Structure of charmed baryons and their productions studied at JPARC

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The 3rd Korea-Japan Workshop on Nuclear and Hadron Physics at J-PARC

March 20-21, Inha, Korea

1. Introduction

Key word: ***Heavy*** quarks/hadrons

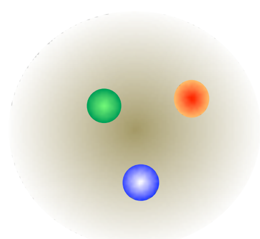
→ • Spin becomes irrelevant, decouples

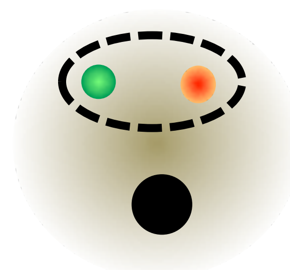
• Flavor symmetry is broken → HQ symmetry

Static source in a baryon

qqq → HQ + diquark

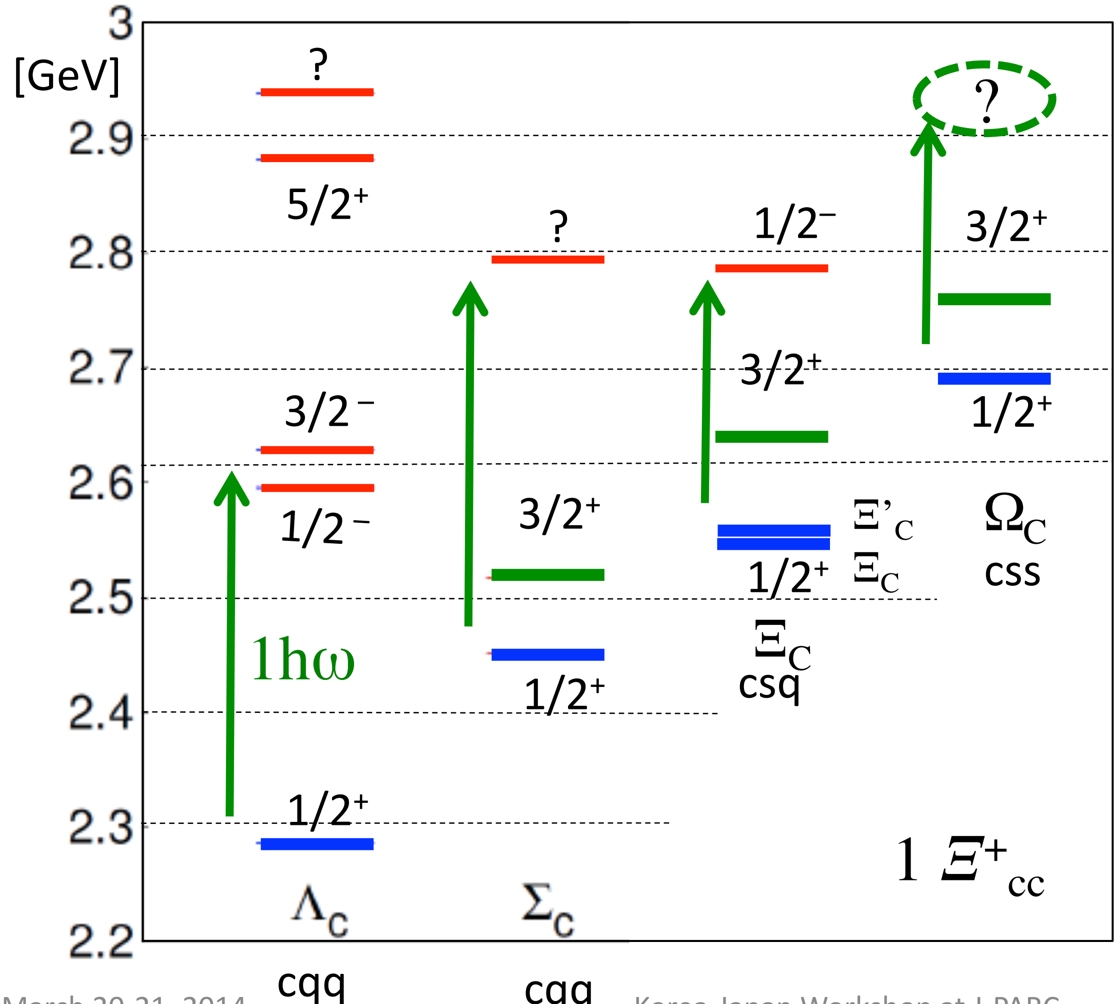
diquark spectroscopy?

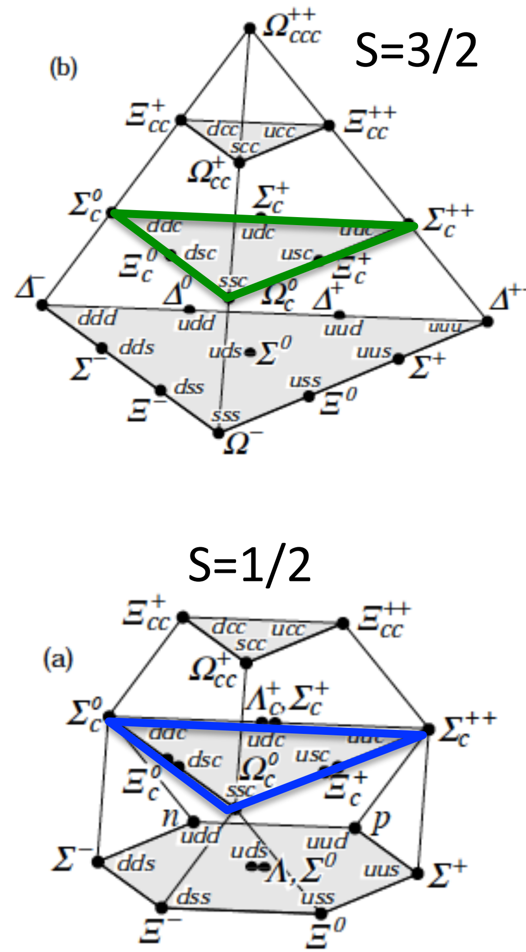




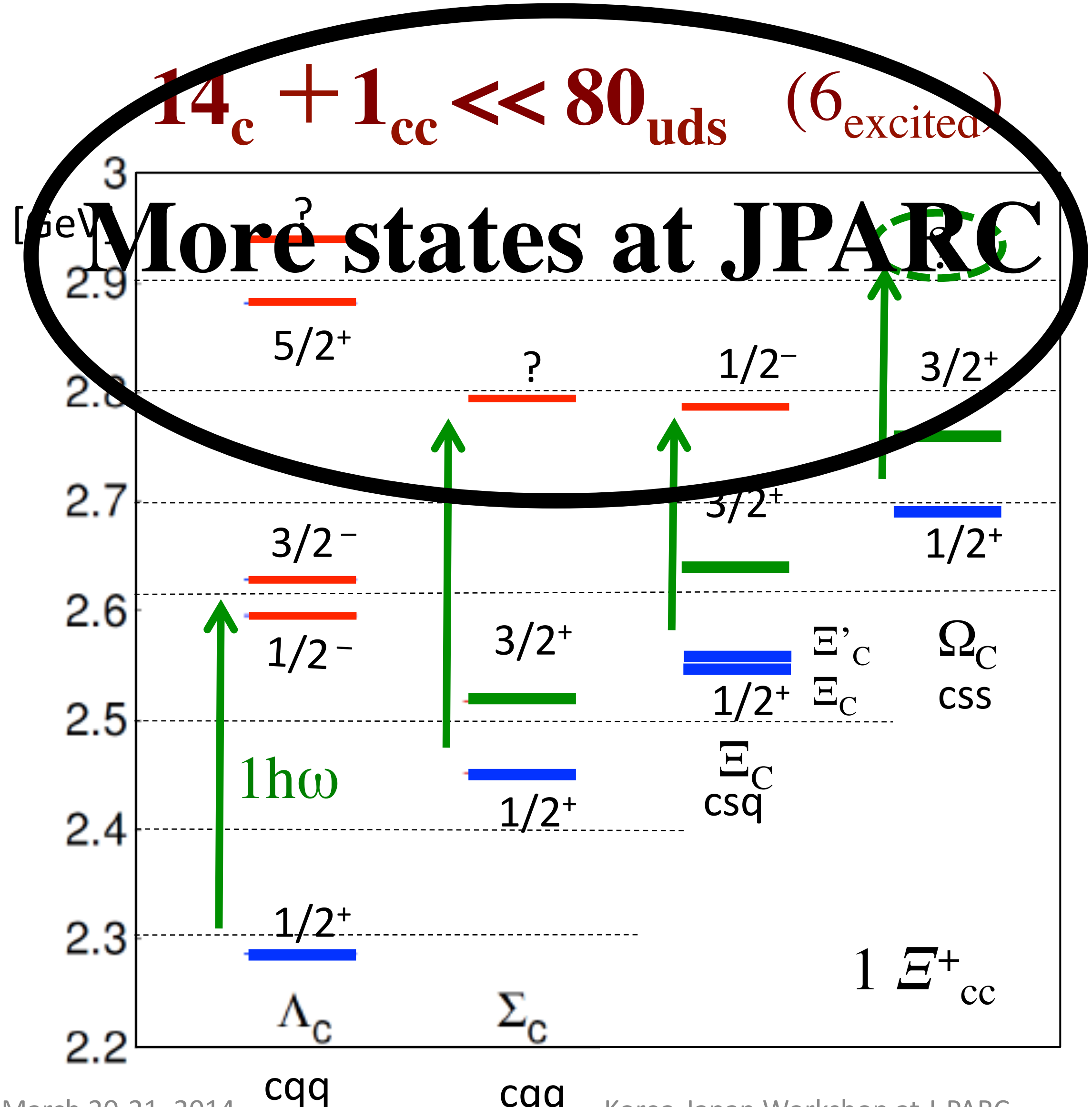
Charmed baryons

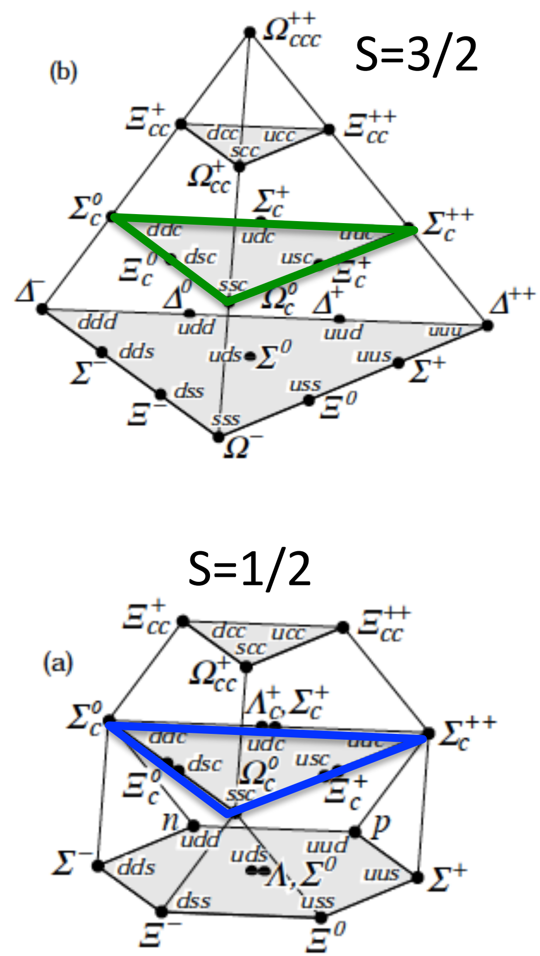
$14_c + 1_{cc} \ll 80_{uds}$ $(6_{excited})$





Charmed baryons





2. Structure

A heavy quark differentiate ***diquark*** motions = ***modes***

Important ingredient for hadron dynamics
to know how they appear in baryon spectroscopy

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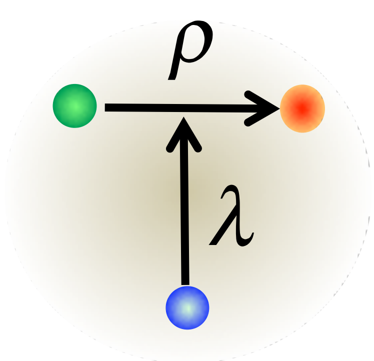
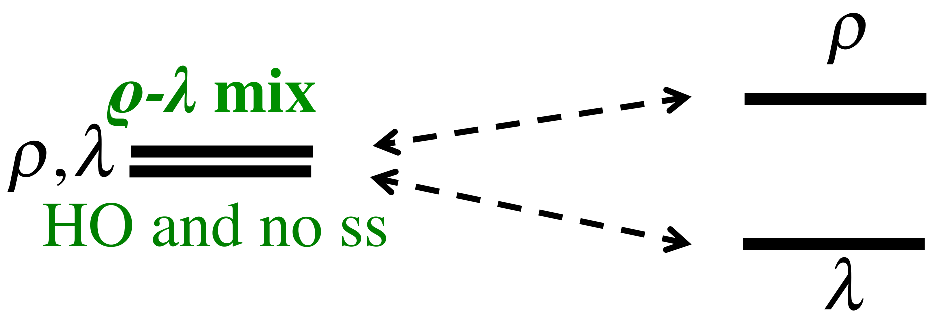
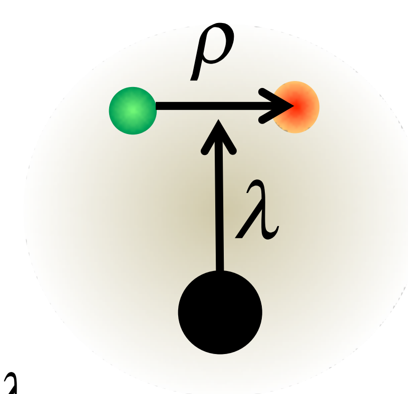
A heavy quark differentiate ***diquark*** motions = modes

Important ingredient for hadron dynamics
to know how they appear in baryon spectroscopy

Excitations, ϱ and λ modes get distinct ~ *isotope shift*





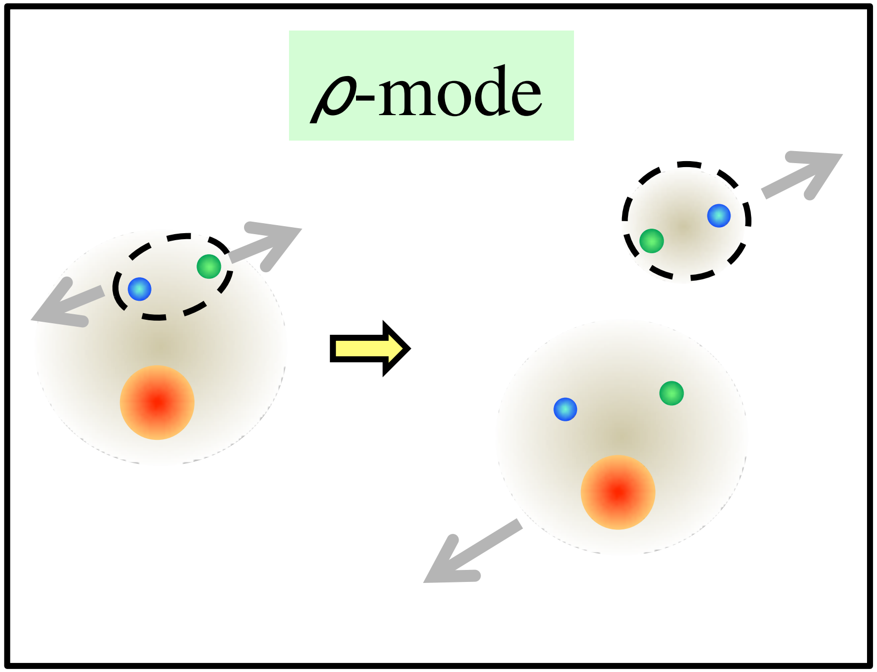


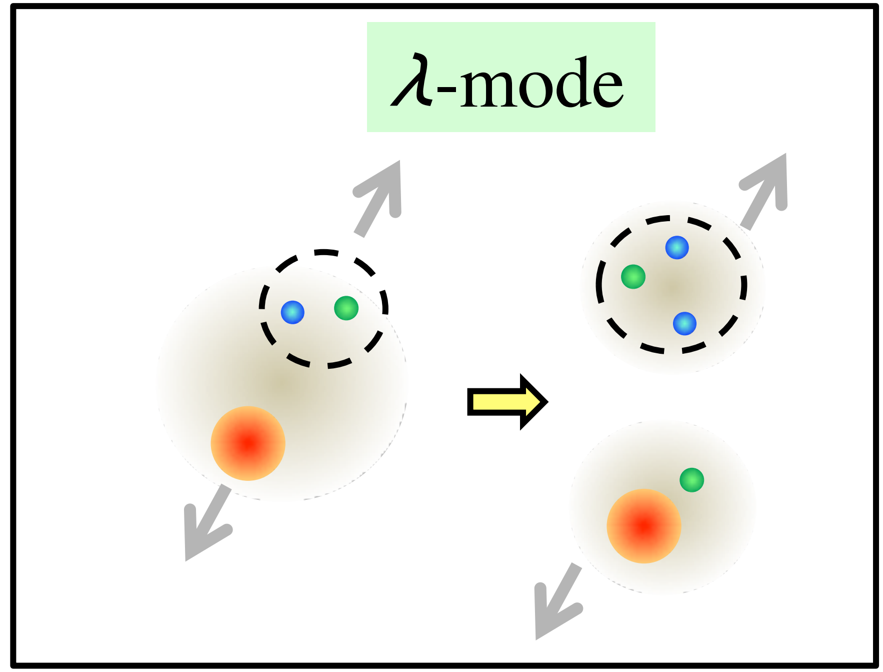
$m_\rho \sim m_\lambda$ $\qquad$ $m_\rho < m_\lambda$

$\omega_\rho \sim \omega_\lambda$ $\qquad$ $\omega_\rho > \omega_\lambda$

λ mode is more collective

Decays



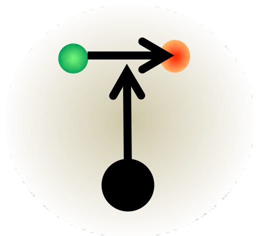


ρ-mode: (qq)* decays by emitting a pion
λ-mode: Q* decays by emitting a heavy meson

How they appear in excited B_c's
➔ *Mixing of the modes*

Wave function

Quark model calculation
with spin-spin interaction:
Yoshida, Sadato, Hiyama, Oka, Hosaka



Mixing of $\psi = c_\lambda |l_\lambda = 1\rangle + c_\rho |l_\rho = 1\rangle$

λ-mode dominant state

Wave function

Quark model calculation
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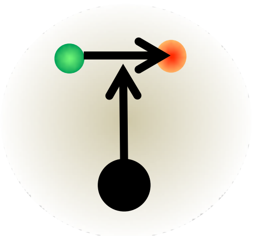
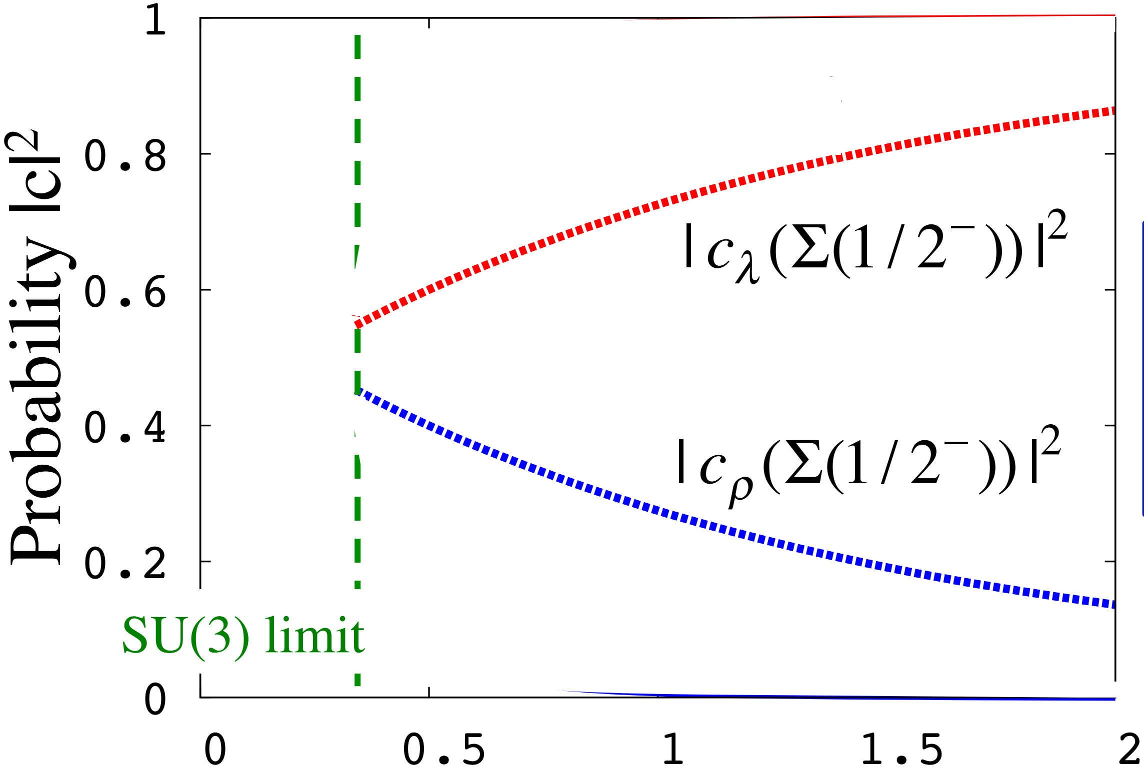
Yoshida, Sadato, Hiyama, Oka, Hosaka



Mixing of $\psi = c_\lambda |l_\lambda = 1\rangle + c_\rho |l_\rho = 1\rangle$

λ-mode dominant state



m_Q [GeV] with m_{ud} = 300 MeV

Spin-spin int

Substantial amount of mixing inΣ

Wave function

Quark model calculation
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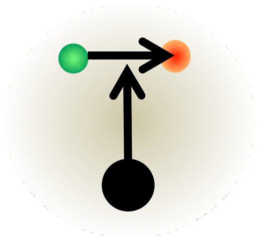
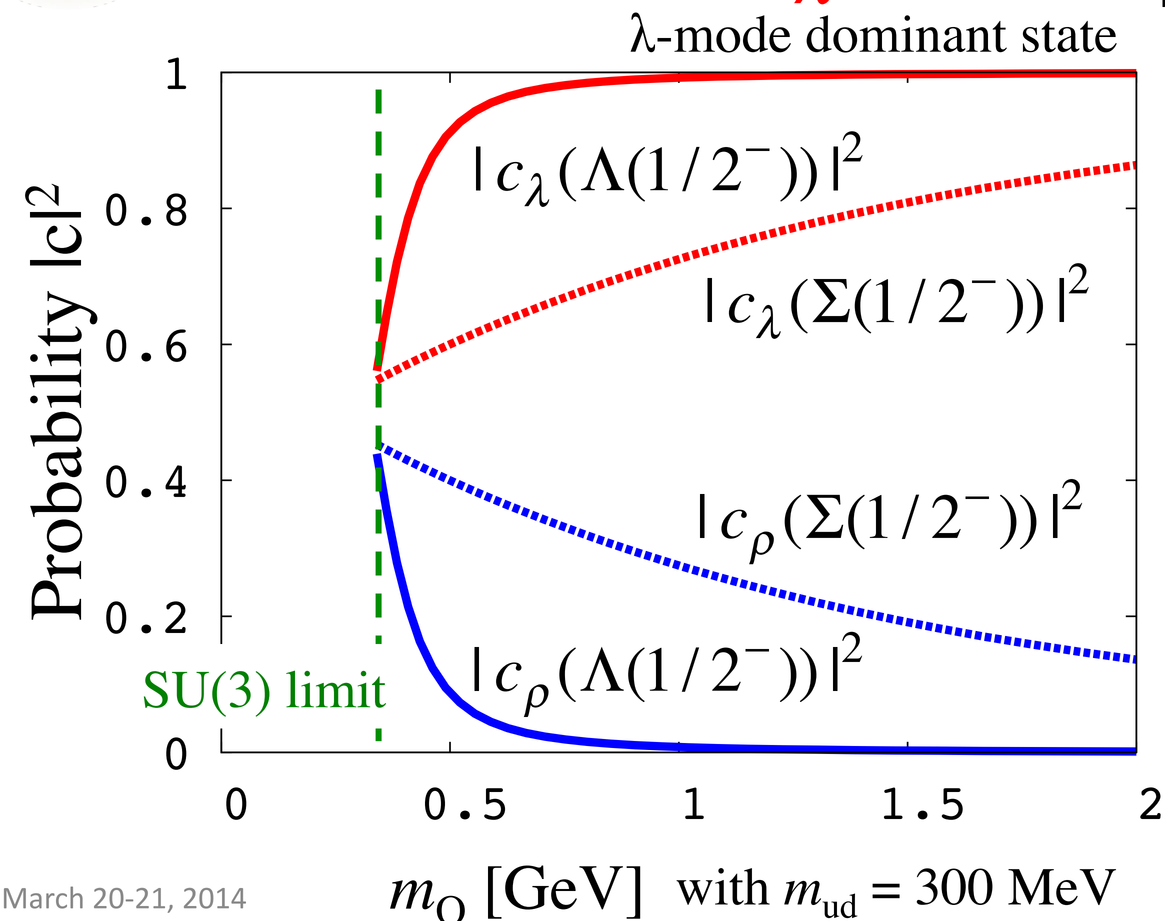


Mixing of $\psi = c_\lambda |l_\lambda = 1\rangle + c_\rho |l_\rho = 1\rangle$



$\Lambda_c{}^*$ is almost pure λ mode
→
Reflect more diquark nature

see Talk by Shirotori

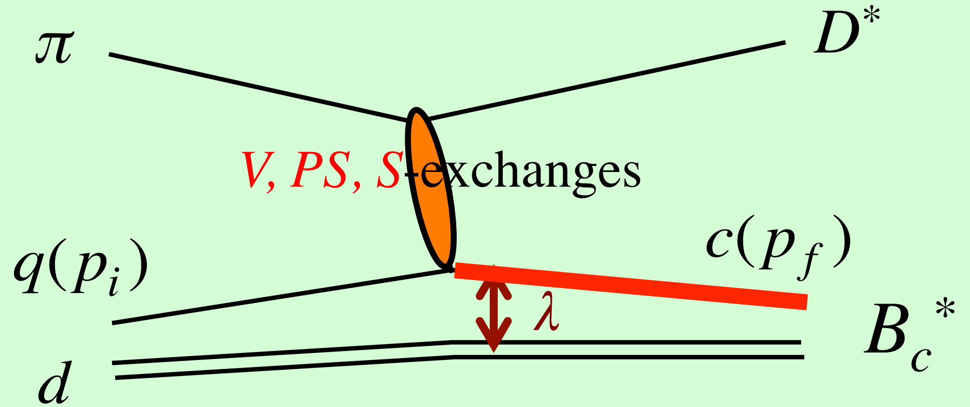
(2) Production

Strategies:

- At high energies: Forward peak → t-channel dominant
- **<u>Absolute values</u>**
  Regge for the estimation of charm vs strange
- **<u>Relative ratios</u>** of transitions to various B_c^*
  One step process in a *Qd* model

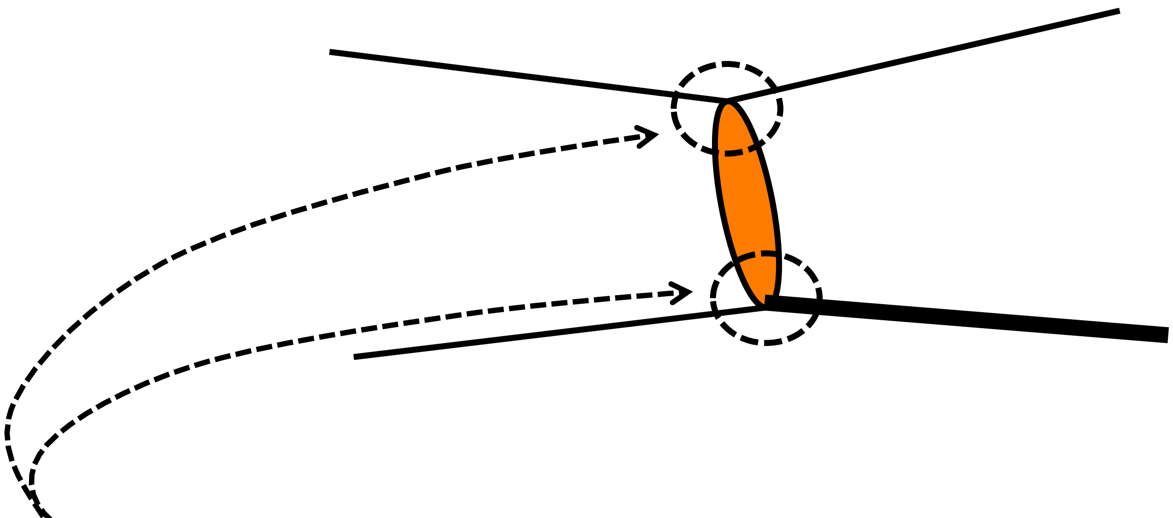
Pion-induced reaction

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



Absolute values

Regge method with couplings fixed at strangeness

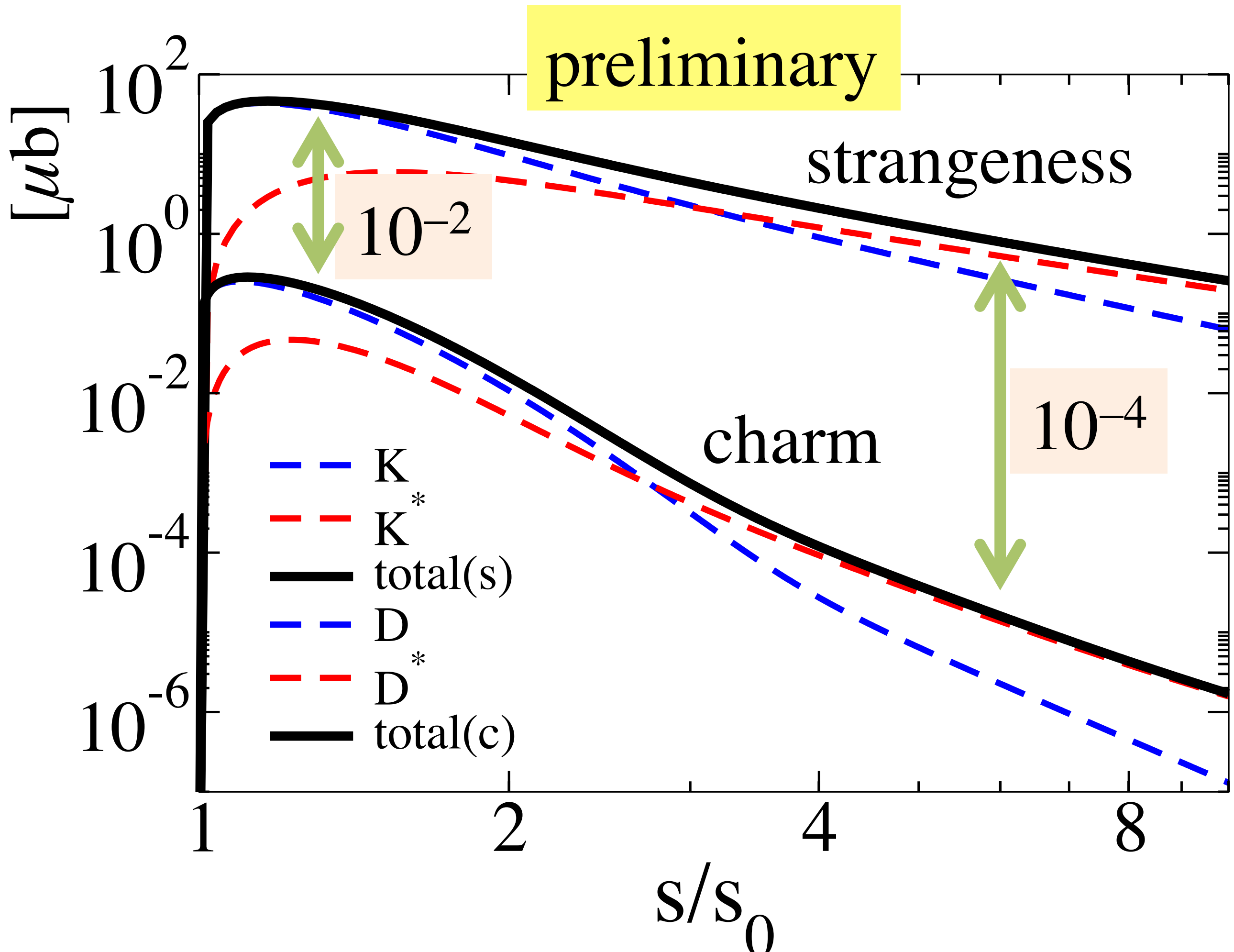


- Couplings are determined by effective Lagrangians
- Propagators are replaced by the Regge's one

$$\frac{1}{t-m_{K^*}^2} \to \mathcal{P}_{regge}^{K^*} = \left(\frac{s}{s_0}\right)^{\alpha_{K^*}(t)-1} \frac{1}{\sin(\pi\alpha_{K^*}(t))} \frac{\pi\alpha'_{K^*}}{\Gamma(\alpha_{K^*}(t))}.$$

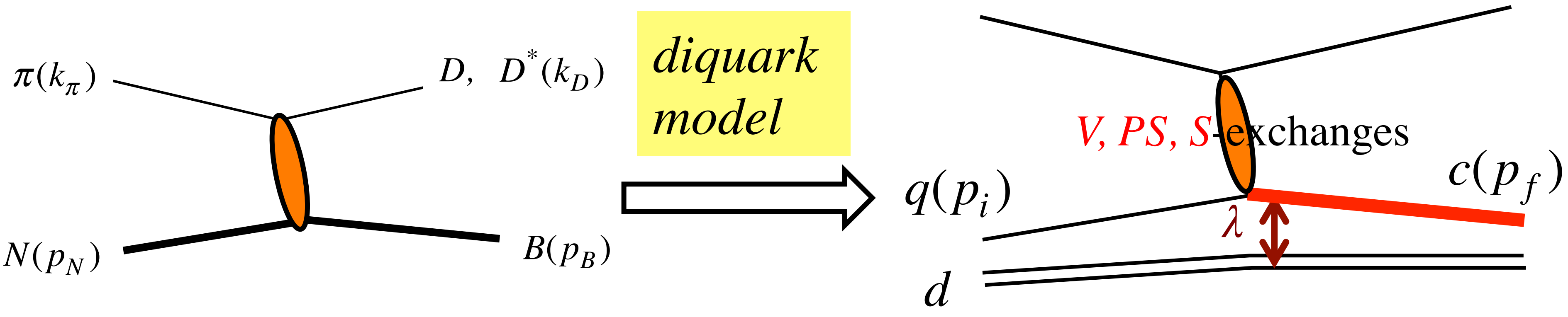
Sang-Ho Kim (talk in this workshop tomorrow)

Regge method with couplings fixed at strangeness

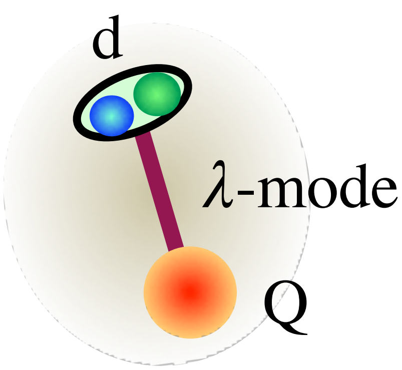


Charm/strangeness productions: $10^{-2} \sim 10^{-4}$

Relative ratios to various B_c

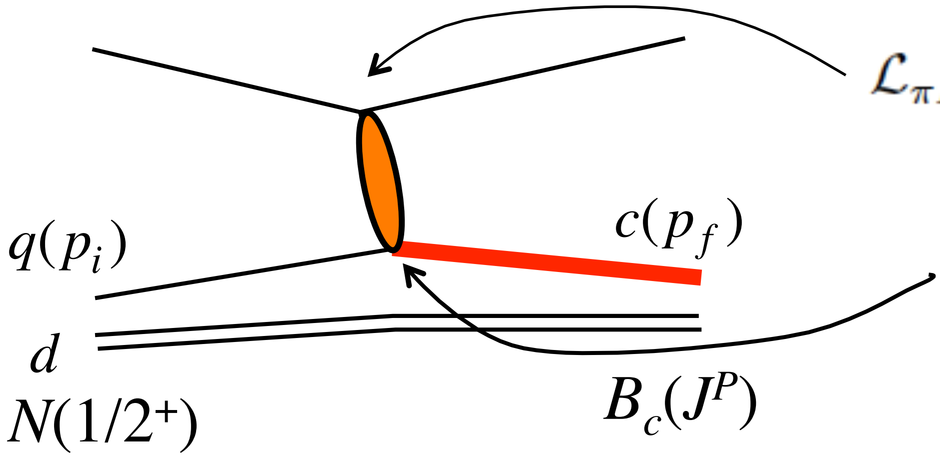


- Single step $q \rightarrow Q$: λ modes are excited
- V, PS for D^* *and* V, S for D productions with various B's of $l_\lambda = 0, 1, 2$ (18 baryons)
- Estimate forward scattering amplitudes



Single-step $qd \rightarrow Qd$ reaction

Example of *V*-exchange

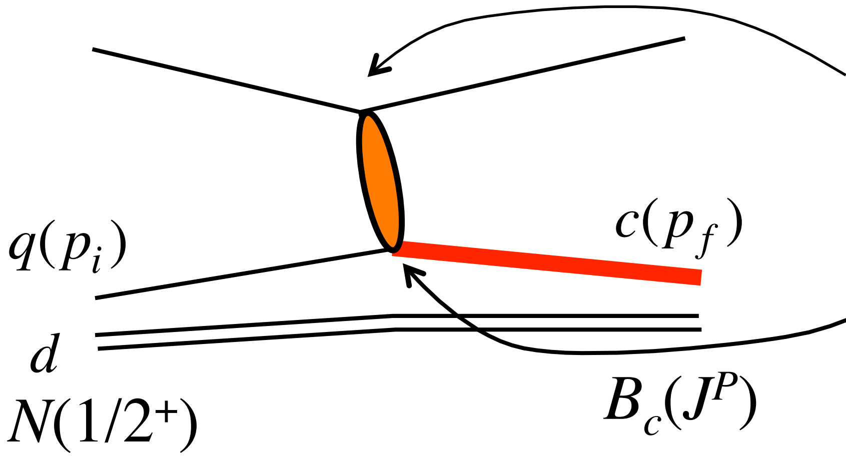


$$\mathcal{L}_{\pi D^* D^*} = f\epsilon_{\mu\nu\alpha\beta}\partial^\mu\pi\partial^\nu D^\alpha D^\beta$$

$$\mathcal{L}_{D^* N B} = g\bar{c}\gamma^\mu D_\mu q$$

Single-step $qd \rightarrow Qd$ reaction

Example of V-exchange



$$\mathcal{L}_{\pi D^* D^*} = f \epsilon_{\mu\nu\alpha\beta} \partial^\mu \pi \partial^\nu D^\alpha D^\beta$$

$$\mathcal{L}_{D^* NB} = g \bar{c} \gamma^\mu D_\mu q$$

$$t \sim 2fg k^0_{D^*} \vec{k}_\pi \times \vec{e} \cdot \vec{J}_{fi} \frac{1}{q^2 - m^2_{D^*}} \qquad \vec{q}_{eff} = \frac{m_d}{m_d + m_q} \vec{P}_N - \frac{m_d}{m_d + m_c} \vec{P}_B$$

$$\vec{J}_{fi} = \int d^3x \, \varphi^\dagger_f \left[\frac{\vec{p}_f}{m_c + E_c} + \frac{\vec{p}_i}{m_q + E_q} + i\vec{\sigma} \times \left(\frac{\vec{p}_f}{m_c + E_c} - \frac{\vec{p}_i}{m_q + E_q} \right) \right] \varphi_i \, e^{i\vec{q}_{eff} \cdot \vec{x}}$$

V-exchange at forward

$$t_{fi} \sim \left(\frac{P_B}{2(m_c + m_d)} - 1 \right) k^0_{D^*} k_\pi \left\langle B_c \middle| \vec{e}_\perp \cdot \vec{\sigma} e^{i\vec{q}_{eff} \cdot \vec{x}} \middle| N \right\rangle \frac{1}{q^2 - m^2_{D^*}}$$

Matrix elements

$$V: \quad \langle B_c | \vec{e}_{\perp} \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}} | N \rangle$$

Transverse

$$PS: \quad \langle B_c | \vec{e}_{//} \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}} | N \rangle$$

Longitudinal

$$S: \quad \langle B_c | 1\, e^{i\vec{q}_{eff}\cdot\vec{x}} | N \rangle$$

$$= \text{(Geometric)} \times \text{(Dynamic)}$$

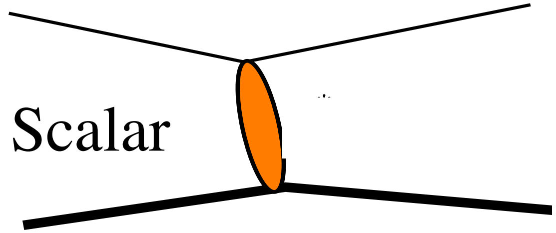
CG coefficients

(Geometric) ~ [spin × angular momentum] × isospin

(Dynamic) ~ Radial wave function

$$\text{Geometric part} = \sum_{\text{spins}} [\text{spin} \times \text{angular momentum}]^2$$

Geometric part = $\sum_{\text{spins}}$ [spin × angular momentum]^{2}



Vector, PScalar, Scalar

$l=0$	$\Lambda_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{3}{2}^+)$
V	1	1/9	8/9
PS	1	1/9	2/9
S	1	1	–

$l=1$	$\Lambda_c(\frac{1}{2}^-)$	$\Lambda_c(\frac{3}{2}^-)$	$\Sigma_c(\frac{1}{2}^-)$	$\Sigma_c(\frac{3}{2}^-)$	$\Sigma'_c(\frac{1}{2}^-)$	$\Sigma'_c(\frac{3}{2}^-)$	$\Sigma'_c(\frac{5}{2}^-)$
V	1/3	2/3	1/27	2/27	2/27	56/135	2/5
PS	1/3	2/3	1/27	2/27	8/27	8/135	24/45
S	1/3	2/3	1/3	2/3	–	–	–

$l=2$	$\Lambda_c(\frac{3}{2}^+)$	$\Lambda_c(\frac{5}{2}^+-)$	$\Sigma_c(\frac{3}{2}^+)$	$\Sigma_c(\frac{5}{2}^+)$	$\Sigma'_c(\frac{1}{2}^+)$	$\Sigma'_c(\frac{3}{2}^+)$	$\Sigma'_c(\frac{5}{2}^+)$	$\Sigma'_c(\frac{5}{2}^+)$
V	2/5	3/5	2/45	3/45	2/45	8/45	38/105	32/105
PS	2/5	3/5	2/45	3/45	8/45	8/45	8/105	16/35
S	2/5	3/5	2/5	3/5	–	–	–	–

Dynamic part ~ radial integral

$$R_{00}(r) = \frac{\alpha^{3/2}}{\pi^{1/4}} 2e^{-(\alpha^2/2)r^2}$$

GS $\quad I_0 = \langle \psi_{000} | \sqrt{2}\, e^{i\vec{q}_{eff}\cdot\vec{x}} | \psi_{000} \rangle = \sqrt{2} \left(\frac{\alpha'\alpha}{A^2} \right)^{3/2} e^{-q_{eff}^2/(4A^2)}$

$$\left(\frac{\alpha' q_{eff}}{A^2} \right)^0$$

$$A^2 = \frac{\alpha^2 + \alpha'^2}{2}$$

p-wave

$$I_1 = \frac{(\alpha'\alpha)^{3/2} \alpha' q_{eff}}{A^5} e^{-q_{eff}^2/(4A^2)} \qquad \left(\frac{\alpha' q_{eff}}{A^2} \right)^1$$

d-wave

$$I_2 = \frac{1}{2} \sqrt{\frac{2}{3}} \frac{(\alpha\alpha')^{3/2}}{A^3} \left(\frac{\alpha' q}{A^2} \right)^2 e^{-q_{eff}^2/(4A^2)} \qquad \left(\frac{\alpha' q_{eff}}{A^2} \right)^2$$

Excited states are not suppressed

Diquarks

$$d_S = qq(S=0), \quad d_A = qq(S=1)$$

ss attractive ss repulsive

B_C

$$\Lambda(1/2^+, gs) = \left|[d_S c]\right\rangle, \quad \Sigma(1/2^+, gs) = \left|[d_A c]\right\rangle$$

$$\Lambda(1/2^-, \lambda) = c_\lambda \left|[d_S c], l_\lambda = 1\right\rangle + c_\rho \left|[d_A c], l_\rho = 1\right\rangle$$

$$\Sigma(1/2^-, \lambda) = c_\lambda \left|[d_A c], l_\lambda = 1\right\rangle + c_\rho \left|[d_S c], l_\rho = 1\right\rangle$$

N

$$p(1/2^+, gs) = c_S \left|[d_S u]\right\rangle + c_A \left|[d_A u]\right\rangle$$

SU(6) quark model: $c_S = c_A$

Strong scalar diquark: $c_S > c_A$

Diquark correlations
enhance Λ, while suppress Σ productions

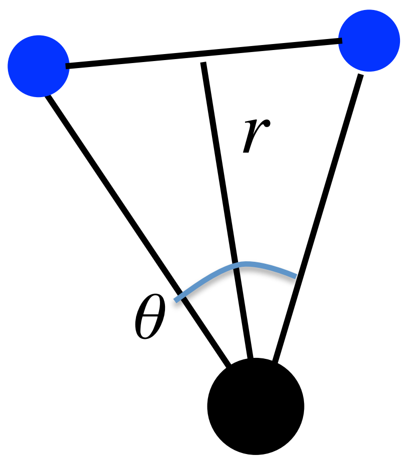
Summary

- ρ and λ modes are separately studied (Isotope shift) better in Λ than in Σ
- ρ-modes may open di-quark spectroscopy
- Systematic study in strangeness is important

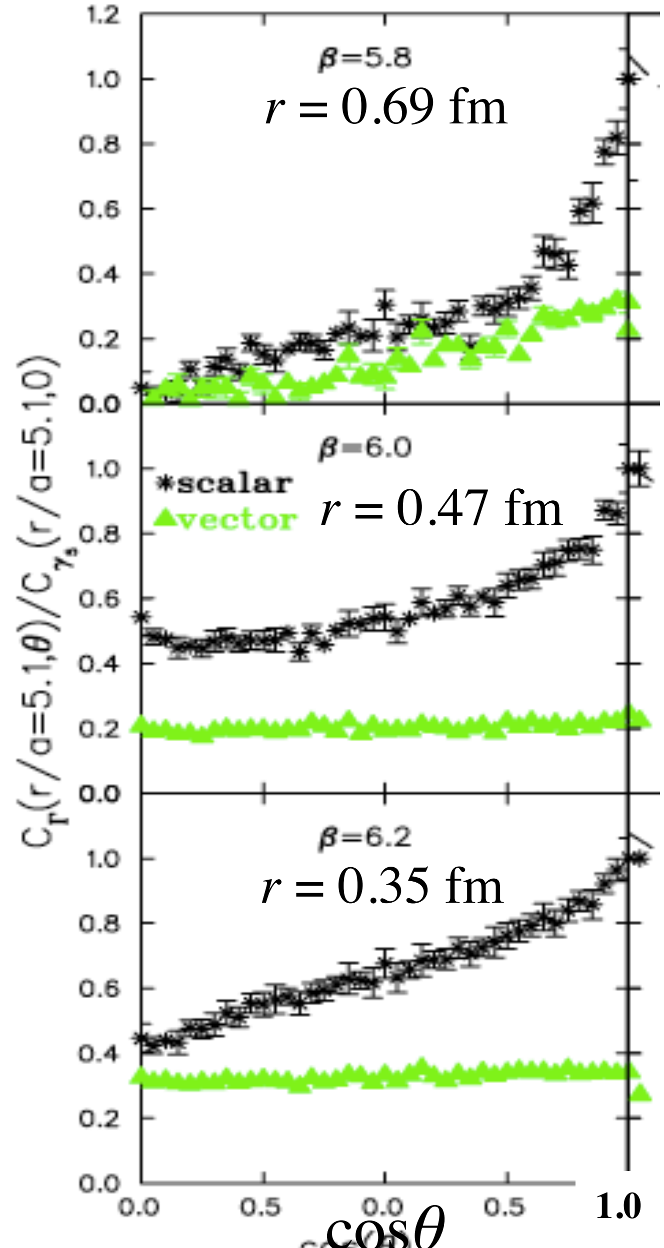
- Production in one step process is studied
- Higher excited (Λ) states can be produced as may as the ground state

Density correlations

Alexandrou, deForcrand, Lucini
PRL 97, 222002 (2006)



Good diquark
Bad diquark



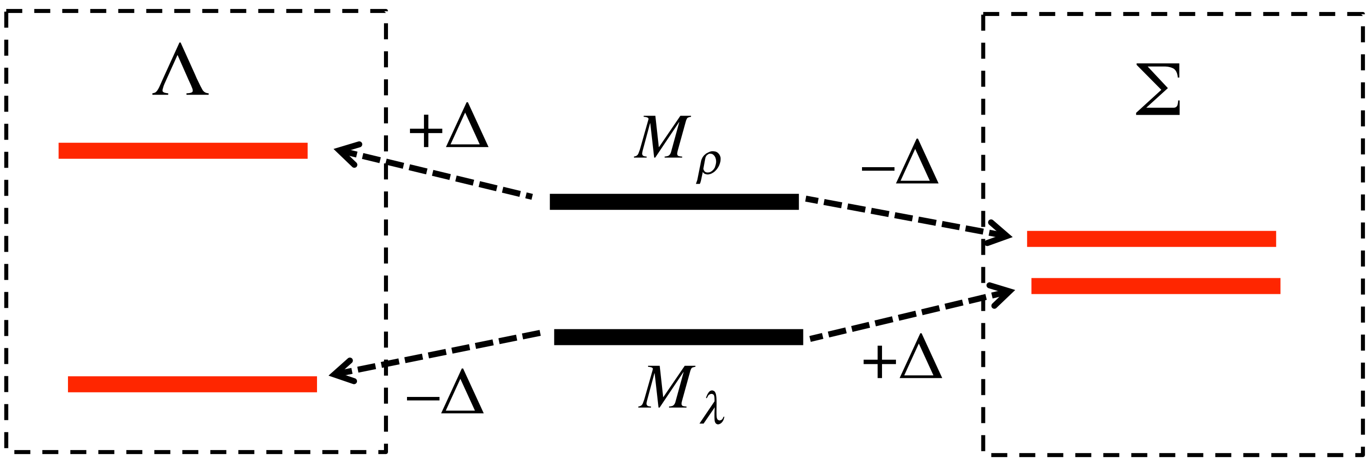
Indicates significant attraction between quarks in good diquark pair

$$d_S = qq(S=0), \quad d_A = qq(S=1)$$

$$\Lambda(1/2^-,\lambda) = \text{dominant}\, \left|[d_S c], l_\lambda = 1\right\rangle + \left|[d_A c], l_\rho = 1\right\rangle$$

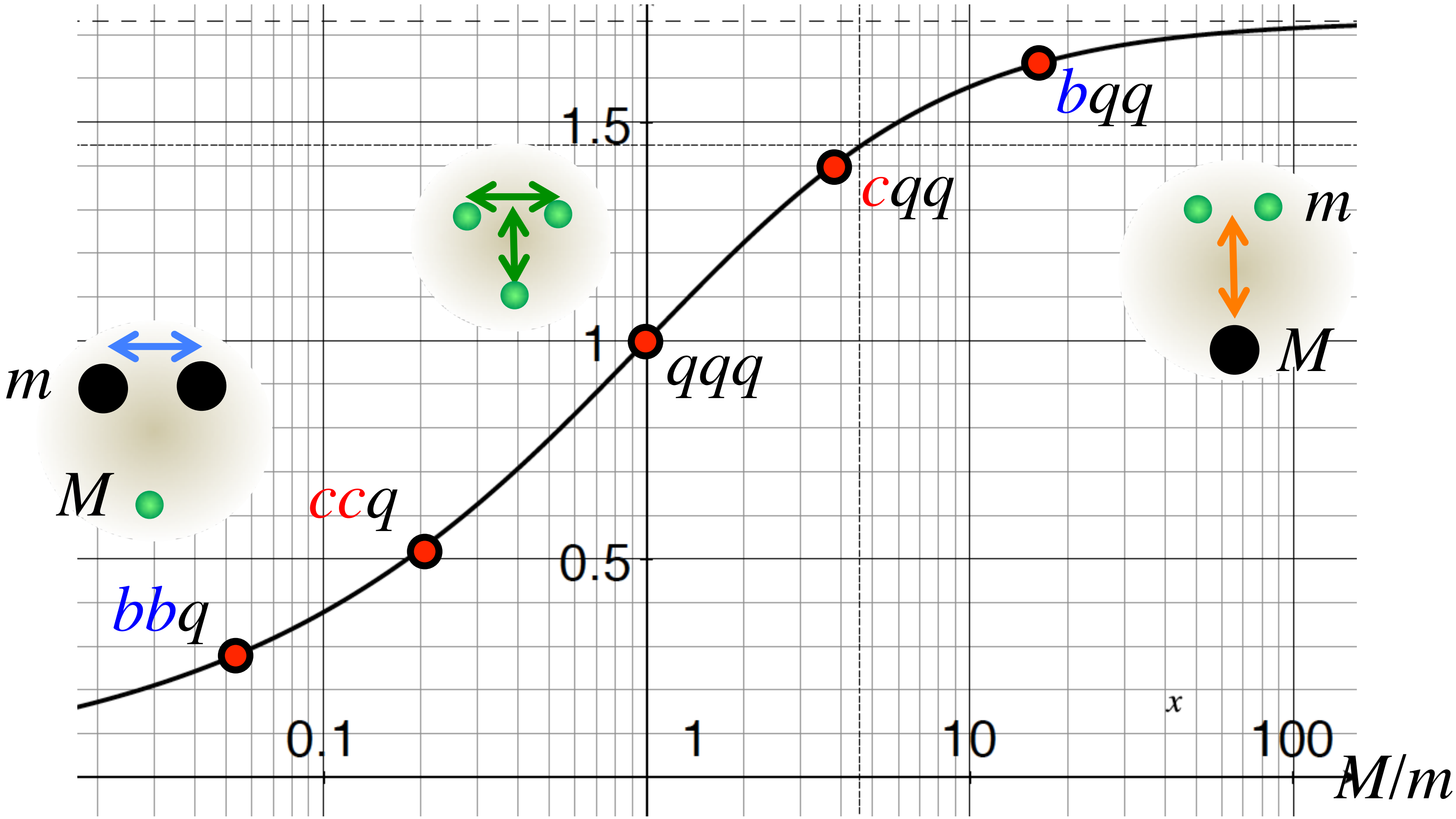
$$\Sigma(1/2^-,\lambda) = \text{dominant}\, \left|[d_A c], l_\lambda = 1\right\rangle + \left|[d_S c], l_\rho = 1\right\rangle$$

$$H = \begin{pmatrix} M_\rho & 0 \\ 0 & M_\lambda \end{pmatrix} \rightarrow \begin{pmatrix} M_\rho \pm \Delta & \delta \\ \delta & M_\lambda \mp \Delta \end{pmatrix}$$

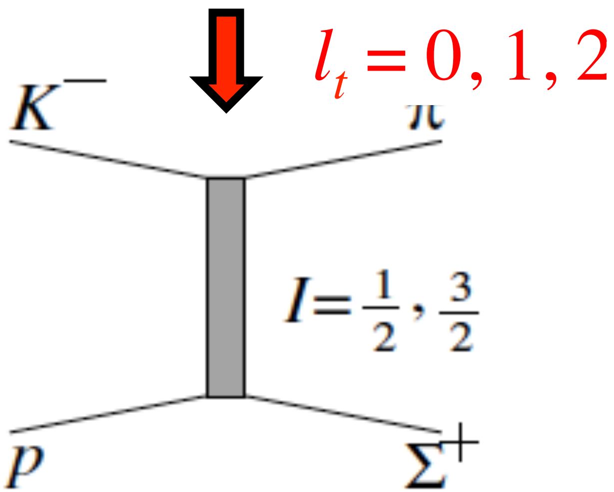


Spectrum

$$\frac{\omega_\lambda}{\omega_\rho} = \left[\frac{1}{3}\left(1+\frac{2m}{M}\right)\right]^{1/2} = \left[\frac{1}{3}(1+2x)\right]^{1/2}$$



Regge amplitude: t-channel and forward



$$A(s,t) = 16\pi \sum_{l=0}^{\infty} (2l+1) A_l(t) P_l(z_t)$$

For one l

$$z_t = \cos\theta_t = 1 + \frac{2s}{t - 4m^2}$$

$$\rightarrow f(t) s^l$$

This violates unitarity

➔ Need to sum over all l

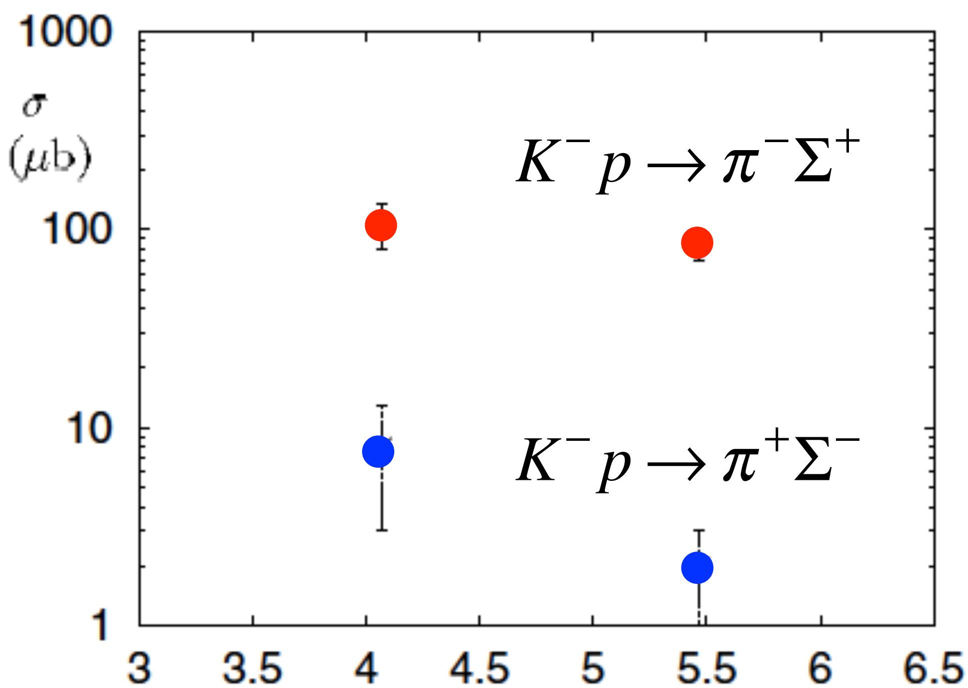
Regge amplitude: $A(s,t) \sim R(\alpha(t)) P_{l=\alpha(t)}(z_t) \sim s^{\alpha(t)}$

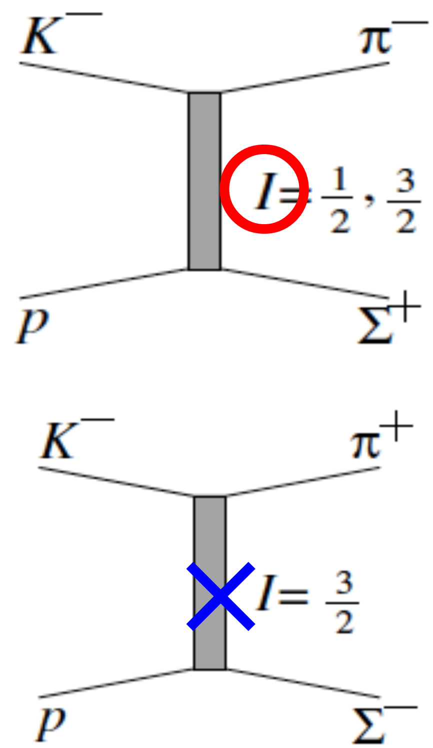
Form factor ~ forward peak

$\alpha(t)$: Regge trajectory

➔ Unitarity OK

Regge's mechanism -- Brief idea --



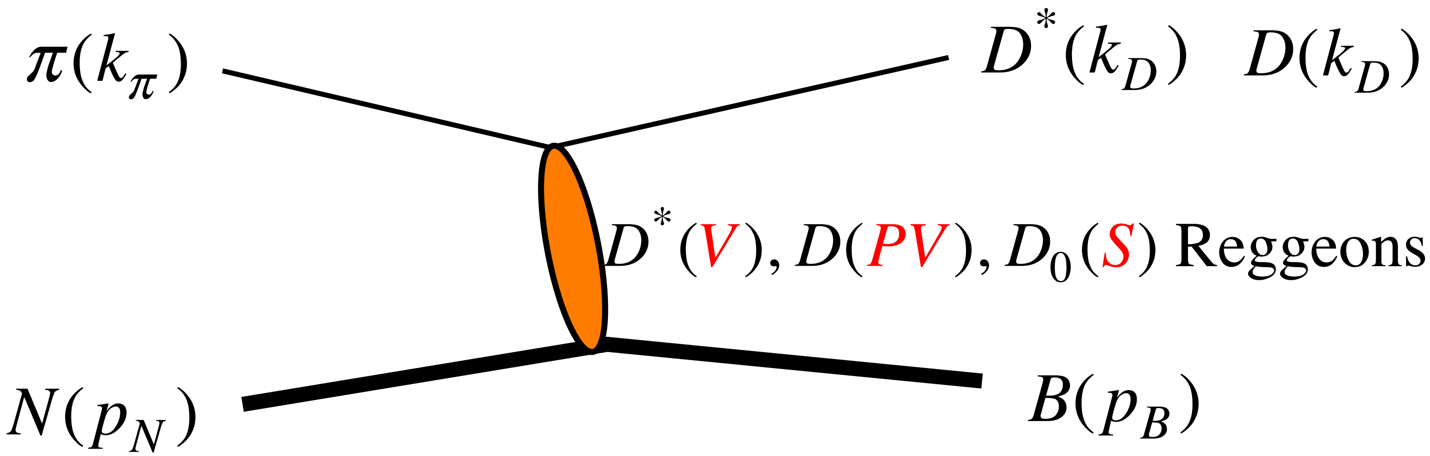


t-channel

$K^- p \to \pi^- \Sigma^+$ Resonances K*, … can be exchanged

$K^- p \to \pi^+ \Sigma^-$ No resonance exists with $Q = 2$

Pion induced reactions



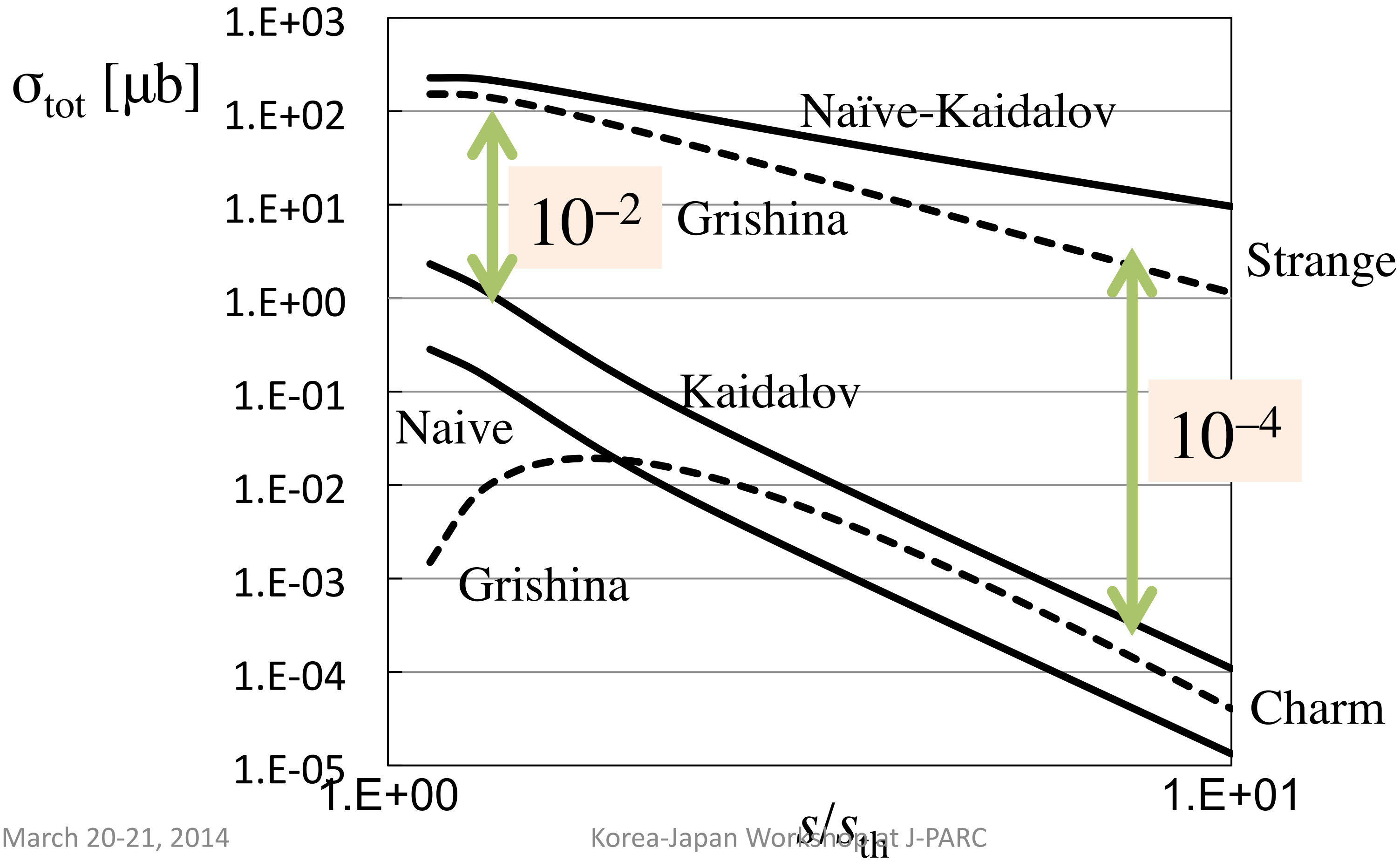
D* production: V and PV

D   production: V and S

Forward peak, where, they do not interfere

Vector Reggeon, some model dependence

$$\sigma \sim \left\{ \begin{array}{ll} \text{Naive/Kaidalov} & \Gamma^2(1-\alpha(t)) \\ \text{Grishina} & \exp(-\Lambda|t|) \end{array} \right\} \times s^{2\alpha(t)-2}$$



Results

$$\mathcal{R} \sim \frac{1}{\text{Flux}} \times \sum_{fi} |t_{fi}|^2 \times \text{Phase space} \quad \sim C_{J^P} |I_L|^2$$

$l=0$	$\Lambda_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{3}{2}^+)$					
	1	1/9	8/9					
$l=1$	$\Lambda_c(\frac{1}{2}^-)$	$\Lambda_c(\frac{3}{2}^-)$	$\Sigma_c(\frac{1}{2}^-)$	$\Sigma_c(\frac{3}{2}^-)$	$\Sigma'_c(\frac{1}{2}^-)$	$\Sigma'_c(\frac{3}{2}^-)$	$\Sigma'_c(\frac{5}{2}^-)$	
	1/3	2/3	1/27	2/27	2/27	56/135	2/5	
$l=2$	$\Lambda_c(\frac{3}{2}^+)$	$\Lambda_c(\frac{5}{2}^+-)$	$\Sigma_c(\frac{3}{2}^+)$	$\Sigma_c(\frac{5}{2}^+)$	$\Sigma'_c(\frac{1}{2}^+)$	$\Sigma'_c(\frac{3}{2}^+)$	$\Sigma'_c(\frac{5}{2}^+)$	$\Sigma'_c(\frac{5}{2}^+)$
	2/5	3/5	2/45	3/45	2/45	8/45	38/105	32/105

Charm $k_\pi = 2.71$ [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

Results

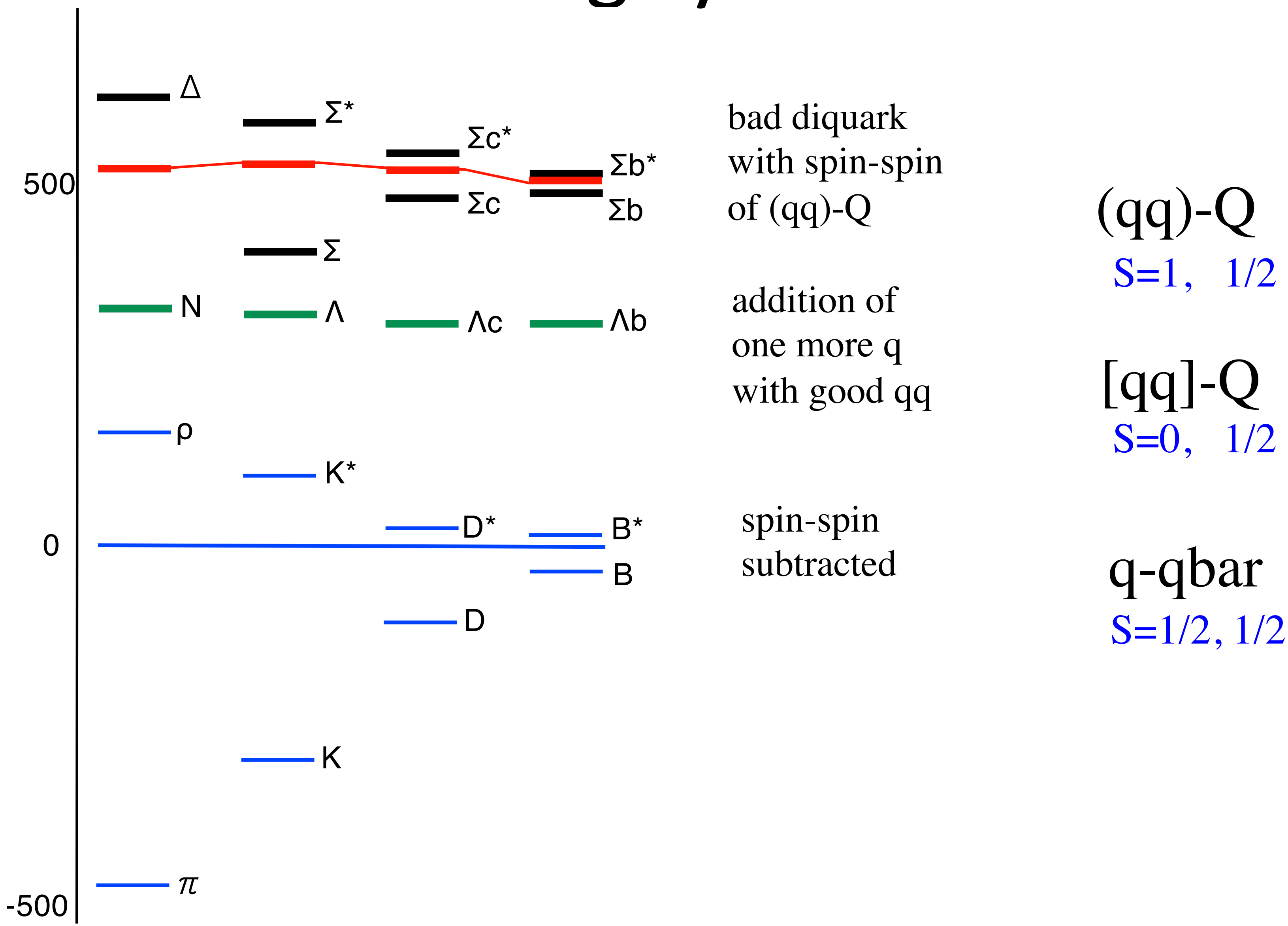
Charm $k_\pi = 2.71$ [GeV]

$l=0$	$\Lambda_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{3}{2}^+)$					
	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 $k_\pi = 1.59$ [GeV]

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

Interesting systematics



Diquark correlation

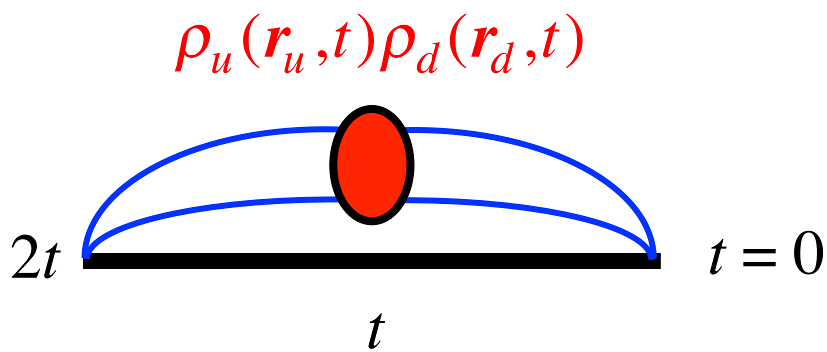
In QCD

$$C(\boldsymbol{r}_u, \boldsymbol{r}_d; t) = \langle 0 | J_\Gamma(0, 2t) \rho_u(\boldsymbol{r}_u, t) \rho_d(\boldsymbol{r}_d, t) J_\Gamma^\dagger(0,0) | 0 \rangle$$

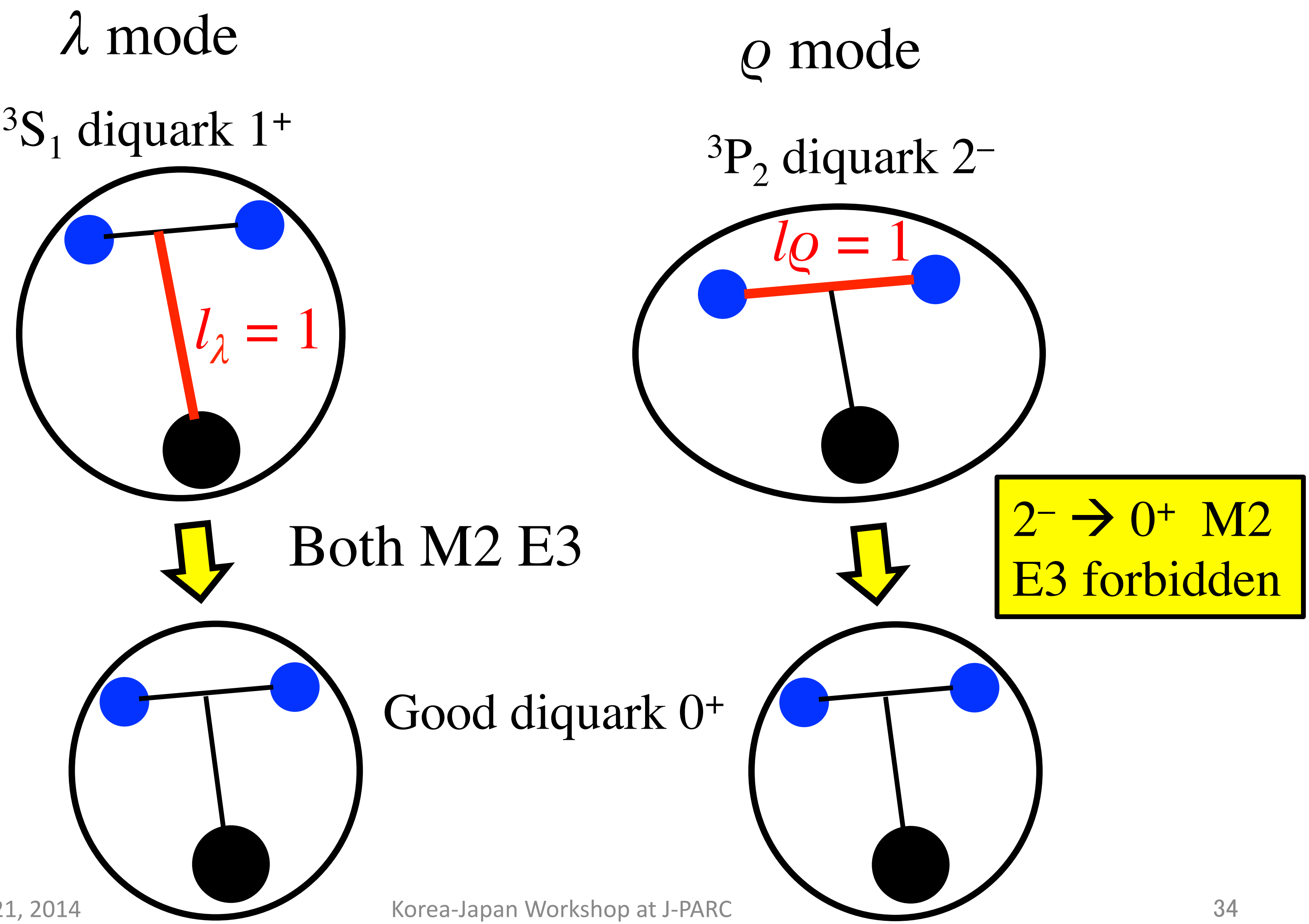
$$\rho(\boldsymbol{r}, t) = \bar{q}_f \gamma_0 q_f, \quad f = u, d$$

$$J_\Gamma(x) = \varepsilon^{abc}[u_a^T(x) C\Gamma d_b(x) \pm d_a^T(x) C\Gamma u_b(x)] s_c(x)$$

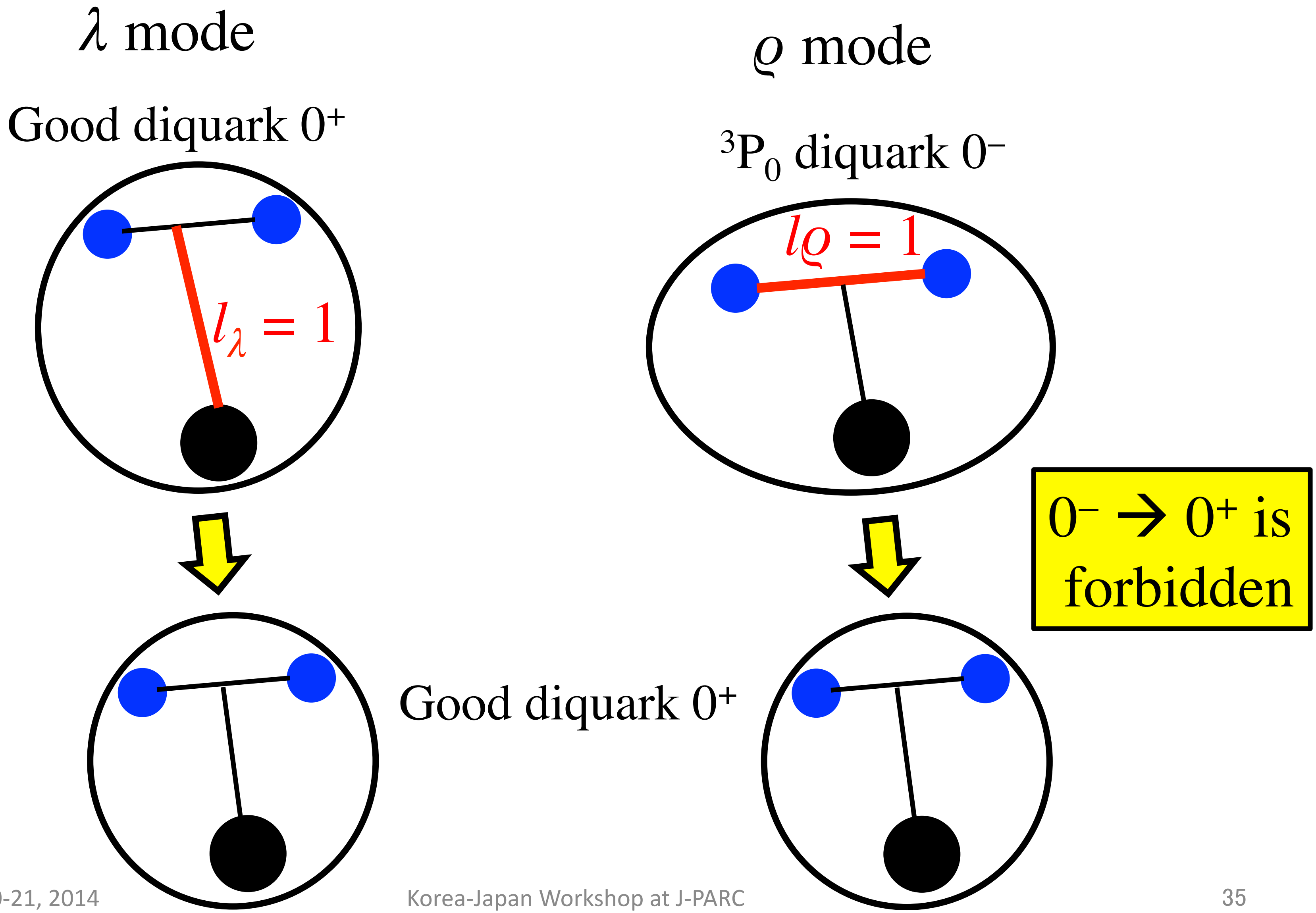
ud-diquark Static heavy quark



$5/2^- \rightarrow 1/2^+$ M2, E3 transition



$1/2^- \rightarrow 1/2^+$ E1 transition



$$y = \left(\frac{x}{a}\right)^n \exp\left(-\frac{x^2}{4a^2}\right) \qquad n \sim \Delta l$$