Coexistence of different structures for hadrons
-- the case of the low-lying Ωc baryons --

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1. What (structures) make hadrons
2. Ω_c baryons
   -- Coexistence of MB and qqq structures --

Exotic hadrons from QCD

Coexistence of molecular and compact quark structures near threshold regions

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1. Introduction — Coexistence
2. Pentaquarks, Pc and Pcs
3. Baryon octet of sss = Ω(2012)
4. Summary

1. What (structures) make hadrons

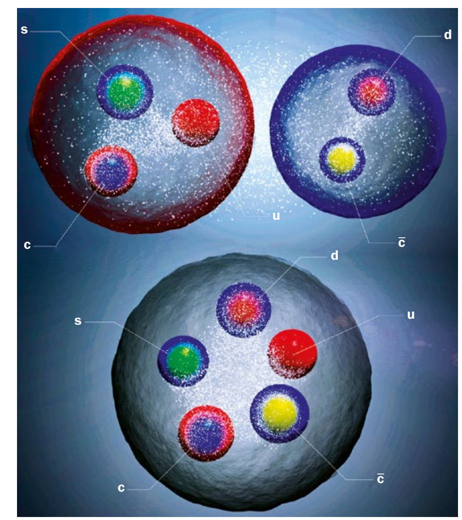
-- Coexistence of MB and *qqq* structures --

Extended　　Compact

CERN COURIER , NOVEMBER/DECEMBER 2024

INSIDE PENTAQUARKS
AND TETRAQUARKS

Marek Karliner and Jonathan Rosner ask what makes tetraquarks and pentaquarks tick, revealing them to be at times exotic **compact** states, at times hadronic **molecules** and at times **both** – with much still to be discovered.



But this is not a new story

Long history in hadron and nuclear physics

For Δ(1232)

Doctor thesis

粒子と共鳴準位の混合効果について

益川 敏英

名古屋大学 物理教室

T. Maskawa

Progress of Theoretical Physics, Vol. 38, No. 1, July 1967

Mixing Effect between Particles and Resonances

Published paper

Toshihide MASKAWA, Hiroki KONDO
and Ziro MAKI*

Department of Physics, Nagoya University, Nagoya
**Research Institute for Fundamental Physics*
Kyoto University, Kyoto

(Received February 23, 1967)

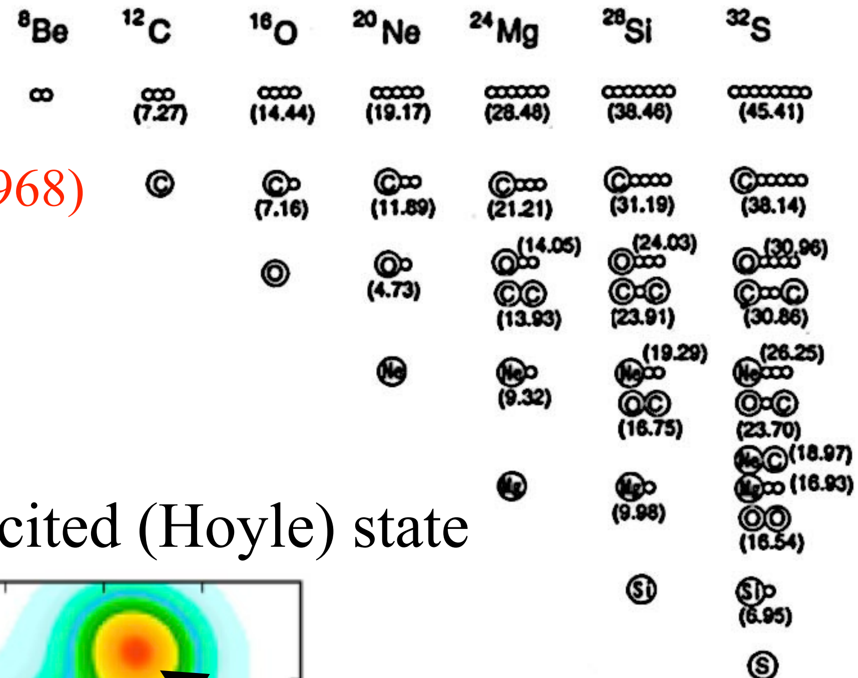
p190-201, Only 3 citations

Molecular like states via clusterization

Not only in hadrons but also in nuclei

Alpha cluster (molecular) structure of nuclei

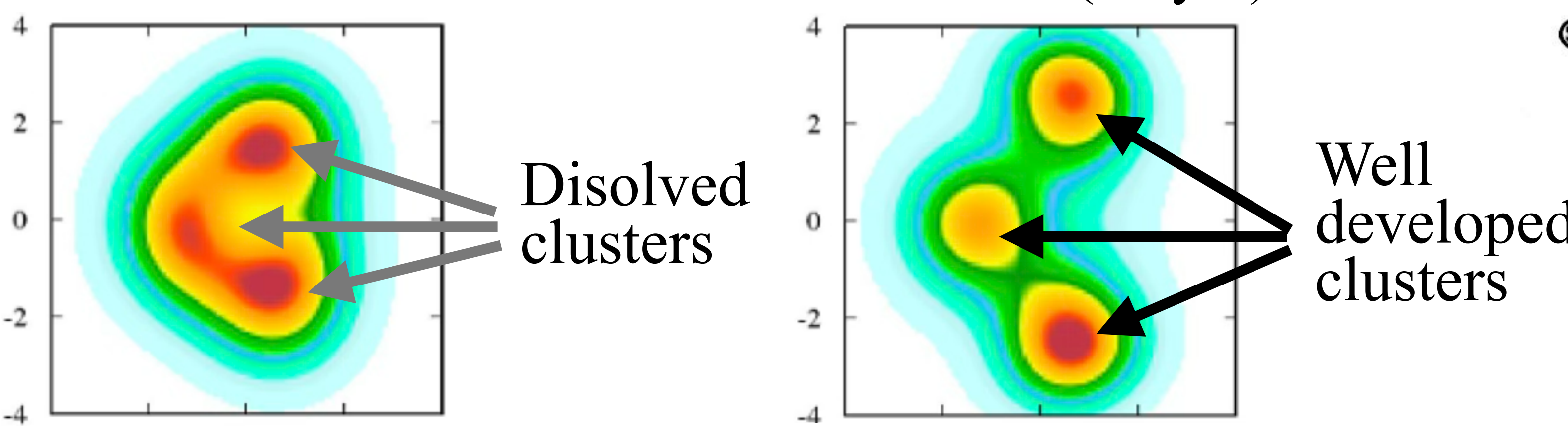
Prog. Theor. Phys. 40, 277 (1968)
Ikeda diagram



Density distributions

^{12}C: Ground state

^{12}C: Excited (Hoyle) state

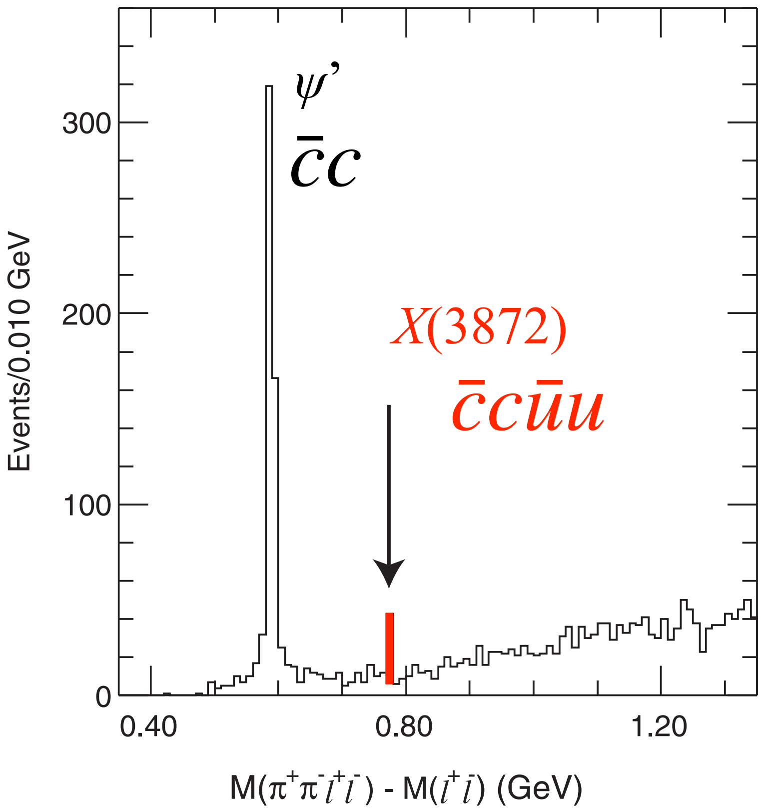


T. Otsuka, Y. Utsuno et al., Nat. Comm. 13, 2234 (2022)

X(3872)

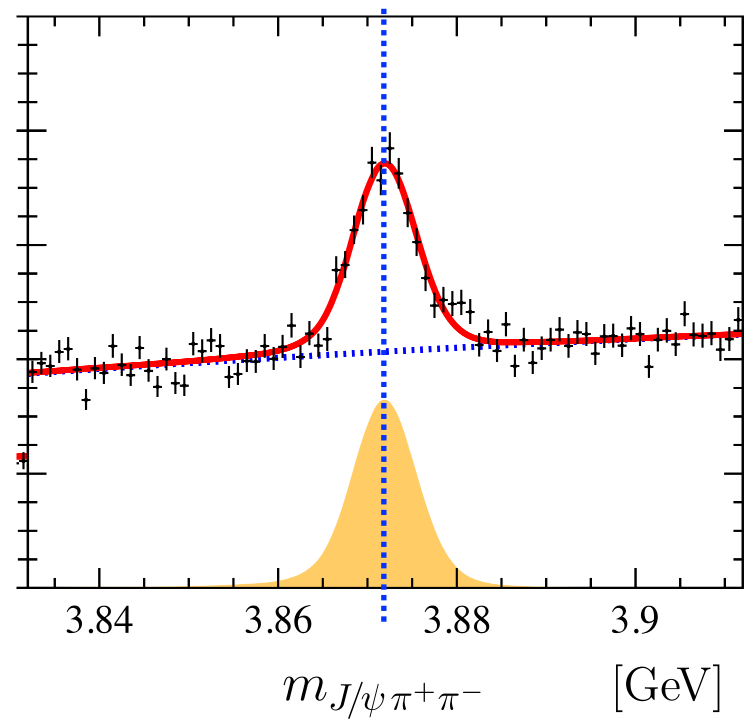
Belle@KEK, PRL91 262001 (2003)

$B^{\pm} \to (J/\psi\pi^+\pi^-)K^{\pm}$



LHCb, PRD 102, 092005 (2020)

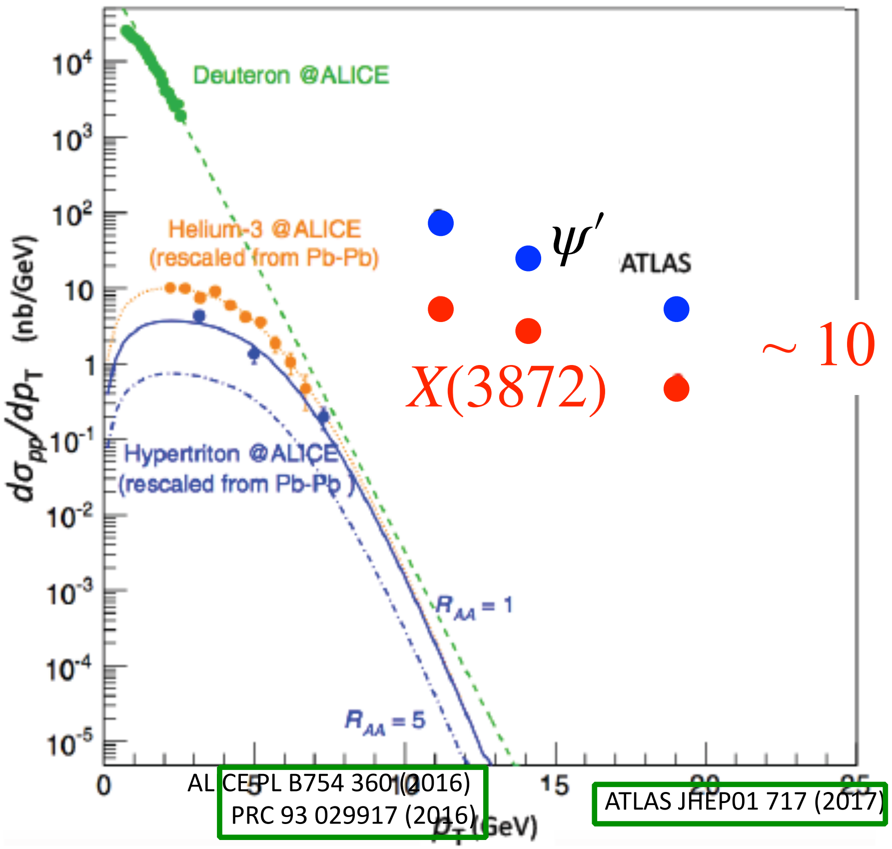
pp collisions at center-of-mass energies of 7 and 8 TeV



The peaks are almost at the threshold of $D\bar{D}^*$ → **Hadronic molecule**

BUT

See Esposito et al., PRD 92 034028 (2015(



ALICE PL B754 360 (2016)
PRC 93 029917 (2016)

ATLAS JHEP01 717 (2017)

Large production rates at large E (~ TeV) and p_T (> GeV)

⇩

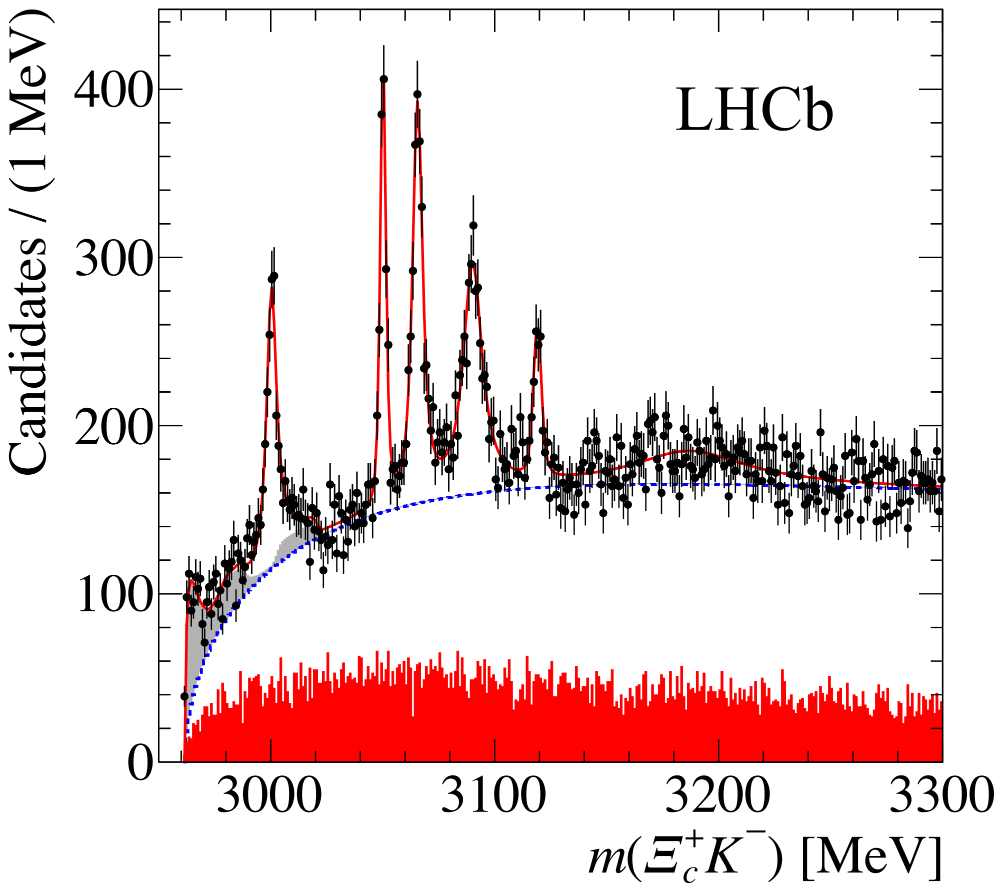
Implies admixture of $D^0\bar{D}^{*0}$ and compact quark core ~ $c\bar{c}$

We have performed analysis

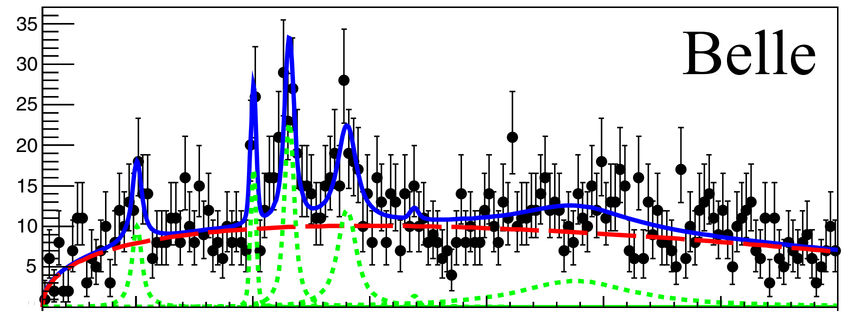
2. Ω_c baryons

Invariant mass analysis of $\Xi_c^+ K^- \rightarrow$ ***SSC***

Phys.Rev.Lett. 118 (2017) no.18, 182001

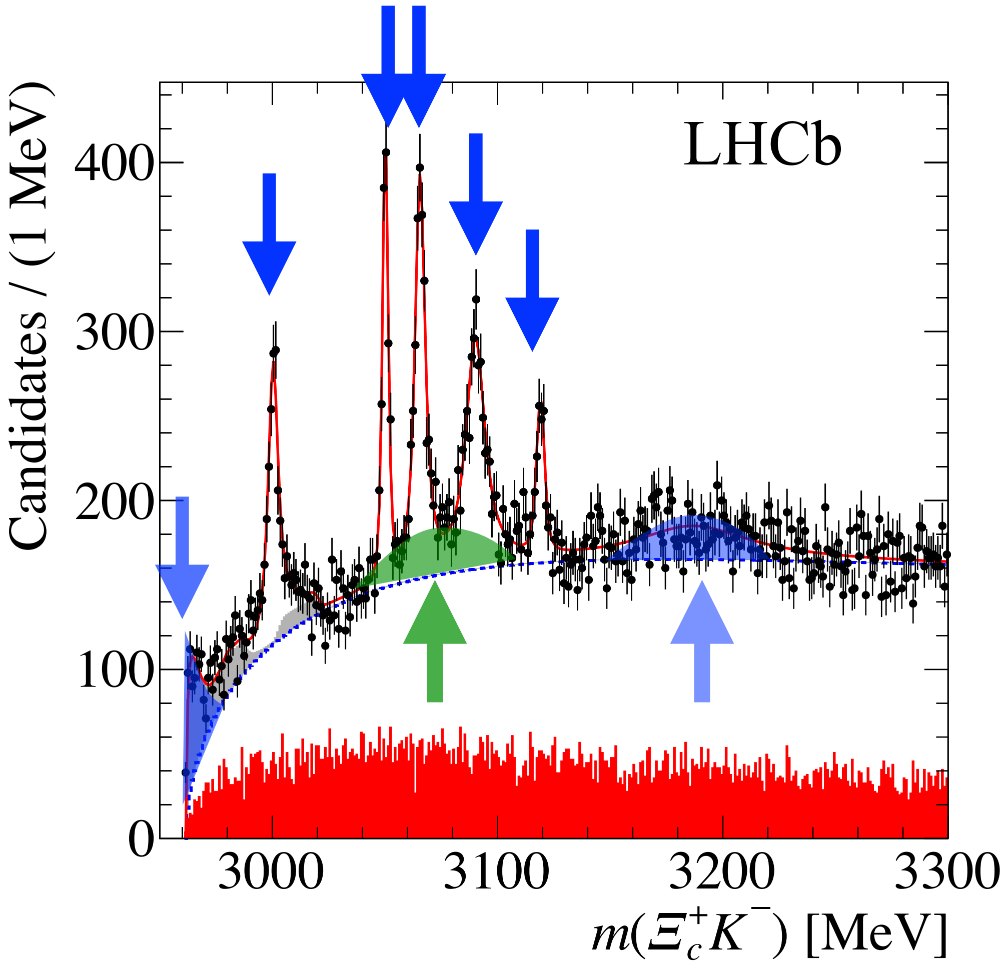


Phys.Rev.D97, 051102(R) (2018)



5 or 4 clear peaks

If we look more carefully . . .



- **5 sharp peaks**
- **Threshold enhancement**
- **Broad bump ~ 3200 MeV**
- **Broad bump ~ 3100 MeV**

⇩

6 (or 8) signals

More from LHCb

Phys.Rev. D 104, L091102 (2021): Angular distribution → **spin assignment**

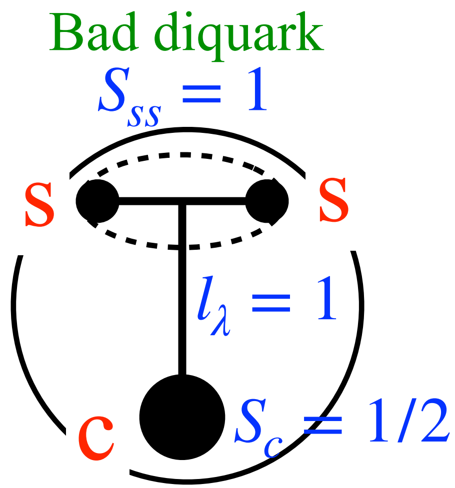
Phys. Rev. Lett.131, 131902 (2023): More states $\Omega_c(3185)$, $\Omega_c(3327)$

Option 1:
5 peaks implies **Quark core** structure
-- λ mode P-wave excitations --

Total spin J :

$$J = (S_{ss} + l_\lambda) \; + \; s_c$$

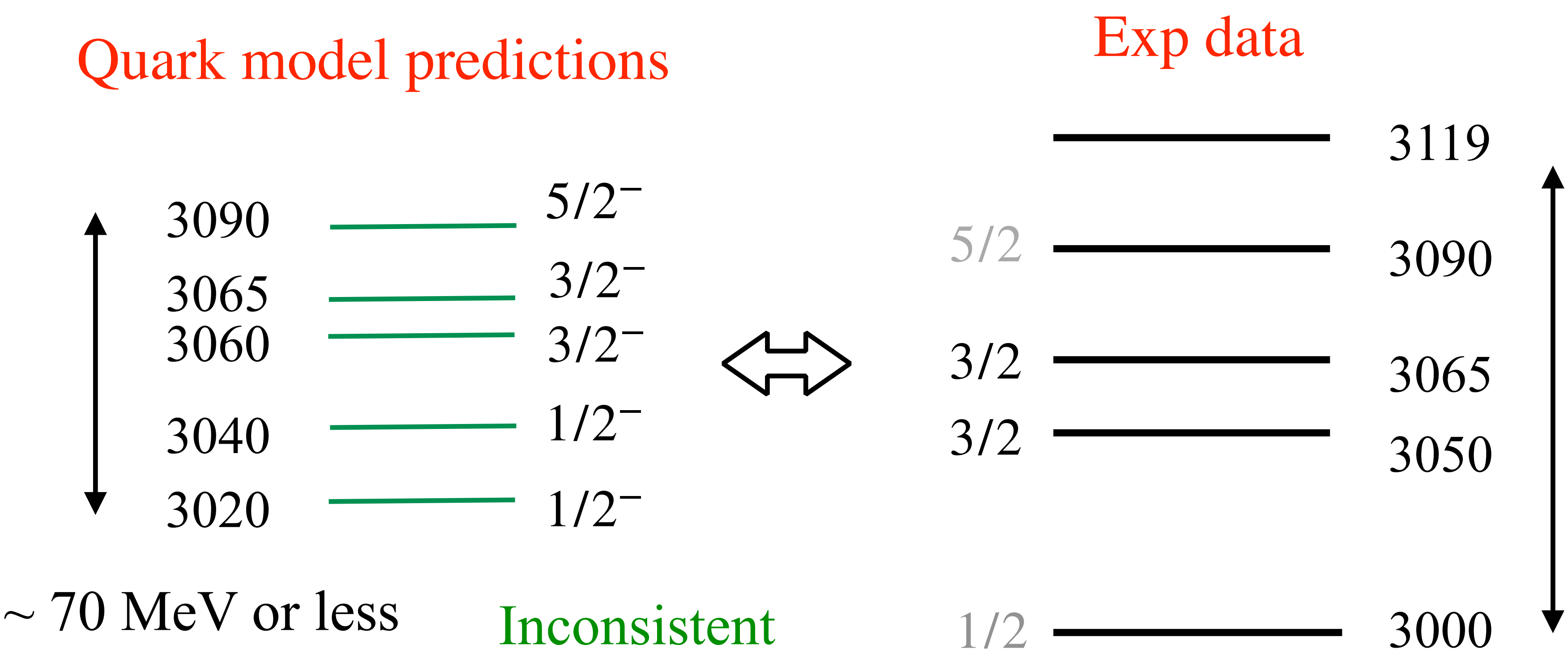
$$= \begin{cases} 0 & + & 1/2 & = & 1/2 \\ 1 & + & 1/2 & = & 1/2, \; 3/2 \\ 2 & + & 1/2 & = & 3/2, \; 5/2 \end{cases}$$



There are **5 states(!)** from lower λ modes
$J^P = 1/2^-, 1/2^-, 3/2^-, 3/2^-, 5/2^-$

BUT difficulties

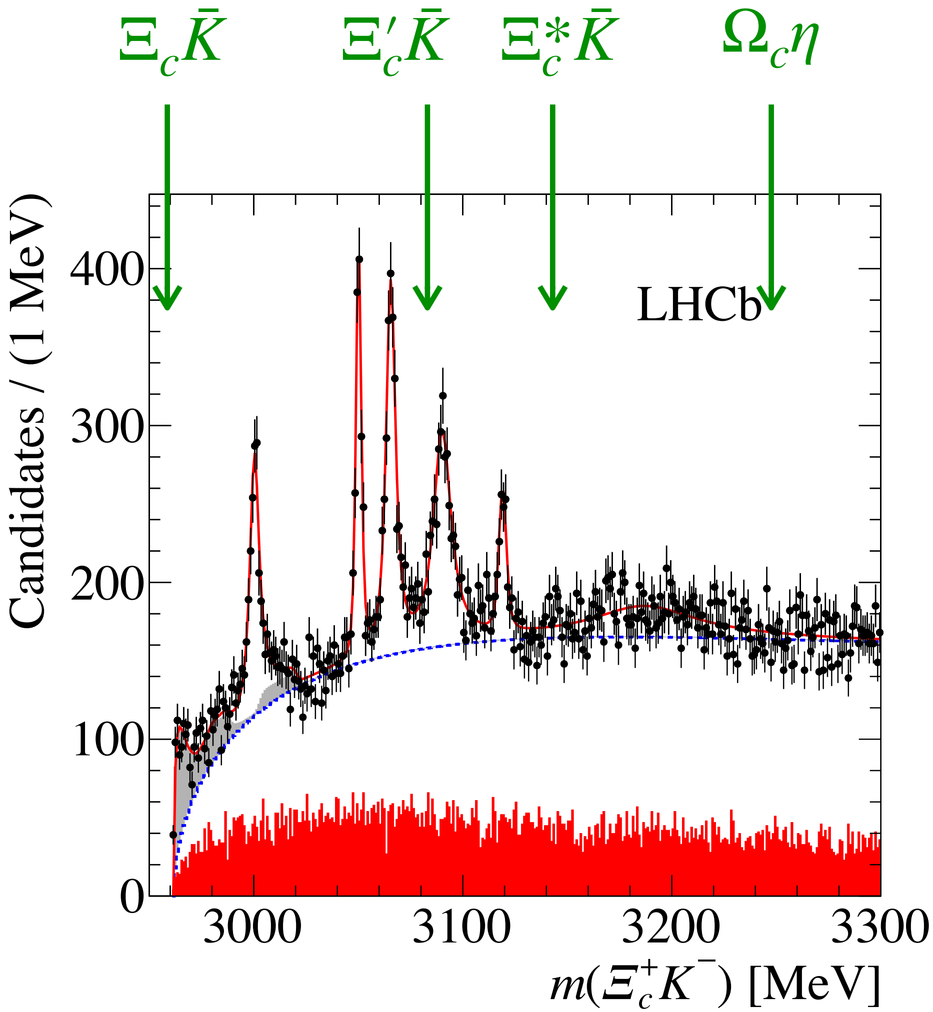
(1) They distribute in a narrow energy range
Spin assignments do not follow data



Inconsistent
with the LHC data
Phys.Rev. D 104, L091102 (2021)

~ 120 MeV

(2) There are MB channels ($\bar{K}\Xi_c$, $\bar{K}\Xi_c'$, $\bar{K}\Xi_c^*$) nearby.

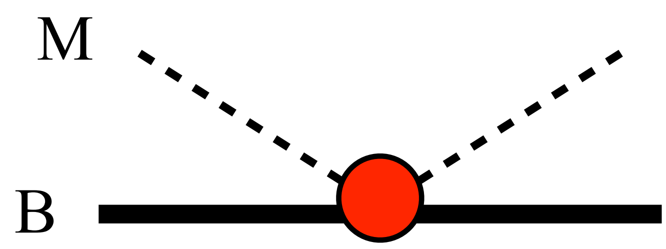


BM thresholds

Exp data

Option 2:
Near threshold implies **MB molecule**

Weinberg-Tomozawa int.



$$L_{KKqq} = -F\frac{i}{8f_\pi^2}tr[\bar{B}\gamma^\mu V_\mu, B] - D\frac{i}{8f_\pi^2}tr\{\bar{B}\gamma^\mu V_\mu, B\}$$

Attractive *MB* channels form bound/resonant/virtual states

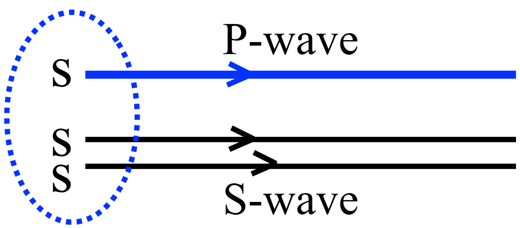
Option 3, Our choice:
Coexistence of quark core and MB molecule

Understanding the low-lying Ω_c structures from a coupled-channel perspective

Zhang, Song, **Lu**, **Nagahiro** and Hosaka, Phys. Rev. D112, 0340035 (2025)

Quark core

$P_{1/2,1/2,\ 3/2,3/2,\ 5/2}$

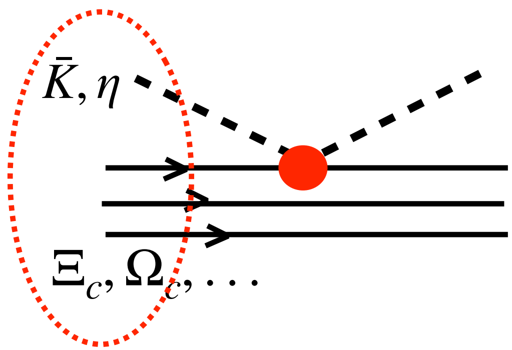


Quark model

+

BM molecule

$\Xi_c \bar{K}, \ldots$

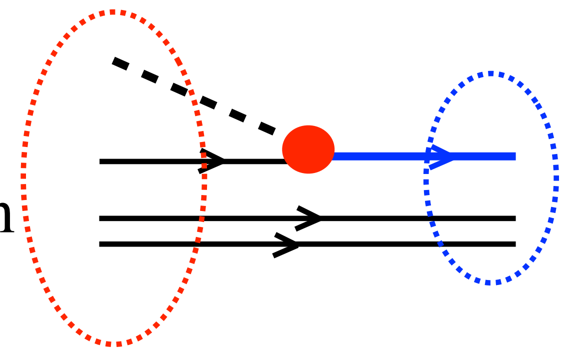


S-wave interaction
Weinberg-Tomozawa

$$L_{KKqq} = -\frac{i}{8f_\pi^2}\bar{q}\gamma^\mu(\partial_\mu K^\dagger K - K^\dagger \partial_\mu K)q$$

with

Coupling



Yukawa interaction

$$L_{Kqq} = \frac{g_A}{2f_\pi}\bar{q}\gamma^\mu\gamma_5\partial_\mu K q$$

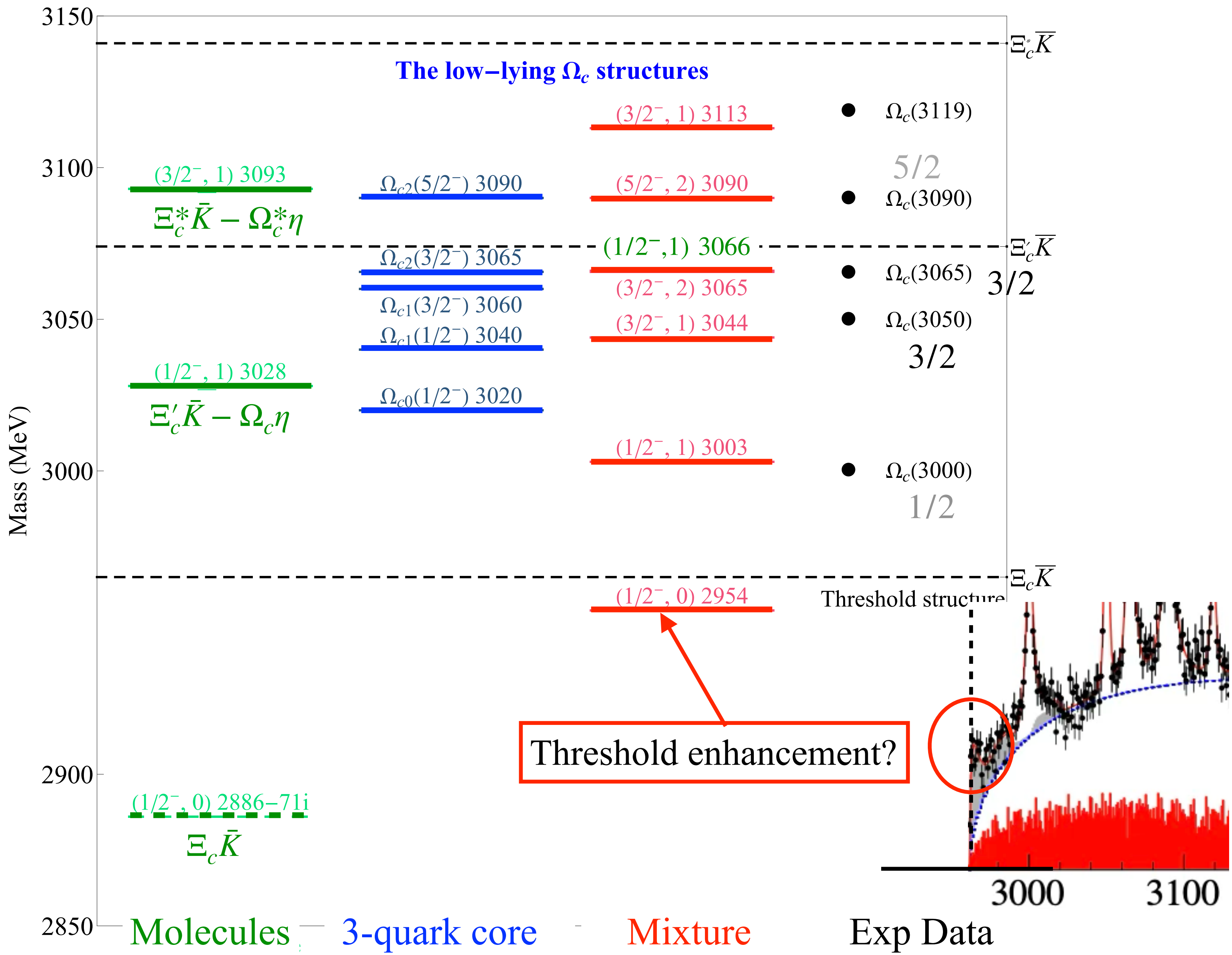
Coupling schemes for [Molecule]-[3quark]

$\Omega_c \sim [{}^3P_j, 1/2_c]^J$

Light spin

Heavy quark symmetry
constrains the MB combination

Light spin	J^P	3-quarks	Molecule
$j=2$	$5/2^-$	$\Omega_c({}^3P_2, 5/2)$	–
	$3/2^-$	$\Omega_c({}^3P_2, 3/2)$	–
$j=1$	$3/2^-$	$\Omega_c({}^3P_1, 3/2)$	$\Xi_c^* \bar{K}$, $\Omega_c^* \eta$
	$1/2^-$	$\Omega_c({}^3P_1, 1/2)$	$\Xi_c' \bar{K}$, $\Omega_c \eta$
$j=0$	$1/2^-$	$\Omega_c({}^3P_0, 1/2)$	$\Xi_c \bar{K}$


The low−lying Ω_c structures
Mass (MeV)
3150
3100
3050
3000
2900
2850
$\Xi_c^* \bar{K}$
$\Xi_c' \bar{K}$
$\Xi_c \bar{K}$
(3/2⁻, 1) 3093
$\Xi_c^* \bar{K} - \Omega_c^* \eta$
(1/2⁻, 1) 3028
$\Xi_c' \bar{K} - \Omega_c \eta$
(1/2⁻, 0) 2886−71i
$\Xi_c \bar{K}$
$\Omega_{c2}(5/2^-)$ 3090
$\Omega_{c2}(3/2^-)$ 3065
$\Omega_{c1}(3/2^-)$ 3060
$\Omega_{c1}(1/2^-)$ 3040
$\Omega_{c0}(1/2^-)$ 3020
(3/2⁻, 1) 3113
(5/2⁻, 2) 3090
(1/2⁻,1) 3066
(3/2⁻, 2) 3065
(3/2⁻, 1) 3044
(1/2⁻, 1) 3003
(1/2⁻, 0) 2954
$\Omega_c(3119)$
5/2
$\Omega_c(3090)$
$\Omega_c(3065)$
3/2
$\Omega_c(3050)$
3/2
$\Omega_c(3000)$
1/2
Threshold structure
Threshold enhancement?
3000
3100
Molecules
3-quark core
Mixture
Exp Data

Summary

- Coexistence of different structures is relevant for various hadrons.
- Ω_c baryons has been studied.
- Computation of decay widths is in progress
- All Ω_c's could be explained by coexistence with a prediction below the $\bar{K}\Xi_c$ threshold.