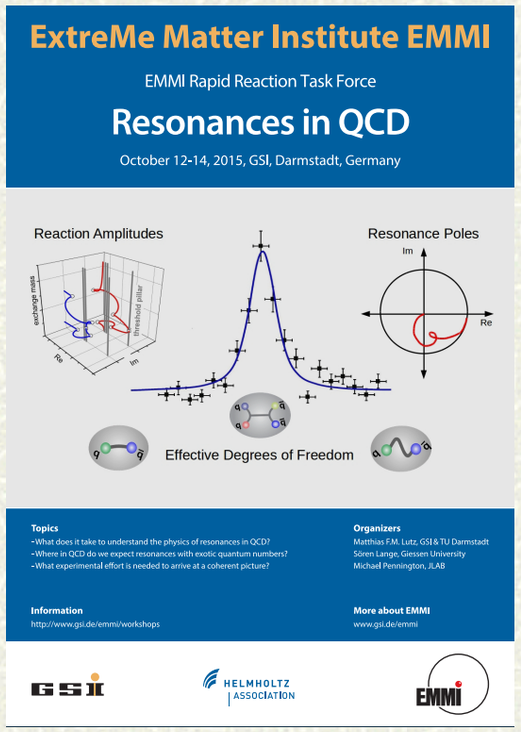
What we know and what we don't know in Light Baryon Spectroscopy



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EMMI Rapid Reaction Task Force
"Resonances in QCD"
13 Oct. 2015@ GSI

Contents

Introduction

We know

- Fundamental theory of hadron structures and interactions is Quantum ChromoDynamics (QCD).
- One of the major goals of QCD is to reproduce and predict the hadron spectrum.
- The hadron spectrum should reveal symmetries and dynamics of the QCD vacuum and clarify effective degrees of freedom of low-energy QCD.
- Recent observations of various types of hadron resonances (+exotics) open up a new-generation hadron spectroscopy.
- There we may learn much from Nuclear Physics, which have treated diverse quantum phenomena of multi-particle systems. (clustering, deformations, collective motions, etc.)

QCD: mass scale

We know

- **QCD Lagrangian**

$$\mathcal{L} = \bar{q}(i\not{D} - m_q)q - \frac{1}{2}\mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}]$$

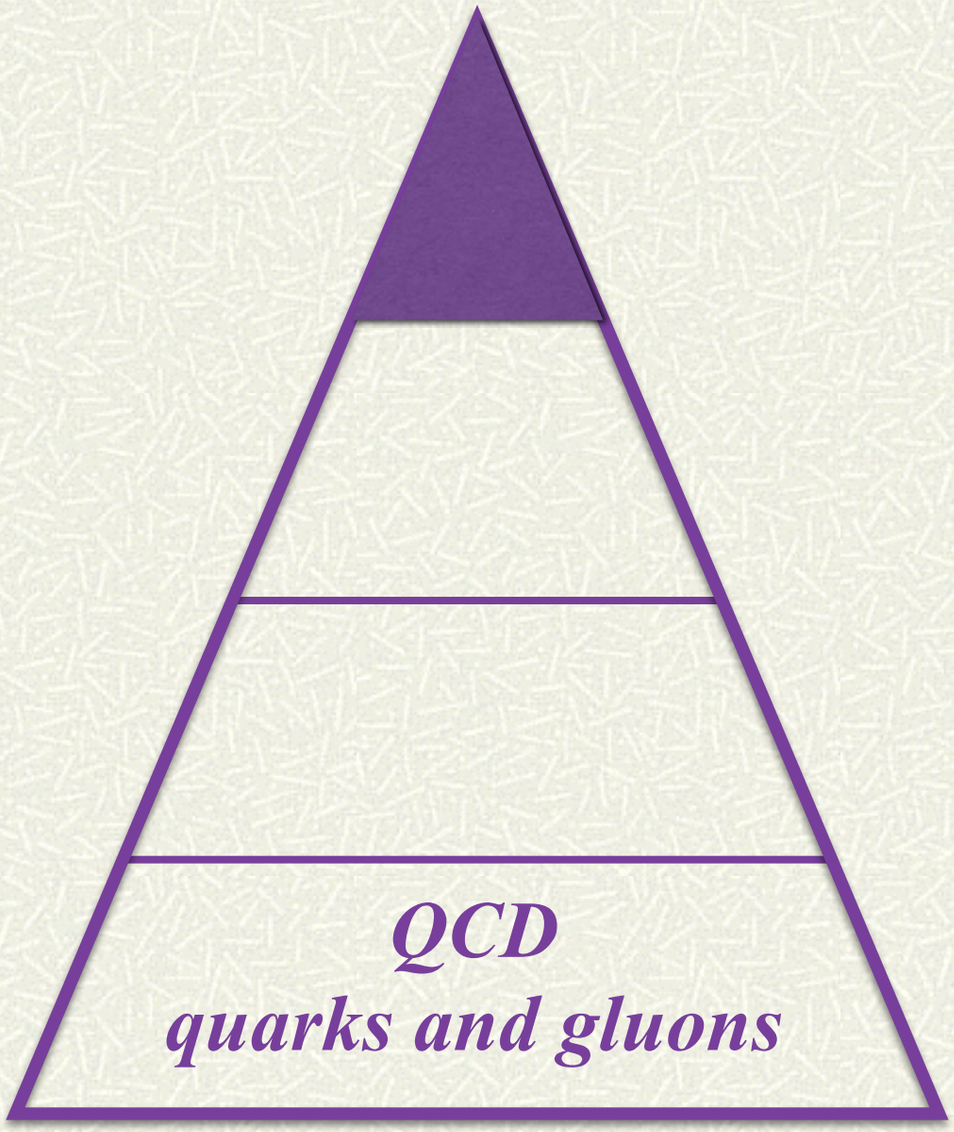
massless gluons + light quarks (m_u= 2.3 MeV, m_d=4.8 MeV)

- **No low energy mode is given by the sum of the constituents. massless gluons => glueballs (m_{GB} ~ 1.4 GeV or larger) light quarks => mesons (>140 MeV), baryons (> 900 MeV)**
- **Scale anomaly Λ_{QCD} ~ 250 MeV and non-trivial vacuum with chiral symmetry breaking:** $\langle \bar{u}u \rangle \simeq \langle \bar{d}d \rangle \sim -(250\,\mathrm{MeV})^3 \sim \mathrm{O}(\Lambda^3)$
- **The QCD quarks+gluons are not enough. The main goal of the hadron spectroscopy is to clarify the roles of effective (low-energy) degrees of freedom, or Quasi-Particles (QP).**

QCD: Effective Degrees of Freedom

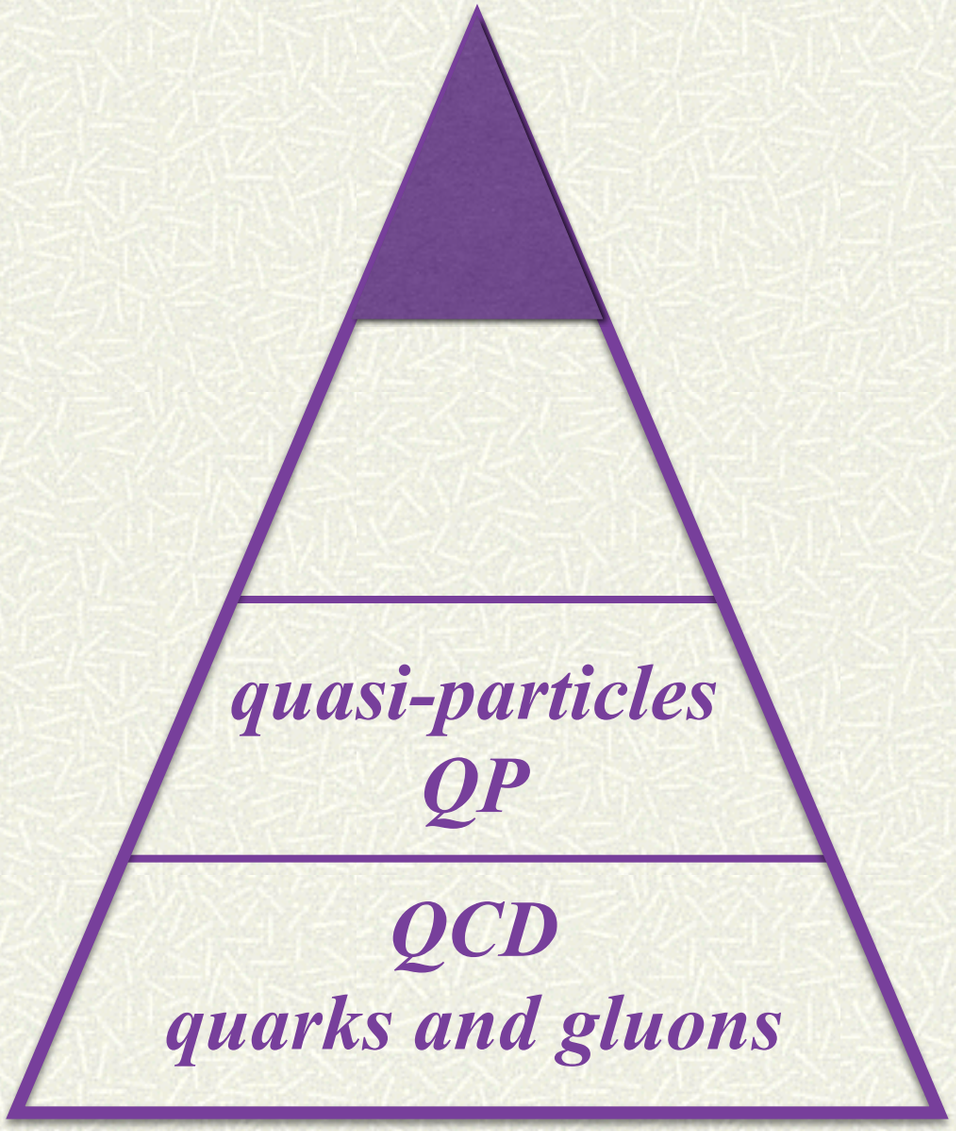
- House of composite hadrons
  1st floor: QCD quarks and gluons

  They do not give quantum numbers of the low-lying eigenstates.
  They do not explain why we do not have exotic multi-quark states.



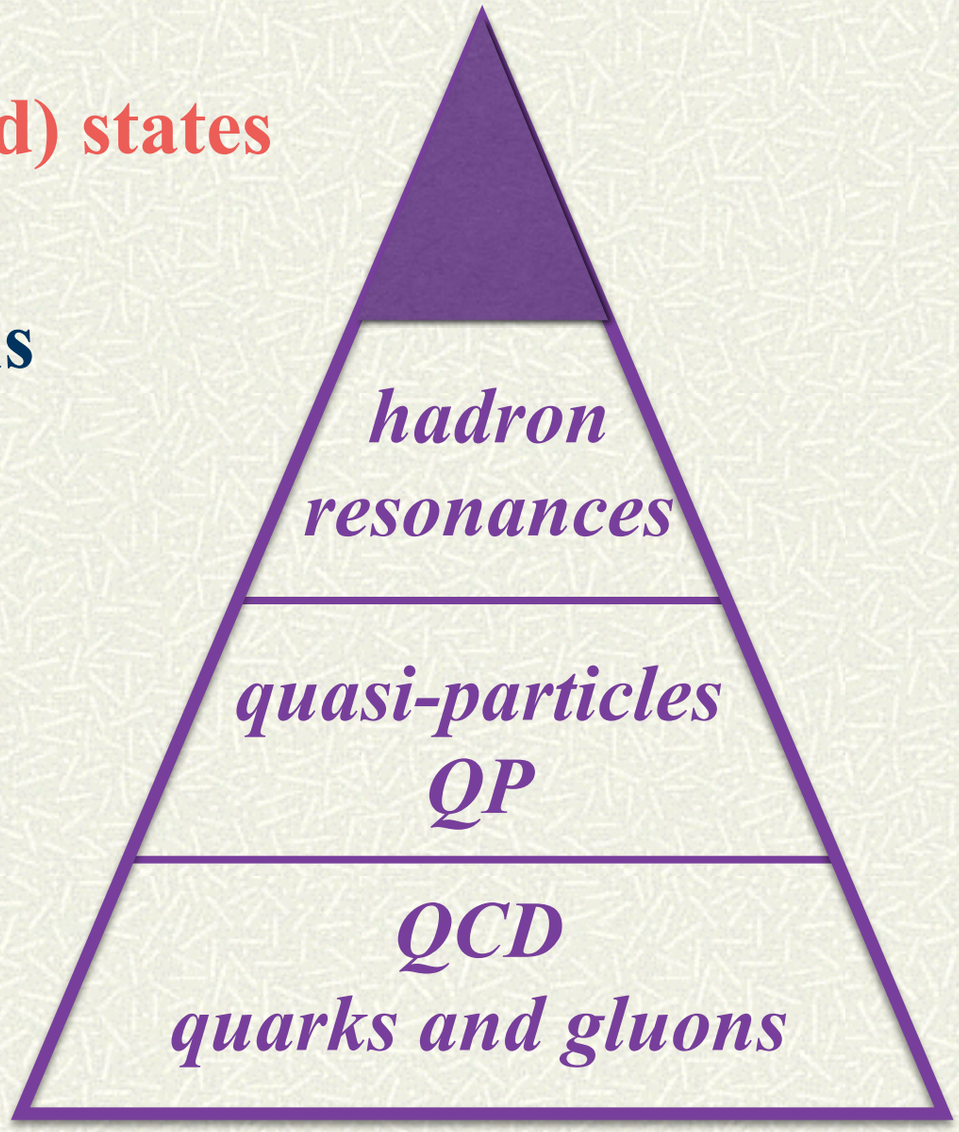
QCD: Effective Degrees of Freedom

- House of composite hadrons
  1st floor: QCD quarks and gluons
  2nd floor: Quasi-Particles
  (Effective Degrees of Freedom)
- Two categories
  colored QP
  constituent quarks
  constituent gluons
  di-quarks
  color-singlet QP
  NG bosons
  low-lying mesons and baryons



QCD: Effective Degrees of Freedom

- House of composite hadrons
  1st floor: QCD quarks and gluons
  2nd floor: Quasi-Particles
  3rd floor: Hadron Resonance (excited) states
- Quasi-Particles in QCD are the key to unlock and predict excited hadrons and spectrum patterns.



Room 201: Colored QP

We don't know

- **Constituent quark with spin 1/2, mass ~ m_q + 350 MeV**
  basis of the constituent quark model
- **Colored diquark**
  diquark correlation, clusters in hadrons
  [ud] (0^+, I=0) : good diquark, mass < 600 MeV
- **Constituent glue**
  explicit gluon degrees of freedom:
  for glueballs, and hybrid mesons ($J^\pi=1^{-+}$, 0^{+-})

Room 202: Hadrons (white QP)

- **Light hadrons as building blocks ("Atoms"):**

  Nambu-Goldstone bosons: π, K, η, D, B, . . .

  Vector mesons: ρ, ω, ϕ, D*, . .

  GS baryons (8+10): N, Δ, Λ, . . .

- **Now, some (not all?) of the excited states,**

  ***such as* Λ(1405), X(3872), . . . ,**

  may be their bound states, i.e., "Molecules".

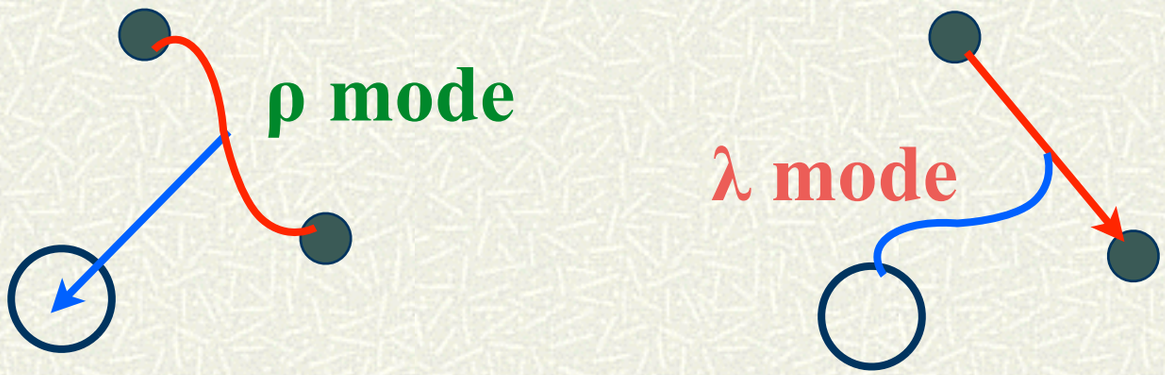
What are the roles of these QPs? Where are they seen?

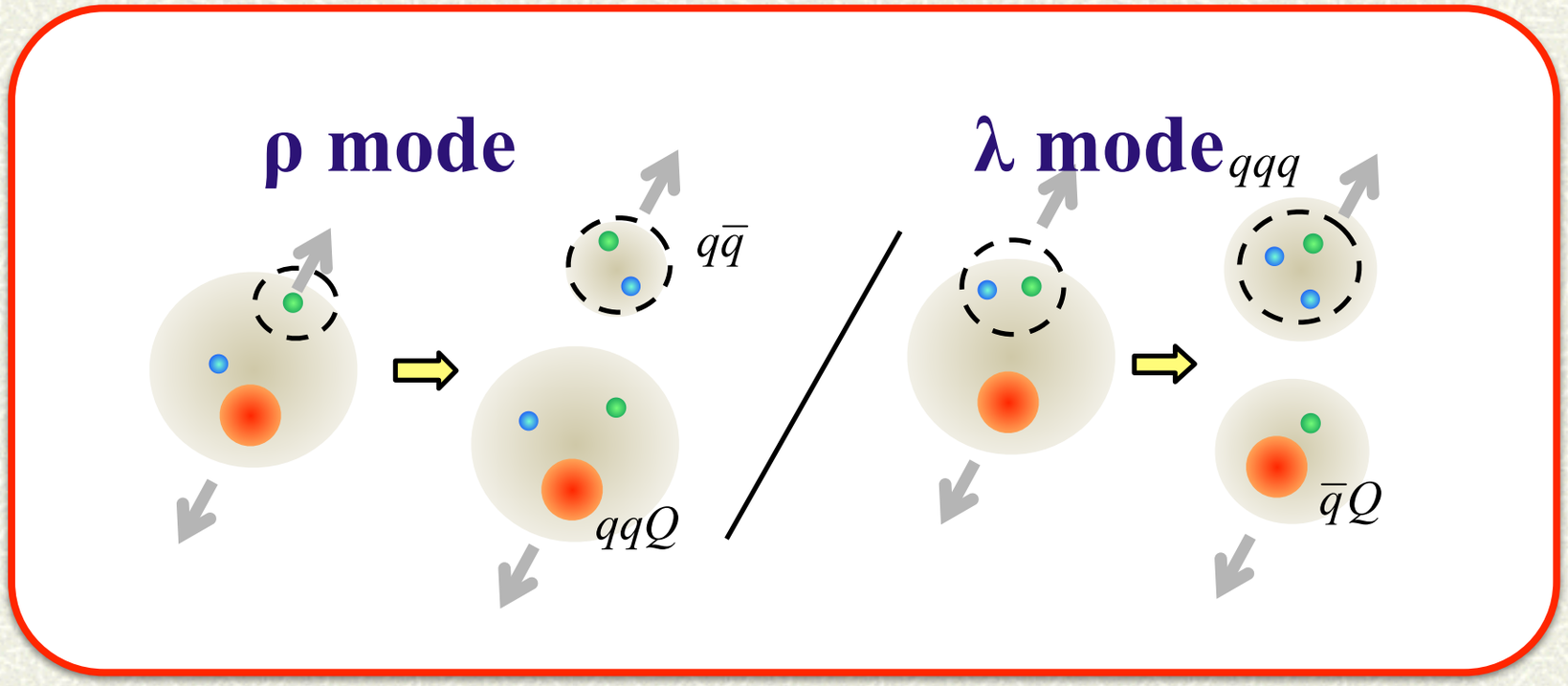
QCD: Effective Degrees of Freedom

- How are they identified, or detected?
- Production rates, decay patterns, and branching ratios are sensitive to the hadron structure.
- Examples:
  $\Delta(1232)\ (3/2^+) \Leftrightarrow N(940)\ (1/2^+) + \gamma$: (M1+E2) photon
  – Mixed E2 is directly related to the deformation of N and Δ.
  – Size of the resonance wave functions can be extracted from the transition rate. It should be larger in hadron molecules.
- N(1535), N(1650) (L=1, S=1/2, 3/2)→ N η, N π
  – Large Nη amplitude of N(1535) indicates a strong (tensor-force) mixing of the spin 1/2 and 3/2 states.

QCD: Effective Degrees of Freedom

- In heavy baryons, the (strong) decay patterns may be useful.

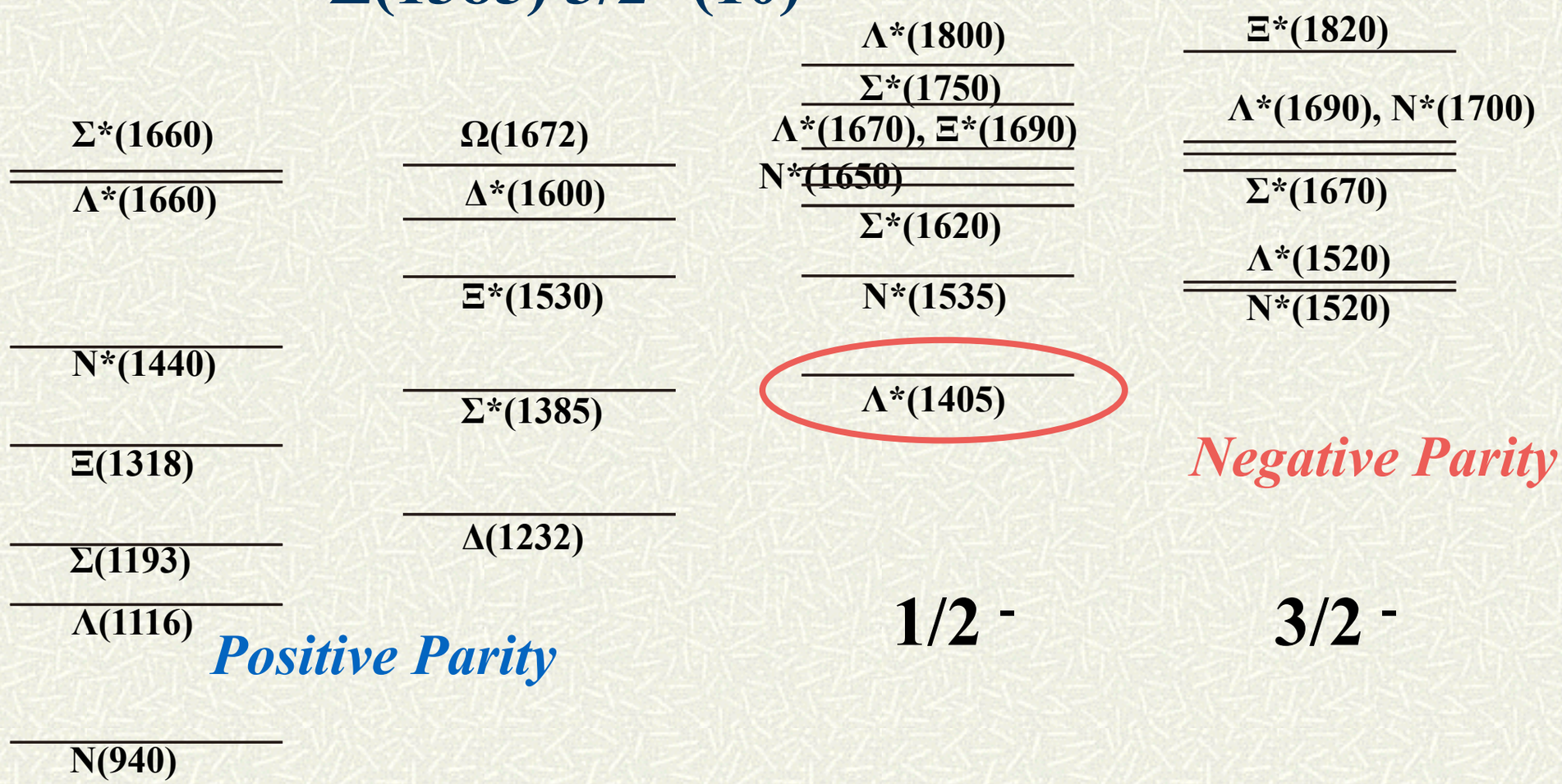




Λ(1405)

Λ(1405) : the *lightest negative-parity* (J^{π}= 1/2$^-$) baryon

~ Σ(1385) 3/2$^+$ (10)



Λ(1405) in QM

We don't know

☆ flavor singlet 3q (uds) S=1/2, L=1 orbital excitation

=> J=1/2$^-$ and 3/2$^-$: spin-orbit partner Λ(1520) 3/2$^-$?

L=1 excitation costs around N(1535) - N(940) ~ 600 MeV

☆ 5q (udsu$\bar{u}$+udsd$\bar{d}$)

L= 0 state, *i.e. No* orbital excitation required.

+ diquark structure

$(ud)_{s=0}$ $(su)_{s=0}$ $\bar{u}$ → S_{tot} = 1/2 (no J=3/2 partner)

adding a pair of quarks costs π(140)/ρ(770) ~ 550MeV

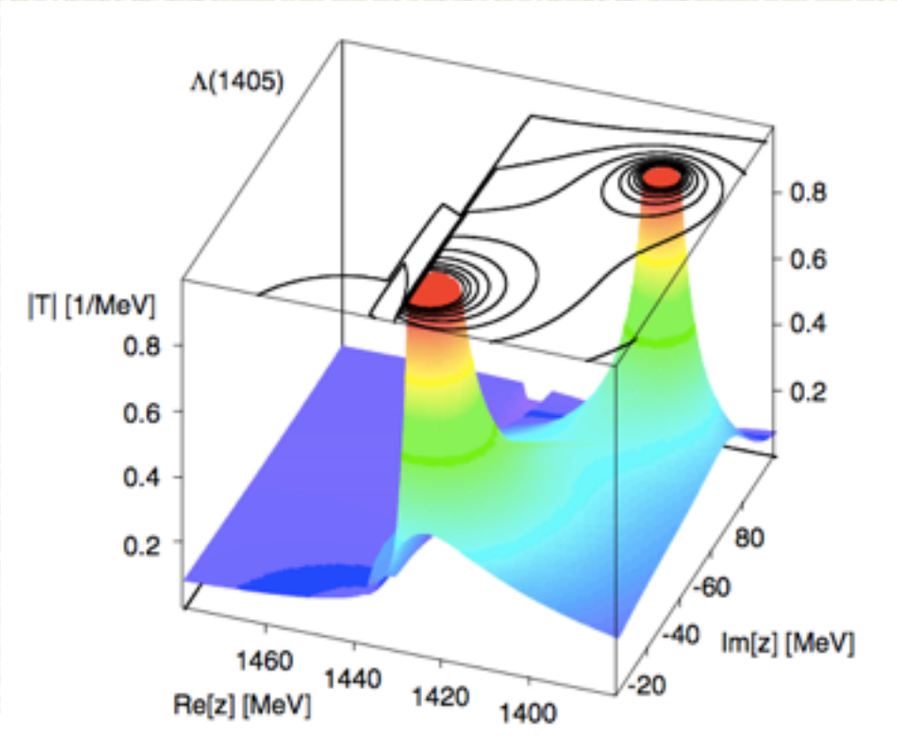
3q excitation *v.s.* pentaquark

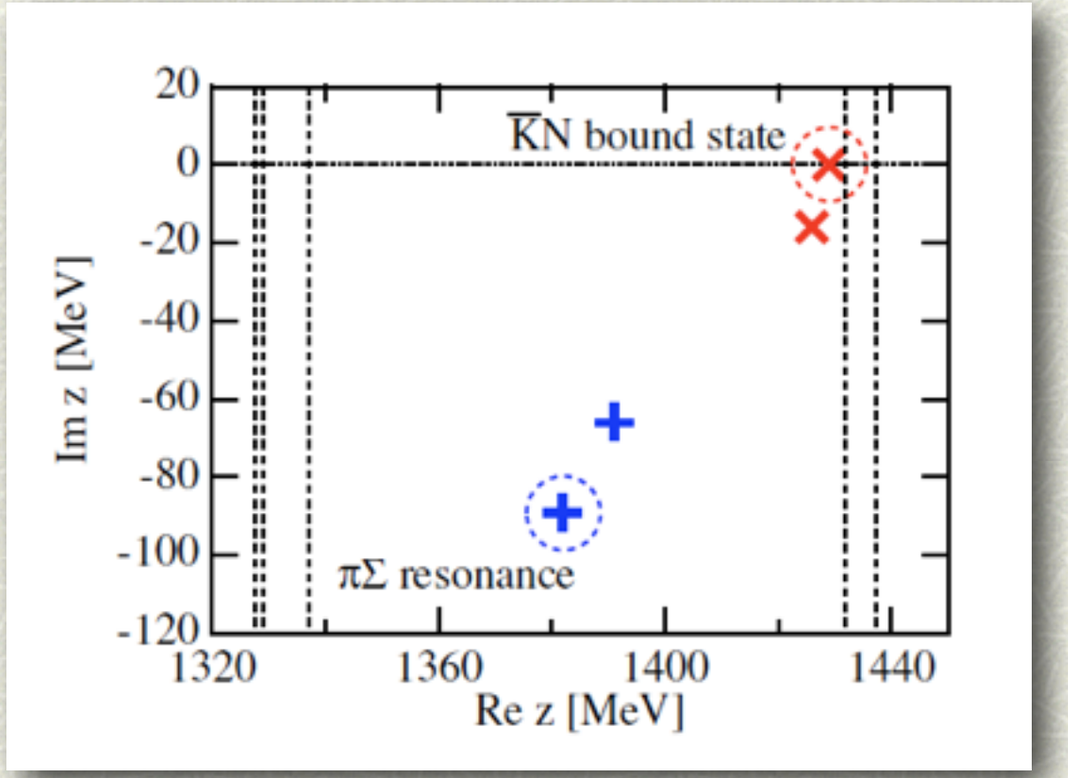
Neither of them gives the low mass of Λ(1405).

Λ(1405) as Molecules

We don't know

- **S-wave bound state of $K^{bar}N$ coupled with πΣ**
  Chiral Unitary Approaches predict two resonance poles for Λ(1405).
  Oller, Meissner, PLB500 (2001) 263; Jido et al., NPA725 (2003) 181
  Consists of a $K^{bar}N$ bound state and a πΣ resonance.
  Hyodo, Weise, PRC77 (2008) 035204





Λ(1405)

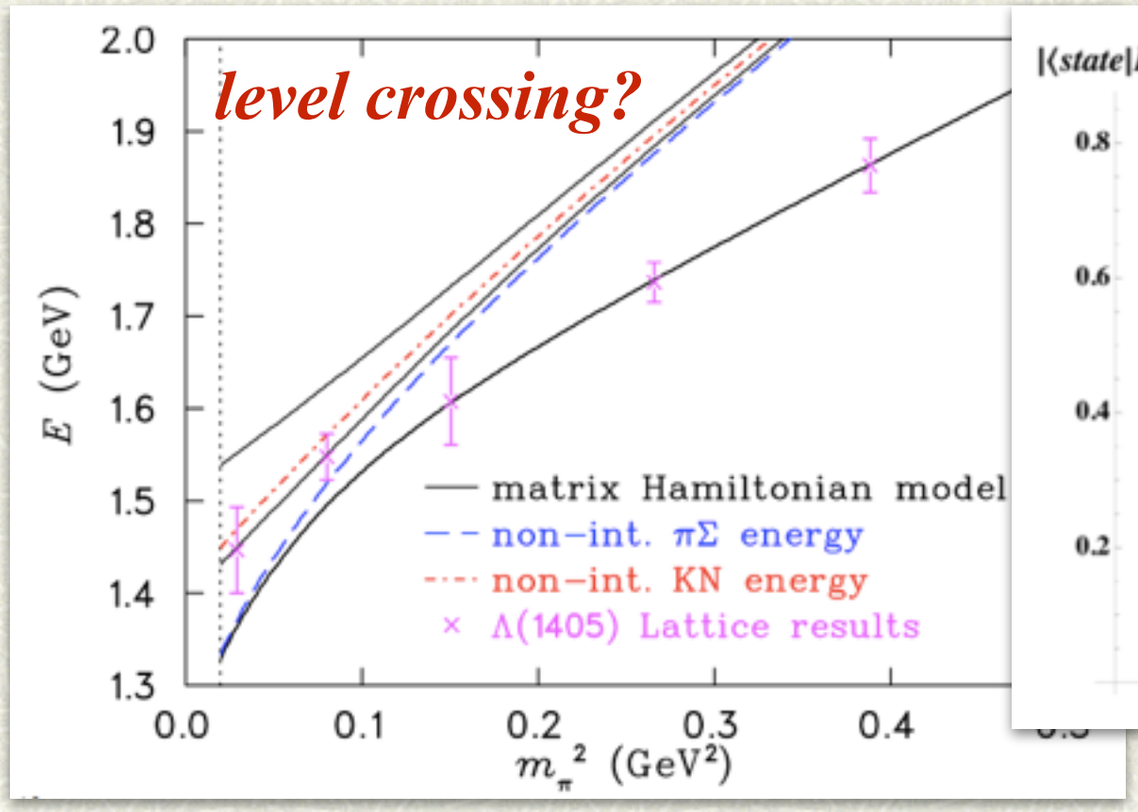
We don't know

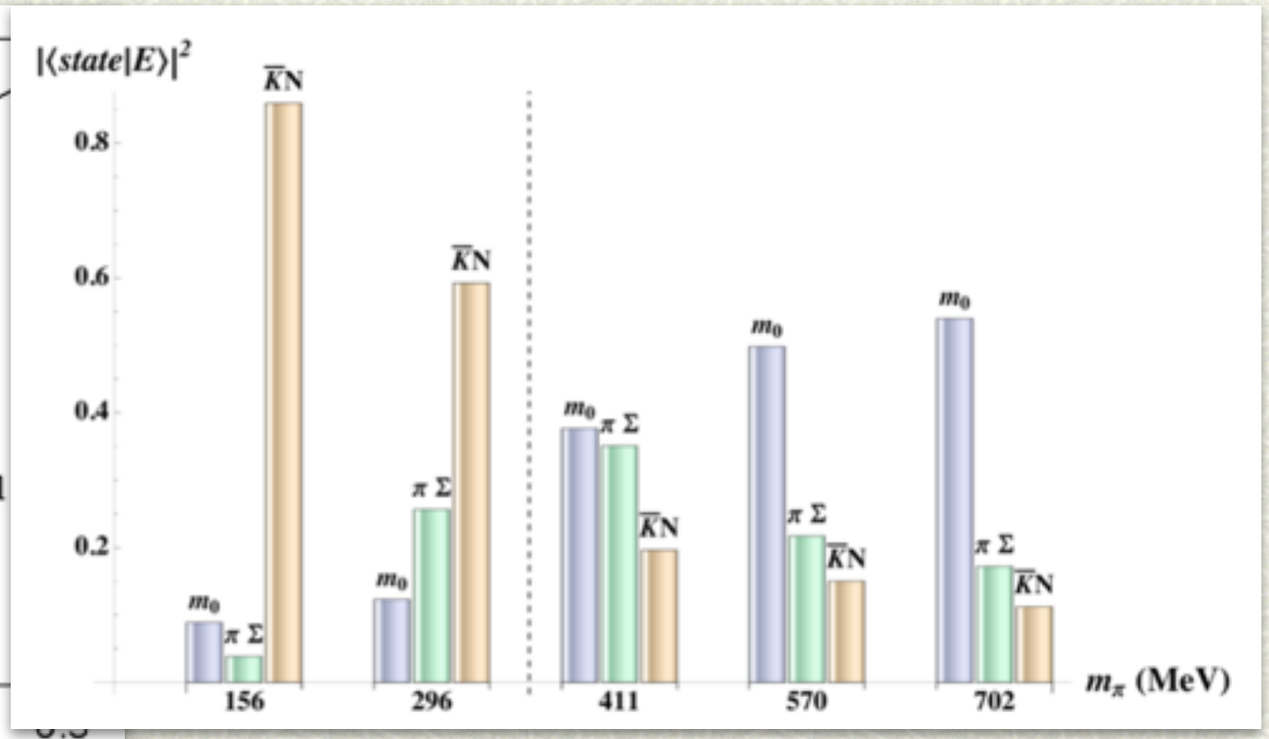
We have two lessons:

- **Excited hadrons are very sensitive to nearby THRESHOLDS.**
- **Complete descriptions of resonances require CHANNEL COUPLINGS.**

Λ(1405) on Lattice

- **A recent LQCD analysis by claims the dominance of the $K^{bar}N$ component using a "matrix Hamiltonian model" analysis.**
  Hall et al. PRL 114 (2015) 132002





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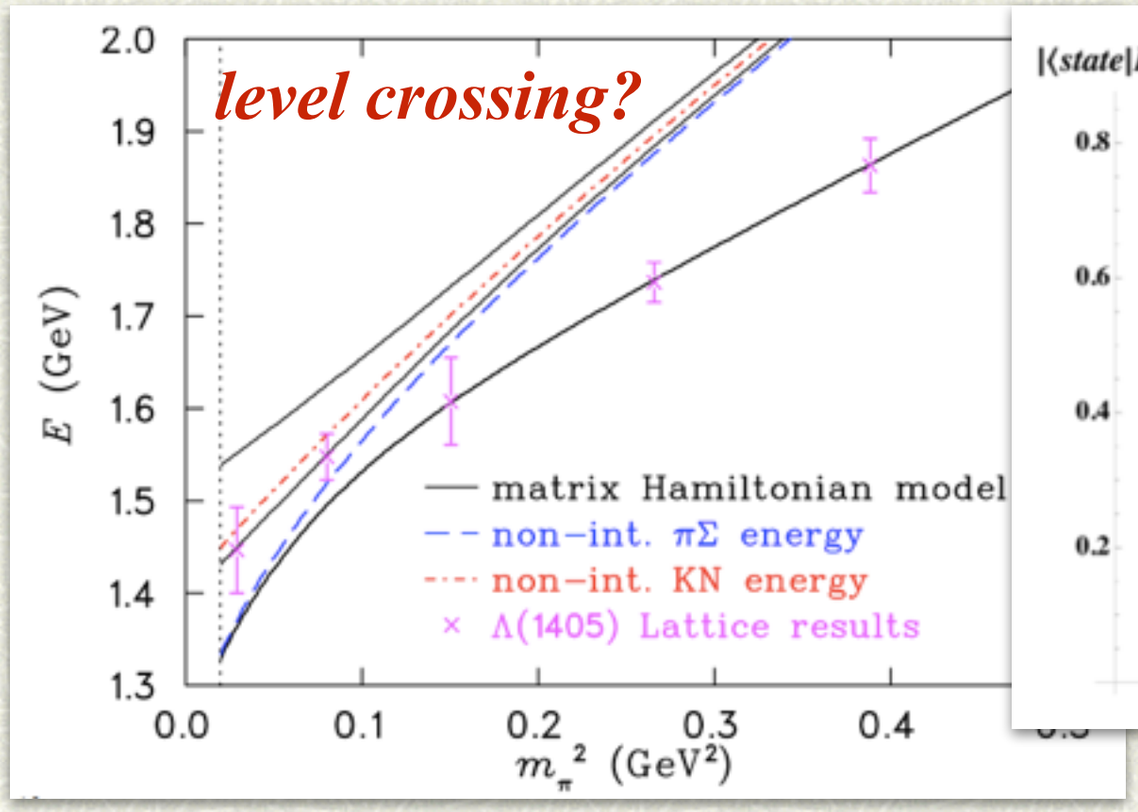
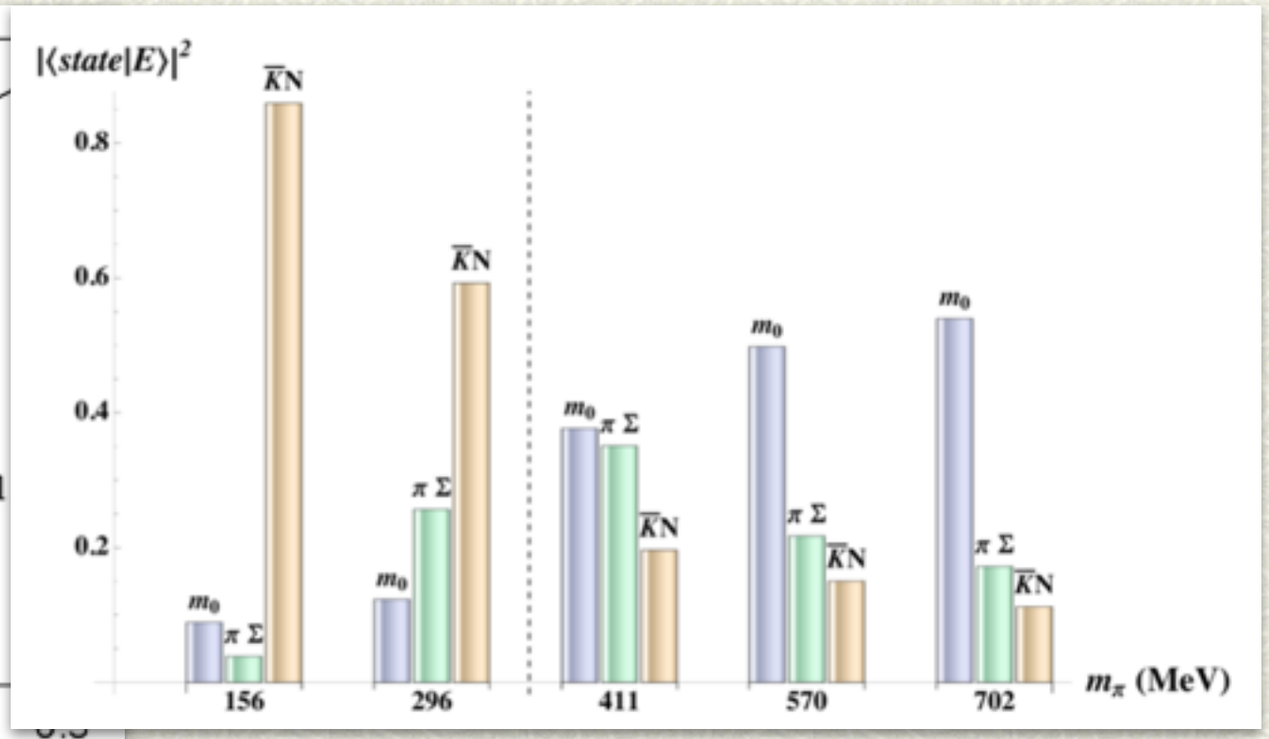




Note: Only three-quark operators are used for this analysis. An alternative approach is to employ B+M operators.

Resonances in Lattice QCD

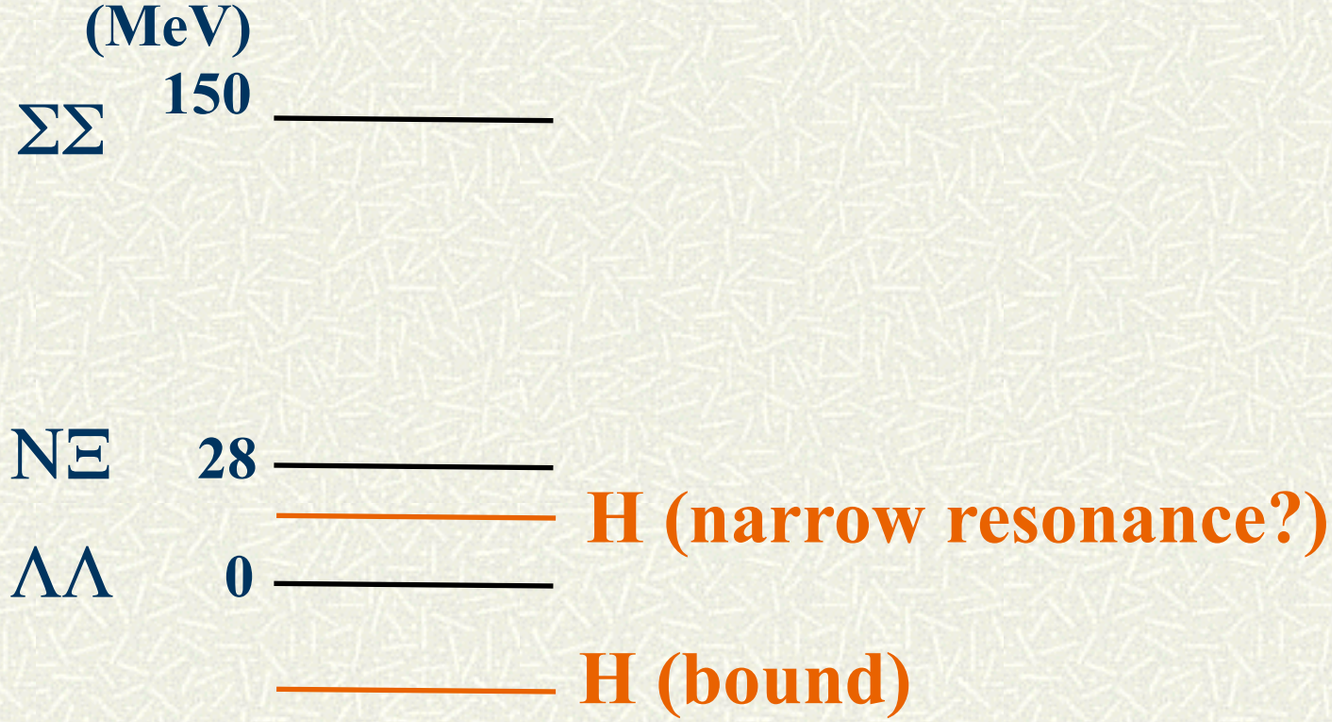
- **Need to distinguish resonance state from hadronic scattering states. On lattice with finite volume, scattering states are also discrete.**
- **Real scaling method may be used to distinguish the resonance from scattering states. The most popular is Lüscher's method by using the 1/L dependences of the discrete spectrum on the lattice.**
- **HAL-QCD has developed a method to define and calculate a phase-shift equivalent (non-local) potential on the lattice. It can be applied to coupled-channel (multi-threshold) systems. Then the resonance can be analyzed in the effective theory approach.**

  N. Ishii, S. Aoki, T. Hatsuda, PRL 99 (2007) 022001; Prog. Theor. Phys. 123 (2010) 89-128.

H di-baryon

The H di-baryon (= $u^2d^2s^2$; $J=0^+$ I=0) predicted by Jaffe (1977) belongs dominantly to flavor SU(3) singlet.
A strong channel coupling is expected among

$$|\mathrm{Singlet}\rangle = \sqrt{\tfrac{1}{8}}|\Lambda\Lambda\rangle + \sqrt{\tfrac{4}{8}}|N\Xi\rangle - \sqrt{\tfrac{3}{8}}|\Sigma\Sigma\rangle$$



H di-baryon

The H di-baryon (= u^2d^2
belongs dominantly to fl
A strong channel couplin

$$|\text{Singlet}\rangle = \sqrt{\tfrac{1}{8}}|\Lambda\Lambda\rangle +$$

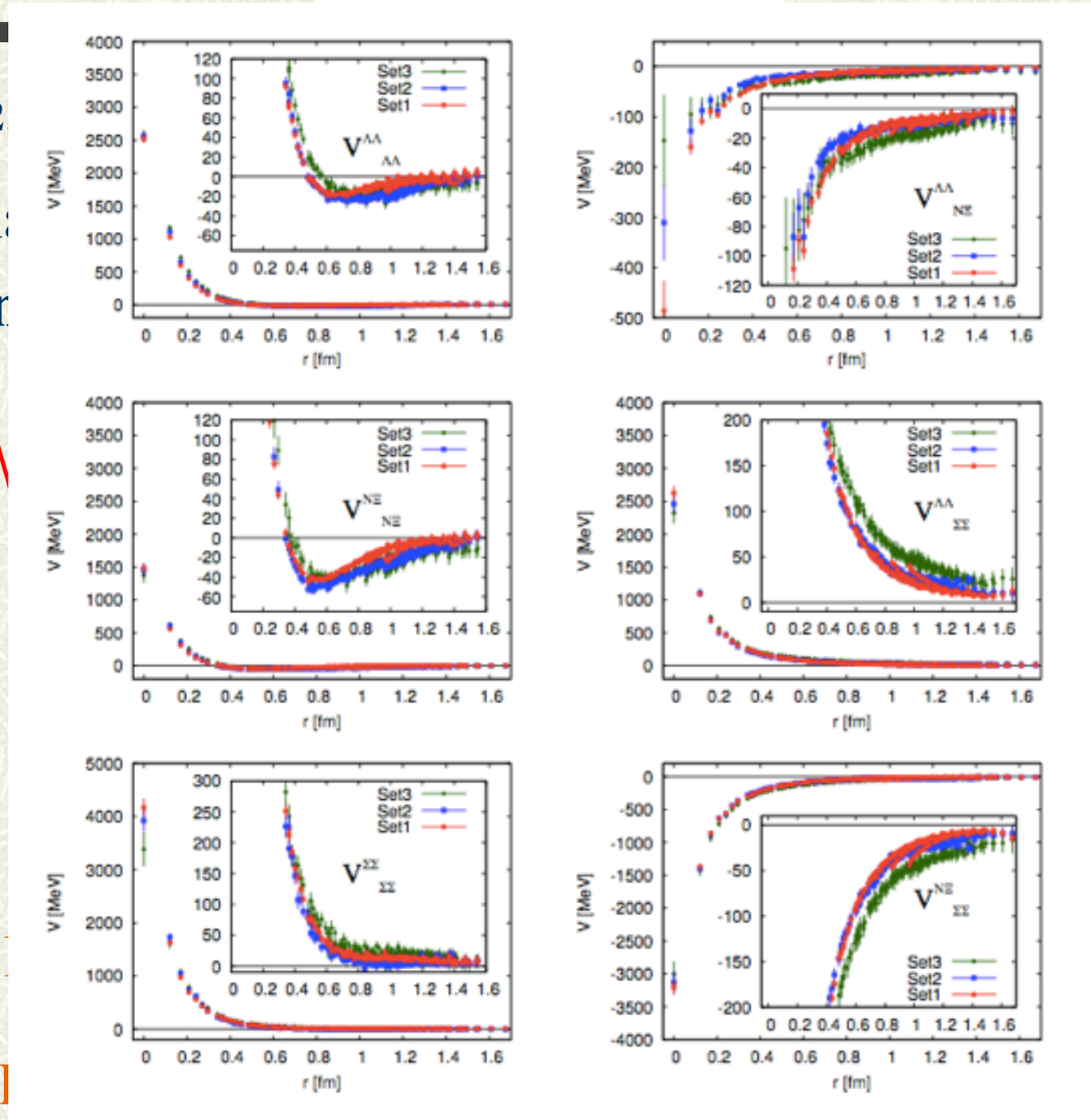
(MeV)

$\Sigma\Sigma$ 150

$N\Xi$ 28

$\Lambda\Lambda$ 0

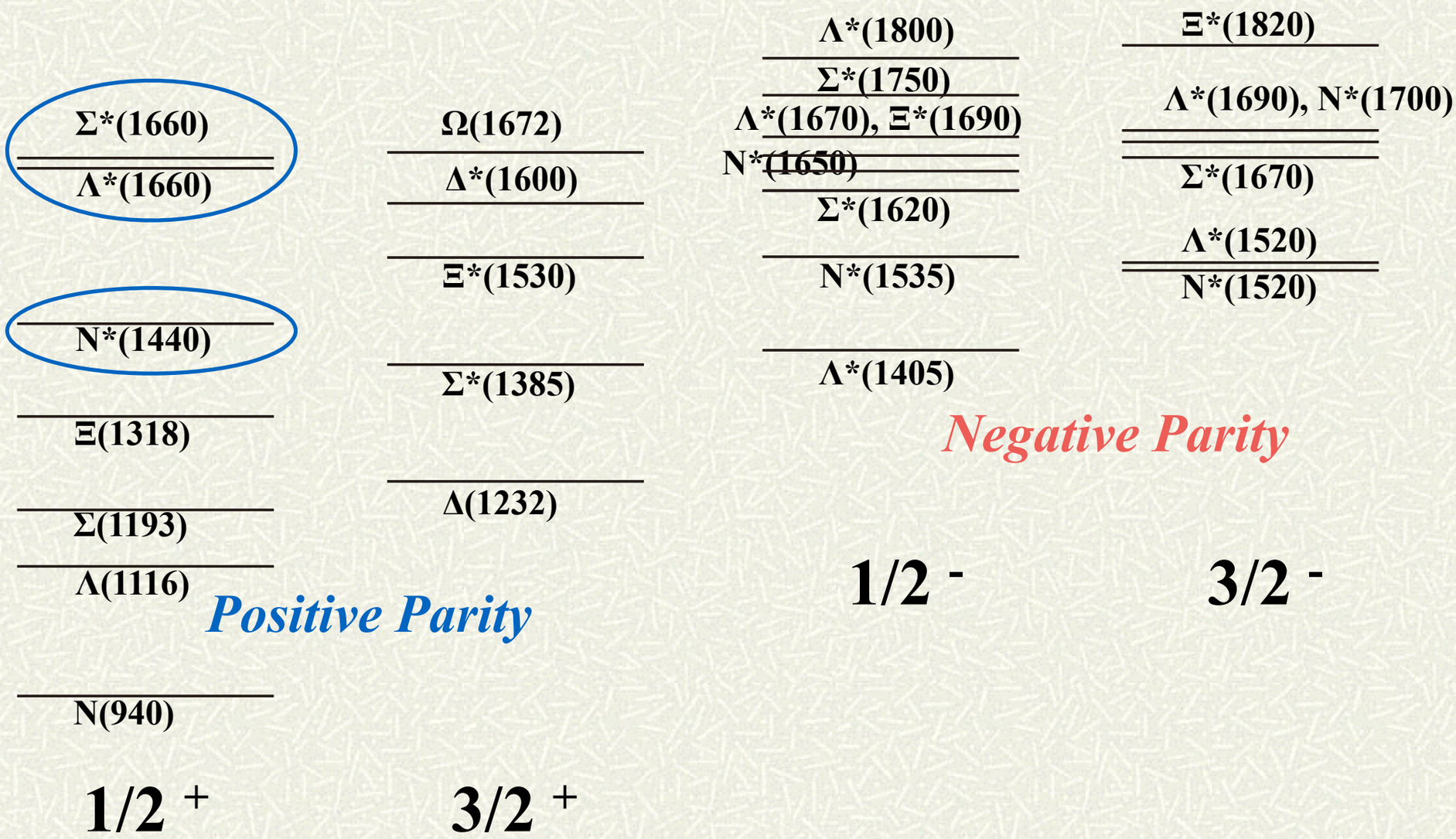
m_π= 660-875 MeV



K. Sasaki et al., (HAL-QCD) arXiv:1504.01717

Roper puzzle

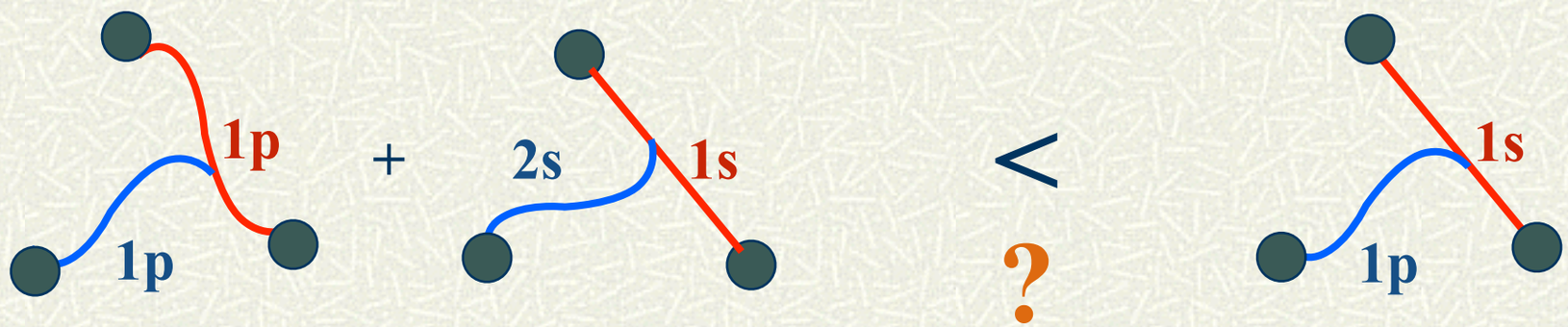
- N(1440) $1/2^+$ resonance and its siblings



Roper puzzle

We don't know

- Quark model picture of "positive-parity" excited states



- Why is this state lighter than N(1520), N(1535), N(1650)?

  $3/2^-$ $1/2^-$

  harmonic/linear confinement → (1p) < (2s)

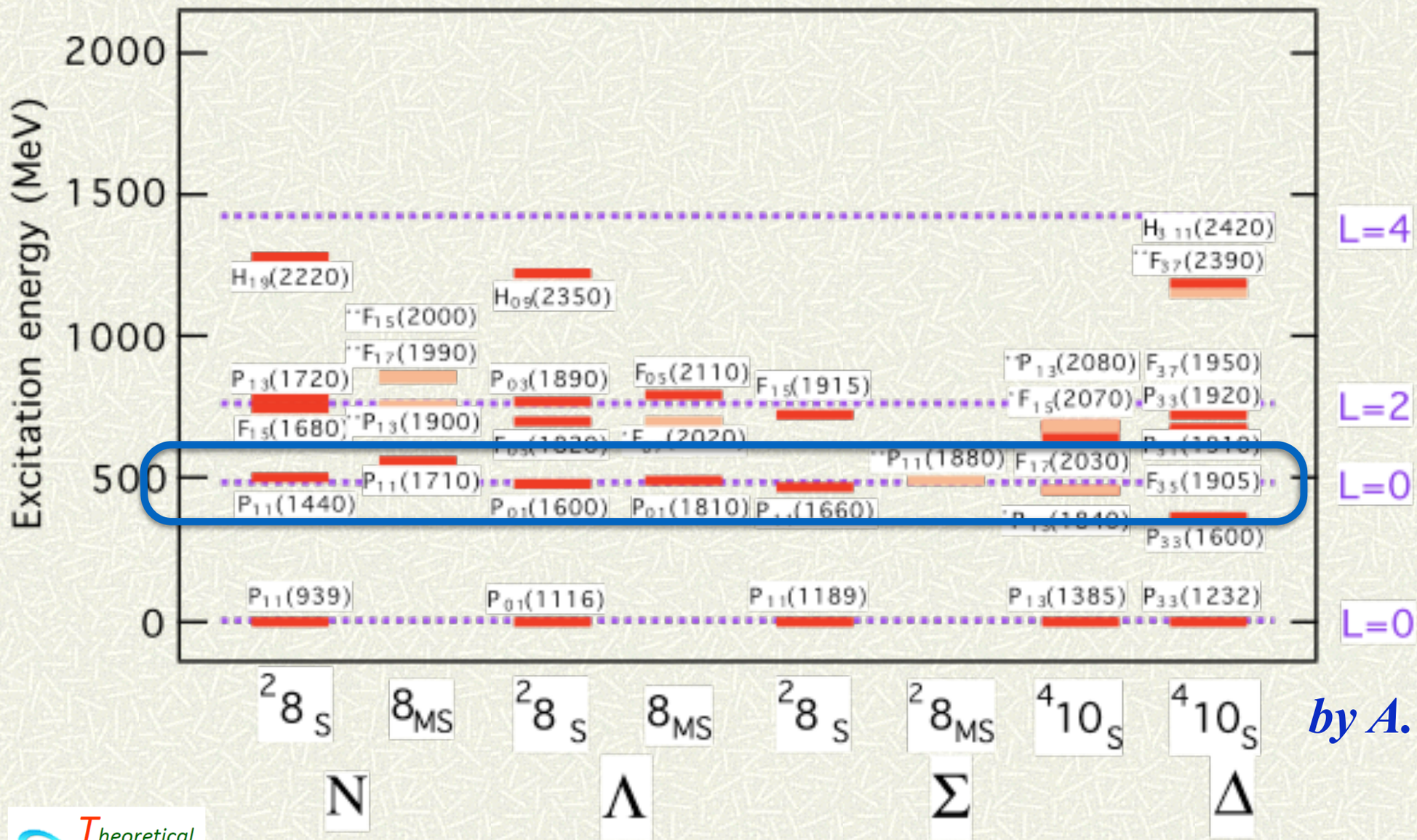
  Coulomb potential → (1p) = (2s)

- The other positive parity states are heavier.

  N(1680) $5/2^+$, N(1710) $1/2^+$, N(1720) $3/2^+$, N(1860) $5/2^+$, . .

Roper puzzle

- **Similar states in the strange/Δ states, which are aligned at 500 MeV above the ground states.**



by A. Hosaka

Roper puzzle

We don't know

- **Possible solutions: Strong channel couplings?**
  Collective (Breathing) mode excitations? (in Skyrmion)
  Pentaquarks? (in Chiral soliton model)
- **What does QCD tell us?**
  Lattice QCD struggles with Roper.

PHYSICAL REVIEW D **76,** 054510 (2007)

Even parity excitations of the nucleon in lattice QCD

B. G. Lasscock,[1] J. N. Hedditch,[1] W. Kamleh,[1] D. B. Leinweber,[1] W. Melnitchouk,[2] A. G. Williams,[1] and J. M. Zanotti[3]

[1]*Special Research Centre for the Subatomic Structure of Matter, Adelaide, South Australia 5005, Australia, and Department of Physics, University of Adelaide, Adelaide, South Australia 5005, Australia*

[2]*Jefferson Lab, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA*

[3]*School of Physics, University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*

(Received 7 May 2007; published 28 September 2007)

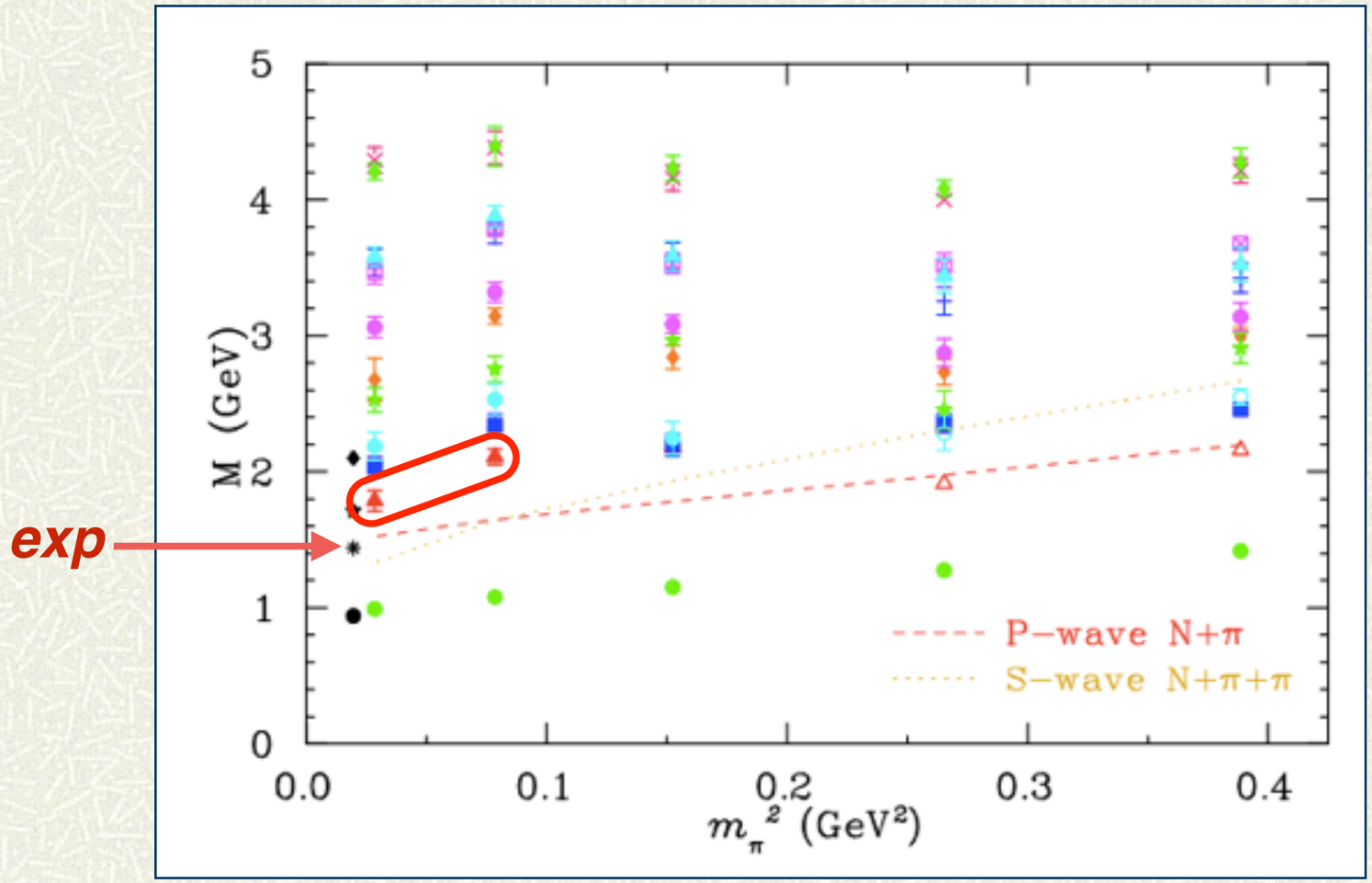
We study the spectrum of the even-parity excitations of the nucleon in quenched lattice QCD. We extend our earlier analysis by including an expanded basis of nucleon interpolating fields, increasing the physical size of the lattice, including more configurations to enhance statistics and probing closer to the chiral limit. With a review of world lattice data, we conclude that there is little evidence of the Roper resonance in quenched lattice QCD.

Roper puzzle

- **Full QCD suggests that the 2nd state may go down ?**

Roper resonance in 2 + 1 flavor QCD *Phys. Lett. B707 (2012)*

M. Selim Mahbub [a,b,*], Waseem Kamleh [a,b], Derek B. Leinweber [a,b], Peter J. Moran [a,b,c], Anthony G. Williams [a,b]



Baryon Resonances

We don't know

- **Competition of different pictures**

  3 valence quarks in orbital excitations

  OR

  compact multi-quark states

  OR

  hadron molecules

- **And we need *couplings to open channels*!**

- **Which is dominant? In which resonance?**

  How can we distinguish them in Experiments?

  And in Theories?

Number of quarks in QCD

"Counting" the number of quarks?

There is no conserved current corresponding to the # of quarks: $N(q)+N(\bar{q})$.

It may depend on choices of the quark operator.

Ex. Bogoliubov transformation may change the # of quarks in a hadron.

Any reasonable definition of the numbers of “valence” quarks?

Parton distribution in the light-cone frame?

Number of quarks in QCD

"Counting" the number of quarks?

There is no conserved current corresponding to the # of quarks: $N(q)+N(\bar{q})$.

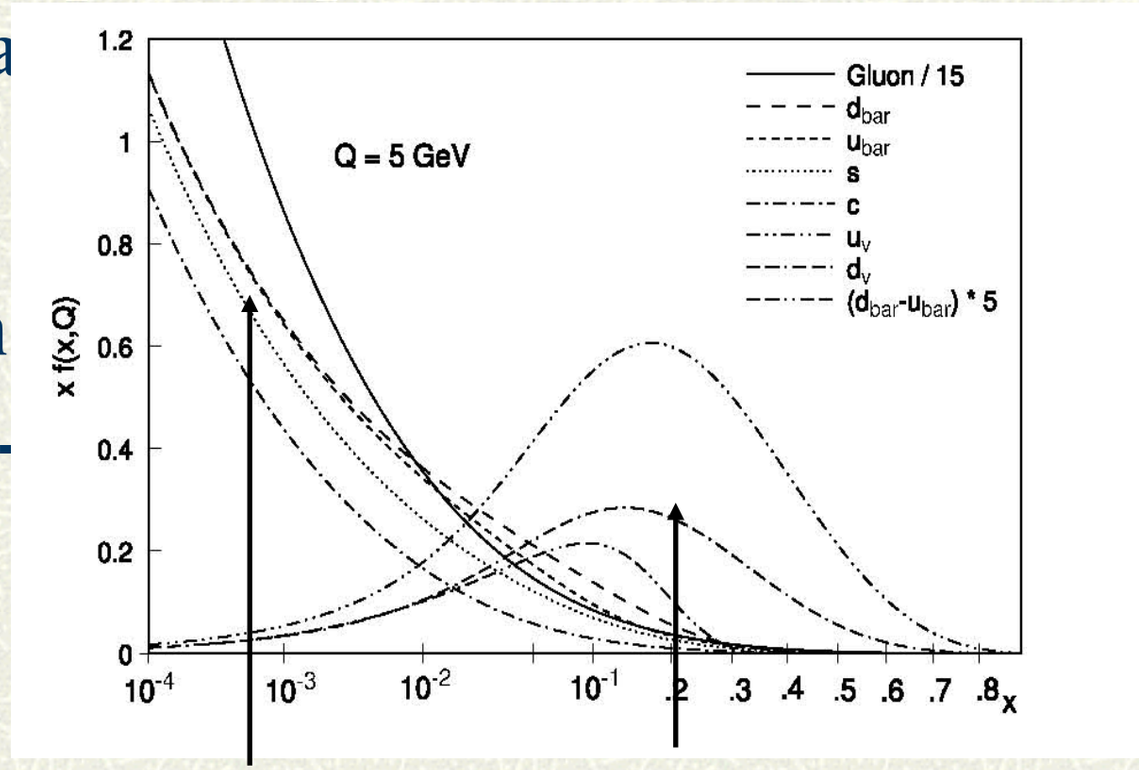
It may depend on choices of the quark operator.

Ex. Bogoliubov transforma

# of quarks in a hadron.

Any reasonable definition of the n

Parton distribution in the light-



sea quarks valence quarks

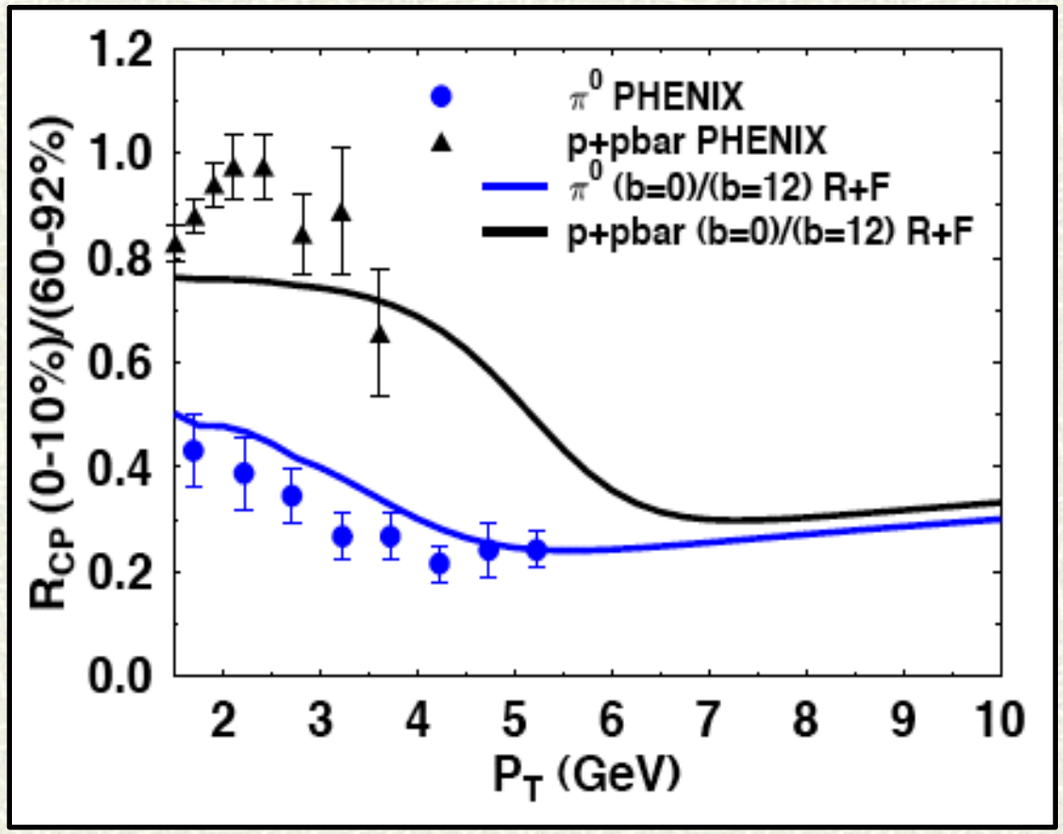
Counting the number of quarks?

Recombination of partons in HI collisions

R. J. Fries, et al., ***PRL 90,202303(2003), PRC68,044902(2003)***

$q\bar{q} \rightarrow 2\,\langle p_T \rangle$

$qqq \rightarrow 3\,\langle p_T \rangle$



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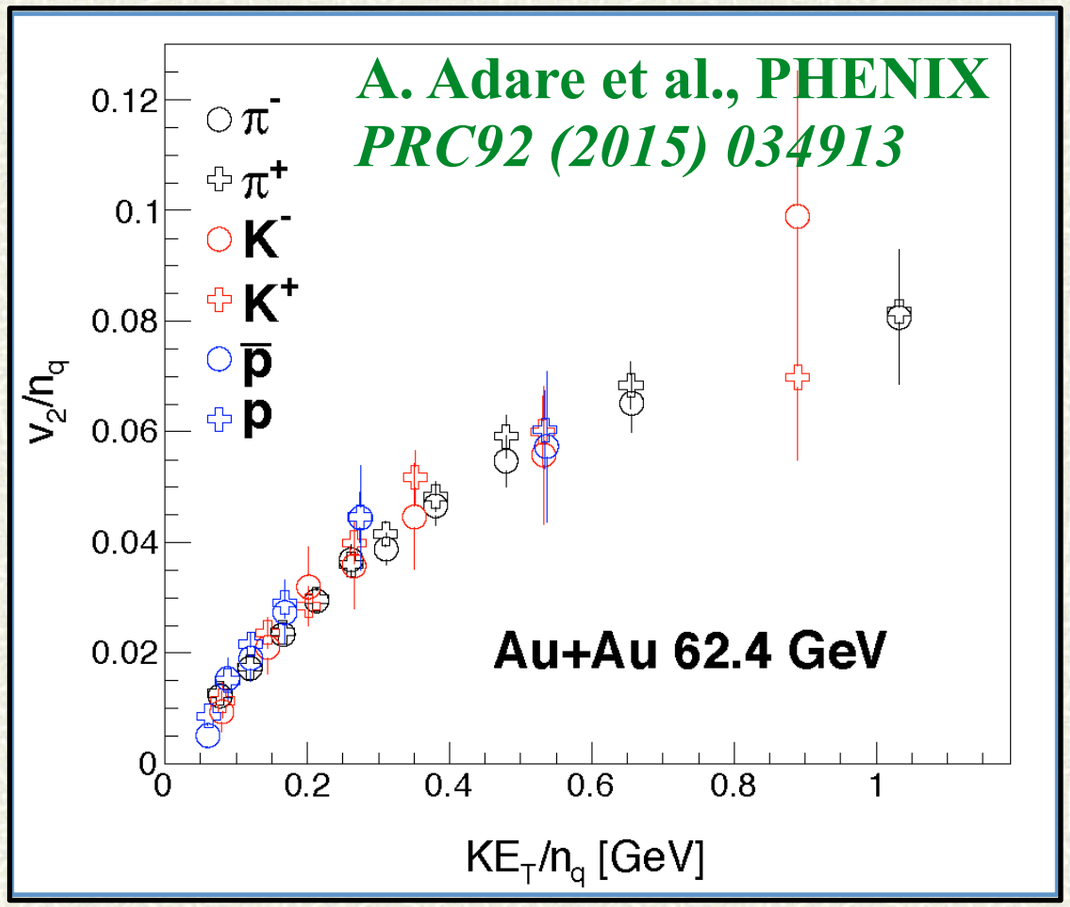
Quark number scaling of the elliptic flow v_2



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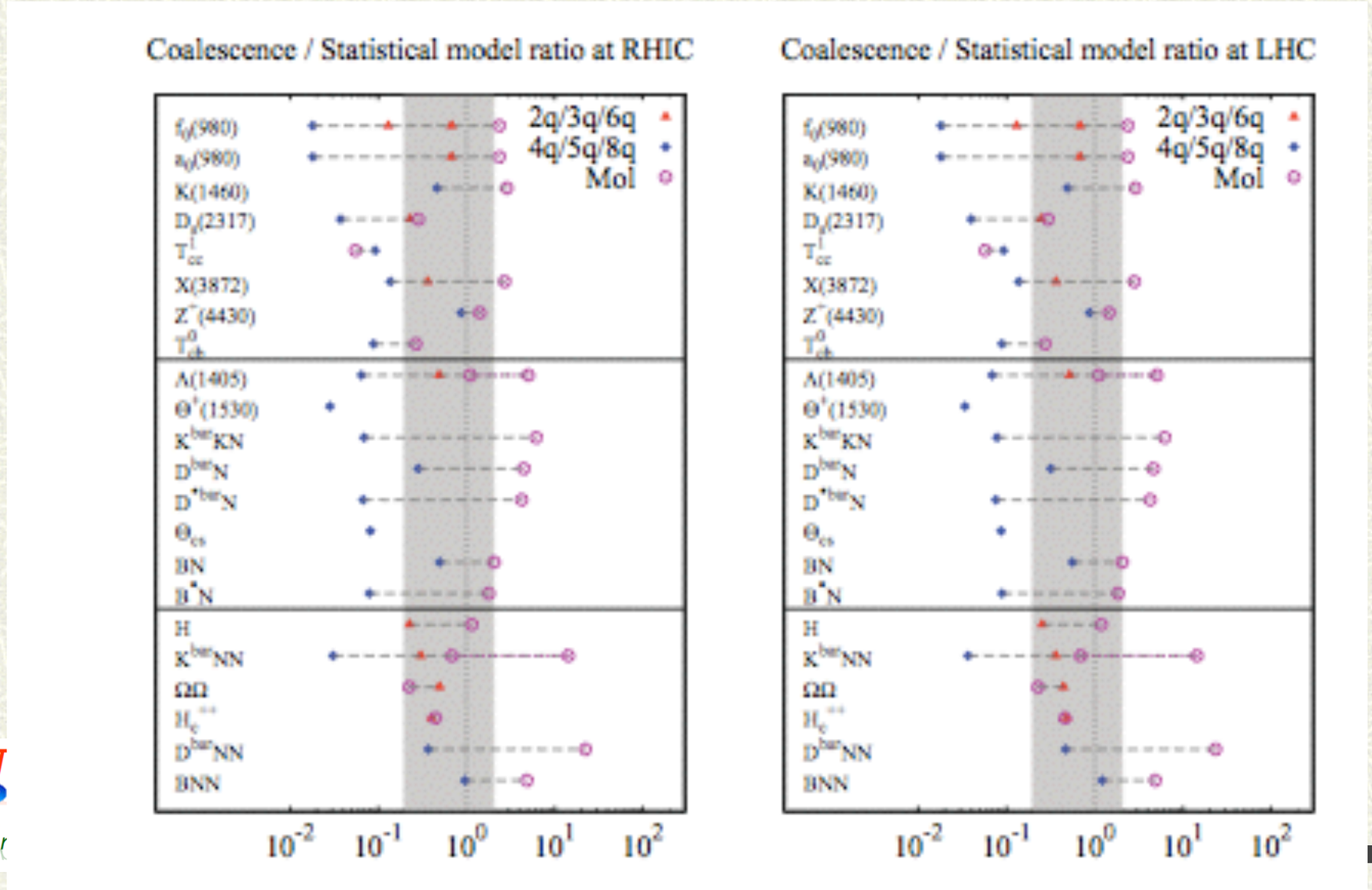
Quark number scaling of the elliptic flow v_2

By counting the number of valence quarks in hadron resonances, we may identify multi-quark exotic states.

Counting the number of quarks?

- **Cho et al. (ExHIC collaboration)** *PRL 106 (2011) 212001*
  PRC84 (2011) 064910

  Coalescence / Statistical model ratios
  Comparison of 3q vs 5q vs BM-molecule structures



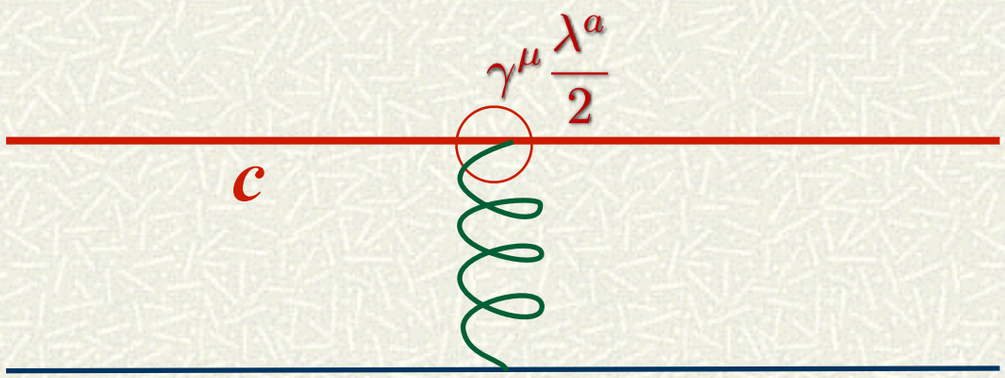
Compositeness

- Can we distinguish compact multi-quark states from hadron molecules (composite)?
- Composite nature of hadron resonances can be formulated by the use of the (re)normalization of the resonance pole. "Compositeness" may be "defined" unambiguously near multi-hadron thresholds.
  – Weinberg, PR137 (1965) B672, "Evidence that the deuteron is not an elementary particle",
  – Sekihara, Hyodo, Jido, PTEP 2015, 063D04, "Comprehensive analysis of the wave function of a hadronic resonance and its compositeness".

Diquarks and Heavy Baryon Resonances

Heavy Quark Spin Symmetry

Magnetic gluon coupling is suppressed



$$\bar{\Psi}\gamma^\mu \frac{\lambda^a}{2}\Psi A^a_\mu \sim \Psi^\dagger \frac{\lambda^a}{2}\Psi A^a_0 - \Psi^\dagger \sigma \frac{\lambda^a}{2}\Psi \cdot \frac{1}{m_Q}(\nabla \times A^a)$$

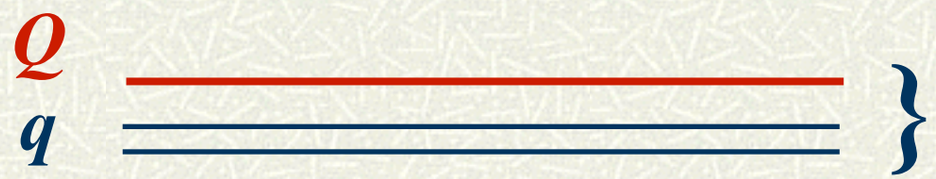
(Color Electric coupling) ≫ (Color Magnetic coupling)

HQ spin-flip amplitudes are suppressed by ($1/m_Q$).

⇨ Heavy Quark Spin Symmetry

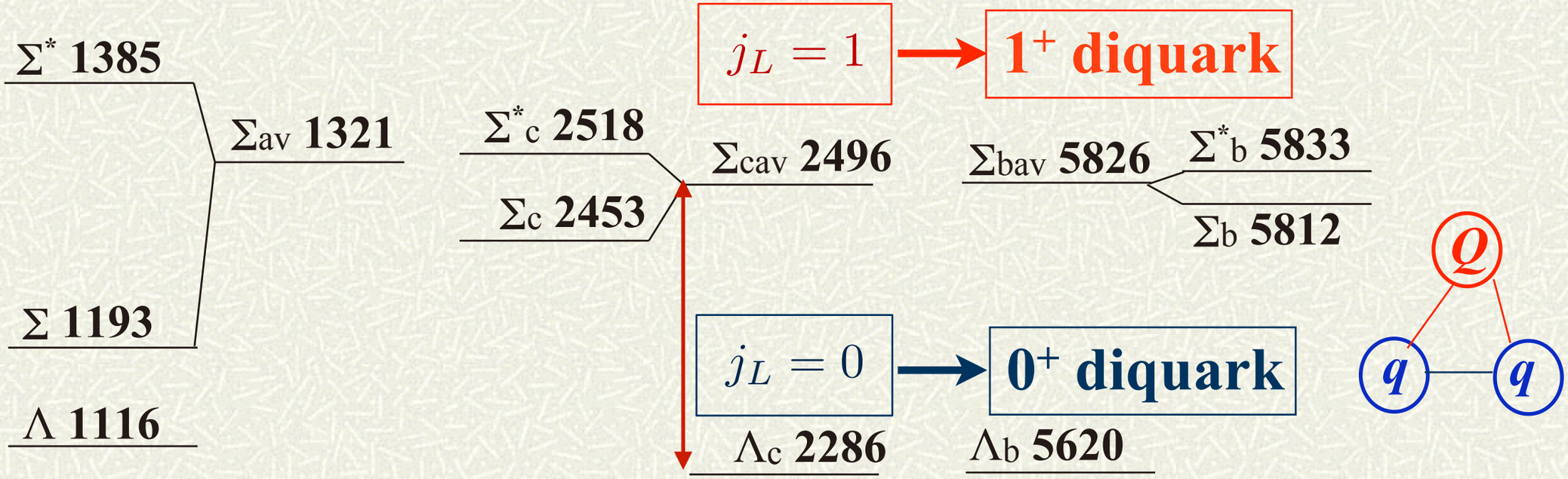
Heavy Quark Spin Symmetry

HQ spin symmetry $[S_Q, H] = O\left(\frac{1}{m_Q}\right)$



$\Big\}$ $\vec{J} = \vec{S}_Q + \vec{j}_L \qquad \vec{j}_L = \vec{S}_q + \vec{L}_q$

$J = j_L \pm \frac{1}{2}$ **states are degenerate in the HQ limit.**



Spectroscopy of Light Diquarks

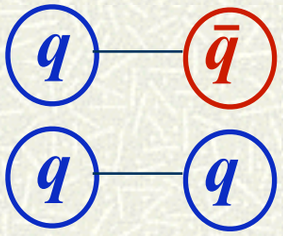
Diquark

- QCD predicts attraction in the PS and S channels:

  PS meson qq^{bar} : color 1, $J^{\pi}=0^{-}$, flavor 1+8

  S diquark $[qq]_0$: color 3^{bar}, $J^{\pi}=0^{+}$,

  flavor SU(3) 3^{bar} : $[ud]_0$, $[ds]_0$, $[sd]_0$



- One gluon exchange - color magnetic interaction

  $CMI = (-\alpha)\, \Sigma_{ij}\, (\lambda_i \cdot \lambda_j)\, (\sigma_i \cdot \sigma_j) = -16\,\alpha$ for PS qq^{bar} meson

  $= -8\,\alpha$ for S qq diquark

- $M(A)-M(S) = (2/3)\,[M(\Delta)-M(N)] \sim 200$ MeV

  $(32/3)\alpha$ $\quad +8\,\alpha - (-8\,\alpha) = 16\,\alpha$

Diquark

- Diquarks in (quenched) lattice calculations
  - Hess, Karsch, Laermann, Wetzorke, PR D58, 111502 (1998)
    from the correlators in the Landau gauge
    $m_q \sim 342$ MeV, M(S) ~ 694 MeV, M(A) ~ 810 MeV
  - Alexandrou, de Forcrand, Lucini, PRL 97, 222002 (2006)
    gauge invariant calculation inside a Qqq system
    M(A) - M(S) ~ 100-150 MeV, R(S) ~ 1 fm
    M(PS) - M(S) ~ 600 MeV
  - Babich, et al., PR D76, 074021 (2007)
    diquark correlation and effective mass in the Landau gauge
    M(S) - $2m_q$ ~ -200 MeV, M(A) - M(S) ~162 MeV
  - DeGrand, Liu, Schaefer, PR D77, 034505 (2008)
    diquark correlation in the light baryon
    S: strongly attractive, PS: attractive for small m_q

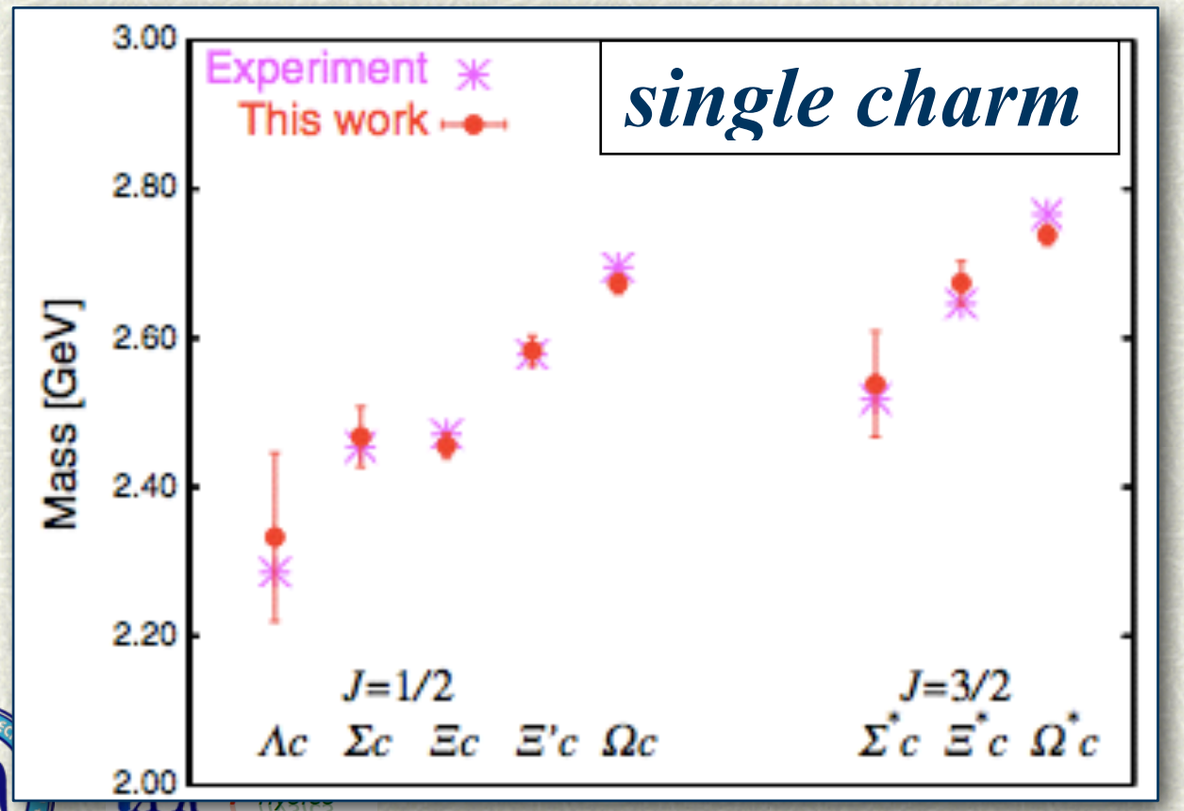
Diquark

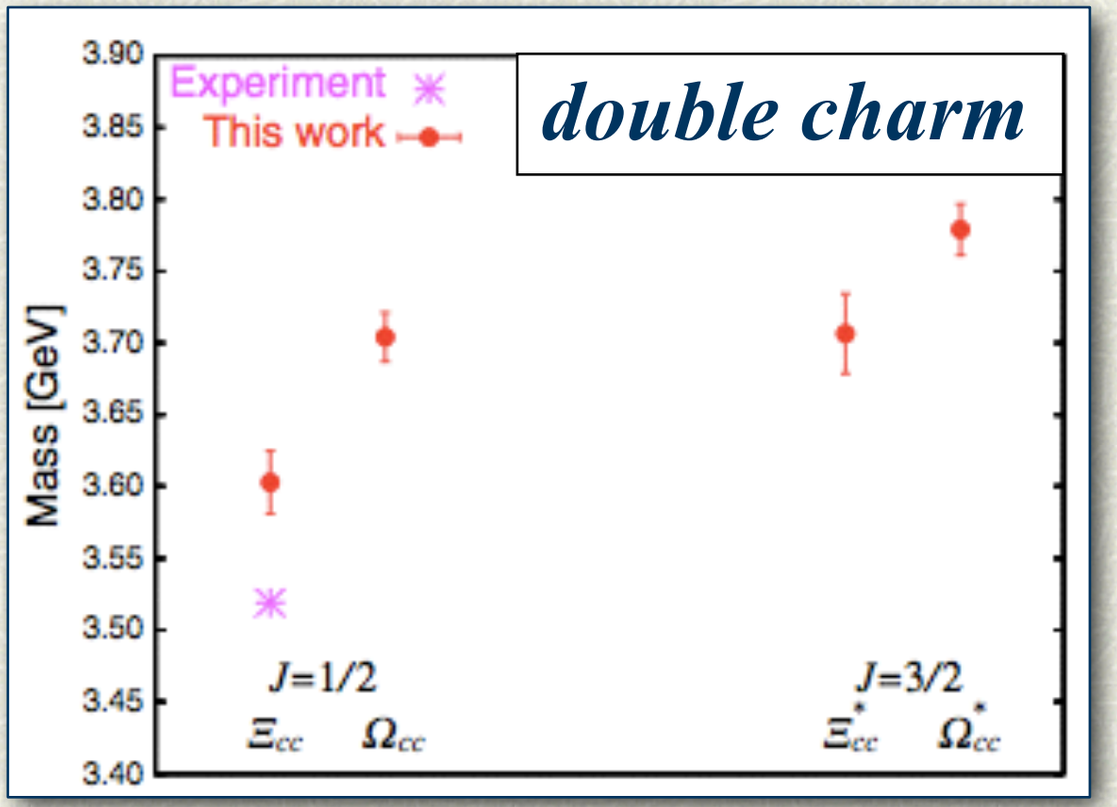
- **Heavy Baryons, Λ_Q, Σ_Q = Q + (qq)**
  Because the spin dependent interaction is suppressed between the heavy Q and light quarks, the heavy baryon spectrum is sensitive to the light diquark (qq) *spin-dependent* correlation.

		J^π	color	flavor
Pseudoscalar	$\epsilon_{abc}(u_a^T C d_b)$	0^-	$\bar{3}$	$\bar{3}$ $(I=0)$
Scalar	$\epsilon_{abc}(u_a^T C\gamma^5 d_b)$	0^+	$\bar{3}$	$\bar{3}$ $(I=0)$
Vector	$\epsilon_{abc}(u_a^T C\gamma^\mu\gamma^5 d_b)$	1^-	$\bar{3}$	$\bar{3}$ $(I=0)$
Axial Vector	$\epsilon_{abc}(u_a^T C\gamma^\mu d_b)$	1^+	$\bar{3}$	6 $(I=1)$
	$\epsilon_{abc}(u_a^T C\sigma^{\mu\nu} d_b)$	$1^+, 1^-$	$\bar{3}$	6 $(I=1)$
color 6 only in Exotic Hadrons	$(u_a^T C d_b) + (a \leftrightarrow b)$	0^-	6	6 $(I=1)$
	$(u_a^T C\gamma^5 d_b) + (a \leftrightarrow b)$	0^+	6	6 $(I=1)$
	$(u_a^T C\gamma^\mu\gamma^5 d_b) + (a \leftrightarrow b)$	1^-	6	6 $(I=1)$
	$(u_a^T C\gamma^\mu d_b) + (a \leftrightarrow b)$	1^+	6	$\bar{3}$ $(I=0)$
	$(u_a^T C\sigma^{\mu\nu} d_b) + (a \leftrightarrow b)$	$1^+, 1^-$	6	$\bar{3}$ $(I=0)$

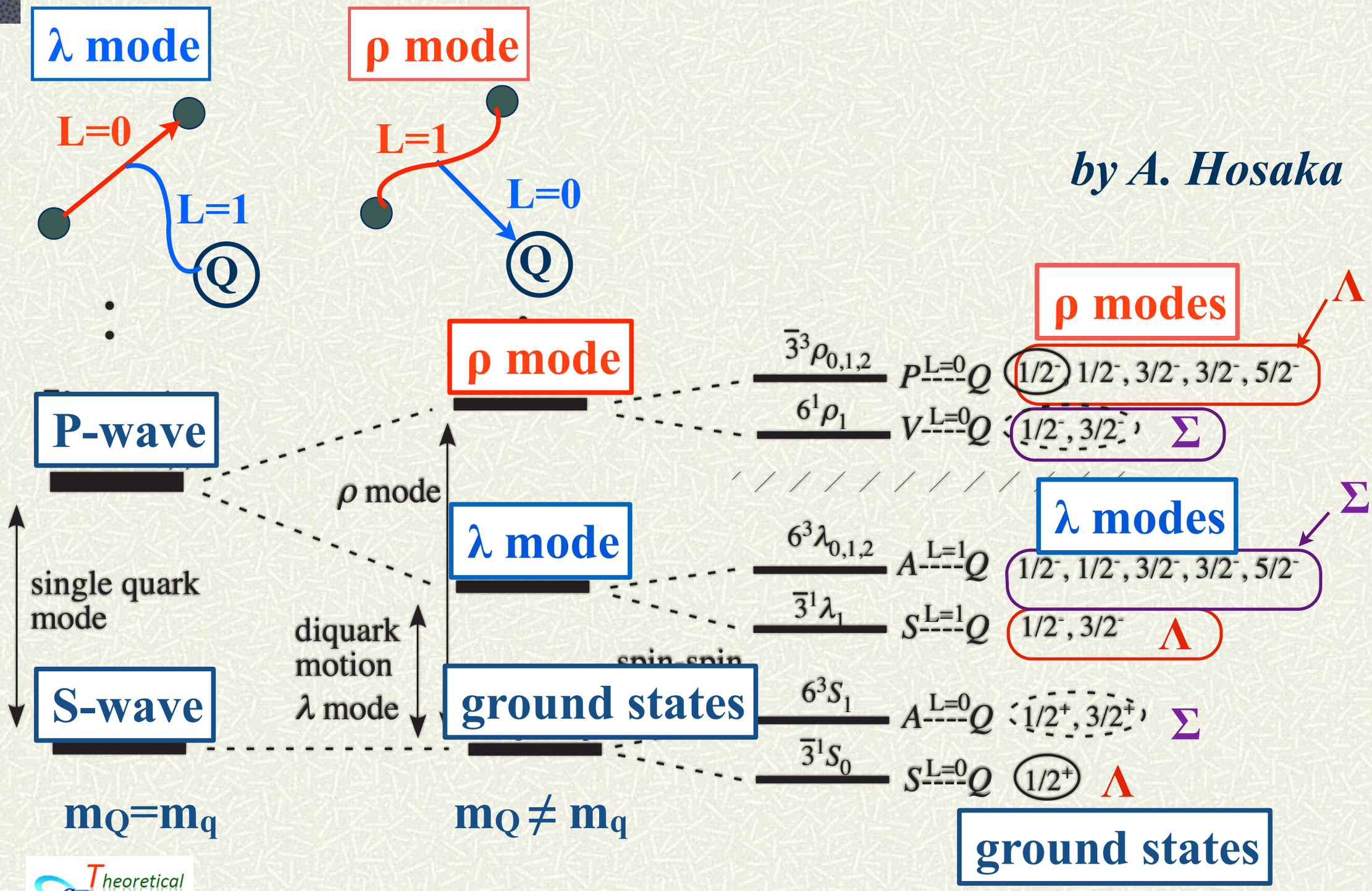
Charmed Baryons: Ground states

- All the ground-state (S-wave) single charm baryons have been observed, and are consistent with the quark model.
- Lattice QCD reproduces the ground state baryon spectrum fairly well.
- Y. Namekawa, et al., (PACS-CS Collaboration) (2+1) flavor with physical quark mass, PRD 87, 094512 (2013)



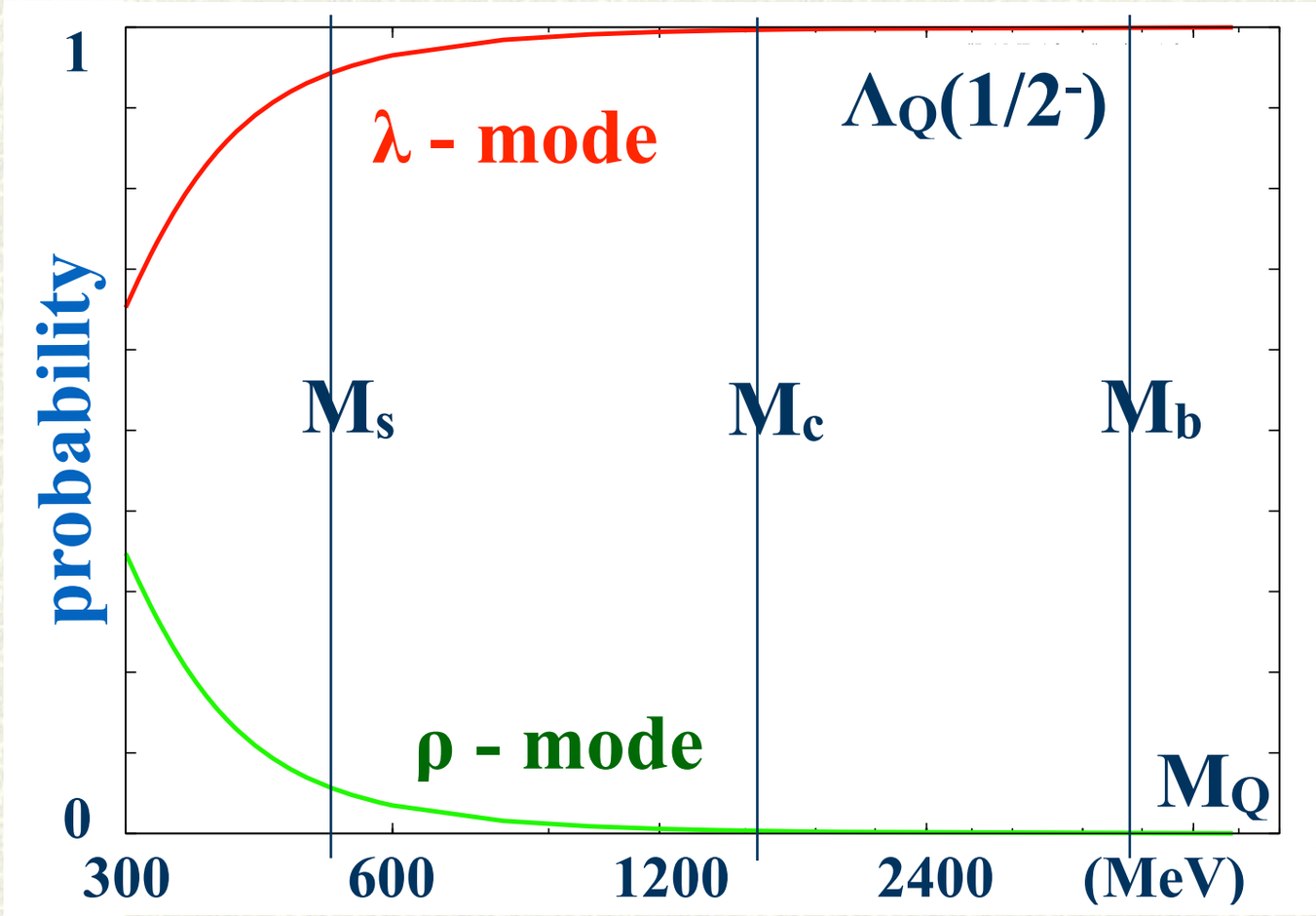


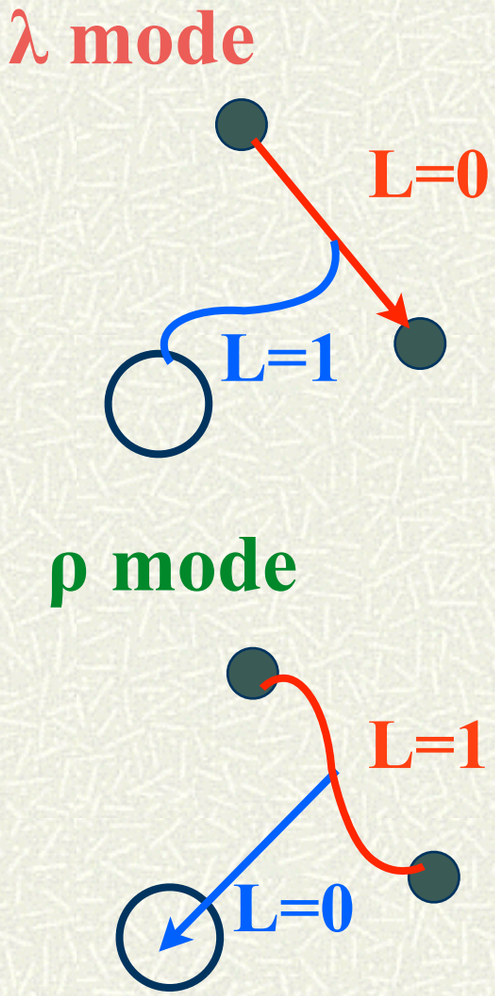
P-wave excited states



P-wave excited states: from s to c

- **Probabilities of λ and ρ modes *v.s.* heavy quark mass by a Hamiltonian quark model with spin-spin, spin-orbit and tensor forces**





Yoshida, et al., ArXiv:1510.01067

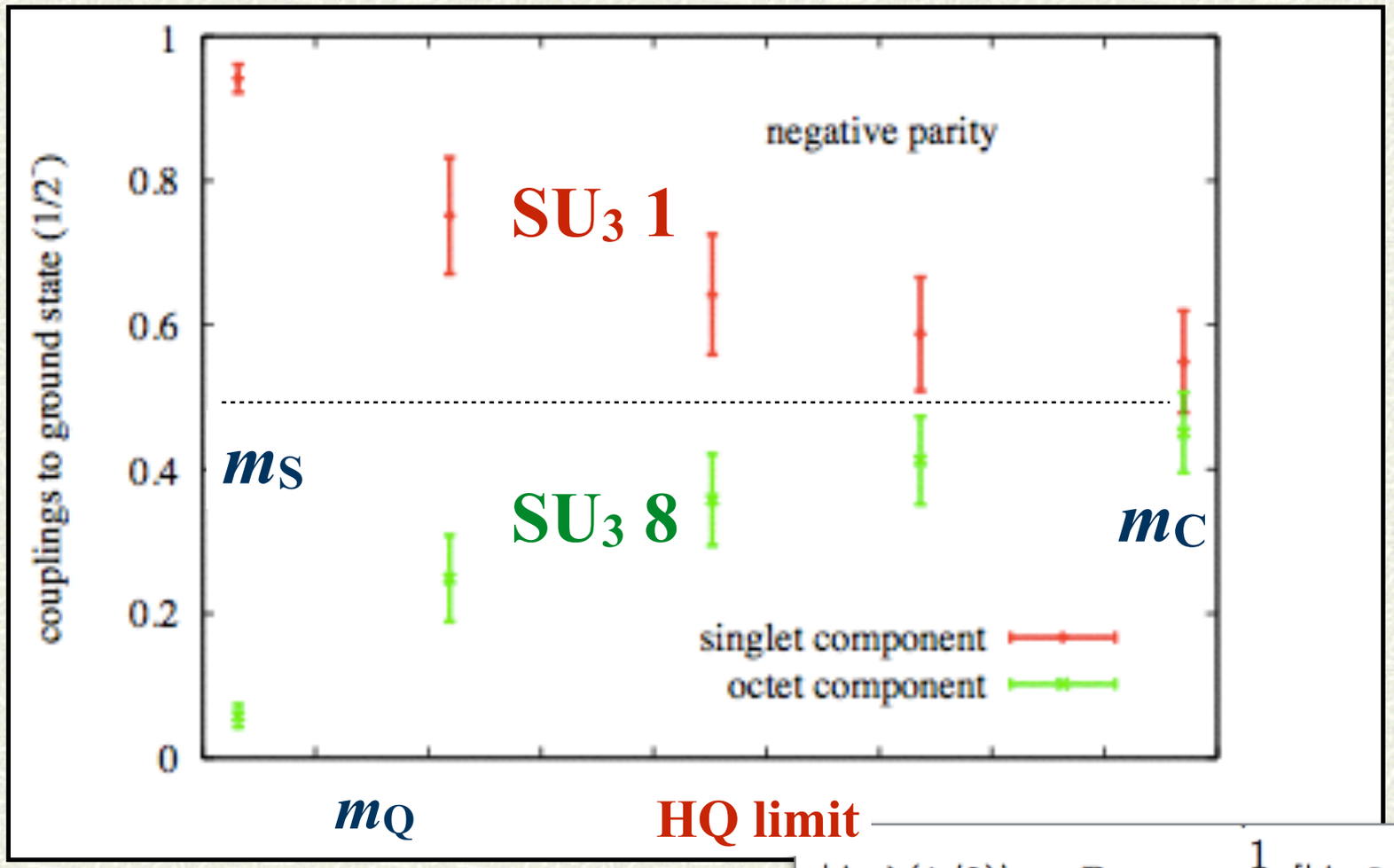
From Strangeness to Heavy Quarks

- For light quarks, $SU(6) \supset SU(3)_f \times SU(2)_s$ determines the overall structure of the spectrum.
  (The spin dependent forces break the SU(6) symmetry.)
- The spin dependent forces are suppressed for HQ systems, and the kinetic energy and the confinement force play the central role.
- The spectrum changes from SU(3) to HQ symmetry.
- The heavy baryons can effectively a spectroscopy of light di-quarks.

P-wave excited states: from s to c

- **Transition from the SU(3)$_f$ to HQ spin symmetry.**
  Lattice QCD for $m_Q = m_S \rightarrow m_C$ with $m_\pi^2 = 410$ MeV

P. Gubler, T.T. Takahashi, M.O., to be published



$$|\Lambda;\lambda(1/2)\rangle = R_\lambda \chi_\rho = \frac{1}{\sqrt{2}}[|\Lambda;\mathbf{8}(1/2)\rangle + |\Lambda;\mathbf{1}(1/2)\rangle]$$

Conclusion

- **What are the REALISTIC degrees of freedom in hadron excited states?**
  The residences in the 2nd floor (*QP*)
  Colored QP: Constituent quark, gluon, diquark
  Colorless QP: low-lying hadrons
- **What are needed experimentally?**
  Determine quantum numbers
  Analyze production, transitions, decay processes
  => need high statistics, new production methods
- **What are needed in theory?**
  Define QPs in QCD and determine their roles in hadrons
  Predict exotic hadrons (mass, quantum numbers)
  Bridge Lattice QCD to coupled channel analyses