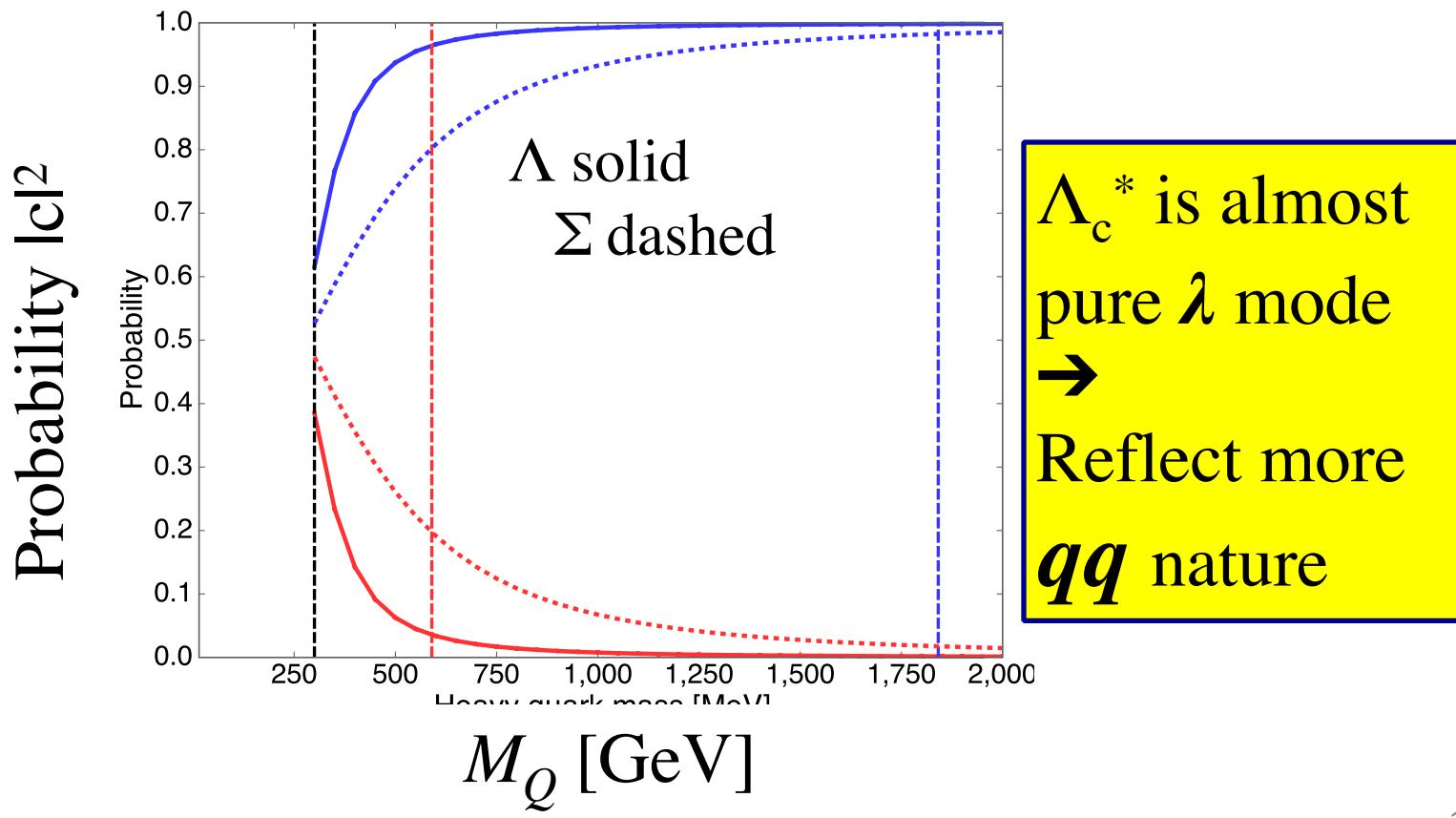
# Negative parity states – p-wave excitations - $1/2^-$ , $3/2^-$



# Wave function

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

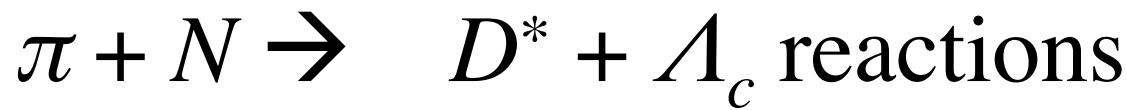
e.g.  $\lambda$ -mode dominant state: How much the other mode mixes?



# Intermediate summary

- Heavy quark spectroscopy will give more information on constituents
- Isotope shift may resolve two diquark modes *collective* and *internal*
- $\Lambda$  baryons may have more chance to see the two modes separately
- Systematic study from strange to heavy is useful

# 3. Productions



Production rate ( $\Lambda_c/\Lambda$ ) and Ratios ( $B_c^*/B_c$ )

# Strategy:

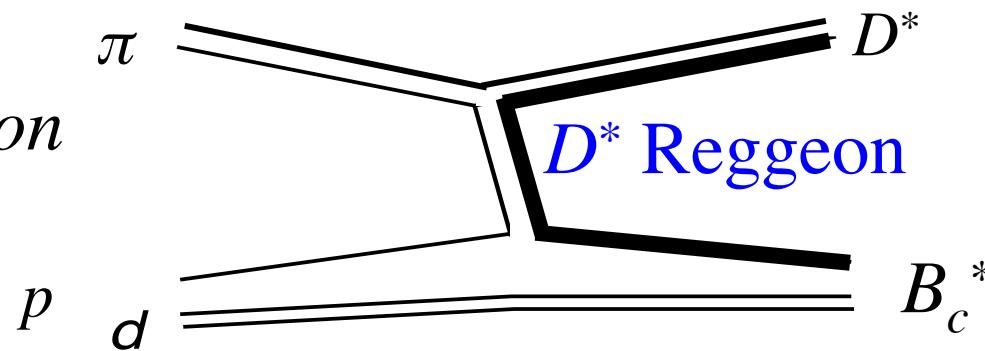
Forward peak (high energy)  $\rightarrow$  t-channel dominant  
Next figure

## We look at:

- (1) Rates ( $\Lambda_c/\Lambda_s$ ) by the Regge model,  $D^*$  Reggeon
- (2) Ratios of  $B_c^*(\lambda \text{ modes}) / B_c$   
by a one step process of  $Qd$  picture for  $\lambda$ -mode

*Pion-induced reaction*

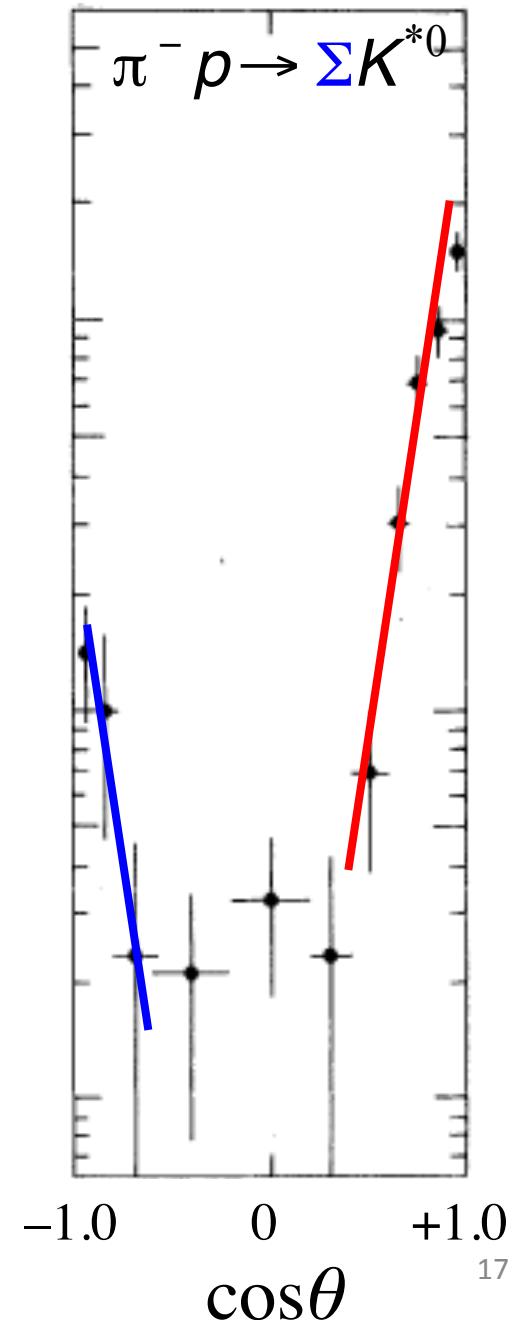
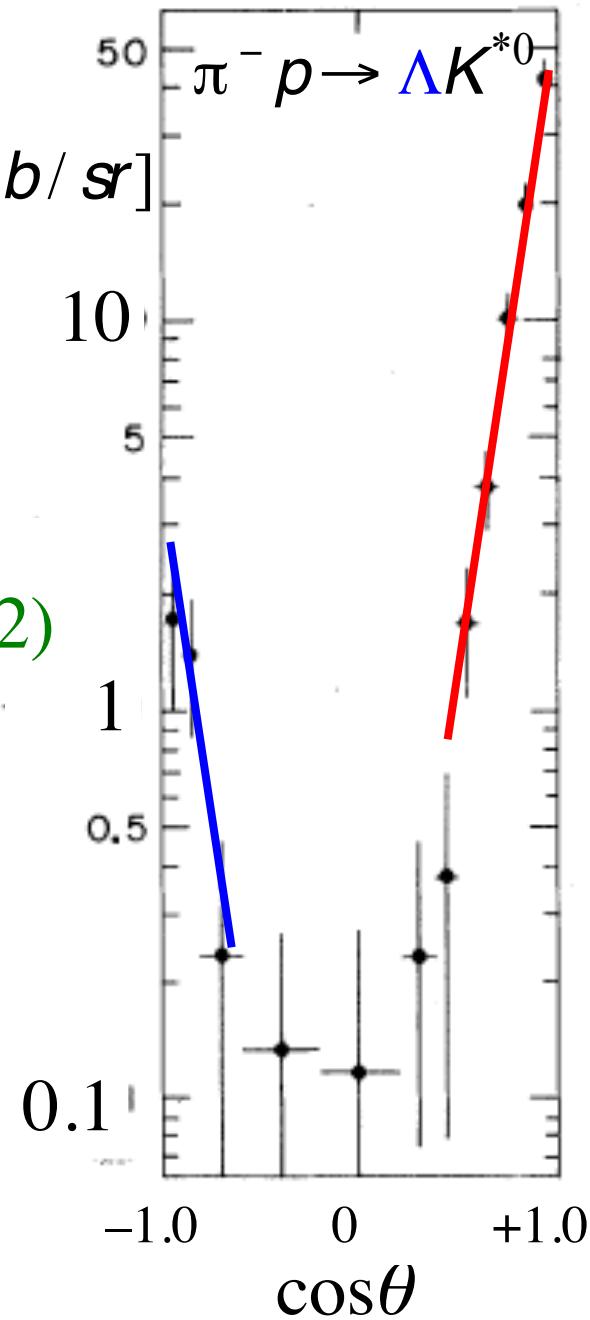
$$\pi + p \rightarrow D^* + B_c^*$$



$$\frac{d\sigma}{d\Omega} [\mu b/sr]$$

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

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

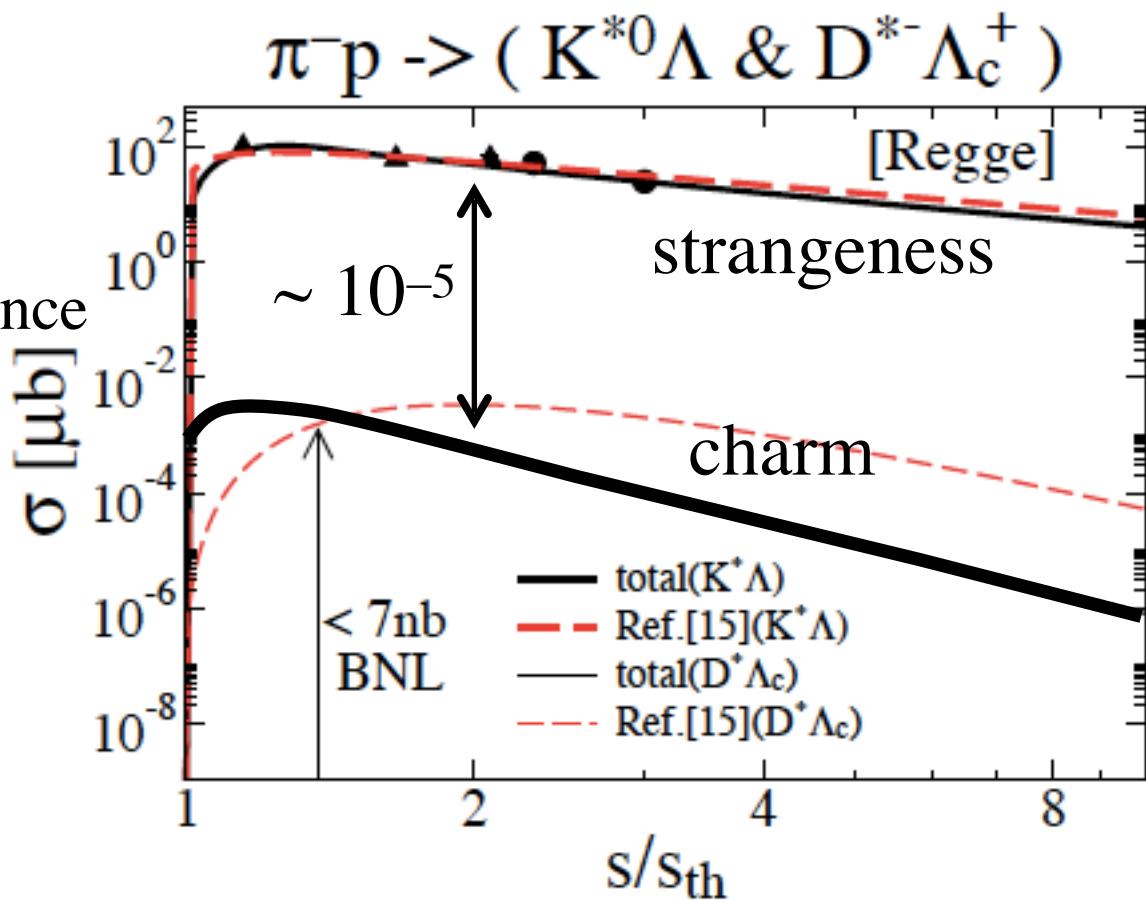


# Absolute values

Regge model (Sang-Ho Kim, in preparation)

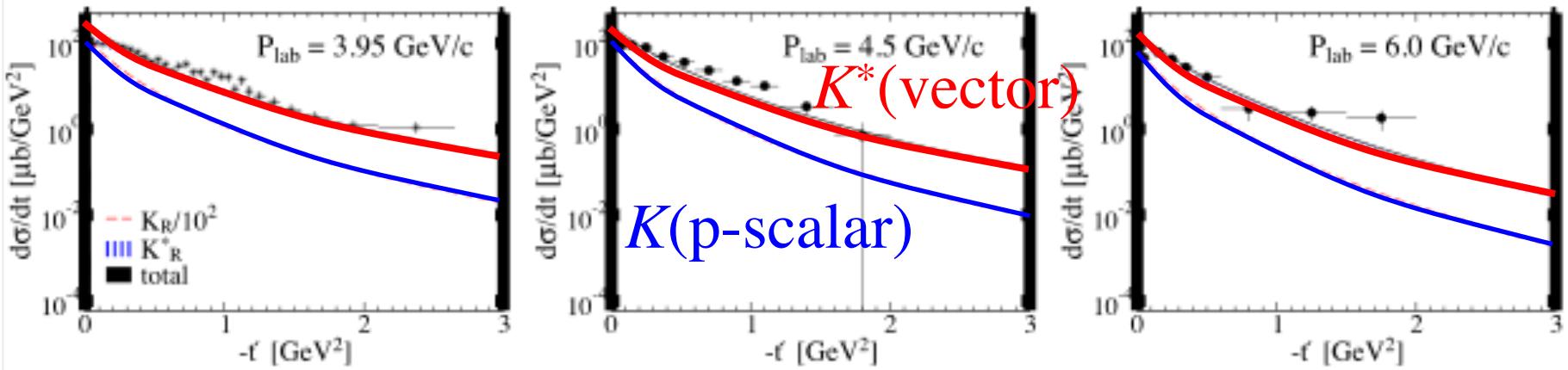
We have examined:

- $K^*$ (strange) productions
- $K^*$  ( $D^*$ ) Reggeon dominance
- Angular dependence
- Small  $u$ -channels  
    ~ Baryon Regge
- Normalizations



Charm/strangeness ratio:  $10^{-4} \sim 10^{-6}$   
→ several nb near the threshold

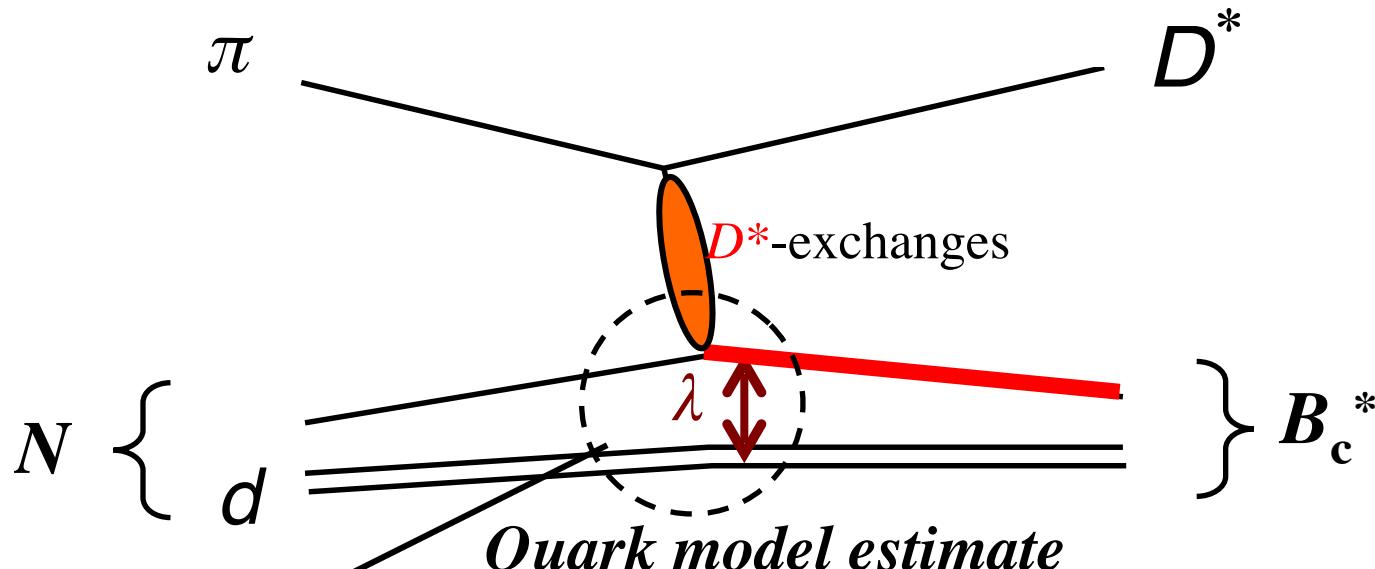
# Vector Reggeon dominance



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

# Relative rates of $(B_c^*/B_c)$

One step process for  $Qd \lambda$ -mode



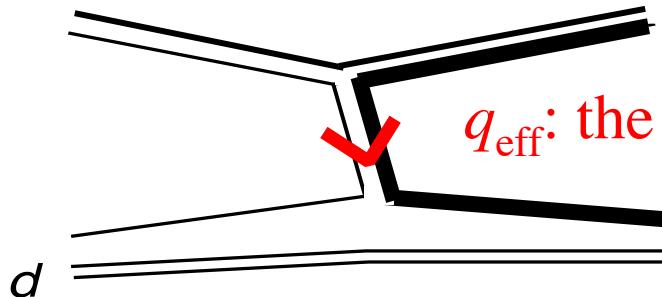
$$t_{fi} \sim \vec{k}_\pi \times \vec{e} \cdot \vec{J}_{fi}$$

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

$CG$  coefficients

$D^* \sim \text{Transverse}$

# Dynamical part $\sim$ radial integral



$q_{\text{eff}}$ : the momentum transfer  $\sim$  Large

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

Excited states

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

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

Transitions to excited states are not suppressed

# Results

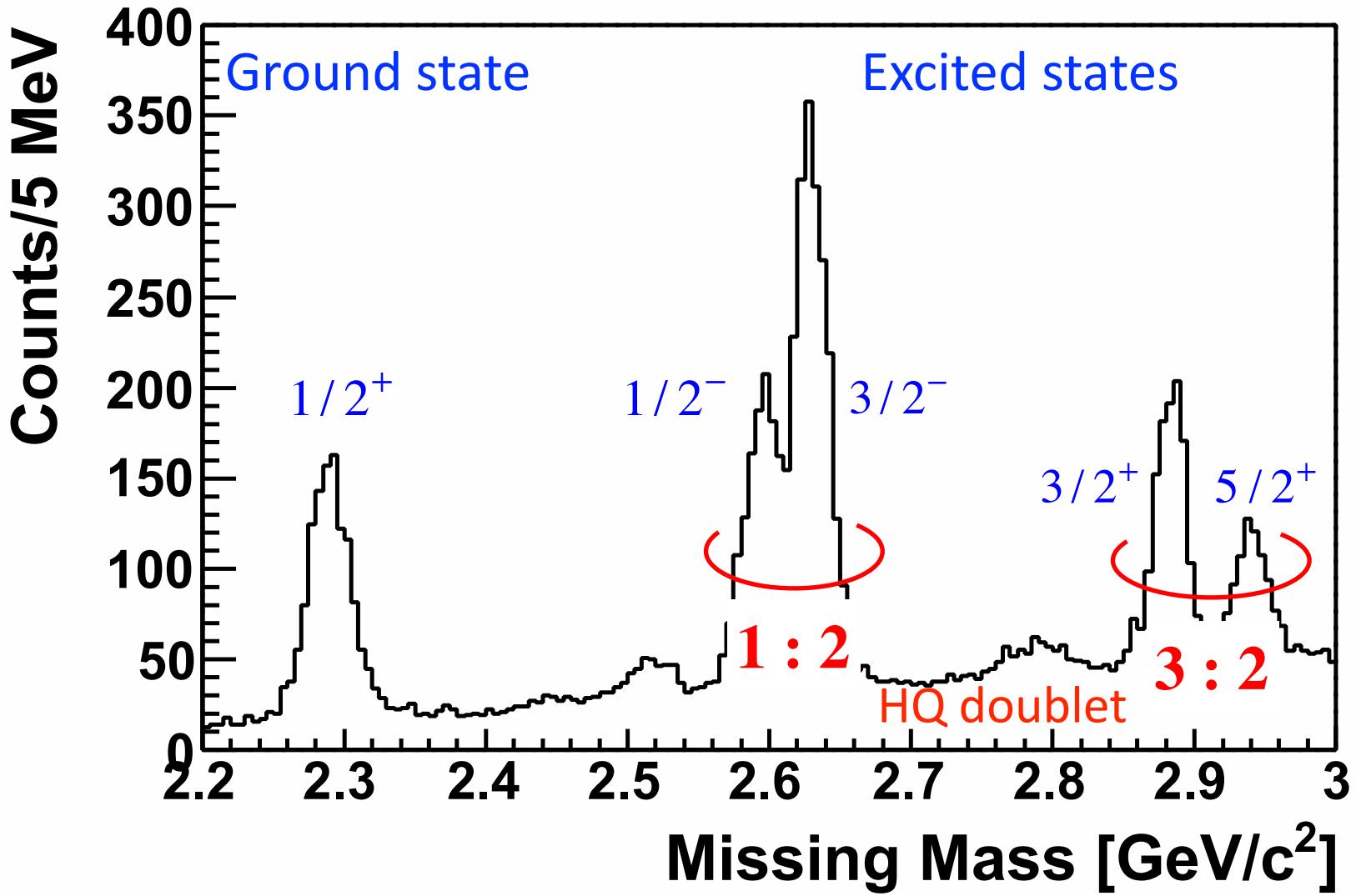
**Charm**  $k_\pi^{CM} = 2.71 \text{ [GeV]} , k_\pi^{Lab} = 16 \text{ [GeV]}$

$l = 0$	$\Lambda_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{3}{2}^+)$					
	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

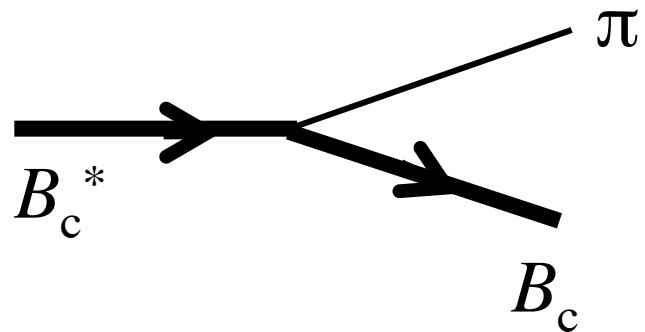
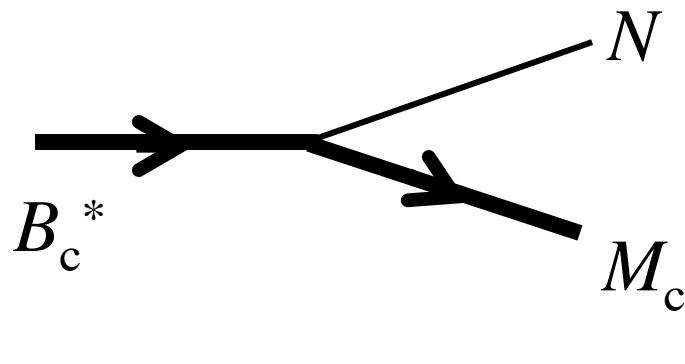
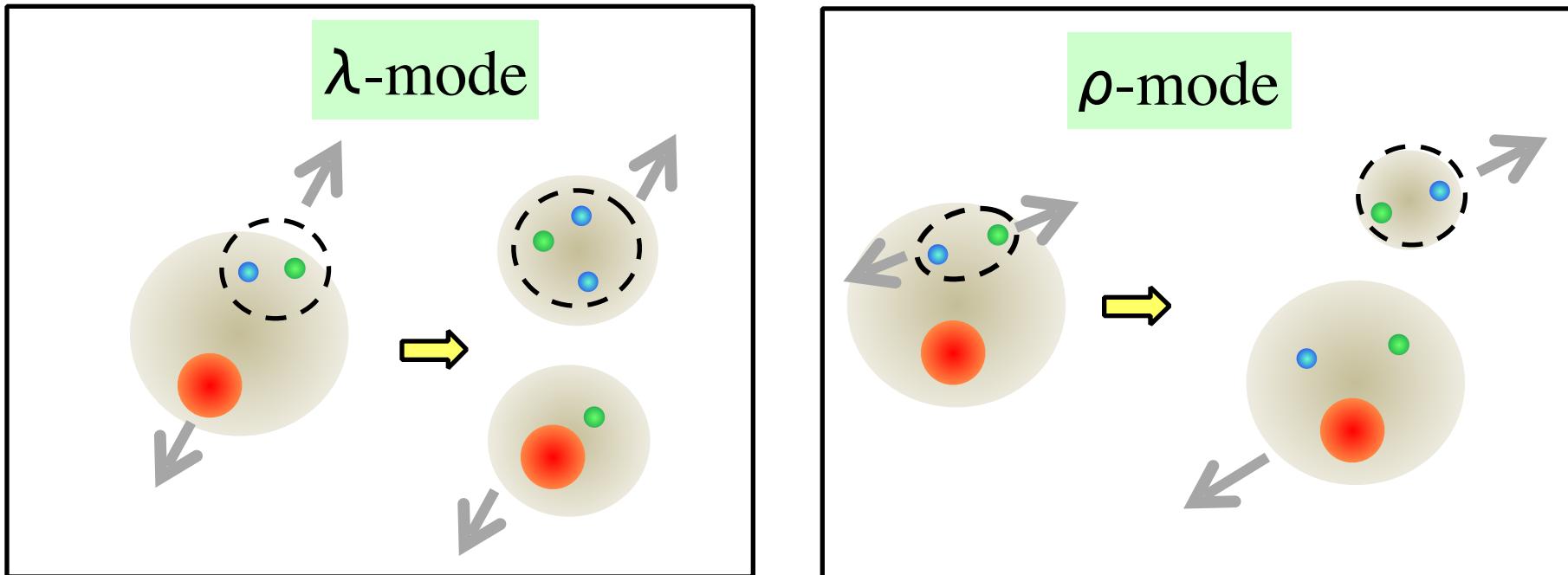
**Strange**     $k_\pi^{CM} = 1.59$  [GeV],  $k_\pi^{Lab} = 5.8$  [GeV]

$l = 0$	$\Lambda_{-}(\frac{1}{2}^{+})$	$\Sigma_{-}(\frac{1}{2}^{+})$	$\Sigma_{-}(\frac{3}{2}^{+})$
	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



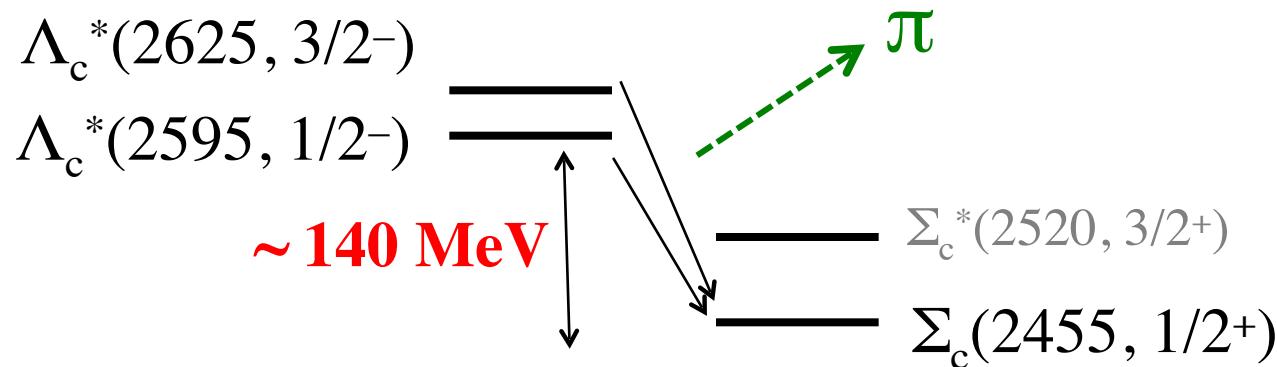
# 4. Decays



# Pion emission – quark model --on going

Things to be looked at:

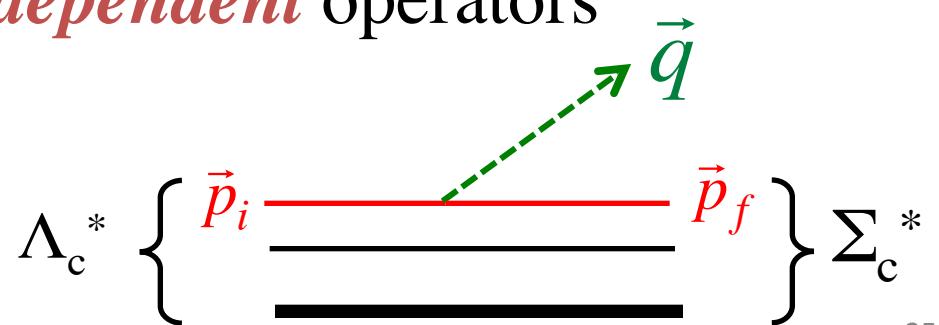
- Pion emission ~ **very near the threshold**



Place to look at the *two independent* operators

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

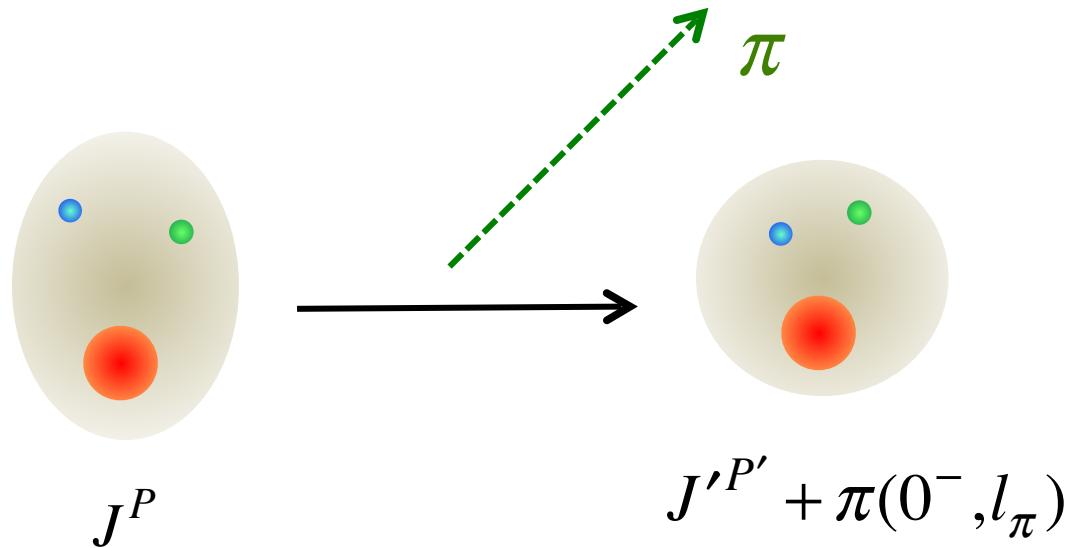
$$\vec{\sigma} \cdot \vec{p}_i, \vec{\sigma} \cdot \vec{p}_f (\vec{\sigma} \cdot \vec{q})$$



# Possible selection rules

$Q$ -modes

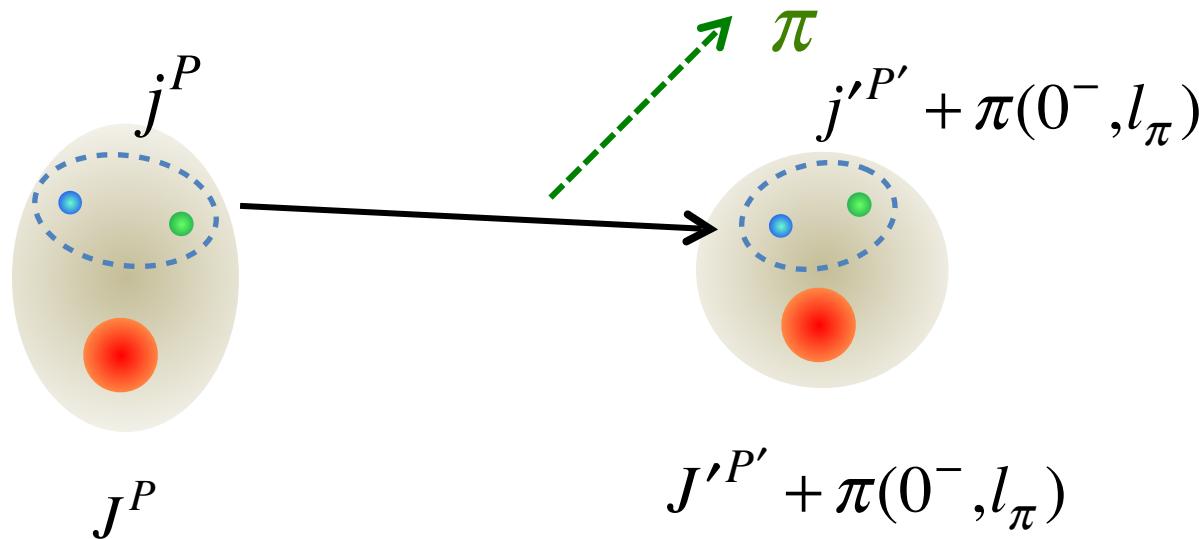
Decays of baryons = of diquarks



# Possible selection rules

$Q$ -modes

Decays of baryons = of diquarks



Two conditions must be satisfied for baryons and for diquarks

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

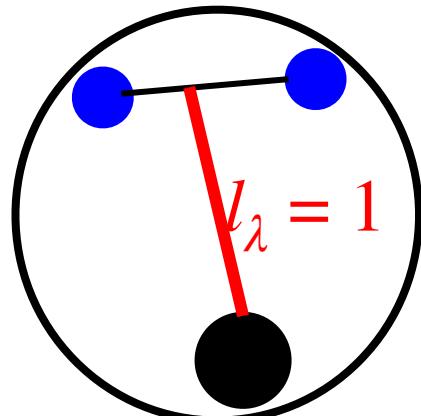
$$d(^3P_0) \rightarrow d(^3S_1) + \pi$$

is not allowed

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

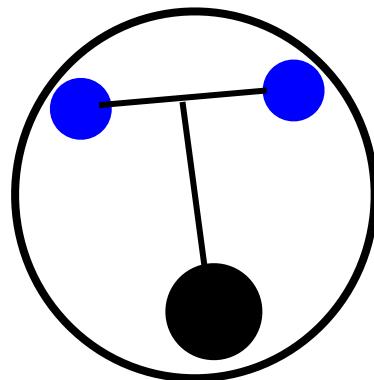
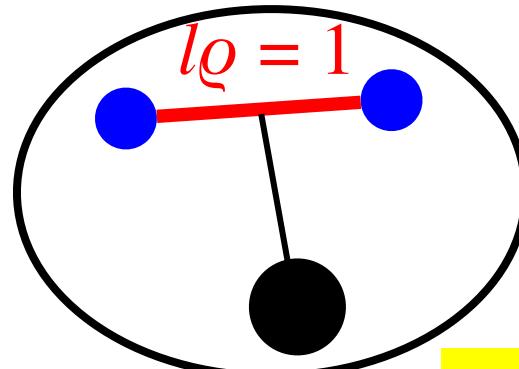
$\lambda$  mode

Good diquark  $0^+$



$\varrho$  mode

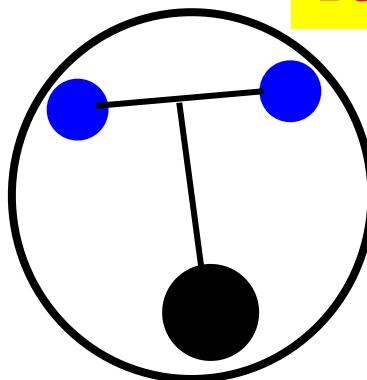
3P0 diquark  $0^-$



Good diquark  $0^+$



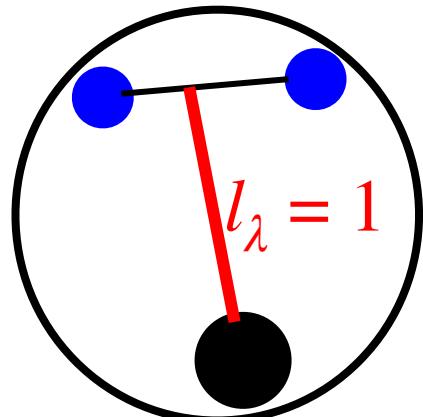
$0^- \rightarrow 0^+$  is  
forbidden



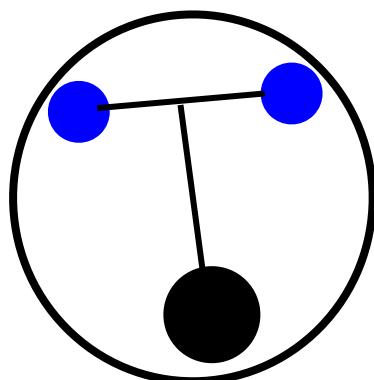
# Radiative decay: $5/2^- \rightarrow 1/2^+$ M2, E3

$\lambda$  mode

$^3S_1$  diquark  $1^+$



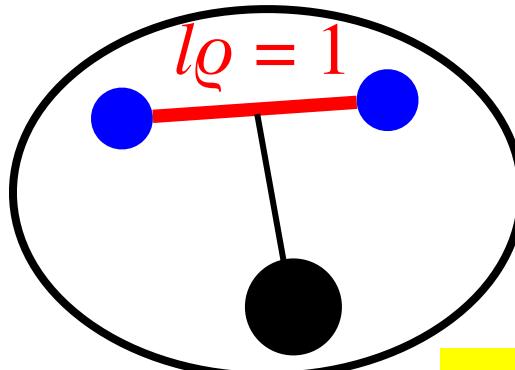
Both M2 E3



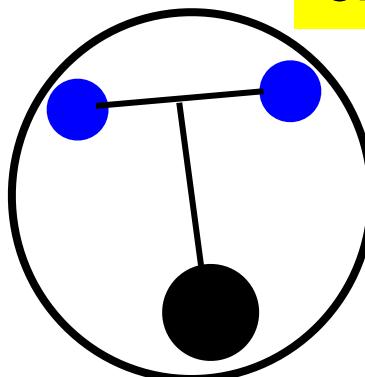
Good diquark  $0^+$

$\varrho$  mode

$^3P_2$  diquark  $2^-$



$2^- \rightarrow 0^+$  is  
only M2



# Summary

- Charmed baryons: there are many open issues
- J-PARC plans to study them
- Production rate: Charm/Strangeness:  $10^{-4} – 10^{-6}$
- Abundant production of excited states
- Decay selection rules are helpful