

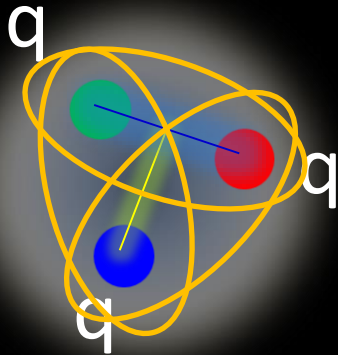
Heavy Hadron Physics at J-PARC

H. Noumi (RCNP, Osaka University)

P50 experiment: Heavy Baryon Spectroscopy
Structure of heavy baryons:

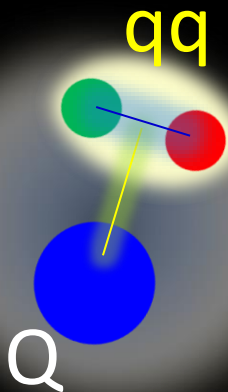
A. Hosaka, K. Sadato, K. Shirotori, and HN

What are essential D.o.F. of baryons?



- Most fundamental question
- Interaction btwn quarks

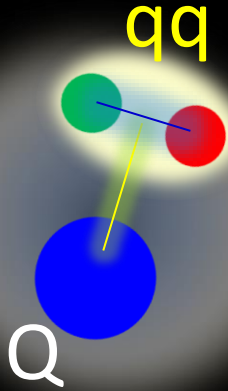
Diquark correlations



→ A heavy quark in a baryon
to close up a “qq” pair

- Weaker Color Magnetic
Interaction with a heavy Quark

Charmed Baryon Spectroscopy



Using **Missing Mass Techniques**

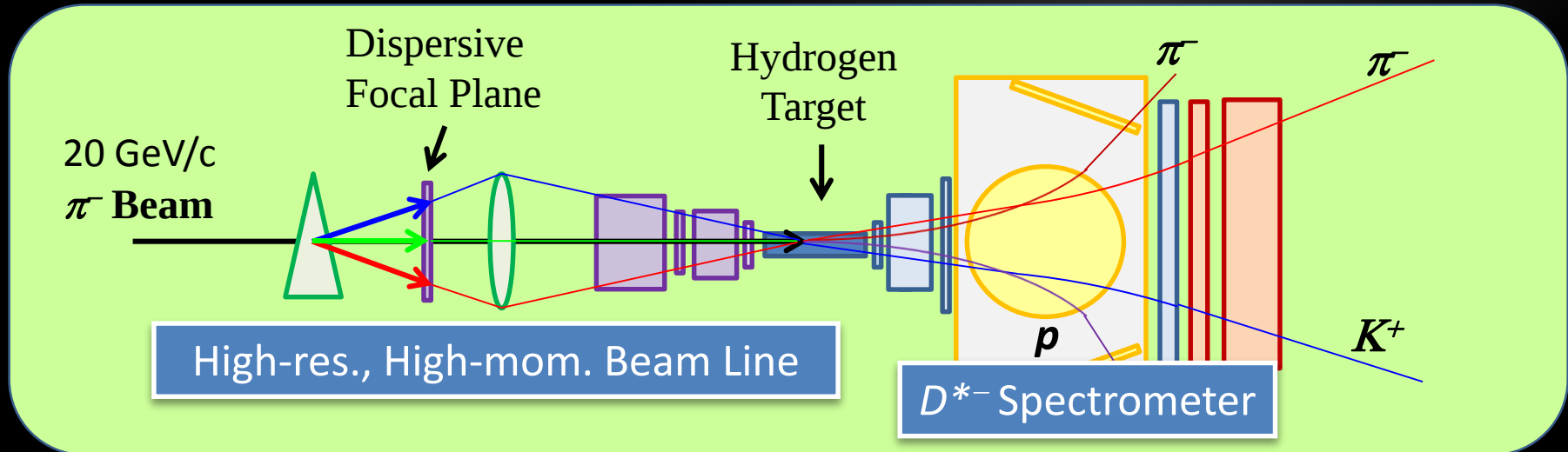
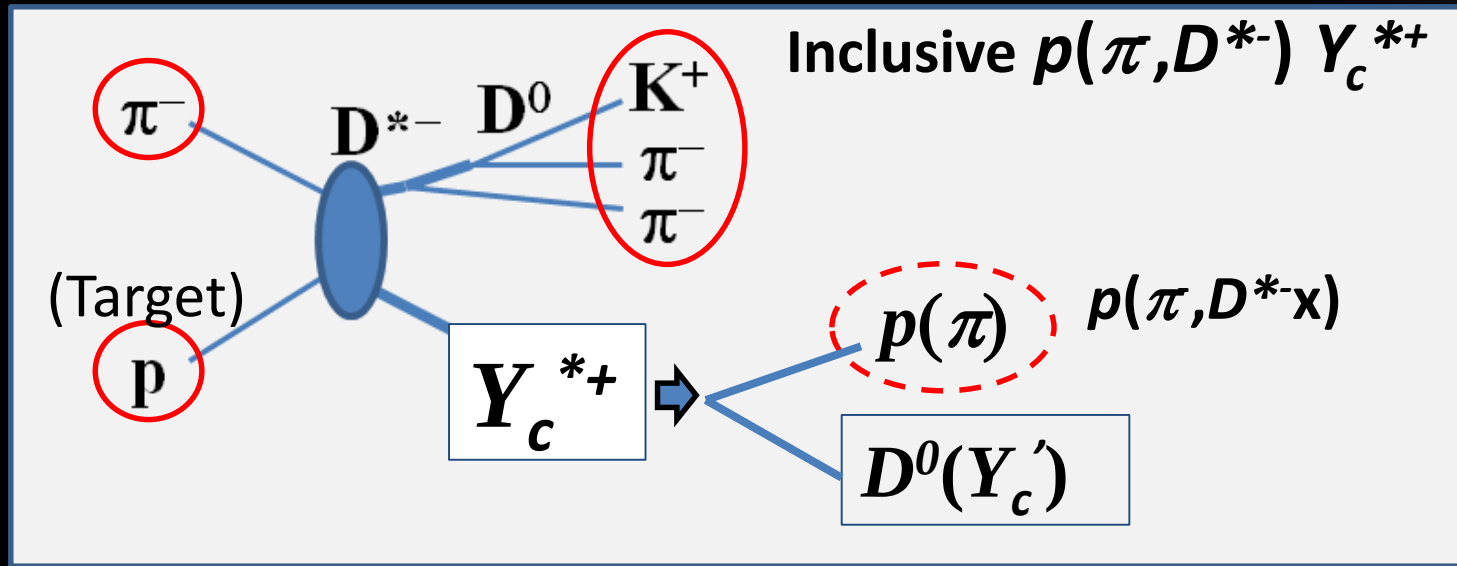
Inclusive measurement

+ Decay Particle Measurement

- inclusive (π^- , D^{*-}) spectrum
 - Level structure of Y_c^*
 - Production Rate
- + Decay Particles
 - Decay Width/Decay Branching Ratios
 - Spin, Parity

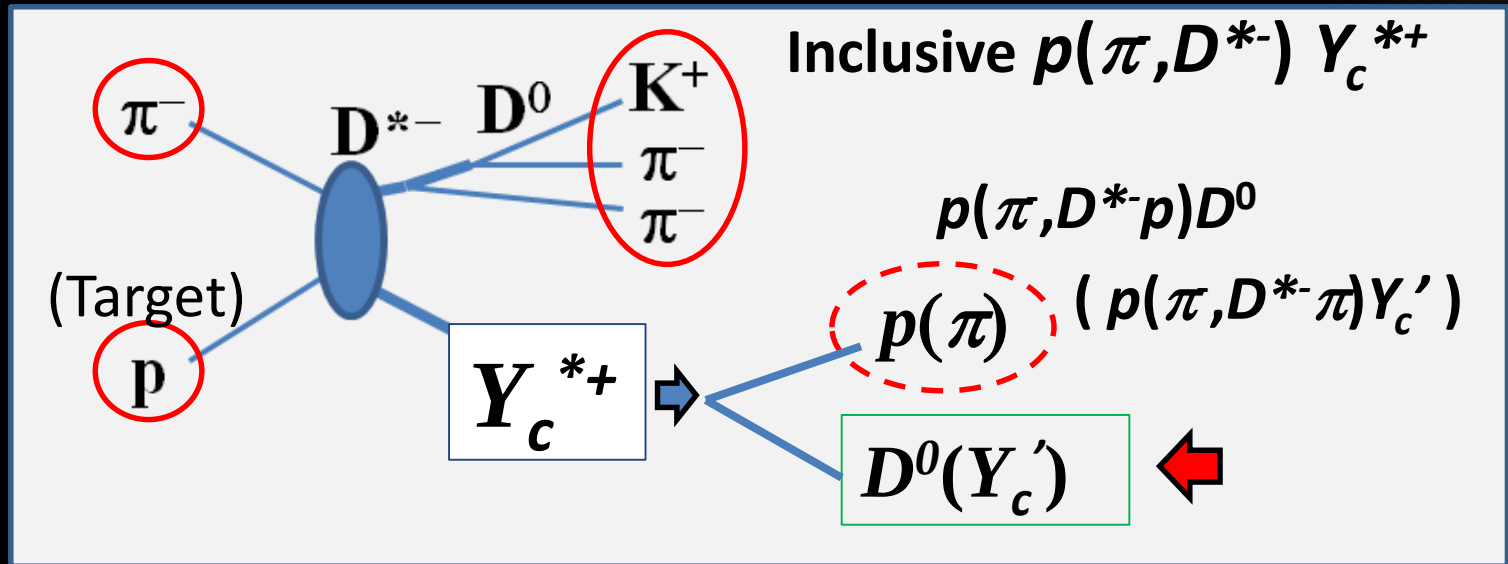
Charmed Baryon Spectroscopy

Using Missing Mass Techniques



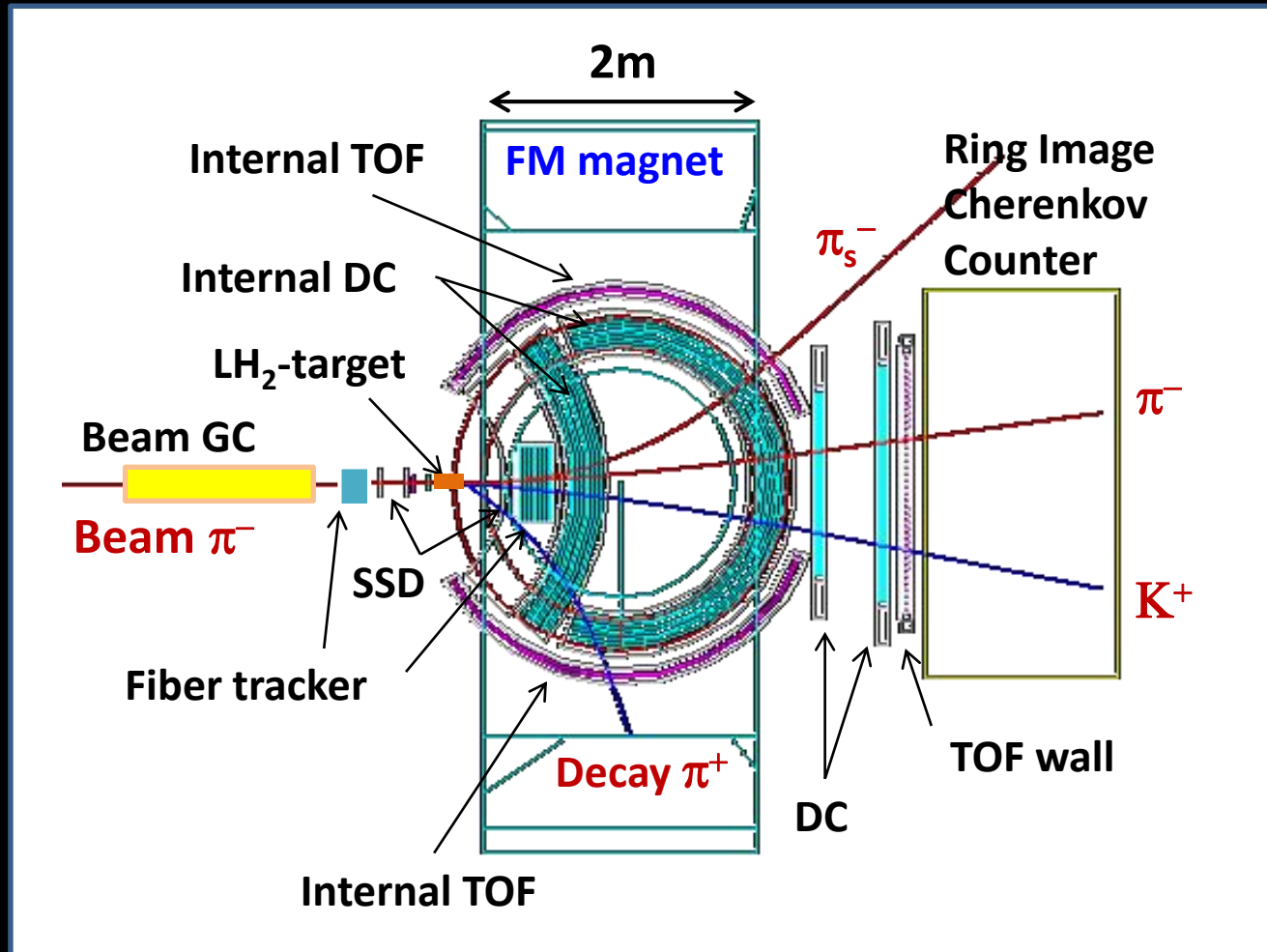
Charmed Baryon Spectroscopy

Using Missing Mass Techniques



- inclusive (π^-, D^{*-}) spectrum
 - Level structure of Y_c^*
 - Production Rate
- Decay Particles
 - Decay Width/Decay Branching Ratios
 - Spin, Parity

Charmed Baryon Spectrometer



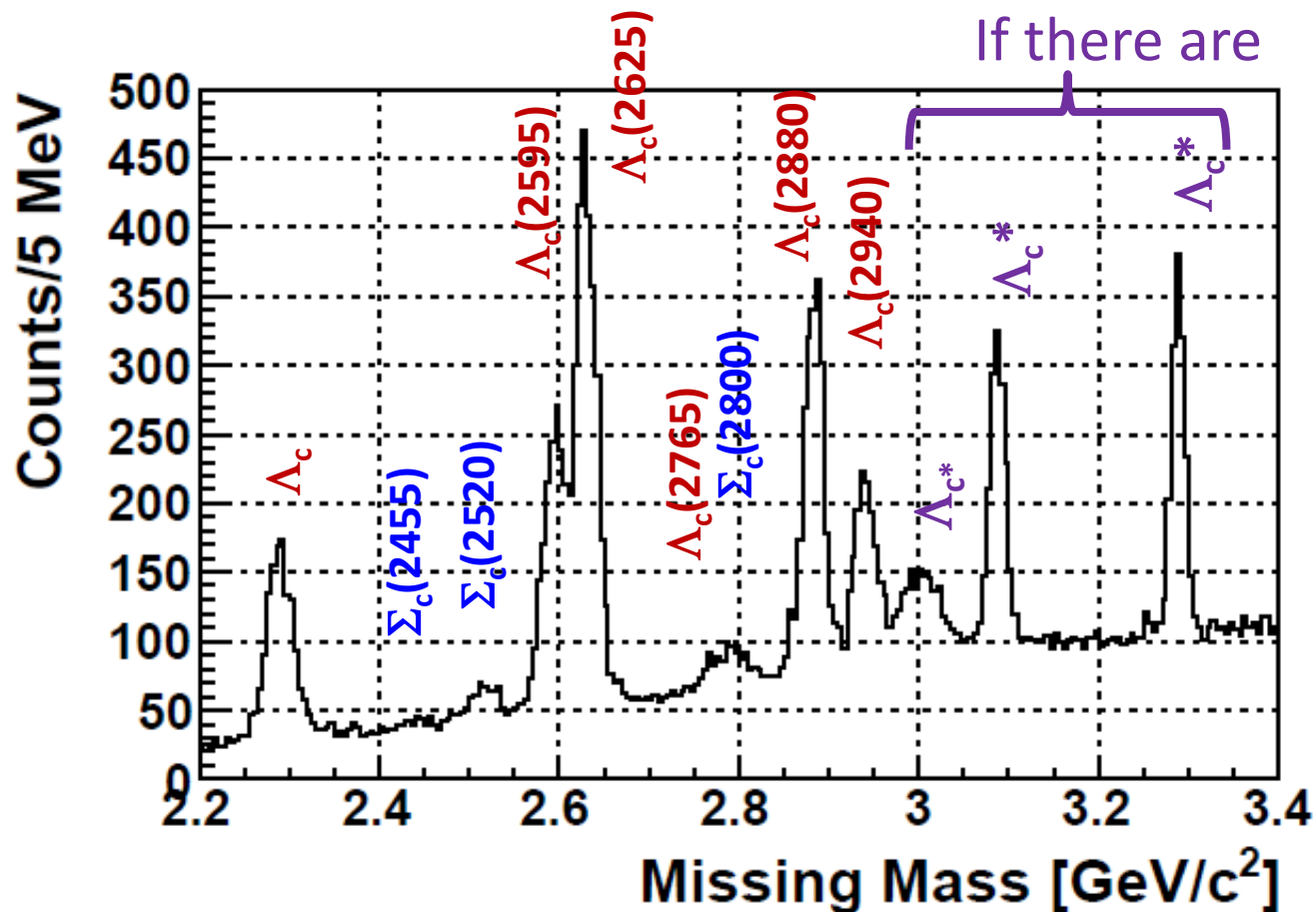
Large acceptance $\sim 60\%$ (for D^*), $\Delta p/p \sim 0.2\%$ at $\sim 5 \text{ GeV}/c$

Expected spectrum: $\sigma_{GS} = 1 \text{ nb}$

$N(Y_c^*) \sim 1000$ events/1nb/100 days

Better mass resolution: $\sim 10 \text{ MeV}/c^2$

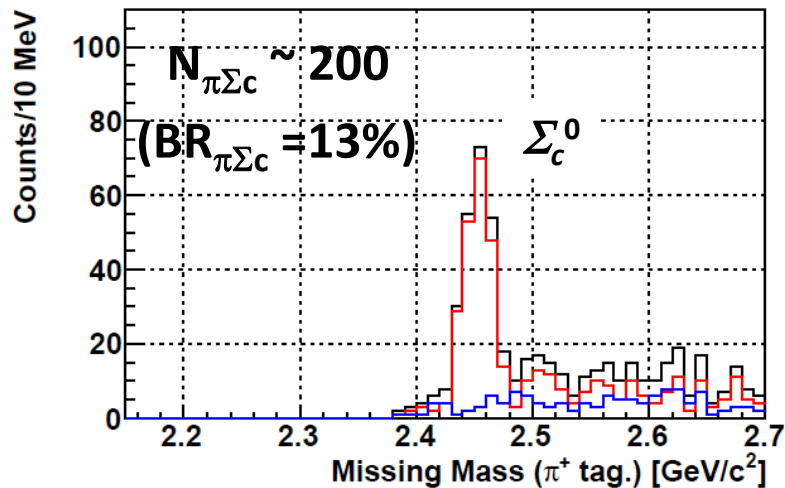
Sensitivity: $\sim 0.1 \text{ nb}$ (3σ , $\Gamma \sim 100 \text{ MeV}$)



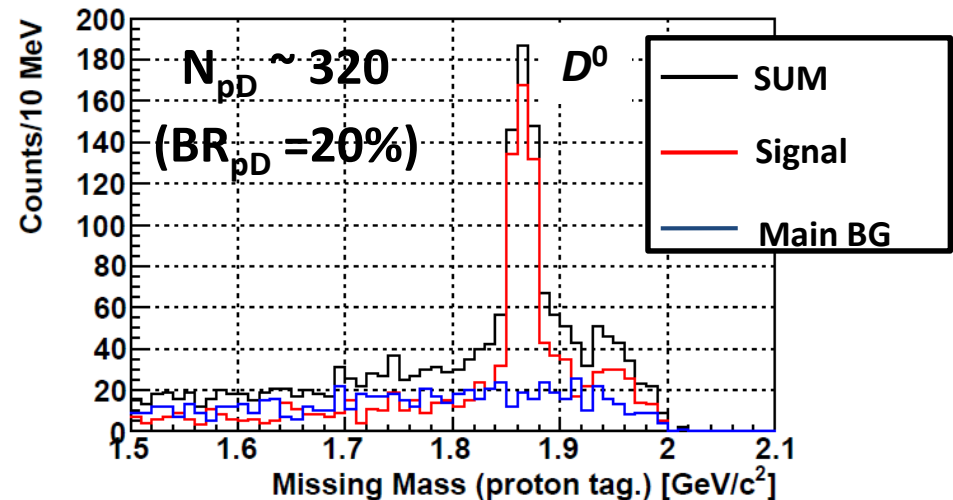
Decay Products

$$\Lambda_c(2940) \rightarrow \Sigma_c^0 \pi^+$$

with $\Lambda_c^+ \pi^+ \pi^-$ selected



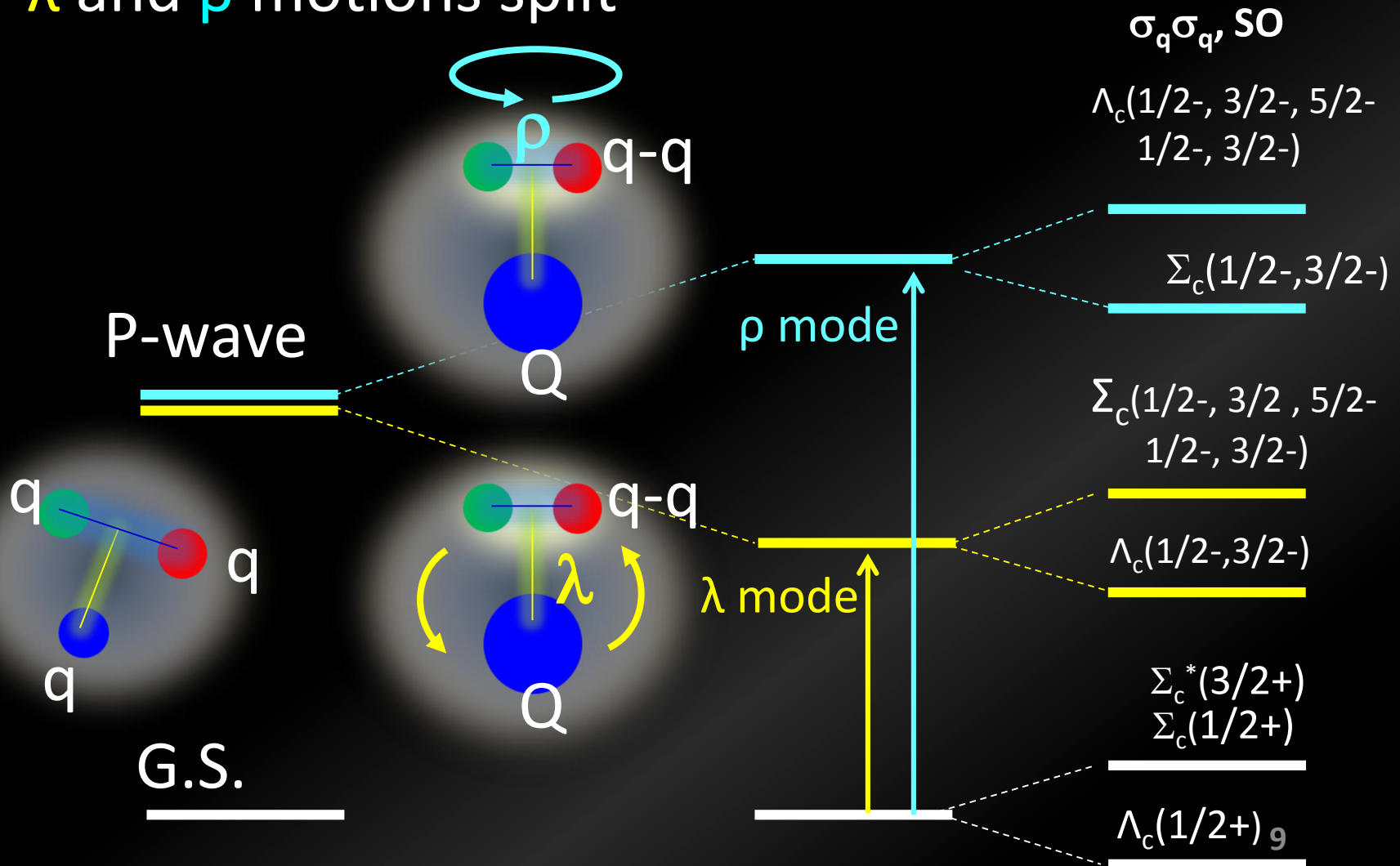
$$\Lambda_c(2940) \rightarrow p D^0$$



- * Decay meas. strongly assists the missing mass spectroscopy.
 - Branching ratios: Diquark corr. affects $\Gamma(\Lambda_c^* \rightarrow pD)/\Gamma(\Lambda_c^* \rightarrow \Sigma_c \pi)$.
 - Angular distribution: Spin, Parity

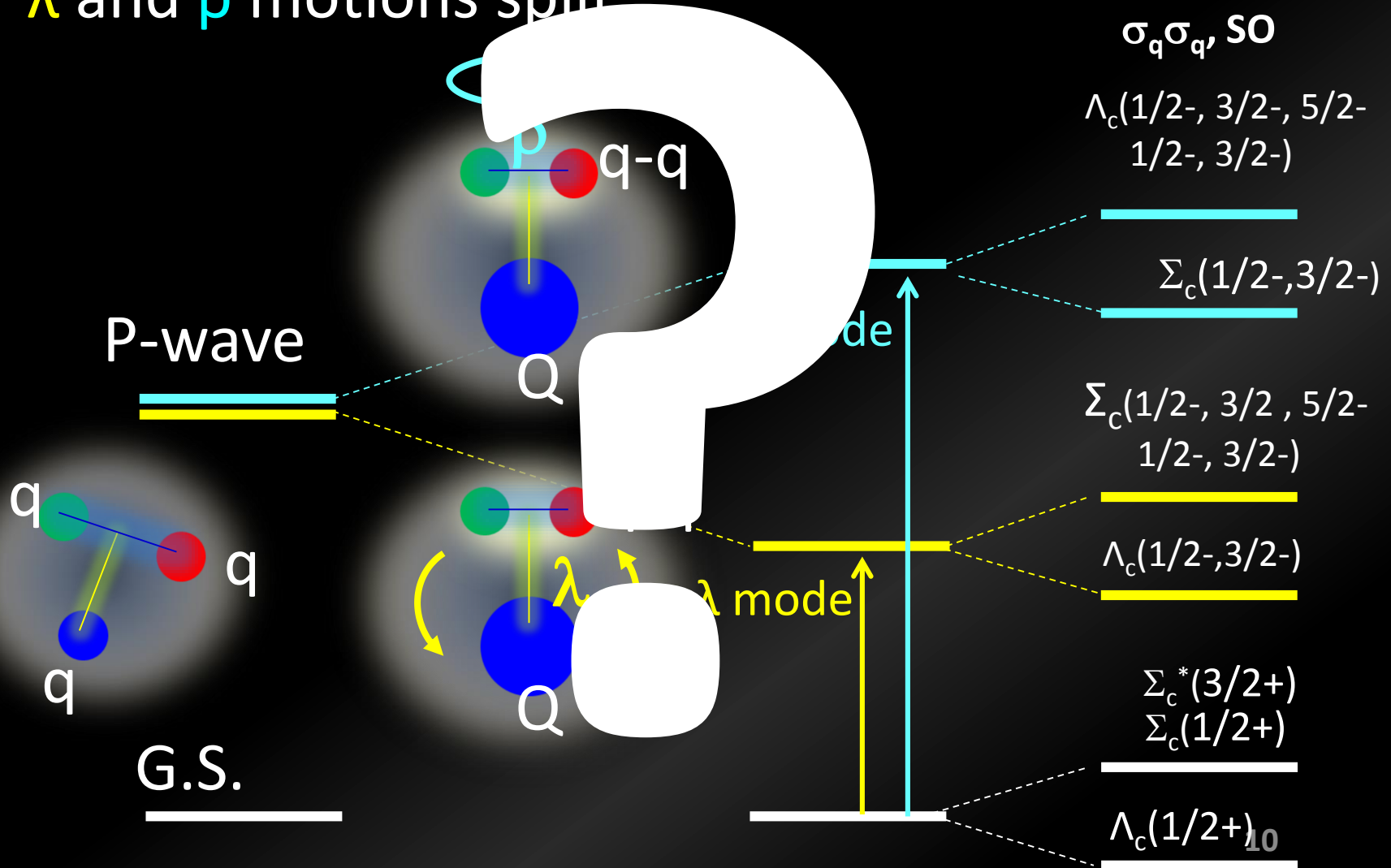
“qq” correlation in charmed baryons

- λ and ρ motions split



“qq” correlation in charmed baryons

- λ and ρ motions split



Confinement

- $H = H_0 + V_c + V_{ss} + \dots$

$\Psi \sim \psi_\ell \chi_S \phi_I(\text{color}) \rightarrow \text{symmetrize (anti-symm.)}$

- $V_c = k/2 \sum r_i^2$

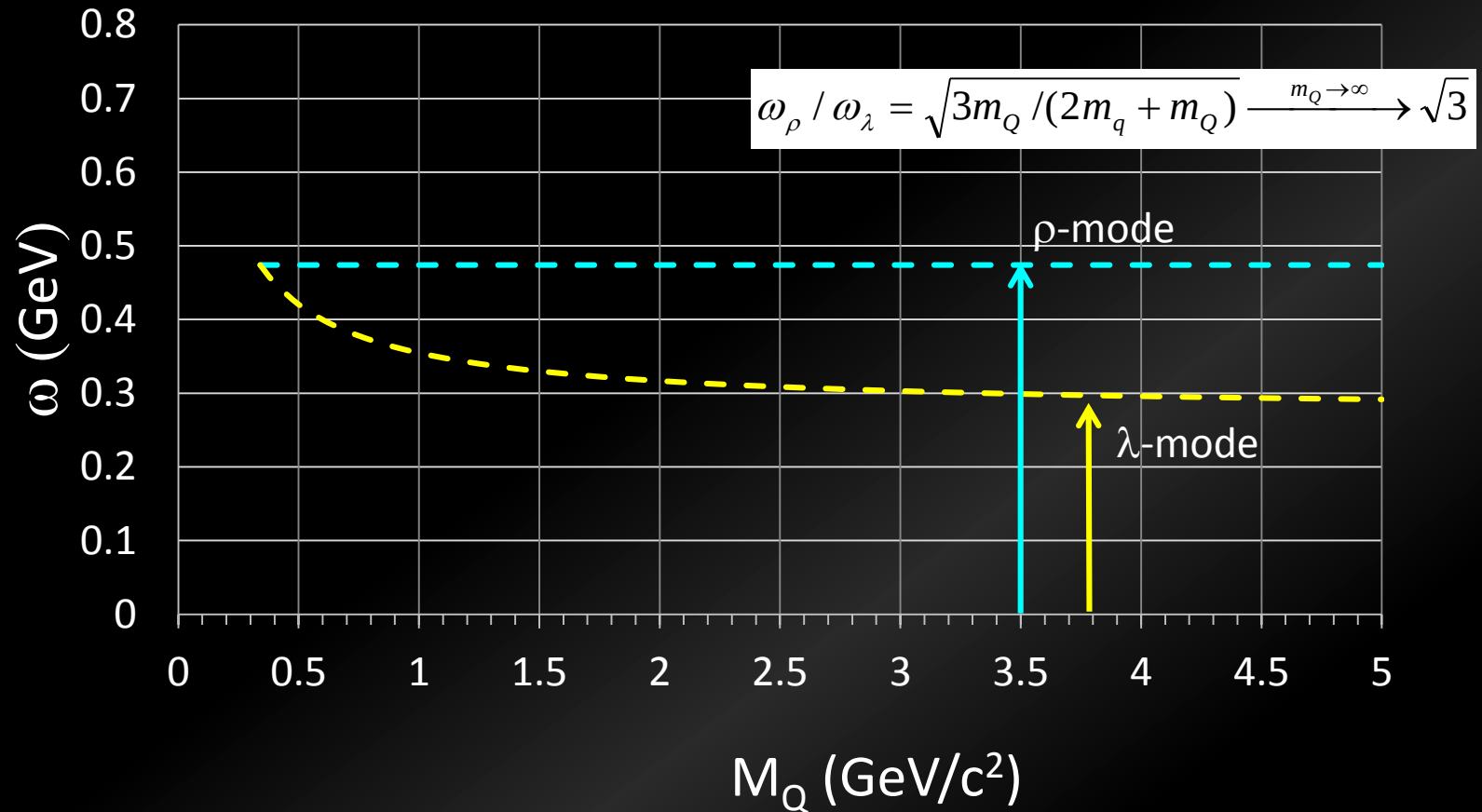
$$\omega_{\lambda,\rho} = \sqrt{3k/m_{\lambda,\rho}}, \quad \left(m_\lambda = \frac{3m_q m_Q}{2m_q + m_Q}, m_\rho = m_q \right)$$

$$k = 0.33^2 m_\lambda / 3, \text{ at } m_Q = 1.5 \text{ GeV}/c^2$$

$$\text{c.f. } 1\hbar\omega_\lambda \sim \frac{\Lambda_c\left(\frac{1}{2}^-\right) + 2\Lambda_c\left(\frac{3}{2}^-\right)}{3} - \Lambda_c\left(\frac{1}{2}^+\right) \sim 0.33 \text{ GeV}/c^2$$

P-wave (ρ , λ -mode excitations)

isotope shift



Spin-spin Interaction

- $H = H_0 + V_c + V_{ss} + \dots$

$\Psi \sim \psi_\ell \chi_S \phi_I(\text{color}) \rightarrow \text{symmetrize (anti-symm.)}$

- $V_c = k/2 \sum r_i^2$

$$\omega_{\lambda,\rho} = \sqrt{3k/m_{\lambda,\rho}}, \quad \left(m_\lambda = \frac{3m_q m_Q}{2m_q + m_Q}, m_\rho = m_q \right)$$

- $V_{ss} = c_s \sum \frac{\sigma_i \cdot \sigma_j}{m_i m_j} \delta(r_{ij}) \quad \langle \chi_S | V_{ss} | \chi_S \rangle:$

$$\Lambda\left(\frac{1}{2}^+\right) = \omega_0 - 3c_s/m_q^2 \quad (S, \chi^\rho) : \text{“qq”-spin anti-symm.}$$

$$\Sigma\left(\frac{1}{2}^+\right) = \omega_0 + c_s \left(\frac{1}{m_q^2} - \frac{4}{m_q m_Q} \right) \quad (S, \chi^\lambda) : \text{“qq”-spin symm., } [qqQ]^{1/2}$$

$$\Sigma^*\left(\frac{3}{2}^+\right) = \omega_0 + c_s \left(\frac{1}{m_q^2} + \frac{2}{m_q m_Q} \right) \quad (S, \chi^S) : \text{“qqQ” spin symm.}$$

Spin-spin Interaction

- $H = H_0 + V_c + V_{ss} + \dots$

$\Psi \sim \psi_\ell \chi_S \phi_I(\text{color}) \rightarrow \text{symmetrize (anti-symm.)}$

- $V_c = k/2 \sum r_i^2$

$$\omega_{\lambda,\rho} = \sqrt{3k/m_{\lambda,\rho}}, \quad \left(m_\lambda = \frac{3m_q m_Q}{2m_q + m_Q}, m_\rho = m_q \right)$$

- $V_{ss} = c_s \sum \frac{\sigma_i \cdot \sigma_j}{m_i m_j} \delta(r_{ij}) \quad \langle \chi_S | V_{ss} | \chi_S \rangle:$

$$\Lambda \left(\frac{1}{2}^+ \right) = \omega_0 - 3c_s/m_q^2$$

$$\Sigma \left(\frac{1}{2}^+ \right) = \omega_0 + c_s \left(\frac{1}{m_q^2} - \frac{4}{m_q m_Q} \right)$$

$$\Sigma^* \left(\frac{3}{2}^+ \right) = \omega_0 + c_s \left(\frac{1}{m_q^2} + \frac{2}{m_q m_Q} \right)$$

$$\left. \begin{array}{l} \Lambda \left(\frac{1}{2}^+ \right) \\ \Sigma \left(\frac{1}{2}^+ \right) \\ \Sigma^* \left(\frac{3}{2}^+ \right) \end{array} \right\} \rightarrow \frac{\Sigma + 2\Sigma^*}{3} - \Lambda = c_s \frac{4}{m_q^2} \sim 0.2 \text{ GeV}/c^2$$

Spin-spin Interaction

- $H = H_0 + V_c + V_{ss} + \dots$

$\Psi \sim \psi_\ell \chi_S \phi_I(\text{color}) \rightarrow \text{symmetrize (anti-symm.)}$

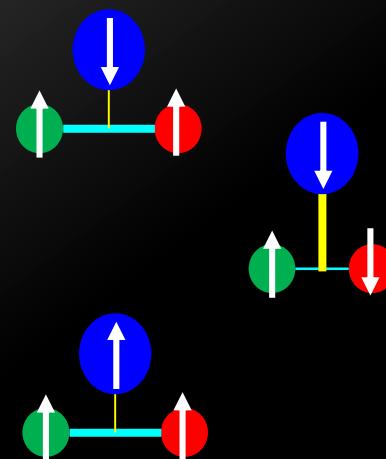
- $V_c = k/2 \sum r_i^2$

$$\omega_{\lambda,\rho} = \sqrt{3k/m_{\lambda,\rho}}, \quad \left(m_\lambda = \frac{3m_q m_Q}{2m_q + m_Q}, m_\rho = m_q \right)$$

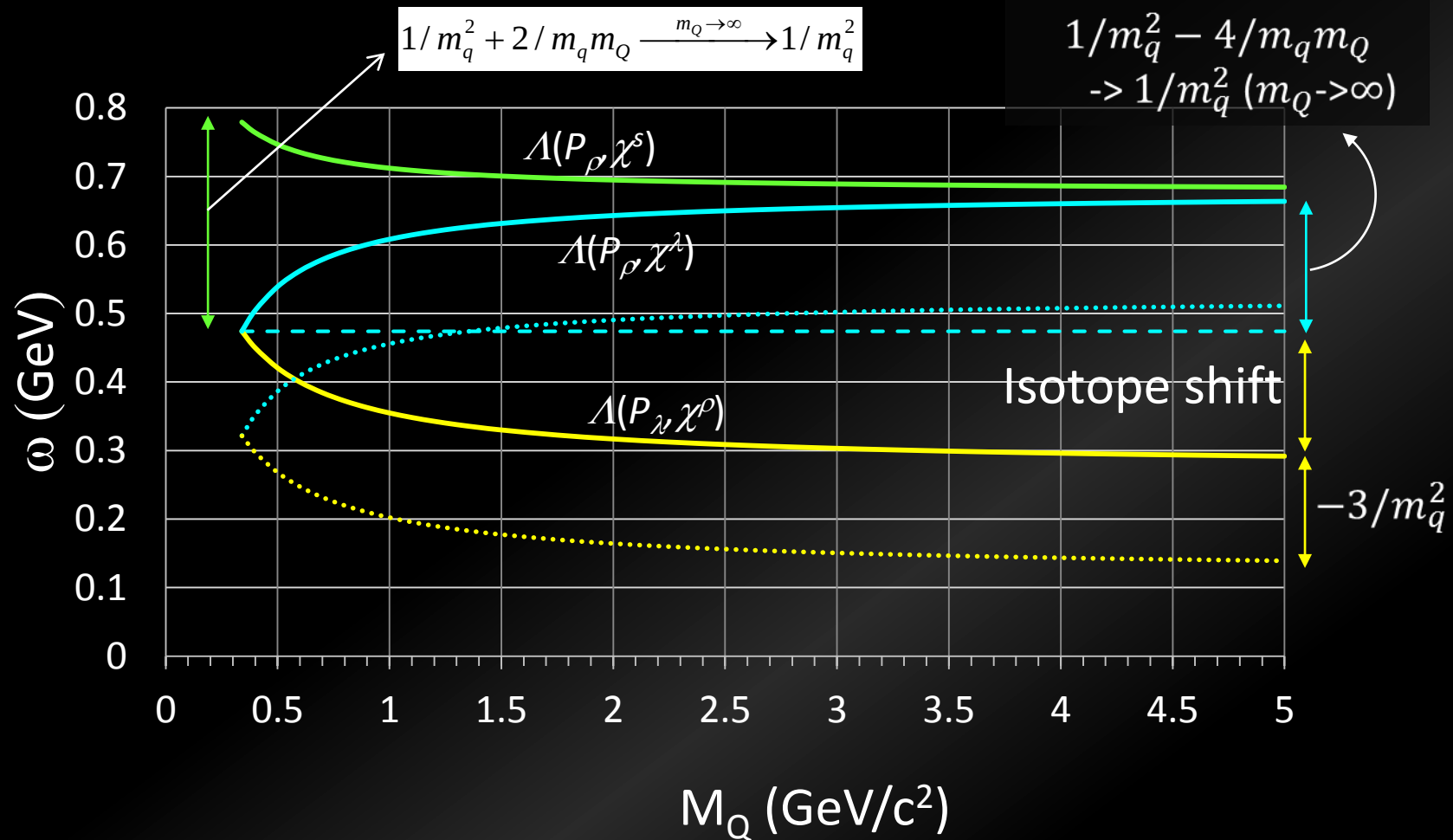
- $V_{ss} = c_s \sum \frac{\sigma_i \cdot \sigma_j}{m_i m_j} \delta(r_{ij}) \quad \langle \chi_S | V_{ss} | \chi_S \rangle:$

$$\Lambda\left(\frac{1}{2}^-, \frac{3}{2}^-\right) = \begin{cases} \omega_\rho - c_s \left(\frac{1}{m_q^2} - \frac{4}{m_q m_Q} \right) & (\ell_\rho = 1, \chi^\lambda) \\ \omega_\lambda - 3c_s/m_q^2 & (\ell_\lambda = 1, \chi^\rho) \end{cases}$$

$$\Lambda\left(\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-\right) = \omega_\rho + c_s \left(\frac{1}{m_q^2} + \frac{2}{m_q m_Q} \right) (\ell_\rho = 1, \chi^s)$$



$\Lambda(P, \chi)$ (ρ, λ -mode excitations w/ V_{ss})



Spin-spin Interaction

- $H = H_0 + V_c + V_{ss} + \dots$

$\Psi \sim \psi_\ell \chi_S \phi_I(\text{color}) \rightarrow \text{symmetrize (anti-symm.)}$

- $V_c = k/2 \sum r_i^2$

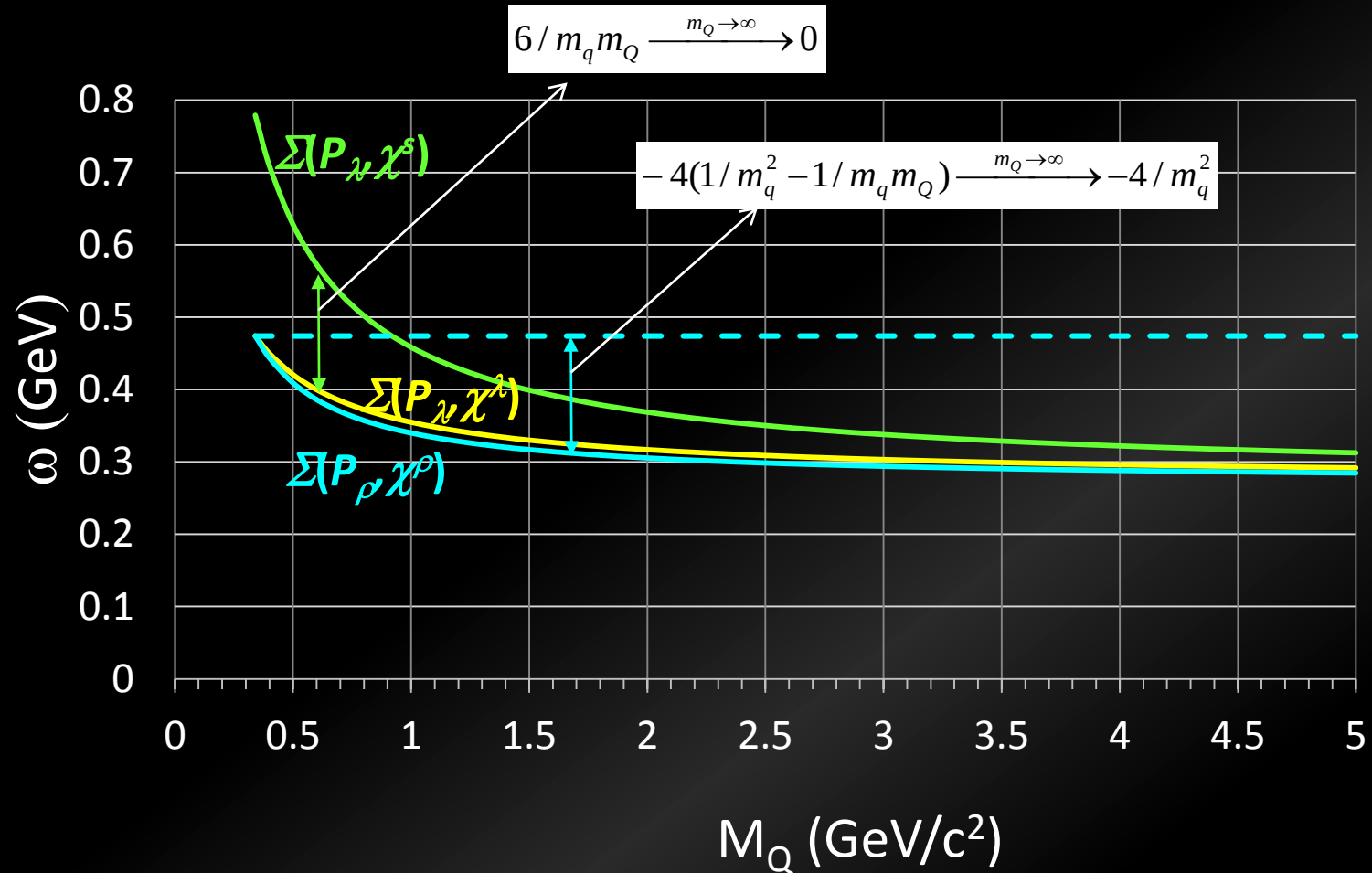
$$\omega_{\lambda,\rho} = \sqrt{3k/m_{\lambda,\rho}}, \quad \left(m_\lambda = \frac{3m_q m_Q}{2m_q + m_Q}, m_\rho = m_q \right)$$

- $V_{ss} \sim c_s \sum \frac{\sigma_i \cdot \sigma_j}{m_i m_j} \delta(r_{ij}) \quad \langle \chi_S | V_{ss} | \chi_S \rangle:$

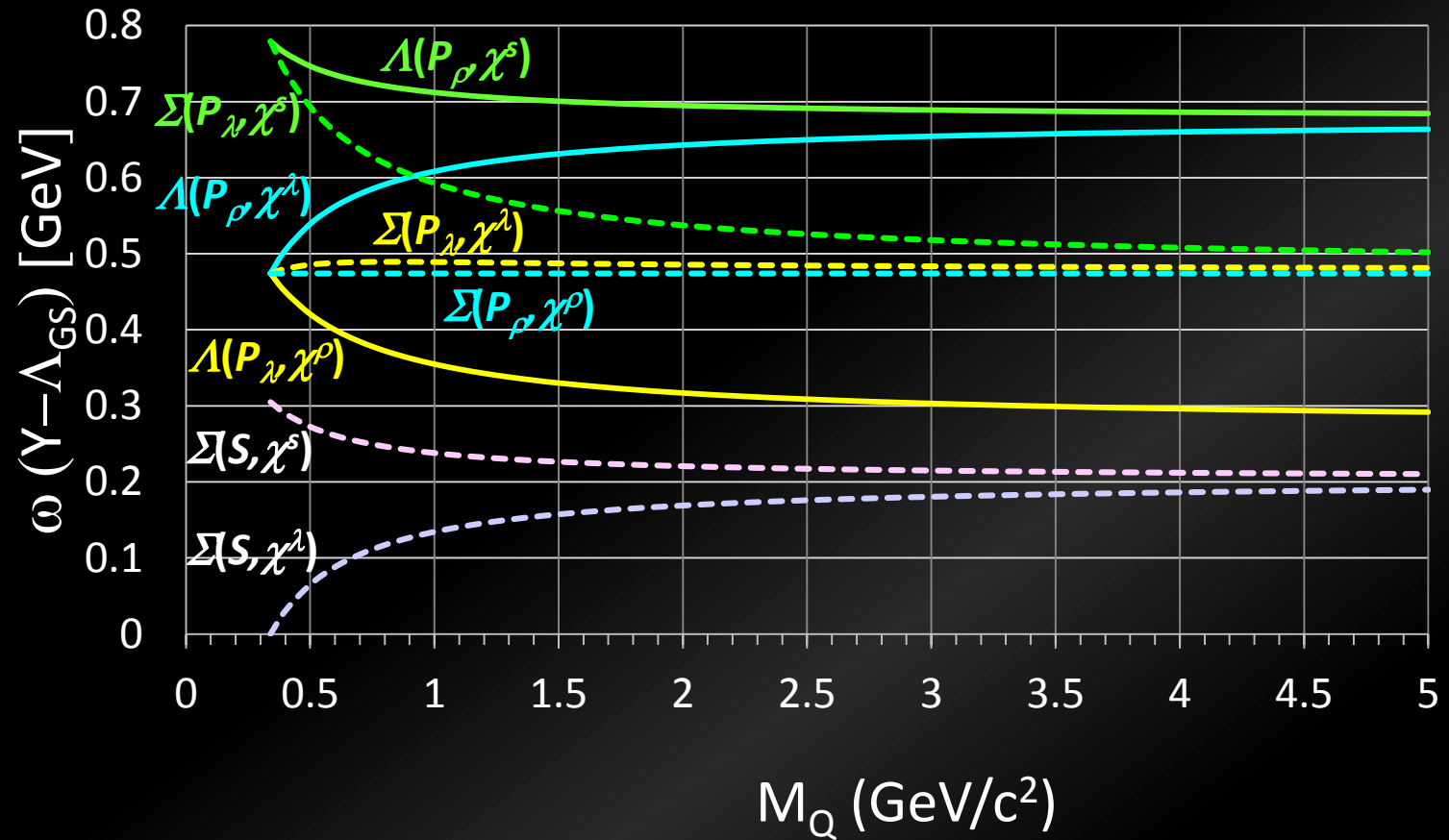
$$\Sigma\left(\frac{1}{2}^-, \frac{3}{2}^-\right) = \begin{cases} \omega_\rho - 3c_s/m_q^2 & (\ell_\rho = 1, \chi^\rho) \\ \omega_\lambda + c_s \left(\frac{1}{m_q^2} - \frac{4}{m_q m_Q} \right) & (\ell_\lambda = 1, \chi^\lambda) \end{cases}$$

$$\Sigma\left(\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-\right) = \omega_\lambda + c_s \left(\frac{1}{m_q^2} + \frac{2}{m_q m_Q} \right) (\ell_\lambda = 1, \chi^s)$$

$\Sigma(P, \chi)$ (ρ, λ -mode excitations w/ V_{ss})

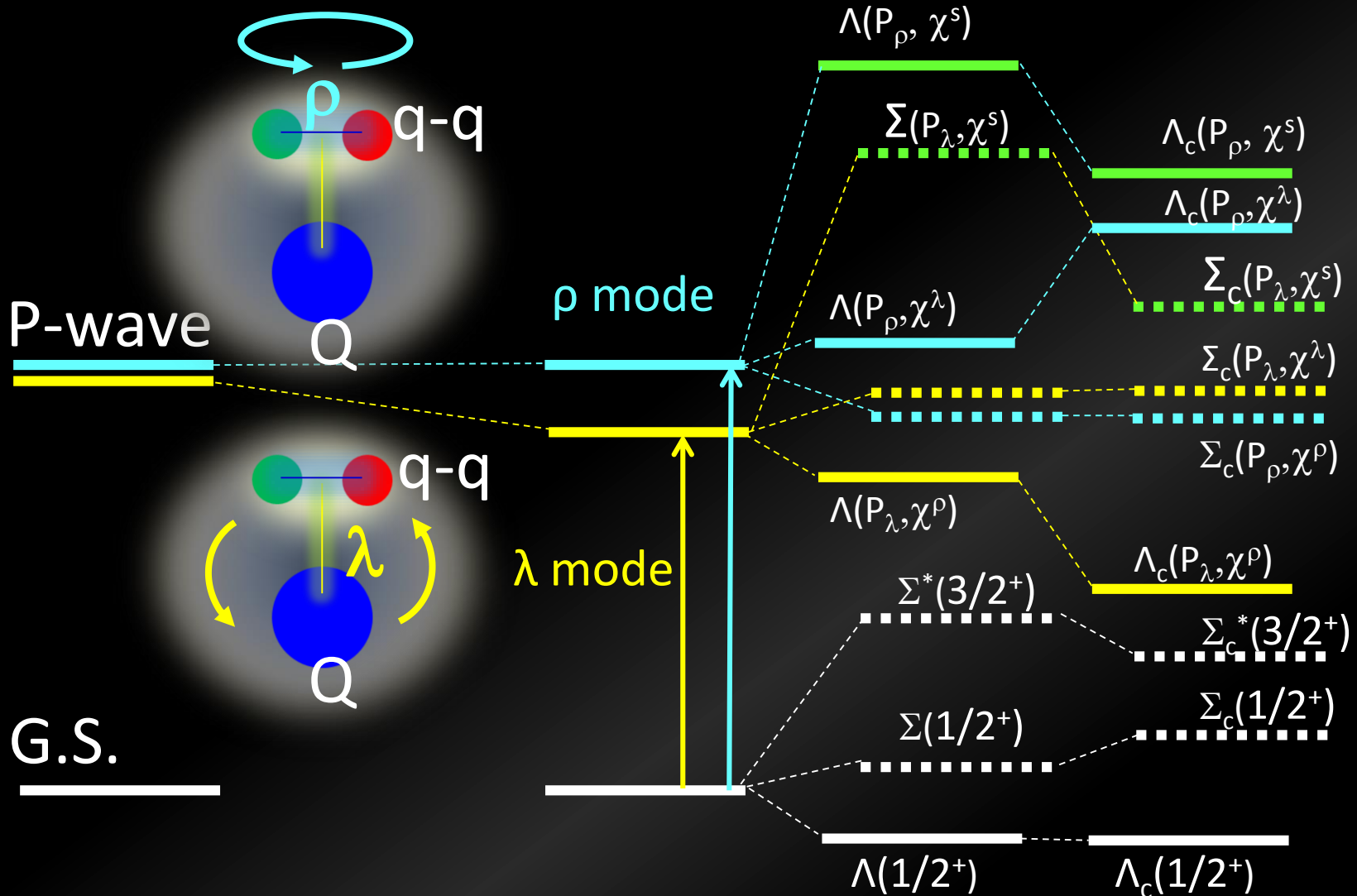


$\Lambda, \Sigma(1/2^-)$ (ρ, λ -mode excitations w/ V_{ss})

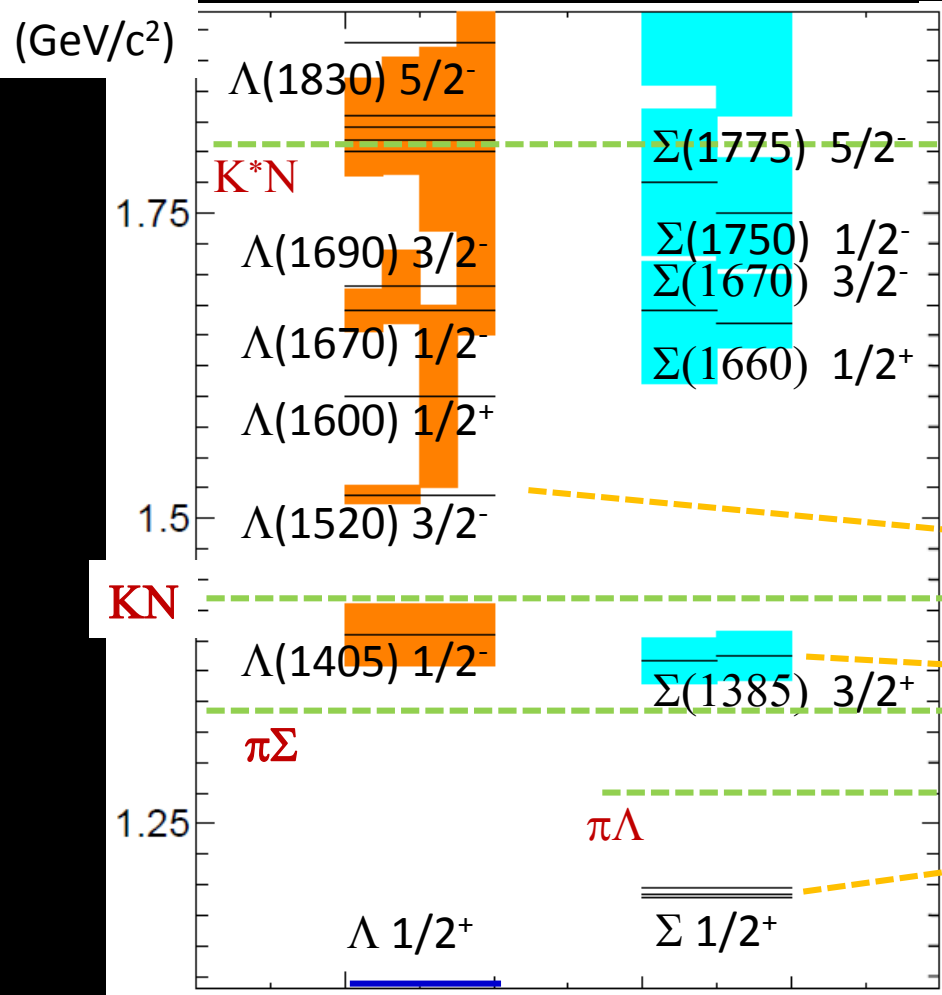


Level Structure of single-Q baryons

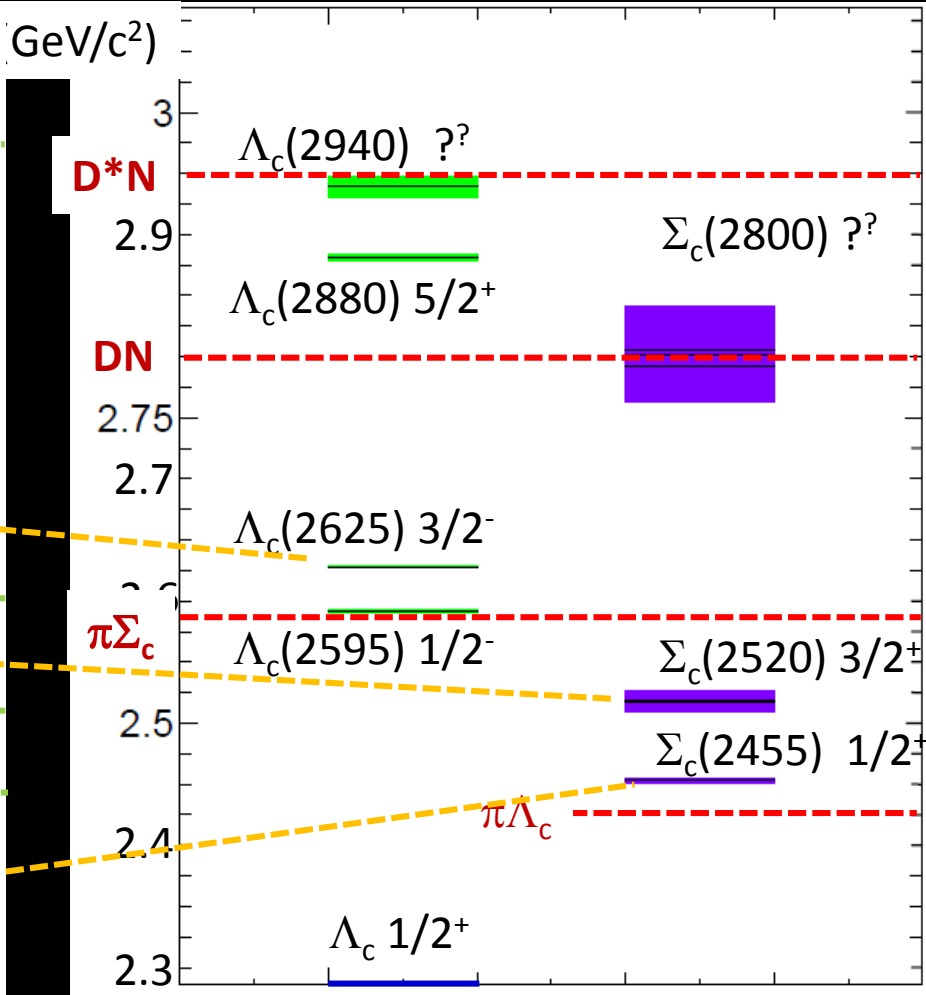
- λ and ρ motions split



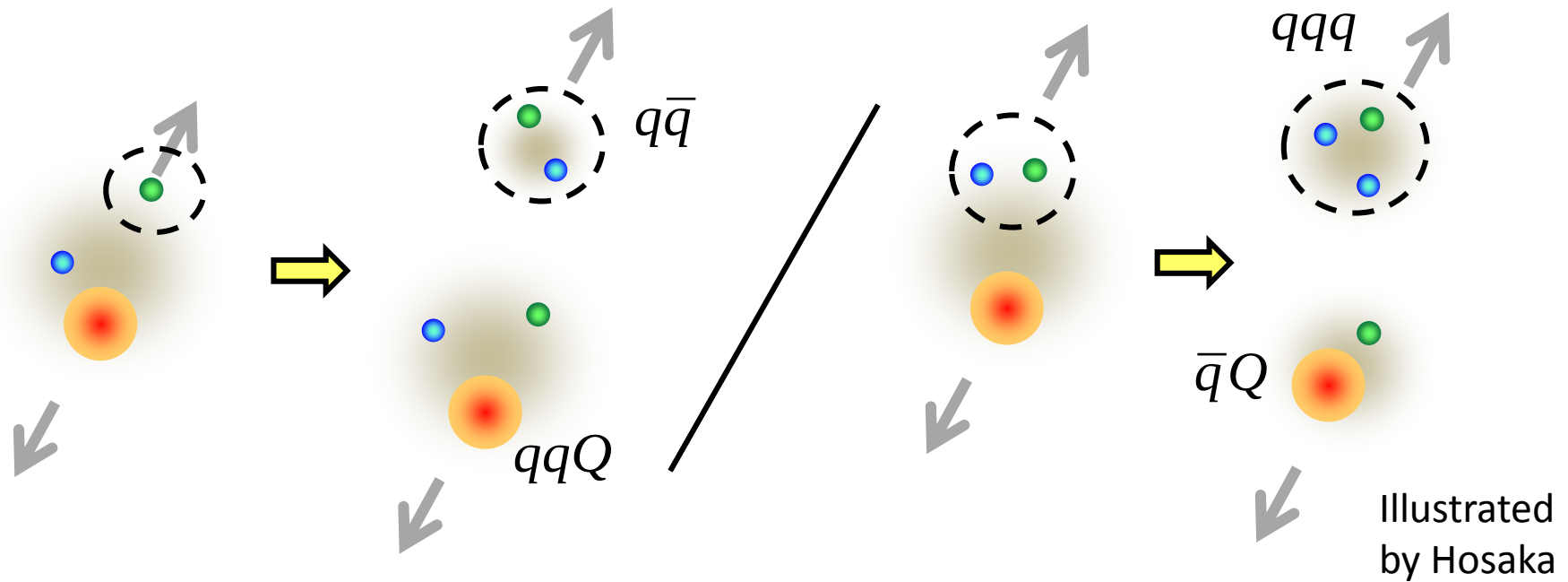
Strange Baryons



Charmed Baryons



Structure and Decay Partial Width



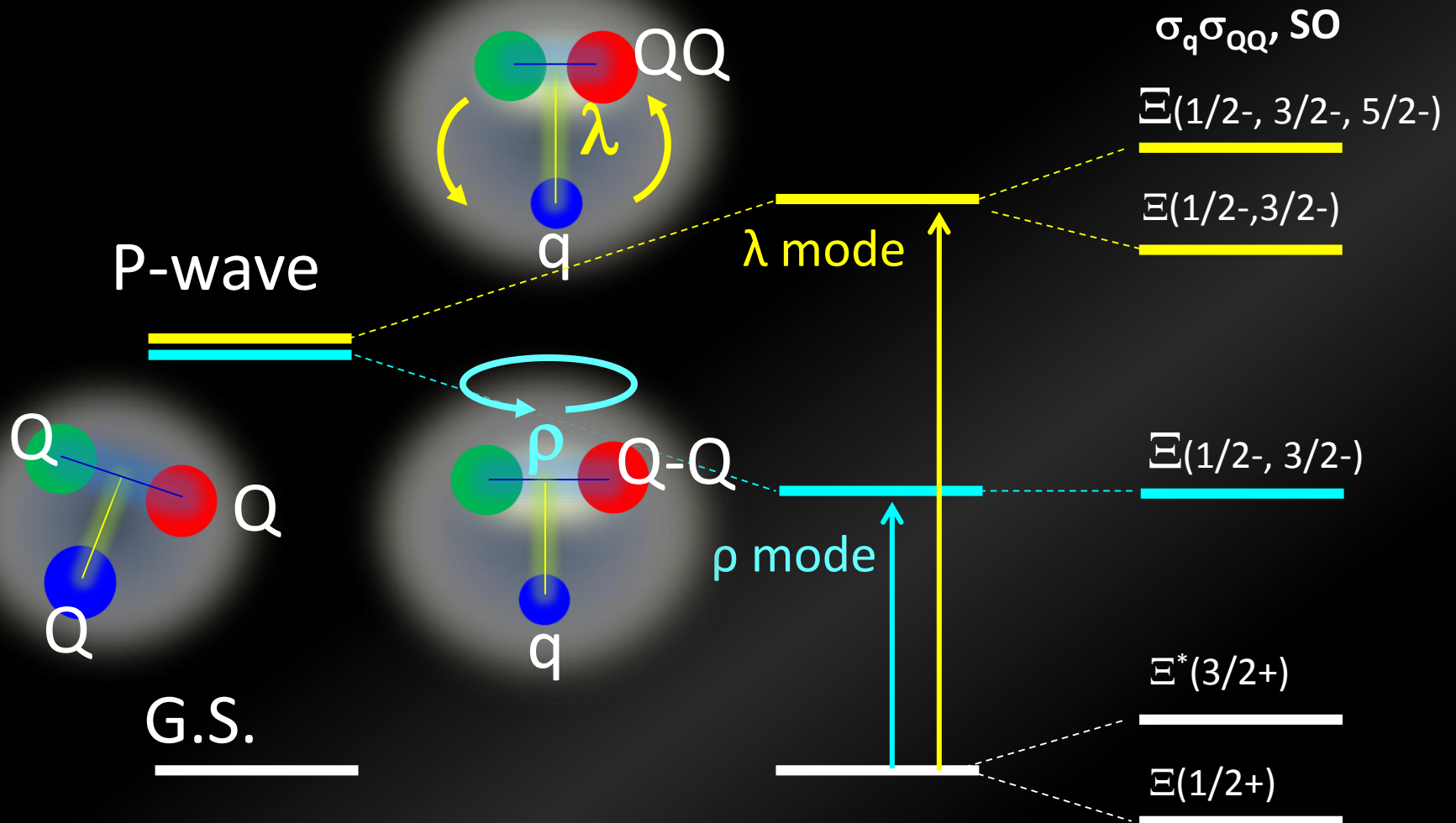
ρ mode (qq)

λ mode [qq]

QQq

Level Structure of double-strange baryons

- λ and ρ mode excitations interchange

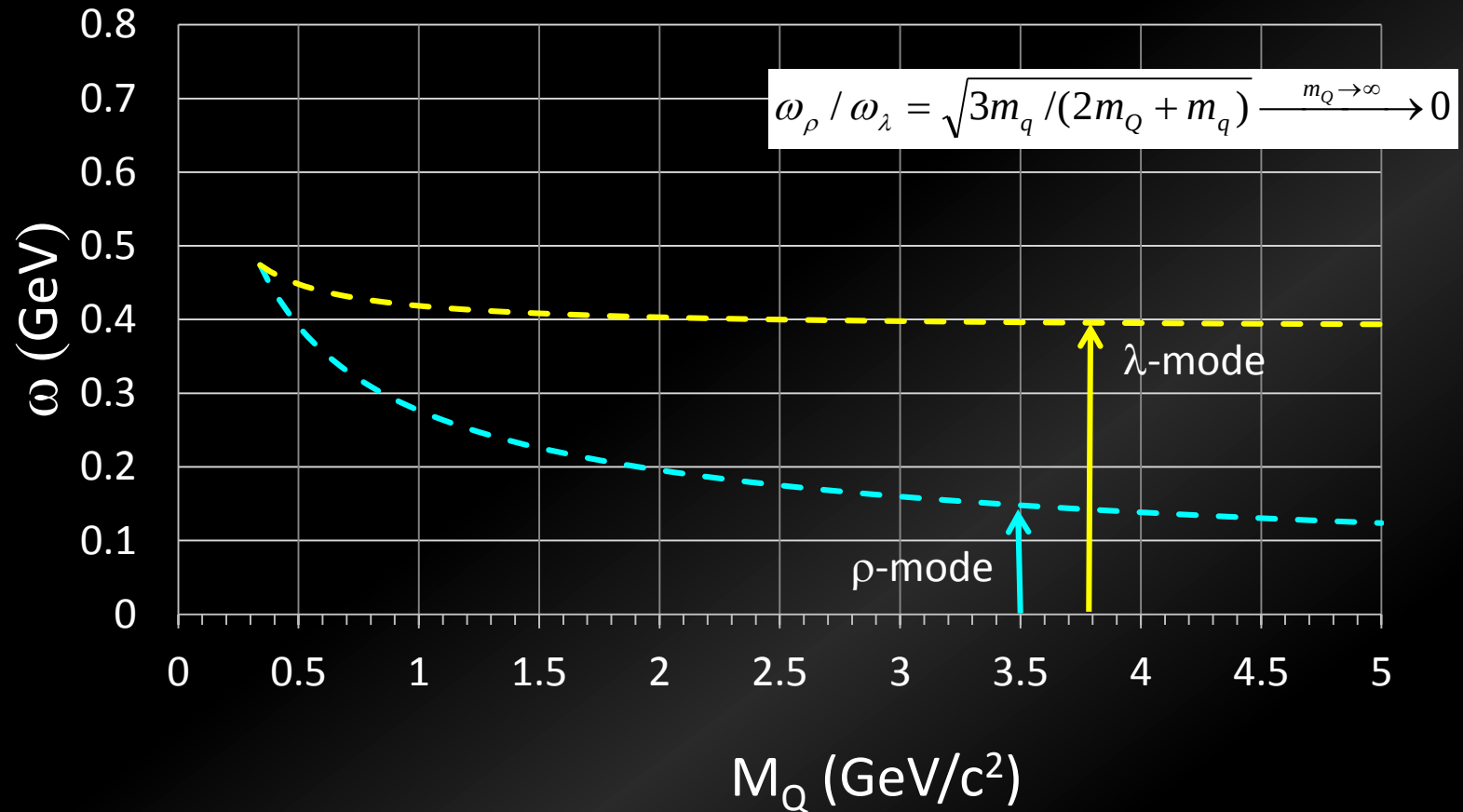


Confinement

- $H = H_0 + V_c + V_{ss} + \dots$
 $\Psi \sim \psi_\ell \chi_S (\text{Isospin} * \text{color}) \rightarrow \text{symmetrize (anti-symm.)}$
- $V_c = k/2 \sum r_i^2$
 $\omega_{\lambda,\rho} = \sqrt{3k/m_{\lambda,\rho}}, \quad \left(m_\lambda = \frac{3m_Q m_q}{2m_Q + m_q}, m_\rho = m_Q \right)$

P-wave (ρ , λ -mode excitations)

isotope shift



Spin-spin Interaction

- $H = H_0 + V_c + V_{ss} + \dots$

$\Psi \sim \psi_\ell \chi_S (\text{Isospin} * \text{color}) \rightarrow \text{symmetrize (anti-symm.)}$

- $V_c = k/2 \sum r_i^2$

$$\omega_{\lambda,\rho} = \sqrt{3k/m_{\lambda,\rho}}, \quad \left(m_\lambda = \frac{3m_Q m_q}{2m_Q + m_q}, m_\rho = m_Q \right)$$

- $V_{ss} = c_s \sum \frac{\sigma_i \cdot \sigma_j}{m_i m_j} \delta(r_{ij}) \quad \langle \chi_S | V_{ss} | \chi_S \rangle:$

$$\Xi \left(\frac{1}{2}^+ \right) = \omega_0 + c_s \left(\frac{1}{m_Q^2} - \frac{4}{m_q m_Q} \right) \quad (S, \chi^\lambda) : \text{“QQ”-spin symm., [QQq]}^{1/2}$$

$$\Xi^* \left(\frac{3}{2}^+ \right) = \omega_0 + c_s \left(\frac{1}{m_Q^2} + \frac{2}{m_q m_Q} \right) \quad (S, \chi^S) : \text{“QQq” spin symm.}$$

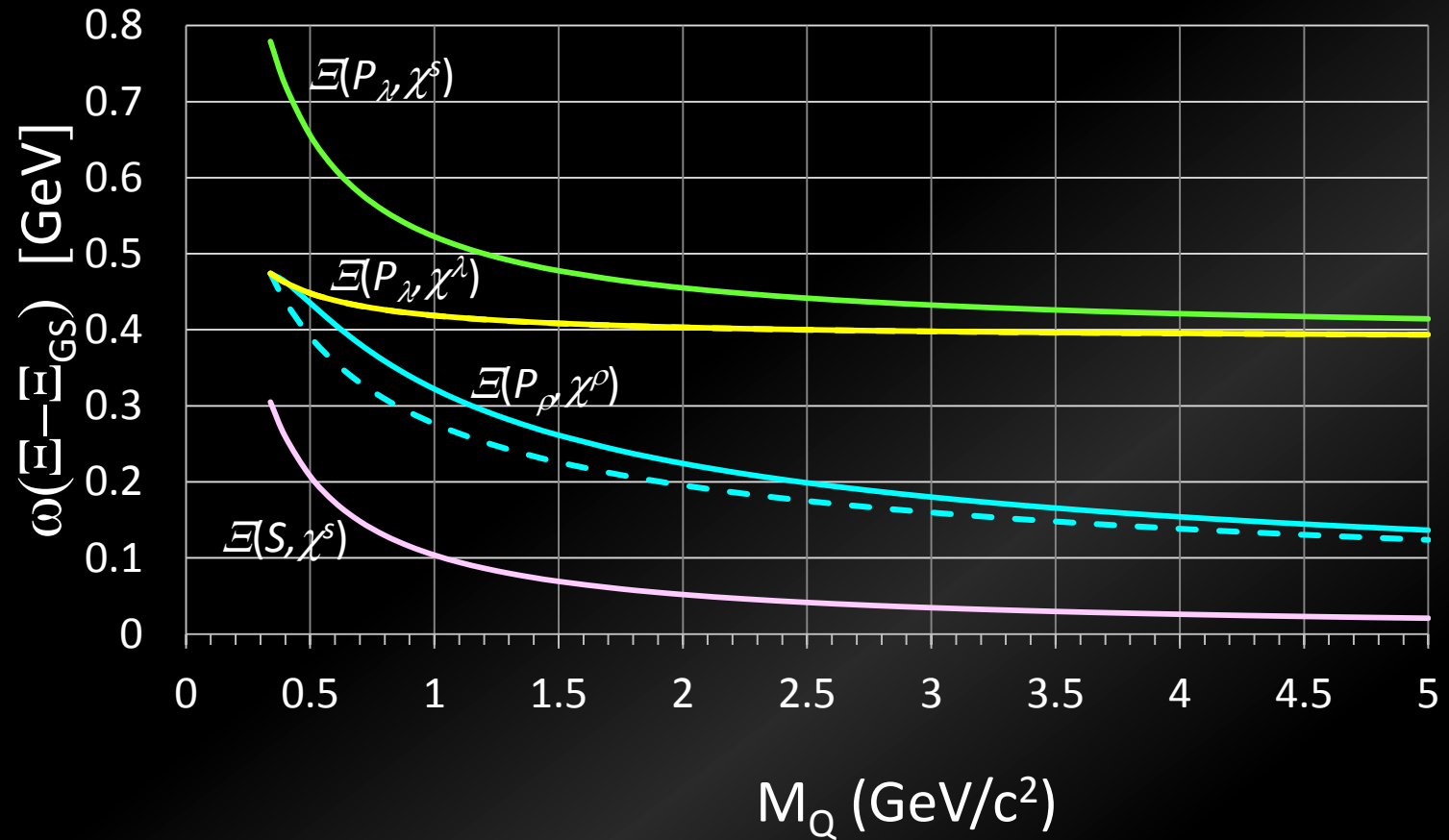
Spin-spin Interaction

- $H = H_0 + V_c + V_{ss} + \dots$
 $\Psi \sim \psi_\ell \chi_S (\text{Isospin} * \text{color}) \rightarrow \text{symmetrize (anti-symm.)}$
- $V_c = k/2 \sum r_i^2$
 $\omega_{\lambda,\rho} = \sqrt{3k/m_{\lambda,\rho}}, \quad \left(m_\lambda = \frac{3m_Q m_q}{2m_Q + m_q}, m_\rho = m_Q \right)$
- $V_{ss} \sim c_s \sum \frac{\sigma_i \cdot \sigma_j}{m_i m_j} \delta(r_{ij}) \quad \langle \chi_S | V_{ss} | \chi_S \rangle:$

$$\Xi \left(\frac{1}{2}^-, \frac{3}{2}^- \right) = \begin{cases} \omega_\rho - 3c_s/m_Q^2 & (\ell_\rho = 1, \chi^\rho) \\ \omega_\lambda + c_s \left(\frac{1}{m_Q^2} - \frac{4}{m_q m_Q} \right) & (\ell_\lambda = 1, \chi^\lambda) \end{cases}$$

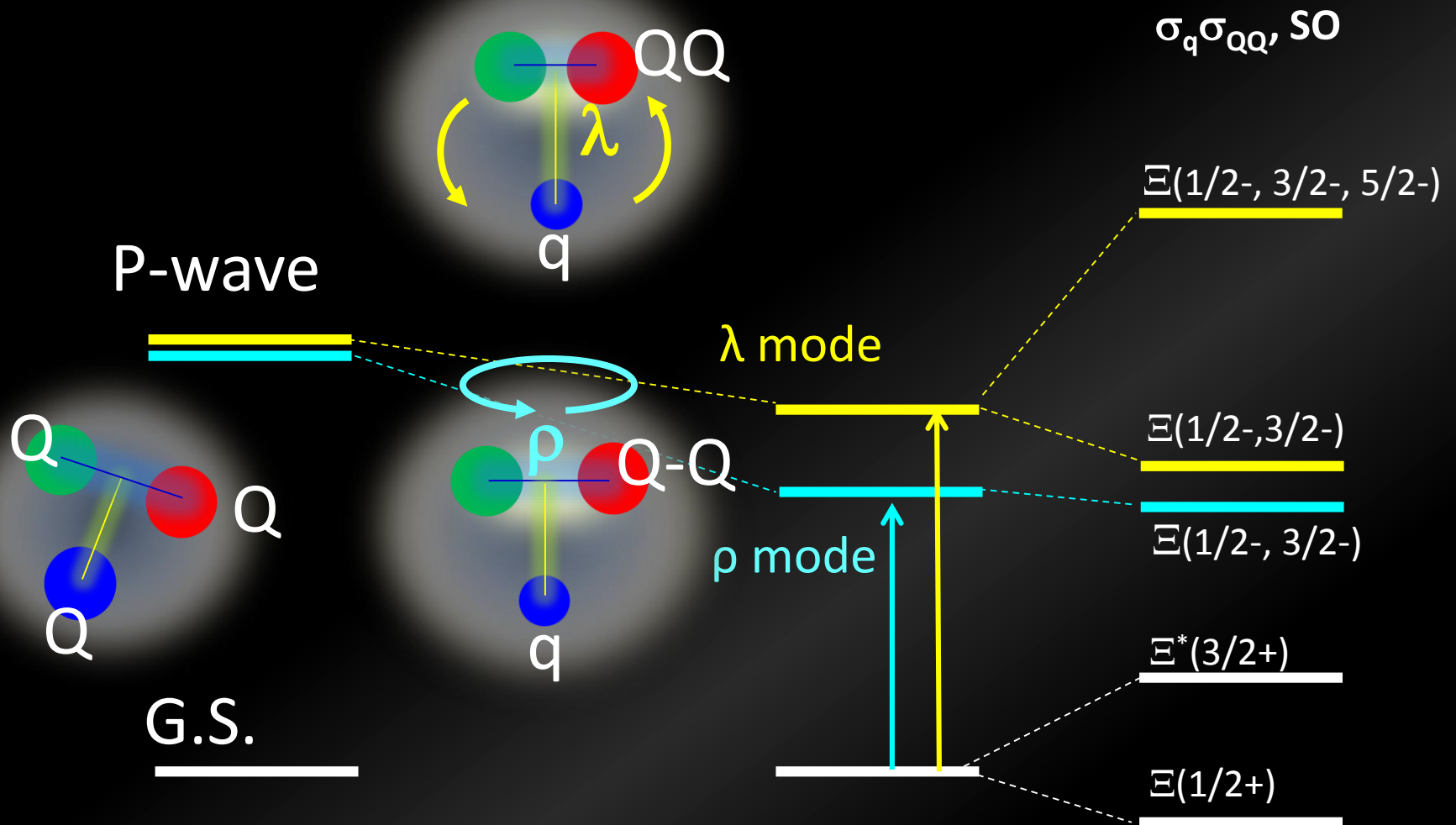
$$\Xi \left(\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^- \right) = \omega_\lambda + c_s \left(\frac{1}{m_Q^2} + \frac{2}{m_q m_Q} \right) (\ell_\lambda = 1, \chi^s)$$

Ξ (ρ , λ -mode excitations w/ V_{ss})

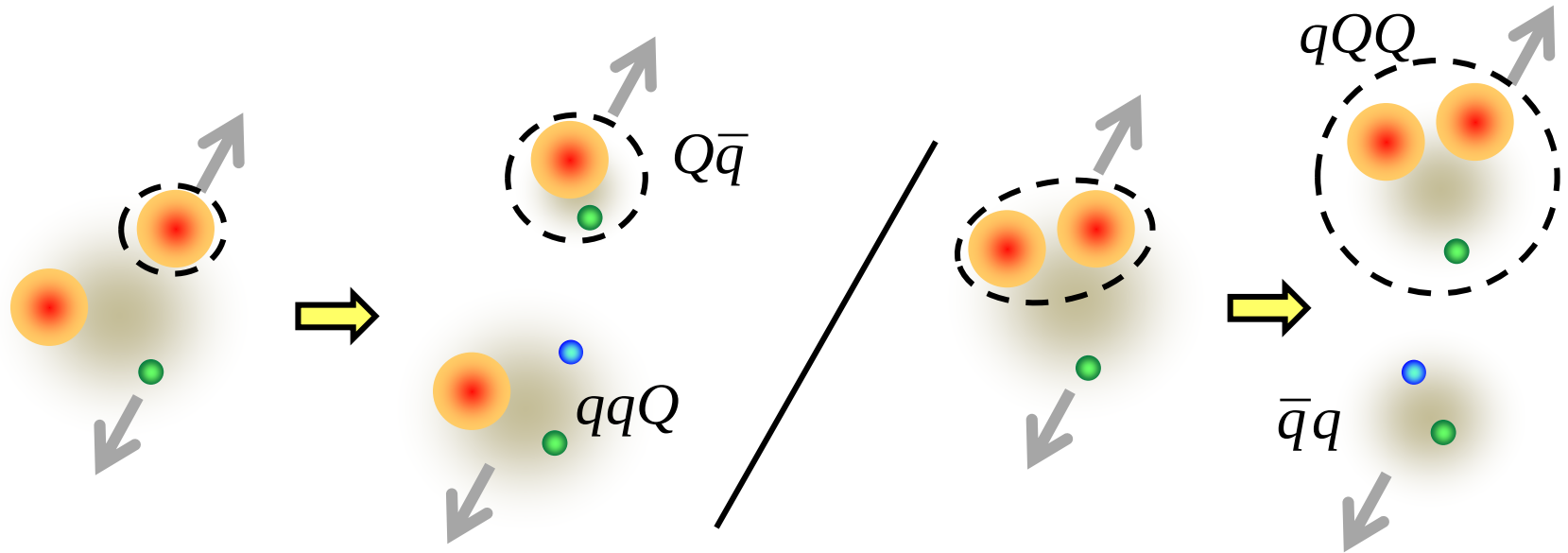


Level Structure of double-strange baryons

- λ and ρ mode excitations interchange



Structure and Decay Partial Width

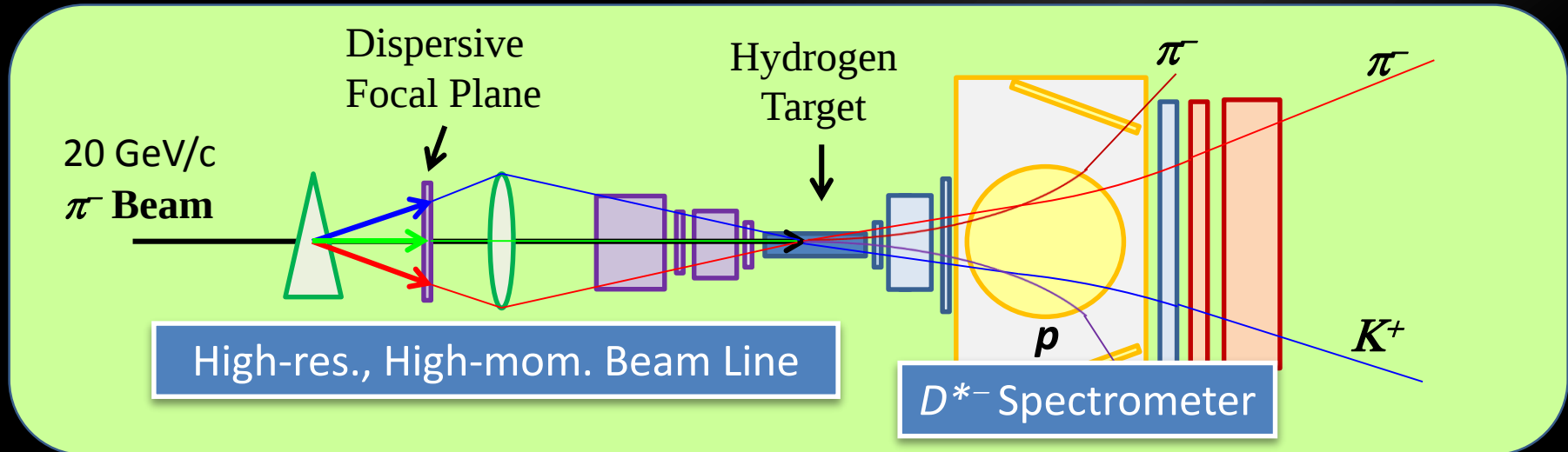
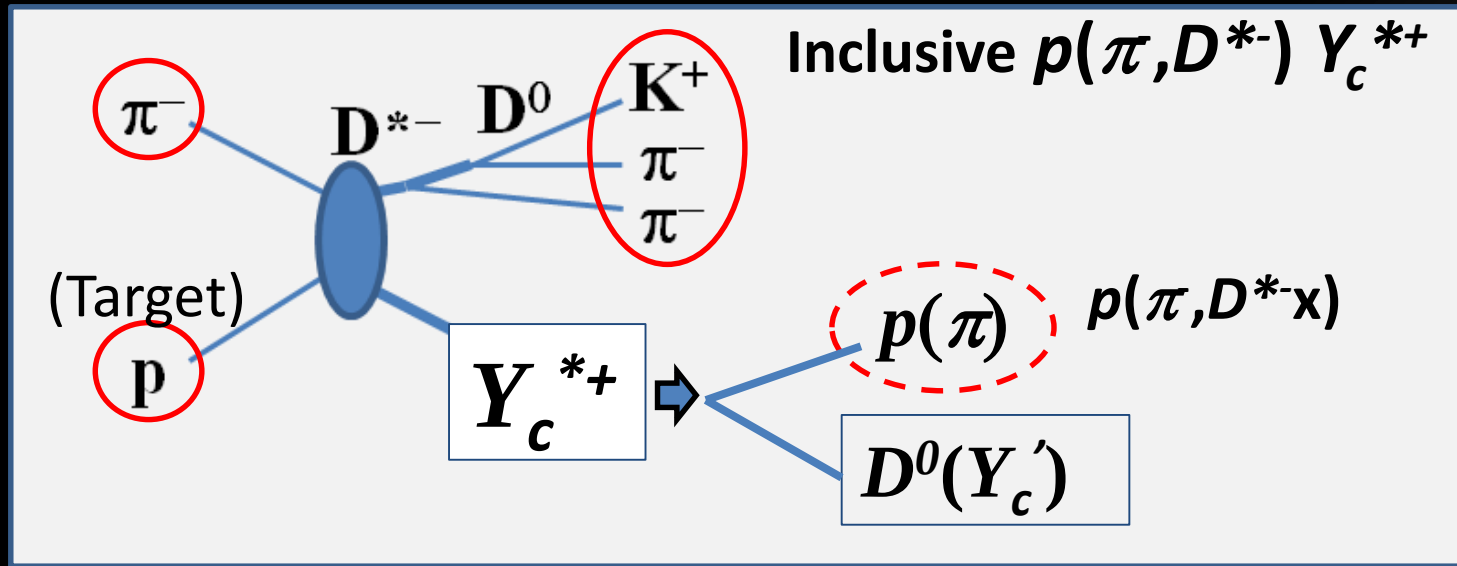


ρ mode (QQ)

λ mode [QQ]

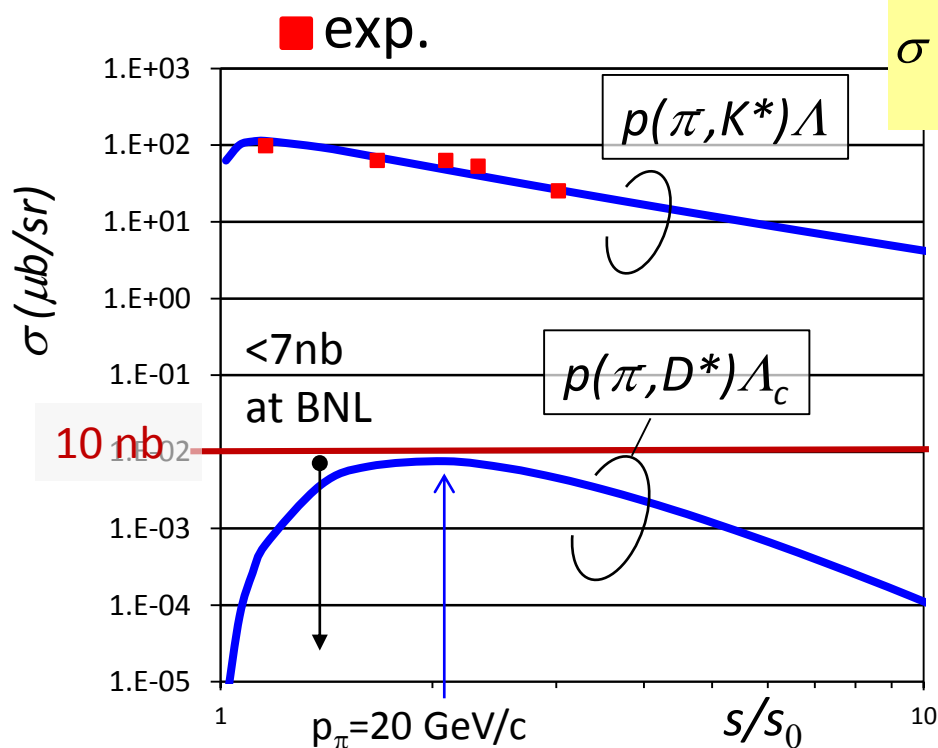
Charmed Baryon Spectroscopy

Using Missing Mass Techniques

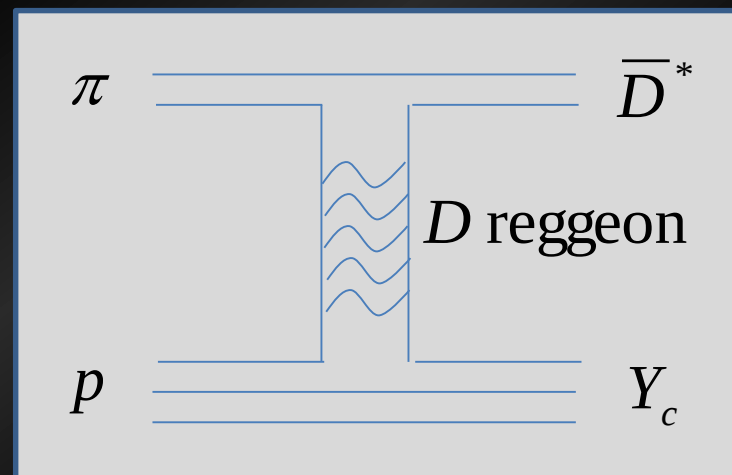


Production Cross Section

- Regge Theory: **Binary Reaction at High E is well described**
- Normalized to strangeness production, $p(\pi^-, K^{*0})\Lambda$
- Charm production: $\sim 10^{-4}$ of strangeness production
 $\rightarrow \underline{\sigma(p(\pi^-, D^{*-})\Lambda_c)} \sim \underline{\text{a few nb}}$ at $p_\pi = 20 \text{ GeV}/c$



$$\sigma \sim C \int \frac{1}{64\pi s (p_\pi^{cm})^2} \exp(2R^2 t) (s/s_0)^{2\alpha(t)} dt$$



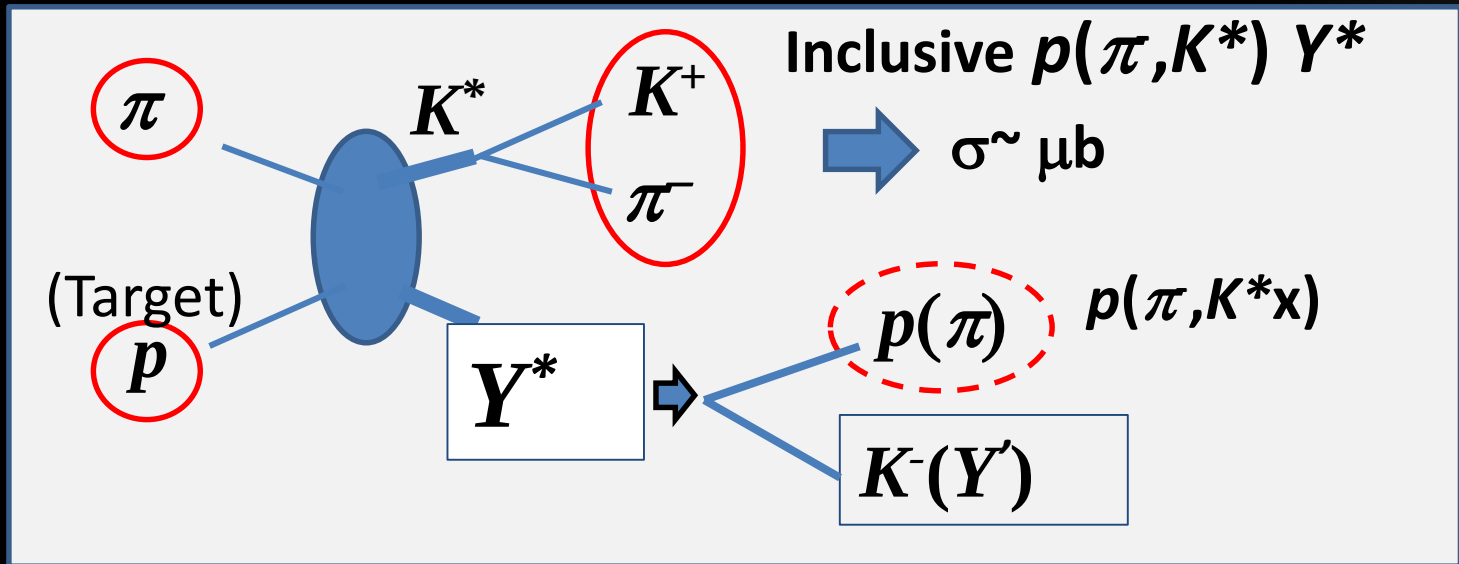
A.B. Kaidalov, ZPC12, 63(1982)

V.Yu. Grishina et al., EPJA25, 141(2005)

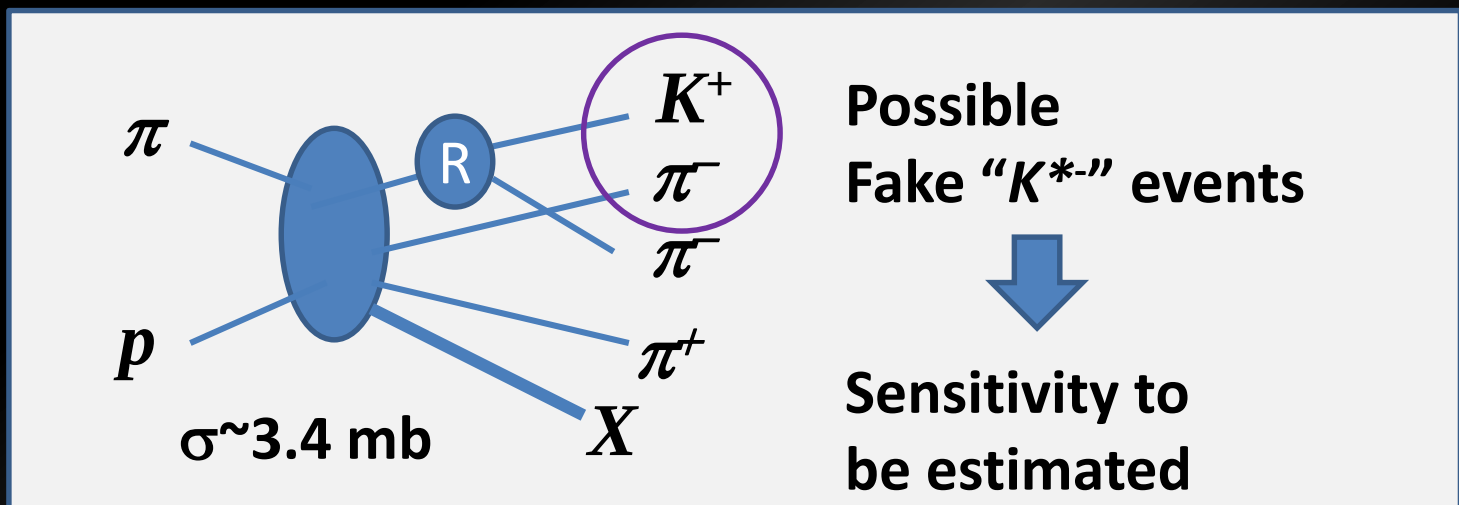
Strange Baryon Spectroscopy

Using Missing Mass Techniques

Signal



BG



Sensitivity: Order Estimation

	[1] C.S. (nb)	[2] D*(K*) Decay Br.	[3] BG (nb)	[4] Reduc tion	S/N $[1]*[2]*[4]/[3]$
Charm	~1	0.03	3E6	1E+8	~1
Strange	~1000	1	3E6	1E+4?	~3?

Threshold			JP	rating	Width [MeV]	→NK [%]	→Λπ [%]	→Σπ [%]	
		Σ(1940)	3/2-	4*	220	<20	seen	Seen	
		Σ(1915)	5/2+	3*	120	5-15	seen	Seen	
	Λ(1890)		3/2+	4*	95	20~35		3~10	
		Σ(1880)	1/2+	2*	220?				
		Σ(1840)	3/2+	1*	120?				
K*N(1830)	Λ(1830)		5/2-	4*	95	3~10	35~75		
	Λ(1820)		5/2+	4*	80	55~65	8~14		
Ση(1790)	Λ(1810)		1/2+	3*	150	20~50	10~40		
	Λ(1800)		1/2-	3*	300	25~40	Seen		
Λη(1710)		Σ(1775)	5/2-	4*	120	37~43	16-25		
		Σ(1750)	1/2-	3*	90	10~40			(Ση)15~55
		Σ(1690)	??	2*					
KN(1432) Σπ(1330)	Λ(1690)		3/2-	4*	60	20~30	20~40		
		Σ(1670)	3/2-	4*	60	7~13	35~75		
	Λ(1670)		1/2-	4*	35	20~30	25~55		
		Σ(1620)	1/2-	1*					
		Σ(1580)	3/2-	1*					
Σ*π(1520)	Λ(1520)			4*	19	45+-1	42+-1		36

Measured Ξ (PDG)

Threshold		JP	rating	Width [MeV]	$\rightarrow \Xi\pi$ [%]	$\rightarrow \Lambda K$ [%]	$\rightarrow \Sigma K$ [%]	
	$\Xi(2500)$	??	1*	150?				
	$\Xi(2370)$	??	2*	80?				$\Omega K \sim 9 \pm 4$
$\Omega K(2166)$	$\Xi(2250)$	??	2*	47+-27?				
	$\Xi(2120)$	??	1*	25?				
$\Sigma K^*(1983)$	$\Xi(2030)$	$\geq 5/2?$	3*	20^{+15}_{-5}	small	~20	~80	
$\Sigma^* K(1878)$	$\Xi(1950)$	??	3*	60+-20	seen	seen		
$\Lambda K^*(1908)$	$\Xi(1820)$	3/2-	3*	24^{+15}_{-10}	small	Large	Small	
$\Xi^* \pi(1665)$	$\Xi(1690)$	??	3*	<30	seen	seen	seen	
$\Sigma K(1685)$	$\Xi(1620)$	??	1*	20~40?				
$\Lambda K(1610)$	$\Xi(1530)$	3/2+	4*	19	100			
$\Xi\pi(1450)$								

Summary

- Level structure of baryons were systematically studied as a function of a quark mass.
- Characteristic changes of level structure can be seen as a quark mass increases.
- Level structure becomes simpler at a heavy quark limit, where the nature of a baryon is determined by a correlation between a light-quark pair.
- Quark-pair (di-quark) correlations may affect the decay properties and production rates.
- Spectroscopy in different flavor sectors are important.