The Origin of Dynamically Generated Resonances

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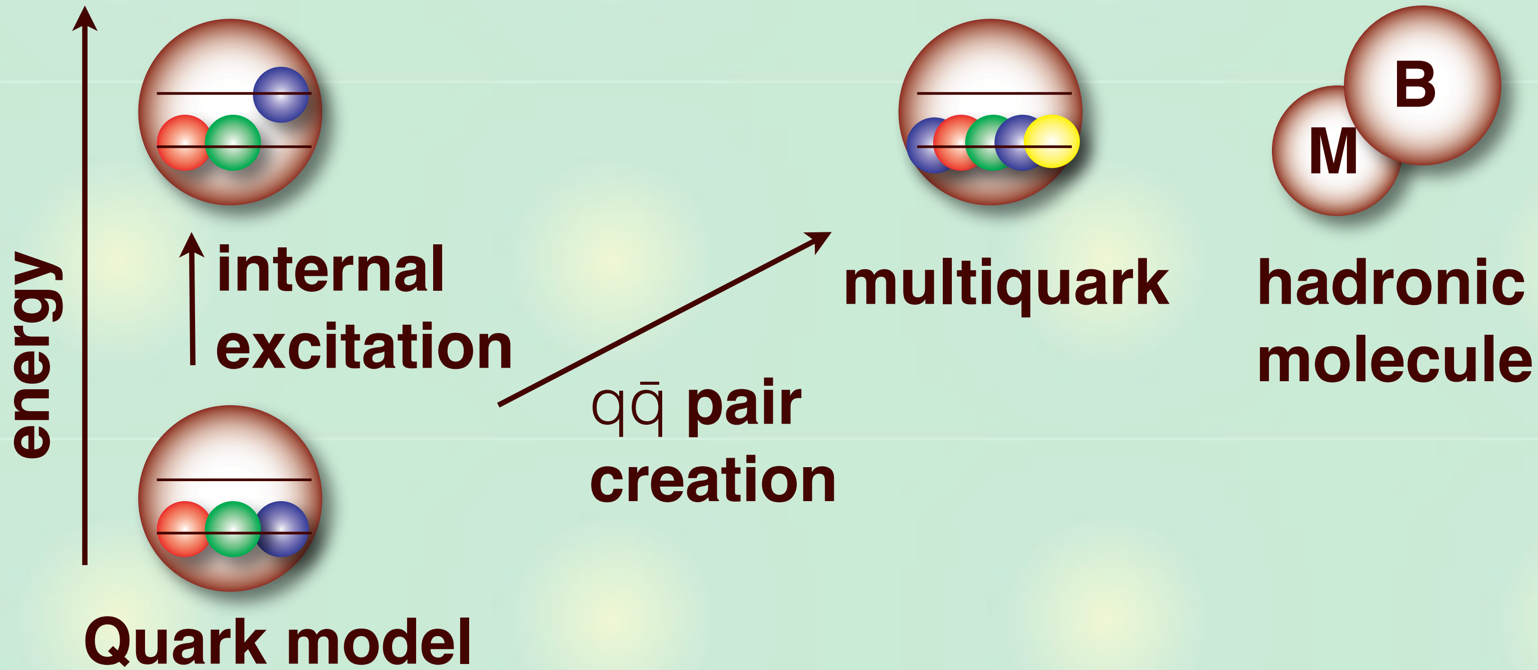
Structure of hadron excited states

Various excitations of baryons



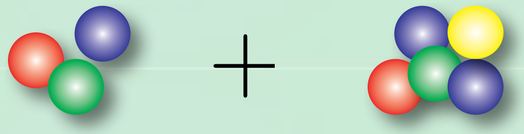
What are 3q state, 5q state, MB state, ...?

- Comparison of data (spectrum, width,...) with quark models
- Analysis of scattering data by dynamical models

Clear (model-independent) definition of the structure?

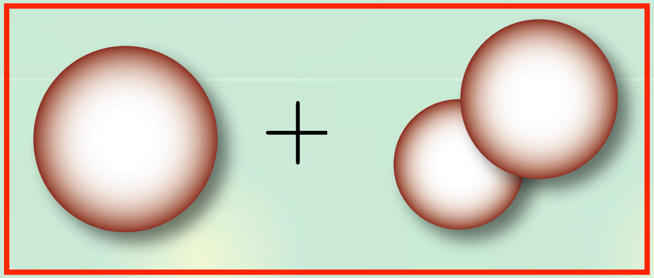
Difficulty 1 : definition and model space

Number of quarks + antiquarks (≠ quark number) ?

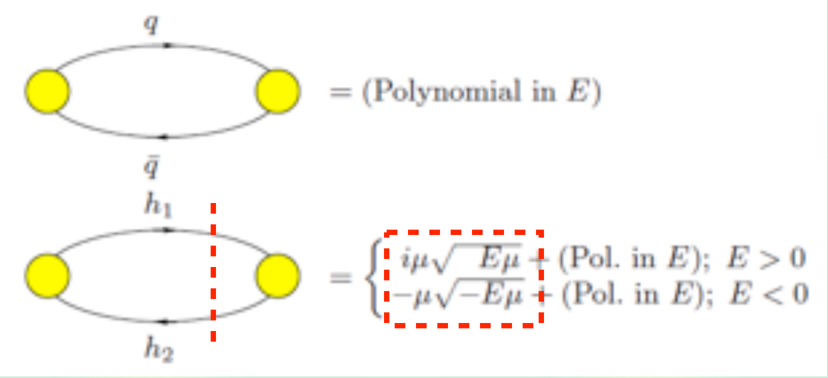
$|\Lambda(1405)\rangle =$  $+ \ldots$

This may not be a good classification scheme.

Number of hadrons

$|\Lambda(1405)\rangle =$  $+ \ldots$

Hadrons are asymptotic states.
--> different kinematical structure



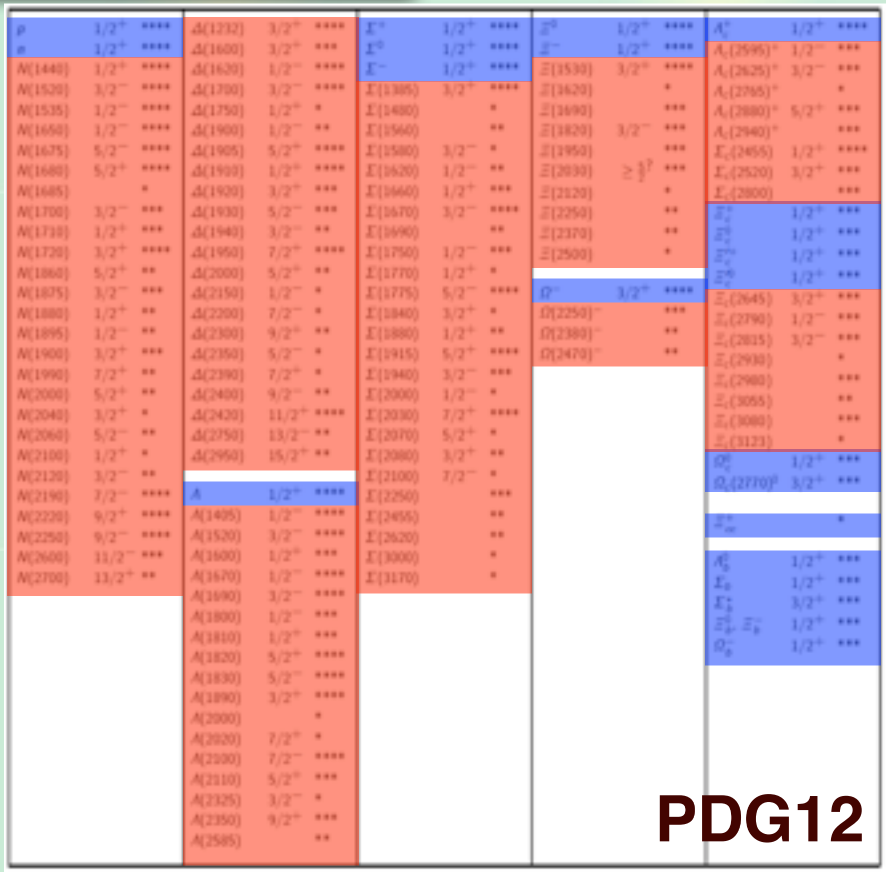
C. Hanhart, Eur. Phys. J. A 35, 271 (2008)

--> compositeness in terms of hadronic degrees of freedom

Difficulty 2 : resonances

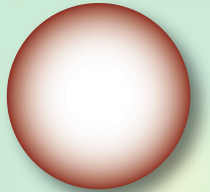
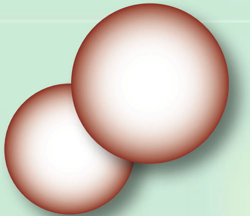
Excited states : finite width
(unstable against strong decay)

- stable (ground) states
- unstable states



Mostly resonances!

"Wave function" of resonance?

$$|\,\Lambda(1405)\,\rangle =$$  $+$  $+ \dots$

↑?

--> First consider stable states, then extend it to resonances.

Contents

- Introduction
- Compositeness 1 - Z (bound states)

  S. Weinberg, Phys. Rev. 137, B672 (1965)
  D. Lurie and A. J. Macfarlane, Phys. Rev. 136, B816 (1963)

- Baryon resonances in a chiral model
  - Compositeness of bound states

    T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C85, 015201 (2012)

  - Structure of resonances

    T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C78, 025203 (2008)
    T. Hyodo, arXiv:1305.1999 [hep-ph]

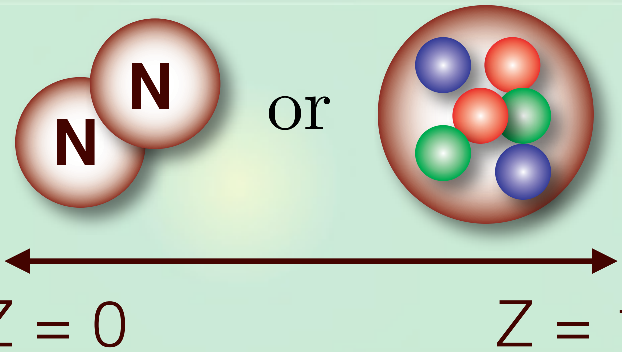
- Summary

Weinberg's compositeness and deuteron

Z: probability of finding deuteron in a bare elementary state

S. Weinberg, Phys. Rev. 137, B672 (1965)

$$|\mathrm{deuteron}\rangle =$$



$\notin$ NN **model space**

~ elementary particle

model-independent relation for weakly bound state

$$a_s = \left[\frac{2(1-Z)}{2-Z}\right] R + \mathcal{O}(m_\pi^{-1}), \quad r_e = \left[\frac{-Z}{1-Z}\right] R + \mathcal{O}(m_\pi^{-1})$$

a_s: **scattering length**

r_e: **effective range** **<-- Experiments**

R: **deuteron radius (binding energy)**

$$a_s = +5.41 \text{ [fm]}, \quad r_e = +1.75 \text{ [fm]}, \quad R \equiv (2\mu B)^{-1/2} = 4.31 \text{ [fm]}$$

$\Rightarrow Z \lesssim 0.2$ **--> deuteron is almost composite!**

Compositeness in quantum mechanics

Hamiltonian of a single channel scattering system

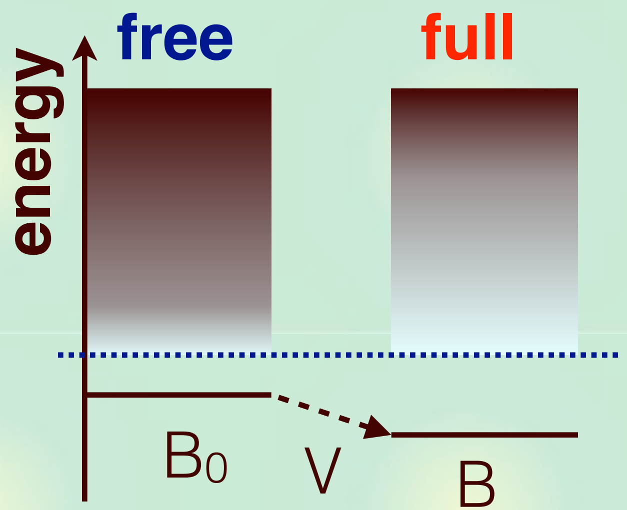
$$\mathcal{H} = \boxed{\mathcal{H}_0} + V$$

Complete set for free Hamiltonian: bare |B₀ > + continuum

$$1 = |\, B_0 \,\rangle\langle\, B_0 \,| + \int d\boldsymbol{k} |\, \boldsymbol{k} \,\rangle\langle\, \boldsymbol{k} \,|$$

Physical bound state |B> with binding energy B

$$(\mathcal{H}_0 + V)|\, B \,\rangle = -B|\, B \,\rangle$$



Z : overlap of B and B_0

$$Z \equiv |\langle\, B_0 \,|\, B \,\rangle|^2$$

For small B, compositeness 1 - Z is

$$1 - Z = 2\pi^2 \sqrt{2\mu^3} \frac{g_W^2}{\sqrt{B}}$$

g_W **: coupling constant**

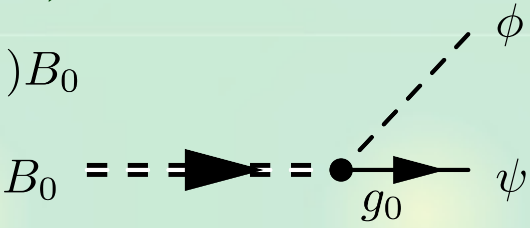
Compositeness in Yukawa theory

Field theory with Yukawa coupling (ψ,φ,B_0)

c.f. D. Lurie and A. J. Macfarlane, Phys. Rev. 136, B816 (1963)

$$\mathcal{L}_0 = \bar{\psi}(i\partial\!\!\!/ - M)\psi + \frac{1}{2}(\partial_\mu \phi \partial^\mu \phi - m^2\phi^2) + \bar{B}_0(i\partial\!\!\!/ - M_{B_0})B_0$$

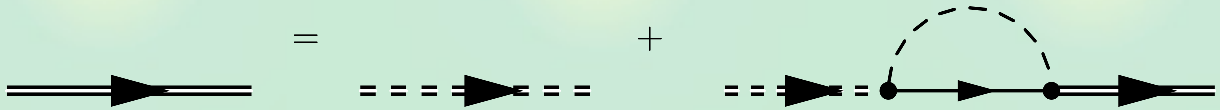
$$\mathcal{L}_{\rm int} = g_0 \bar{\psi}\phi B_0 + ({\rm h.c.})$$



Physical bound state B at total energy W=M_B

Free (full) propagator of B_0 (B) field (positive energy part)

$$\Delta_0(W) = \frac{1}{W - M_{B_0}}, \quad \Delta(W) = \Delta_0(W) + \Delta_0(W) g_0 G(W) g_0 \Delta(W) = \frac{\boxed{Z}}{W - M_B}$$



Z: **field renormalization constant**

Compositeness in Yukawa theory

$$1 - Z = -g^2 G'(M_B)$$

G(W) **: loop function,** g **: coupling**

Compositeness: summary

Compositeness of bound states

- **Quantum mechanics (model independent for small B)**

$$1 - Z = 2\pi^2\sqrt{2\mu^3}\frac{g_W^2}{\sqrt{B}}$$

- **Yukawa theory (any M_B, but Lagrangian dependent)**

$$1 - Z = -g^2 G'(M_B)$$

Mass M_B and coupling constant g^2

- **are the pole position and the residue of amplitude**

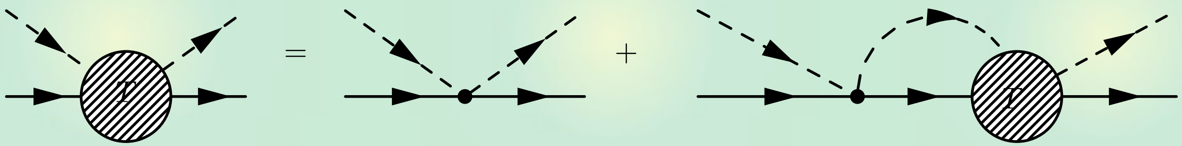
$$T(W) = \frac{g^2}{W - M_B} + T_{\mathrm{BG}}(W)$$

- **can be calculated in models, lattice QCD, experiments, ...?**
- **can be calculated for resonances?**

Chiral coupled-channel model

Baryon resonances in s-wave meson-baryon scattering

- Interaction <-- chiral perturbation theory
- Amplitude <-- unitarity in coupled channels



A review: T. Hyodo, D. Jido, Prog. Part. Nucl. Phys. 67, 55 (2012)

Unitarized amplitude

$$T(W) = \frac{1}{1 - V(W)G(W;a)} V(W)$$

<-- **cutoff parameter**

- generate physical resonances, Λ(1405), N(1535), ...
- **pole position** and **residue** by analytic continuation

Natural renormalization scheme

Model contains no bare pole states.
--> generated states are all two-body composite?

This is not always the case: CDD pole contribution

L. Castillejo, R.H. Dalitz, F.J. Dyson, Phys. Rev. 101, 453 (1956)
G.F. Chew, S.C. Frautschi, Phys. Rev. 124, 264 (1961)

ambiguity of subtractions of dispersion relation
--> contribution from “independent” particles

Natural renormalization condition
<-- to exclude CDD pole contributions from the loop function

T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C78, 025203 (2008)

$$G(W = M; a_{\text{natural}}) = 0$$

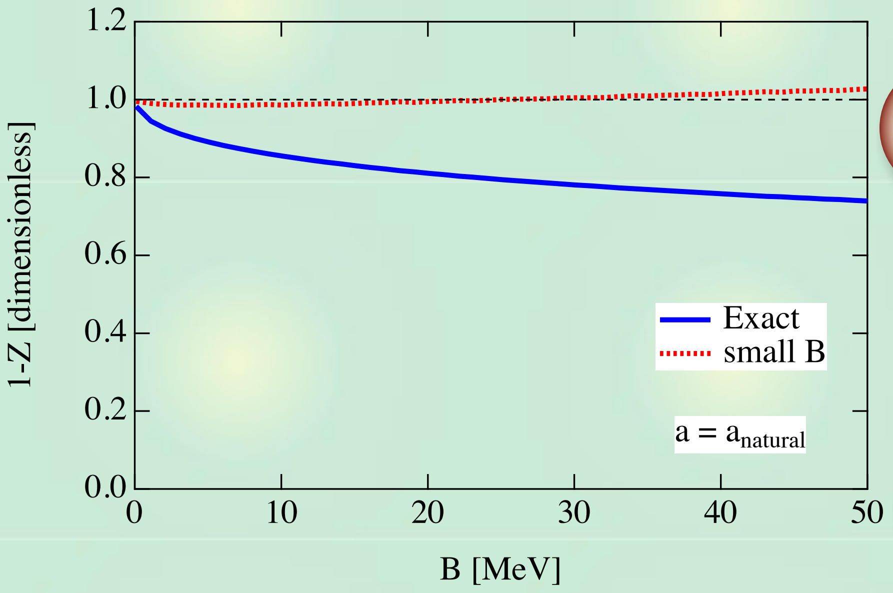
Compositeness in natural renormalization scheme?

Check of natural renormalization scheme

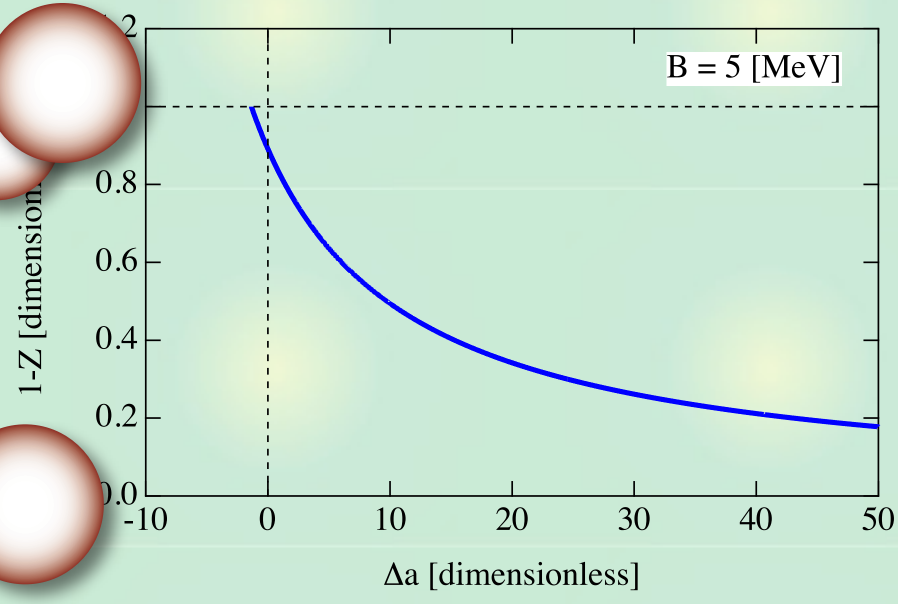
Test: single-channel scattering with a bound state

T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C85, 015201 (2012)

1) $a = a_{natural}$**, vary** B



2) B = 5 **MeV, vary** a



natural scheme --> Z ~ 0

large deviation --> Z ~ 1

dynamical state in natural scheme <==> compositeness

Compositeness of resonances

Application to resonances

- integration of spectral density (for narrow resonances)

V. Baru *et al.*, Phys. Lett. B586, 53 (2004)

- analytic continuation of the bound state formula

$$1 - Z = -g^2 G'(M_B)$$

residue ↑ ↑ pole position

Interpretation: absolute value($|Z| > 1$)? real part($\mathrm{Re}Z < 0$)?

- no completeness: Z is not normalized
- g, M_B are complex: Z is complex

Example: Λ(1405)

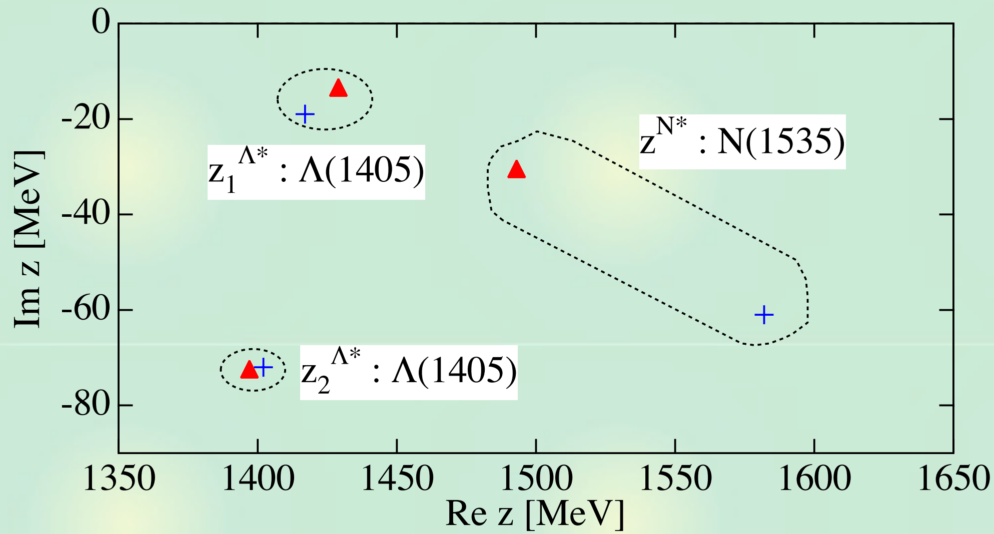
- higher energy pole: Z = 0.00 + 0.09i
- lower energy pole: Z = 0.86 - 0.40i

T. Sekihara, T. Hyodo, Phys. Rev. C87, 045202 (2013)

Analysis by natural scheme

Pole positions in natural / phenomenological scheme

T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C78, 025203 (2008)



▲ natural

+ phenomenological

Magnitude of deviation : amount of CDD pole contribution

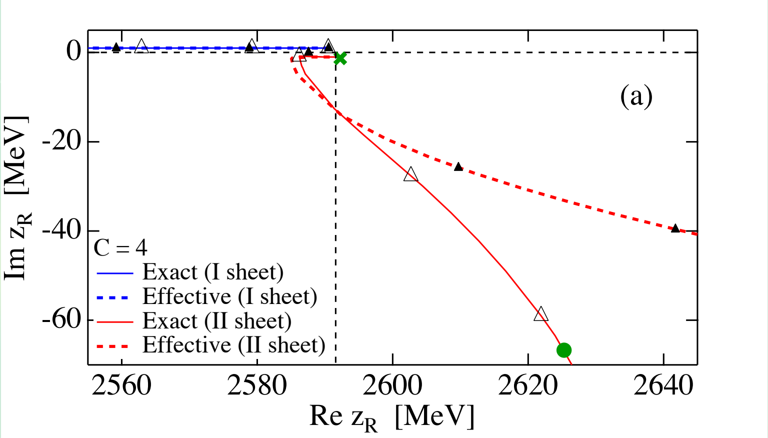
--> Λ(1405) : mostly composite, N(1535) : mixture

- **higher energy pole:** $Z = 0.00 + 0.09i$
- **lower energy pole:** $Z = 0.86 - 0.40i$ **??**

Near-threshold states

Near-threshold resonances: effective range expansion

$$f(k) = \left(\frac{1}{a} - ki + \frac{r_e}{2}k^2\right)^{-1}$$



Amplitude is given by 2 parameters

--> residue is determined by the pole position

T. Hyodo, arXiv:1305.1999 [hep-ph]

$$Z = 1 - \sqrt{1 - \frac{1}{1 + a/(2r_e)}}$$

1 - Z **is pure imaginary for resonances and** 0 < |1 - Z| < 1**.**

- **normalized quantity**
- **measures deviation from** 1 - Z = i **?**

Summary 1

Classification of hadron structure

- **Field renormalization constant** Z

$Z = 0$ **(composite)** $Z = 1$ **(elementary)**

- Z **<-- mass + coupling (pole + residue)**

S. Weinberg, Phys. Rev. 137, B672 (1965)
D. Lurie and A. J. Macfarlane, Phys. Rev. 136, B816 (1963)

- **Models, lattice, experiments,...**

Summary 2

Application to resonances

- Z for resonances is in general **complex** and **not normalized**. Interpretation?
- Combination with other analysis (natural scheme, Nc scaling, ...) may help it.

  T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C78, 025203 (2008)
  T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C85, 015201 (2012)
- Near-threshold resonances: effective range expansion may help it.

  T. Hyodo, arXiv:1305.1999 [hep-ph]