Coexistence of extended and compact structures: for the case Ω(2012)

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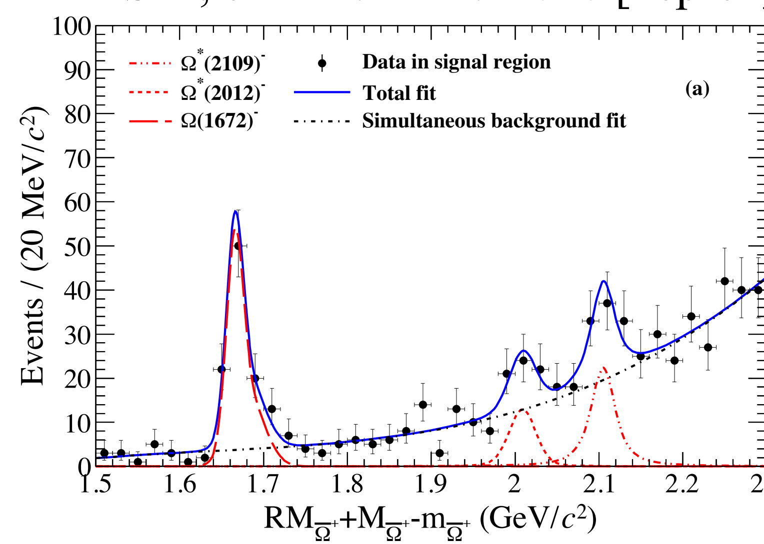
BESIII, e-Print: 2411.11648 [hep-ex]

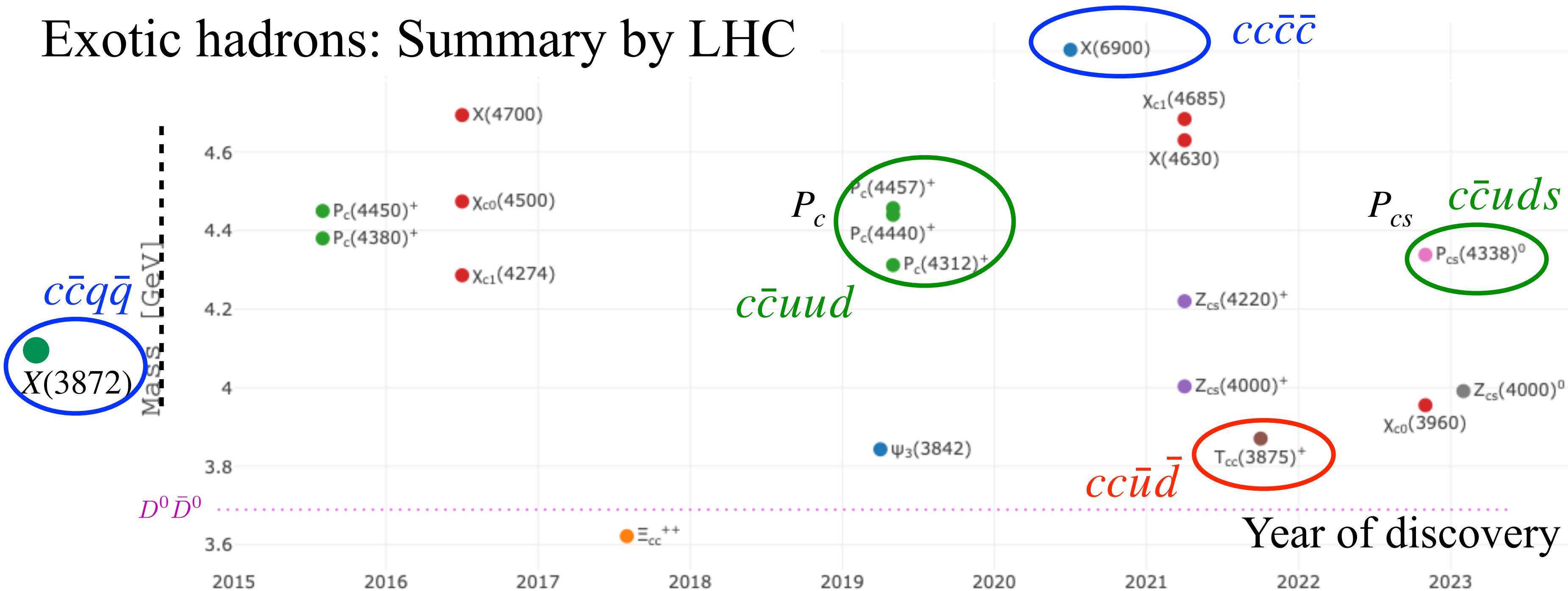


1. Introduction
2. Evidences of coexistence
   X(3872), Pc
3. sss baryon Ω(2012)

1. Introduction

Many exotics have been observed near/around thresholds

Exotic hadrons: Summary by LHC



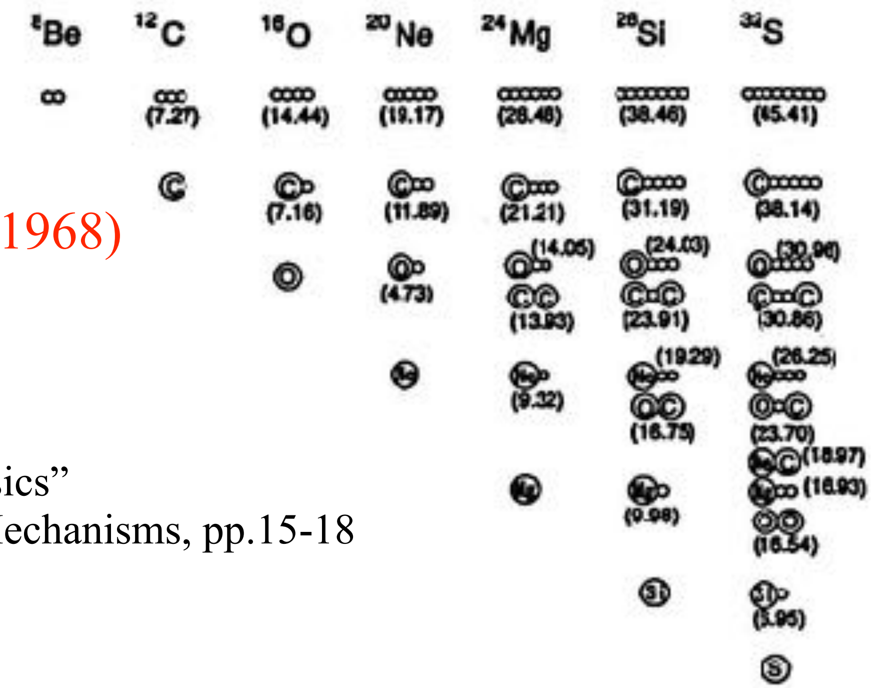
- Hidden charm meson: $c\bar{c}q\bar{q}$, $X(3872)$, … , $T_{\psi\psi}(6900)$, …
- Hidden charm baryon: $c\bar{c}qqq$, P_c, P_{cs}, . . .
- Doubly charm meson: $cc\bar{q}\bar{q}$, $T_{cc}(3875)$, …

Not only in hadrons but

Similar α-cluster structure in nuclei

Alpha cluster (molecular) structure of nuclei

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



Also see,
Brink, D M (Oxford U., Theor. Phys.)
"Prof. Ikeda's important contributions to nuclear physics"
12th International Conference on Nuclear Reaction Mechanisms, pp.15-18
15 - 19 Jun 2009, Villa Monastero, Varenna, Italy
https://cds.cern.ch/record/1237837/files/p15.pdf

Are hadrons (near threshold) molecular-like?

粒子と共鳴準位の混合効果について

Doctor thesis

益川敏英

名古屋大学 物理教室

1967. 2.

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

$$H^{int} = H^{int}_{I} + H^{int}_{II}$$

qqq SU(6) πN~Yukawa Molecule

ここで H_I は SU(6)−不変な部分であり，H_{II} はそうでない部分を表わしている。 Yukawa 相互作用は SU(6) 対称性を破る部分 H_{II} から導びかれると考えられよう。 この故に まず最初に H_I により urbaryon から核子が構成され，質量スペクトルが決められる。そして核子等が H_{II} により中間子の雲を着る。このとき H_{II} によって重粒子の質量スペクトラムは多少修正されても質的な変化はもたらされないと考える”

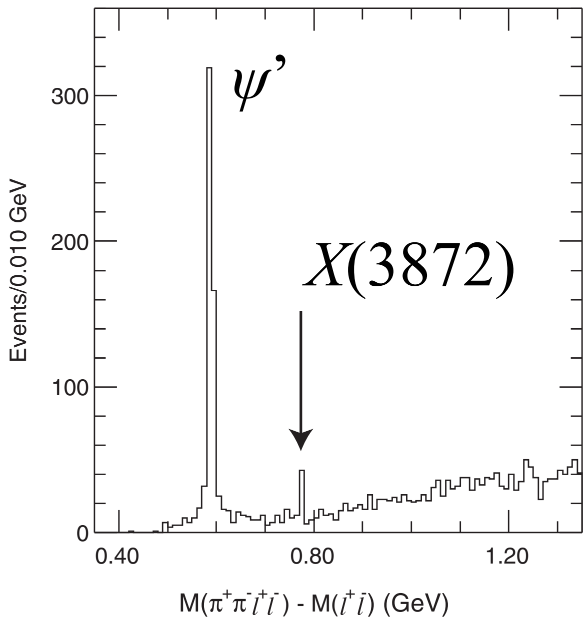
しかしながら Yukawa 相互作用は十分に弱いとは考えられない。

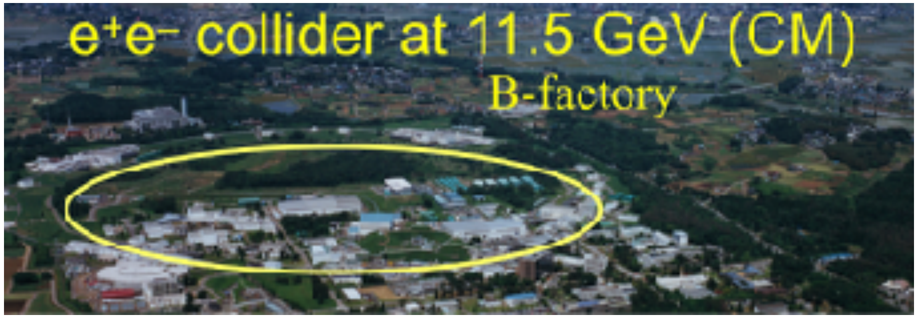
The system of pion, nucleon, and (3–3) particle acting mutually through the Yukawa interaction is investigated by means of the static meson theory. It is assumed that these particles (including the (3–3) particle) can be treated as elementary ones although they are equally constructed from urbaryons. An integral equation for the scattering amplitude is solved in some reasonable approximation. Since the Yukawa interaction is strong enough to produce resonances between pion and nucleon, one may expect that two resonances (or bound states) exist in the (3–3) state of pion-nucleon scattering. In fact, the solution with two resonances is obtained in case the mixing energy is small. It is shown, however, that one of them disappears when the mixing energy increases.

— 1 —

2. Evidences, X(3872)

Belle@KEK, PRL91, 262001 (2003)
and further confirmed at Fermi Lab, SLAC, LHC, BEP, …





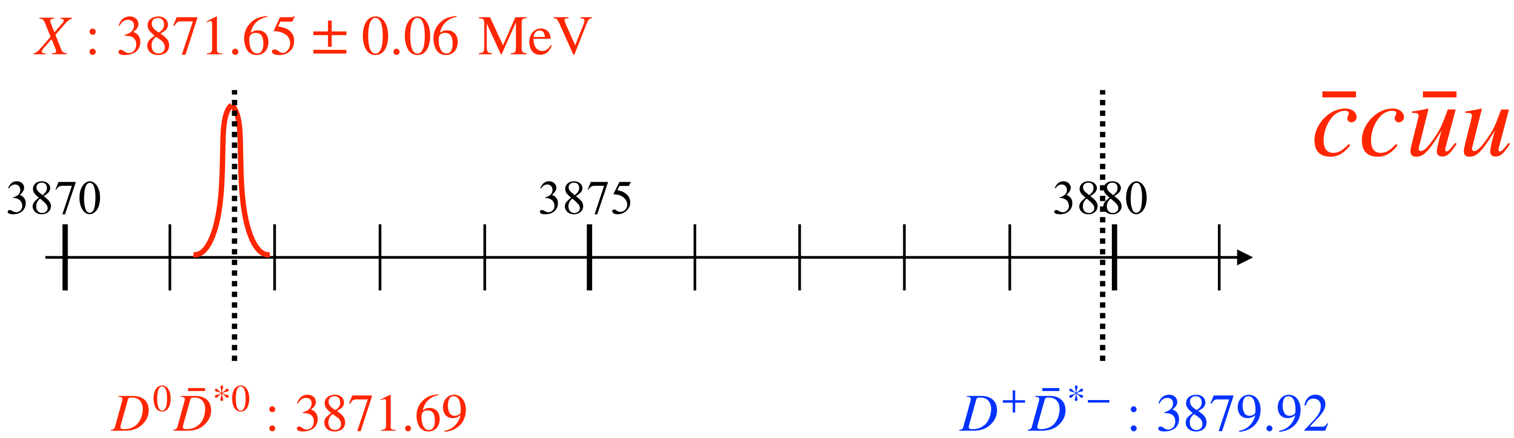
$u\bar{u}c\bar{c},\ d\bar{d}c\bar{c}$

Heavy and light quarks

Many other findings have are following

2. Evidences, X(3872)

- Located almost at the threshold $D^0\bar{D}^{*0}$



- Large isospin violation

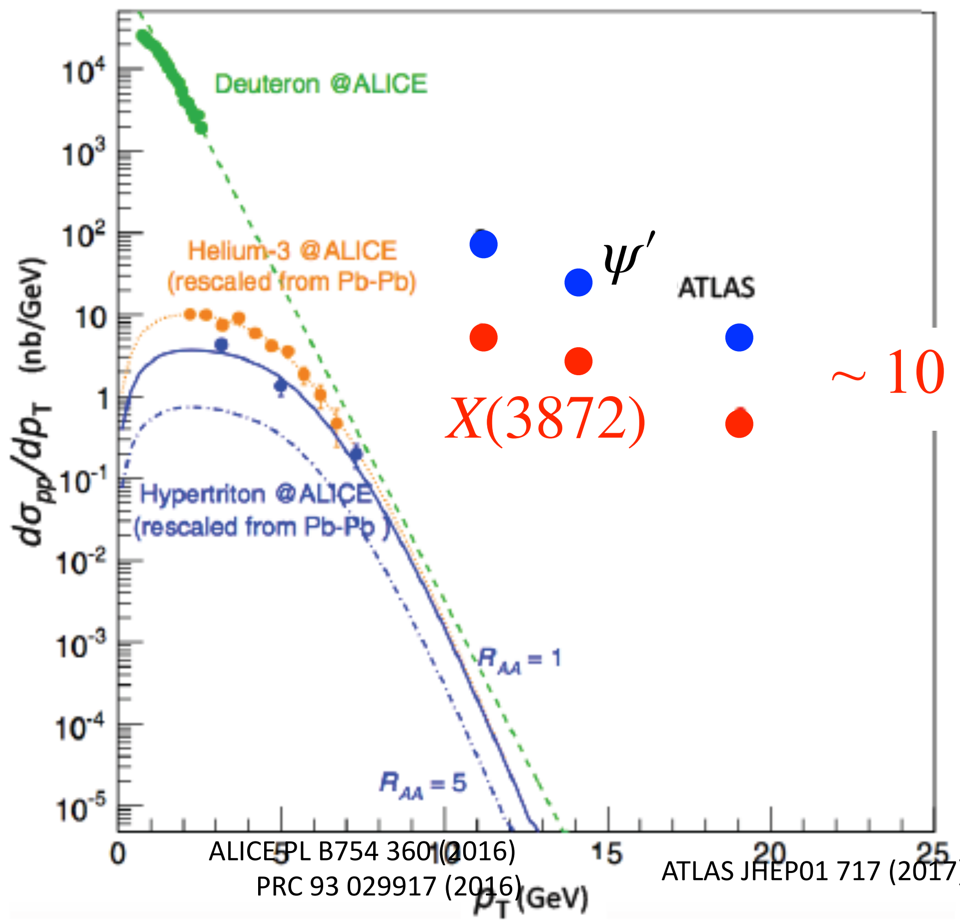
$$\frac{Br(X \to \pi^+\pi^-\pi^0 J/\psi)}{Br(X \to \pi^+\pi^- J/\psi)} = 1.0 \pm 0.4 \pm 0.3$$

- Spin-parity $J^{PC} = 1^{++}$ from angular correlation

BUT

Large production rate
by high energy collisions

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



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

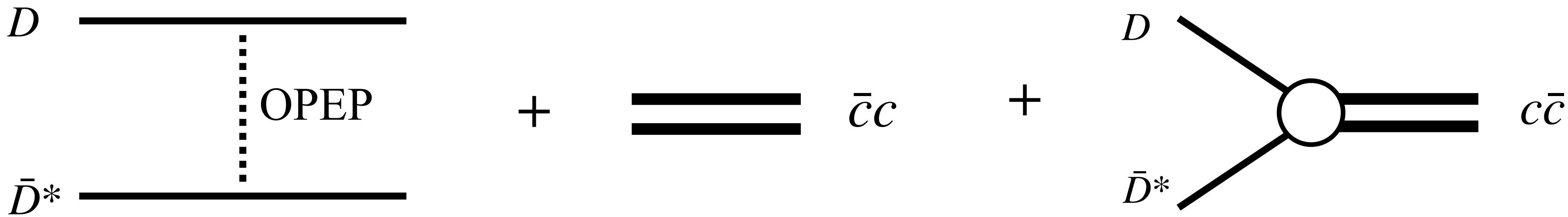
ATLAS JHEP01 717 (2017)

Implies admixture of $D^0\bar{D}^{*0}$ and quark core ($\sim c\bar{c}$)

Hybrid of $D\bar{D}^*$ and $c\bar{c}$

- $c\bar{c}$ - $D\bar{D}^*$ (without $D\bar{D}^*$ interaction)
  M. Takizawa and S. Takeuchi, Prog. Theor. Exp. Phys. 2013, 093D01
- $c\bar{c}$ - $D\bar{D}^*$ (with OPEP for $D\bar{D}^*$)
  Y. Yamaguchi, A. Hosaka, S. Takeuchi and M. Takizawa, J.Phys.G 47 (2020) 5, 053001

Extended molecular $\psi_{D\bar{D}^*}$ Compact $\bar{c}c$ $\psi_{c\bar{c}}$ Coupling



$$H = H_{D\bar{D}^*} + H_{c\bar{c}} + V$$

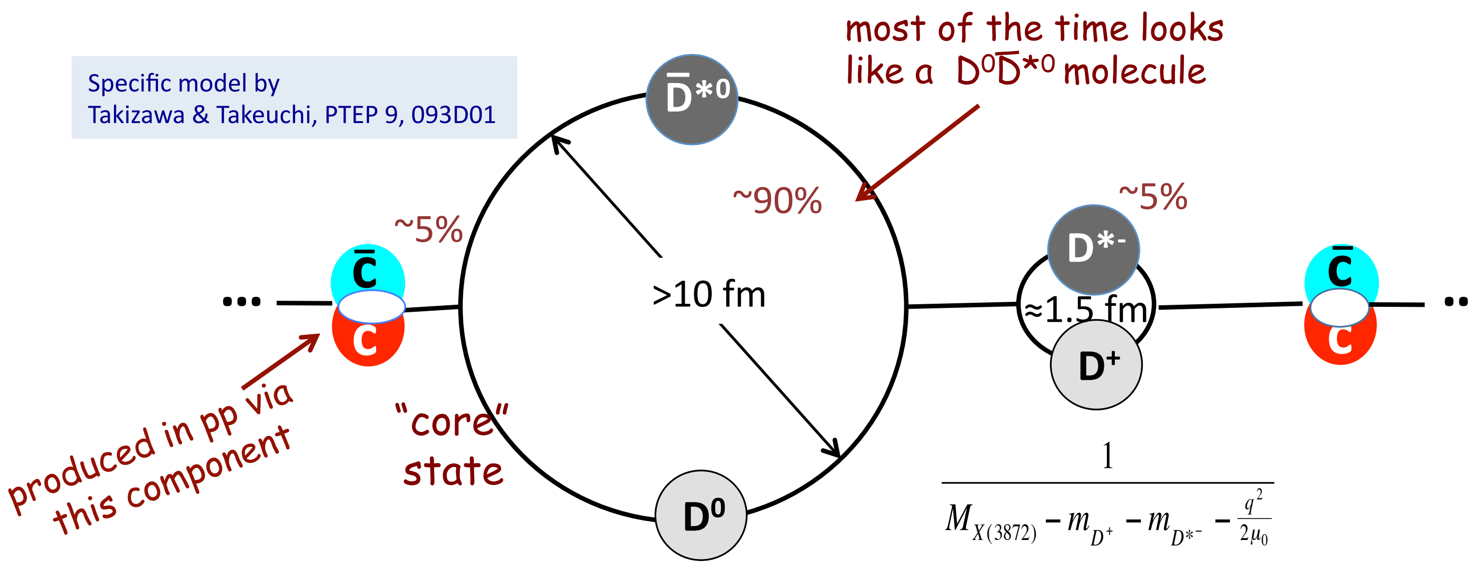
$$\psi_{tot} = c_{c\bar{c}}\psi_{c\bar{c}} + c_0\psi_{D^0\bar{D}^{*0}} + c_{\pm}\psi_{D^+D^{*-}}$$

$$\rightarrow \quad \psi_{c\bar{c}} + \psi_{D\bar{D}^*}$$ Superposition of two structures

From Steve Olsen

Consensus(?): mixture of $D\bar{D}^*$ & a $c\bar{c}$ "core"

Specific model by
Takizawa & Takeuchi, PTEP 9, 093D01



$$\frac{1}{M_{X(3872)} - m_{D^0} - m_{D^{*0}} - \frac{q^2}{2\mu_0}}$$

$|BE| < 0.2$ MeV

$d_{\text{rms}}^{D^0\bar{D}^{*0}} > 10$ fm

$$\frac{1}{M_{X(3872)} - m_{D^+} - m_{D^{*-}} - \frac{q^2}{2\mu_0}}$$

$|BE| \approx 8$ MeV

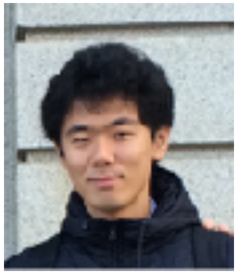
$d_{\text{rms}}^{D^+D^{*-}} \simeq 1.5$ fm

$$d_{\text{rms}} \approx \frac{1}{\sqrt{2\mu_D |BE|}}:$$

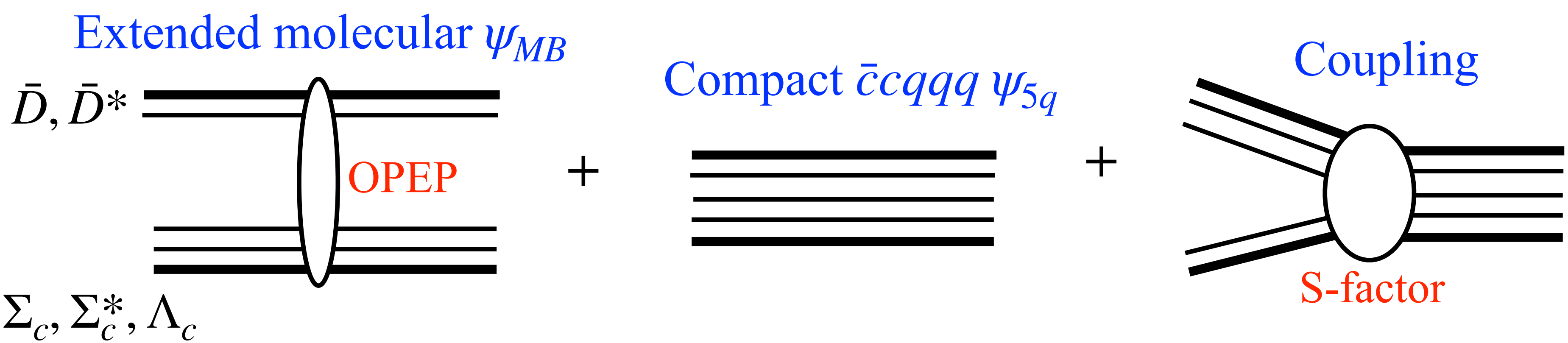
reduced mass

$|m_D + m_{D^*} - m_{X3872}|$

2. Evidences, Pc's

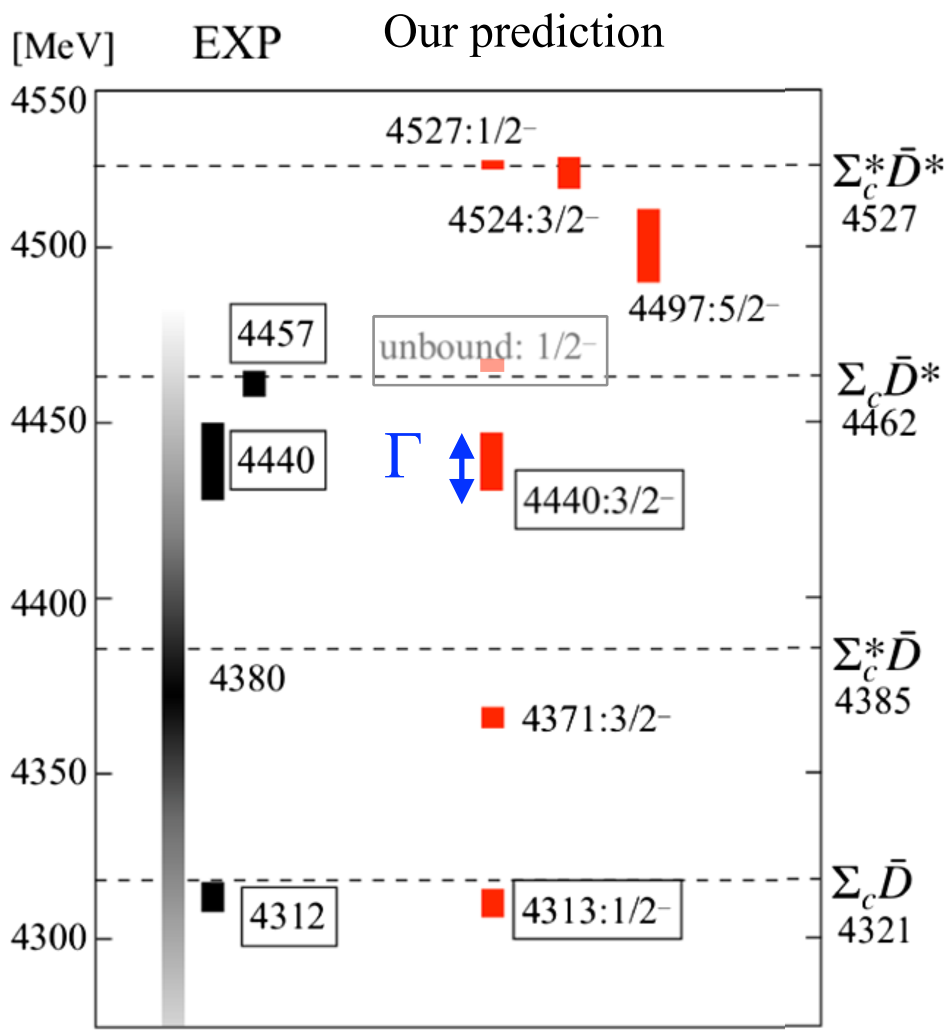


Y. Yamaguchi et al, Phys. Rev. D 96, 114031 (2017): P_c
Y. Yamaguchi et al, Phys. Rev. D 101, 091502 (2020) : P_c
A. Giachino et al, Phys. Rev. D 108 (2023) 7, 074012: P_{cs}



$$\Psi_{tot} = c_{MB}\psi_{MB} + c_{5q}\psi_{5q}$$

Results for P_c



Phys. Rev. D 96, 114031 (2017)
Phys. Rev. D 101, 091502 (2020)

- 4312, 4440 and 4457 agree with data
- Their spin and parities are predicted.
- $\Sigma_c^* D$ singlet and $\Sigma_c^* D^*$ triplet are predicted
- OPEP and V^{5q} are both important for binding
- Widths and spin splittings are due to OPEP

3. sss baryon Ω(2012)

J. Yelton et al. (Belle Collaboration), PRL121, 052003 (2018)

3-quark *sss* *

- p-wave excitation of *sss*
- Spin-orbit partners

  $J^P = 1/2^-,\ 3/2^-$

OR

Molecule of $\bar{K}\Xi^*$?

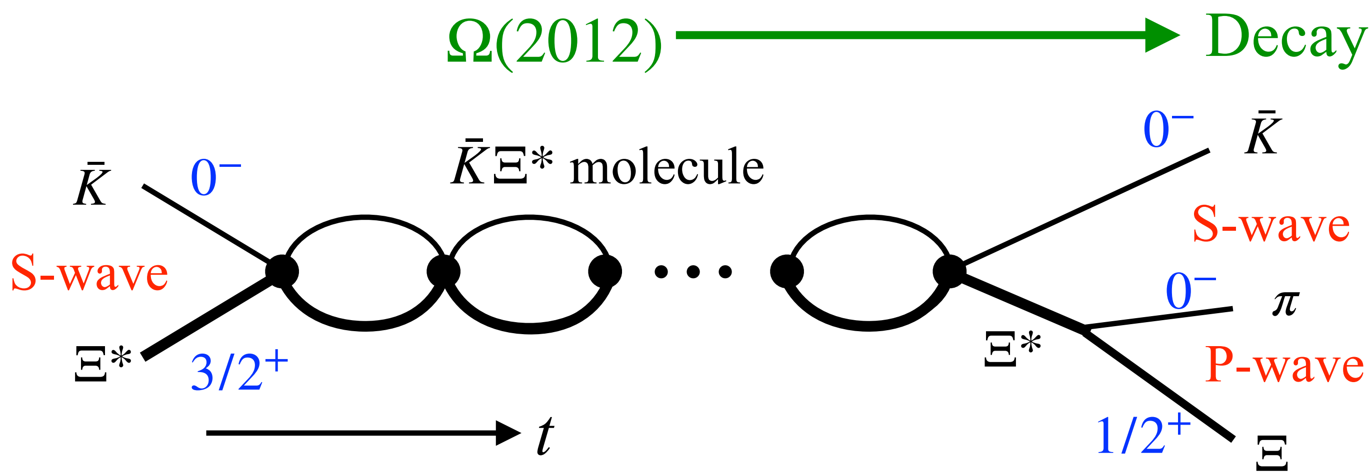
- Near $\bar{K}\Xi^*(3/2^+)$ threshold
- $M \sim 2012 - i\ 6.4/2$ MeV

  $\underset{\bar{K}}{}$ 2025 MeV ~ $\underbrace{495}_{\bar{K}} + \underbrace{1530}_{\Xi^*}$
- $J^P = 3/2^-$

Decays

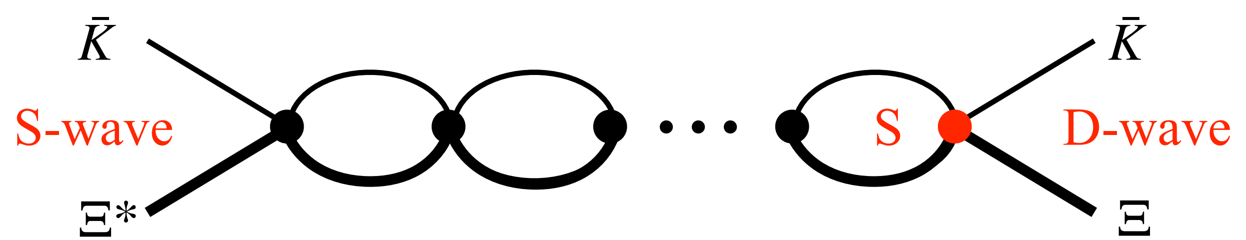
IF: Molecular state

- S-wave structure $\bar{K}\Xi^*$ implies $\bar{K}\Xi\pi$ **3-body decay**



Dominant?

- Not easy to explain decay into $\bar{K}\Xi$ (D-wave)



Controversy in Experiments

Decays $\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} \equiv \dfrac{\mathcal{B}[\Omega(2012) \to \Xi(1530)\bar{K} \to \Xi\pi\bar{K}]}{\mathcal{B}[\Omega(2012) \to \Xi\bar{K}]}$

PRD 100, 032006 (2019)

Using data samples of e^+e^- collisions collected at the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ resonances with the Belle detector, we search for the three-body decay of the $\Omega(2012)$ baryon to $K\pi\Xi$. This decay is predicted to dominate for models describing the $\Omega(2012)$ as a $K\Xi(1530)$ molecule. No significant $\Omega(2012)$ signals are observed in the studied channels, and 90% credibility level upper limits on the ratios of the branching fractions relative to $K\Xi$ decay modes are obtained.

Our result strongly disfavors the molecular interpretation

VS

arXiv:2207.03090v1

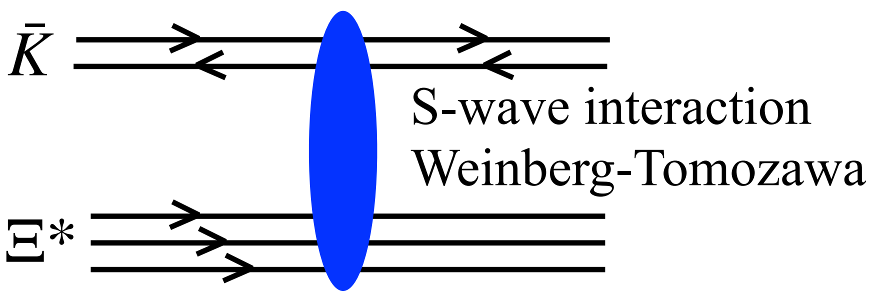
Using $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ data collected by the Belle detector, we discover a new resonant three-body decay $\Omega(2012)^- \to \Xi(1530)^0 K^- \to \Xi^-\pi^+K^-$ with a significance of 5.2σ. The mass of the $\Omega(2012)^-$ is $(2012.5 \pm 0.7 \pm 0.5)$ MeV and its effective couplings to $\Xi(1530)\bar{K}$ and $\Xi\bar{K}$ are $(41.1 \pm 35.8 \pm 6.0) \times 10^{-2}$ and $(1.7 \pm 0.3 \pm 0.3) \times 10^{-2}$, where the first uncertainties are statistical and the second are systematic. The ratio of the branching fraction for the resonant three-body decay to that for the two-body decay to ΞK is $0.97 \pm 0.24 \pm 0.07$, consistent with the molecular model of $\Omega(2012)^-$, which predicts comparable rates for $\Omega(2012)^-$ decay to $\Xi(1530)\bar{K}$ and $\Xi\bar{K}$.

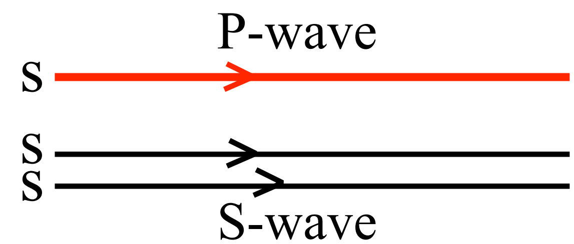
Similar strategy

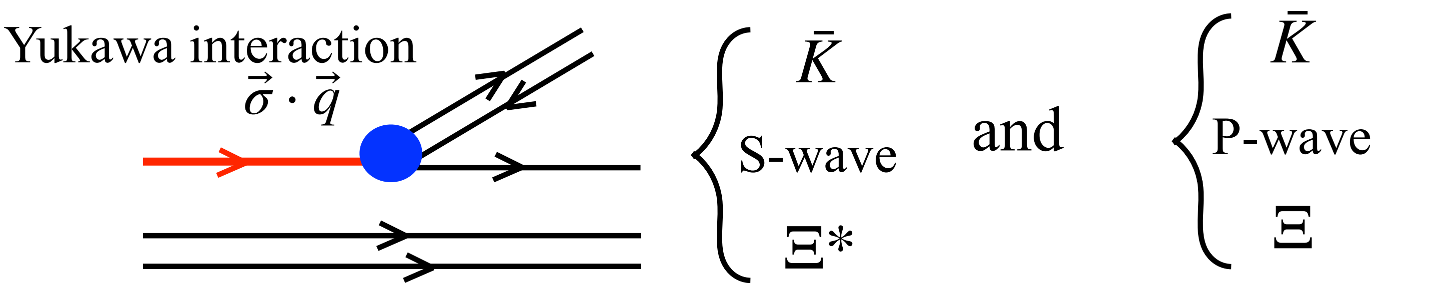
Q.-F. Lyu, H, Nagahiro and AH, Phys.Rev.D 107 (2023) 1, 014025

With inputs from the quark model and chiral symmetry

Extended molecular $\psi_{K\Xi^*}$ + Compact sss ψ_{sss}





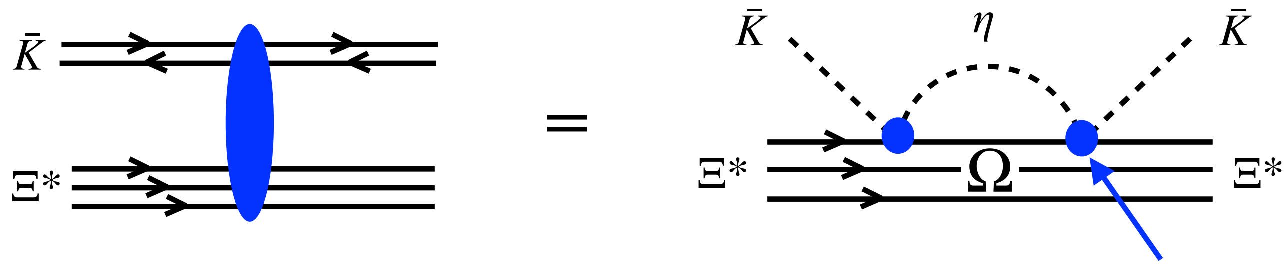


(for decays)

$$\Psi_{tot} = c_{K\Xi^*}\psi_{K\Xi^*} + c_{sss}\psi_{sss}$$

Interactions

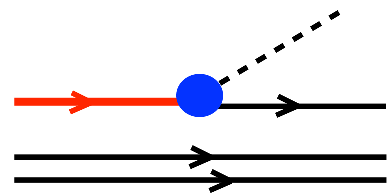
- $\bar{K}\Xi^*$ interaction: Weinberg-Tomozawa



Generated by the coupling to $\eta\Omega$

$$\mathcal{L}_{WT} = -\frac{i}{8f_p^2}\bar{q}\gamma_\mu(\phi^\mu\phi - \phi\phi^\mu)q$$

- $\bar{K}\Xi^*$-sss interaction: Yukawa



$$\mathscr{L}_{Ksq} = \frac{1}{2f_\pi}\bar{q}\gamma_\mu\partial^\mu\phi q \rightarrow \vec{\sigma}\cdot\vec{q}$$

- Hamiltonian

$$H = \begin{array}{c} \begin{array}{ccc} \bar{K}\Xi^* & \eta\Omega & sss \end{array} \\ \left(\begin{array}{cc|c} K_{\bar{K}\Xi^*} & F & V_{sss^*-\bar{K}\Xi^*} \\ F & K_{\eta\Omega} & 0 \\ \hline V_{sss^*-\bar{K}\Xi^*} & 0 & H_{sss^*} \end{array}\right) \end{array} \begin{array}{c} \bar{K}\Xi^* \\ \eta\Omega \\ sss \end{array} \rightarrow \begin{array}{c} \begin{array}{cc} \bar{K}\Xi^* & sss \end{array} \\ \left(\begin{array}{c|c} K_{\bar{K}\Xi^*} + V_{\bar{K}\Xi^*} & V_{\bar{K}\Xi^*-sss^*} \\ \hline V_{sss^*-\bar{K}\Xi^*} & H_{sss^*} \end{array}\right) \end{array} \begin{array}{c} \bar{K}\Xi^* \\ sss \end{array}$$

Further eliminate sss
$\rightarrow$ Effective hamiltonian for $\bar{K}\Xi^*$ $\rightarrow$ Scattering amplitudes

Structure of the scattering amplitude

$$T_{A\to A} = \sum_i g_{Ai} D_{ij} g_{jA}$$

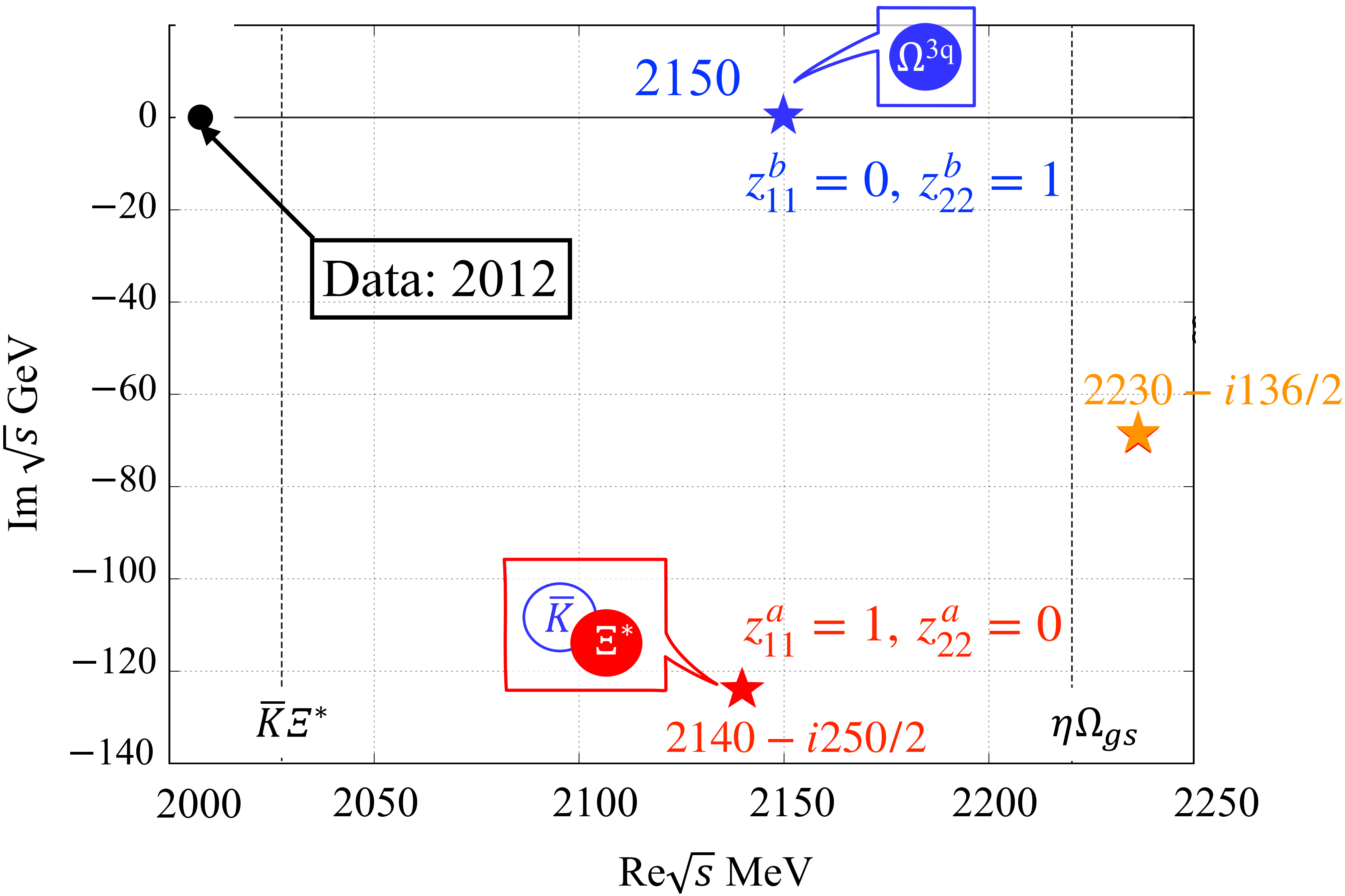
- g_{Ai}: Coupling the scattering state A to the basis state i
- D_{ij}: Propagator matrix expanded by the basis states i, j
- The residues (at a pole a = physical state) of the diagonal components $D_{ii}(a)$ corresponds to the mixing rates z_{ii}^a of the basis states i.

$$D_{ii}\left(\sqrt{s}\right) \sim \frac{z_{ii}^a}{\sqrt{s}-\sqrt{s_a}} + \frac{z_{ii}^b}{\sqrt{s}-\sqrt{s_b}} + \cdots, \quad i = 1,2$$

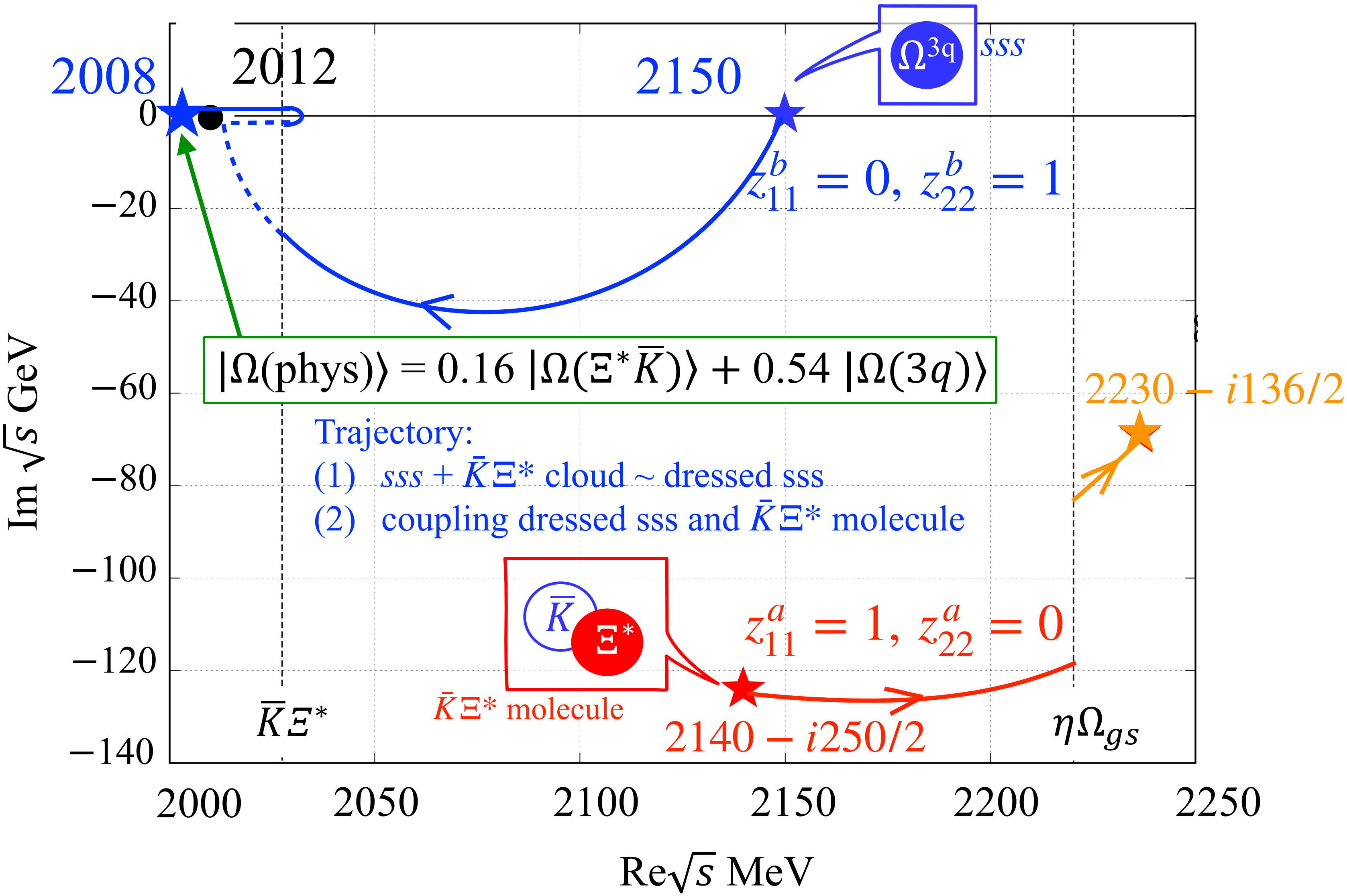
$$|\psi_a\rangle = \sum_i z_{ii}^a |i\rangle$$

Question:
How z_{ii}, wave function components, change as the coupling is varied

Molecule ★ and sss* (3q ★) states



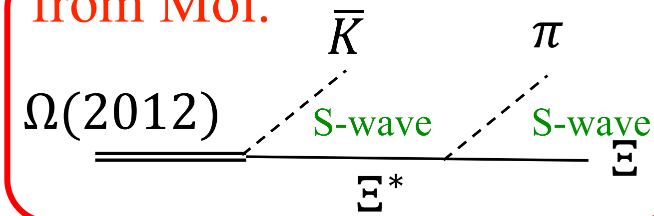
Trajectory



2008
2012
2150
Ω^{3q}
sss
0
−20
−40
−60
−80
−100
−120
−140
$z^b_{11} = 0,\ z^b_{22} = 1$
$|\Omega(\text{phys})\rangle = 0.16\ |\Omega(\Xi^*\bar{K})\rangle + 0.54\ |\Omega(3q)\rangle$
$2230 - i136/2$
Trajectory:
(1) $sss + \bar{K}\Xi^*$ cloud ~ dressed sss
(2) coupling dressed sss and $\bar{K}\Xi^*$ molecule
$\bar{K}$
Ξ^*
$z^a_{11} = 1,\ z^a_{22} = 0$
$\bar{K}\Xi^*$
$\bar{K}\Xi^*$ molecule
$2140 - i250/2$
$\eta\Omega_{gs}$
2000
2050
2100
2150
2200
2250
Im $\sqrt{s}$ GeV
Re$\sqrt{s}$ MeV

Decay rate $\Omega(2012) \to \Xi\pi\bar{K}$, $\Xi\bar{K}$; $\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}}$

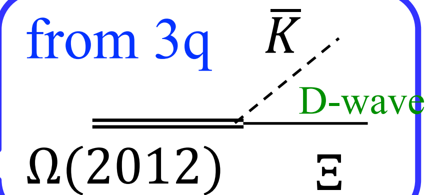
from Mol.



Width $\Gamma = 6.4^{+2.5}_{-2.0} \pm 1.6$ [PDG]

$$\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} \equiv \frac{\mathcal{B}[\Omega(2012) \to \Xi(1530)\bar{K} \to \Xi\pi\bar{K}]}{\mathcal{B}[\Omega(2012) \to \Xi\bar{K}]}$$

from 3q



$\Gamma_2 \sim 3.02$ MeV
$\Gamma_3 \sim 0.92$ MeV

$$\boxed{\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} \equiv 30}$$

$\Gamma(\Xi\pi) = 3.02$ MeV $\Leftarrow$ $\Omega(3q)$

$\Omega(\Xi^*\bar{K})$ because of the lack of $\Xi^*\bar{K} \to \Xi\bar{K}$

$\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} < 11.9\%$	$\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} = 0.97 \pm 0.24 \pm 0.07$
S.Jia et al. (Belle), PRD100, 032006(2019)	Belle, arXiv:2207.03090 (July 2022)

sss dominance in the sum rule

N. Su, H.X. Chen and A. Hosaka, Phys.Rev.D 110 (2024) 3, 034007

Two-point function

$$\Pi(q^2) = \int d^4x \; e^{iqx} \langle 0 | T J_\Omega(x) J_\Omega(0) | 0 \rangle$$

OPE QCD $\longleftrightarrow$ *Dispersion relation* $\longleftrightarrow$ Spectral sum Phenomena

Three types of *sss* currents J_Ω:

for spin 1/2, 3/2 with derivative, J, J_μ

for spin 3/2 without derivative, J'_μ

$$J_\Omega = \begin{cases} J = -2\epsilon^{abc}[(D^\mu s_a^T)C\gamma_5 s_b]\gamma_\mu s_c, \\ J_\mu = -2\epsilon^{abc}[(D^\nu s_a^T)C\gamma_5 s_b]\left(g_{\mu\nu} - \frac{1}{4}\gamma_\mu\gamma_\nu\right)s_c \\ J'_\mu = -\sqrt{3}\epsilon^{abc} s_a^T C\gamma_\mu s_b s_c \end{cases}$$

Current	State	Mass [GeV]	
J	$\vert\Omega; 1/2^+\rangle$	$3.05^{+0.21}_{-0.15}$	
	$\vert\Omega; 1/2^-\rangle$	$2.07^{+0.07}_{-0.07}$	→ (Unobserved) Ω*
J_μ	$\vert\Omega; 3/2^+\rangle$	$3.13^{+0.27}_{-0.18}$	
	$\vert\Omega; 3/2^-\rangle$	$2.05^{+0.09}_{-0.10}$	→ Observed $\Omega^-(2012)$
J'_μ	$\vert\Omega'; 3/2^+\rangle$	$1.59^{+0.10}_{-0.12}$	→ Established $\Omega^-(1672)$
	$\vert\Omega'; 3/2^-\rangle$	$3.15^{+0.16}_{-0.17}$	

Summary

- Different configurations may coexist in hadron states.
- For Ω(2012) $|\Omega(\text{phys})\rangle = 0.16\,|\Omega(\Xi^*\bar{K})\rangle + 0.54\,|\Omega(3q)\rangle$

  Ω(2012) assuming $J^P = 3/2^-$
- Pole flow analysis suggests its sss origin.
- Properties;

  $$M \sim 2008 - i4.1/2\ \text{MeV}, \quad \mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} \sim 0.35$$

  $$M(exp) \sim 2012 - i6.4^{+2.5}_{-2.0}/2\ \text{MeV}$$ BESIII, e-Print: 2411.11648 [hep-ex]

  $$\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}}(exp) \le 0.12, \sim 1\ ??$$

  (Chengping Shen's talk)
- Yet another state Ω(2109)

  ~ Hint to LS splitting