Coexistence of extended and compact structures
— Omega(2012) —

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RCNP (Osaka) and ASRC (JAEA, Tokai)
with Qifang Lyu (Hunan Normal U)
and Hideko Nagahiro (Nara Women's U)

- Belle:
  e-Print: 2207.03090 [hep-ex]
  Phys.Rev.D 104, 052005 (2021) • e-Print: 2106.00892 [hep-ex]
  Phys.Rev.D 100, 032006 (2019) • e-Print: 1906.00194 [hep-ex]
- Our paper by Lyu, Nagahiro and Hosaka
  Phys.Rev.D 107 (2023) 1, 014025 • e-Print: 2212.02783 [hep-ph]
- Valencia group:
  Phys.Rev.D 101 (2020) 9, 094016 • e-Print: 2003.07580 [hep-ph]

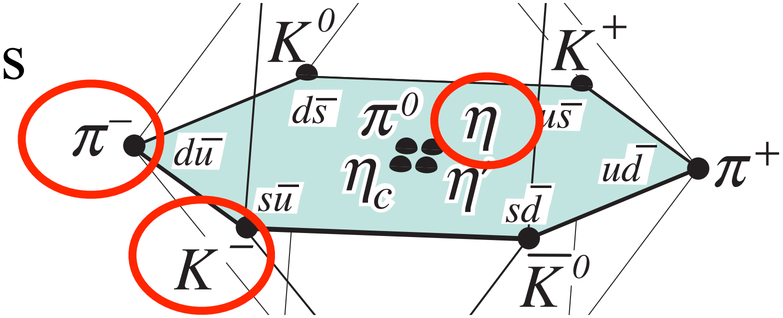
and many others…

Relevant particles, names, …

Strange quarks, s, sss, p-wave, $\bar{K}(0^-)$, $\Xi_{gs}(1/2^+)$, $\Xi^*(3/2^+)$

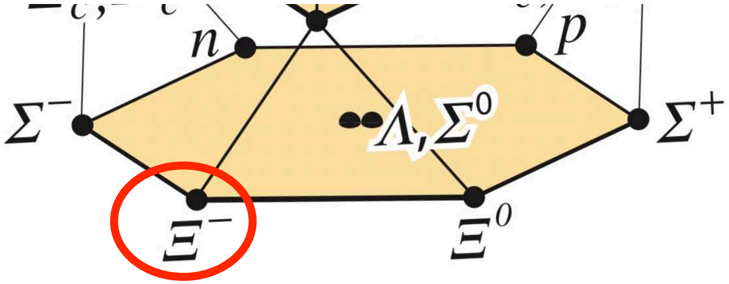
495 1320 1530

Octet mesons

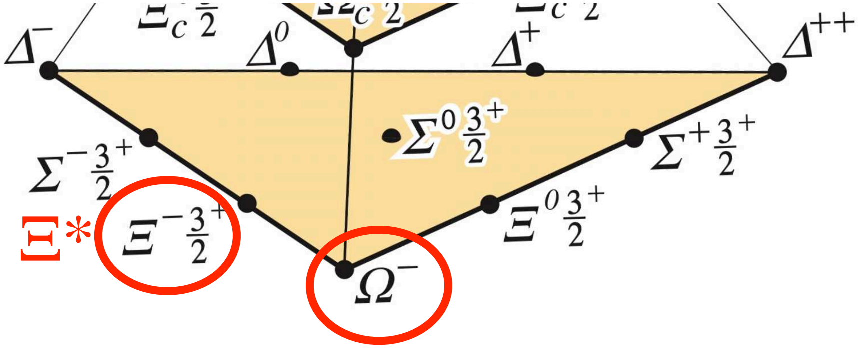


Pictures from PDG

Octet baryons



Decuplet baryons



Motivations

- Hadrons (made of quarks) have multi-faces
- Are baryons 3 quark or meson-(bare)baryon states?

compact extended molecular

- Long standing issue, Δ(1232), Λ(1405), P_c's, …

Dr. Thesis of T. Maskawa (1967)

Today I will discuss Ω(2012)

- Discovered by Belle
- 3-quark and molecular make different predictions

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

1967. 2.

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

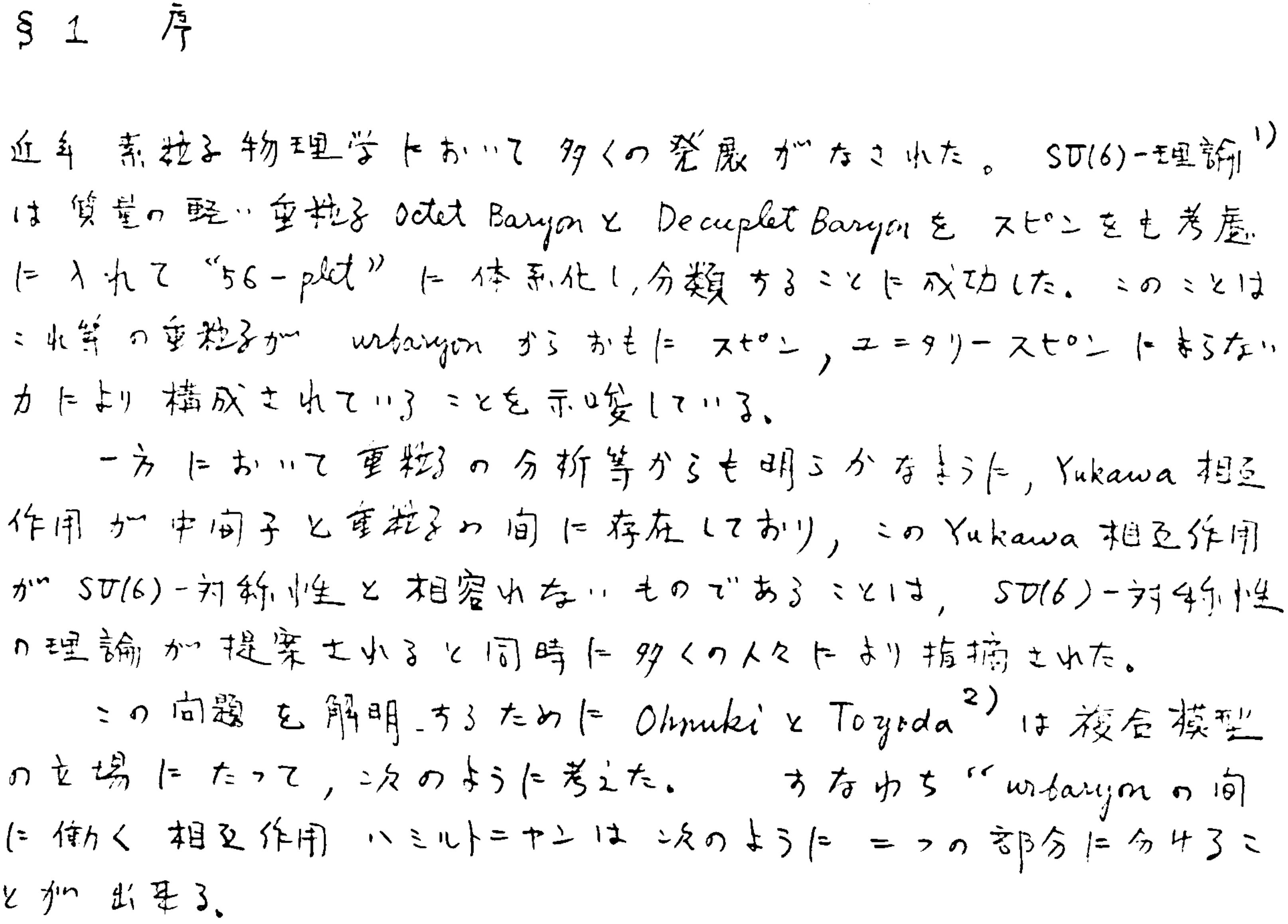
Mixing Effect between Particles and Resonances

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

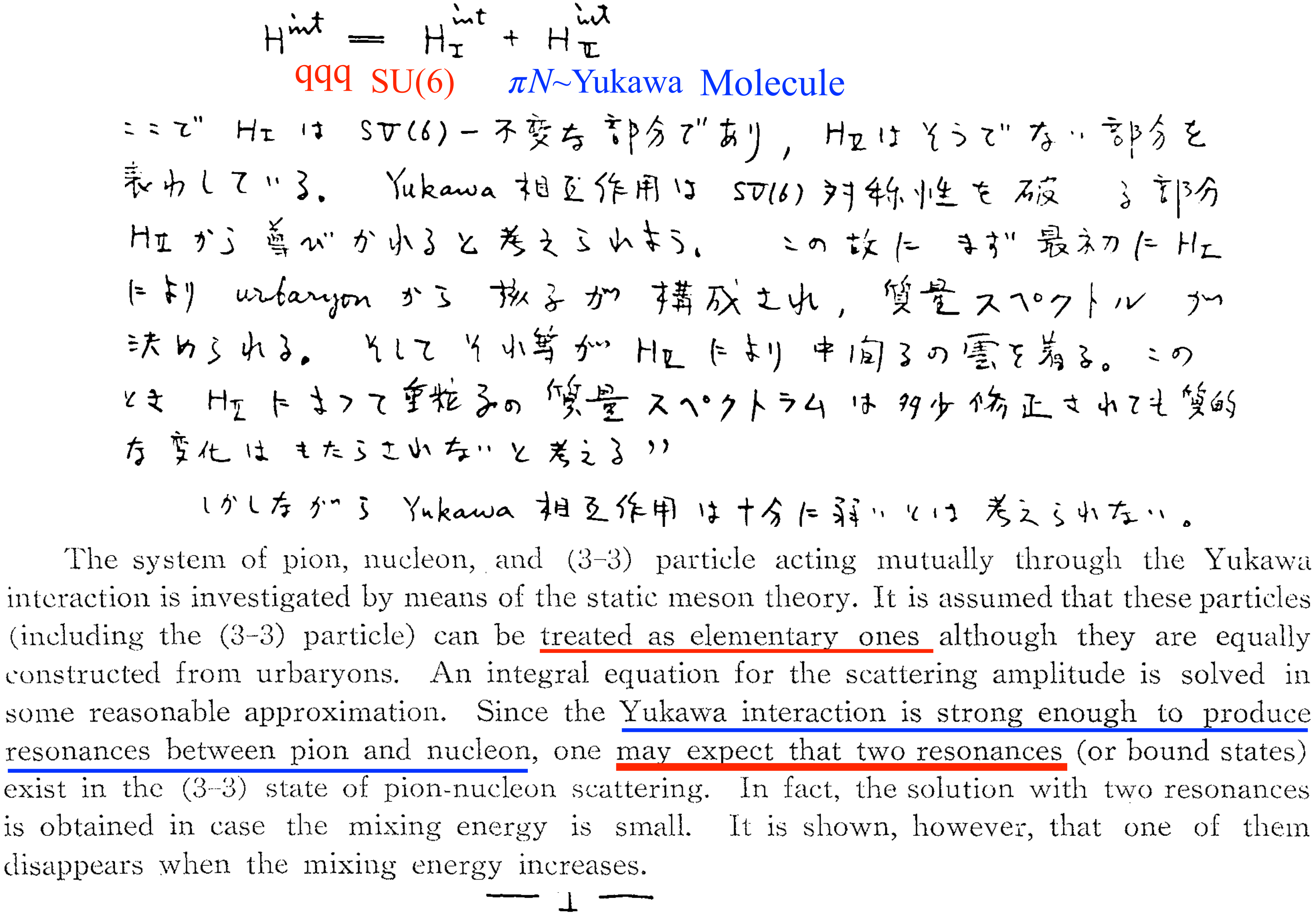


§1 序

近年 素粒子物理学において 多くの発展がなされた。SU(6)-理論1) は質量の軽い重粒子 Octet Baryon と Decuplet Baryon を スピンをも考慮に入れて "56-plet" に体系化し, 分類することに成功した。このことはこれ等の重粒子が urbaryon からおもにスピン, ユニタリースピンによらない力により構成されていることを示唆している。

一方において重粒子の分析等からも明らかなように, Yukawa 相互作用が中間子と重粒子の間に存在しており, この Yukawa 相互作用が SU(6)-対称性と相容れないものであることは, SU(6)-対称性の理論が提案されると同時に多くの人々により指摘された。

この問題を解明するために Ohnuki と Toyoda2) は複合模型の立場にたって, 次のように考えた。すなわち "urbaryon の間に働く相互作用ハミルトニアンは次のように二つの部分に分けることが出来る。



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

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。そしてそれ等が 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 —

$\Omega(2012)$: The first excited state of sss

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

Naively 3-quark sss^*

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

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

OR

Can it be a molecule of $\bar{K}\Xi^*$?

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

  $2025 \text{ MeV} \sim \underset{\bar{K}}{495} + \underset{\Xi^*}{1530}$

- $J^P = 3/2^-$

Ω BARYONS ($S = -3$, $I = 0$)

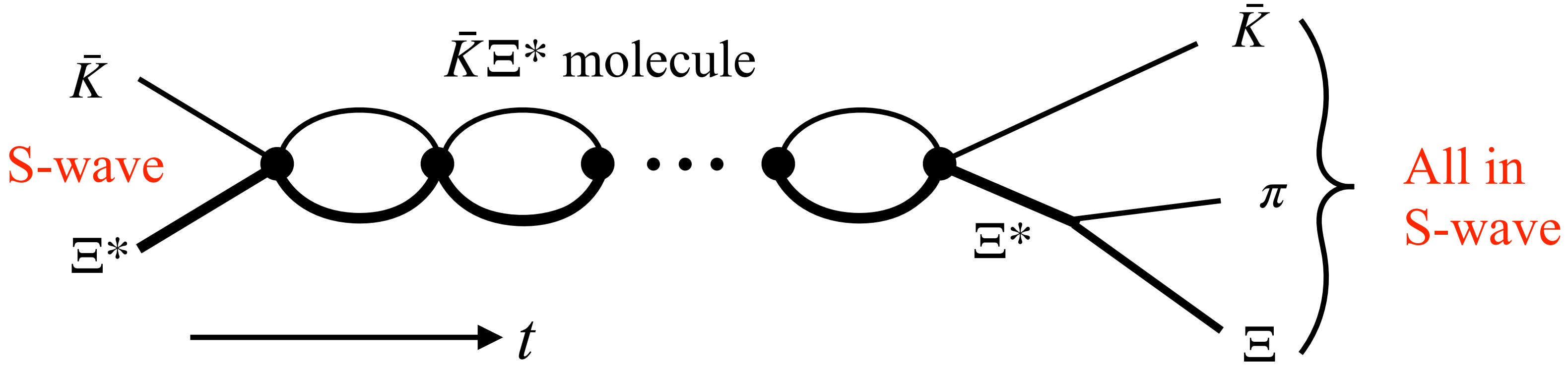
$\Omega^- = s\,s\,s$

Ω^-	$3/2^+$	****
$\Omega(2012)^-$	$?^-$	***
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

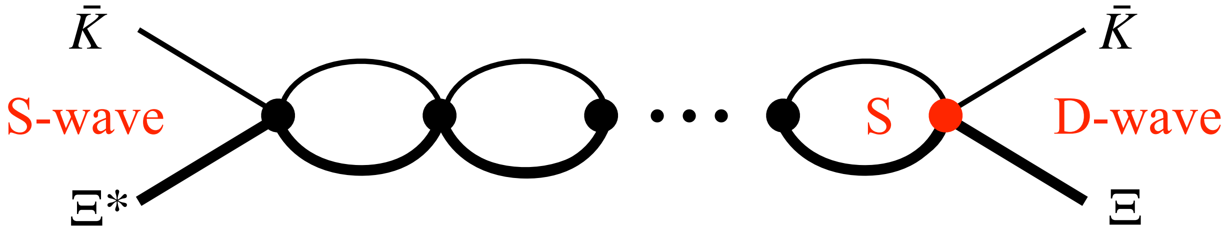
Decays

Molecular state

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

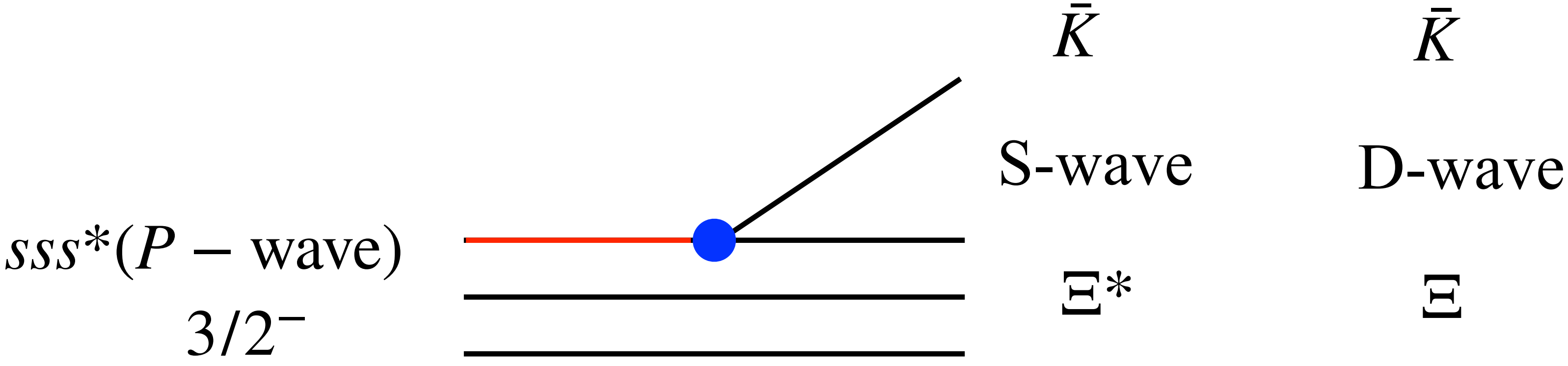


- Not easy to explain decay into $\bar{K}\Xi$ (D-wave)



3q sss^* state

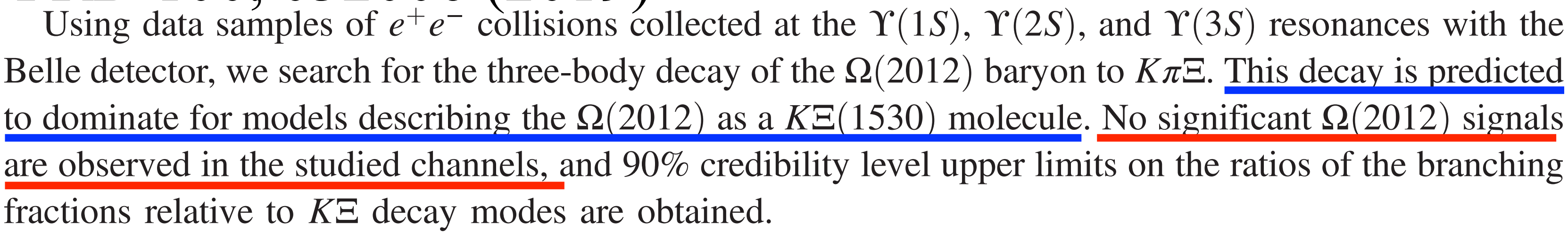
- Allows both $\bar{K}\Xi^*(\to \bar{K}\Xi\pi)$ and $\bar{K}\Xi$ (D-wave)



Controversy in Experiments

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

PRD 100, 032006 (2019)

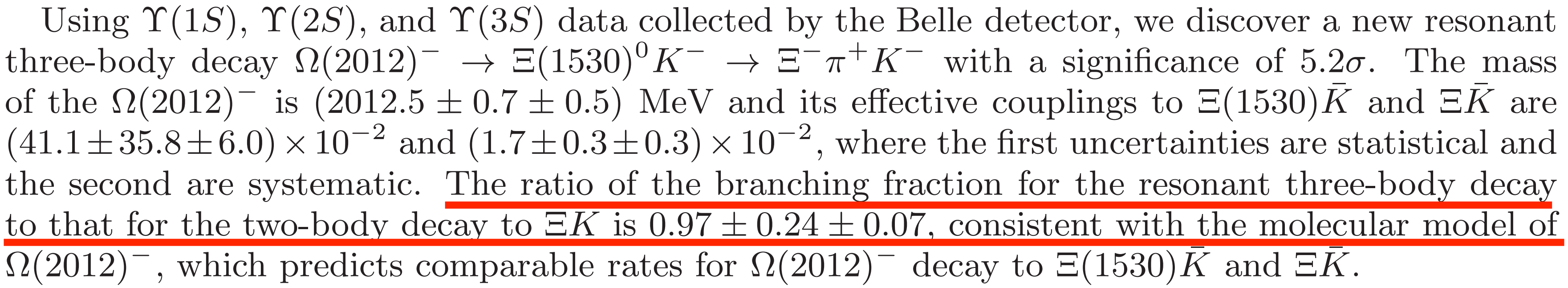


Using data samples of e^+e^- collisions collected at the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ resonances with the Belle detector, we search for the three-body decay of the $\Omega(2012)$ baryon to $K\pi\Xi$. This decay is predicted to dominate for models describing the $\Omega(2012)$ as 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 $\Xi\bar{K}$.

Motivated by $\bar{K}\Xi^*$ molecule

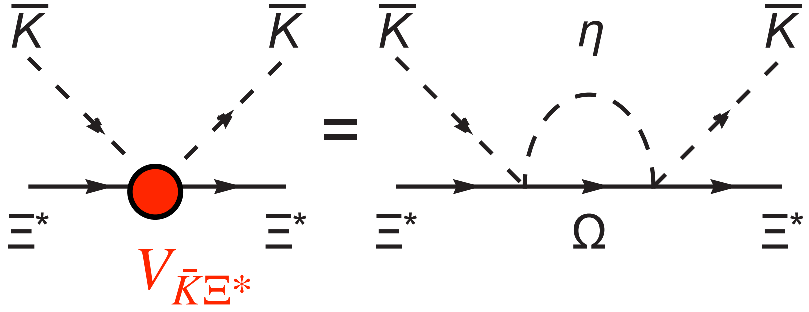
Chiral unitary approach

- Two channels: $\bar{K}\Xi^*, \eta\Omega$

$$V = \begin{array}{cc} \begin{array}{cc} \bar{K}\Xi^* & \eta\Omega \end{array} & \\ \begin{pmatrix} 0 & 3F \\ 3F & 0 \end{pmatrix} & \begin{array}{c} \bar{K}\Xi^* \\ \eta\Omega \end{array} \end{array}$$

- WT interaction is only for $\bar{K}\Xi^* - \eta\Omega$, no direct $\bar{K}\Xi^* - \bar{K}\Xi^*$
  $\bar{K}\Xi^*$ attraction is provided by the virtual loop of $\eta\Omega$

Eliminate the $\eta\Omega$ channel via Feshbach method



- D-wave transition
  Added by hand/parameter

$$V = \begin{array}{cc} \begin{array}{ccc} \bar{K}\Xi^* & \eta\Omega & \bar{K}\Xi \end{array} & \\ \begin{pmatrix} 0 & 3F & \alpha q_{\rm on}^2 \\ 3F & 0 & \beta q_{\rm on}^2 \\ \alpha q_{\rm on}^2 & \beta q_{\rm on}^2 & 0 \end{pmatrix} & \begin{array}{c} \bar{K}\Xi^* \\ \eta\Omega \\ \bar{K}\Xi \end{array} \end{array}$$

Our strategy

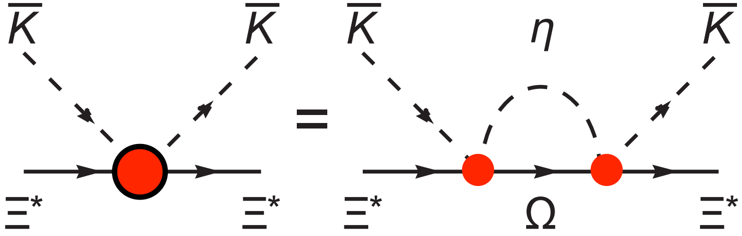
Coupled channel of $\bar{K}\Xi^*$ (S-wave) and sss^* (p-wave)

Mixing, coexistence, hybrid, …

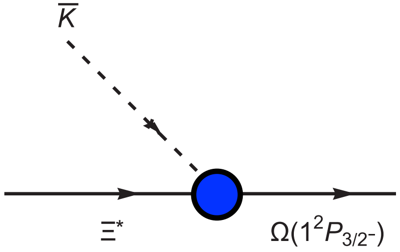
Eliminate $\eta\Omega$ channel

$$H = \left(\begin{array}{cc:c} K_{\bar{K}\Xi^*} + \cancel{V_{\bar{K}\Xi^*}} & 3F & V_{sss^*-\bar{K}\Xi^*} \\ 3F & K_{\eta\Omega} + \cancel{V_{\eta\Omega}} & 0 \\ \hdashline V_{sss^*-\bar{K}\Xi^*} & 0 & H_{sss^*} \end{array}\right) \rightarrow \left(\begin{array}{c:c} K_{\bar{K}\Xi^*} + V_{\bar{K}\Xi^*} & V_{\bar{K}\Xi^*-sss^*} \\ \hdashline V_{sss^*-\bar{K}\Xi^*} & H_{sss^*} \end{array}\right)$$

$V_{\bar{K}\Xi^*}$

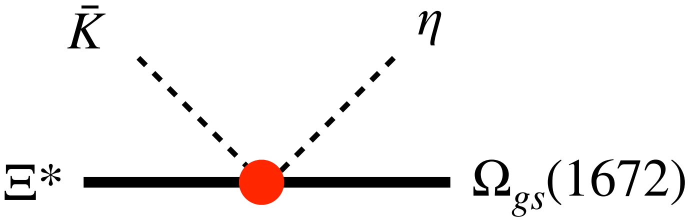


$V_{\bar{K}\Xi^*-sss^*}$

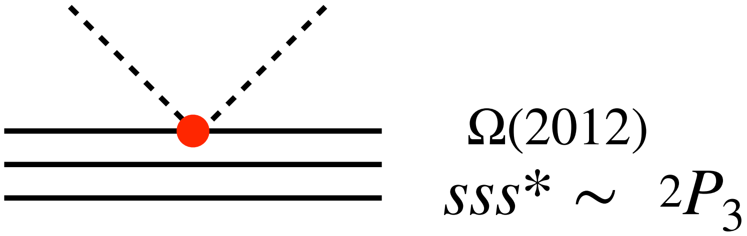


Inputs from the quark model

$V_{\bar{K}\Xi^*}$

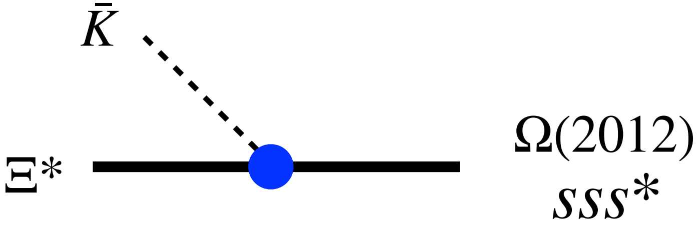


s-wave scattering

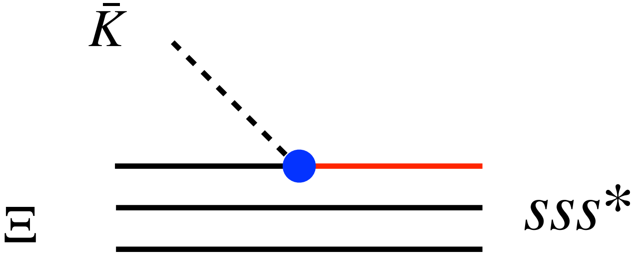


$$\mathcal{L}_{WT} = -\frac{i}{8f_p^2}\bar{q}\gamma_\mu(\phi^\mu\phi - \phi\phi^\mu)q$$

$V_{\bar{K}\Xi^*-sss^*}$



d-wave decay



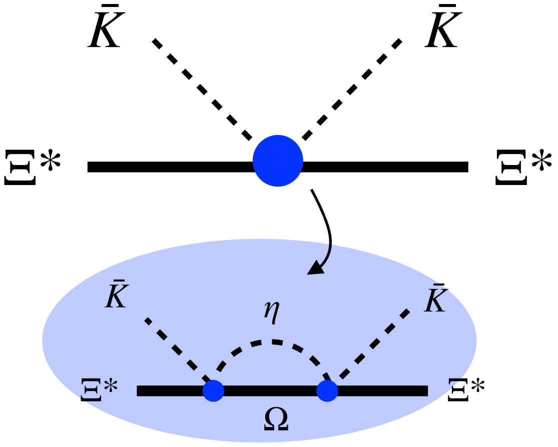
$$\mathcal{H}_{\rm NR} = \frac{g_A^q}{2f_p}\left[\boldsymbol{\sigma}\cdot\boldsymbol{q} + \frac{\omega}{2m}(\boldsymbol{\sigma}\cdot\boldsymbol{q} - 2\boldsymbol{\sigma}\cdot\boldsymbol{p}_i)\right]$$

$\bar{K}\Xi^* \to \bar{K}\Xi^*$ scattering

Eliminate the qqq channel from $H = \begin{pmatrix} K_{\bar{K}\Xi^*} + V_{WT} & V_{\bar{K}\Xi^* - sss^*} \\ V_{sss^* - \bar{K}\Xi^*} & H_{sss^*} \end{pmatrix}$

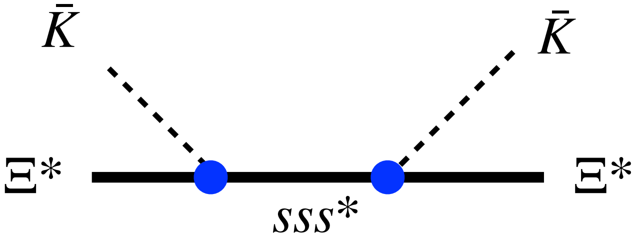
and we can write

$$V_{tot} = V_{WT} + V_{sss}$$



V_{WT}

$+$

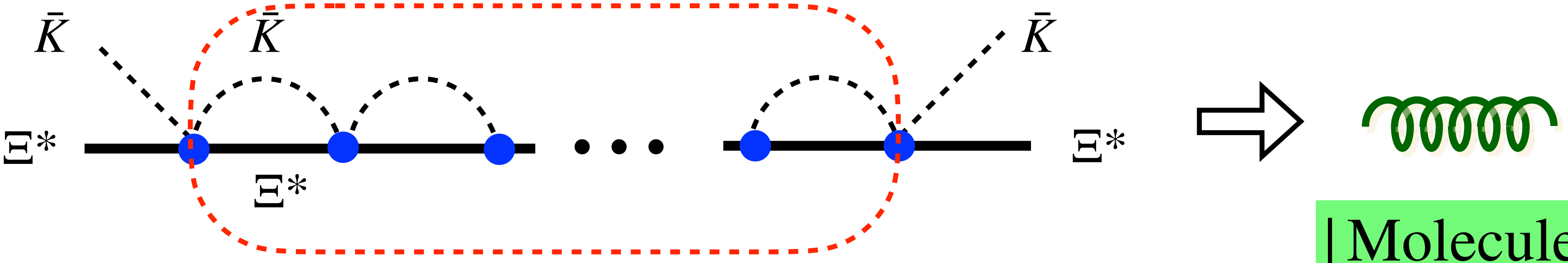


V_{sss^*}

$$\boxed{t_{\bar{K}\Xi^* \to \bar{K}\Xi^*} = \frac{V_{tot}}{1 - V_{tot} G_{\bar{K}\Xi^*}}}$$

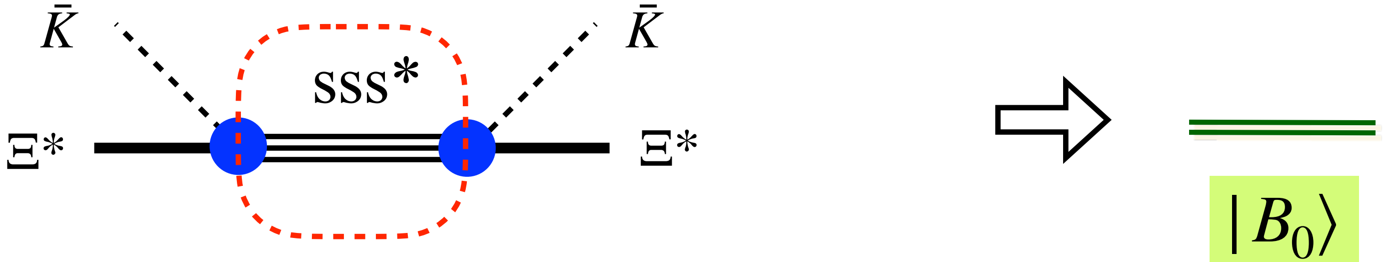
Two (three) bases

- $\bar{K}\Xi^*$ molecular



$|\text{Molecule}\rangle$

- sss* quark

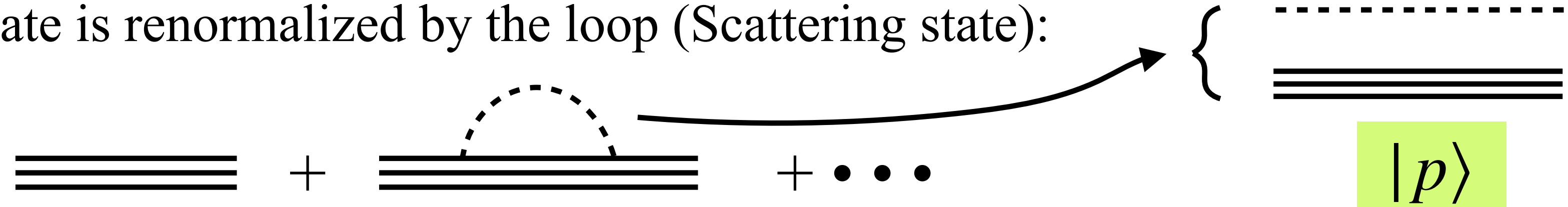


$|B_0\rangle$

Hyodo's talk

- $\bar{K}$-sss* scattering states

sss state is renormalized by the loop (Scattering state):

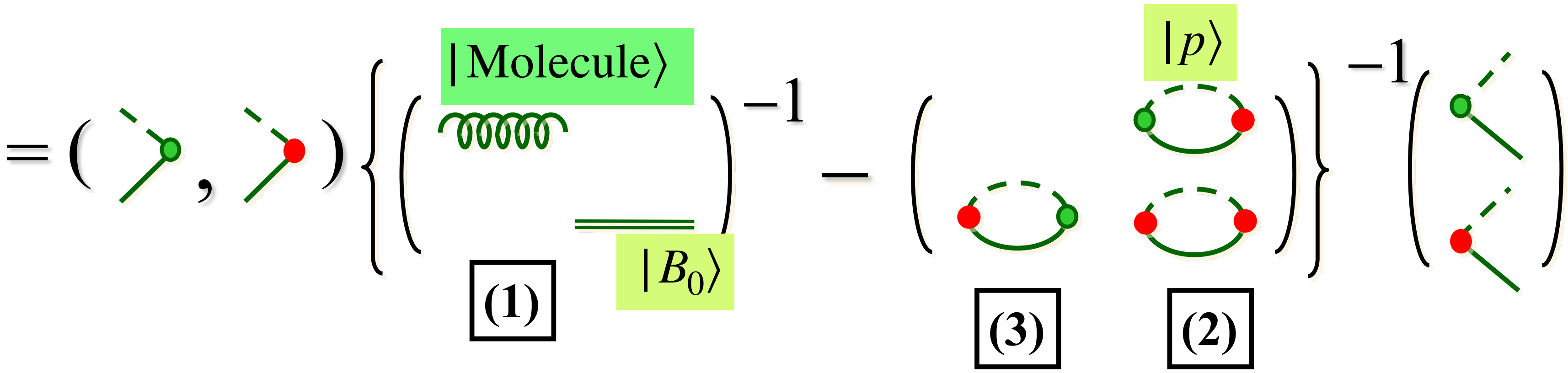


$|p\rangle$

Scattering matrix

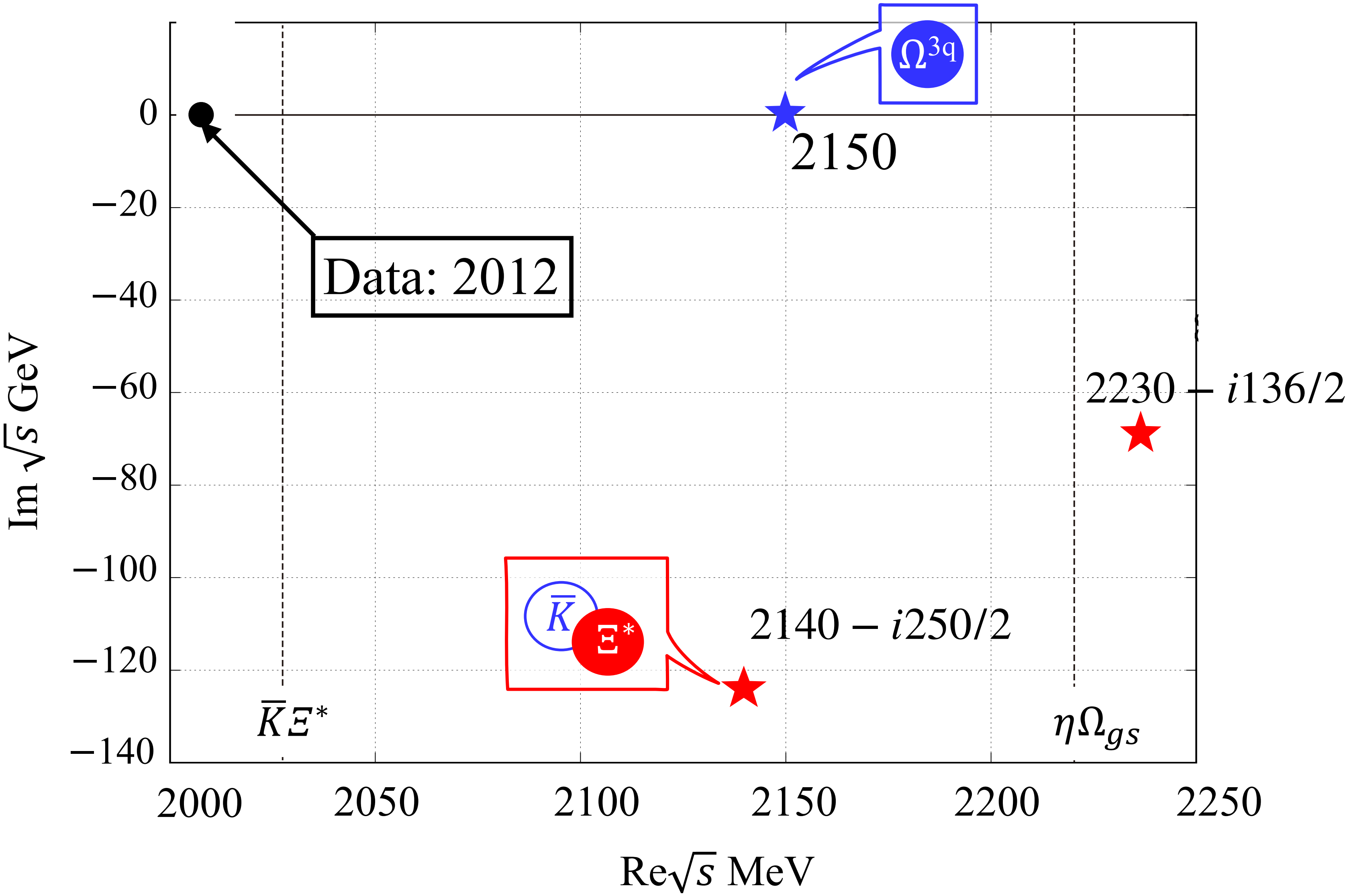
$$\mathrm{T}= \frac{v_{\mathrm{WT}}+v_{\mathrm{bare}}}{1-(v_{\mathrm{WT}}+v_{\mathrm{bare}})G}$$

$$= (g_R, g)\frac{1}{\begin{pmatrix} s-s_p & 0 \\ 0 & s-m_0^2 \end{pmatrix} - \begin{pmatrix} 0 & g_R G g \\ g G g_R & g G g \end{pmatrix}}\begin{pmatrix} g_R \\ g \end{pmatrix}$$



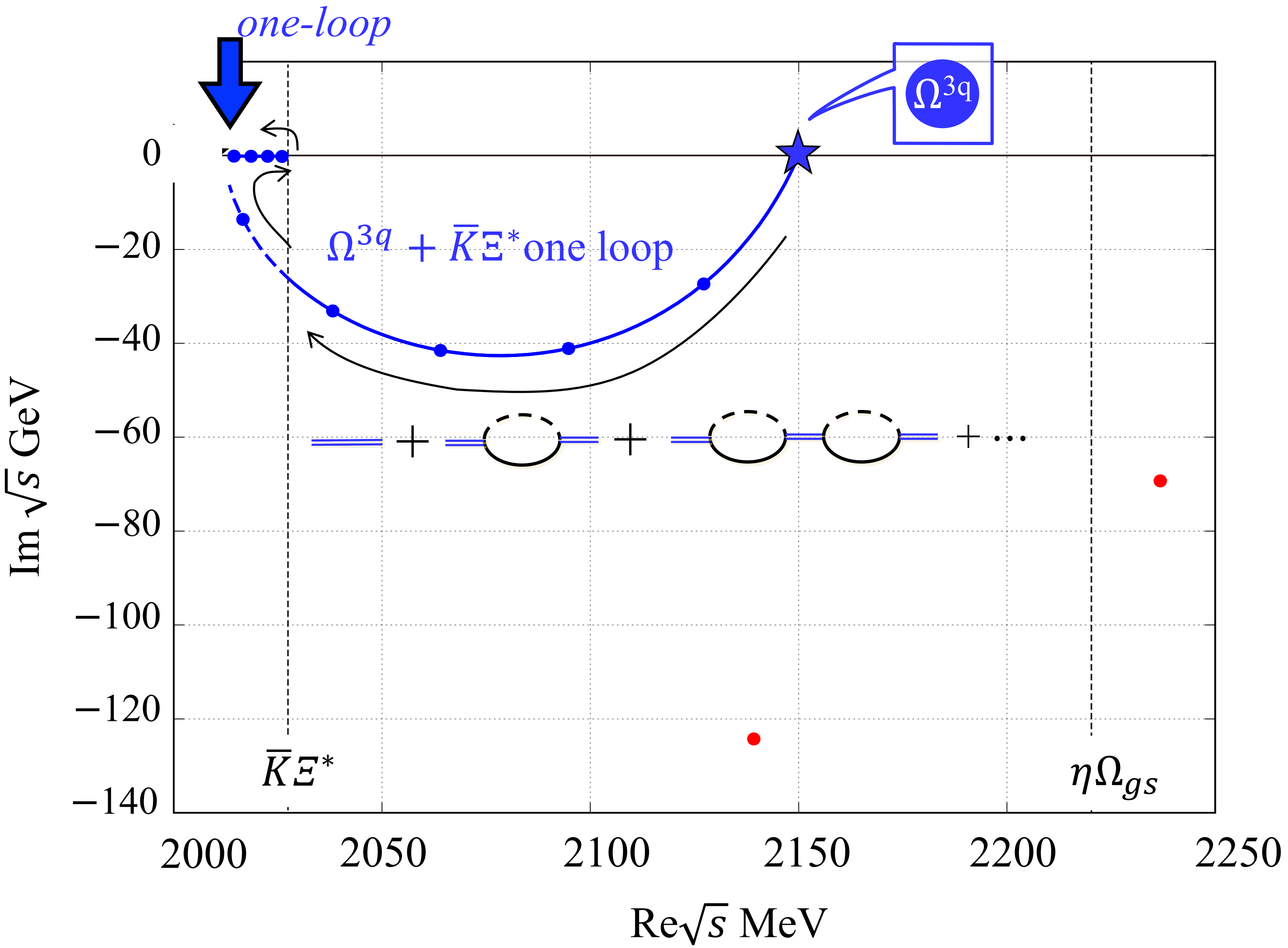
(1) Find the molecule and sss states
(2) Include the self energy for sss
(3) Coupling (mixing) the molecule and sss
(4) Find residues (composite/elementary)

(1) Find the molecule and sss* (3q) states



(2) Include the self energy for sss

with WT interaction turned off

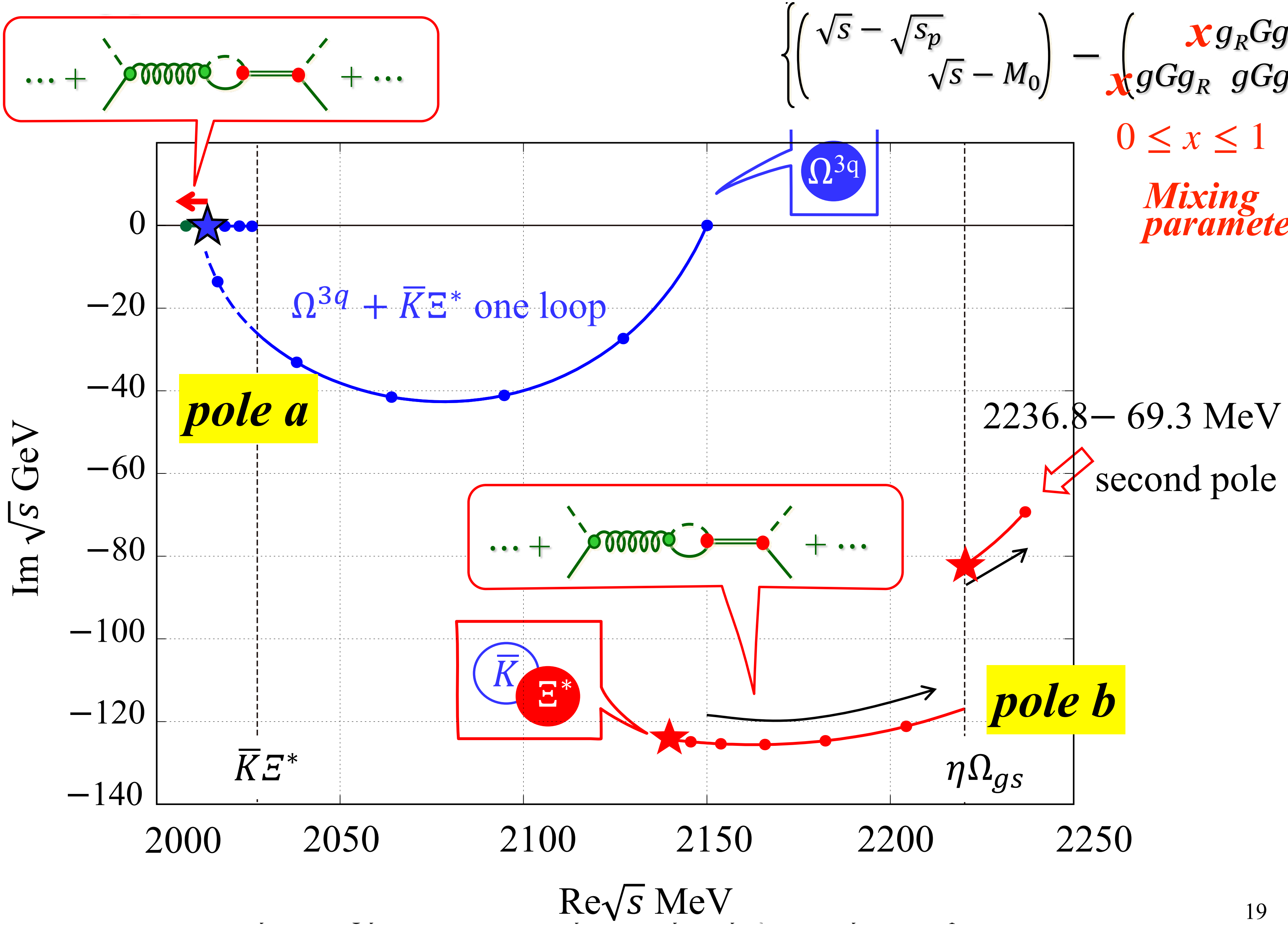


(3) Coupling (mixing) the molecule and sss

$$\left\{\begin{pmatrix} \sqrt{s}-\sqrt{s_p} & \\ & \sqrt{s}-M_0 \end{pmatrix} - \begin{pmatrix} & x\, g_R G g \\ x\, g G g_R & g G g \end{pmatrix}\right\}$$

$0 \leq x \leq 1$

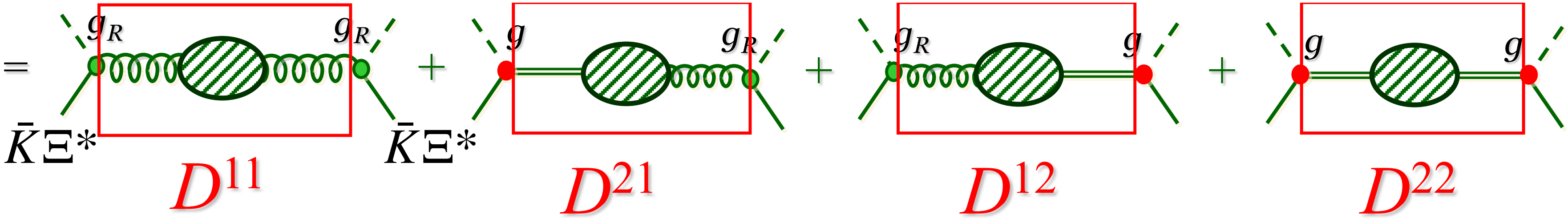
Mixing parameter



(4) Find residues

$$T_{\bar{K}\Xi^*\to\bar{K}\Xi^*}(s) = (g_R, g)\left[\begin{pmatrix}\sqrt{s}-M_{\text{Molecule}} & 0 \\ 0 & \sqrt{s}-M_{sss}\end{pmatrix} - \begin{pmatrix}0 & g_R G g \\ g G g_R & g G g\end{pmatrix}\right]^{-1}\begin{pmatrix}g_R \\ g\end{pmatrix}$$

g_R: Molecule - $\bar{K}\Xi^*$ coupling
g: sss - $\bar{K}\Xi^*$ coupling



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

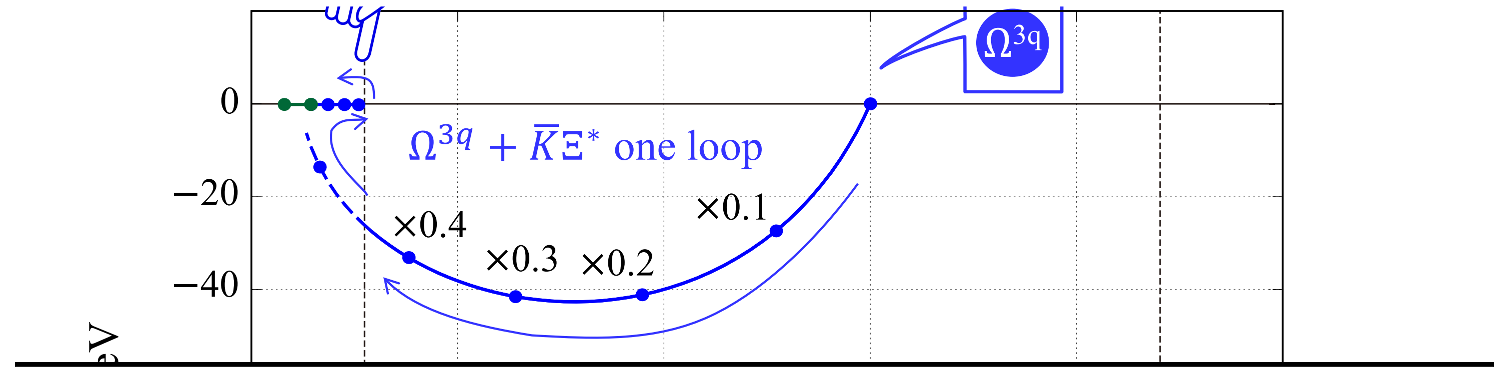
$z_{ii}^{a,b}$ Probability of finding *the basis state i* in the *physical state* (pole) *a, b*

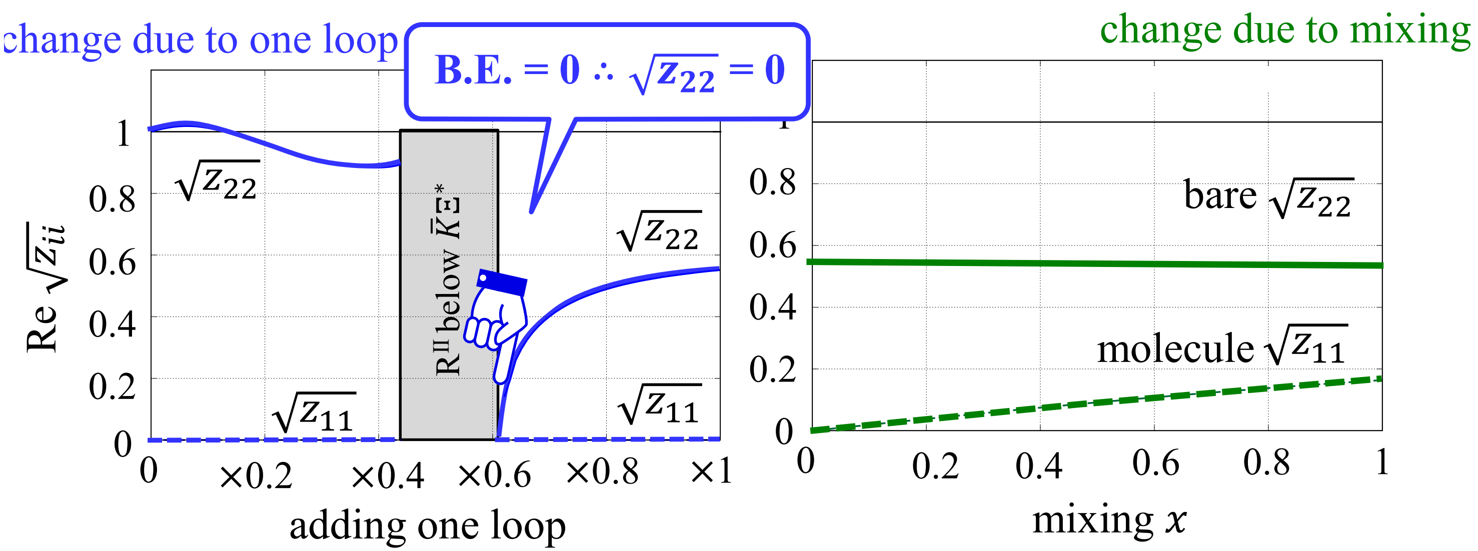
Components of ***pole a***, $z_{11}^{a} \sim \bar{K}\Xi^{*}$ (molecule), z_{22}^{a} sss^{*} (3q)

$$\sqrt{z_{11}} = 0.16 + 0.07i$$
$$\sqrt{z_{22}} = 0.54 - 0.6 \times 10^{-3}i$$

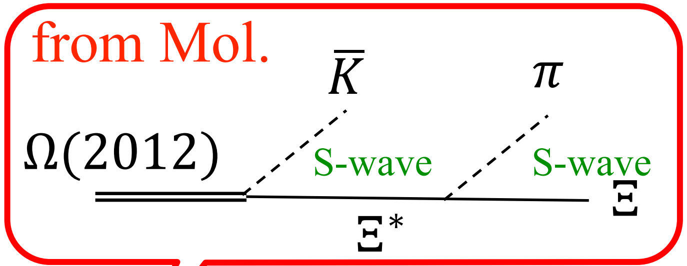
➡

$$\boxed{|\Omega(\text{phys})\rangle = 0.16\ |\Omega(\Xi^{*}\bar{K})\rangle + 0.54\ |\Omega(3q)\rangle}$$



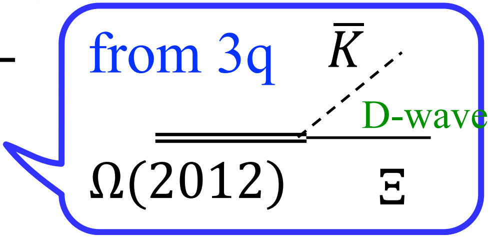


Decay rate $\Omega(2012) \to \Xi\pi\bar{K},\ \Xi\bar{K};\ \mathscr{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}}$


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

$$\boxed{\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} \equiv 0.35}$$

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

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

$\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} < 11.9\%$

S.Jia et al. (Belle), PRD100, 032006(2019)

$\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} = 0.97 \pm 0.24 \pm 0.07$

Belle, arXiv:2207.03090 (July 2022)

Summary

- Different configurations may coexist in hadron states.
- For Ω(2012) $|\Omega(\text{phys})\rangle = 0.16\ |\Omega(\Xi^*\bar{K})\rangle + 0.54\ |\Omega(3q)\rangle$
- Pole flow analysis suggests its 3q origin.
- Properties;

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

$$M(exp) \sim 2012 - i6.4^{+2.5}_{-2.0}/2 \text{ MeV}, \quad \mathscr{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}}(exp) \leq 0.12$$

- Higher resonant state is predicted at ~ 2250 MeV
- More information for decays is useful to know better.