Universal physics of three bosons with isospin

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T. Hyodo, T. Hatsuda, Y. Nishida, Phys. Rev. C89, 032201(R) (2014)

Universal physics

Universal: **different systems share the identical feature**

Critical phenomena around phase transition

- **large correlation length ξ**
- **scaling, critical exponent, ...**
- **liquid-gas transition ~ ferromagnet**

N. Goldenfeld, *"Lectures on phase transitions and the renormalization group"* (1992)

Universal physics in few-body system

- **large two-body scattering length |a|**
- **scaling, shallow bound state**

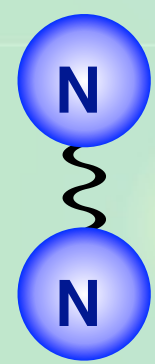
vdW

strong

$$a \to \lambda a, \quad E \to \lambda^{-2} E$$

$$B_2 = \frac{1}{ma^2}$$

	N [MeV]	^{4}He [mK]
B_2	**2.22**	**1.31**
$1/ma^2$	**1.41**	**1.12**



^{4}He

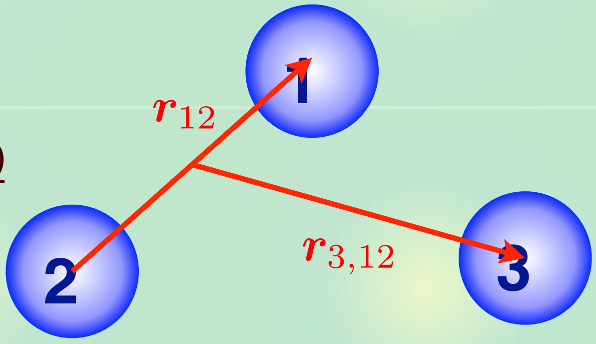
E. Braaten, H.-W. Hammer, Phys. Rept. 428, 259 (2006)

Three-body system: scaling and its violation

Three-body system in hyperspherical coordinates

$$(\boldsymbol{r}_{12}, \boldsymbol{r}_{3,12}) \leftrightarrow (\underline{R}, \underline{\alpha_3, \hat{\boldsymbol{r}}_{12}, \hat{\boldsymbol{r}}_{3,12}})$$

hyperradius **hyperangular variables** Ω **(dimensionless)**



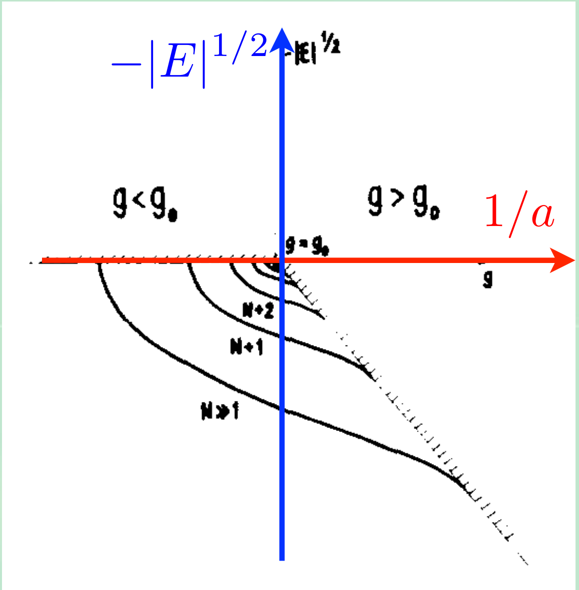
For |a| —> ∞, system is scale invariant.

$$V(R,\Omega) \propto \frac{1}{R^2}$$

Efimov effect : attractive $1/R^2$ **for identical three bosons**

V. Efimov, Phys. Lett. B 33, 563-564 (1970)

- **infinitely many bound states**
- **discrete scale invariance --> limit cycle**



P.F. Bedaque, H.-W. Hammer, U. van Kolck, Phys. Rev. Lett. 82, 463-437 (1999)

Pion interaction

$\pi\pi$ scattering length <— chiral low energy theorem

S. Weinberg, Phys. Rev. Lett. 17, 616-621 (1966)

$$a^{I=0} \propto -\frac{7}{4}\frac{m_\pi}{f_\pi^2}, \quad a^{I=2} \propto \frac{1}{2}\frac{m_\pi}{f_\pi^2}$$

- $1/f_\pi^2$ **~ spontaneous breaking of chiral symmetry**
- m_π **~ explicit breaking of chiral symmetry**

In nature, the scattering lengths are small <— m_π is small

- $a^{I=0}$ ~ -0.31 fm, $a^{I=2}$ ~ 0.06 fm **/ QCD scale ~** 1 fm

If we can adjust m_π or f_π, |a| may be increased by $m_\pi \nearrow$ or $f_\pi \searrow$

- **sufficient attraction**
  --> bound state in I=0
  --> diverging |a|

- **sigma:** I=0 **resonance**

$f_0(500)$ or σ
was $f_0(600)$

$I^G(J^{PC}) = 0^+(0^{++})$

A REVIEW GOES HERE – Check our WWW List of Reviews

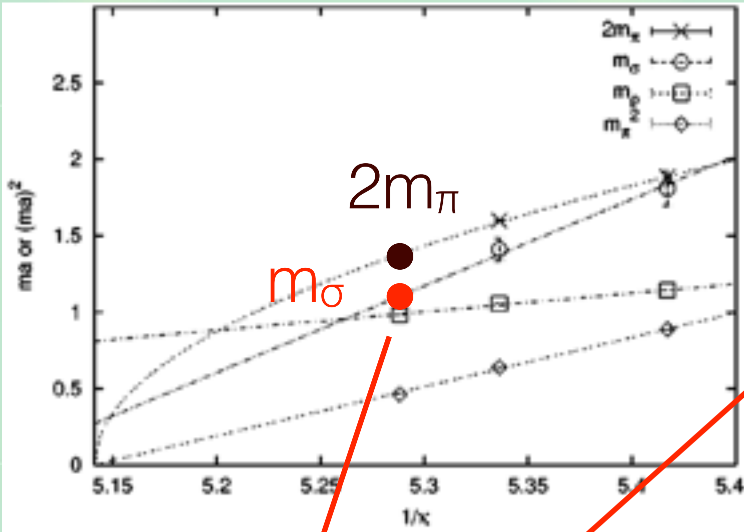
$f_0(500)$ T-MATRIX POLE $\sqrt{s}$

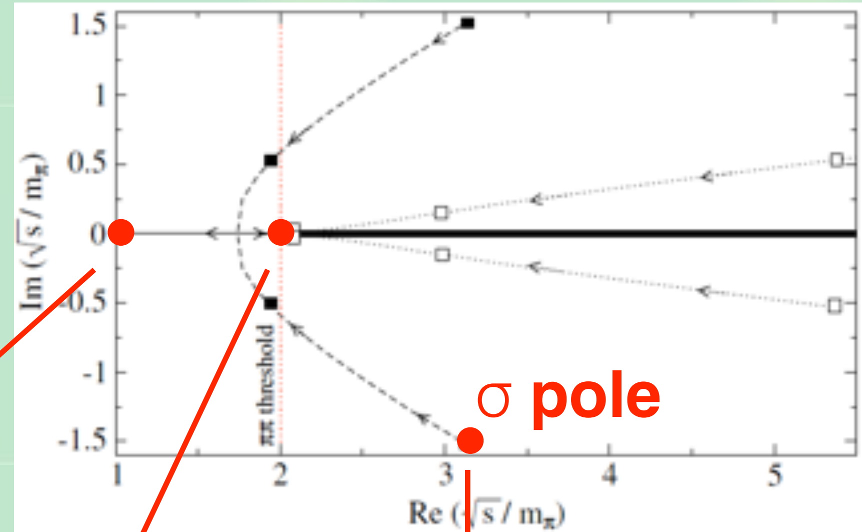
Note that $\Gamma \approx 2\ \mathrm{Im}(\sqrt{s_{pole}})$.

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
(400–550)–i(200–350) OUR ESTIMATE			

Increase pion mass

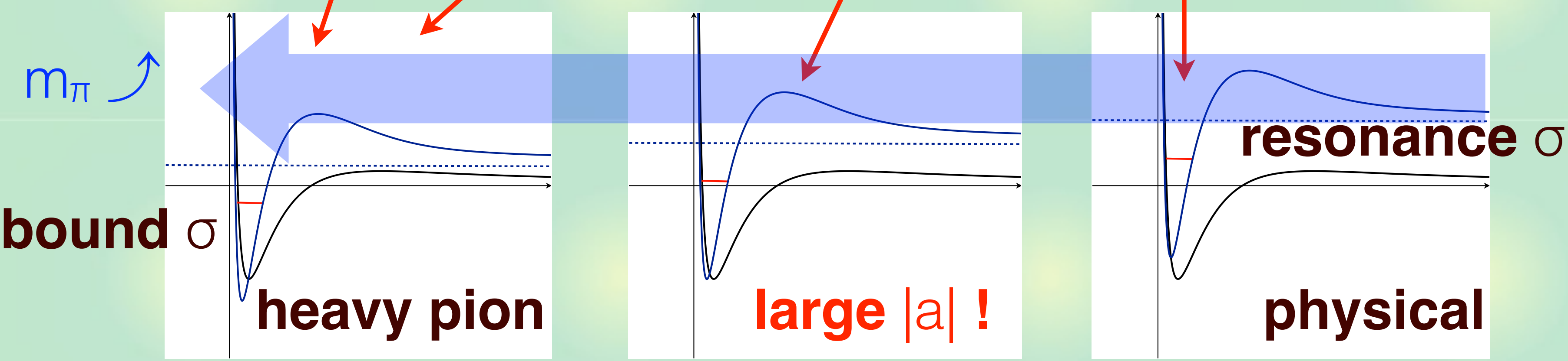
Lattice QCD/chiral EFT can tune the pion mass





T. Kunihiro *et al.* (SCALAR Collaboration), Rev. Rev. D70, 034504 (2004)

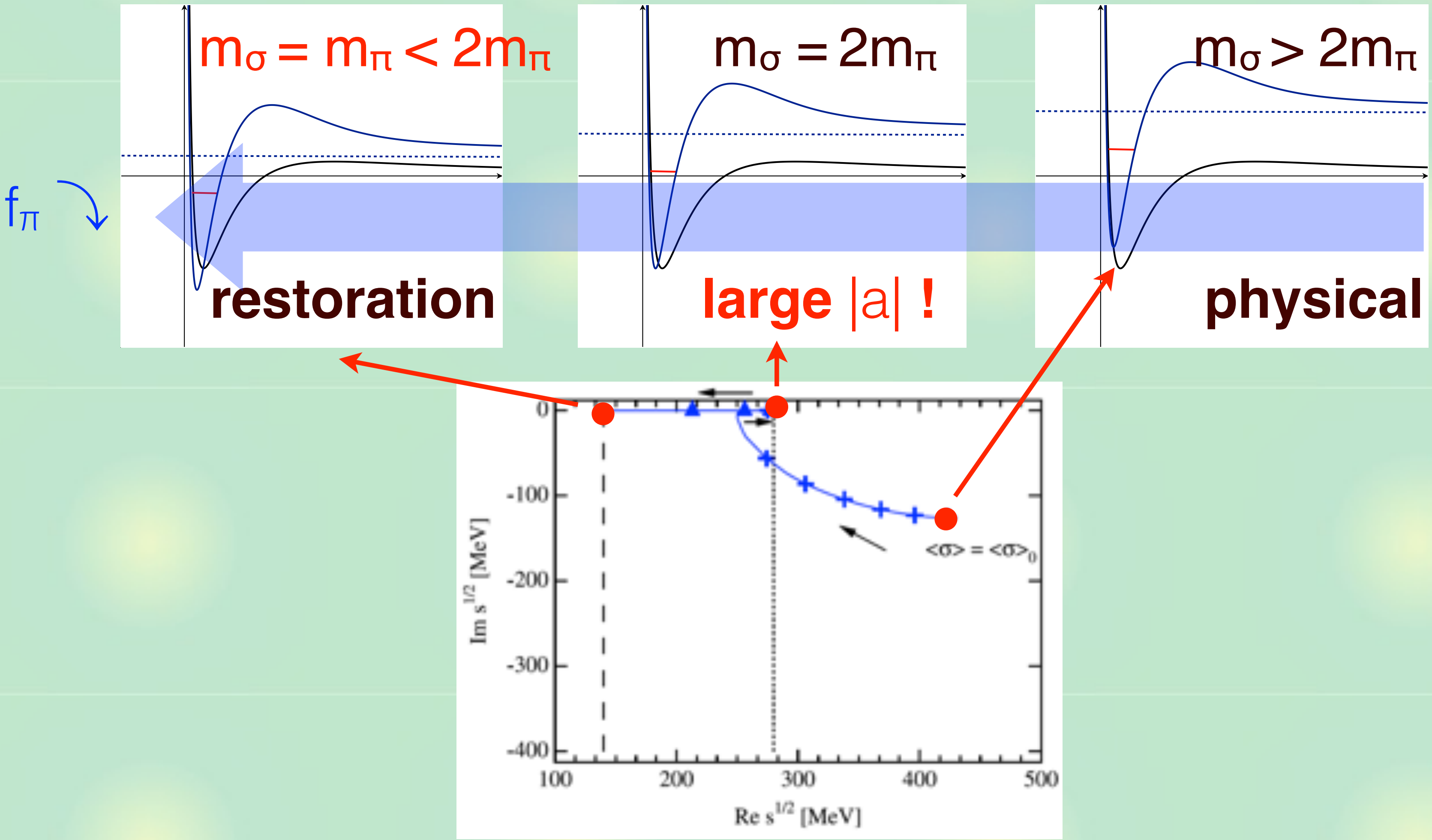
C. Hanhart, J.R. Pelaez, G. Rios, Phys. Rev. Lett. 100, 152001 (2008)



==> Numerical experiment (lattice QCD)!

Decrease pion decay constant

Chiral symmetry restoration ~ reduction of f_π



T. Hyodo, D. Jido, T. Kunihiro, Nucl. Phys. A848, 341-365 (2010)

==> Real experiment (in-medium symmetry restoration) !

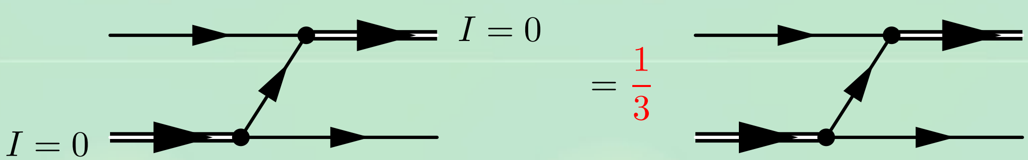
Three pions with isospin symmetry

Large I=0 scattering length

$$f_{I=0} = \frac{1}{-1/a - ip}, \quad f_{I=2} = 0$$

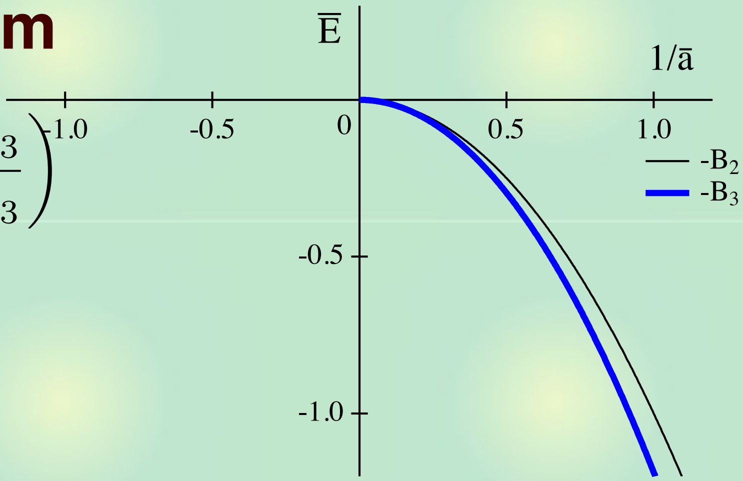
S-wave three-pion system in total I=1

$$\begin{pmatrix} |\, \pi \otimes [\pi \otimes \pi]_{I=0} \,\rangle_{I=1} \\ |\, \pi \otimes [\pi \otimes \pi]_{I=2} \,\rangle_{I=1} \end{pmatrix} = \begin{pmatrix} 1/3 & \sqrt{5}/3 \\ \sqrt{5}/3 & 1/6 \end{pmatrix} \begin{pmatrix} |\, [\pi \otimes \pi]_{I=0} \otimes \pi \,\rangle_{I=1} \\ |\, [\pi \otimes \pi]_{I=2} \otimes \pi \,\rangle_{I=1} \end{pmatrix}$$



Eigenvalue equation for 3-body system

$$z(|\boldsymbol{p}|) = \frac{2}{3\pi} \int_0^\infty d|\boldsymbol{q}| \frac{|\boldsymbol{q}|}{|\boldsymbol{p}|} \ln\left(\frac{\boldsymbol{q}^2 + \boldsymbol{p}^2 + |\boldsymbol{q}||\boldsymbol{p}| + mB_3}{\boldsymbol{q}^2 + \boldsymbol{p}^2 - |\boldsymbol{q}||\boldsymbol{p}| + mB_3} \right) \times \frac{z(|\boldsymbol{q}|)}{\sqrt{\frac{3}{4}\boldsymbol{q}^2 + mB_3} - \frac{1}{a}}$$



$$B_3 = \frac{1.04391}{ma^2} \quad \text{for } 1/a > 0 \qquad \text{c.f.} \quad B_2 = \frac{1}{ma^2}$$

Three pions with isospin breaking

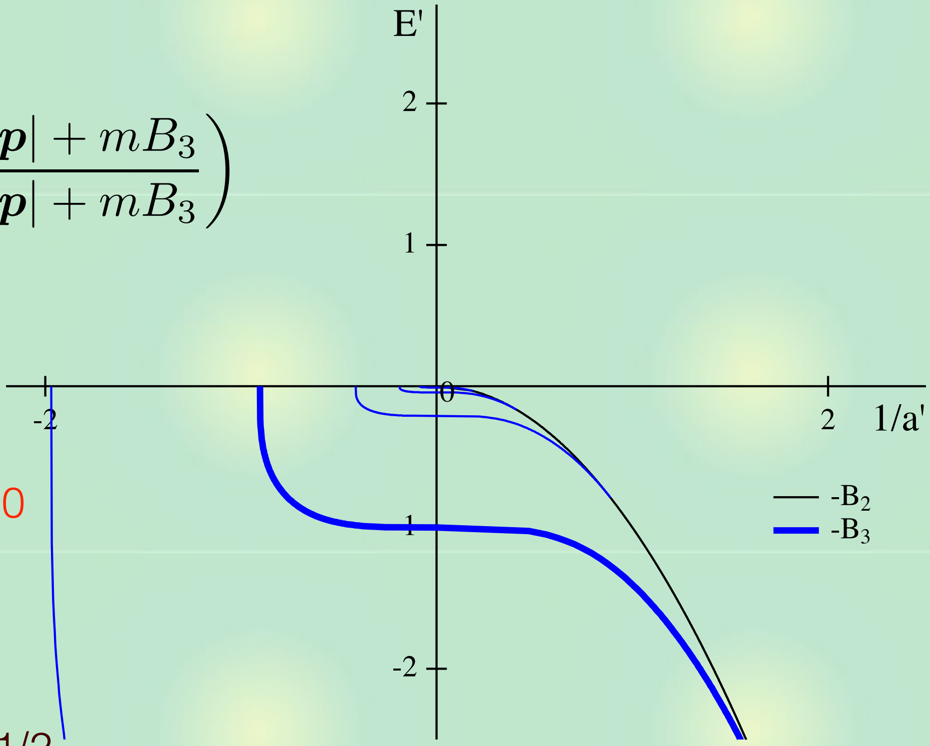
Isospin breaking: $m_{\pi^\pm} = m_{\pi^0} + \Delta$ **with** $\Delta > 0$

- In the energy region $E \ll \Delta$**, heavy** $\pi^\pm$ **can be neglected.**

Identical three-boson system with a large scattering length
--> Efimov effect

$$z(|\boldsymbol{p}|) = \frac{2}{\pi}\int_0^\infty d|\boldsymbol{q}|\frac{|\boldsymbol{q}|}{|\boldsymbol{p}|}\ln\left(\frac{\boldsymbol{q}^2+\boldsymbol{p}^2+|\boldsymbol{q}||\boldsymbol{p}|+mB_3}{\boldsymbol{q}^2+\boldsymbol{p}^2-|\boldsymbol{q}||\boldsymbol{p}|+mB_3}\right) \times \frac{z(|\boldsymbol{q}|)}{\sqrt{\frac{3}{4}\boldsymbol{q}^2+mB_3}-\frac{1}{a}} f_\Lambda(|\boldsymbol{q}|)$$

cutoff ~ $1/r_0$



Universal physics at $E \ll (2m\Lambda)^{1/2}$

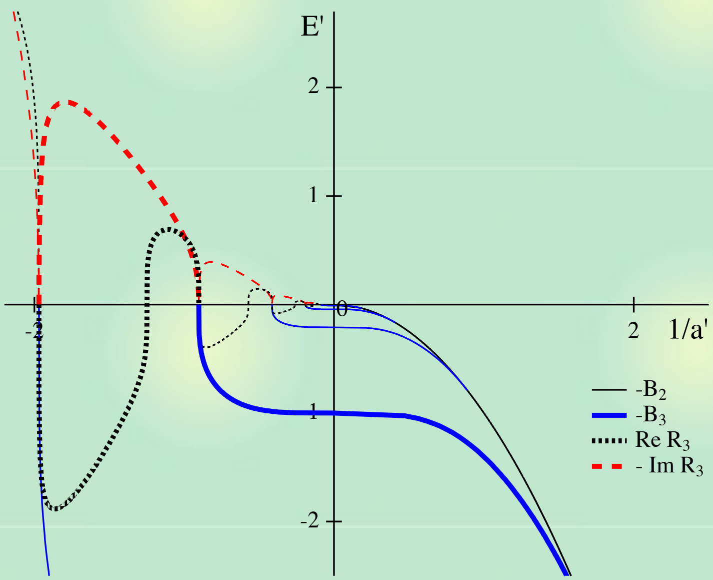
<-- Efimov parameter κ_*

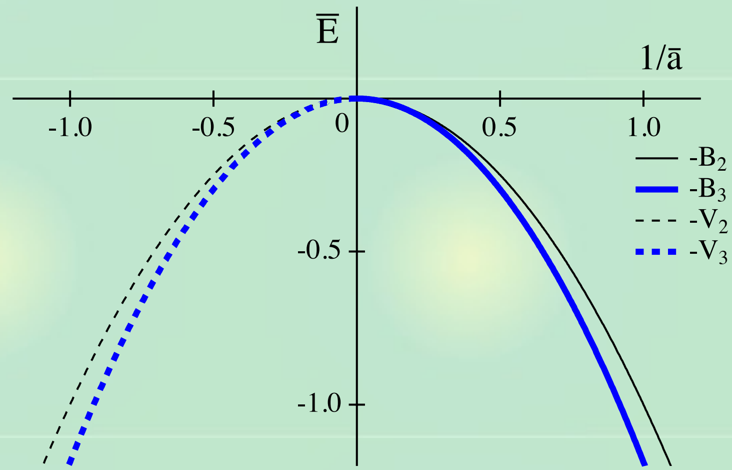
Coupled-channel effect

Two universal phenomena : existence of the coupled channel

$$z(|\boldsymbol{p}|) = \frac{2}{\lambda\pi}\int_0^\infty d|\boldsymbol{q}|\frac{|\boldsymbol{q}|}{|\boldsymbol{p}|}\ln\left(\frac{\boldsymbol{q}^2+\boldsymbol{p}^2+|\boldsymbol{q}||\boldsymbol{p}|+mB_3}{\boldsymbol{q}^2+\boldsymbol{p}^2-|\boldsymbol{q}||\boldsymbol{p}|+mB_3}\right)\frac{z(|\boldsymbol{q}|)}{\sqrt{\frac{3}{4}\boldsymbol{q}^2+mB_3}-\frac{1}{a}}$$

$\lambda < 2.41480$ | $2.41480 < \lambda < 3.66811$ | $3.66811 < \lambda$





no universal bound state

discrete scale invariance

scale invariance

Both cases can be realized in three-pion systems.

Implication in hadron physics

Numerical experiment by lattice QCD : $m_\pi \nearrow$

- **Find the quark mass with which** σ **appears at threshold**
- **Calculate the energy of three-pion system**
- **Note: to confirm the Efimov effect, the simulation requires very high resolution.**

In-medium restoration of chiral symmetry : $f_\pi \searrow$

- **existence of shallow bound state(s) for** $1/|a| \longrightarrow 0$
- **When the** $\sigma(I=J=0)$ **softens,** $\pi^*(I=1, J=0)$ **also softens simultaneously.**
- **Note:** σ **softening is difficult to confirm due to the final state interaction, mixing with quark number fluctuation, …**

Summary

Universal physics of three pions

- Large $\pi\pi$ scattering length (I=0) can be obtained by $m_\pi \nearrow$ or $f_\pi \searrow$.
- Universal phenomena with large a:
  - single bound state (isospin symmetry)
  - Efimov states (isospin breaking)
- Consequence in hadron physics:
  - realization in lattice QCD
  - simultaneous softening of σ and π^*

T. Hyodo, T. Hatsuda, Y. Nishida, Phys. Rev. C89, 032201(R) (2014)