"Exotic" hadrons at JPARC
-- New states and long standing issues --

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at Workshop on J-PARC hadron physics in 2014

CONTENTS

1. Introduction

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

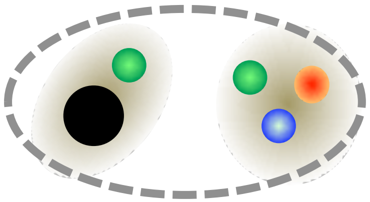
→
- Kinetic energy is suppressed, NR treatment
- Spin becomes irrelevant, decouples
- Flavor symmetry is broken → HQ symmetry

(1)

More attraction for hadron-hadron interaction

→

New molecular states

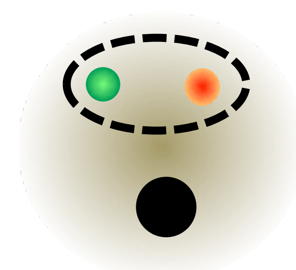


(2)

Static source in a baryon

→

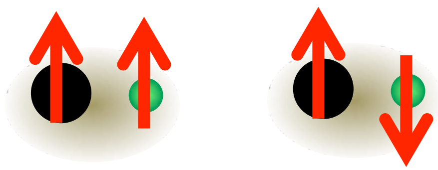
HQ + diquark



2. Heavy exotic hadrons (baryons)

Hadronic molecules under HQ and chiral symmetries
Example: $\bar{D}$-N

Decoupling of spin in $\bar{D}$ and $\bar{D}^*$

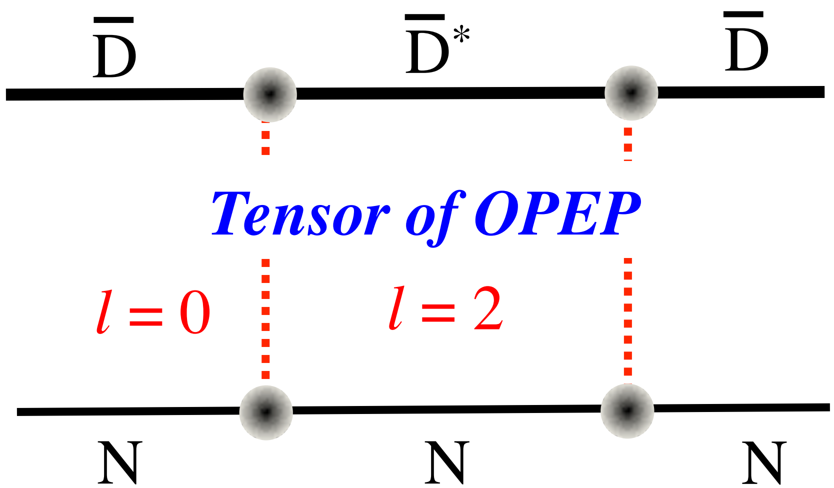


$$m(\bar{D}^*) \sim m(\bar{D})$$

$$m_{K^*} - m_K \sim 400\ MeV$$

$$m_{D^*} - m_D \sim 140\ MeV$$

$$m_{B^*} - m_B \sim 35\ MeV$$

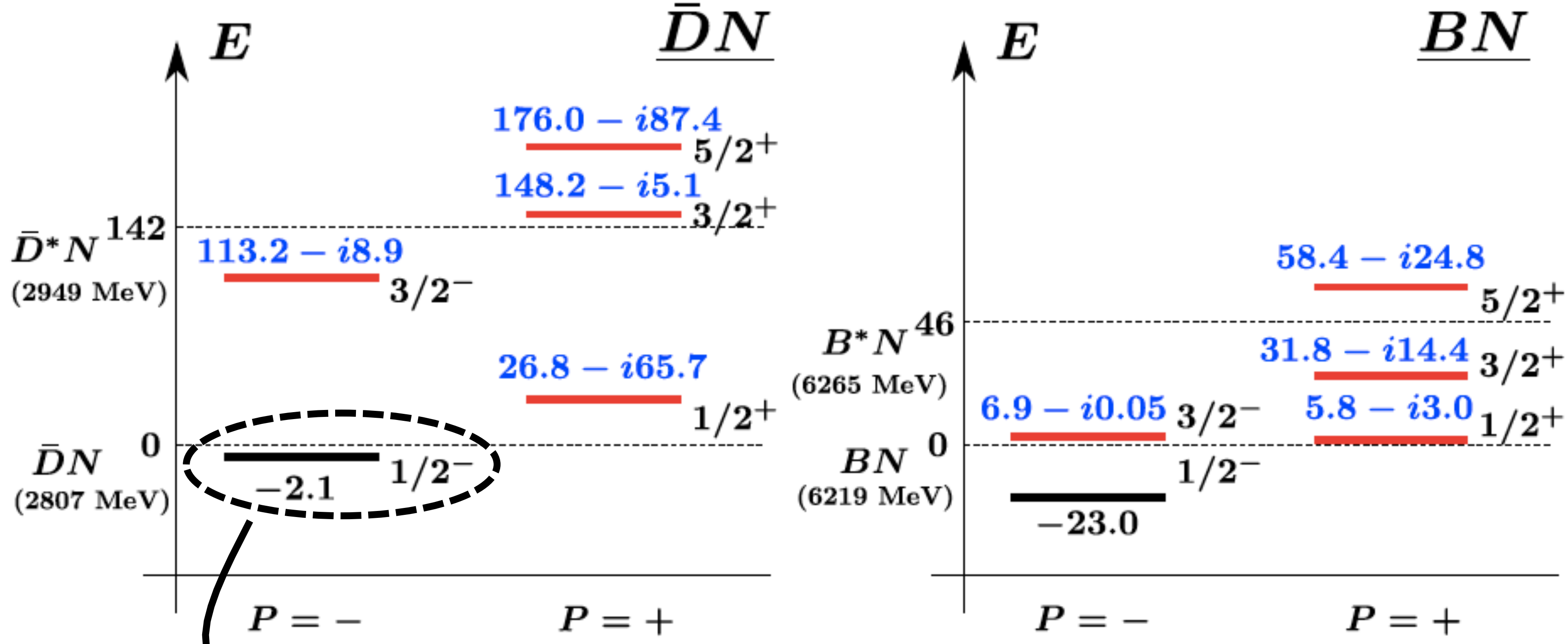


Loosely bound
$\bar{D}$-N($J^P = 1/2^-$)
➔
Analogue to the deuteron

Low-lying states near threshold

Yasui-Sudoh, PRD80, 034008, 2009

Yamaguchi-Ohkoda-Yasui and Hosaka, PRD84:014032,2011



$E_B \sim 2$ MeV, $\langle r^2 \rangle^{1/2} \sim 3$ fm

There could be many molecular states near thresholds including exotic channels

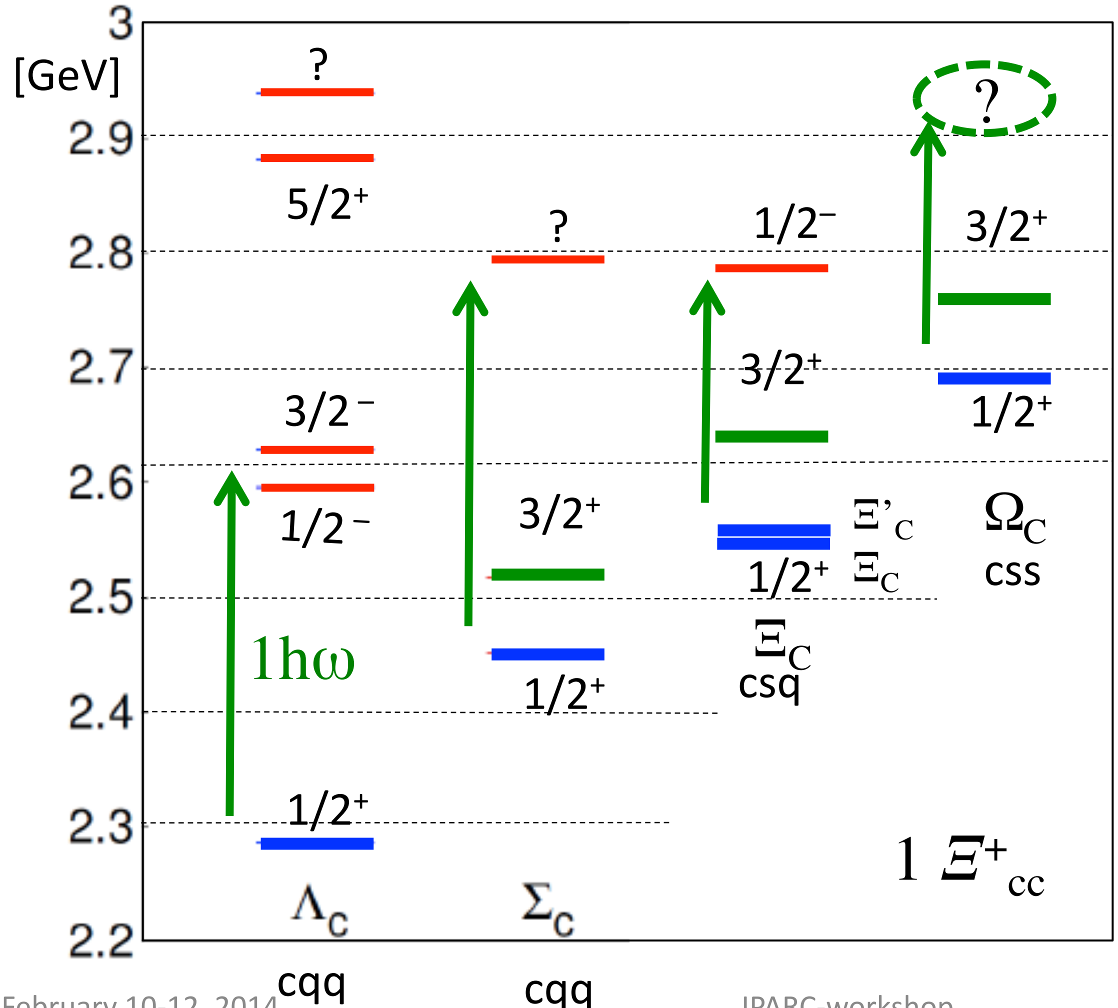
More states in BB* molecules

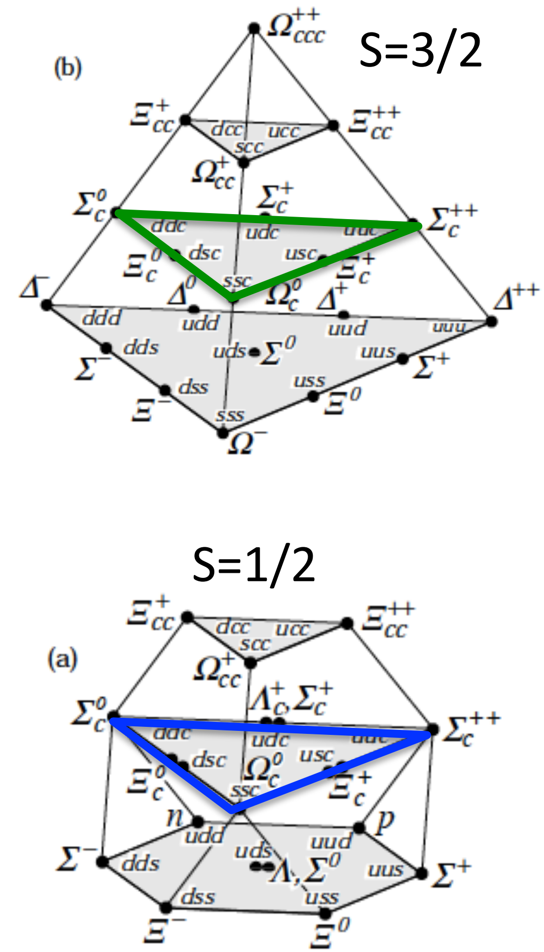
Z_b and related topics

Bondar et al, Phys.Rev. D84 (2011) 054010
Ohkoda et al, Phys.Rev. D86 (2012) 014004
M. B. Voloshin, Phys. Rev. D 84, 031502 (2011)
Ohkoda et al, Phys.Rev. D86 (2012) 117502

3. Charmed baryons

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

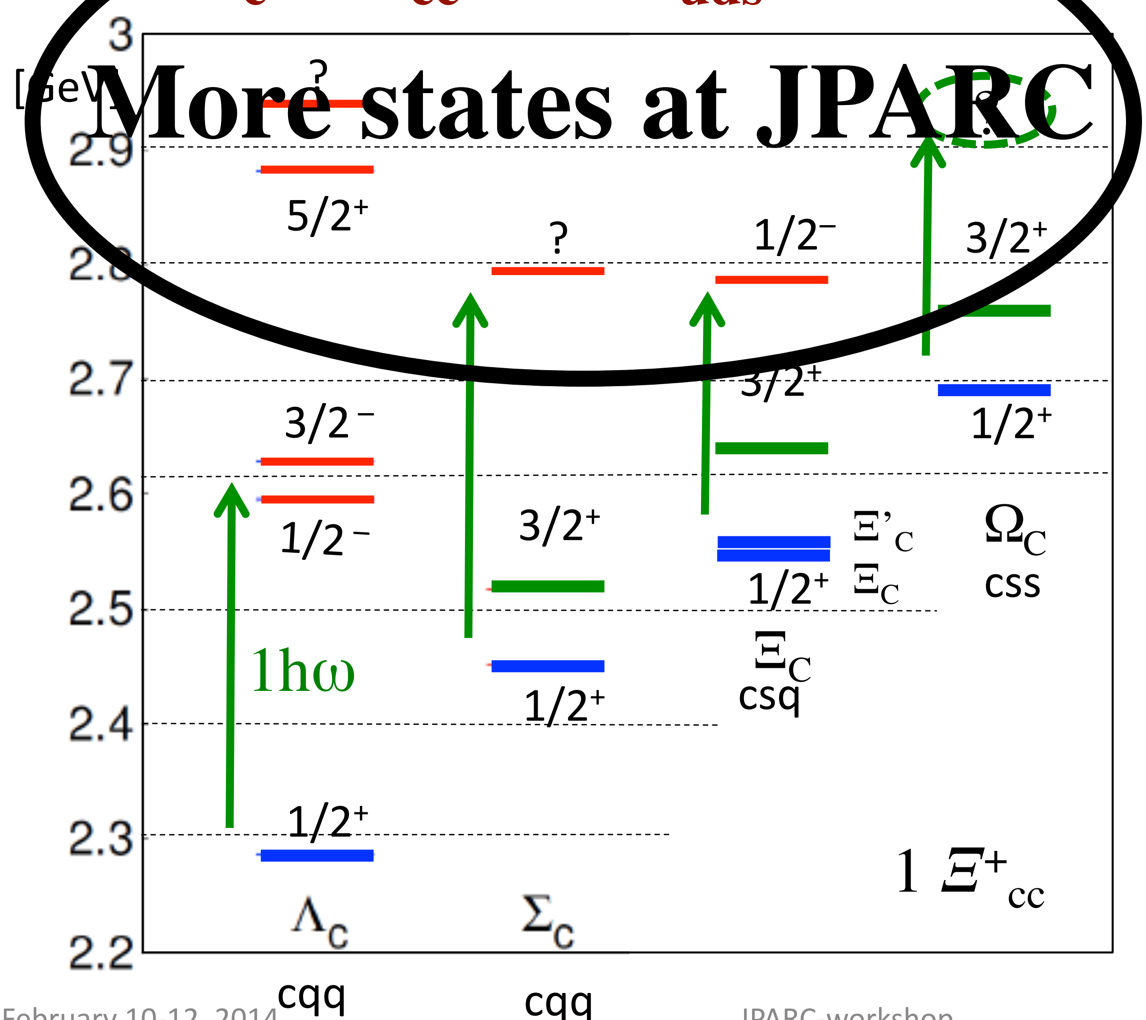


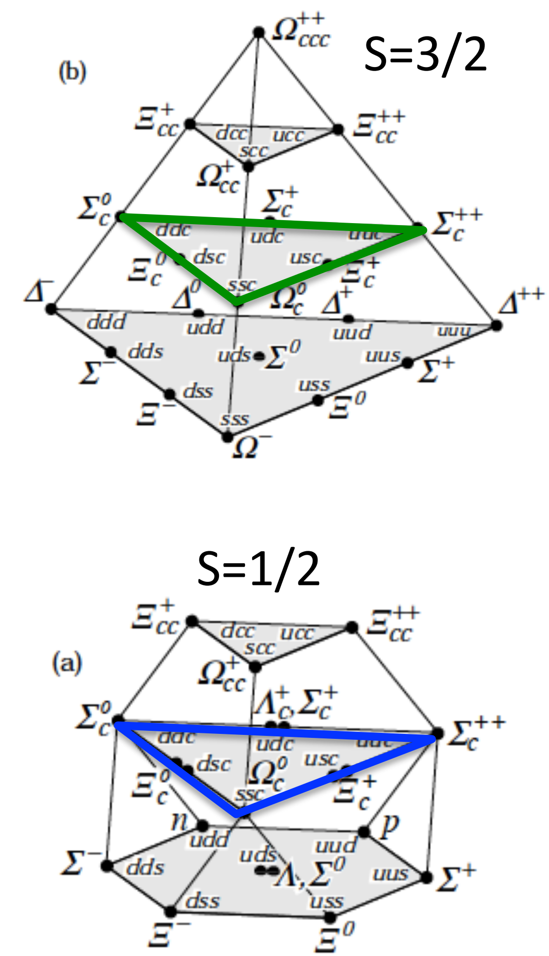


3. Charmed baryons

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

More states at JPARC





(1) 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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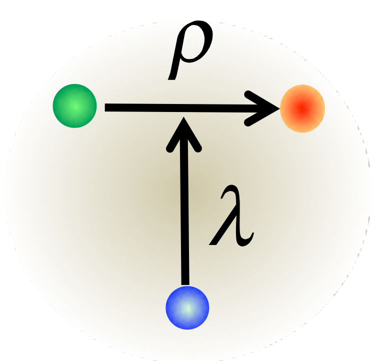
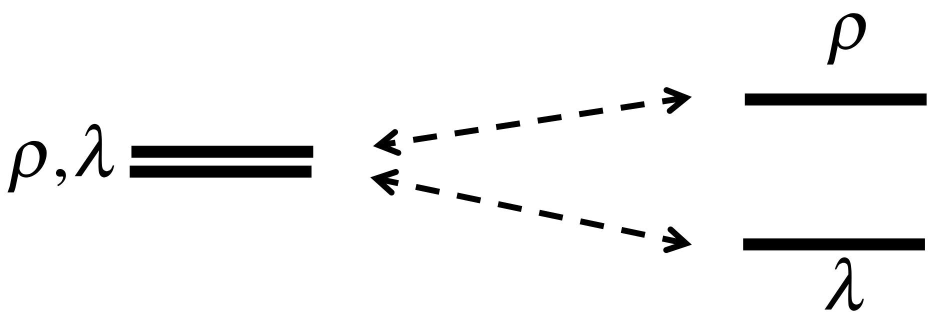
A heavy quark differentiate ***diquark*** motions = modes

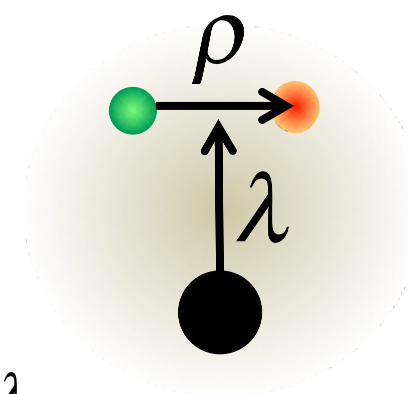
Important ingredient for hadron dynamics

To know how they appear in baryon spectroscopy

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





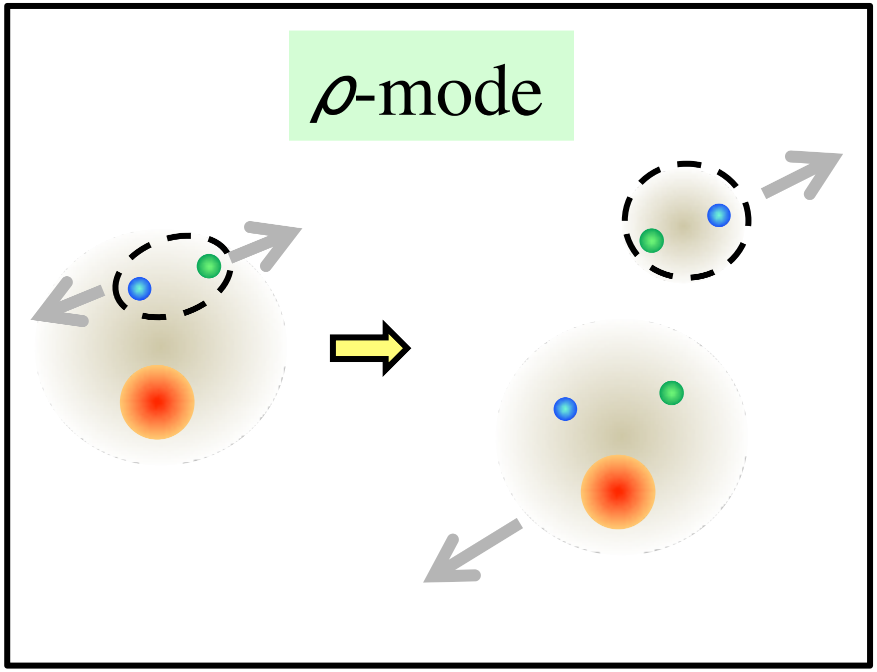


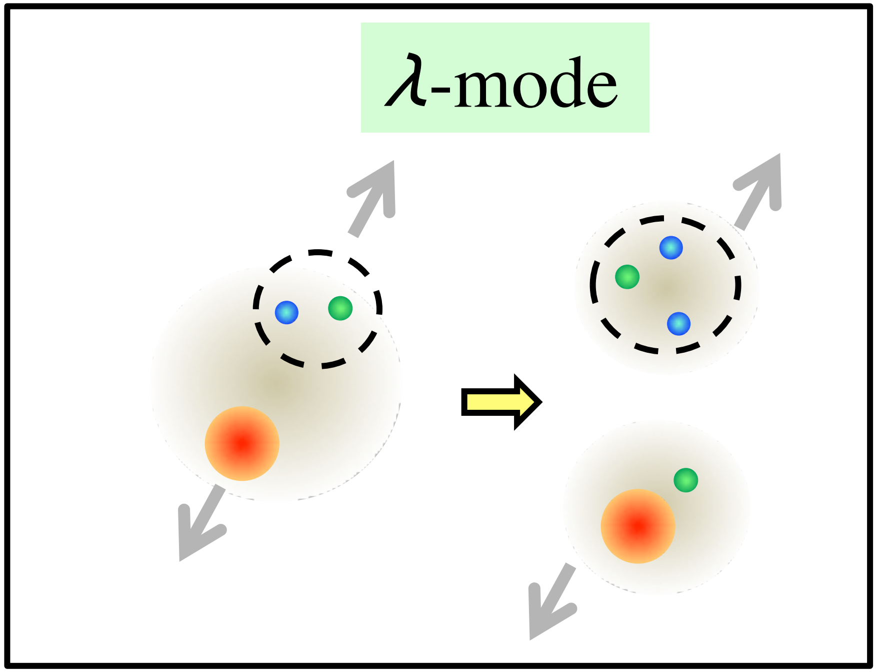
$m_\rho \sim m_\lambda$ $\qquad$ $m_\rho < m_\lambda$

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

λ mode is more collective

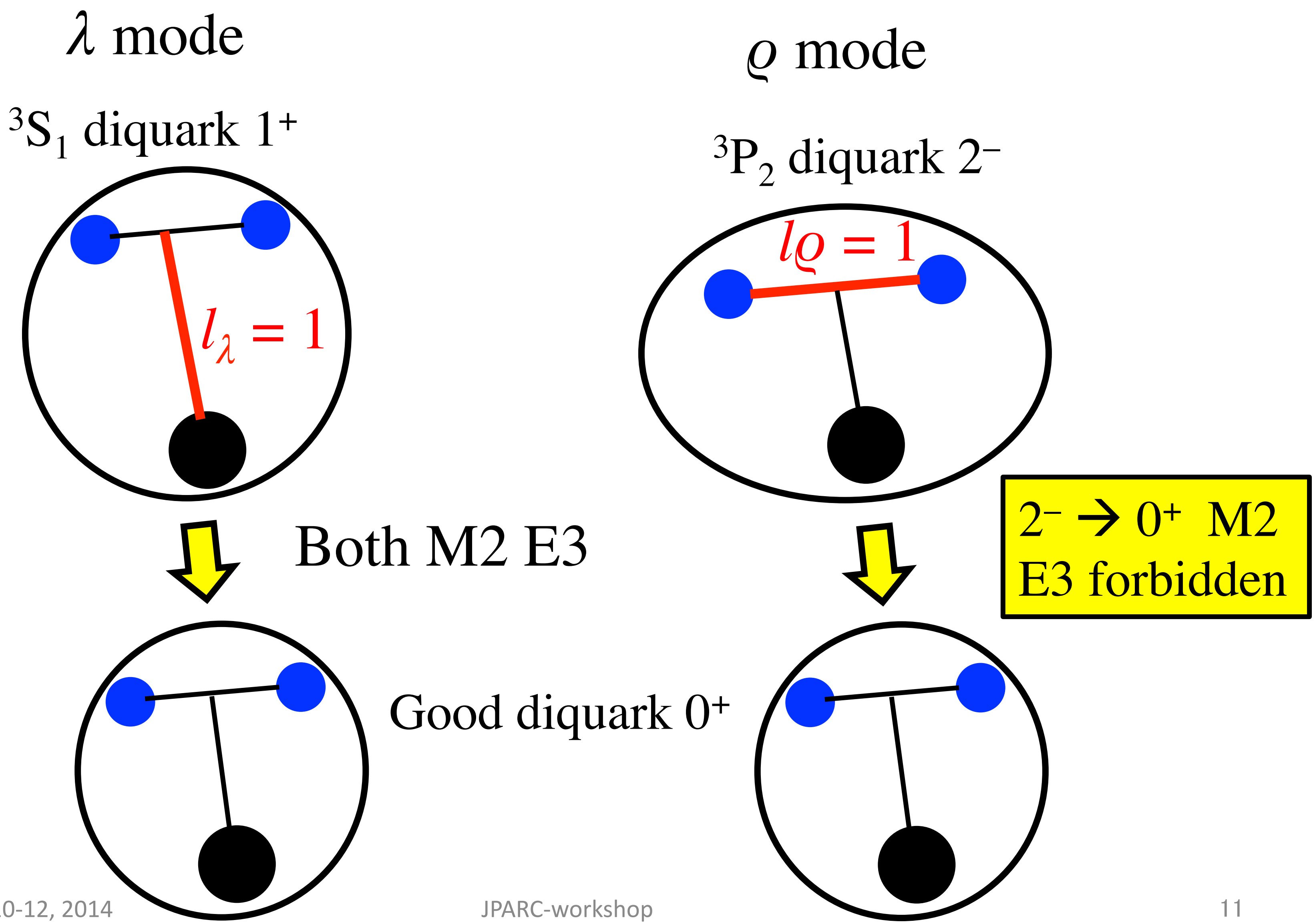
Decays





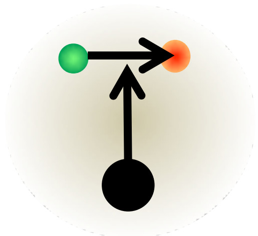
ϱ-mode: (qq)* decays by emitting a pion
λ-mode: Q* decays by emitting a heavy meson

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



Wave function

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



For λ-mode $\psi = c_\lambda |l_\lambda = 1\rangle + c_\rho |l_\rho = 1\rangle$

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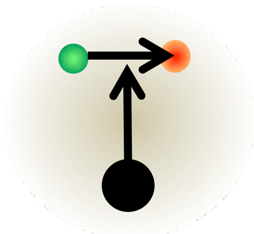
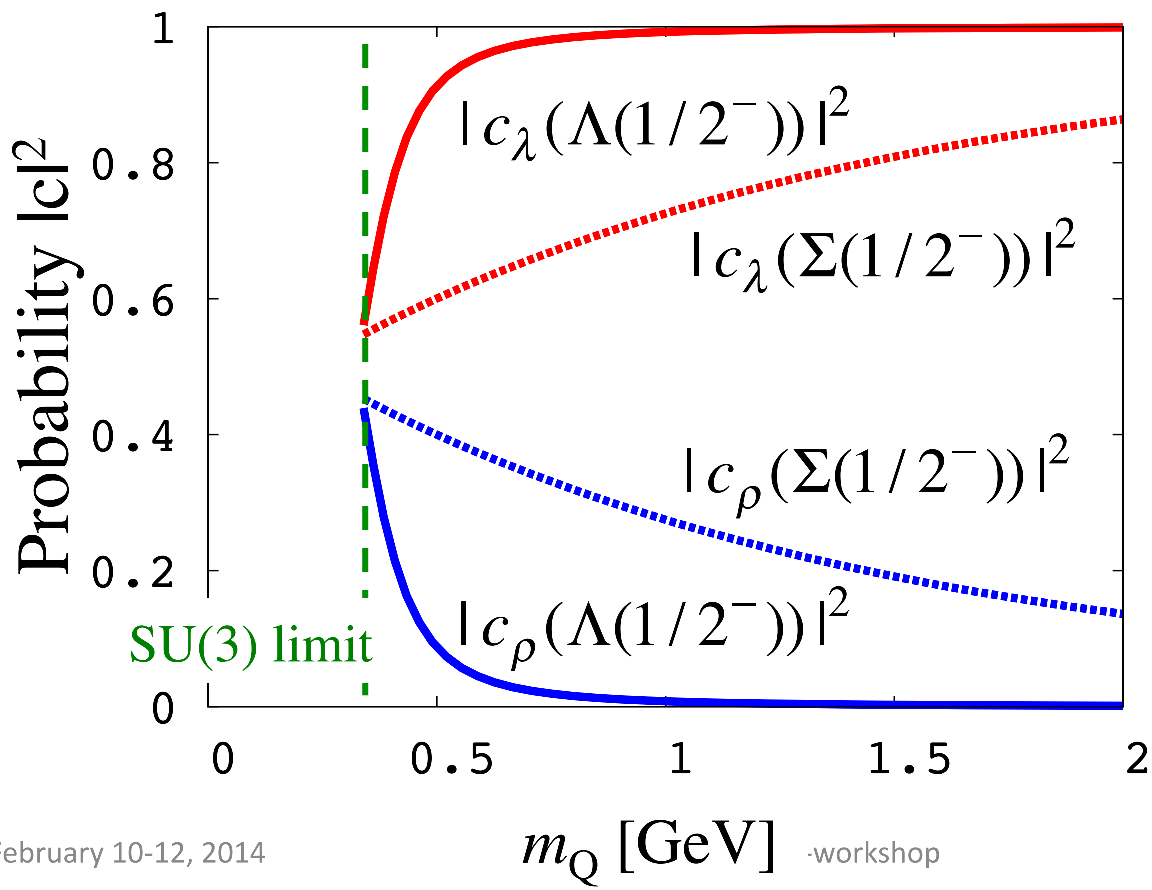


For λ-mode $\psi = c_\lambda |l_\lambda = 1\rangle + c_\rho |l_\rho = 1\rangle$

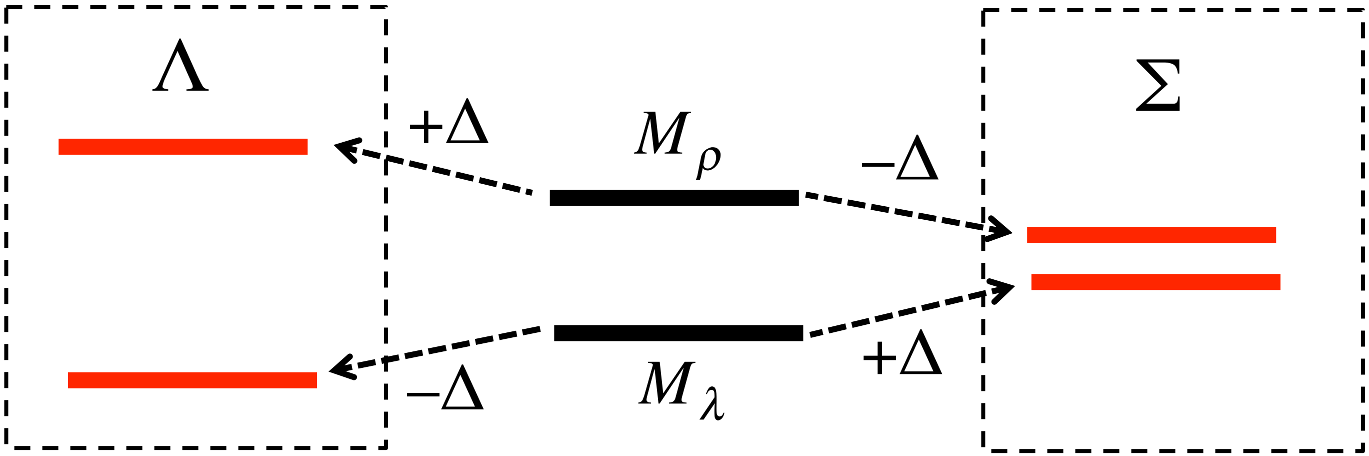


Λ_c^* is almost pure λ mode
➔
Reflect more diquark nature

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

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

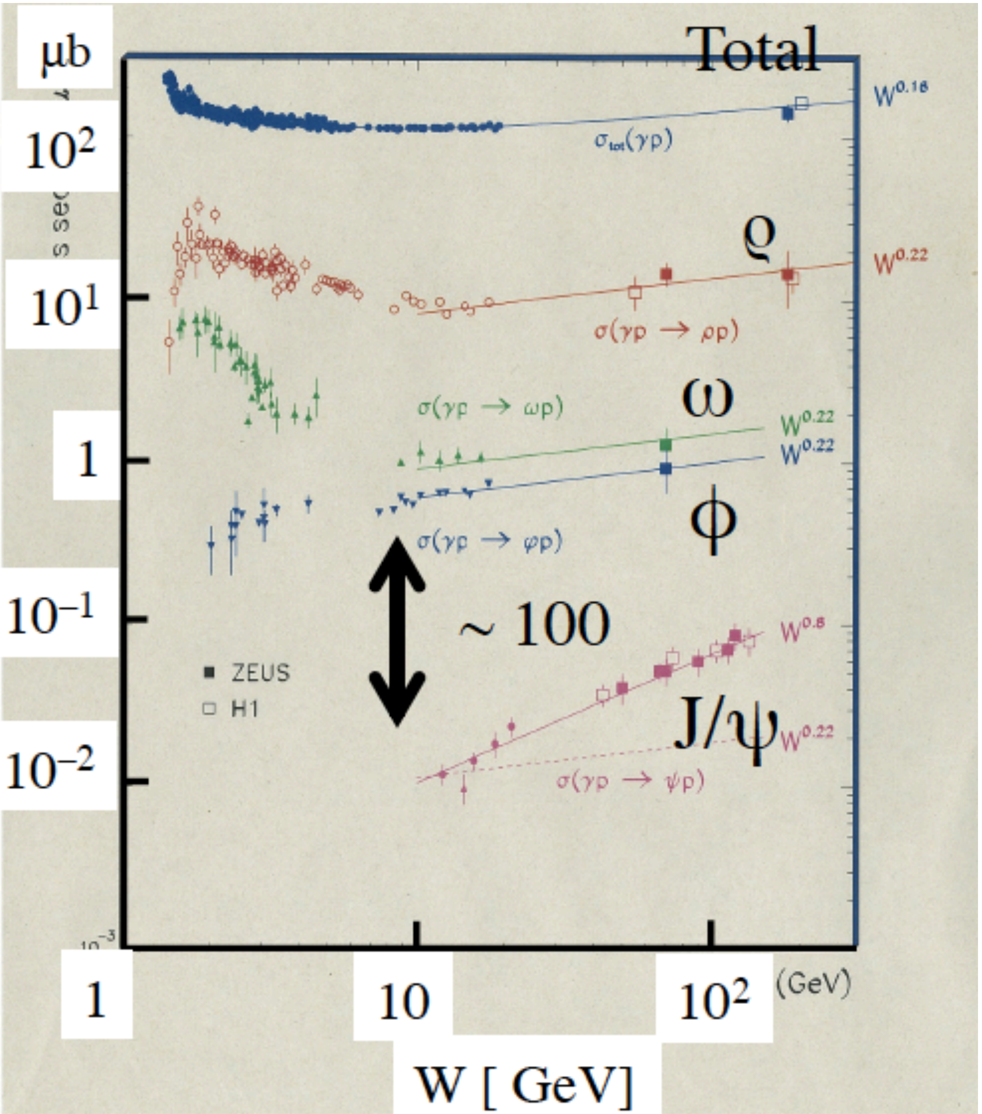
$$H = \begin{pmatrix} M_\rho & 0 \\ 0 & M_\lambda \end{pmatrix} \rightarrow \begin{pmatrix} M_\rho \pm \Delta & \delta \\ \delta & M_\lambda \mp \Delta \end{pmatrix}$$



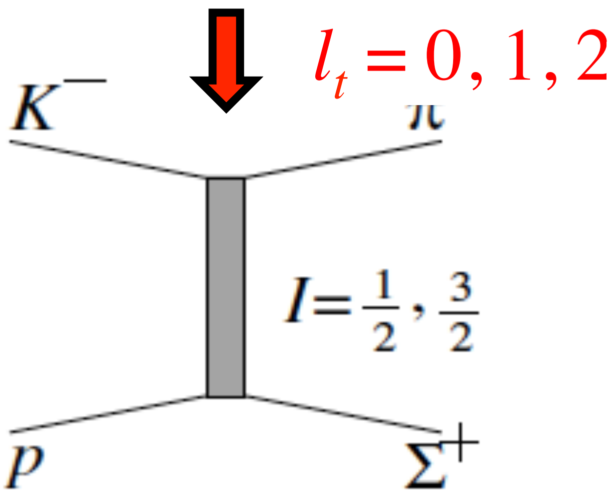
(2) Production Absolute and relative rates

About 100 times
smaller than
strangeness production

What about for
the pion induced reaction



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

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

This violates unitarity

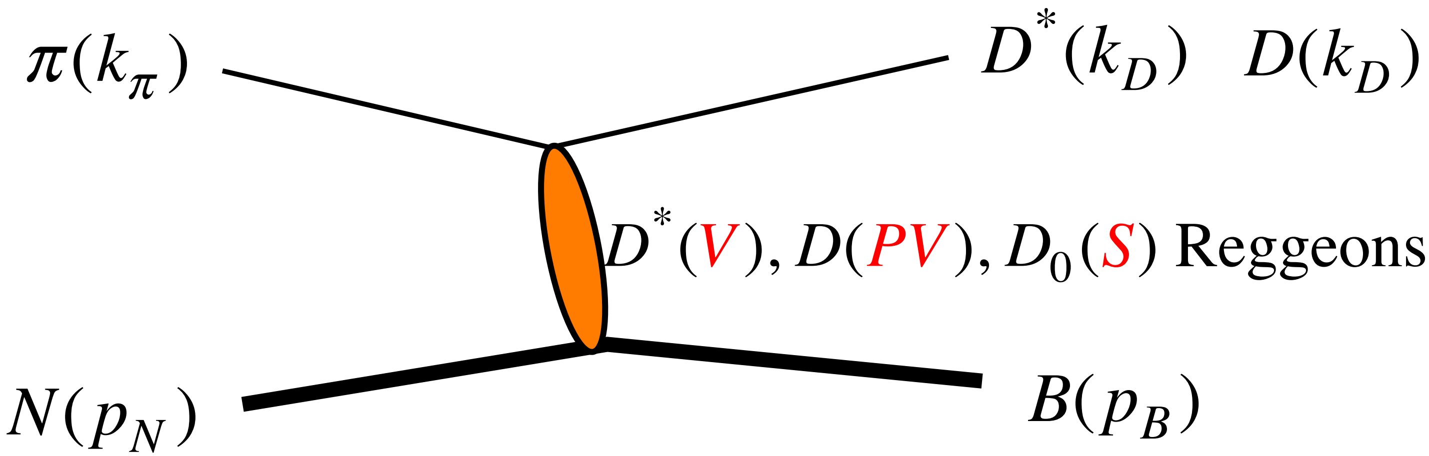
➔ Need to sum over all l

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

Pion induced reactions

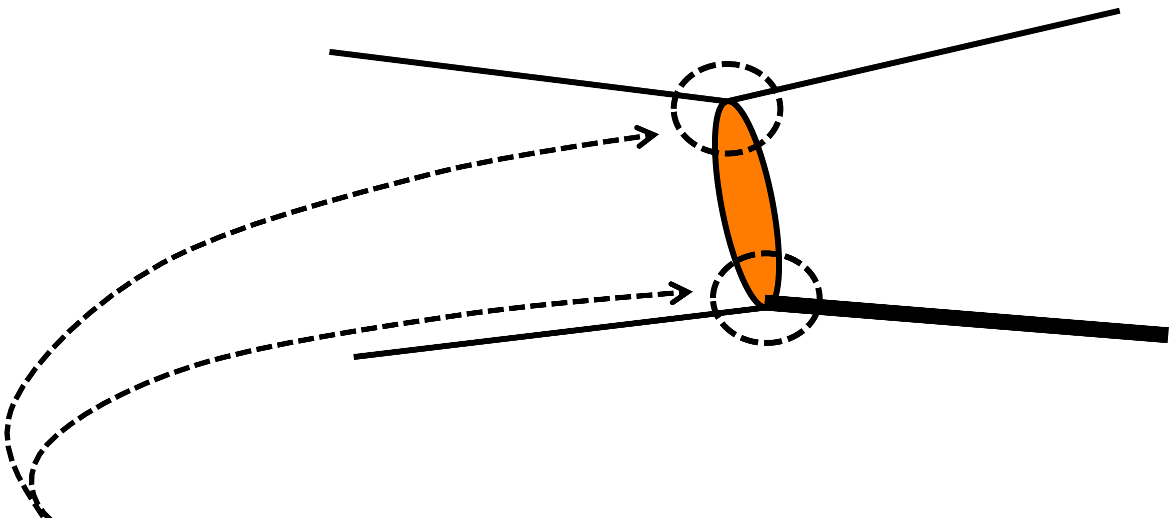


D* production: *V* and *PV*
D   production: *V* and *S*

Forward peak, where, they do not interfere

Sang-Ho Kim (poster in this workshop)

Regge method with couplings fixed at strangeness



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

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

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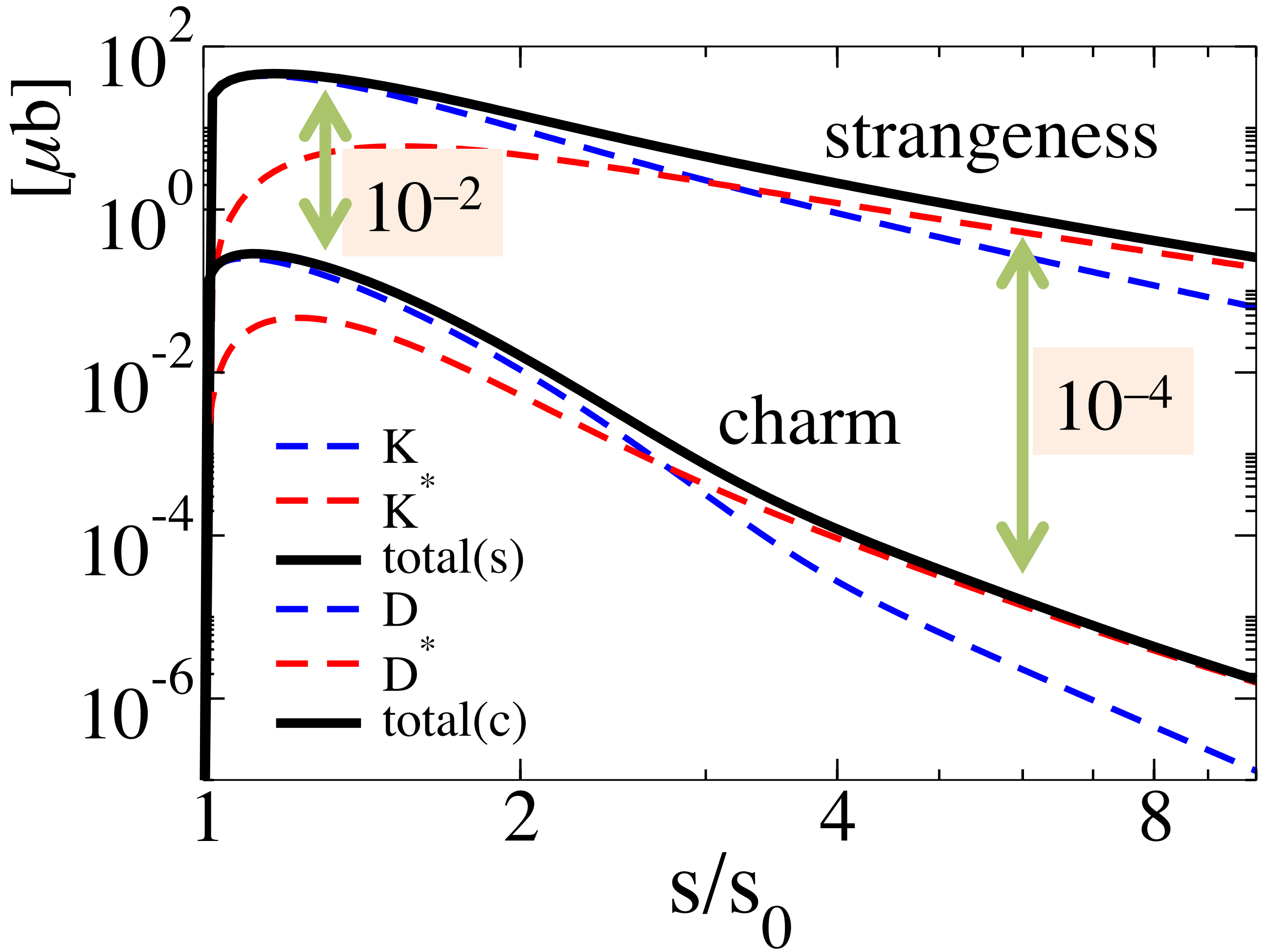
Regge method with couplings fixed at strangeness



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

Relative rates to various B_c

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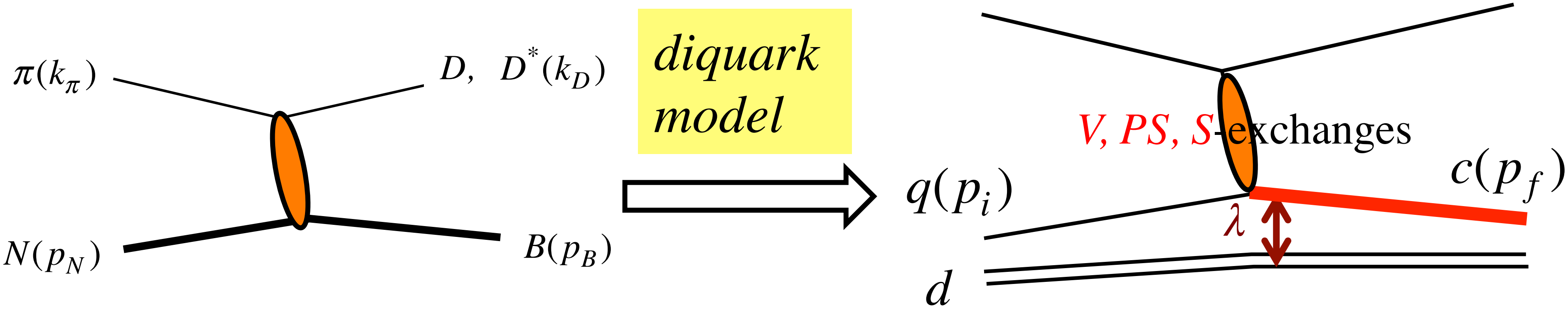
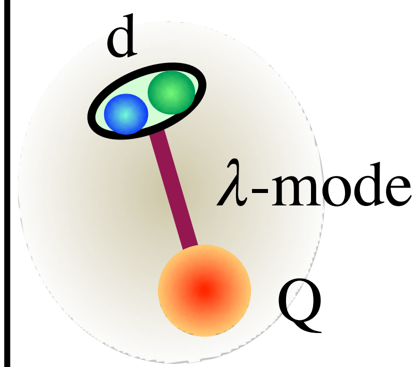
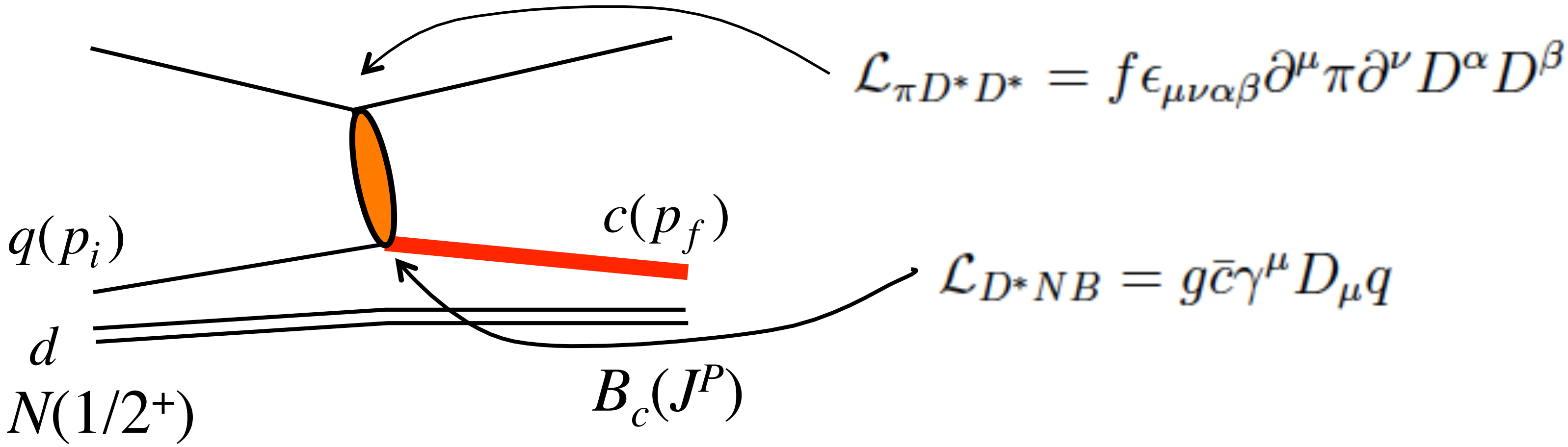


- Single step $q \rightarrow Q$, ➔ λ modes are excited
- *V, PS* for D^* *and* *V, S* for D productions with various B's of $l_\lambda = 0, 1, 2$ (18 baryons)
- Estimate forward scattering amplitudes



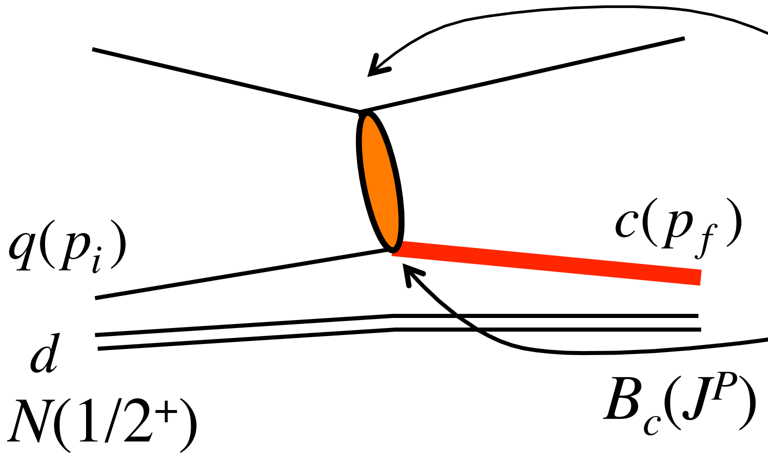
Single-step $qd \rightarrow Qd$ reaction

Example of *V*-exchange



Single-step $qd \to Qd$ reaction

Example of V-exchange



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

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

V-exchange at forward

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

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

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

$= \;$ (Geometric) × (Dynamic)

CG coefficients

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

(Dynamic) ~ Radial wave function

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

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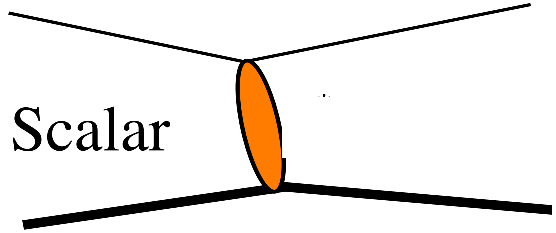
Vector, PScalar, Scalar



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

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

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

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

p-wave

$$I_1 = \frac{(\alpha'\alpha)^{3/2}\alpha' q_{eff}}{A^5}\cos\theta_{q_{eff}} e^{-q_{eff}^2/(4A^2)}$$

$$\left(\frac{\alpha' q_{eff}}{A^2}\right)^1$$

d-wave

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

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

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: $c_S > c_A$

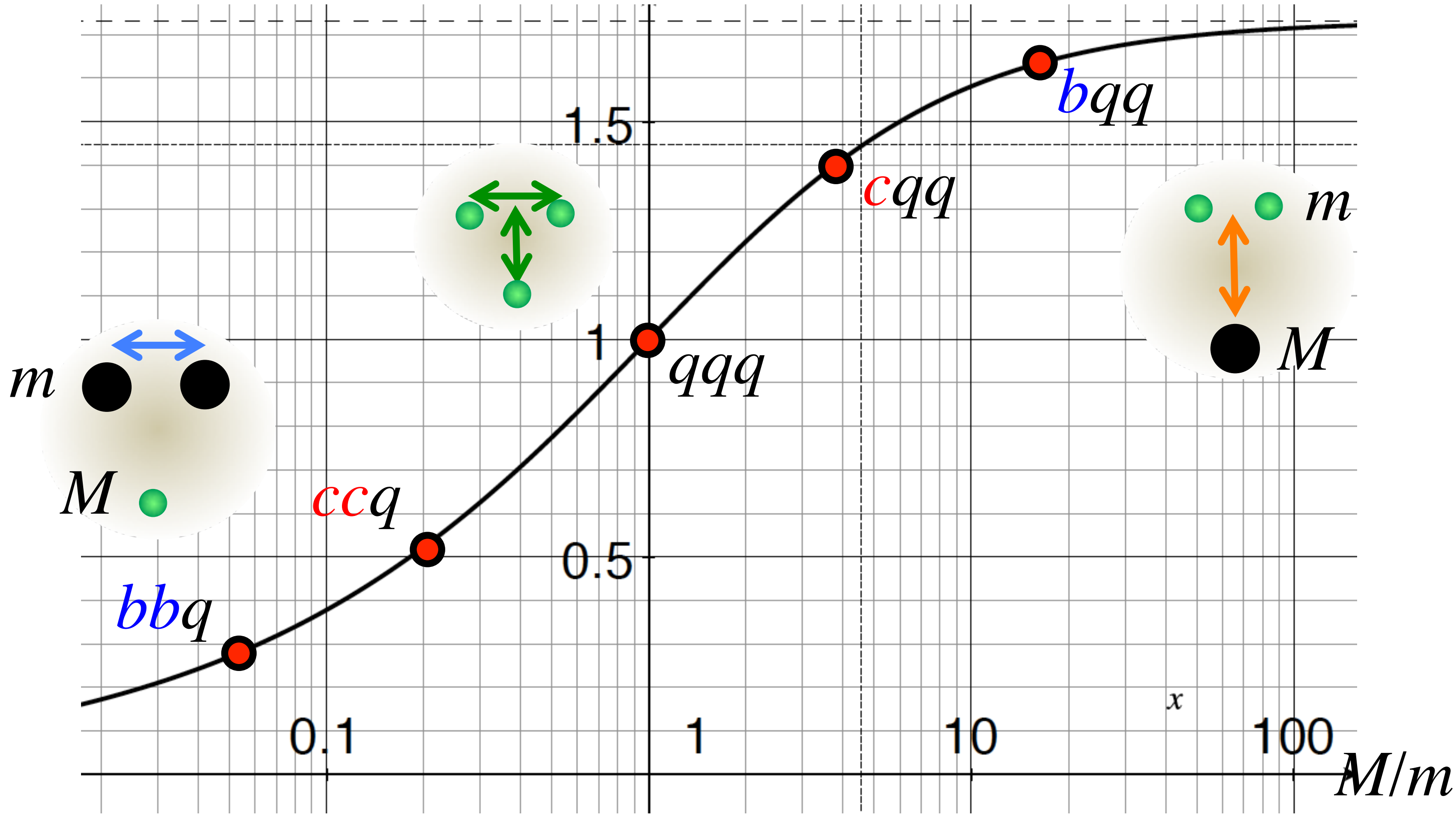
Diquark correlations
enhance Λ, while suppress Σ productions

Summary

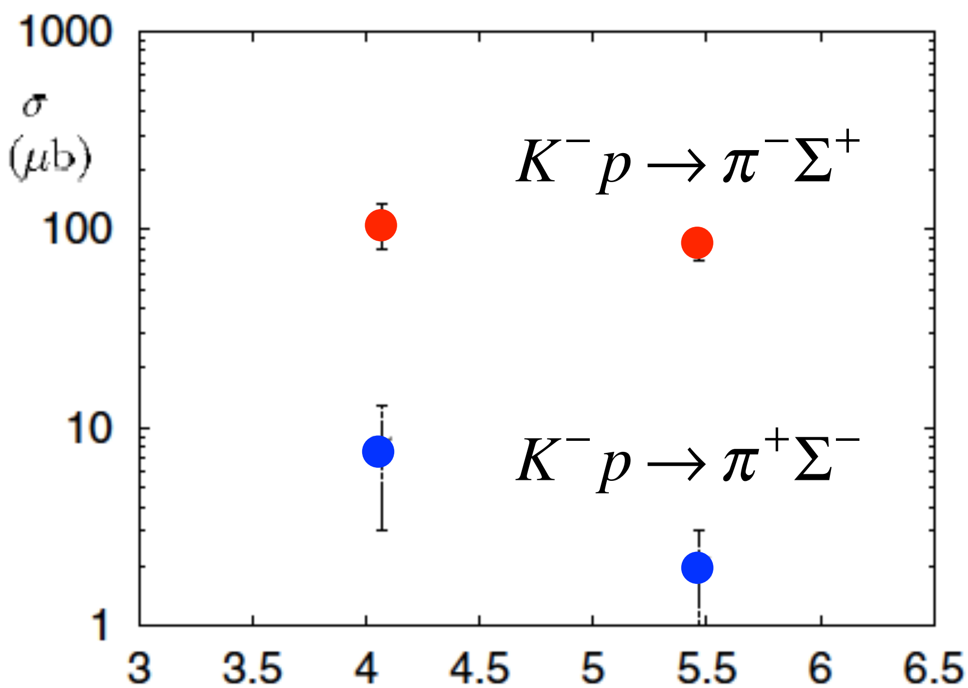
- Exotic Dbar-N (BN) baryons (and more) were predicted
  There is no kaonic analogue
- Λ_c baryons show cleaner λ/ϱ excitations than Σ_c
  Diquarks may be well studied in Λ_c baryons
- Production rates were studied in Regge methods
  with V, PS and S exchanges, forward peak
  Charm/strangeness $\sim 10^{-2} - 10^{-4}$
- Diquark model is used for various productions
  Production of excited states are not suppressed
  Diquark correlation in *N* enhances Λ productions

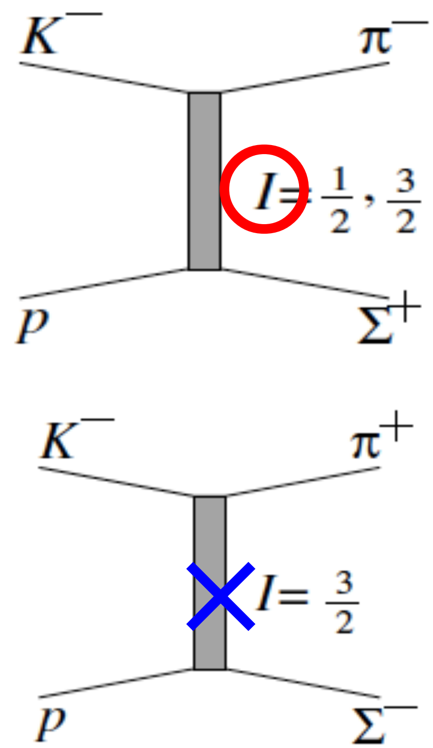
Spectrum

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



Regge's mechanism -- Brief idea --





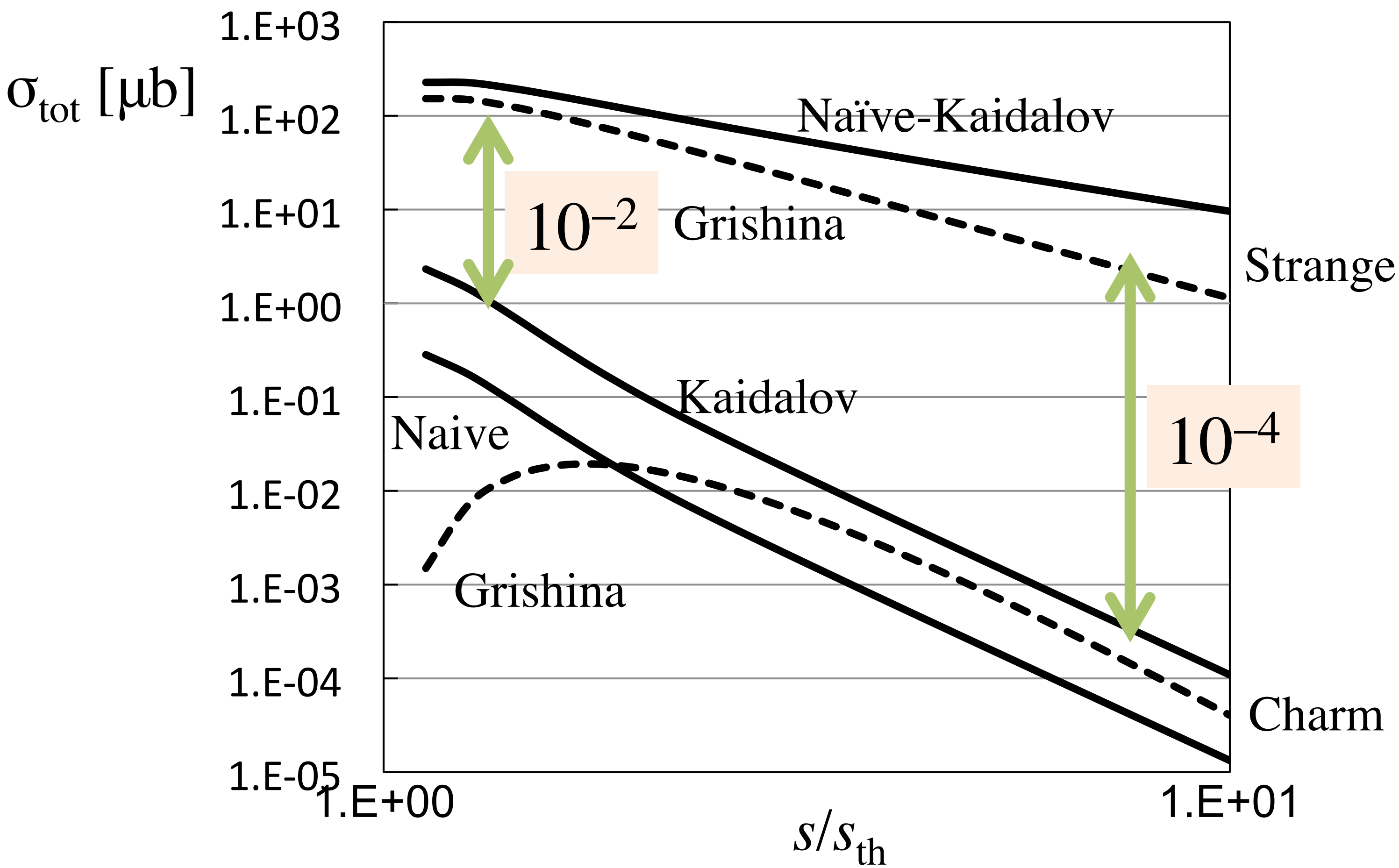
t-channel

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

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

*V*ector 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

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

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

Charm $k_\pi = 2.71$ [GeV]

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

Results

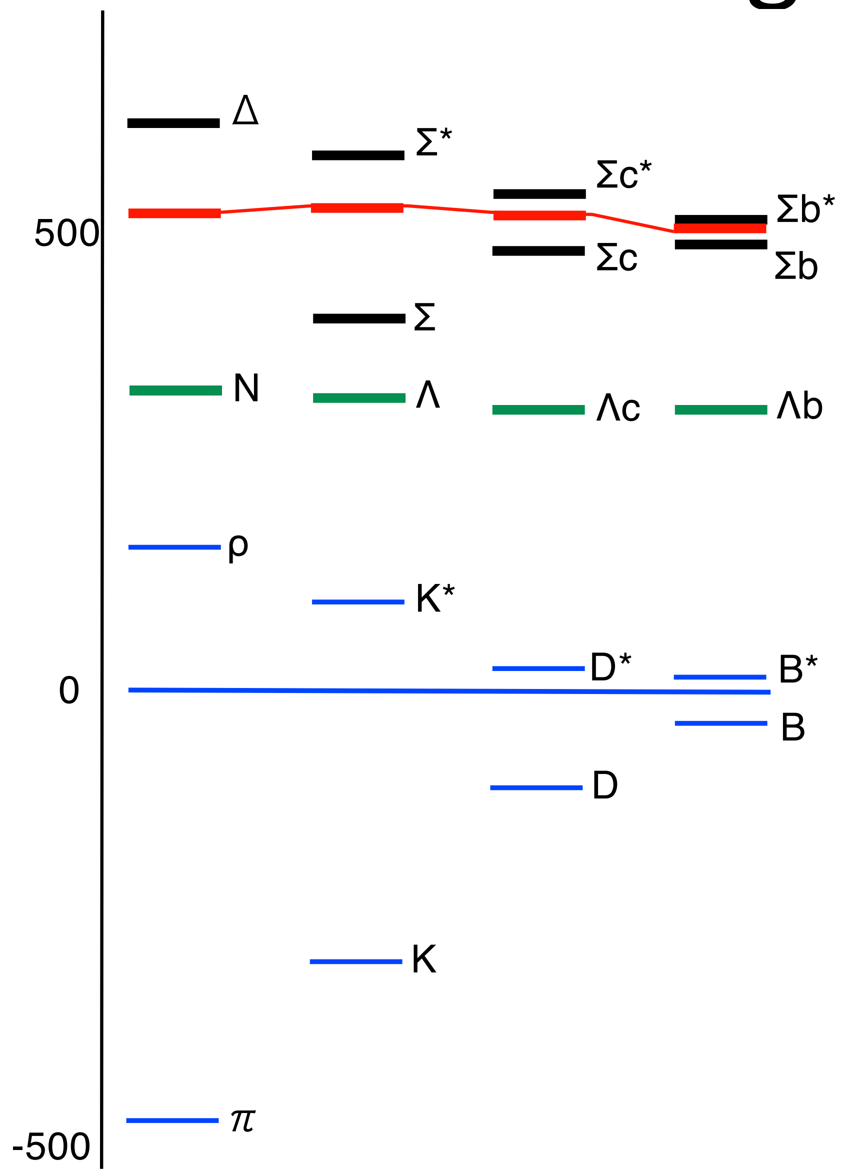
Charm $k_\pi = 2.71$ [GeV]

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



bad diquark
with spin-spin
of (qq)-Q

addition of
one more q
with good qq

spin-spin
subtracted

(qq)-Q
S=1, 1/2

[qq]-Q
S=0, 1/2

q-qbar
S=1/2, 1/2

Diquark correlation

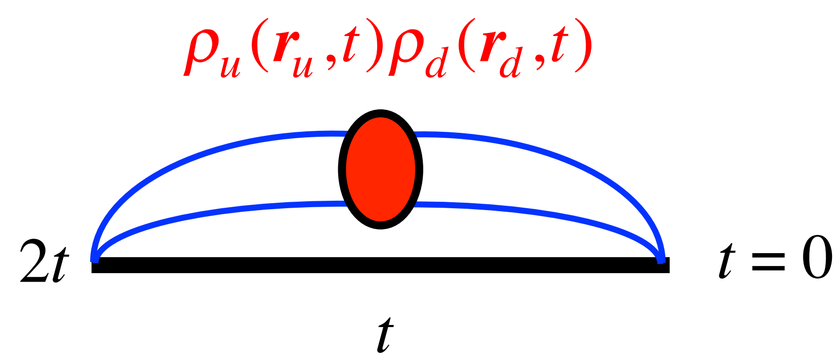
In QCD

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

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

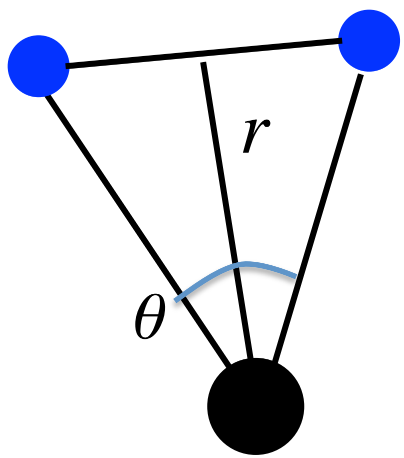
$$J_\Gamma(x) = \varepsilon^{abc} [u_a^T(x) C\Gamma d_b(x) \pm d_a^T(x) C\Gamma u_b(x)] s_c(x)$$

ud-diquark Static heavy quark

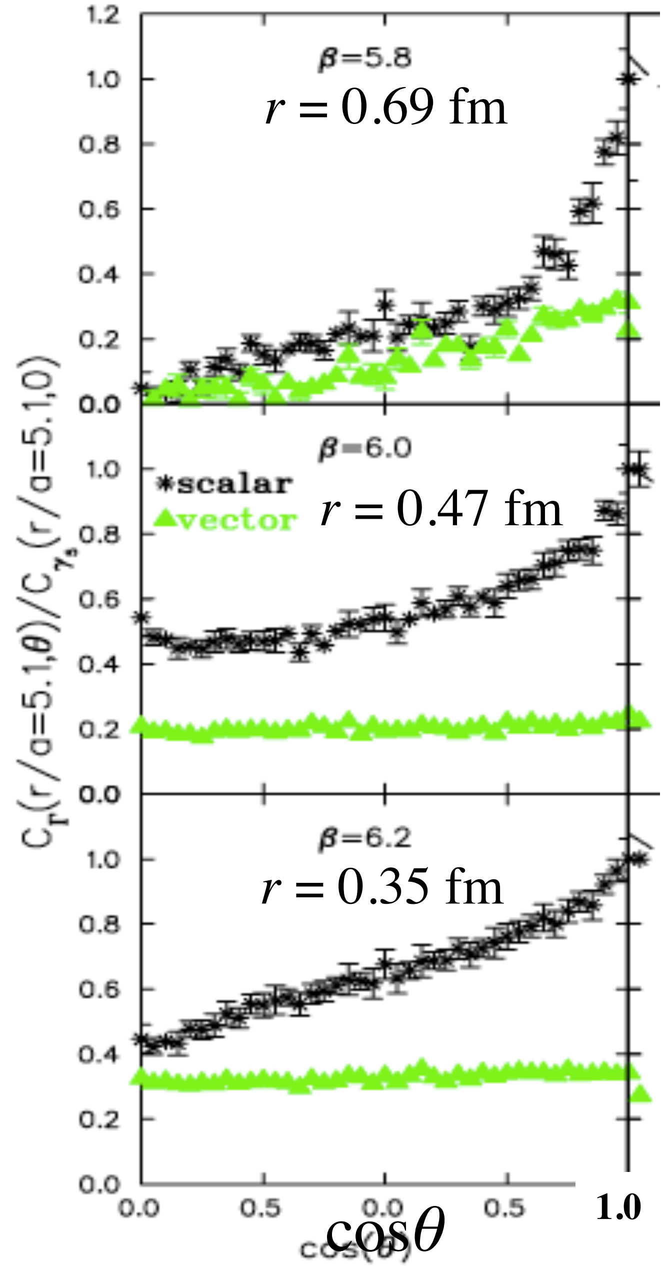


Density correlations

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



Good diquark
Bad diquark



Indicates significant attraction
between quarks in good diquark pair

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