Lambda baryons from lattice QCD - from strange to charm -

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Our target is Λ

Negative parity Λ (1405)

- difficulty in mass reproduction in quark models
- possibility of meson-baryon (NK, πΣ) molecule
- NK strong attraction
- Has been problematic in Lattice QCD analyses
- Recently Λ(1405) was identified in lattice QCD calculation
  PRL 108, 112001 (2012)

Lattice QCD

Spin-orbit partner of Λ

- Properties of spin 3/2 Λ, which is the Λ(1405)'s partner

Λ(1405)'s structures

- Flavor structures
  Internal wavefunctions

Λc's properties

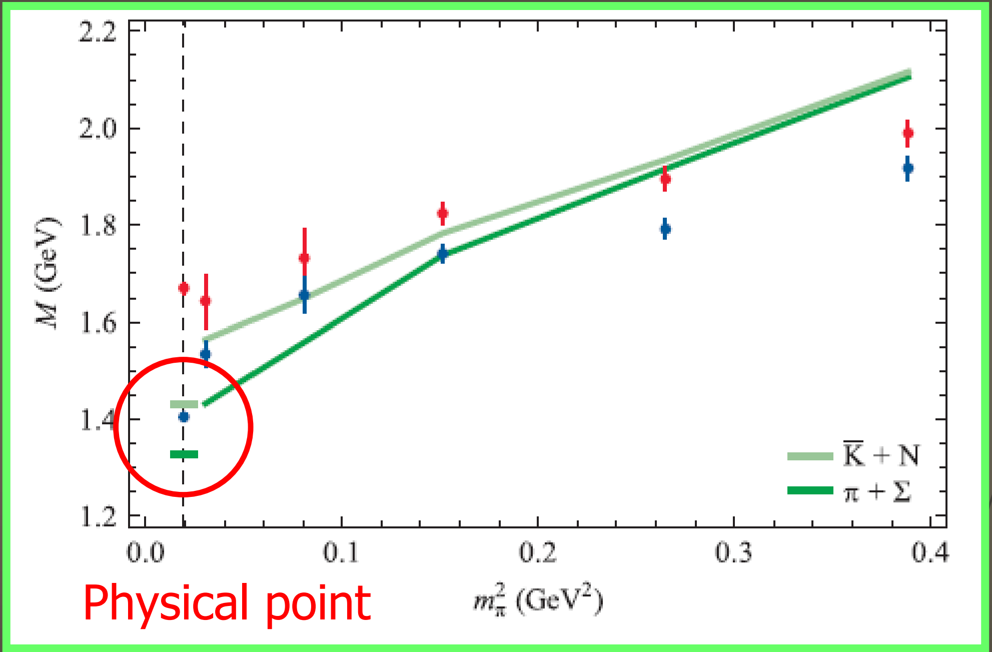
- properties of Λc, where the strange is replaced with the charm
- What does the HQ symmetry cause?

Recent lattice QCD study

Recent Lattice study of Λ

Isolating the Λ(1405) in Lattice QCD,
Adelaide group ; PRL 108, 112001 (2012)

2+1 conf. by PACS-CS
Pion mass → 156∼702 MeV



Brief summary

- Correlation matrix analyses with many types of interpolating fields
- lowest state lies between KN, πΣ thresholds
  → Same order as the real world
  → Claim to have identified Λ(1405) signal

Still too heavy

- Adjusted the valence s-quark mass so as to correctly reproduce the K-meson mass (partially quenching)

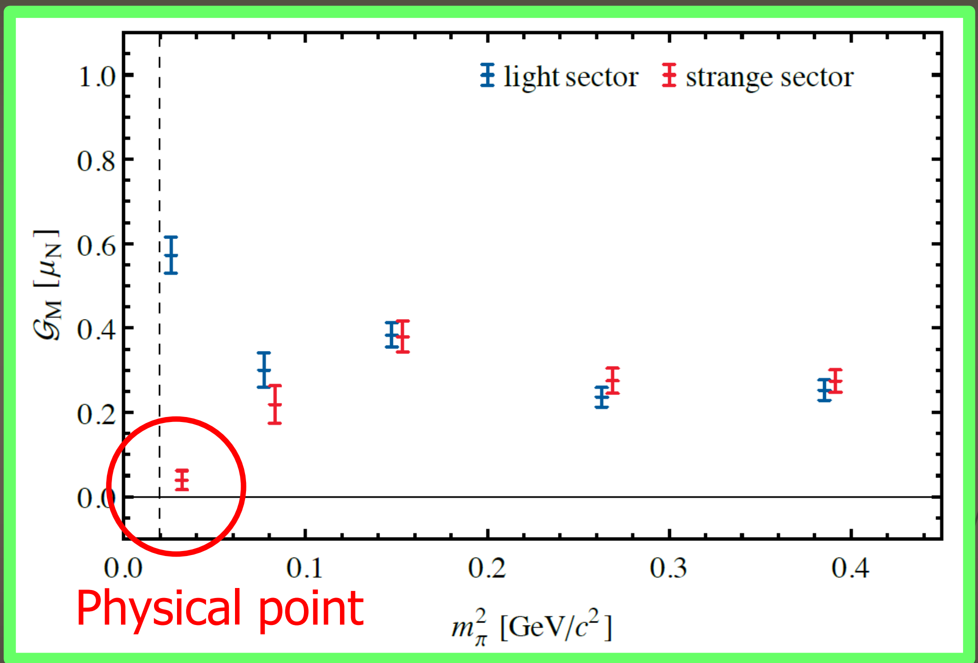
Gets experimental value

- lowest → singlet dominant
  2^{nd} lowest → octet dominant

Recent Lattice study of Λ

Lattice QCD Evidence that the Λ(1405) Resonance is an Antikaon-Nucleon Molecule
Adelaide group ; Phys.Rev.Lett. 114 (2015) 13, 132002

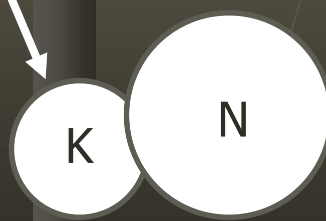
2+1 conf. by PACS-CS
Pion mass → 156～702 MeV



Electromagnetic properties

- Strange-quark magnetic moments in Λ(1405) vanishes.

  → The strange quark is confined in the spin-0 Kaon in Λ(1405)



There are several issues to be clarified,
but the signal can be the Λ(1405).

Why Λ_c ?

Our target is Λ

Replace S with C

udS – Λ → udC – Λ

$m_u = m_d < m_s$

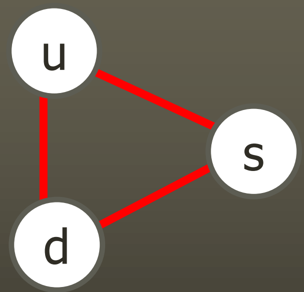
SU(3)F symmetry

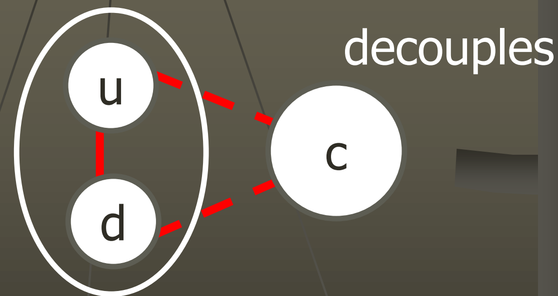
$m_u = m_d \ll m_c$

Heavy quark spin symmetry appears
- Spin-spin interactions become weak
- Heavy quark spin decouples and is irrelevant

Largely broken SU(3)F symmetry
- Two excitation modes may decouple

Hadron spectra would be much simpler

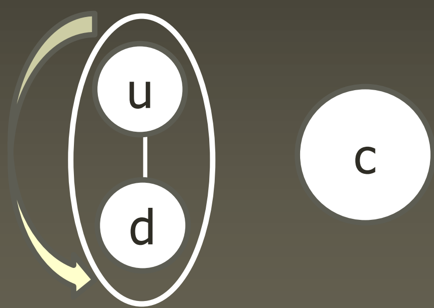




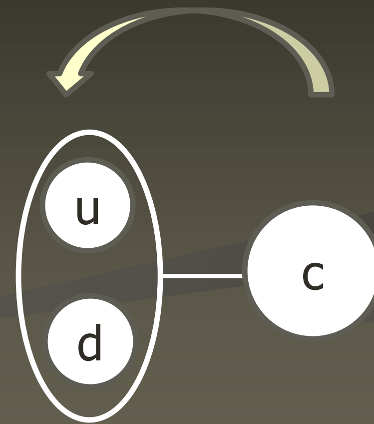
Manifestation of Diquark DOF ?

Diquarks

Two diquark motion (ρ and λ modes) may decouple in heavy baryons

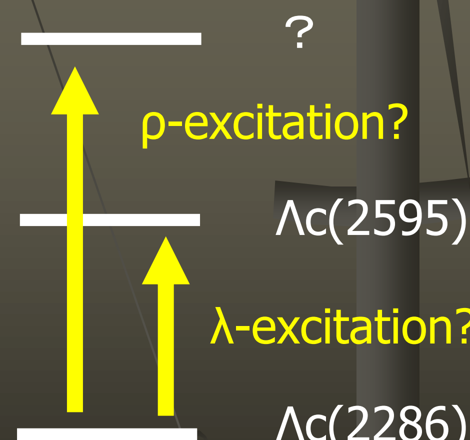


ρ-mode excitation
Diquark's relative motion



λ-mode excitation
Diquark's CM motion

Then, excited Λc spectra can be simply explained in terms of diquarks (?)



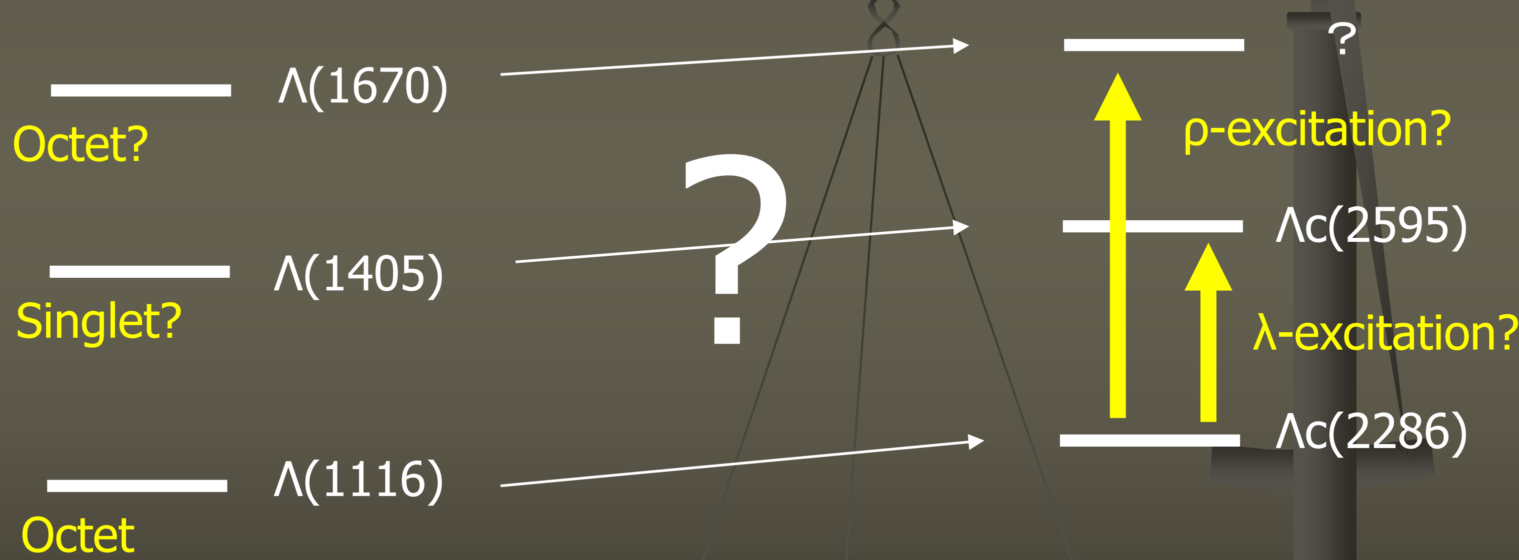
Diquarks

Replace S with C

udS – Λ → udC – Λ

$m_u = m_d < m_s$ | $m_u = m_d \ll m_c$

SU(3)F symmetry | HQ symmetry



Then, what is the relationship between uds-Λ and udc-Λ ?

→ Internal structure change
→ Manifestation of diquark's degrees of freedom

Strategies

Our strategy

We investigate masses and flavor structures of udQ-Λ baryons

Q-quark mass

Real world	Virtual world	Real world
Q=Strange quark(～100MeV)	⟷	Q=Charm quark(～1.3GeV)
uds-Λ		udc-Λ

Interpolation using lattice QCD
by changing Q-quark mass

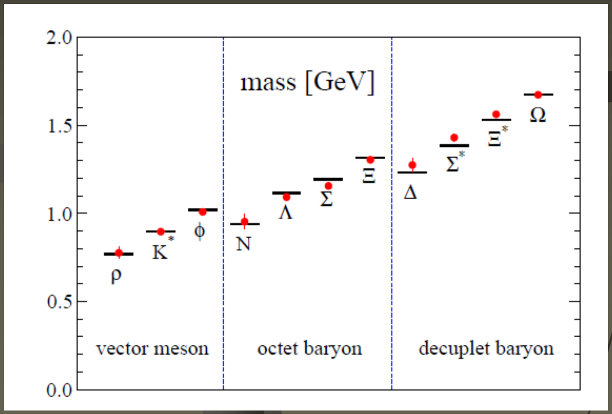
We investigate the Q-dependences of
(1) Λ mass spectra
(2) Internal flavor structures

Our strategy

-- Lattice QCD setups --

2+1 gauge configuration by PACS-CS
Iwasaki gauge action, Wilson quark action
32^3 x 64, a~0.1 fm, cut off ~2.2GeV

→ Well reproduces light hadron mass spectra



We do not employ Relativistic Heavy Quark actions

→ cut off of 2.2 GeV may be insufficient for mQ > 1GeV
→ not good, but use a common quark action for u, d, Q quarks
in order to see the internal structure changes

Our strategy

-- Hadronic operators --

We employ operators classfied in terms of Cubic group irreducible rep.
→4x4 corrlation matrix (We can extract ground～3rd excited states.)

u, d, Q quark operator sizes are the same.
→ Operator mixing vanishes in the flavor-SU(3) limit (mu=md=mQ)
→ Easy to see the flavor structures of Λ particles

PRD72 (2005) 074501
LHPC group

Operator examples

TABLE VIII: Quasi-local Λ baryon operators.

$\overline{\Psi}^{\Lambda,k}_{S,S_z}$	$\overline{\Lambda}_{\mu_1\mu_2\mu_3}$	$\overline{\Psi}^{\Lambda,k}_{S,S_z}$	$\overline{\Lambda}_{\mu_1\mu_2\mu_3}$
$\overline{\Psi}^{G_{1g},1}_{\frac{1}{2},\frac{1}{2}}$	$\overline{\Lambda}_{121}$	$\overline{\Psi}^{G_{1u},1}_{\frac{1}{2},\frac{1}{2}}$	$\overline{\Lambda}_{123}+\overline{\Lambda}_{141}+\overline{\Lambda}_{321}$
$\overline{\Psi}^{G_{1g},1}_{\frac{1}{2},-\frac{1}{2}}$	$\overline{\Lambda}_{122}$	$\overline{\Psi}^{G_{1u},1}_{\frac{1}{2},-\frac{1}{2}}$	$\overline{\Lambda}_{124}+\overline{\Lambda}_{142}+\overline{\Lambda}_{322}$
$\overline{\Psi}^{G_{1g},2}_{\frac{1}{2},\frac{1}{2}}$	$\overline{\Lambda}_{143}+\overline{\Lambda}_{323}+\overline{\Lambda}_{341}$	$\overline{\Psi}^{G_{1u},1}_{\frac{1}{2},\frac{1}{2}}$	$\overline{\Lambda}_{343}$
$\overline{\Psi}^{G_{1g},2}_{\frac{1}{2},-\frac{1}{2}}$	$\overline{\Lambda}_{144}+\overline{\Lambda}_{324}+\overline{\Lambda}_{342}$	$\overline{\Psi}^{G_{1u},1}_{\frac{1}{2},-\frac{1}{2}}$	$\overline{\Lambda}_{344}$
$\overline{\Psi}^{G_{1g},3}_{\frac{1}{2},\frac{1}{2}}$	$\overline{\Lambda}_{134}+\overline{\Lambda}_{323}-\overline{\Lambda}_{341}$	$\overline{\Psi}^{G_{1u},1}_{\frac{1}{2},\frac{1}{2}}$	$-\overline{\Lambda}_{141}-\overline{\Lambda}_{312}+\overline{\Lambda}_{123}$
$\overline{\Psi}^{G_{1g},3}_{\frac{1}{2},-\frac{1}{2}}$	$\overline{\Lambda}_{144}+\overline{\Lambda}_{423}-\overline{\Lambda}_{342}$	$\overline{\Psi}^{G_{1u},1}_{\frac{1}{2},-\frac{1}{2}}$	$-\overline{\Lambda}_{322}-\overline{\Lambda}_{241}+\overline{\Lambda}_{124}$
$\overline{\Psi}^{G_{1g},4}_{\frac{1}{2},\frac{1}{2}}$	$\sqrt{\frac{2}{3}}(\overline{\Lambda}_{134}+\overline{\Lambda}_{341}+\overline{\Lambda}_{413})$	$\overline{\Psi}^{G_{1u},4}_{\frac{1}{2},\frac{1}{2}}$	$-\sqrt{\frac{2}{3}}(\overline{\Lambda}_{123}+\overline{\Lambda}_{231}+\overline{\Lambda}_{312})$
$\overline{\Psi}^{G_{1g},4}_{\frac{1}{2},-\frac{1}{2}}$	$\sqrt{\frac{2}{3}}(\overline{\Lambda}_{234}+\overline{\Lambda}_{342}+\overline{\Lambda}_{423})$	$\overline{\Psi}^{G_{1u},4}_{\frac{1}{2},-\frac{1}{2}}$	$-\sqrt{\frac{2}{3}}(\overline{\Lambda}_{124}+\overline{\Lambda}_{241}+\overline{\Lambda}_{412})$
$\overline{\Psi}^{H_g}_{\frac{3}{2},\frac{3}{2}}$	$\overline{\Lambda}_{133}$	$\overline{\Psi}^{H_u}_{\frac{3}{2},\frac{3}{2}}$	$\overline{\Lambda}_{131}$
$\overline{\Psi}^{H_g}_{\frac{3}{2},\frac{1}{2}}$	$\overline{\Lambda}_{134}+\overline{\Lambda}_{143}+\overline{\Lambda}_{233}$	$\overline{\Psi}^{H_u}_{\frac{3}{2},\frac{1}{2}}$	$\overline{\Lambda}_{132}+\overline{\Lambda}_{141}+\overline{\Lambda}_{231}$
$\overline{\Psi}^{H_g}_{\frac{3}{2},-\frac{1}{2}}$	$\overline{\Lambda}_{144}+\overline{\Lambda}_{234}+\overline{\Lambda}_{243}$	$\overline{\Psi}^{H_u}_{\frac{3}{2},-\frac{1}{2}}$	$\overline{\Lambda}_{142}+\overline{\Lambda}_{232}+\overline{\Lambda}_{241}$
$\overline{\Psi}^{H_g}_{\frac{3}{2},-\frac{3}{2}}$	$\overline{\Lambda}_{244}$	$\overline{\Psi}^{H_u}_{\frac{3}{2},-\frac{3}{2}}$	$\overline{\Lambda}_{242}$

- ½ octet (octet-1)
- ½ octet (octet-2)
- ½ octet (octet-3)
- ½ singlet
- 3/2 octet

Correlation matrix analyses

-- Mass and flavor structures --

2pt cross correlator QCD transfer matrix

$$\langle \Lambda^i(T)\Lambda^j(0)\rangle = \langle 0|\Lambda^i e^{-HT}\Lambda^j|0\rangle = \langle 0|\Lambda^i|k\rangle \exp(-E_k T)\langle k|\Lambda^j|0\rangle$$

i,j are operator indices

$$= c^T \Lambda(E_k) c$$

eigenvectors

eigenvalues

$$\Lambda(E_k) = diag(-E_1 T, -E_2 T, \ldots)$$

Eigenvalue of correlation matrix → mass of the state
Eigenvector of correlation matrix → operator overlaps with the state

$$\langle 0|\Lambda^i|target\ state\rangle$$

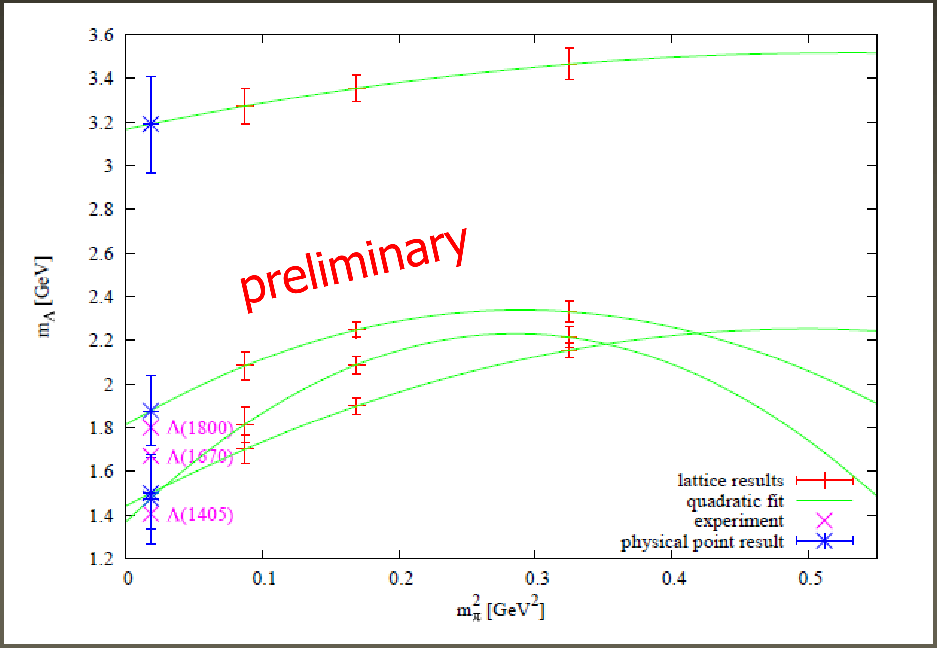
We can investigate internal structures.

Mass spectra

Mass spectra

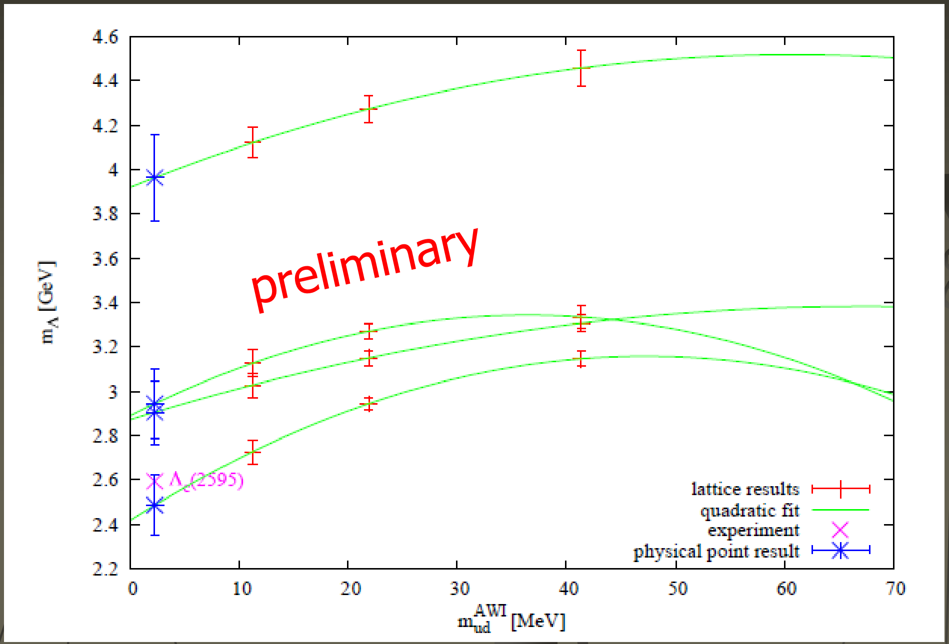
UDS

½ negative Λ channel



UDC

½ negative Λc channel



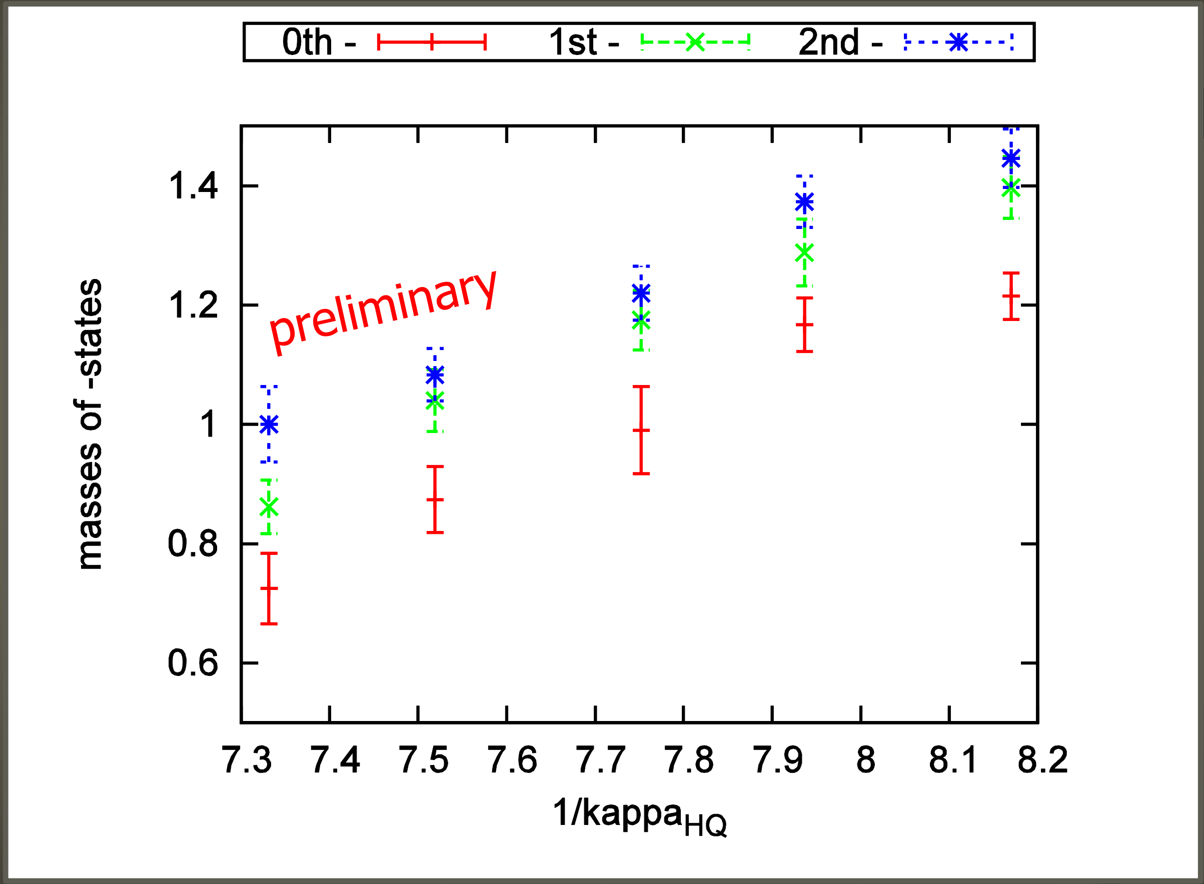
Spectra are similar in Λ and Λc channel

Still heavier than 1405 MeV
→ But very close

2nd state's behavior is a bit different from the Λs channel
→ Difference in internal structures

Mass spectra

Hadron mass dependences on Q-quark mass



Λ(1800)

Λ(1670)

Λ(1405)

Λc(∼2950)

Λc(∼2900)

Λc(2595)

UDS

Q-quark mass

UDC

Flavor structures

Flavor structures

We consider "flavor symmetry" for u , d , Q quarks.
(even if Q=charm, we classify states still in terms of SU(3))

Singlet component $C_s = \langle \Lambda | O_s | vac \rangle$

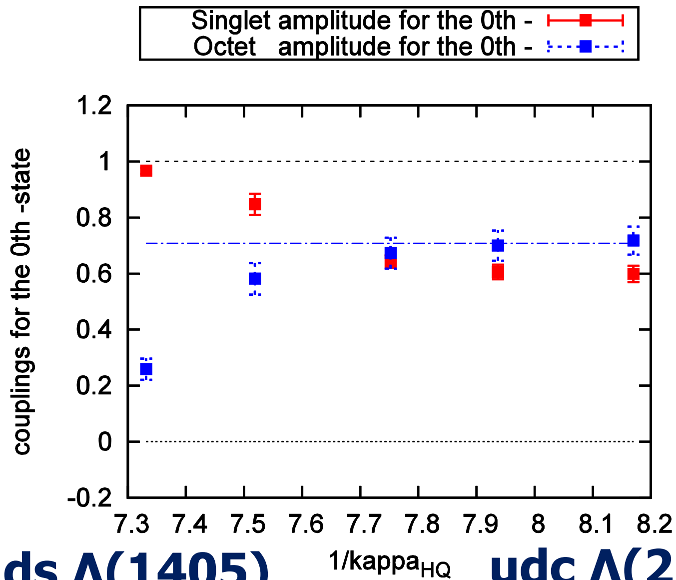
$$O_s = \frac{1}{\sqrt{3}}\left(u(dQ) + d(Qu) + Q(ud)\right)$$

Octet component $C_O = \langle \Lambda | O_o | vac \rangle$

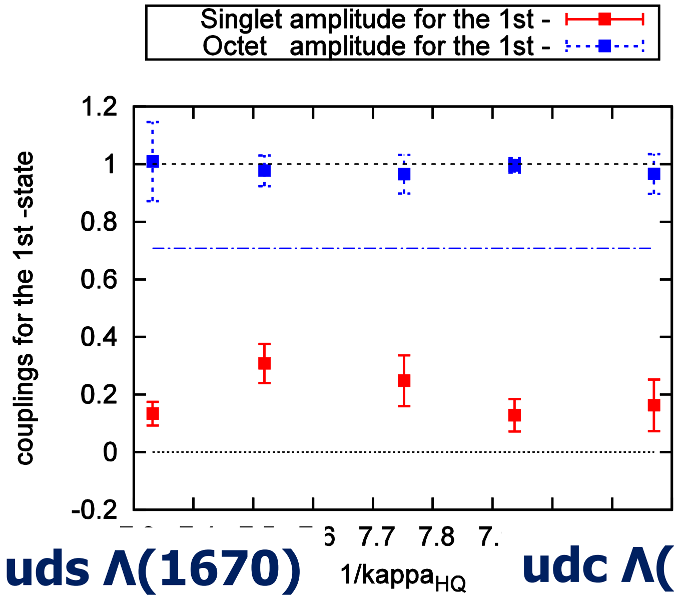
$$O_o = \frac{1}{\sqrt{6}}\left(u(dQ) + d(Qu) - 2Q(ud)\right)$$

Flavor structures

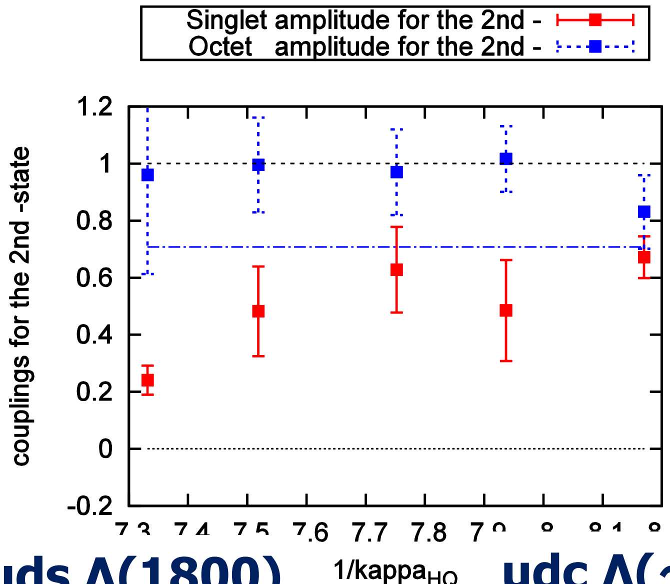
Lowest 3 states in ½- channel



uds Λ(1405) **udc Λ(2595)**



uds Λ(1670) **udc Λ(～2900)**

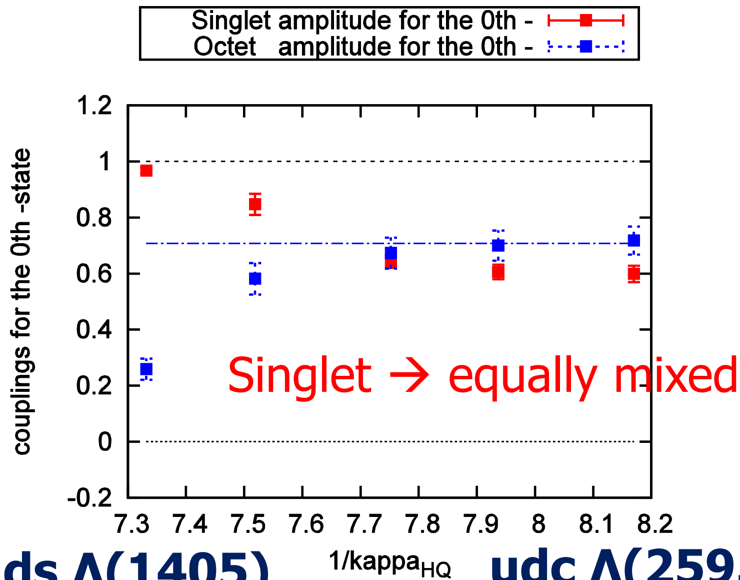


uds Λ(1800) **udc Λ(～2950)**

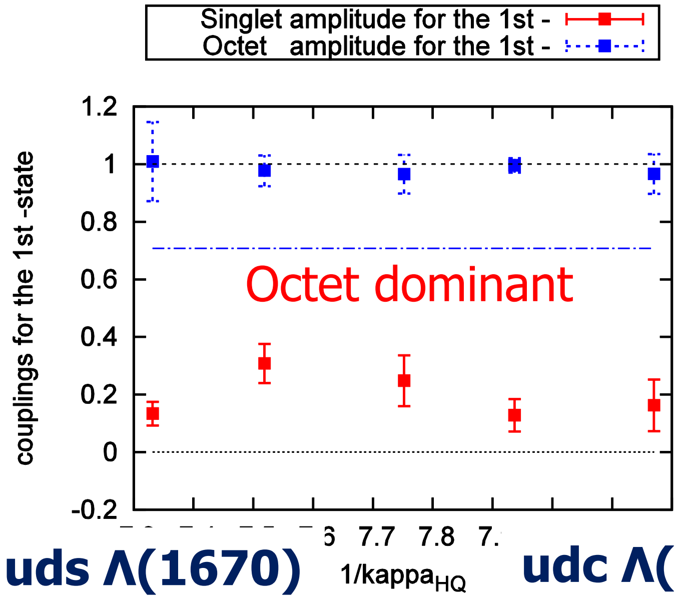
preliminary

Flavor structures

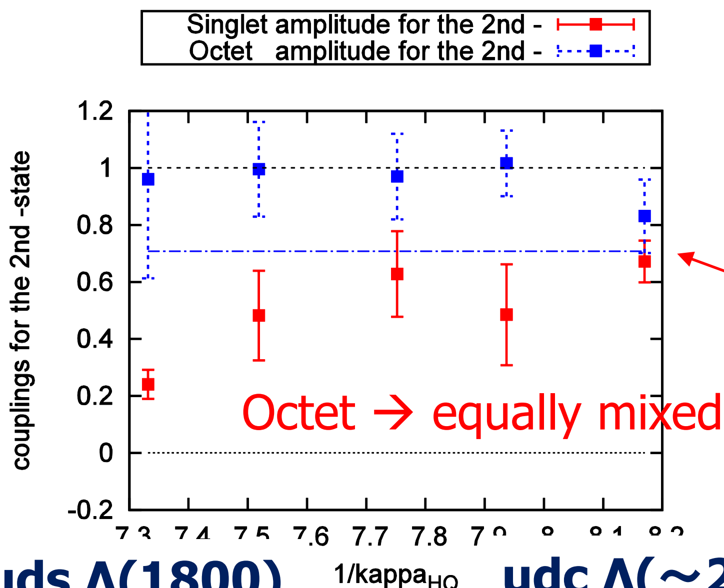
Lowest 3 states in ½- channel



uds Λ(1405) **udc Λ(2595)**



uds Λ(1670) **udc Λ(～2900)**



uds Λ(1800) **udc Λ(～2950)**

preliminary

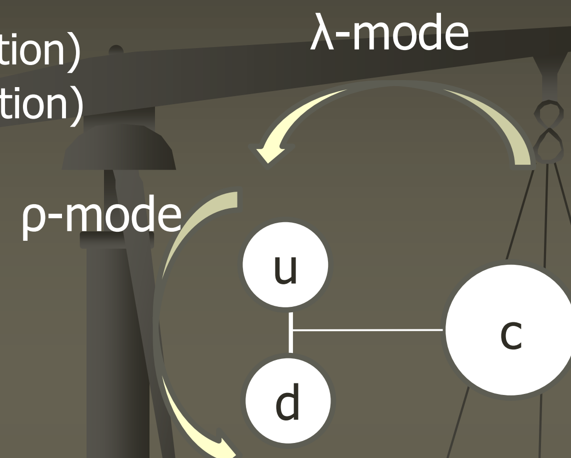
Amplitudes here are normalized
so that squared sum is 1.
The ratio $1/\sqrt{2}$: $1/\sqrt{2}$ implies 50:50 mixture

Flavor structures to Diquark picture

SU(3) wave functions can be expressed in terms of diquark wave functions

ORBITAL
- R_ρ → ρ mode (diquark p-wave excitation)
- R_λ → λ mode (diquark's CM p-wave excitation)

SPIN
- χ_ρ → Diquark has spin 1 (total 1/2)
- χ_λ → Diquark has spin 0 (total 1/2)
- χ_s → Diquark has spin 1 (total 3/2)



singlet $|\Lambda\,;1\,\rangle = \frac{1}{\sqrt{2}}(R_\lambda\chi_\rho - R_\rho\chi_\lambda)$ λ-mode – ρ-mode

octet $|\Lambda\,;8\,\rangle = \frac{1}{\sqrt{2}}(R_\lambda\chi_\rho + R_\rho\chi_\lambda)$ λ-mode + ρ-mode

octet $|\Lambda\,;8\,\rangle = \frac{1}{\sqrt{2}}(R_\rho\chi_s)$ ρ-mode

Flavor structures to Diquark picture

Spin ½ negative parity channel

Replace S with C

udS – Λ → udC – Λ

$m_u = m_d < m_s$

SU(3)F symmetry

$m_u = m_d \ll m_c$

Broken SU(3)F

Λ(1800)
Octet dominant → O:S=1:-1 → Λc(∼2950)
ρ-mode dominant

Λ(1670)
Octet dominant → O:S=1:0 → Λc(∼2900)
ρ-mode dominant (spin total 3/2)

Λ(1405)
Singlet dominant → O:S=1:1 → Λc(2595)
λ-mode dominant

Diquark DOF seem to appear around mQ∼700MeV

Flavor structures to Diquark picture

Spin ½ negative parity channel

Replace S with C

udS – Λ

udC – Λ

$m_u = m_d < m_s$

SU(3)F symmetry

$m_u = m_d \ll m_c$

Broken SU(3)F

Possibility of level crossing (or misidentification?)

Λ(1800)
Octet dominant

O:S=1:-1

Λc(∼2950)
ρ-mode dominant

Λ(1670)
Octet dominant

O:S=1:0

Λc(∼2900)
ρ-mode dominant (spin total 3/2)

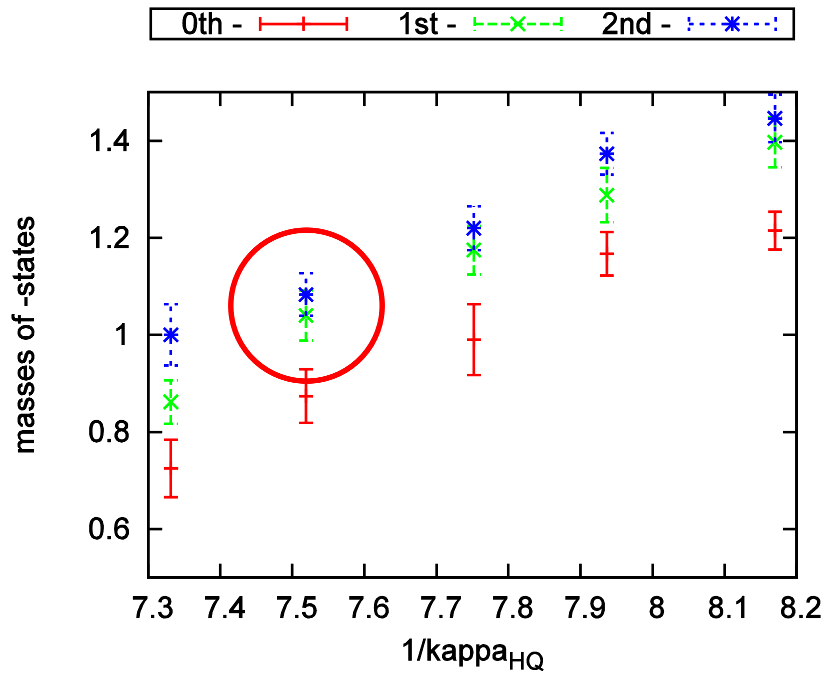
Λ(1405)
Singlet dominant

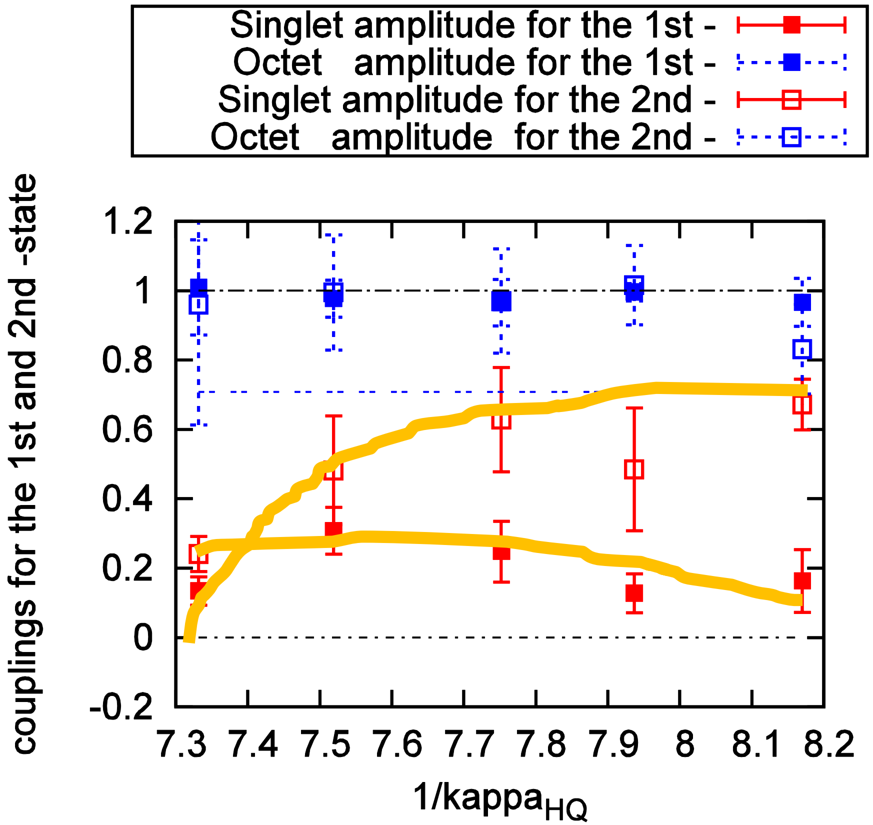
O:S=1:1

Λc(2595)
λ-mode dominant

Flavor structures to Diquark picture

Level crossing occurs ?





Summary

We investigated the flavor structure of the low-lying Λ's in lattice QCD.

Mass

The mass spectra of Λc and Λs are similar
though their flavor structures are completely different

Flavor structure

Ground state : (UDS) singlet dominant state → (UDC) λ-mode excitation

Excited state : (UDS) octet dominant state → (UDC) ρ- and λ-mode excitations

Well classified in terms of diquark excitations
above (current) mQ > 700 MeV

Future work?

Other channels?
More sophisticated analysis on the internal structures of Λ baryons