Quark clusters in heavy hadrons

—— What, Where and How ——

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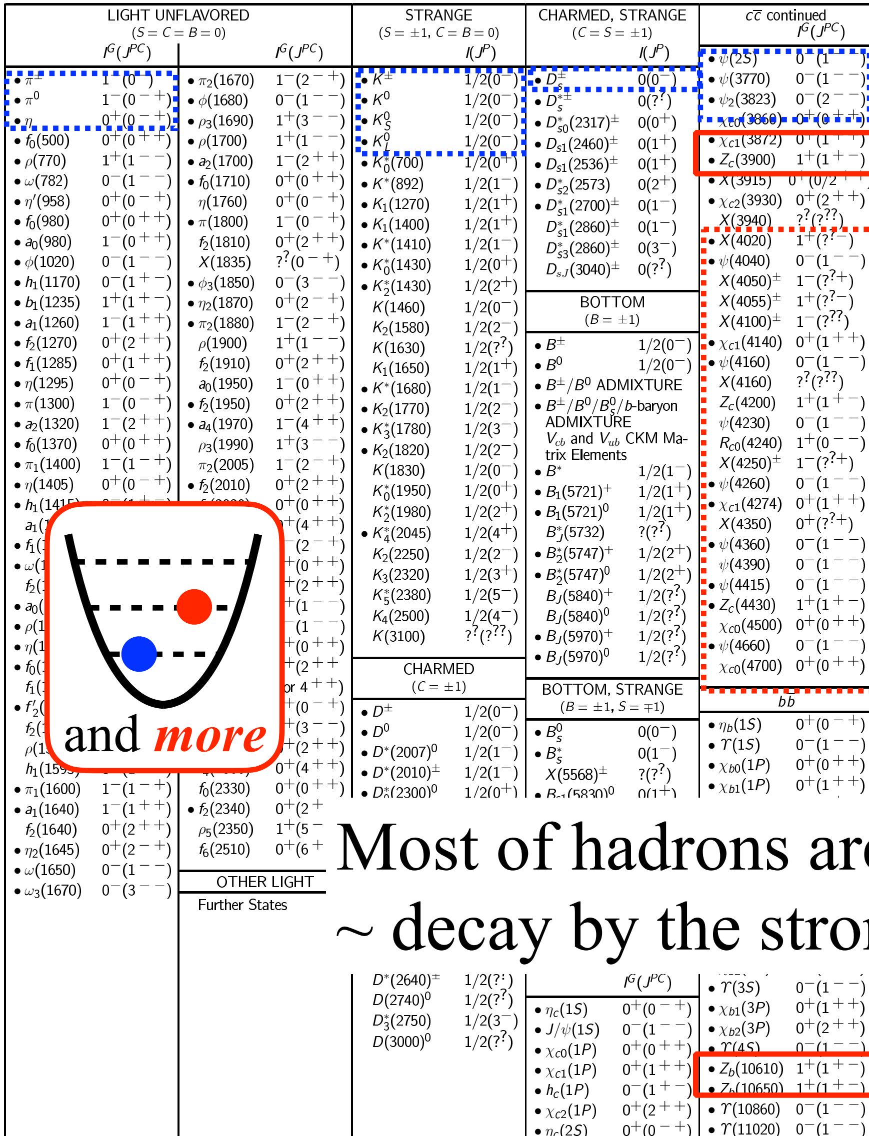
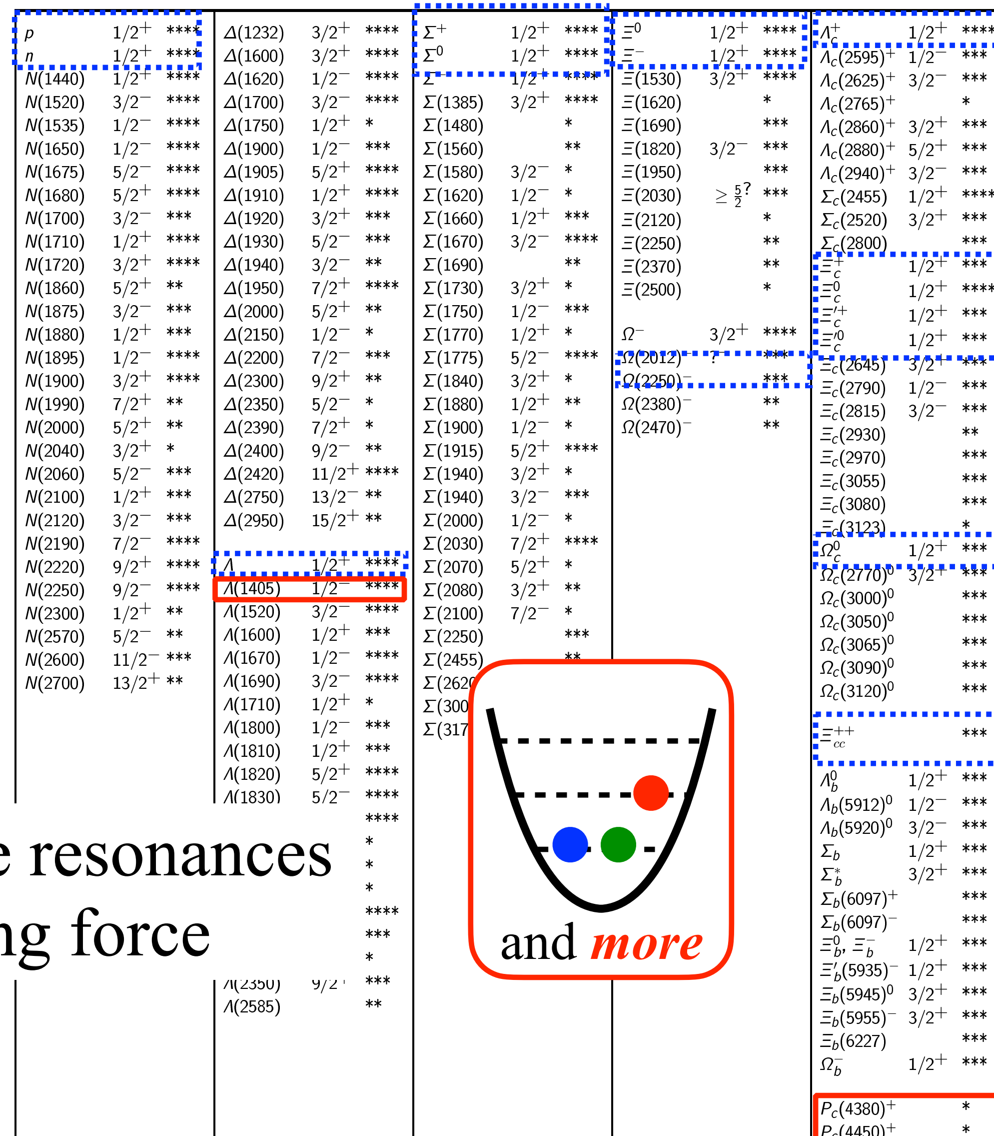
RCNP/Osaka & JAEA/Tokai & RIKEN

新学術クラスター階層研究会 hosted by TITech via Zoom

1. Introduction

rpp2019-qtab-mesons　　Particle Data Group　　rpp2019-qtab-baryons





Most of hadrons are resonances

~ decay by the strong force

What we should do for (exotic) hadrons

We know QCD, but we can not answer the questions:

Do they exist?
If they do, which ones?
What is their internal structure?
How best to look for them?
Marek Karliner, QNP proceedings, 2018@Tsukuba
https://journals.jps.jp/doi/book/10.7566/QNP2018

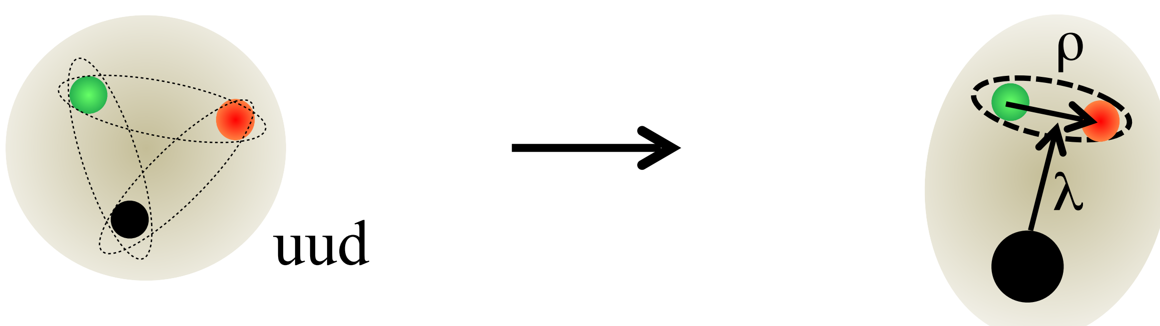
Studying heavy exotic hadrons is somewhat similar to investigating the social life of heavy quarks:

(a) Who with whom?
(b) For how long?
(c) A short episode? or
(d) “Till Death Us Do Part”?

2. Unsolved and new problems

A. Roper and analogues: Light diquarks in heavy baryons
B. Pc: Hadronic clusters for molecules
C. Doubly heavy: Heavy diquarks in tetra and hexaquarks

Open clusters (colored subsystem) in hadrons

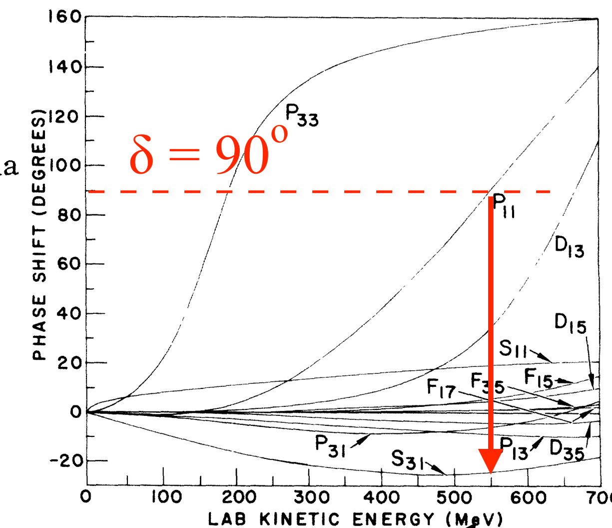


A. Roper and analogues: Light diquarks in heavy baryons

First excited state of 1/2+

EVIDENCE FOR A P_{11} PION-NUCLEON RESONANCE AT 556 MeV†

L. David Roper
Lawrence Radiation Laboratory, University of California, Livermore, California
(Received 17 February 1964)

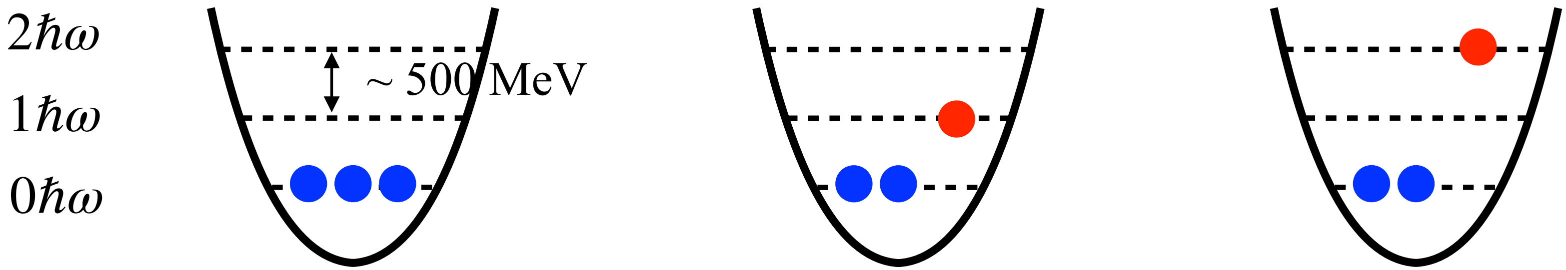


$\Delta E_{Lab} \sim 550$ MeV $\rightarrow$ Mass 1.48 GeV

p	$1/2^+$
n	$1/2^+$
$N(1440)$	$1/2^+$
$N(1520)$	$3/2^-$
$N(1535)$	$1/2^-$
$N(1650)$	$1/2^-$
$N(1675)$	$5/2^-$
$N(1680)$	$5/2^+$

Parity inversion

Standard (naive) quark model



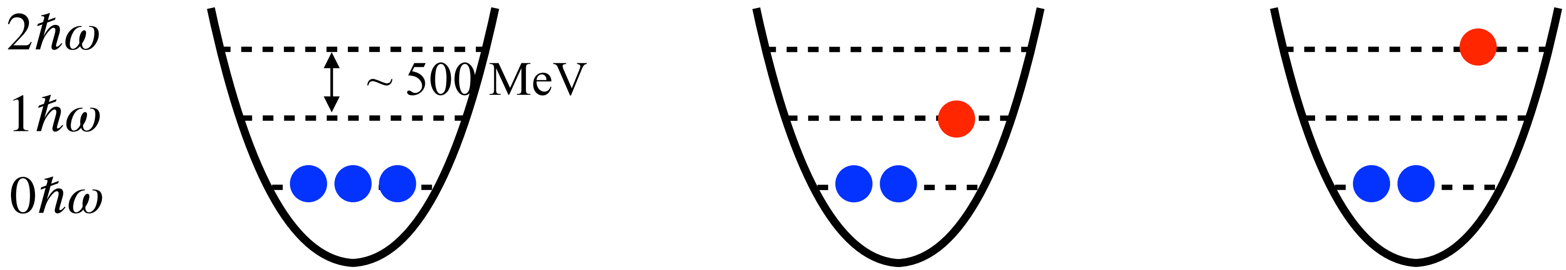
Ground state
$1/2^+$, $3/2^+$

1st excited state
$1/2^-$, $3/2^-$, $5/2^-$

2nd excited state
$1/2^+$, $3/2^+$, $5/2^+$, …
Roper resonance

$$\boxed{E_{ground} < E_{negative\ parity} < E_{positive\ parity}}$$

Standard (naive) quark model



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Roper resonance

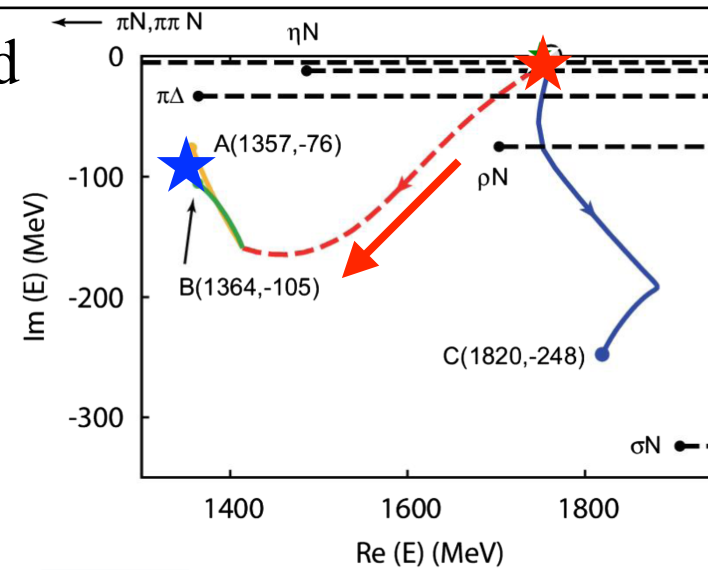
$$E_{ground} < E_{negative\ parity} < E_{positive\ parity}$$

Radial excitation with meson cloud

e.g. Burkart-Roberts, RevModPhys.91.011003

Suzuki, N., B. Julia-Diaz, H. Kamano, T. S. H. Lee, A. Matsuyama, and T. Sato, 2010, Phys. Rev. Lett. 104, 042302.

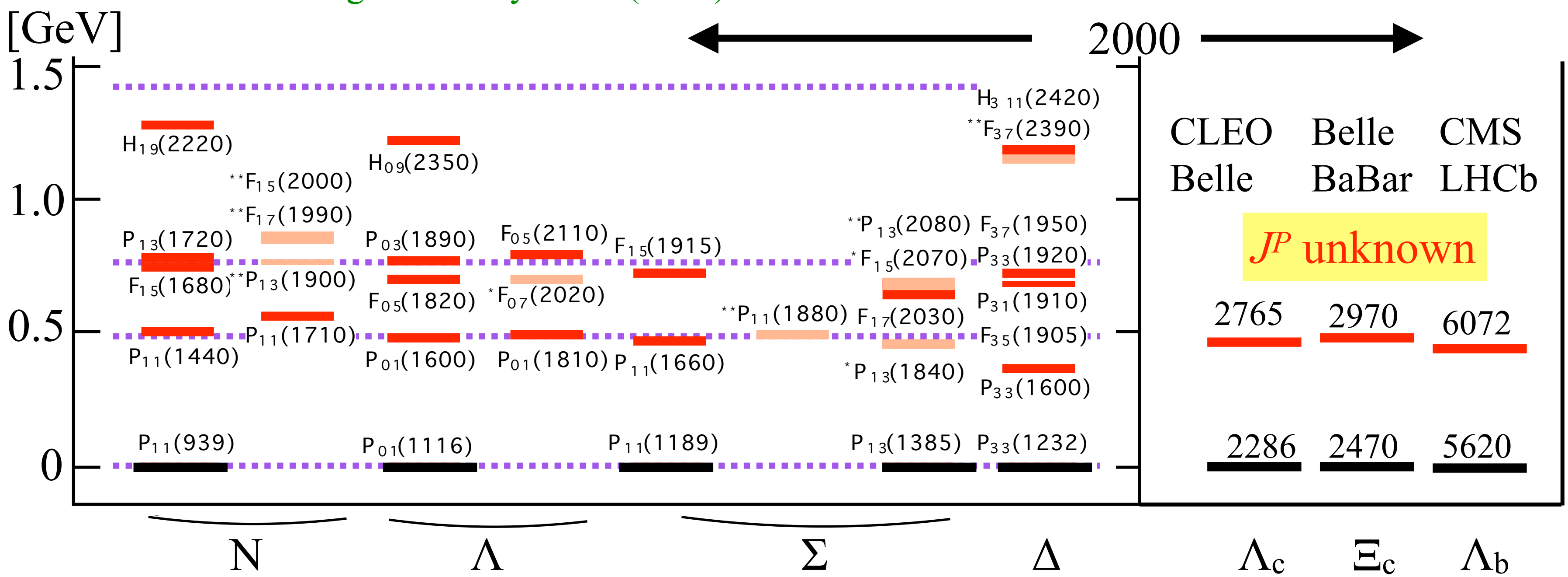
Large quark core mass ★ is reduced by coupling to meson clouds ★



More states systematically

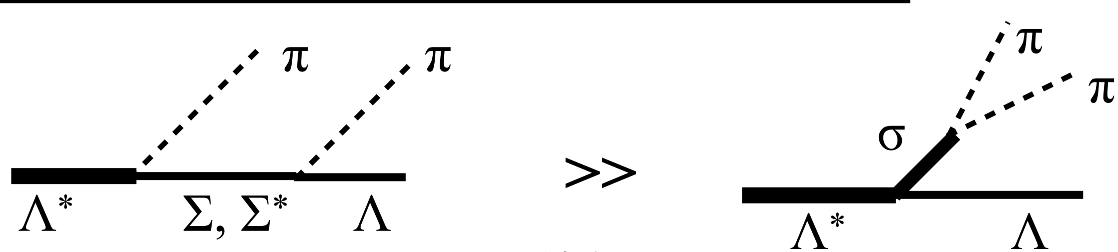
Takayama, Toki, Hosaka
Prog.Theor.Phys. 101 (1999) 1271-1283

Arifi, Nagahiro, Hosaka, Tanida,
e-Print: 2004.07423[hep-ph], PRD



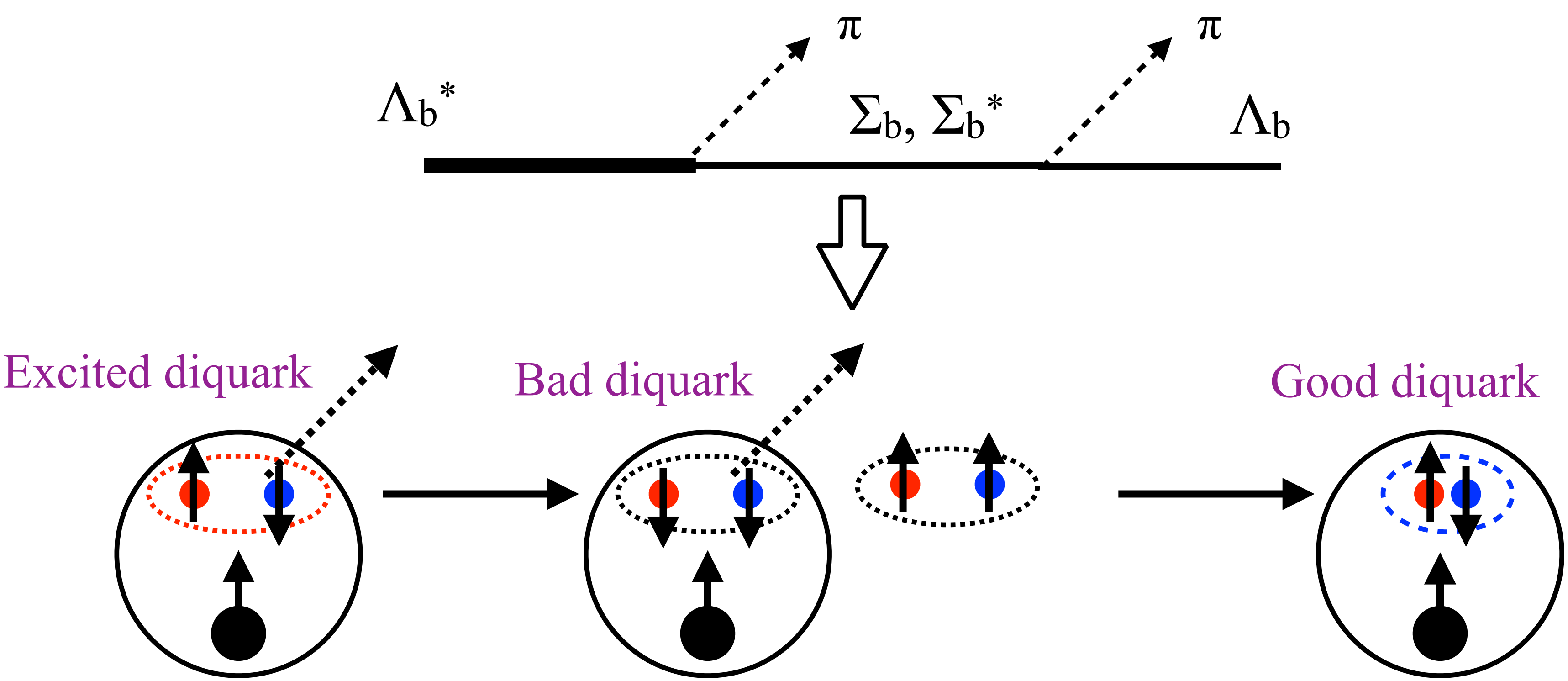
- Masses are almost universally ~ 500 MeV
- Large $\pi\pi$ sequential decays

Kato san's talk this morning



Possible senario

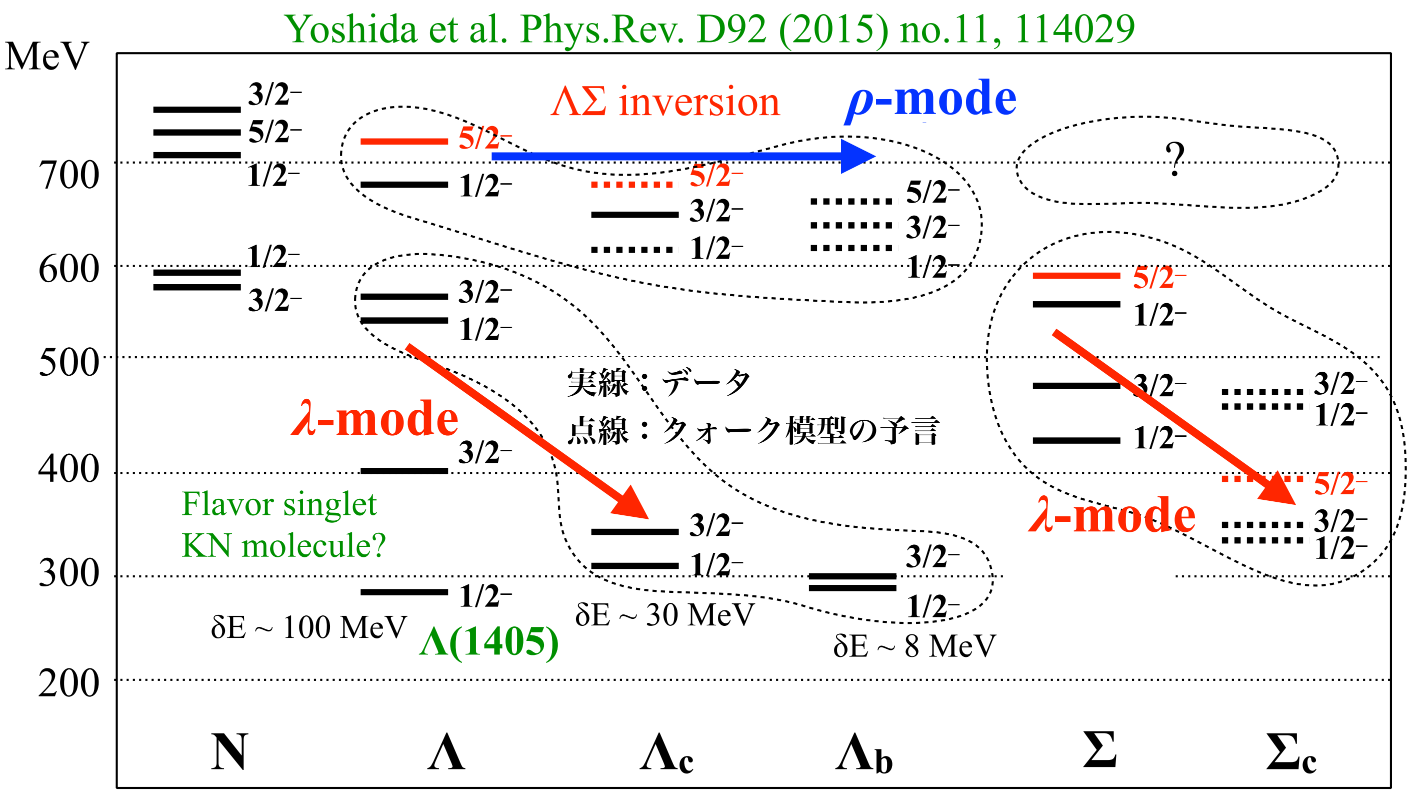
Transitions between diquark clusters

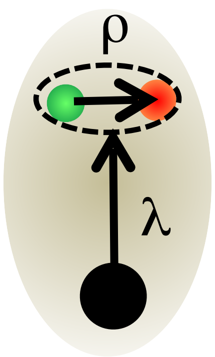


The transitions between **diquark** + **spectator heavy quark**

Decay pattern is computable in a model independent manner in the HQ limit

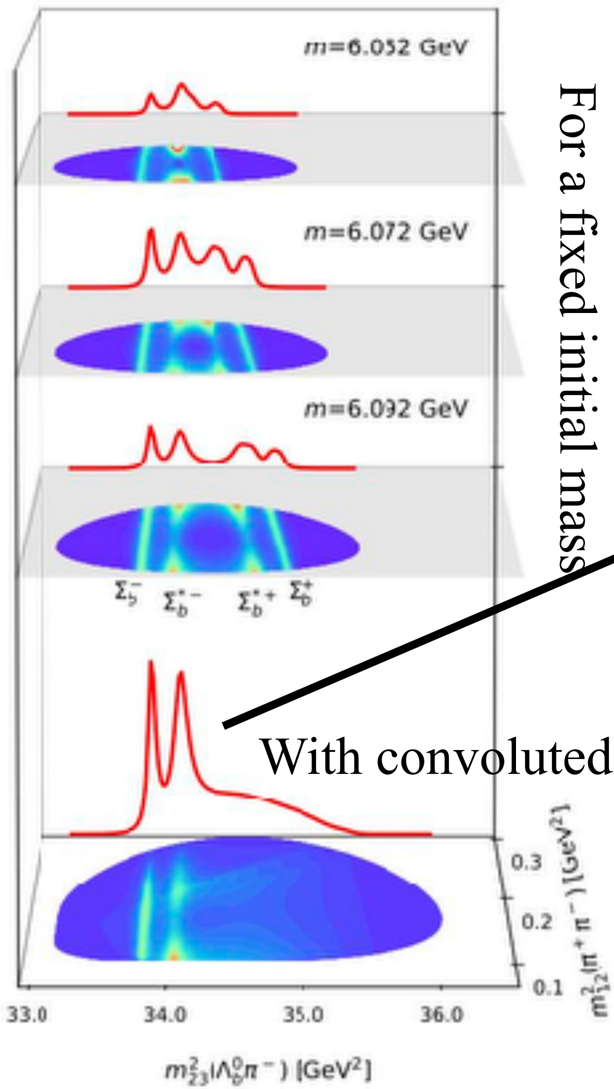
Evidence of diquarks (correlation)





Recent study

Arifi-Nagahiro-Tanida-Hosaka, Three-body decays of
$\Lambda_c(2765)$: arXiv:2003.08202 [hep-ph], to appear in PRD
$\Lambda_b(6072)$: arXiv:2004.07423 [hep-ph], just accepted by PRD TODAY!



For a fixed initial mass

With convoluted masses

R. Aaij et al. [LHCb Collaboration]
arXiv:2002.05112 [hep-ex]

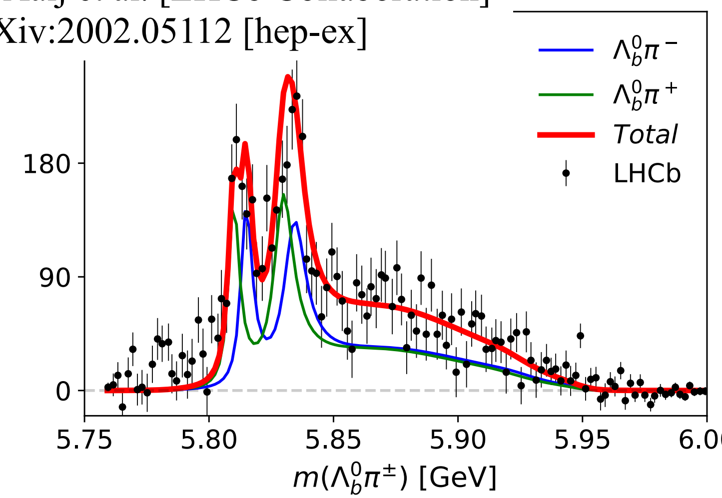
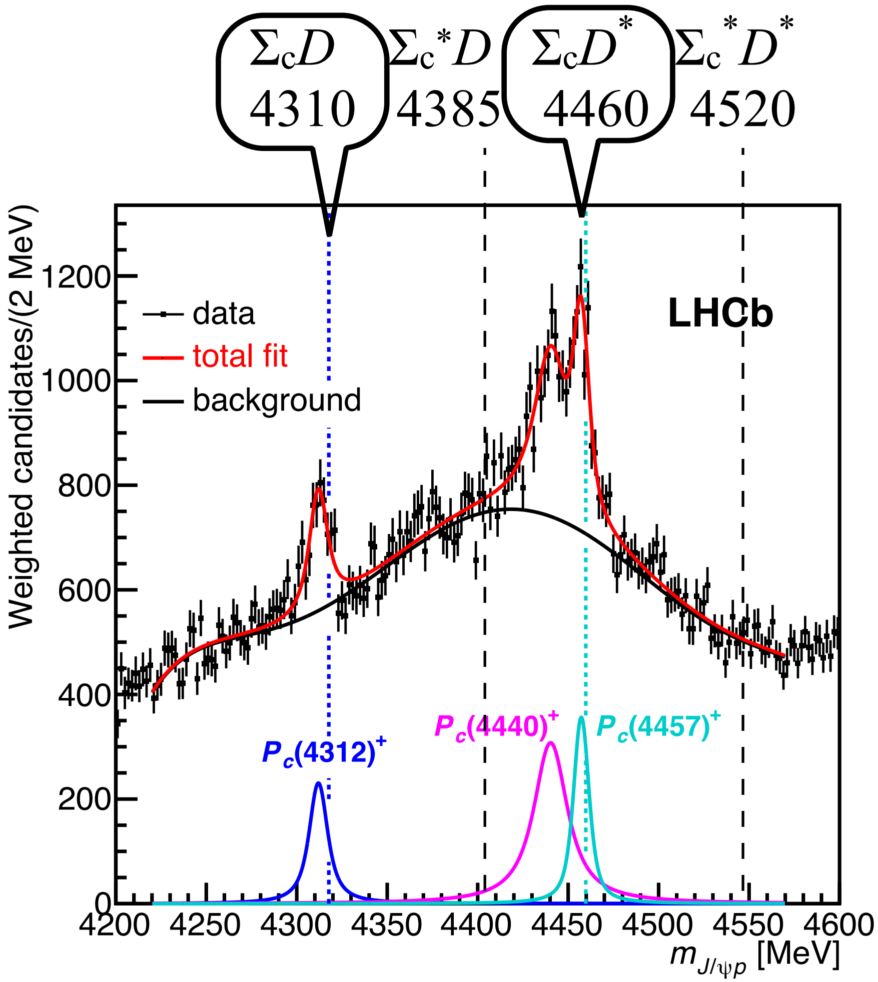


FIG. 4. Invariant mass plots of $\Lambda_b^0\pi^-$ (blue), $\Lambda_b^0\pi^+$ (green) and their sum (red). The data from LHCb is the sum of these two [2] and compared with the red line.

- Line shape is well reproduced
- BUT QM strength is too small
- The origin of the universal ~ 500 MeV

B. P_c: Hadronic clusters for molecules

PRL122 (2019) no.22, 222001



Narrow

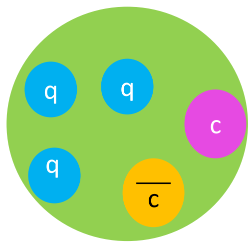
One peak at $\Sigma_c D$ => $J = 1/2$

Two peaks at $\Sigma_c D^*$ => $J = 1/2, 3/2$

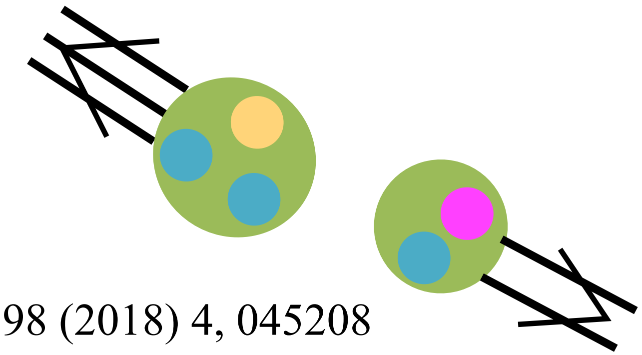
Hadronic Molecule?

Quark model

Closed-pentaquark + Fallapart



+



Hiyama et.al. Phys.Rev.C 98 (2018) 4, 045208
Qi Meng et al, Phys.Lett.B 798 (2019) 135028

$$H = \sum_i \left(m_i + \frac{\boldsymbol{p}_i^2}{2m_i}\right) - T_G - \frac{3}{16}\sum_{i<j} \lambda_i.\lambda_j \, V_{ij}(r_{ij})$$

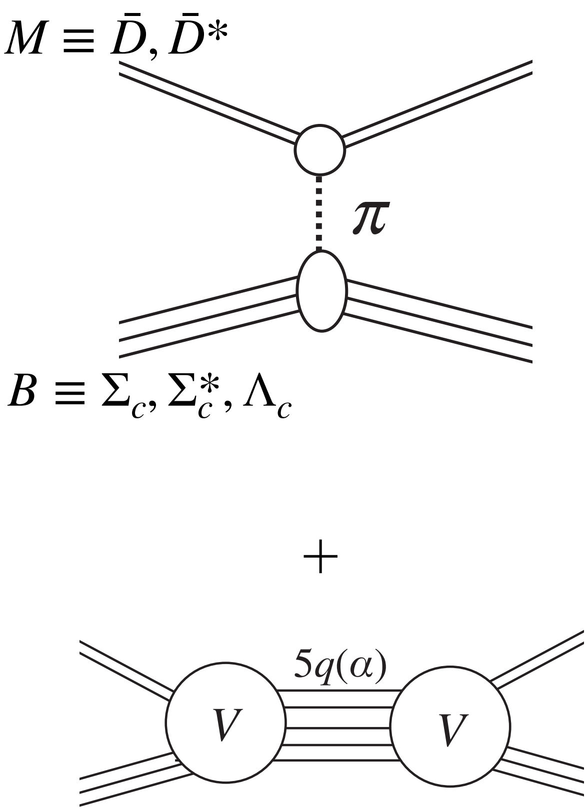
$$V_{ij}(r) = -\frac{\kappa}{r} + \lambda r^p - \Lambda + \frac{2\pi\kappa'}{3m_i m_j}\,\frac{\exp(-r^2/r_0^2)}{\pi^{3/2}\, r_0^3}\,\boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j$$

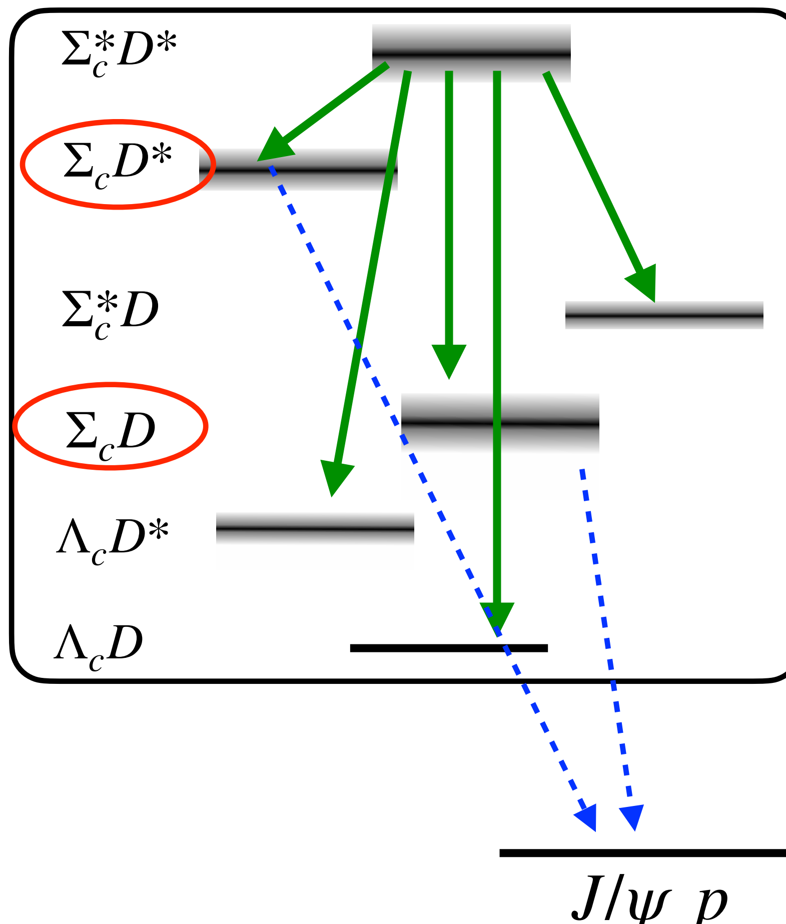
- This cannot hold states near thresholds
- Allow compact states at some higher than thresholds

Model calculation

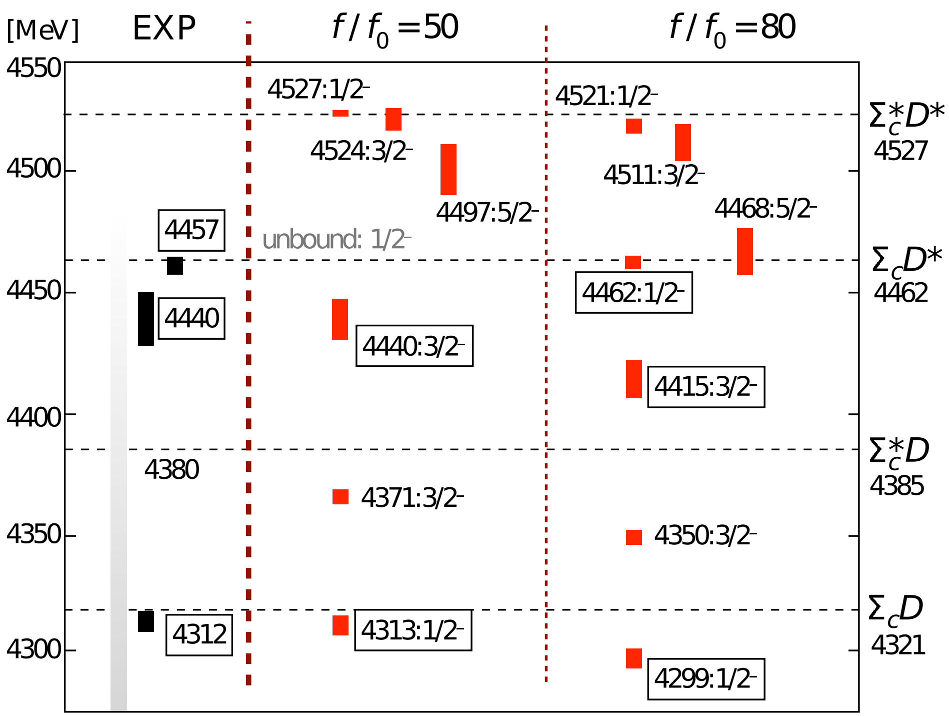
Yamaguchi et al, Phys.Rev. D96 (2017), 114031; Phys.Rev.D101 (2020) 9, 091502

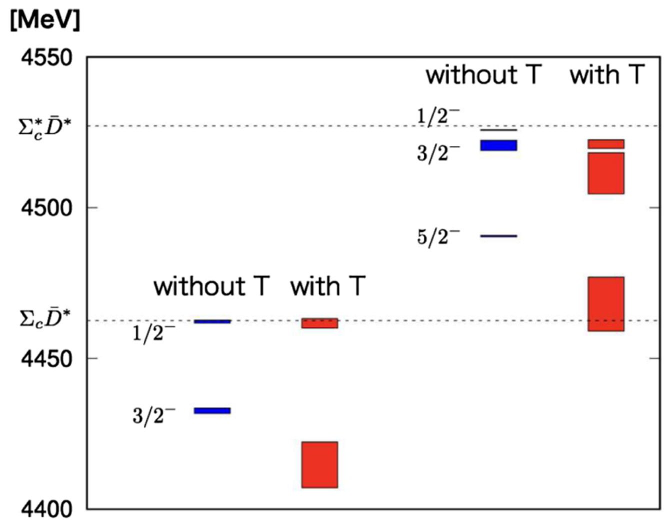
Hadronic molecule of coupled channels with OPEP + 5q core





Predictions and data

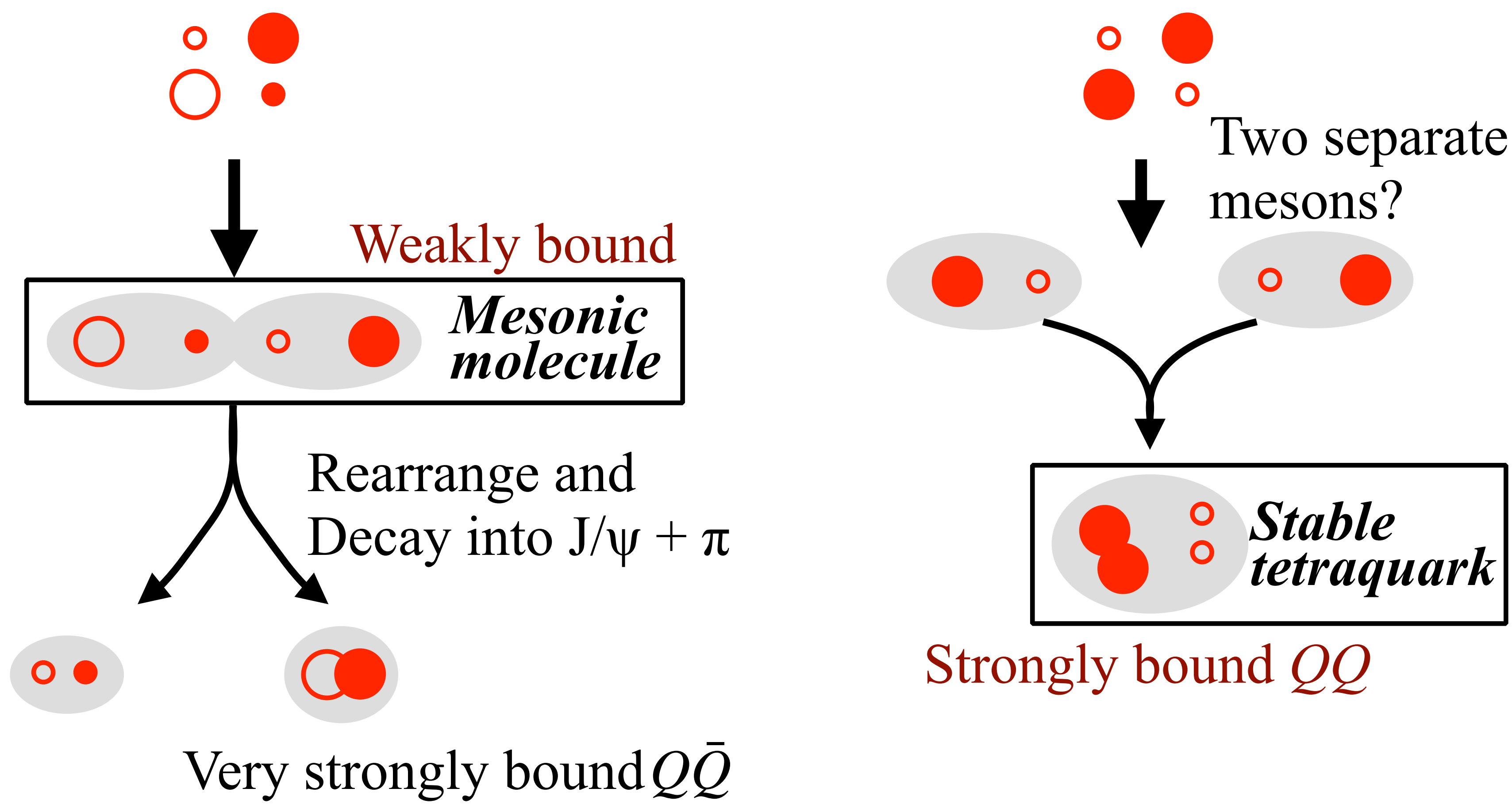




- For systems of $Q\overline{Q}$, molecules are well developed (Next discussion)
- With one parameter *f*, tendency of masses are reproduced
- Width are explained by the OPEP tensor force

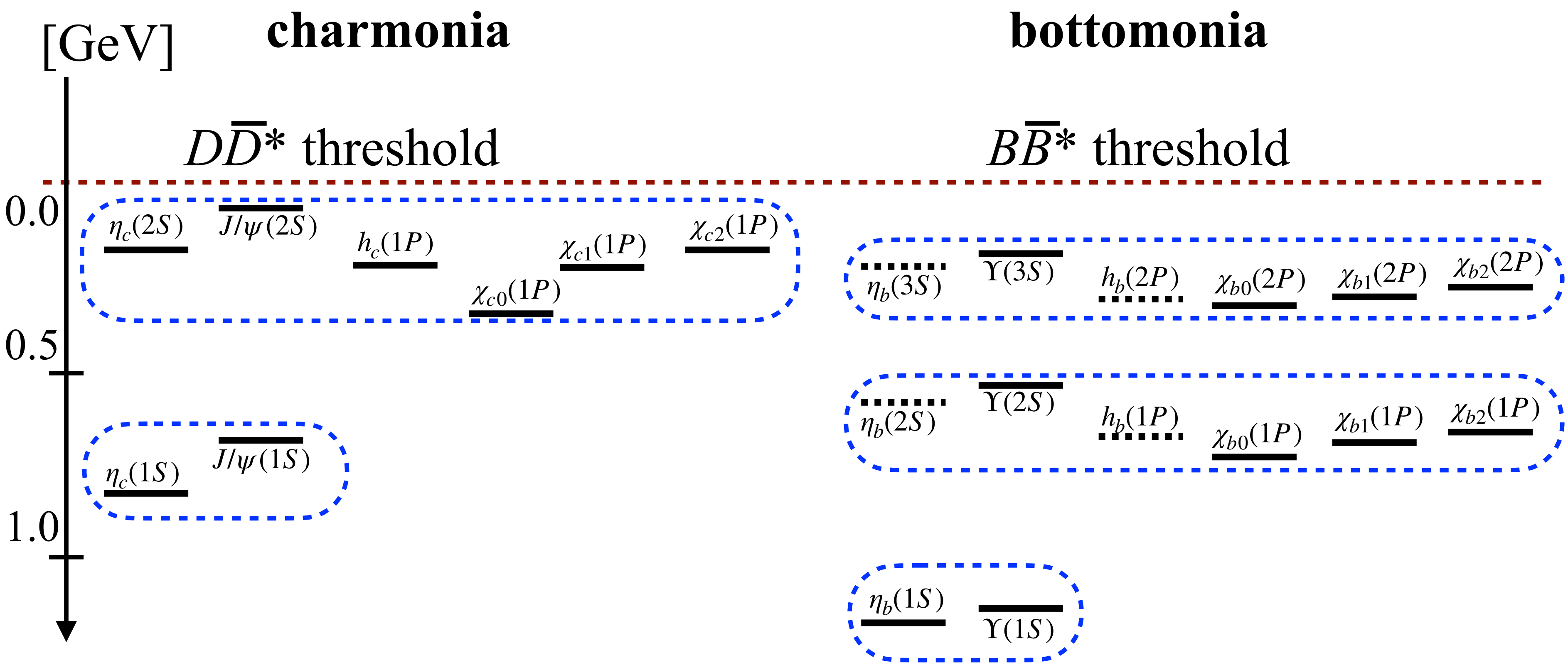
C. Other exotics — Doubly heavy

Hidden heavy $Q\bar{Q}q\bar{q}$ Double heavy $QQ\bar{q}\bar{q}$



Color electric attraction ~ – $\alpha^2 M$

Strongly bound charmonia and bottomonia



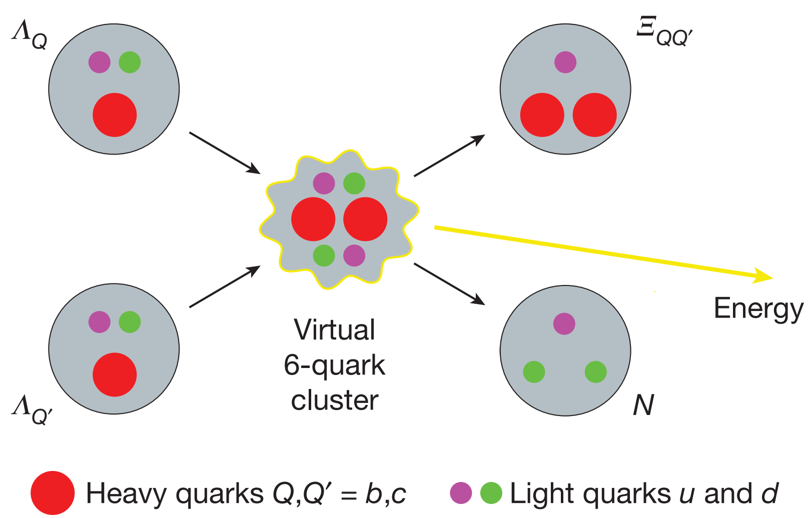
LETTER

doi:10.1038/nature24289

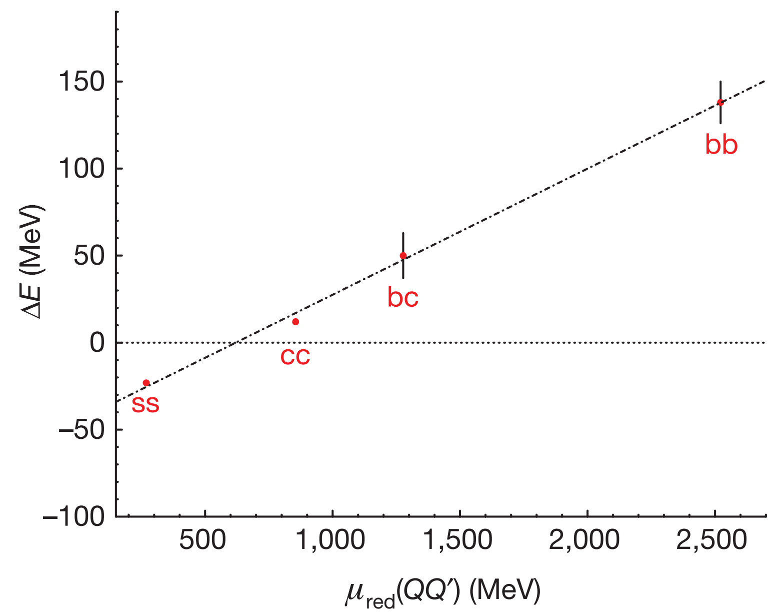
Quark–level analogue of nuclear fusion with doubly heavy baryons

Marek Karliner[1] & Jonathan L. Rosner[2]

Formation of double heavy baryon



Energy release as a function of mass



Summary

- **Roper resonances:** Arifi et al, $\Lambda_c(2765)$: arXiv:2003.08202 [hep-ph], to appear in PRD
  $\Lambda_b(6072)$: arXiv:2004.07423 [hep-ph], just accepted by PRD TODAY

  Flavor blind ~ Another evidence of light diquark clusters.

  Two pion decays explained by baryon sequential process

  Conventional quark model, too high mass, too small width

- **P_c:** Hiyama et.al. Phys.Rev.C 98 (2018) 4, 045208, Qi Meng et al, Phys.Lett.B 798 (2019) 135028
  Yamaguchi et al, Phys.Rev. D96 (2017), 114031; Phys.Rev.D101 (2020) 9, 091502

  Likely to be molecules of hadronic clusters.

  OPEP alone does not seem provide enough attraction => other attractive source

  The origin of force is to be understood => Lattice simulations and models

- **Doubly heavy stable states:**

  QQ Heavy diquarks strongly attractive => stable exotics

  Systematic theory calculation is on-going (Meng, Hiyama, Oka, …)