Λ(1405) and Negative-Parity Baryons in Lattice QCD

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The Λ(1405) Particle

- **Mass: ~1406.5 MeV Width: ~50 MeV**
  I=0, J=1/2, Negative-parity

  discovered by 1961 (Alston et al. PRL6,698)

- **Lightest negative-parity baryon**
  although it has a s-quark.

  (c.f. N(1535))

Ordinary 3-quark state?

Meson-baryon composite state?

3-quark state picture of Λ(1405)

- **Quark Model**

  spin-flavor SU(6) 70-plet rep. $(L = 1^-)$

SU(3)	J	S=0	S=-1,I=0	S=-1,I=1	S=-2	S=-3
8(2)	1/2	N(1535)	Λ(1670)	Σ(1620)	Ξ(?)	
	3/2	N(1520)	Λ(1690)	Σ(1670)	Ξ(1820)	
8(4)	1/2	N(1650)	Λ(1800)	Σ(1750)	Ξ(?)	
	3/2	N(1700)	Λ(?)	Σ(?)	Ξ(?)	
	5/2	N(1675)	Λ(1830)	Σ(1775)	Ξ(?)	
10(2)	1/2	Δ(1620)		Σ(?)	Ξ(?)	Ω(?)
	3/2	Δ(1700)		Σ(?)	Ξ(?)	Ω(?)
1(2)	1/2		Λ(1405)			
	3/2		Λ(1520)			

From Reviews of Particle Data

3-quark state picture of Λ(1405)

- **Quark Model**

  Λ(1405): flavor-singlet $J^P = \frac{1}{2}^-$

  Prediction: ~1.5 GeV

almost degenerate with Λ(1520), $J^P = \frac{3}{2}^-$

Isgur and Karl,PRD18,4187(1978)

“LS Puzzle”

Λ(1520) - Λ(1405) splitting needs a large LS force.

However, other states have very small LS contribution.

(c.f. N(1535)-N(1520), Λ(1670)–Λ(1690))

Naïve quark model fails to reproduce Λ(1405).

Meson-Baryon Composite Picture

$\Lambda(1405)$ is just below the $\overline{K}N$ threshold (~1440 MeV) and clearly seen in $K^- p \to \Sigma\pi$ reactions.

⇒ $\overline{K}N$ **bound state?**

(or $\pi\Sigma$ resonance state?)

5-quark state rather than a 3-quark state?

If so, where is the missing flavor-singlet 3-quark state? Is it a mixed state between two pictures?

⇓

No definite conclusion

Recent Work

- 3-quark picture

1/Nc approach Schat,Goity,Scoccola, PRL88,100202(2002)

States: Constituent quark picture

Nc-1 “core” quarks in the ground state and an (l=1) excited quark

Operators: pick up all possible ops up to 1/Nc

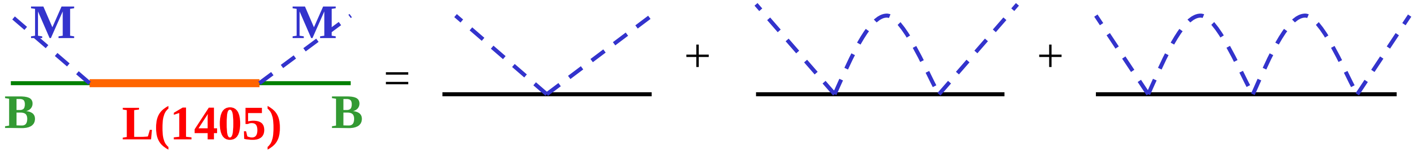
Ex: $S^C \cdot S^C$ term Core quark spin-spin int.

This does not affect the singlet Λ.

It resolves Λ(1405)-Λ(1520) splitting and concludes they are LS partners of the flavor-singlet.

- Meson-baryon composite picture

chiral dynamics Lutz’s talk, Hyodo’s talk



chiral unitary approach Osaka, Valencia group

Two resonances around 1.4 GeV.

Lower pole strongly couples to $\pi\Sigma$ channels.

Flavor-singlet

Higher pole strongly couples to $\bar{K}N$ channels.

Flavor-octet, isosinglet

Λ(1405) is a superposition of these two resonances.

What's interesting?

If Λ(1405) is 5-quark (like $\bar{K}N$) dominant, …

- **Λ(1405) in nuclear medium**

Pauli blocking effect of the prorton in the Λ(1405) changes K^-p scattering amplitudes.

$$\Longrightarrow \left\{ \begin{array}{l} \textbf{Mass shift of } \Lambda(1405) \\ \textbf{Change of the } K^- \textbf{ potential} \end{array} \right.$$

Kaon condensation, such as, in neutron stars

K^- nuclear bound states

Akaishi's talk, Yamazaki's talk, Dote's talk

It is important to identify the quark content in astrophysics and hyper-nuclear physics, too.

Λ(1405) in Lattice QCD

- 3 or 5?

  All the calculations are based on the 3-quark picture.
  5-quark evaluation has not been done yet.

Recent work based on the 3-quark picture (quenched calc.)

- **Y.N, N.Nakajima, H.Matsufuru, H.Suganuma**
  PRD68, 094505 (2003) (Our result)

- **W.Melnitchouk, S.Bilson-Thompson, F.D.R.Bonnet, J.N.Hedditch, F.X.Lee, D.B.Leinweber, A.G.Williams, J.M.Zanoti, J.B.Zhang (Australia group)**
  PRD67, 114506 (2003)

- **F.X.Lee, S.J.Dong, T.Draper, I.Horvath, K.F.Liu, N.Mathur, J.B.Dong (Kentucky group)**
  NP(Proc.Suppl.)119, 296(2003) (proc. of Lattice2002)

Basics of Lattice QCD

Evaluate path integral for QCD using important sampling

$$\int [dU][d\psi][d\bar{\psi}]\exp\left\{\sum[-\beta S_g + \bar{\psi}(\not{D}+m)\psi]\right\} = \int [dU]\det(\not{D}+m)\exp\left\{\sum(-\beta S_g)\right\}$$

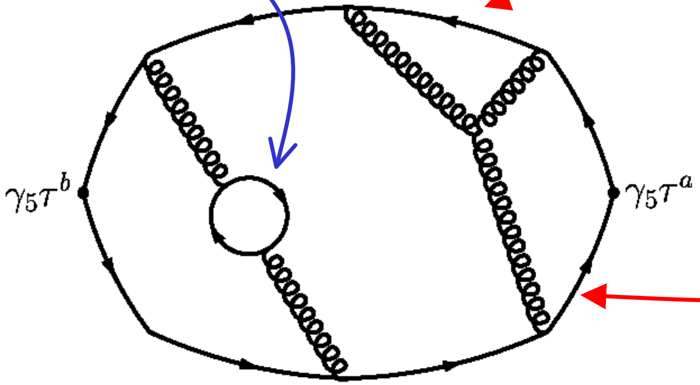
2-point pion correlation function (Baryons are similar.)

$$\left\langle (\bar{\psi}\gamma_5\tau^a\psi)_x (\bar{\psi}\gamma_5\tau^b\psi)_y \right\rangle$$

$$= \frac{1}{Z}\int [dU]\det(\not{D}+\underline{m})\exp\left\{\sum(-\beta S_g)\right\}\mathrm{Tr}[\gamma_5\tau^a(\not{D}+\underline{m})^{-1}_{x,y}\gamma_5\tau^b(\not{D}+\underline{m})^{-1}_{y,x}]$$

sea

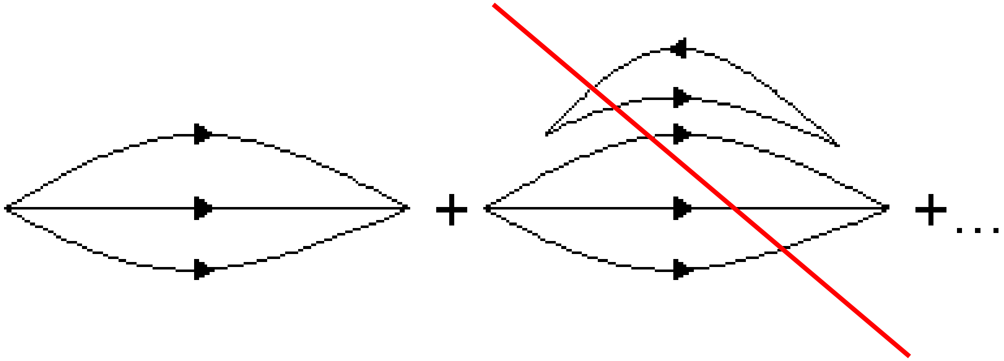
valence



Leaving out $\det(\not{D}+m)$ is quenching.

Quenching effects

- **No sea quark**



The quench QCD is more "valence-like" than full QCD.

⇓

It is more suitable to study whether Λ(1405) is 3-q dominant or 5-q dominant than full QCD.

Λ(1405) currents

- **flavor-singlet operator**

$$(uC\gamma_5 d)s + (dC\gamma_5 s)u + (sC\gamma_5 u)d$$

C : charge conjugate matrix

c.f. nucleon operators (proton)

$(uC\gamma_5 d)u$ **and** $(uCd)\gamma_5 u$ **2 linear independent ops.**

- **“common” operator (Australia group)**

$$\begin{array}{rl} \text{octet:} & -2(uC\gamma_5 d)s + \\ \text{singlet:} & (uC\gamma_5 d)s + \end{array} \boxed{\begin{array}{l} (dC\gamma_5 s)u + (sC\gamma_5 u)d \\ (dC\gamma_5 s)u + (sC\gamma_5 u)d \end{array}}$$

common: $(dC\gamma_5 s)u + (sC\gamma_5 u)d$

- **flavor-octet operator (Kentucky group)**

$$-2(uC\gamma_5 d)s + (dC\gamma_5 s)u + (sC\gamma_5 u)d$$

Negative-parity baryon masses

Spectrum of excited state baryons is, in general, hard to compute. It is (much) noisier than the ground state ones.

BUT

Lowest-lying negative parity baryons are exceptional.

Baryon currents couple to both the positive- and negative-parity states.

→ m_{B^-} **can be obtained by a simple exp. fitting after parity projection.**

$$\langle J_B \overline{J_B} \rangle \sim C \exp(-m_{B^-} t)$$

after zero-mom. and parity projections.

No need to do 2-pole mass fitting, constrained curve fitting, MEM, or etc.

Lattice parameters and results

- Anisotropic lattice $20^3 \times 160(\beta = 6.10, a^{-1} = 1.871(14)\mathrm{GeV})$ set by m_{K*}

  Anisotropy: $a_s / a_t = 4$

  $V \sim (2.1\mathrm{fm})^3$
- Wilson gauge action (quench)

  Number of configs.:400
- O(a) improved Wilson (clover) quark action

  4 kinds of quark masses

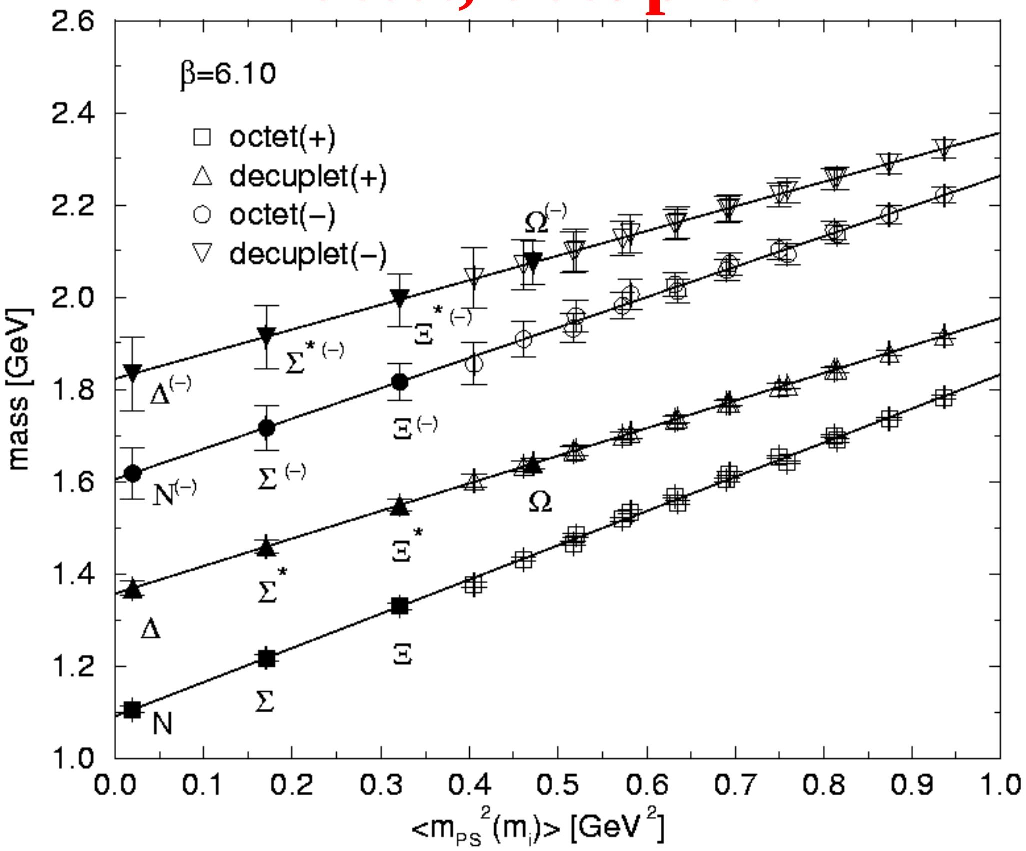
  $m_\pi = 630 \sim 940$ MeV

  smeared source, point sink
- linear chiral extrapolation

  $m_{u,d}$:set by m_π

  m_s :set by m_K

octet, decuplet



PRD68,094505(2003)

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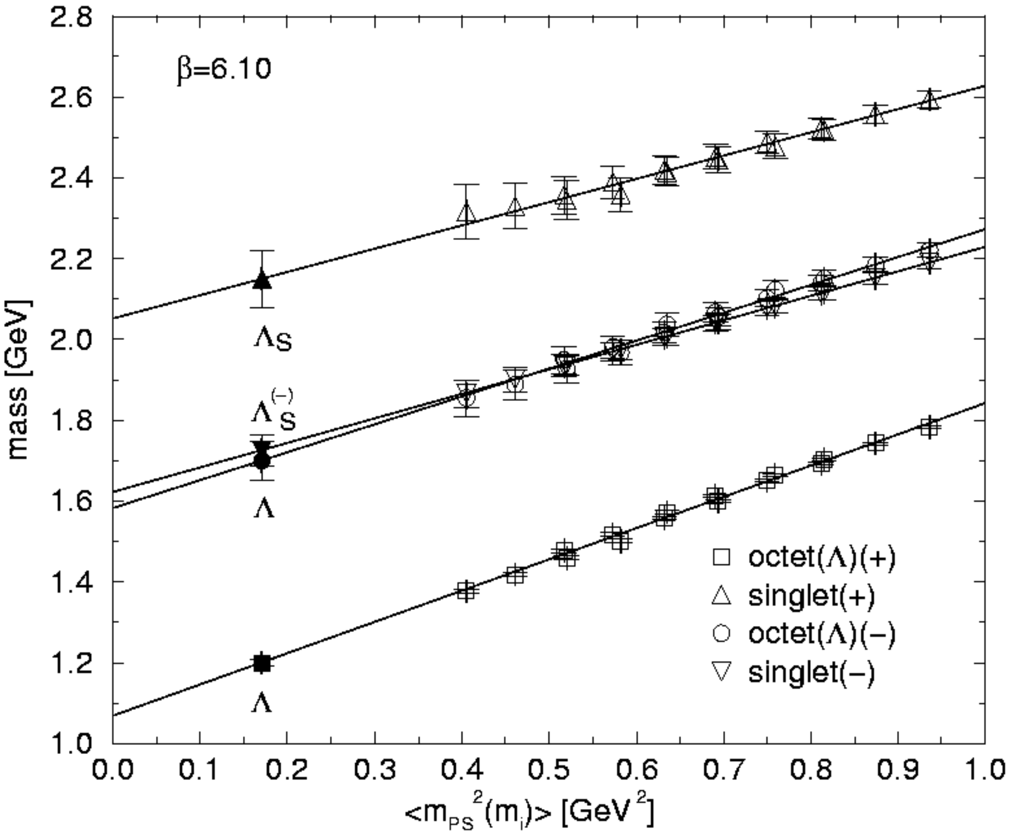
octet Λ, singlet



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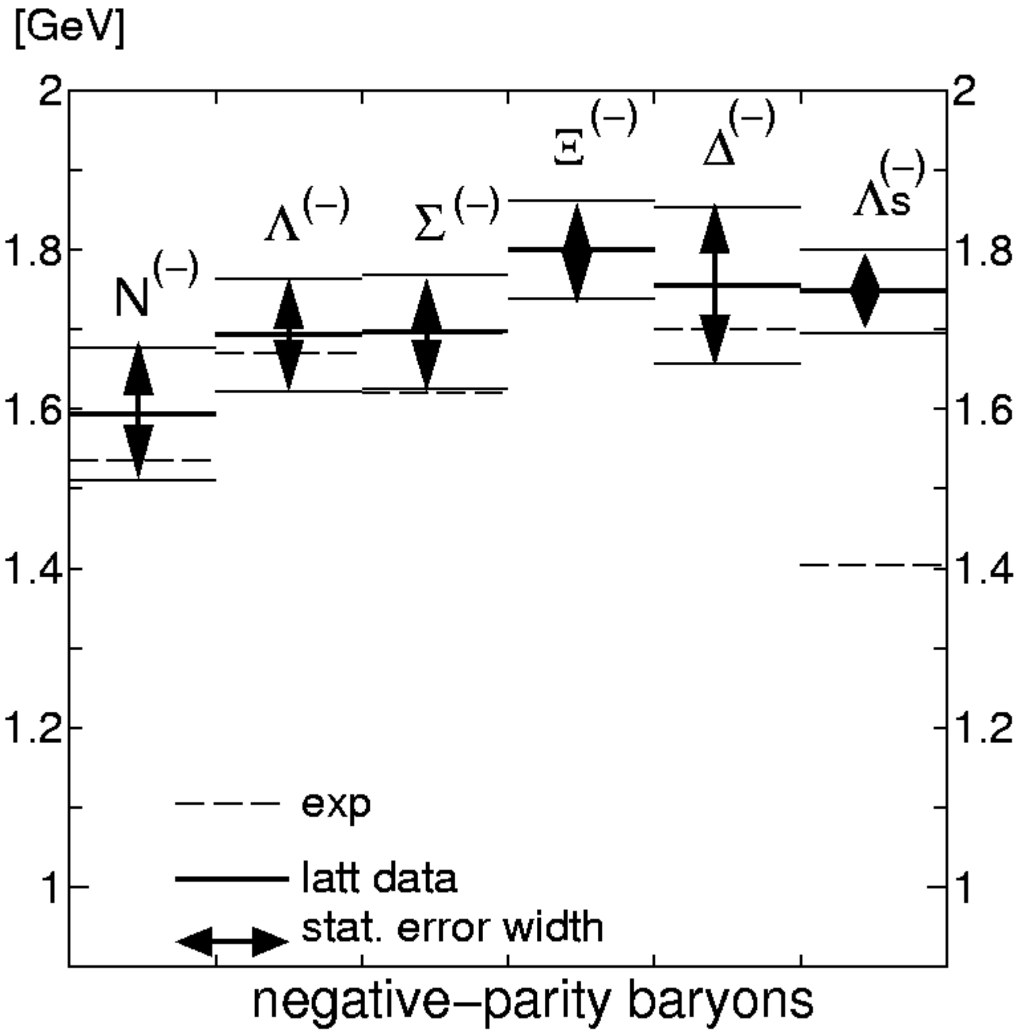


PRD68,094505(2003)

Lattice parameters and results

Australia group

Isotropic lattice (quench):

$16^3 \times 32 (a^{-1} \sim 1.6\ \text{GeV})$

$V \sim (1.9\text{fm})^3$

$O(a^2)$ improved Wilson gauge ac.

400 configs.

$O(a)$ improved Wilson quark ac.

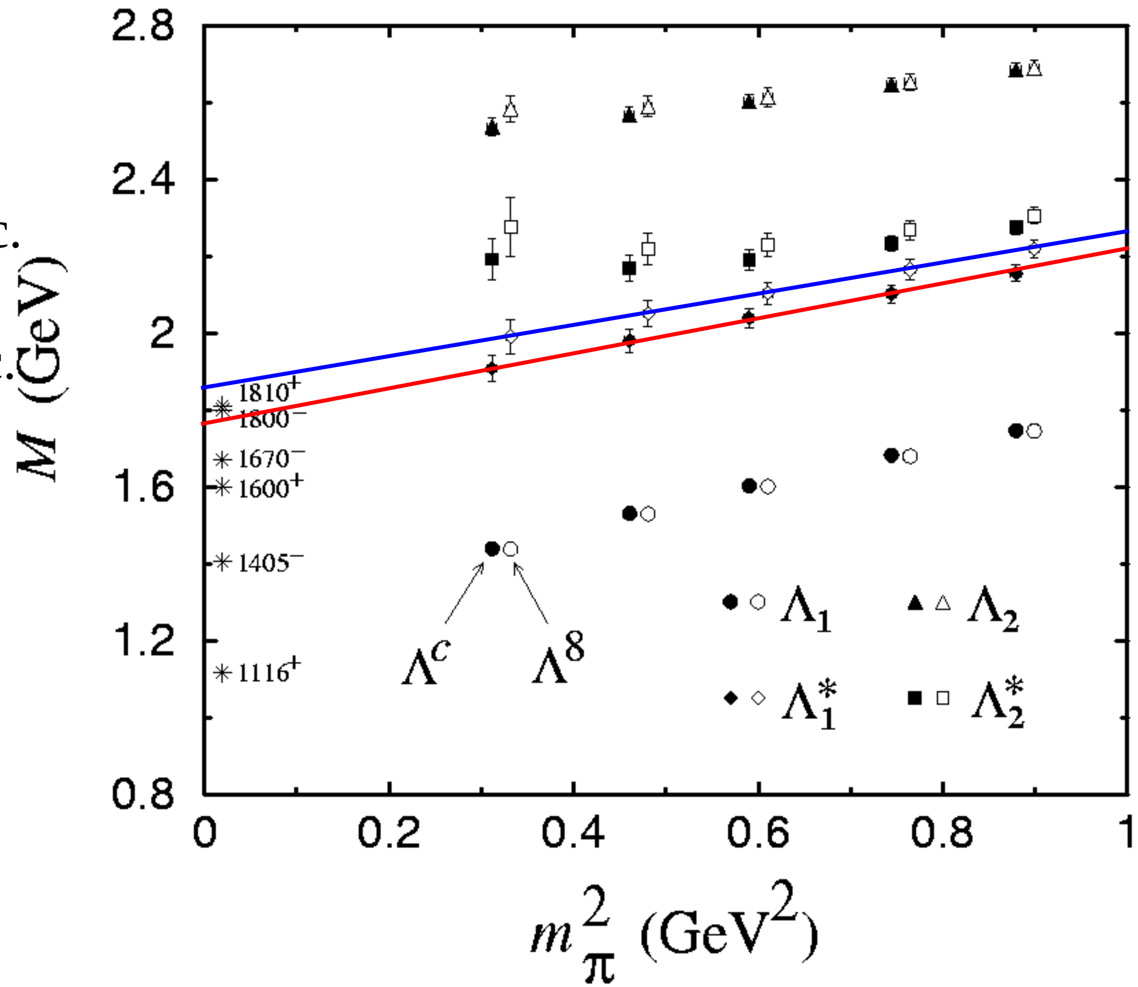
FLIC action

5 quark masses

$m_\pi \approx 550 \sim 950$ MeV

smeared source

point sink



Λ^8 : octet lambda

Λ^C : common

* : negative-parity

PRD67,114506(2003)

Lattice parameters and results

Kentucky group

octet Λ masses

$16^3 \times 28(a^{-1} \sim 1\text{GeV})$ quench

$V \sim (3.2\text{fm})^3$

80 configs.

overlap fermions

$m_\pi \geq 180\text{MeV}$

constrained curve fitting

ground and 1st excited

states for both parities

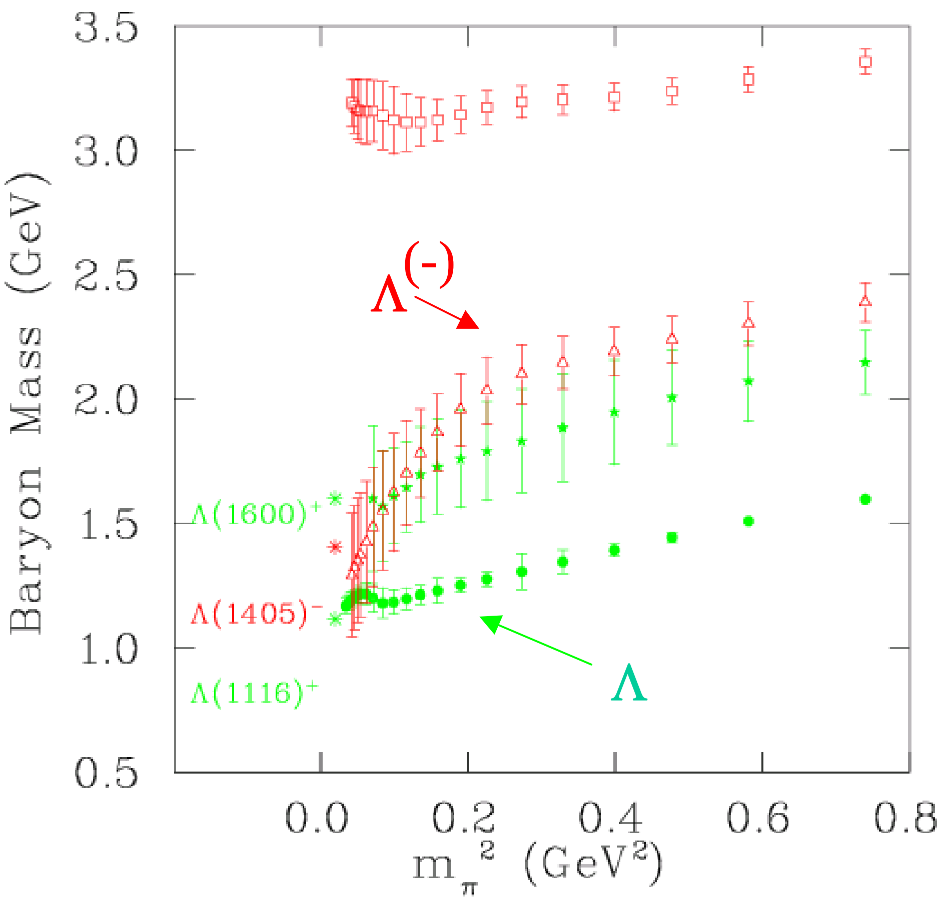
Non-analytic (non-linear) quark mass dependence is seen at $m_\pi^2 < 0.2\text{GeV}^2$.

But…

coarse lattice

ghost contamination(?)

Mathur's talk



Proc. of Lattice2002

Summary

- flavor-singlet baryon (our results)

  The 3-quark state based on the flavor-singlet has a large mass (1.7~1.8GeV), while the flavor-octet states are relatively close to the experiments.

- “common” baryon (Australia group)

  The mass is also far from Λ(1405) (~1.8GeV).

- flavor-octet negative-parity baryon (ours and Australia group)

  The mass is similar to (almost degenerate with) the flavor-singlet and common states.

Both results exclude the 3-quark picture of Λ(1405) .

- flavor-octet negative-parity baryon (Kentucky group)

  The mass becomes very light around light pion masses (non-linear behavior), but it might come from systematic errors. (preliminary)

Therefore further analysis of systematic errors must be done.

- Scaling behavior (Need for the continuum limit).   Nakamura’s talk
- Finite size effects for excited state baryons
- Chiral extrapolation (Linear chiral extrapolation is wrong?)
- Quenching effects (Although it is more “valence-like” picture…)