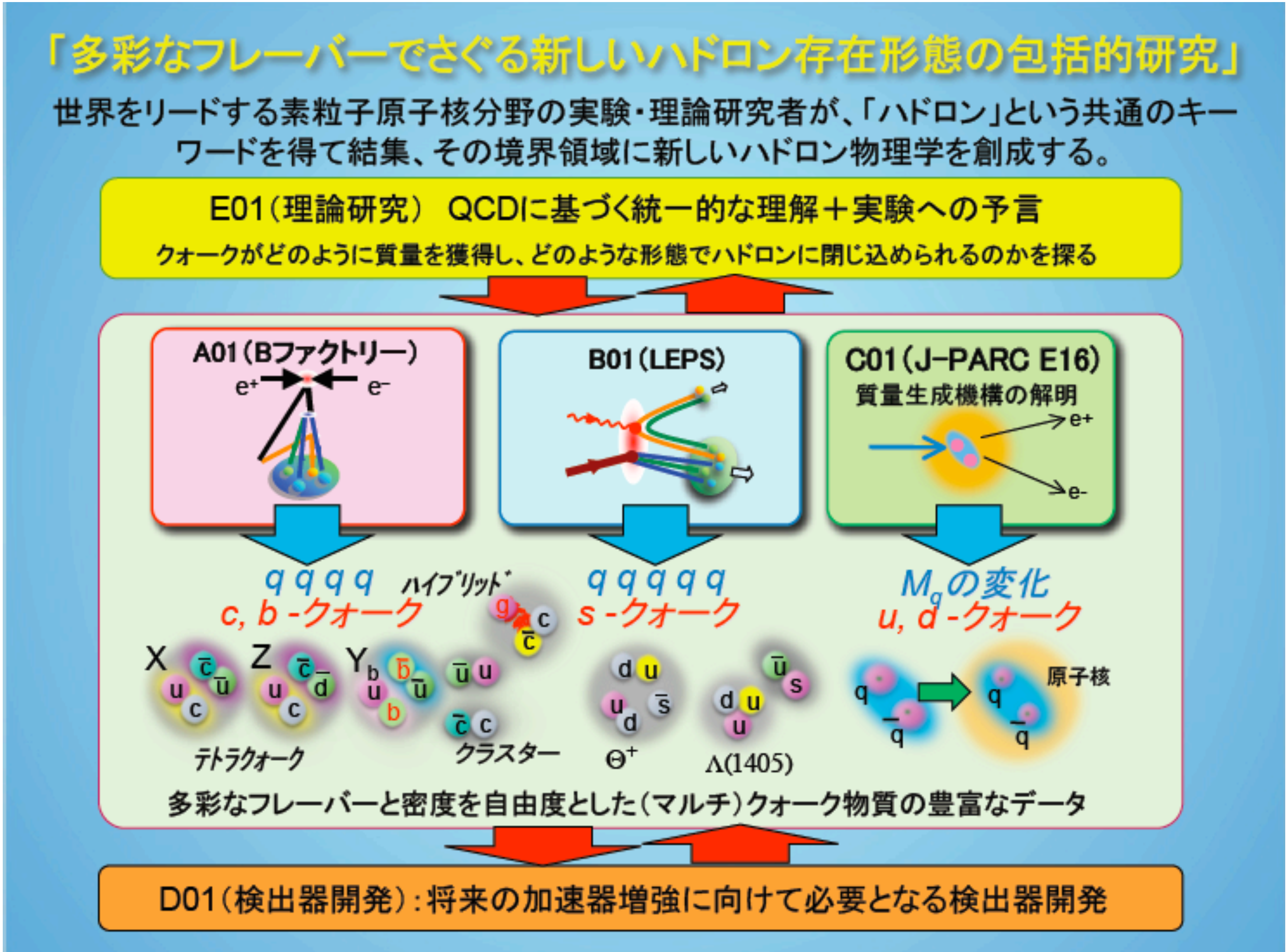
Hadron Spectroscopy
— Past, Present (and Future) —

Atsushi Hosaka
RCNP, Osaka University
Advanced Science Research Center, JAEA

KMI2025 : The 6th KMI International Symposium
Nagoya, March 5 - 7, 2025

1. Introduction
2. Evidences of coexistence:
   X(3872), Ω(2012)
3. Summary

We have the fundamental theory: QCD
Question: How QCD develop hadronic/femtoscopic matter?


「多彩なフレーバーでさぐる新しいハドロン存在形態の包括的研究」
世界をリードする素粒子原子核分野の実験・理論研究者が、「ハドロン」という共通のキーワードを得て結集、その境界領域に新しいハドロン物理学を創成する。
E01（理論研究） QCDに基づく統一的な理解＋実験への予言
クォークがどのように質量を獲得し、どのような形態でハドロンに閉じ込められるのかを探る
A01（Bファクトリー）
e+
e-
B01（LEPS）
C01（J-PARC E16）
質量生成機構の解明
e+
e-
q q q q
ハイブリッド
c, b -クォーク
q q q q q
s -クォーク
M_qの変化
u, d -クォーク
X
Z
Y_b
テトラクォーク
クラスター
Θ^+
Λ(1405)
原子核
多彩なフレーバーと密度を自由度とした（マルチ）クォーク物質の豊富なデータ
D01（検出器開発）：将来の加速器増強に向けて必要となる検出器開発

1. Introduction

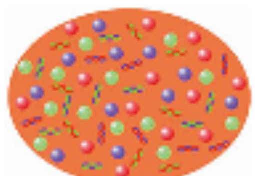
Strongly interacting femtoscopic world

QGP (high T)

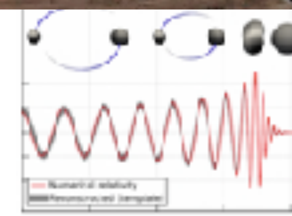
Neutron stars (High ρ)

Observatories

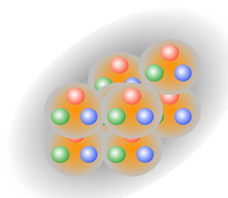
PQCD, Simulations



RIKEN BNL



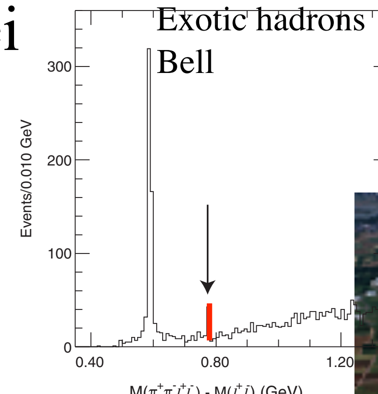
Many-body dynamics



Atomic nuclei

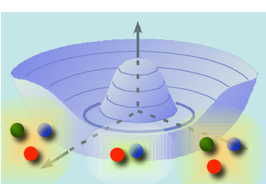
Effective theories

Quasi-particles

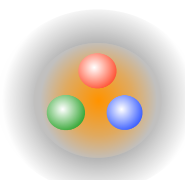


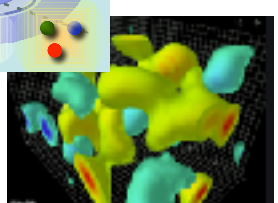
Accelerators

Chiral symmetry breaking
Color confinement
Mass generation

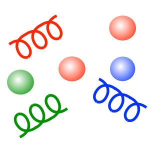


Hadrons

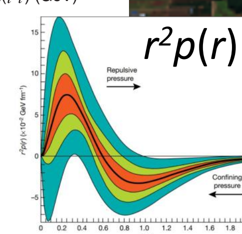




D. Leinweber



Quarks and gluons



Proton pressure
V. Burkert, et al

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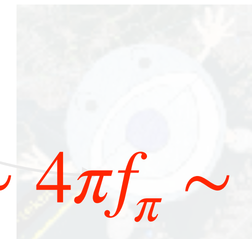
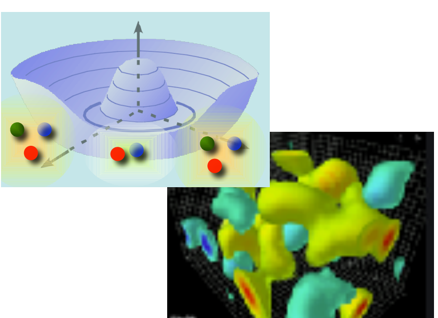


$$\Lambda_{QCD} \sim 200\ MeV, \quad \Lambda_\chi \sim 4\pi f_\pi \sim 1\ GeV$$

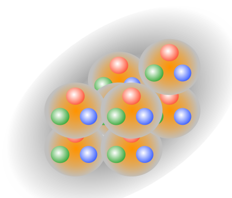
Many-body dynamics

Effective theories
Quasi-particles

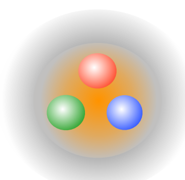
Chiral symmetry breaking
Color confinement
Mass generation



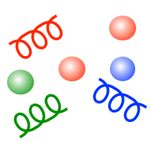
D. Leinweber



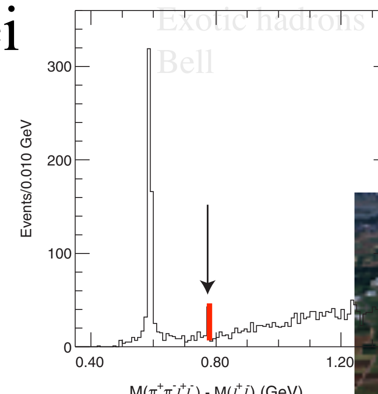
Atomic nuclei



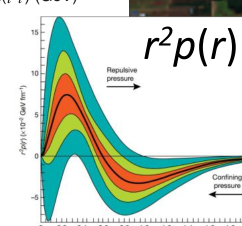
Hadrons



Quarks and gluons



Accelerators



Proton pressure
V. Burkert, et al

Quick history

1956: p,n, Λ model: Sakata

1959: Λ(1405), Dalitz and Tuan

1959: Kinematical singularities, Landau

1961: Skyrme model

1961: SSB of Chiral symmetry, Nambu

1964: Quark model, Gell-Mann and Zweig

1976: Discovery of charm quark

1977: Molecular Charmonium, Rujula-Georgi-Glashow

1982: Revival of Skyrme model, Witten and others

2003: Discovery/observation of X(3872), Θ+

2007: HALQCD for HH forces, Aoki-Hatsuda-Ishii

2015: Discovery of P_c, Pentaquark with $c\bar{c}$

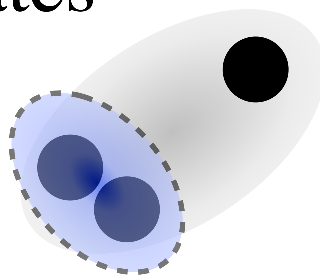
2020: Prediction of T_{cc}, Karliner and Rosner

2022: Discovery of T_{cc}, Tetraquark with cc

Exotics
~ Multi-quarks near/above **Threshold**

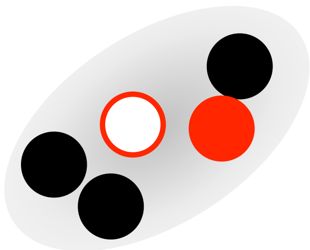
Multi-quarks of various shapes with **clustering**

Excited states



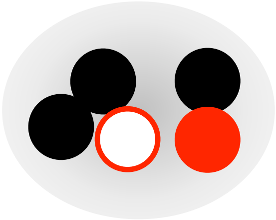
Quark excitation

OR



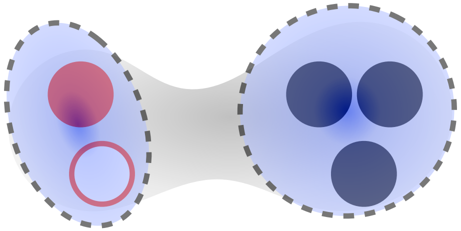
Pair created multiquarks

Multiquarks



Compact
e.g., diquark + triquark

OR



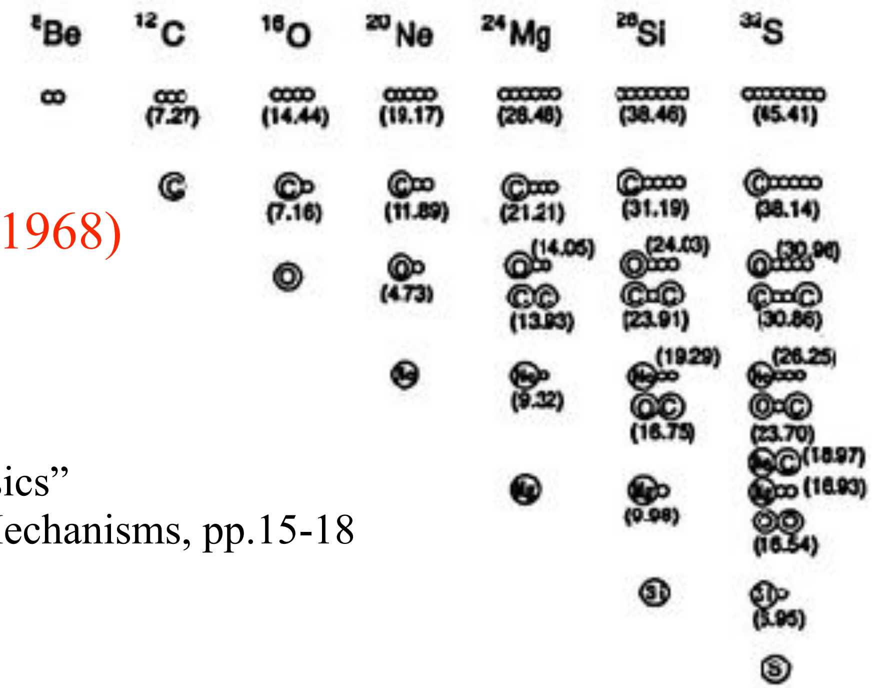
Extended
e.g., meson + baryon

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



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?

How are they?

Marek Karliner says

1. Do they exist?
2. If they do, which ones?
3. What is their internal structure?
4. 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 various quarks:

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

Do hadrons form one of the shapes in previous page?

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

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

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。

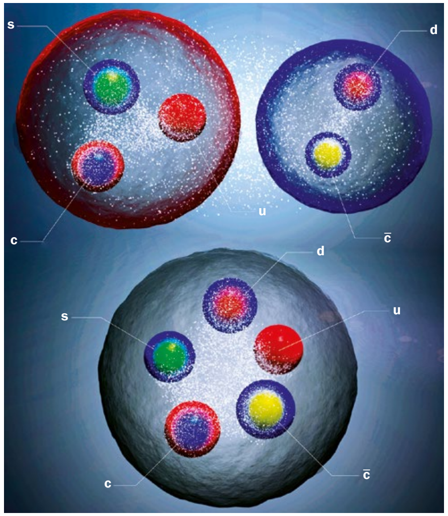
The system of pion, nucleon, and (3–3) particle acting mutually through the Yukawa interaction is investigated by means of the static meson theory. It is assumed that these particles (including the (3–3) particle) can be treated as elementary ones although they are equally constructed from urbaryons. 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. Coexistence of different structures

Experimental fact:
Many new states are observed near/above threshold

INSIDE PENTAQUARKS
AND TETRAQUARKS



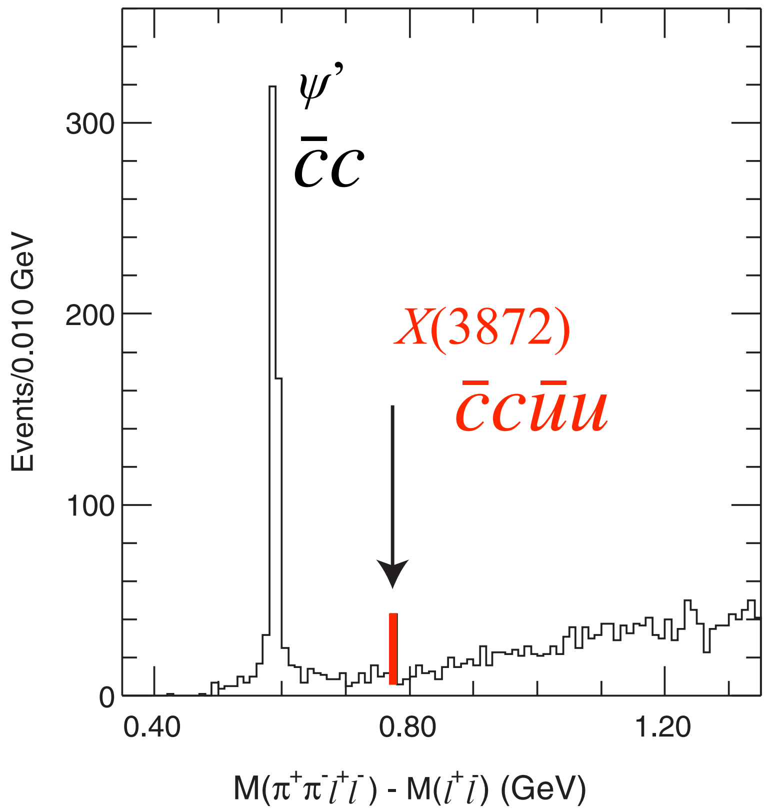
Marek Karliner and Jonathan Rosner ask what makes tetraquarks and pentaquarks tick, revealing them to be at times exotic compact states, at times hadronic molecules and at times both – with much still to be discovered.

CERN COURIER NOVEMBER/DECEMBER 2024

Evidences, X(3872)

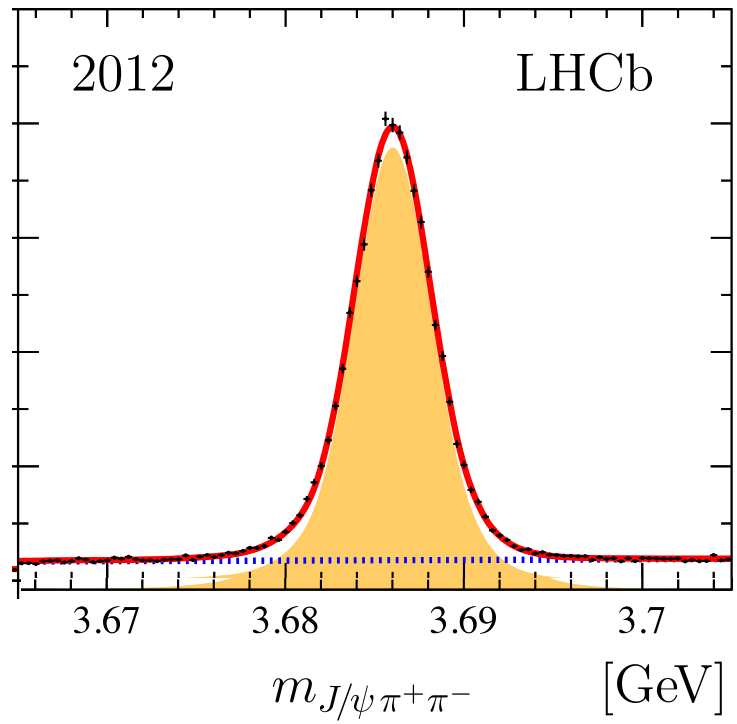
Belle@KEK, PRL91 262001 (2003)

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



LHCb, PRD 102, 092005 (2020)

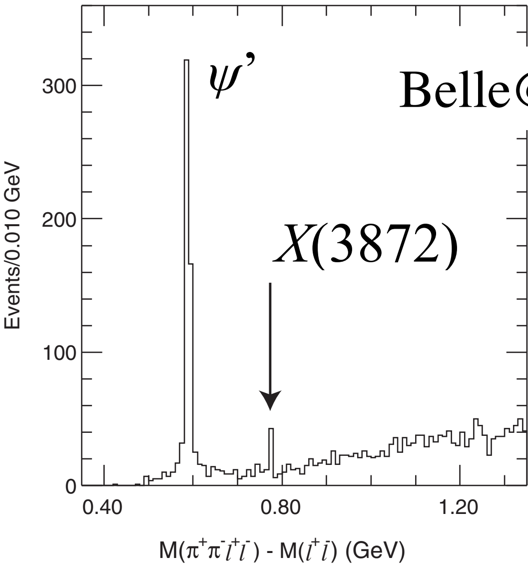
pp collisions at center-of-mass energies of 7 and 8 TeV



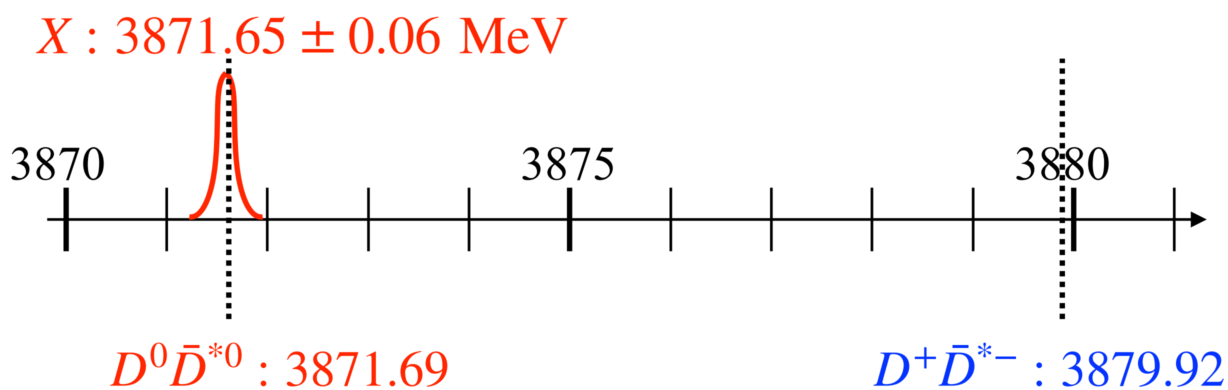
Why Molecule ?

- Located almost at the threshold $D^0(c\bar{u})\bar{D}^{*0}(\bar{c}u)$

$J^P = 0^+ \quad 1^+$



Belle@KEK, PRL91, 262001 (2003)



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

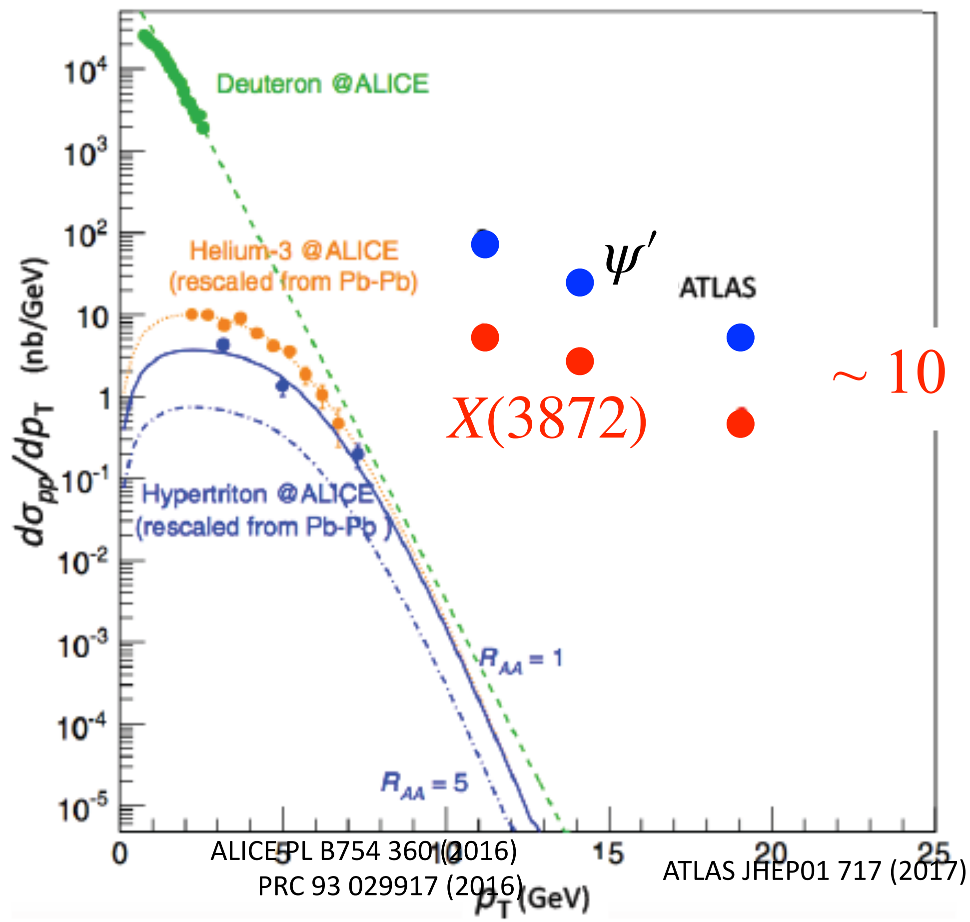
Consistent with S-wave $D\bar{D}^{*0}$ molecule

$D\bar{D}^*$ with small binding energy → Large spatial size

BUT

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

Large production rates
in collisions at
high energy and
large transverse momentum
is not likely to occur



⇩

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

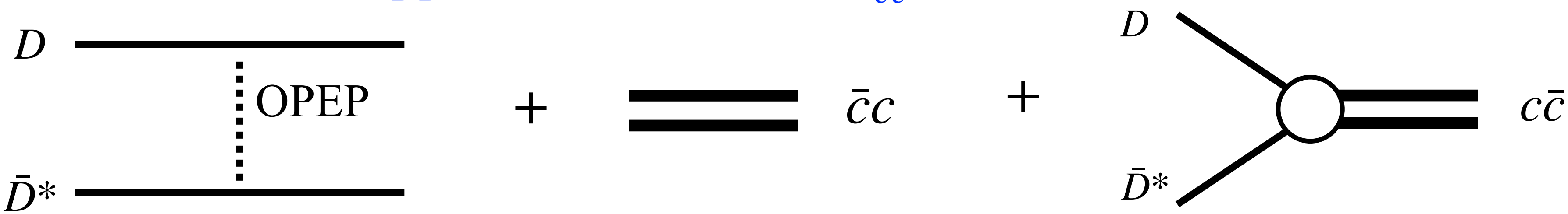
Hybrid of $D\bar{D}^*$ and $c\bar{c}$

- $c\bar{c}$ - $D\bar{D}^*$ (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

Prepare convenient bases and couplings

Chiral and heavy-quark symmetries

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

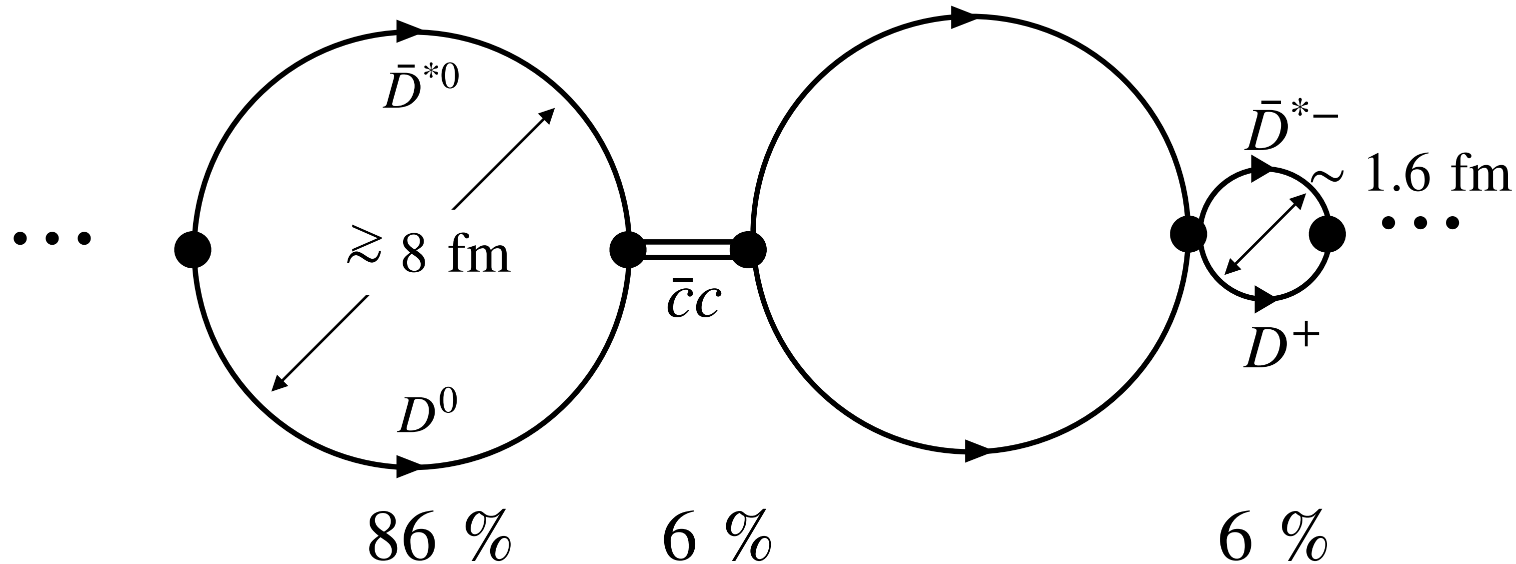


$$H = H_{D\bar{D}^*} + H_{c\bar{c}} + V$$

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

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

Cartoons for X(3872)



Takeuchi & Takizawa, PTEP9, 093D01

Yamaguchi, AH, Takeuchi & Takizawa, J.Phys.G 47 (2020) 5, 053001

AH, Kanada-En'yo & Yamaguchi, to appear in EPJA

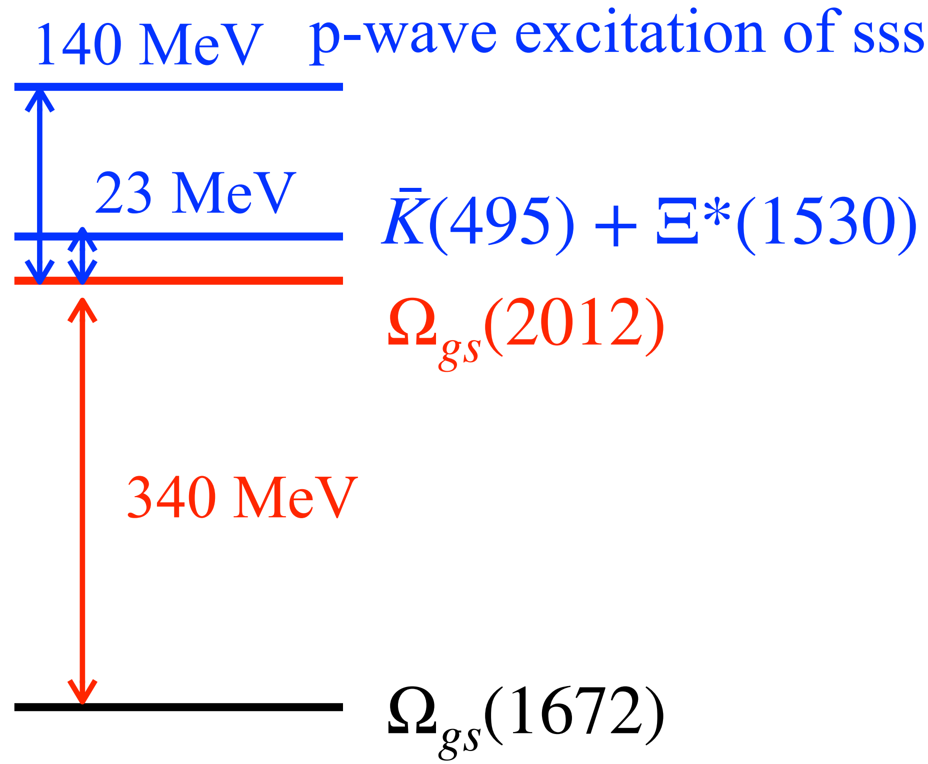
Most strange baryon Ω(2012) ~ sss

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

Expected to have a simple structure

From PDG

Ω BARYONS ($S = -3$, $I = 0$)		
$\Omega^- = sss$		
Ω^-	$3/2^+$	****
$\Omega(2012)^-$	$?^-$	***
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**



Is Ω(2012) $\bar{K}\Xi^*$ molecule?

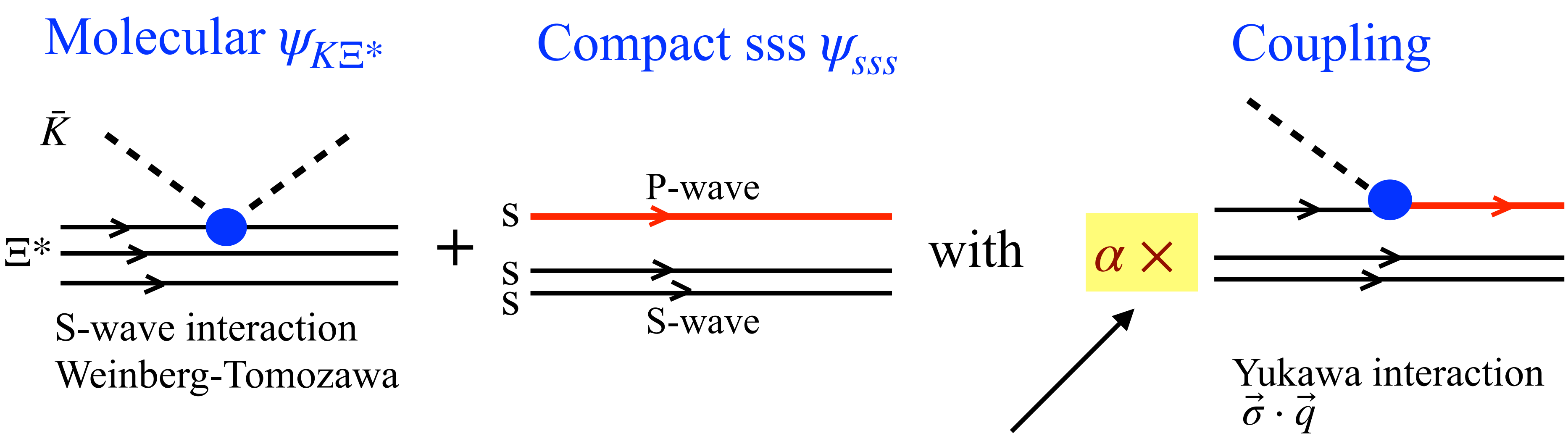
Similar strategy

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

With inputs from the **quark model** and **chiral symmetry**

Prepare convenient bases and couplings

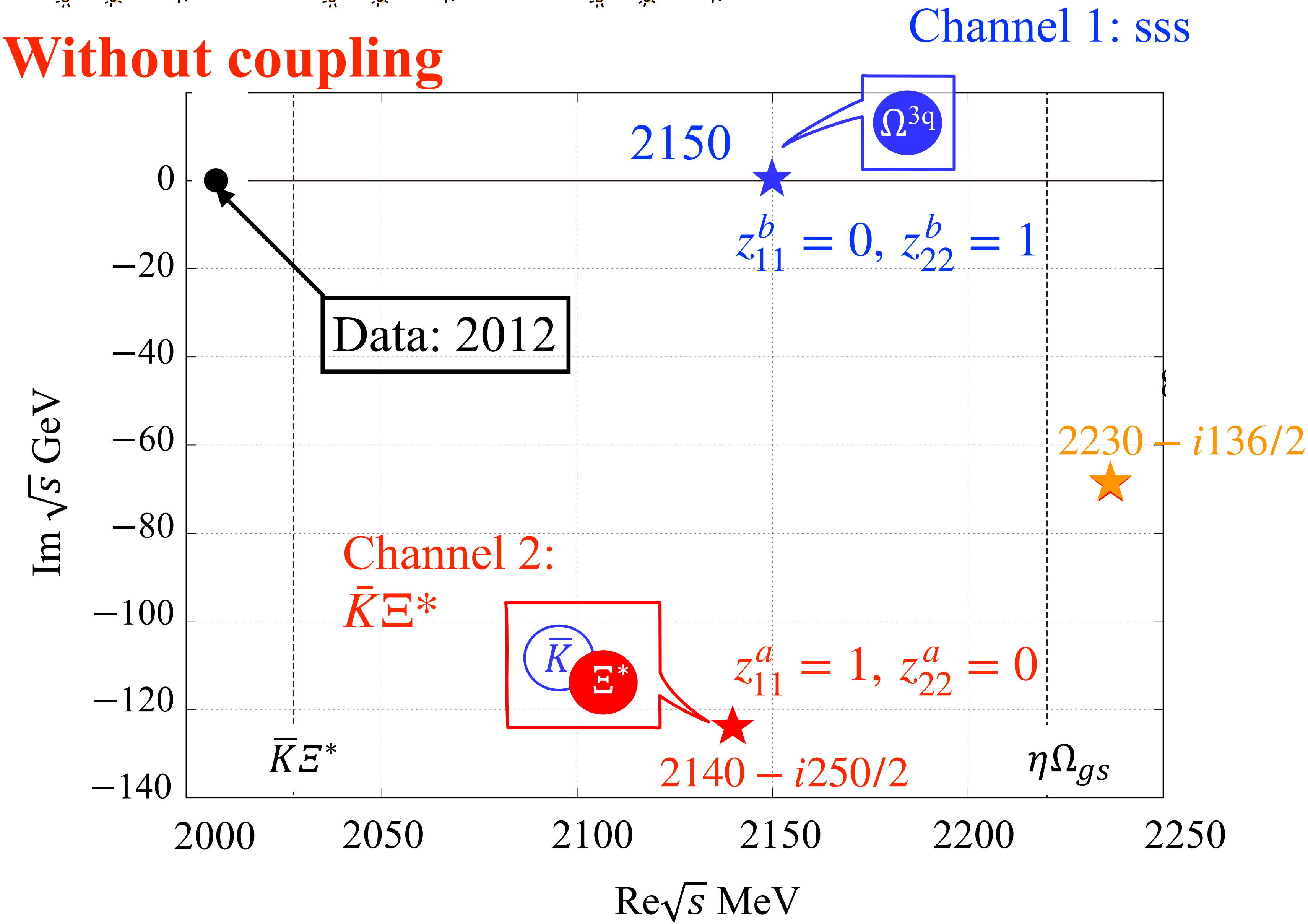
Chiral symmetry for constituent quarks



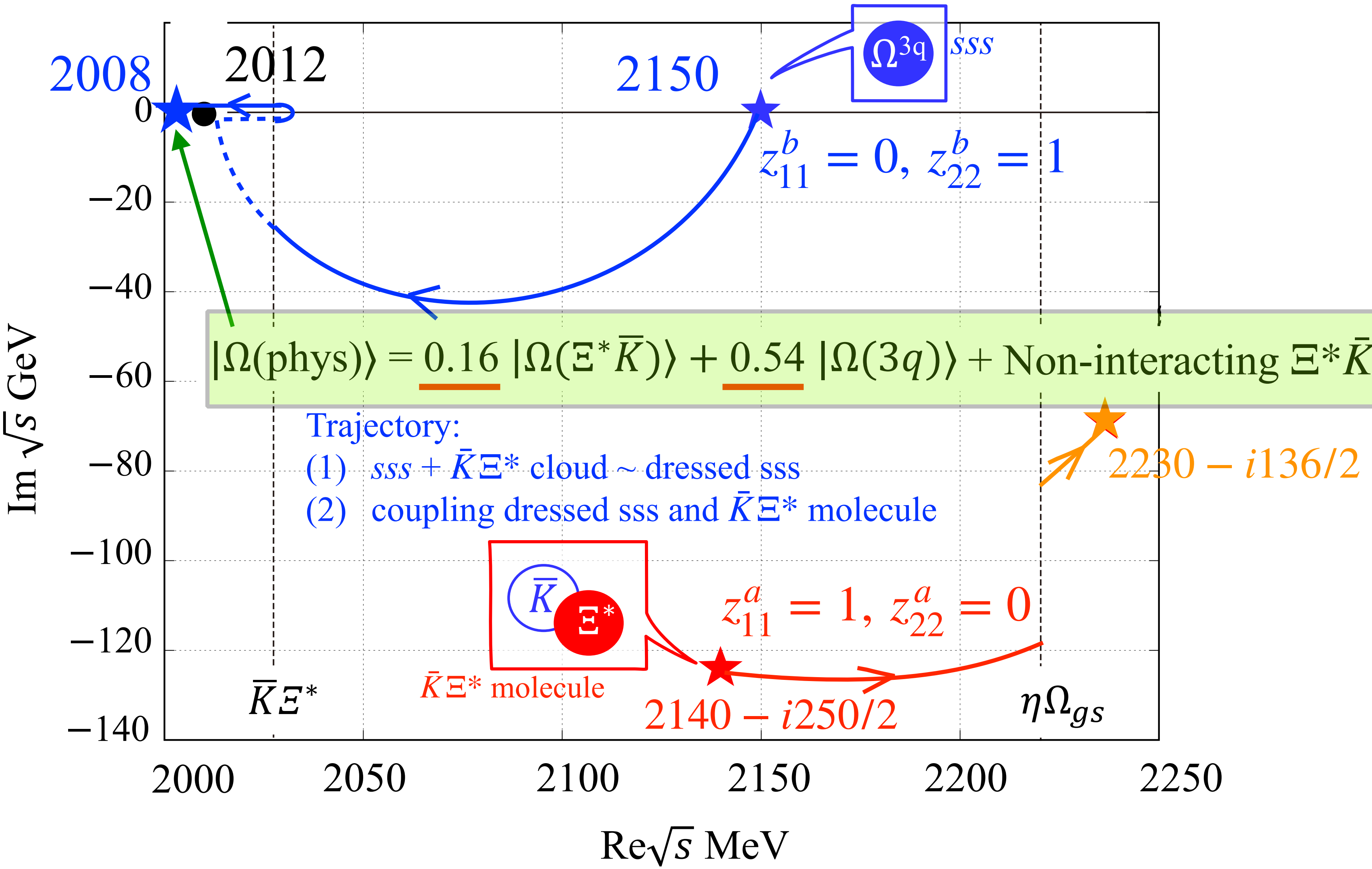
Vary the coupling α, **Pole trajectory**

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

Molecule ★ and sss* (3q ★) states: $\alpha = 0$



Trajectory when varying the coupling α



Summary so far

- Hadrons are basics for strongly interacting femtoscopic matter
- Hadrons show various faces:

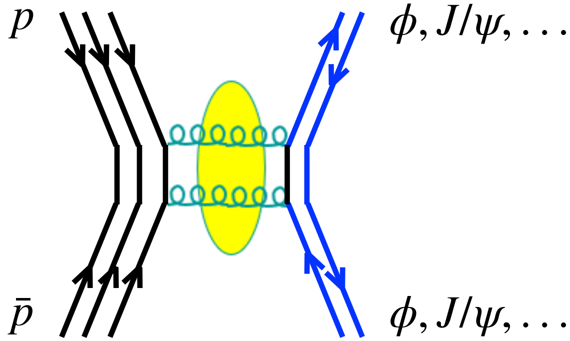
  Single particle excitations, Multiquarks with correlations…
  clusters

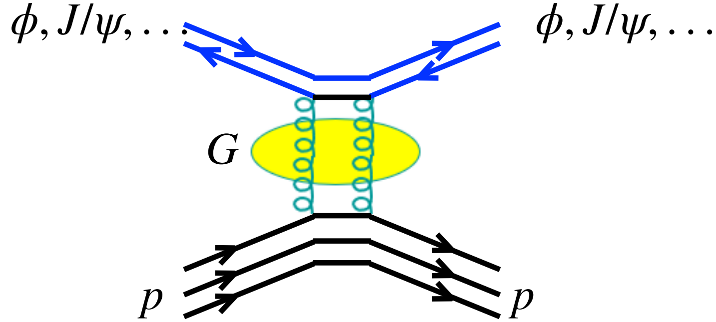
- X(3872) is dominated by $D\bar{D}^*$ molecule with fraction of $\bar{c}c$
- $\Lambda(1405)$ is dominated by $\bar{K}N$
- P_c are dominated by $\bar{D}\Lambda_c$
- $\Omega(2012)$ has large component of sss* with some $\bar{K}\Sigma^*$

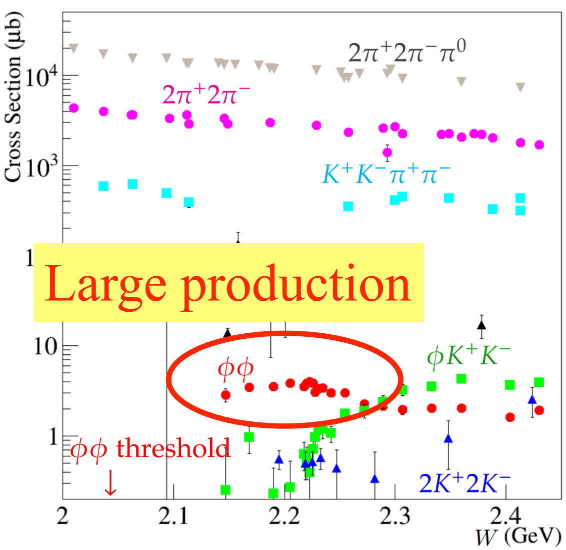
- New experimental data will come; Belle, LHC, BES, Jlab, …

Many unexplained phenomena

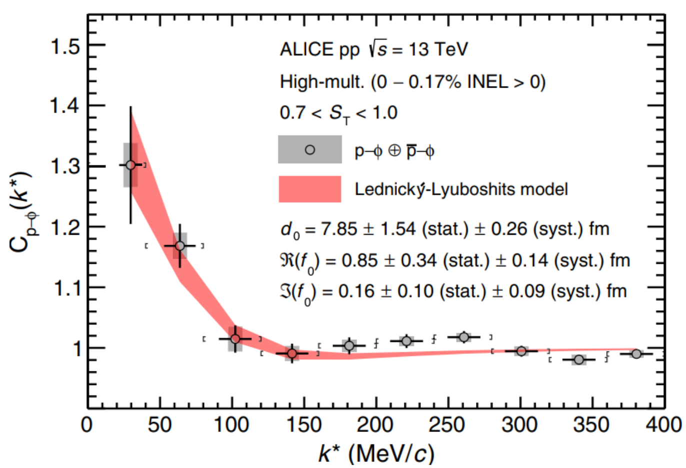
- Hadrons dominated by gluons ~ scalar mesons?
- Production rates for strangeness, charm and bottom
- Interactions beyond the OZI rule
- . . .







Correlation function by ALIS
Phys.Lett.B 848 (2024) 138358



$V(\phi N)$ Lattice (HALQCD)
Phys. Rev. D 106, 074507 (2022)