Hadron physics /Past-Present-future

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International workshop
on the Extension Project for the J-PARC Hadron Experimental Facility (J-PARC HEF-ex WS)

1. Introduction
2. Scenario from QCD
3. Heavy and strange quarks
4. Unsolved/unsettled Problems
5. Toward J-PARC-Extension
6. Summary

1. Introduction

Before around 1950:

Nucleons, ..were elementary

1934: **Yukawa's pion**

1947: Kaon, Λ in cosmic ray

1948: Pion in cosmic ray

1952: Λ, Σ, Ξ in accelerator…

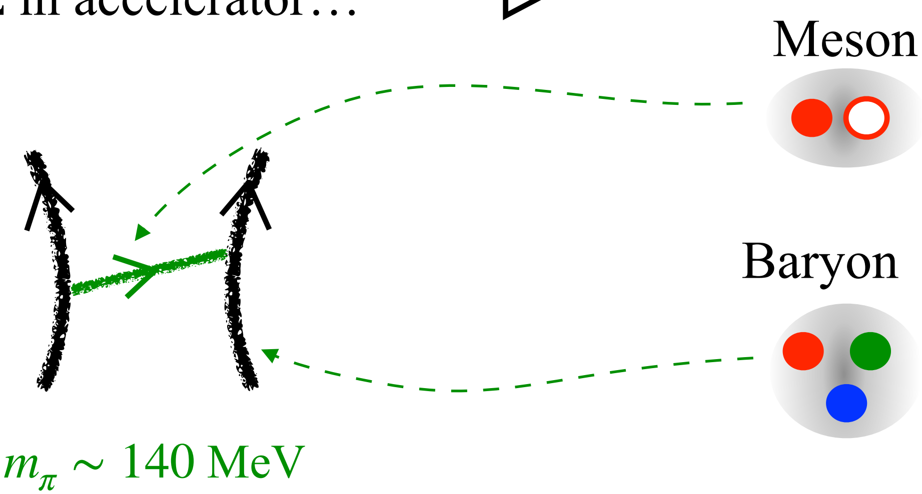
But then

1962:

Gell-Mann, Zweig's

Quark model

H. Yukawa



M. Gell-Mann

G. Zweig

Octets and decuplets: Systematics in the ground states

Hadrons are **composite particles** → **Spectroscopy**

Spectroscopy — What's interest

In itself:

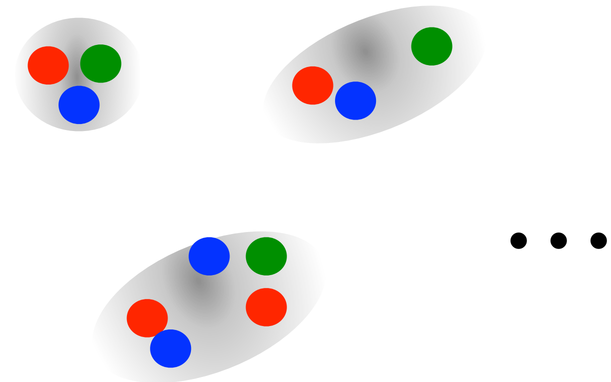
Ground states:

Masses, charge/magnetic densities

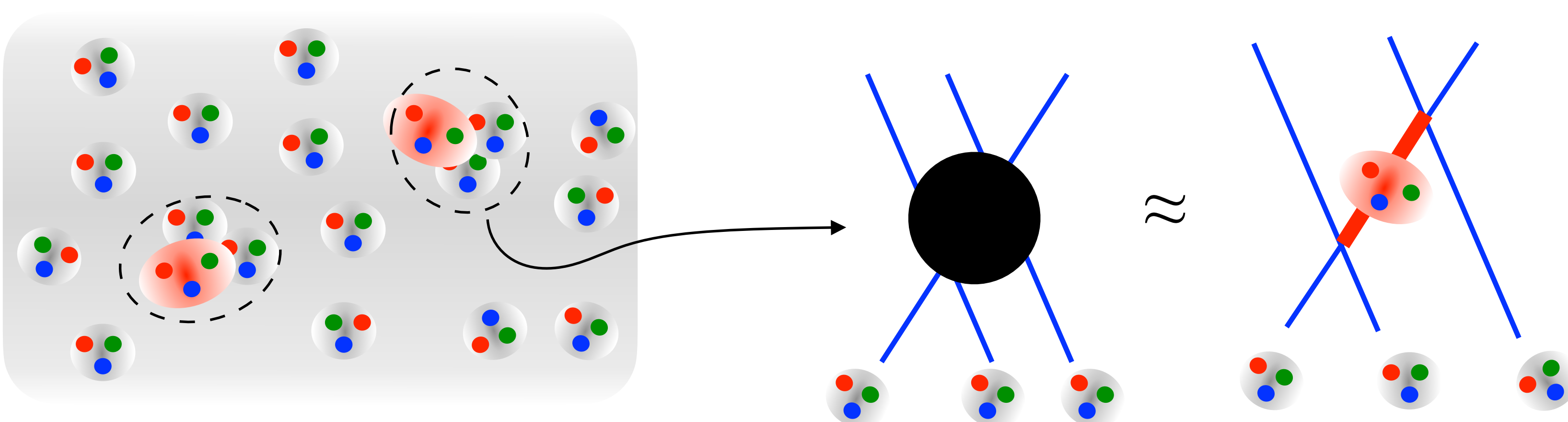
Excited states:

What states, what structures

Which ones are ***truly exotic***?



Relevance to: many-body systems/forces

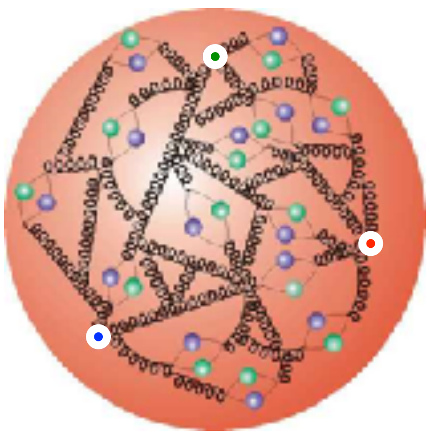


How quarks build baryons

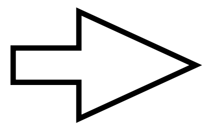
*From now on, discussions are mostly **baryons***

Today’s approach for ***baryons***

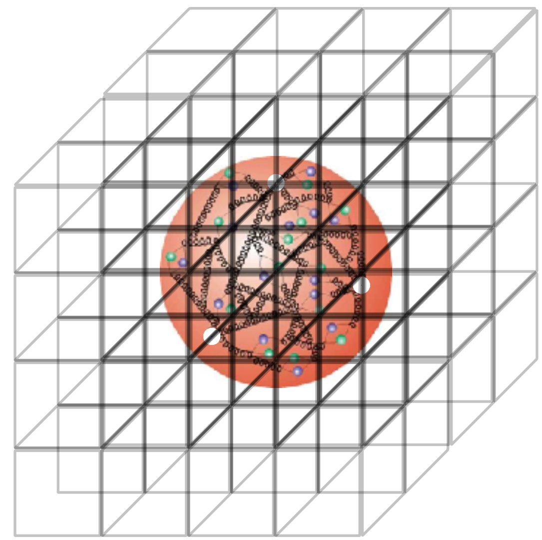
First principle calculations Lattice QCD



http://ppwww.phys.sci.kobe-u.ac.jp/~yamazaki/lectures/07/modernphys-yamazaki07.pdf



3 current (bare) quarks
Many virtual $\bar{q}q$ pairs
mediated by gluons

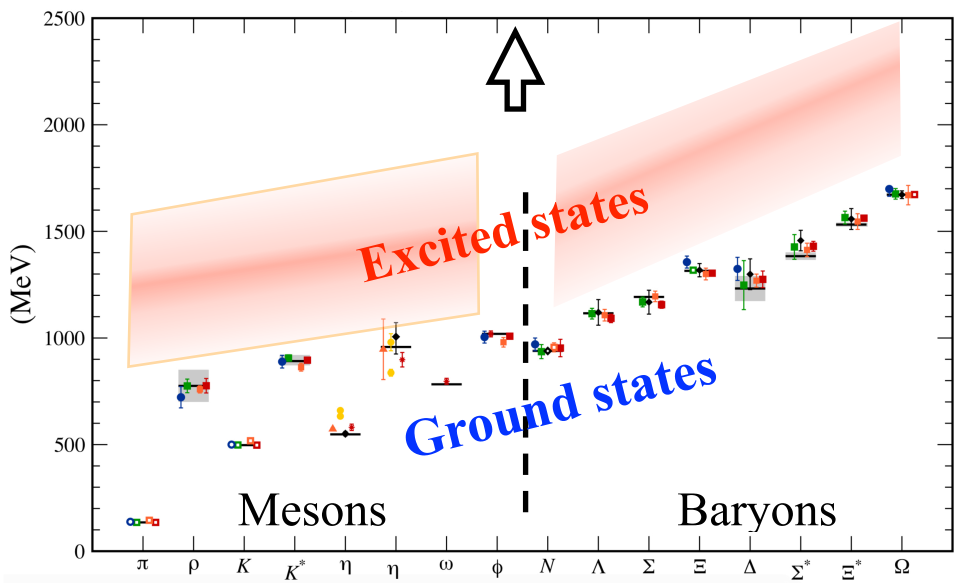


Hadrons from QCD — Lattice

Ground state (G.S.) properties are systematically reproduced

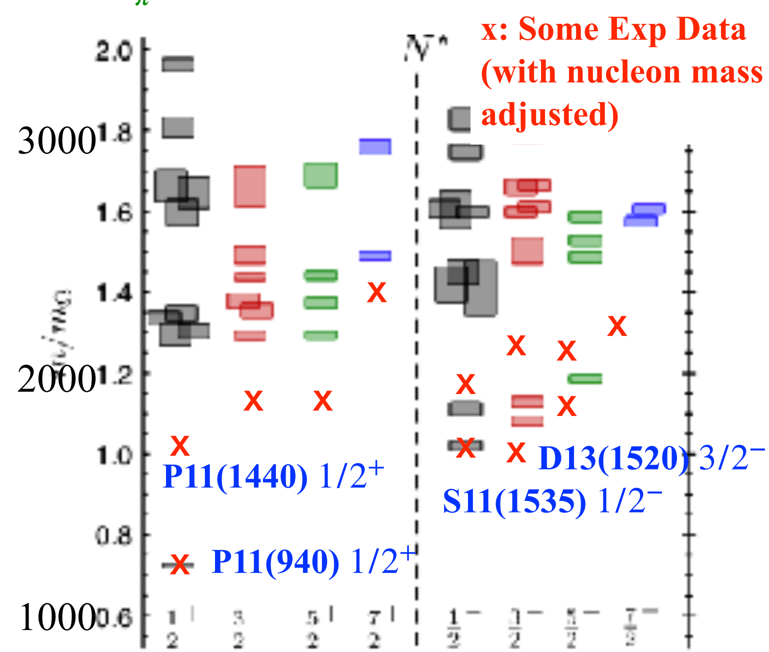
Hadron spectrum (**G.S.**) from lattice QCD (***from pdg***)

$m_\pi \sim$ Physical



Nucleon **resonances**

Edwards et al, PRD84, 074508 (2011)
$m_\pi = 396$ MeV

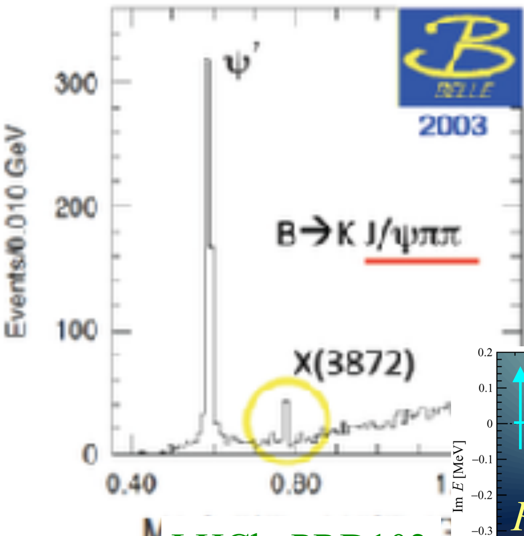


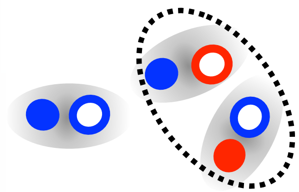
Resonances seem complicated, and yet…

New (exotic?) phenomena

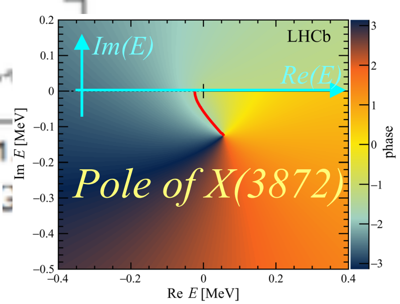
X(3872)

Belle, PRL91 (2003) 262001





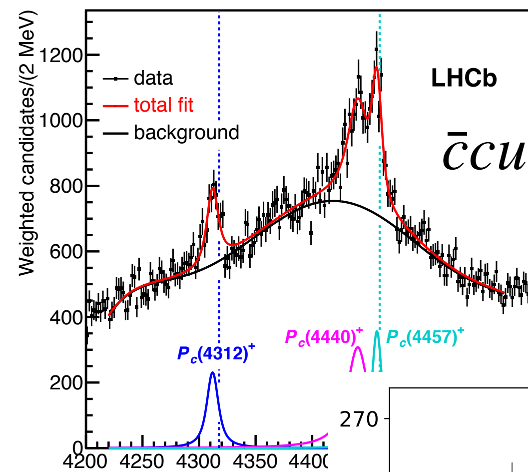
$\bar{c}c$ or D^*–$\bar{D}$

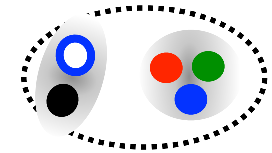


LHCb, PRD102 092005 (2020)

P_c(4310, 4460, 4520)

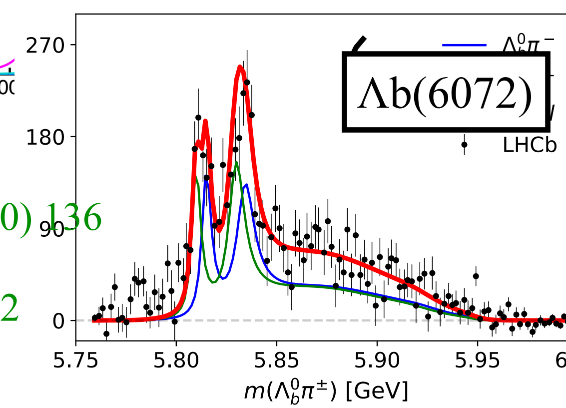
LHCb, PRL122 (2019) 222001





$\bar{c}cuud \to (\bar{c}u)(cdd)$

Λb(6072)



LHCb, JHEP 06 (2020) 136
Arifi et al, PRD 101 (2020) 111502

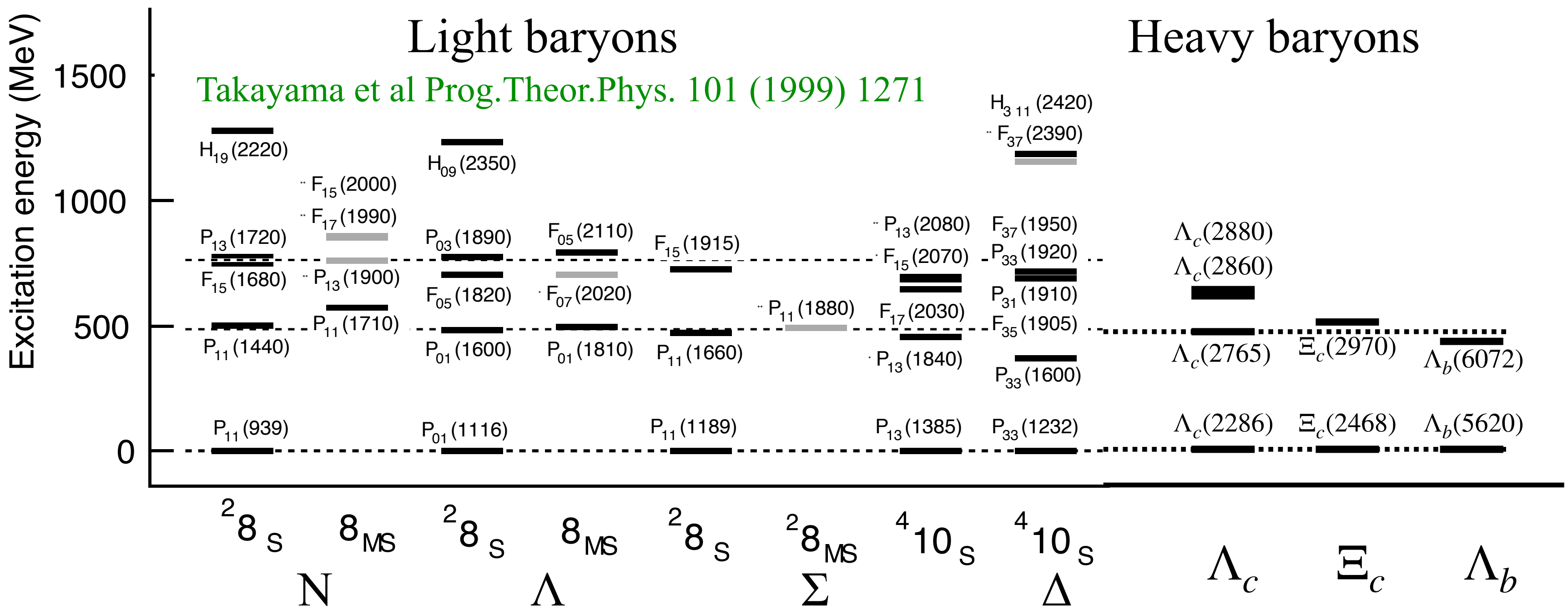
- Many of them contain heavy and light quarks
- Near/above threshold *excited states*
  ~ low energy dynamics ~ interactions/scatterings/resonances

⇨ Are they really complicated?

Systematic behavior: excited states

u, d, s baryons

Positive parity baryon resonances



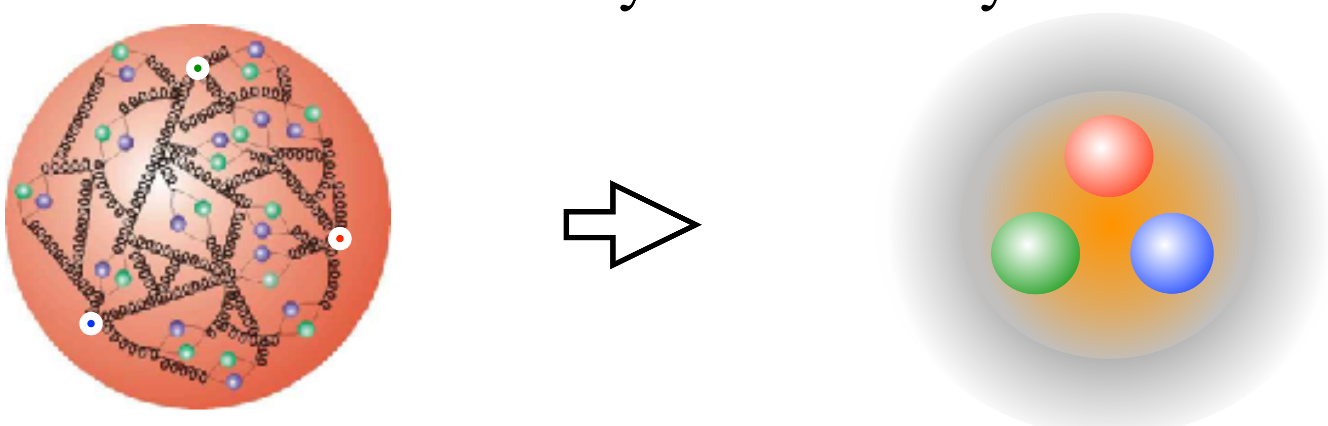
=> Natural to expect *simple dynamics*

Simple dynamics?

(Light u,d,s quarks)

- Many **d**egrees **o**f **f**reedom
  → Fewer **dof** with simple dynamics at low energies

- Common features many-body dynamics
  Useful for the study of various systems



Light quarks and gluons

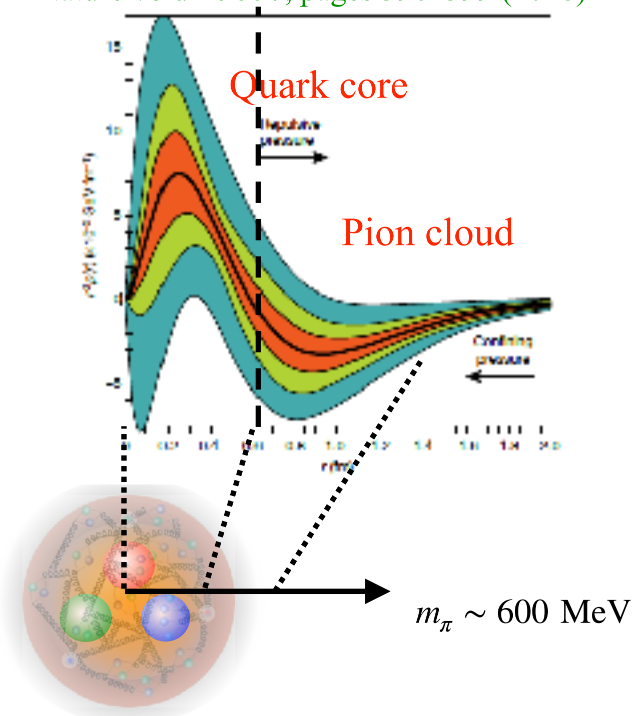
http://ppssh.phys.sci.kobeu.
ac.jp/~yamazaki/lectures/07/modernphys-yamazaki07.pdf

Confined constituent quarks
+ pion cloud

Evidences

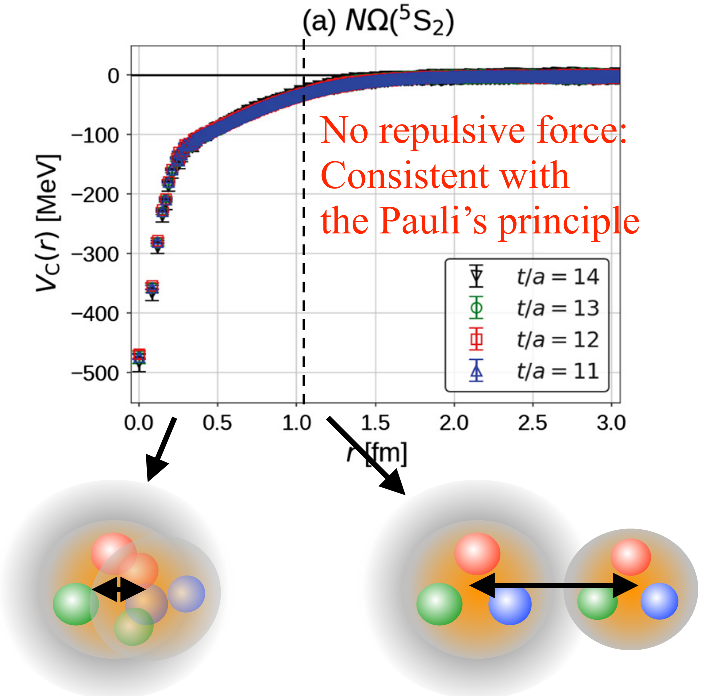
Pressure distribution inside the proton

V.D. Burkert, L. Elouadrhiri & F. X. Girod
Nature volume 557, pages 396–399 (2018)



Ω-N interact at short distances

T. Iritani et αl, HALQCD collaboration
PLB792 (2019) 284



Lattice study of charge radius Ω ~ 0.5-6 fm vs p ~ 0.87 fm

Core ***Core + cloud***

Boinepalli et al, D 80, 054505 (2009); For Δ at $m_\pi \sim 600$ MeV

Alexandrou et al, PRD 82, 034504 (2010); For Ω at $m_\pi \sim 297$ MeV

Can et al, PRD 92, 114515 (2015) For Ω at $m_\pi \sim 156$ MeV

2. Scenario from QCD

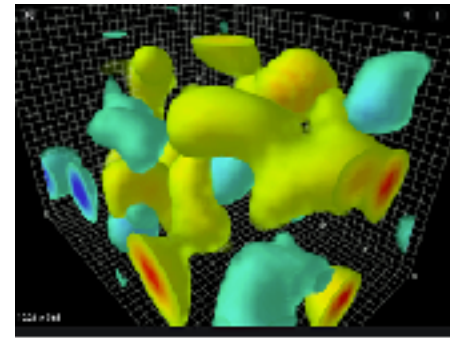
Uniqueness of QCD as a many-body problem → Non-trivial dynamics

QCD vacuum is not empty ~ Instantons are created and annihilated

- Extended (topological) object of gluons, of size ~ 0.2 fm
- QCD vacuum is topologically nontrivial
- Chiral symmetry is broken spontaneously $m \neq 0$

$$\langle \bar{q}q \rangle \sim \int \frac{d^4k}{i(2\pi)^4} \mathrm{tr} \frac{1}{m - \not{k}} \sim \int_{\infty}^{\infty} d\lambda \nu(\lambda) \frac{\mu}{\lambda^2 + \mu^2} |_{\mu \to 0}$$

Banks-Casher, NPB169(1989)193
D. Diakonov, PPNP51(2003)173
Fukaya et al, PRL104.122002 (2010), PRD.83.074501 (2011)

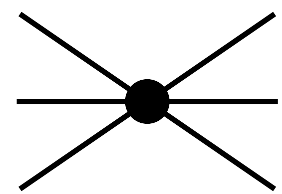


Snapshot of topological densities fluctuating in the vacuum
Derek Leinweber, 2003, 2004
http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/index.html

- Instanton Induced Interaction (III) with $U_A(1)$ breaking

Kobayashi-Maskawa_PTP44(1970)1422
G. 't Hooft, PRL37.8 (1976), PRD14, 3432 (1976)

$$\mathscr{L}_{III} = g_D \left(\det[\bar{q}_i(1 - \gamma_5)q_j] + h.c. \right)$$



Systematic study: Hatsuda-Kunihiro: Phys. Repts. 247 (1994) 221-367

Effective theory

Building blocks **Confined constituent quarks + pions around**

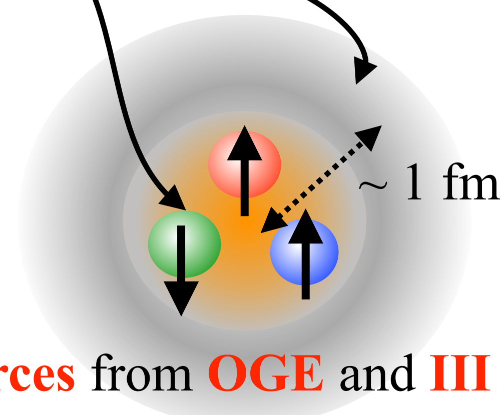
Manohar-Georgi' chiral quark model, NPB234 (1984) 189, with III

$$\mathscr{L} = \bar{q}(i\partial\!\!\!/ - g A\!\!\!/)q - m\bar{q}q + \mathscr{L}_{III}$$

Quark core

$$+\bar{q}V\!\!\!/ q + g_A \bar{q} A\!\!\!/ \gamma_5 q + \frac{1}{4} f_\pi^2 \mathrm{tr}\, \partial^\mu U \partial_\mu U^\dagger - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \cdots$$

Meson cloud



Meson cloud at long distances, ***r* > 1 fm**

Systematically explored by chiral perturbation theory

Quark core at intermediate distances

0.2 fm < *r* < 1 fm

Massive constituent quarks: $m_u \sim m_d \sim 360$, $m_s \sim 540$ MeV

Spin-dependent forces **spin-spin (*SS*)** and **spin-orbit (*LS*) forces** from **OGE** and **III**

Unsettled issues in page 15 and after → Main discussions at J-PARC extension

Parameters are determined by exp data or matching with QCD

At the same time ***Explore their dynamical origin***

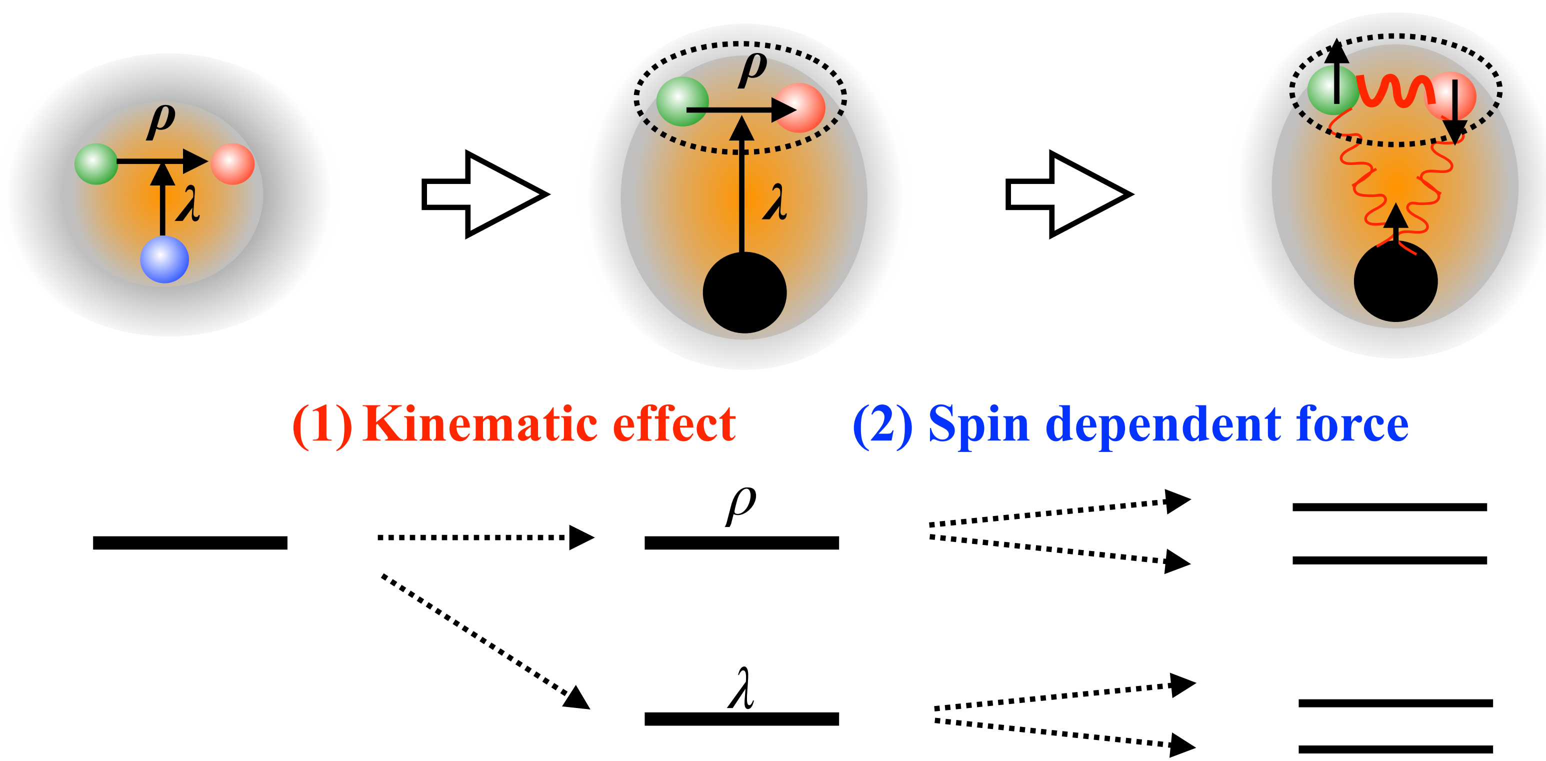
3. Heavy and strange quarks

(1) **Kinematic effect** disentangle λ and ρ modes: Internal motion

(2) **Spin-dependent force** of OGE vs III: non-trivial features of QCD

→ (Light) ***Diquarks***

(3) $U_A(1)$ anomaly in baryons: ρ and λ inversion



Heavy and strangeness

(1) Kinematic effect disentangle λ and ρ modes: Internal motion

(2) Spin-dependent force of OGE vs III: non-trivial features of QCD

(3) $U_A(1)$ anomaly in baryons: ρ and λ inversion

u, d, s + Q (c, b)

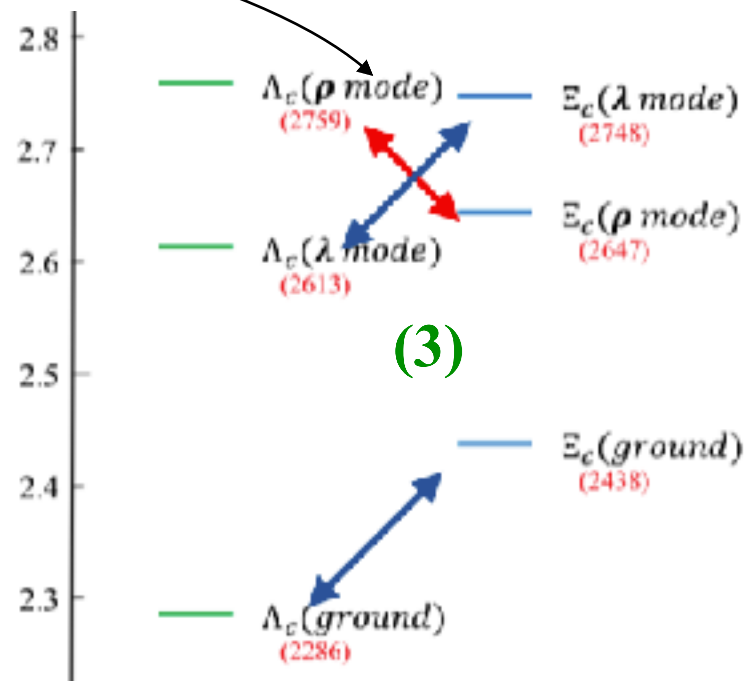
Inverse mass hierarchy:

- 0^+ and 0^- diquarks as chiral partners
- $U_A(1)$ anomaly included

0^-: M(us), M(ds) < M(ud) ~ ρ mode

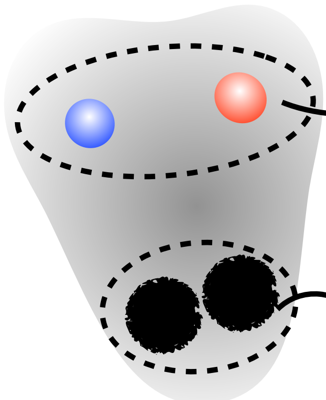
0^+: M(us), M(ds) > M(ud) ~ λ mode

Kim et al, Phys.Rev.D 102 (2020) 014004



Multi-heavy hadrons

Example: $QQ - \bar{q}\bar{q}$ tetraquark



$m_{\bar{q}}$: at $\sim \Lambda_{QCD}$

Mixture of dynamics ***at and beyond*** Λ_{QCD}

M_Q : at $\gg \Lambda_{QCD}$

Stable strongly; decays only weakly

Karliner-Rosner, PRL 119(20) (2017) 202001
Meng et al, PLB 814 (2021) 136095

How rich hadrons can be? beyond the today's discussion…

4. Unsolved/unsettled problems

Dynamics at **intermediate distances, 0.2 fm < r < 1 fm**

Spin-dependent force

(1) **Spin-Spin**: Too large α_S^{ss}?

(2) **LS**: **missing** in light baryons but evidence in heavy baryons

Different mass dependence of OGE and III

Quark motion

(3) **Roper like-resonances**

Low mass: Universal independent of flavors?

Wide width: directly proportional to $\langle p_i^2 \rangle \sim 1/\langle r^2 \rangle$

⟶ Takizawa's talk

(1) α_S^{ss}: Too large in Spin-Spin interaction?

- Baryon Masses

(From T. Kunihiro, Textbook in Japanese: クォークハドロン物理学入門, サイエンス社, 2013)

$$m_{u,d} = 335 \text{ MeV}, \ m_s = 527 \text{ MeV}$$

Phenomenological mass formula

$$M_B = M_0 + \sum_i^{uds} \left[m_i + \frac{a}{2m_i} \right] + b \sum_{i<j} \frac{\sigma_i \cdot \sigma_j}{m_i m_j}$$

$a = (175.2 \text{ MeV})^2$
$b = (176.4 \text{ MeV})^3$
$M_0 = -56.4 \text{ MeV}$

Data:	Λ(1116)	Σ(1193)	Σ*(1385)	Ξ(1320)	Ξ*(1507)
Calc.	1114	1186	1372	1332	1519

$$V(r) = \frac{\alpha_S^{Coul}}{r_{ij}} \lambda_i \lambda_j + \frac{8\pi \alpha_S^{ss}}{m_i m_j} \delta^3(\vec{r}_{ij}) \sigma_i \sigma_j \lambda_i \lambda_j + \cdots$$

If V(r) is from OGE

It should be $\alpha_S^{Coul} = \alpha_S^{ss}$ BUT $\alpha_S^{Coul} \sim 0.5 \neq \alpha_S^{ss} \sim 1$ or larger

Instanton Induced Interaction (III)

Evidence in the large η' mass ~ $U_A(1)$ problem

原子核物理の将来　— 核理論の課題 —

各論シリーズ　第 12 回

Soryushiron Kenkyu 素粒子論研究 1992

Roles of instantons in the quark model

クォーク模型におけるインスタントンの役割

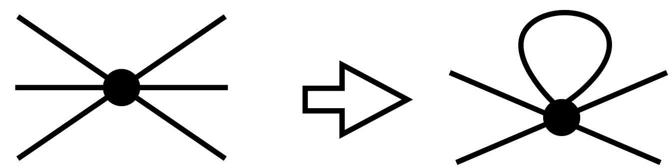
Tokyo Inst. Tec.

Makoto Oks and Sachiko Takeuchi

（1992年12月7日受理）

3-body III reduced to 2-body

Oka-Takeuchi, PRL63, 1780(1989)



$$V_{\mathrm{III}2} = \frac{1}{2} U_0^{(2)} \sum_{i<j} \xi_i \xi_j \left[1 + \frac{3}{32} \lambda_i \cdot \lambda_j + \frac{9}{32} \lambda_i \cdot \lambda_j \, \sigma_1 \cdot \sigma_2 \right] \delta(\vec{r}_{ij})$$

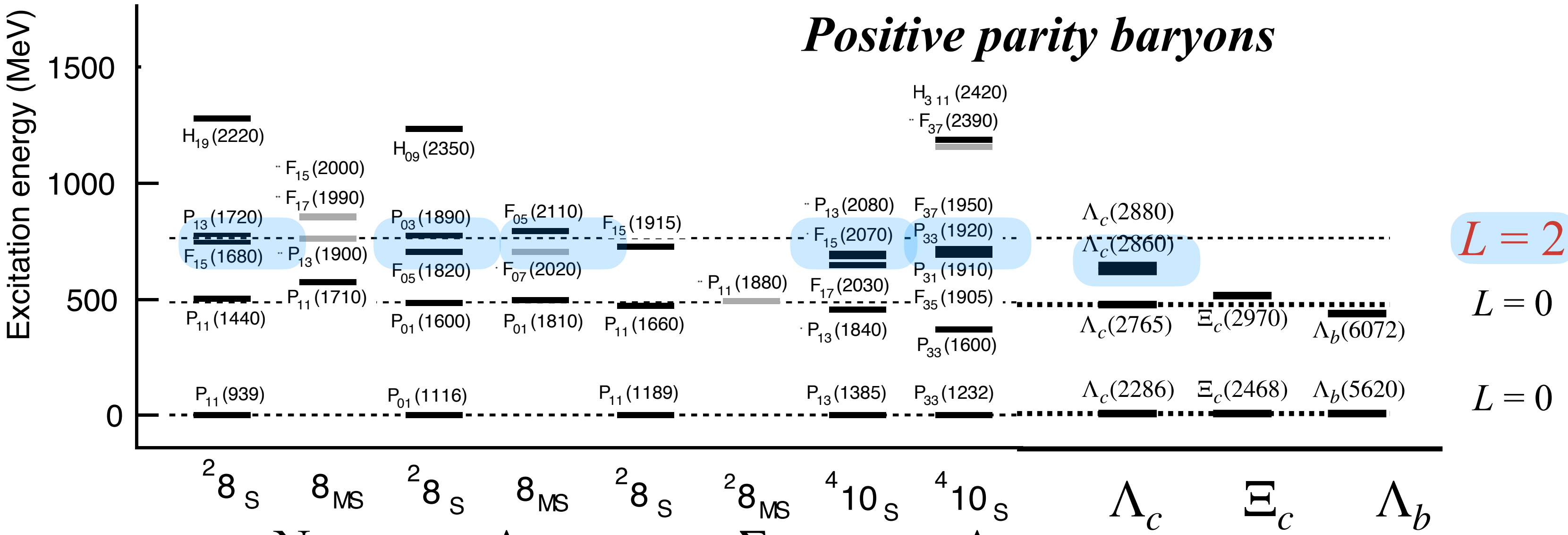
$$\xi_i \equiv m_u / m_i$$

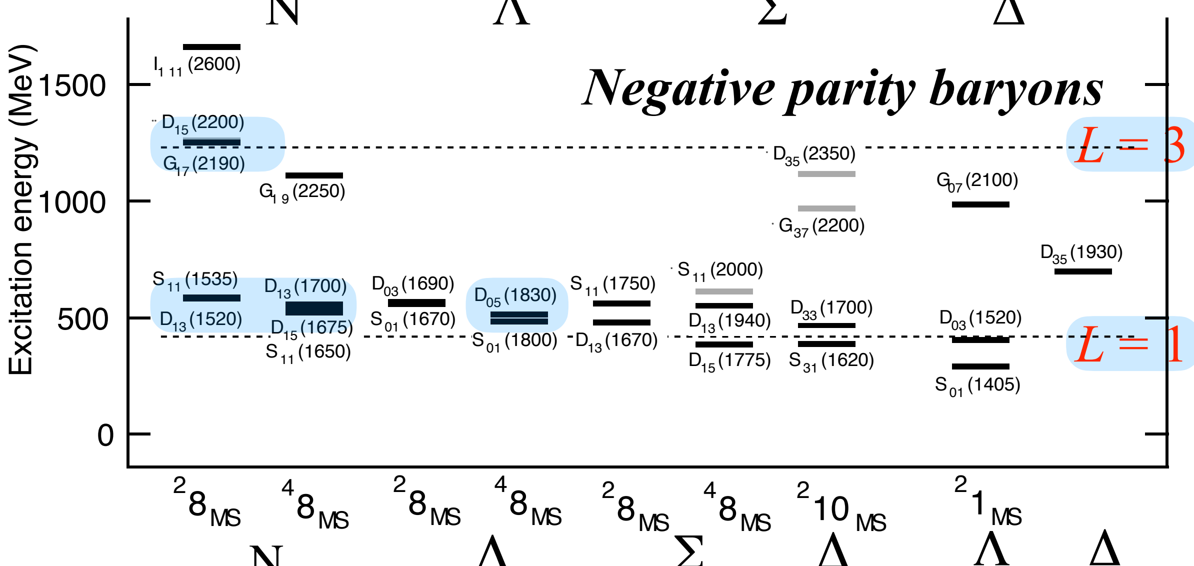
III and OGE are constructive

The strength of III by the $\eta - \eta'$ mass difference

About 40 % of α_S^{ss} is from III　Oka-Takeuchi, PRL66, 1271(1991)

(2) Missing LS in light baryons?





Suppressed LS splittings

⇕

Large splittings
from OGE alone

Do III + OGE save this problem?

Nuclear Physics A 642 (1998) 543–561

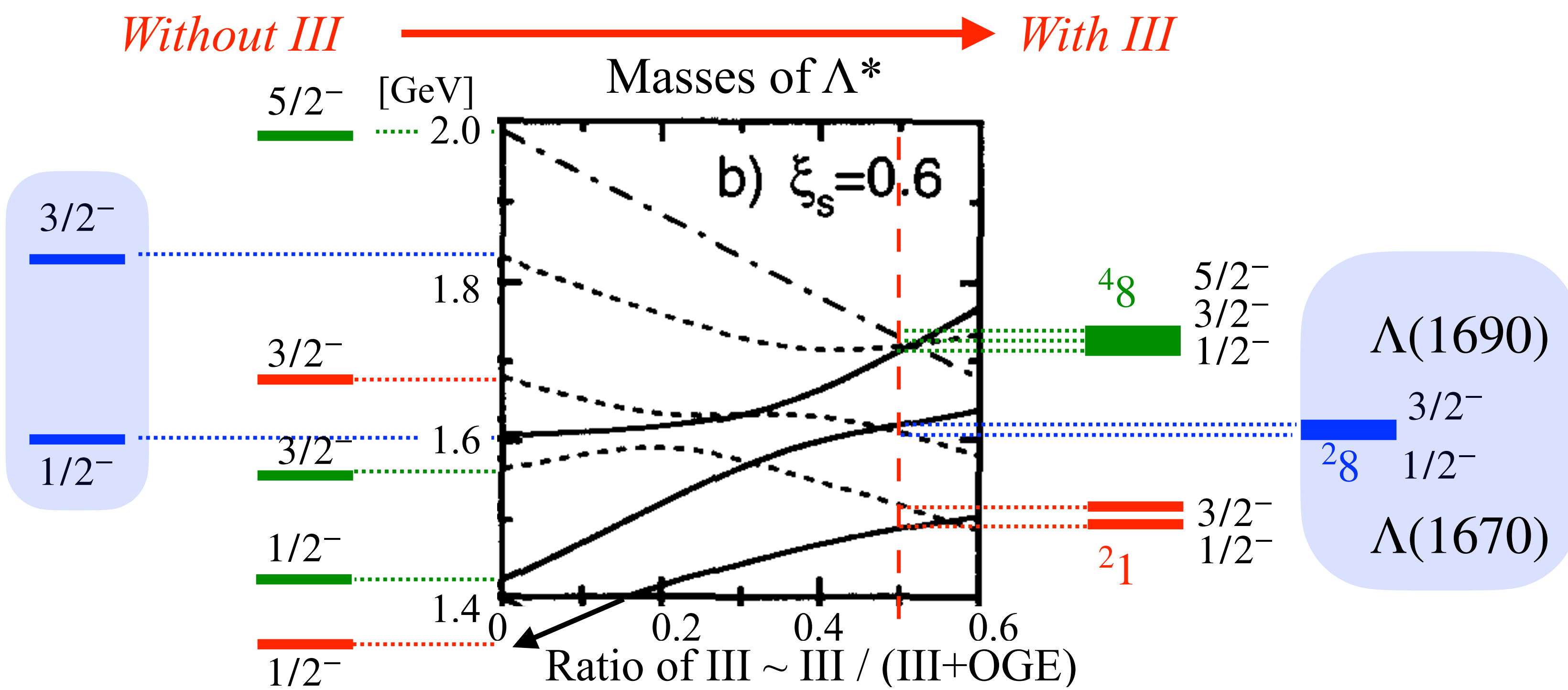
Spin–orbit force of instanton-induced interaction in strange and charmed systems

Sachiko Takeuchi [1]

Department of Public Health and Environmental Science, School of Medicine, Tokyo Medical and Dental University, 1-5-45 Yushima, Bunkyo, Tokyo 113-8519, Japan

Received 6 July 1998; revised 30 July 1998; accepted 15 September 1998

III and OGE are destructive

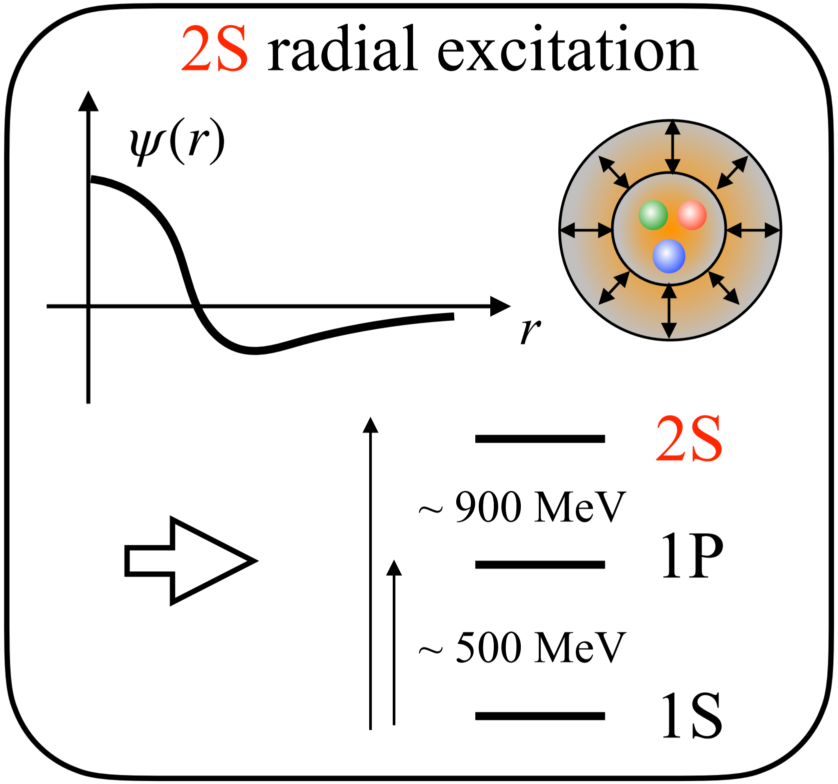


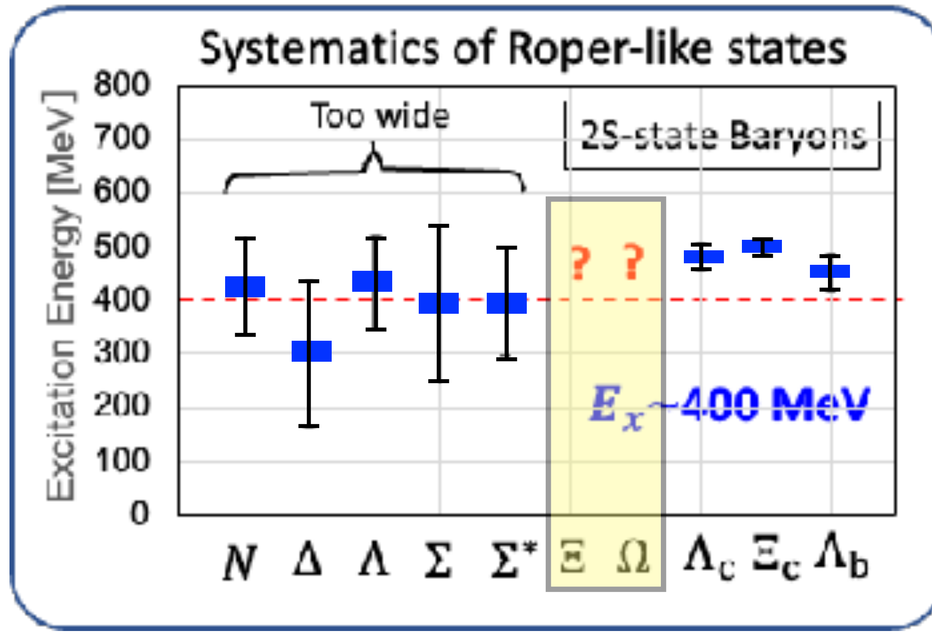
Cancellation between OGE and III explains the small LS

(3) The Roper like states

$J^P = 1/2^+$ for N, and $3/2^+$ for Ω

L.D. Roper, Phys. Rev. Lett. 12, 340 (1964)



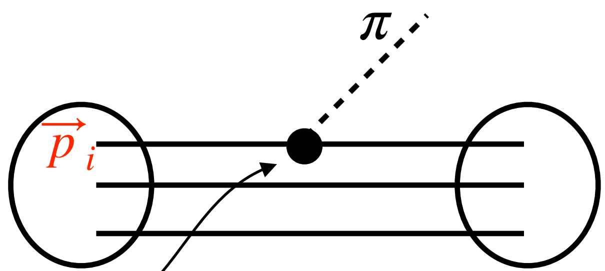


- Small ΔE ~ 400 - 500 MeV ~ universal?
- Large decay width >> Conventional quark model

(3) The Roper like states

Another method to look at the internal quark motion

Decay of Roper like stats



G.S.

NR expansion of ME

$$\langle \mathrm{Roper} | \mathcal{O} | \mathrm{G.S.} \rangle \sim \langle \vec{\sigma} \cdot \vec{q} \rangle (\cancel{a_0} + a_2 \vec{p}_i^{\,2} + \cdots)$$

Leading order (LO) suppressed

Unique for radial excitations

Next to leading order (NLO)

$$\langle p_i^2 \rangle \sim \frac{1}{\langle r^2 \rangle} \quad \sim \mathrm{Size}$$

Arifi et al, *PRD* 103 (2021) 9, 094003

- Previous calculations (LO): too small
- Inclusion of NLO: 50 - 100 MeV for $\Omega^*(3/2^+)$

5. Toward J-PARC-Extension

Baryon spectroscopy of charm and multi-strangeness

Where and how non-trivial (many-body) dynamics works

A simple and working picture for resonances? ~ 1 GeV

Updated theoretical studies

Spin dependent structures/interactions

Quark motion

Where to look at: Figures for Ξ, Ω and charm/bottom baryons

Production and decay processes

Coupled channel scattering theory

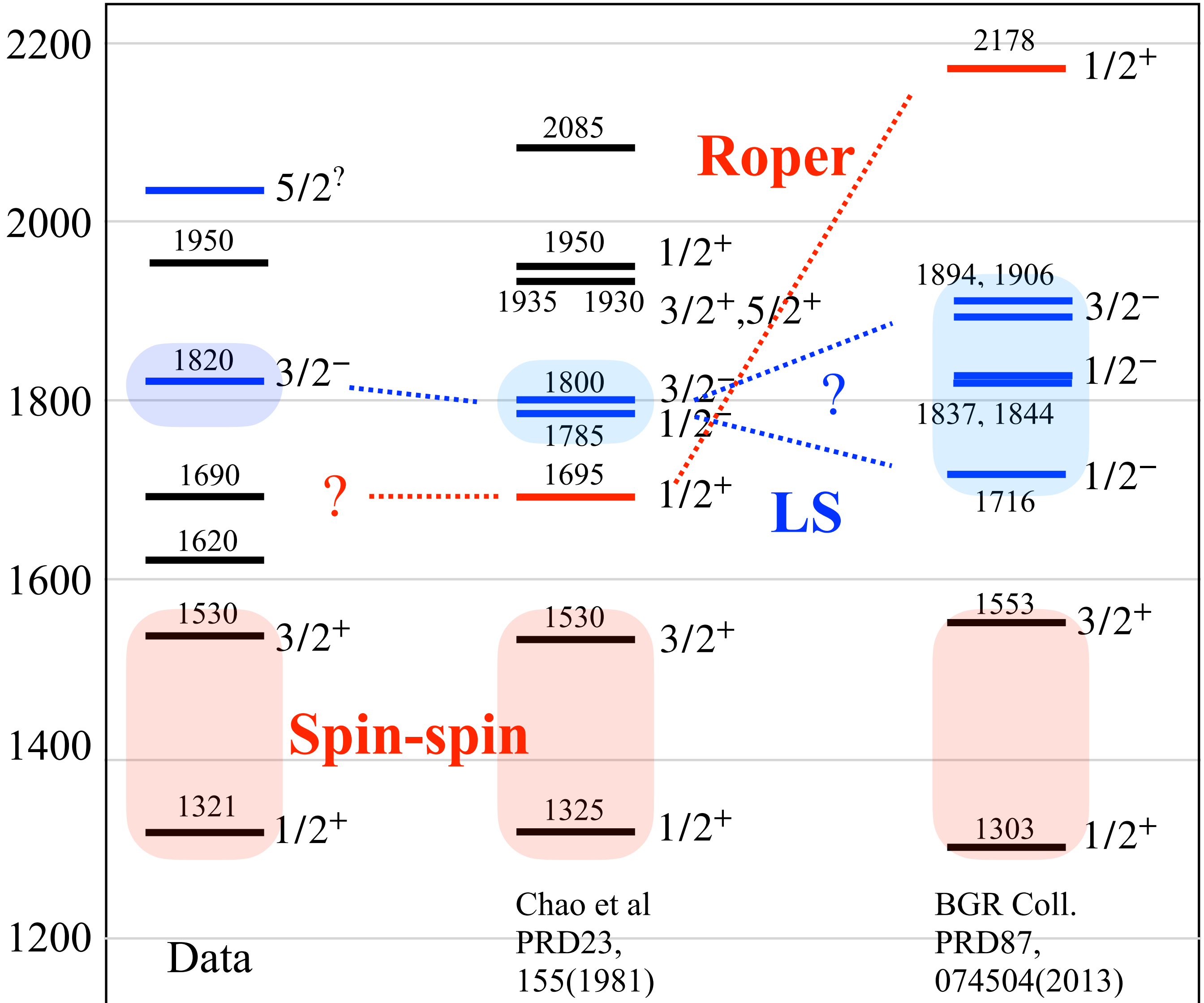
To answer questions for exotic hadrons

Important theoretical issues to extract physics from exp

Explain conventional and observed phenomena

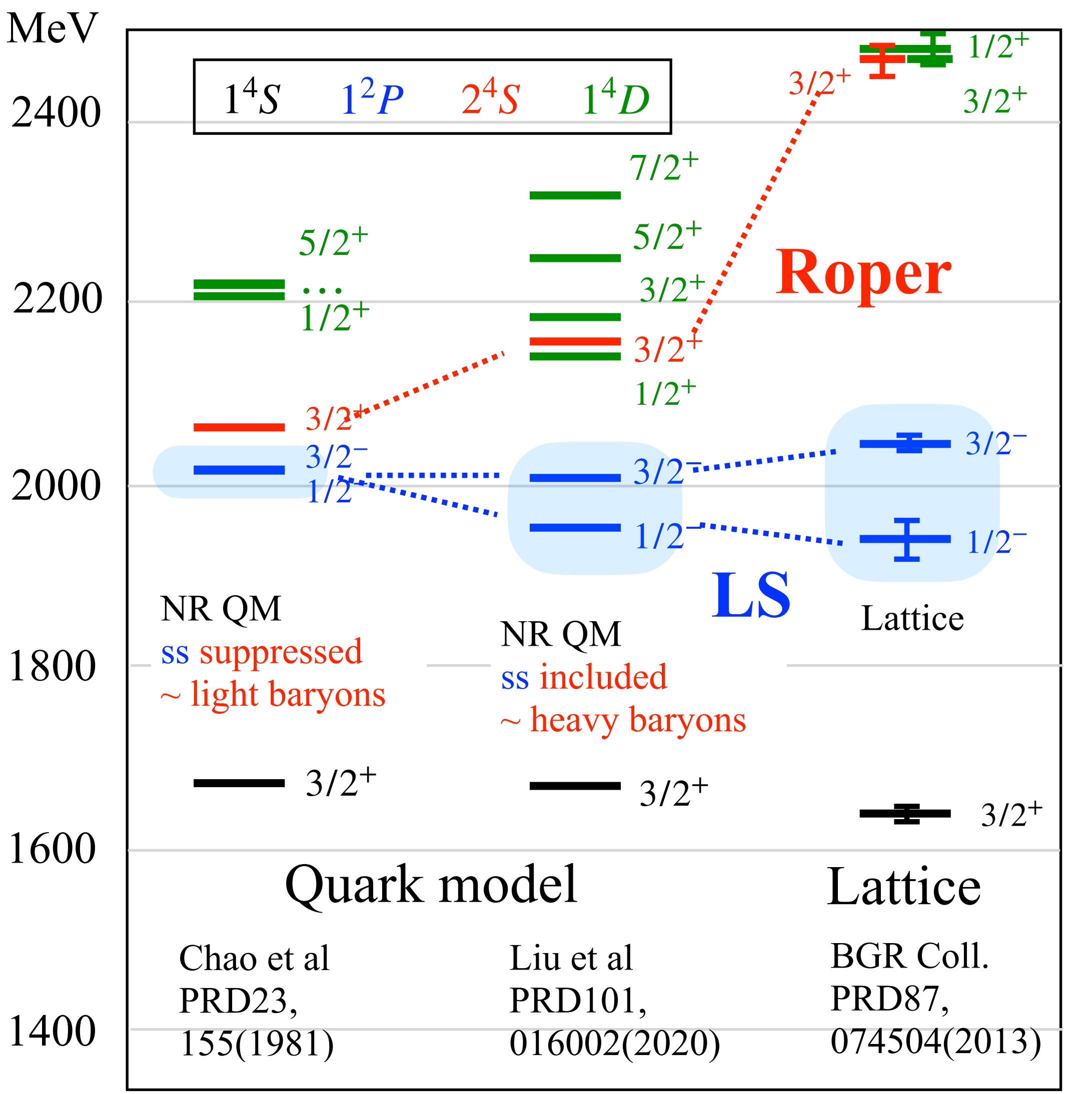
Predict new signals and suggest where/what to study

Ξ baryons



2200
2000
1800
1600
1400
1200
Data
5/2?
1950
1820
3/2⁻
1690
1620
1530
3/2+
1321
1/2+
?
2085
1950
1/2+
1935 1930
3/2+,5/2+
1800
1785
3/2⁻
1/2⁻
1695
1/2+
1530
3/2+
1325
1/2+
Roper
LS
?
Spin-spin
2178
1/2+
1894, 1906
3/2⁻
1/2⁻
1837, 1844
1716
1/2⁻
1553
3/2+
1303
1/2+
Chao et al PRD23, 155(1981)
BGR Coll. PRD87, 074504(2013)

Ω baryons



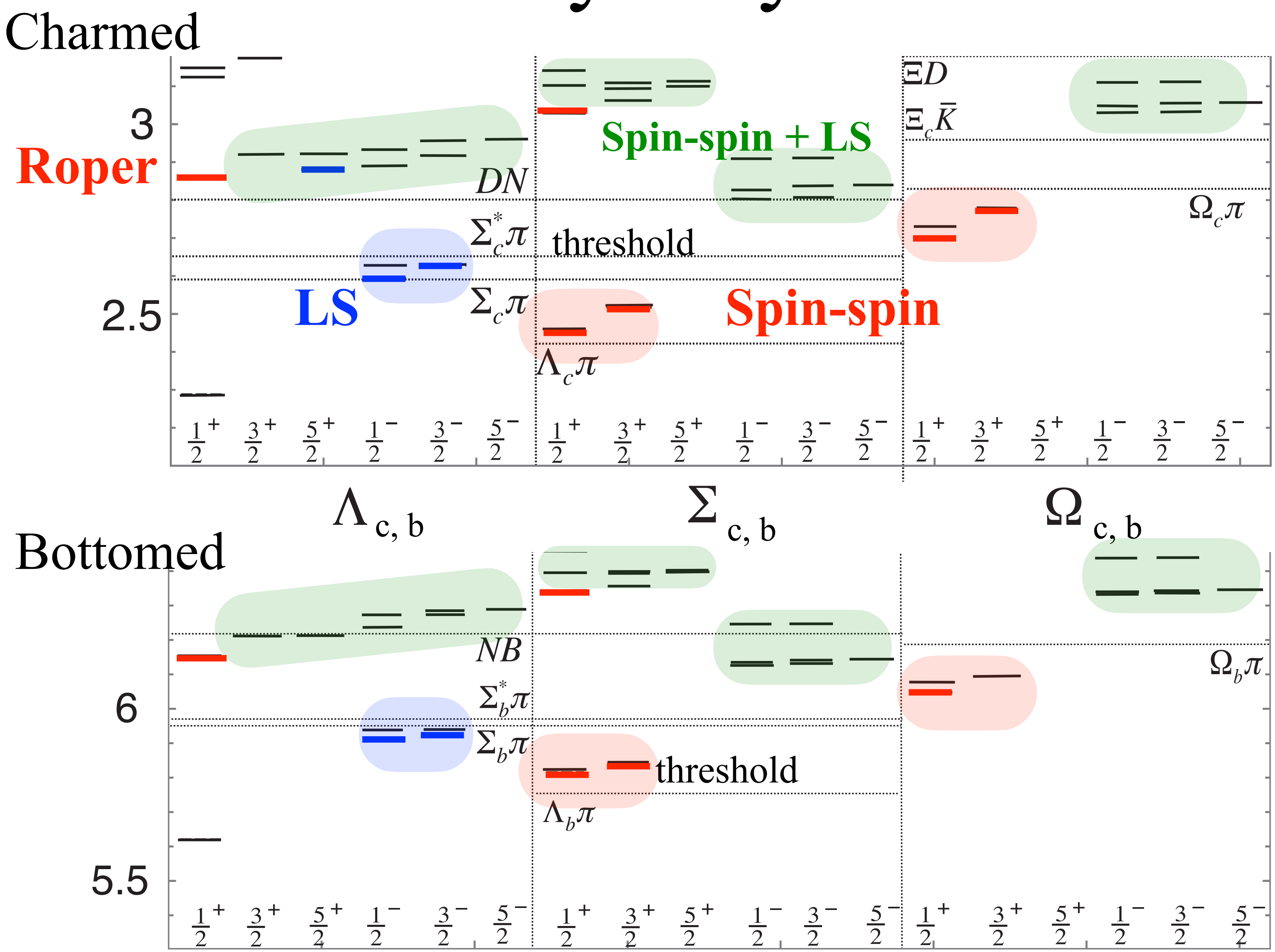
D-waves $1/2^+, \dots$
Masses & splittings scatter

S-waves $1/2^+$ (Roper like)
Masses scattered
Narrow width

P-waves $1/2^-$, $3/2^-$
Splittings scatter

Ground state OK

Heavy baryons



6. Summary

- We have discussed baryon spectroscopy studied at J-PARC.
- More inputs will be from QCD (lattice, effective theories…) and Experiments to explore non-perturbative dynamics of low energy QCD.

Further discussions and comments are welcome!