フレーバーで探るハドロンの新しい存在形態：理論

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DN composite
Heavy quark system

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D. Jido (YITP, Kyoto)

Mixing
for a_1

「J-PARCで展開されるハドロン原子核物理」研究会
２０１１年６月１０日（金）－６月１１日（土）

1. Introduction

Exotic structure of hadron

resonances qq $q\bar{q}$

and/or correlations

2. Hadronic composites

Dynamically generated

Λ(1405), New *Qqqqq ~ DN, BN*

3. Recent analysis for a_1

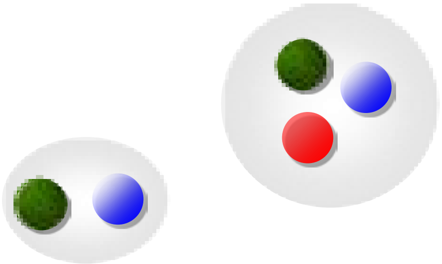
Coexistence/mixing of two components

This comes out by solving the scattering eq

1. Introduction

"*Constituent quark*"

Ingredients of the **standard** quark model
at low energies
$q\bar{q}$ and qqq structure for hadrons



Light quarks:

$$m_{u,\,d,\,s}\ (\ll \Lambda_{QCD})\ \text{-->}\ m^*_{u,\,d,\,s}\ (\sim\Lambda_{QCD})$$

Spontaneous breaking of chiral symmetry

PR122, 345; 124, 246 (1961)

Heavy quarks: $m_{c,b,t}\ (\gg \Lambda_{QCD})$

Y. Nambu

Motivated by observation of exotic hadrons

Θ^+, $\Lambda(1405)$, …, X(3872), $Z^+(4430)$, etc

Pentaquarks ***Hadronic molecule*** ***Tetraquarks***

Not easy to explain by the conventional picture of $q\bar{q}$ and qqq
=> Multiquark components

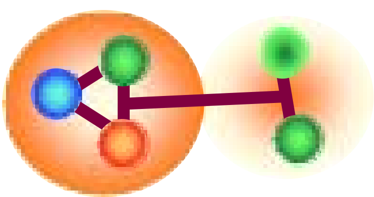
Motivated by observation of exotic hadrons

Θ^+, Λ(1405), …, X(3872), Z^+(4430), etc

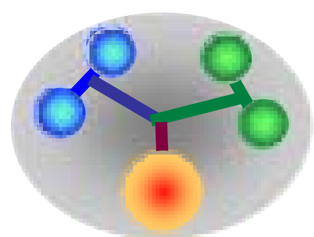
Pentaquarks ***Hadronic molecule*** ***Tetraquarks***

Not easy to explain by the conventional picture of $q\bar{q}$ and qqq
=> Multiquark components

Key question:
What multiquark configurations survive hadrons?

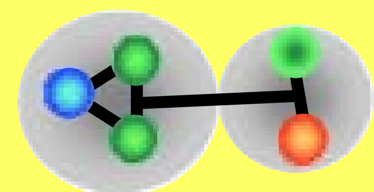


Triquark



Diquark

Colored correlation



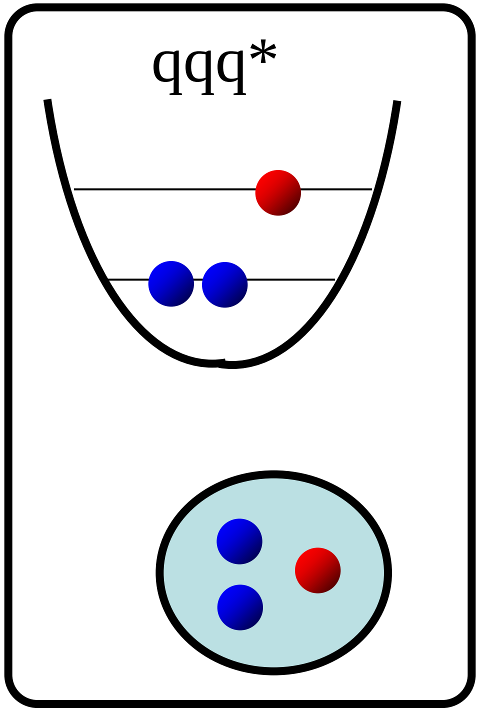
Hadronic composite

Colorless correlation

Different structures may mix

=> Coexistence in ***resonances***

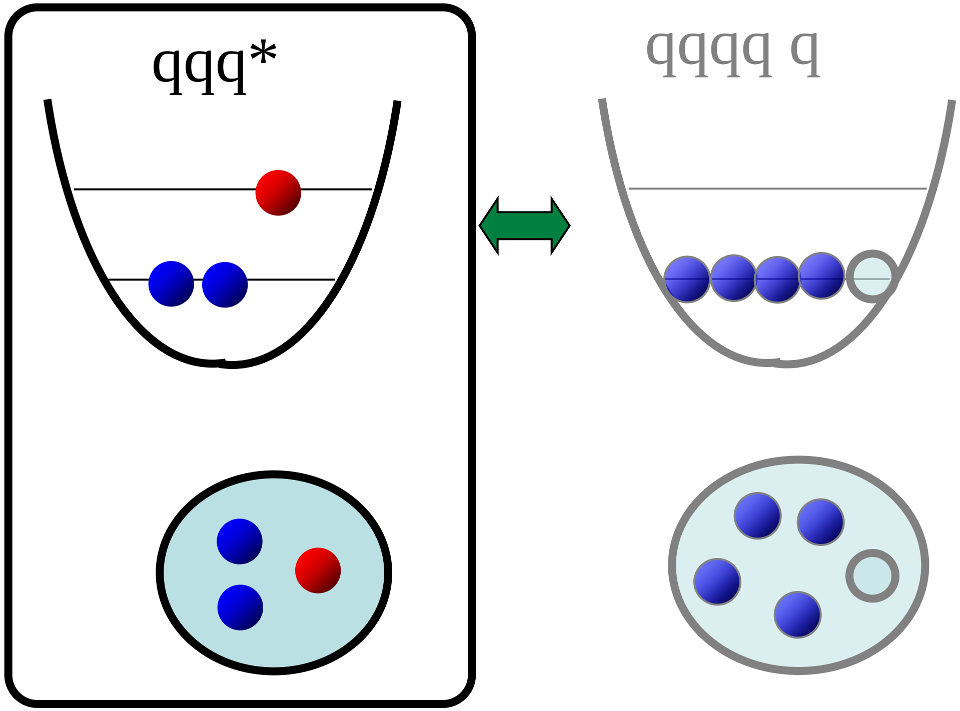
Different structures may mix
=> Coexistence in ***resonances***



Bare elementary

Single particle

Different structures may mix
=> Coexistence in resonances

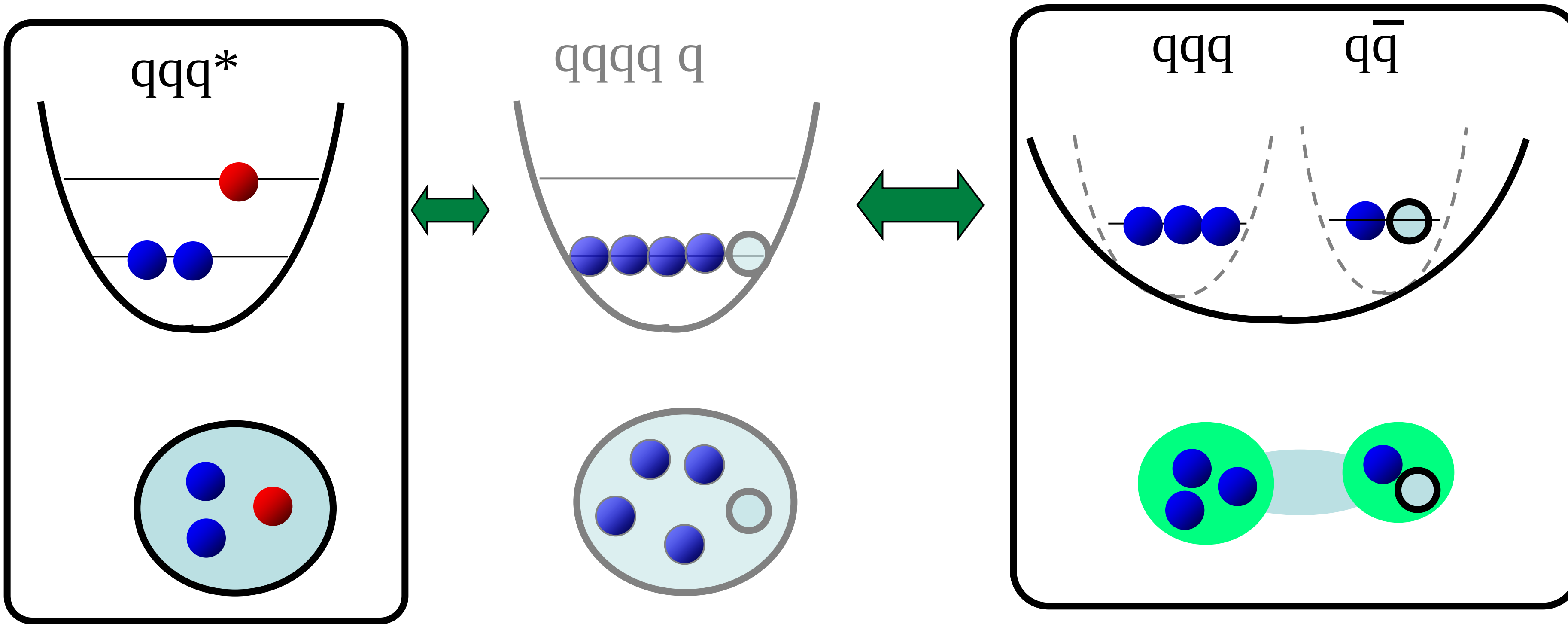


Bare elementary

Pair creation

Single particle

Different structures may mix
=> Coexistence in resonances



Bare elementary

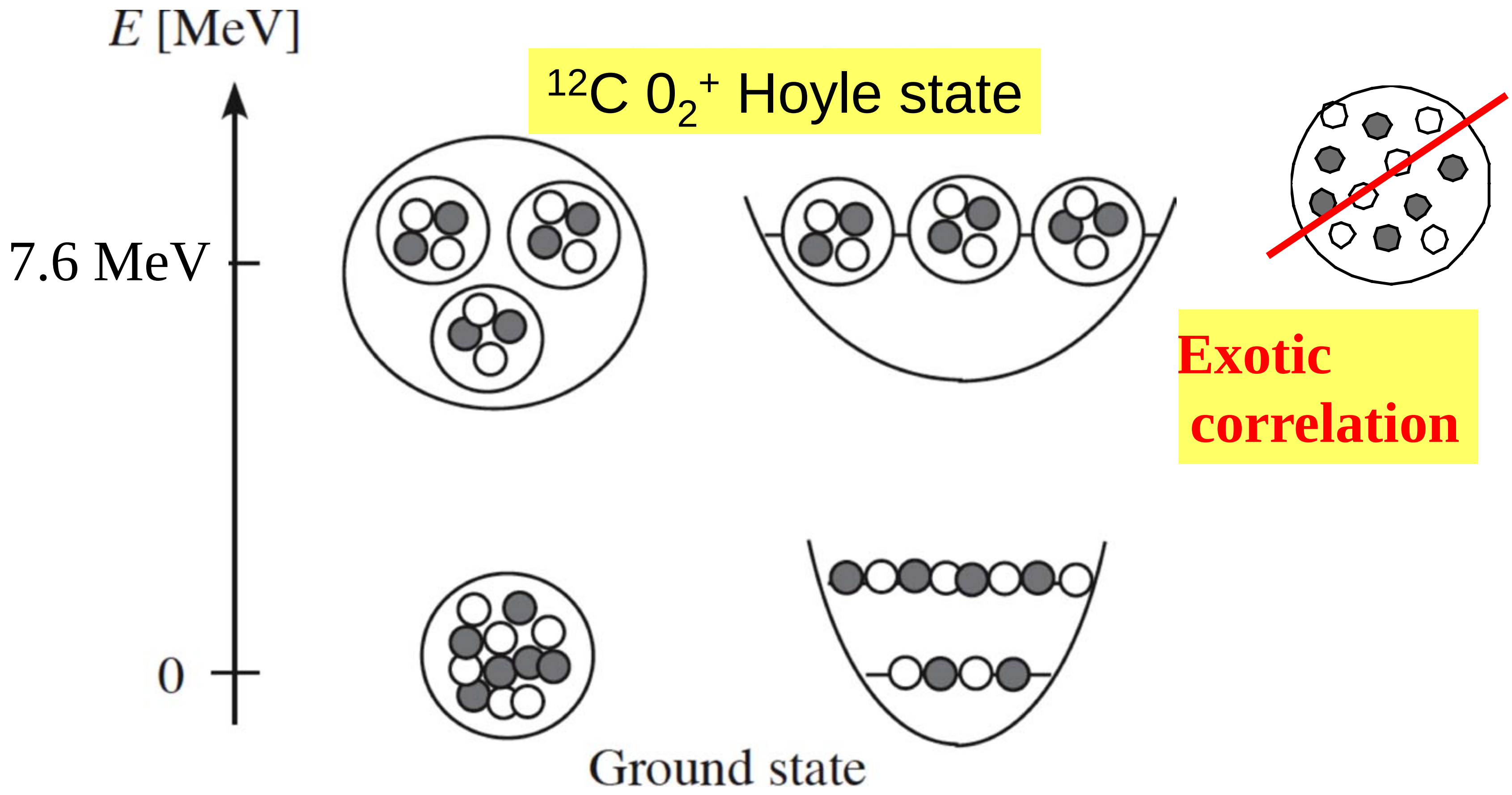
Single particle

Pair creation

Hadronic composite

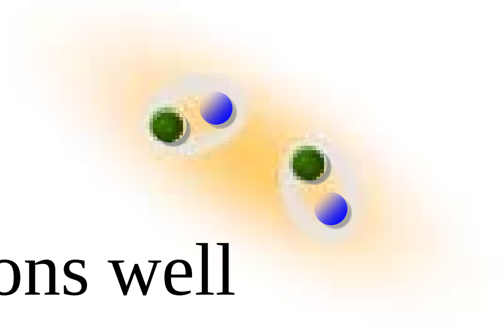
Cluster formation

Example in Nuclear Physics



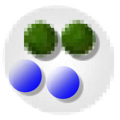
Single particle like

Strategy



- Solve hadron-hadron systems
  for ***hadron composites*** ***(dynamically generated)***
  Assuming that we know hadron interactions well
  (at least better than those between colored objects)

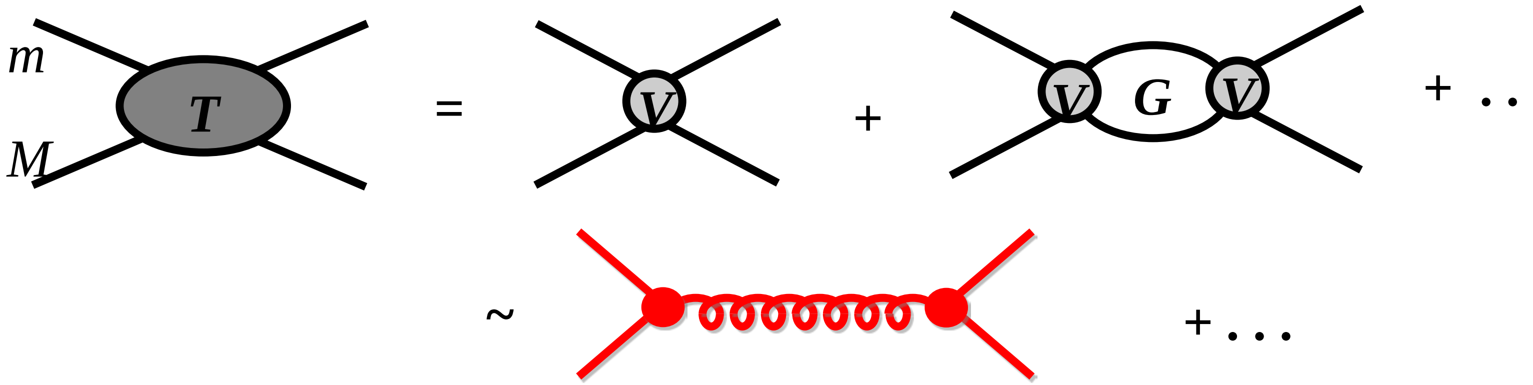
- Study:
  What are described by the ***hadron composites*** and
  What are not
  => Mixing of ***elementary*** components



2. Hadronic composites

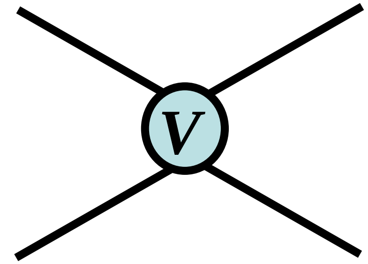
Scattering equation

$$T(E) = V + VG(E)T(E)$$
$$= V + VGV + \ldots \quad \sim \quad g\frac{1}{E-M}g + \ldots$$



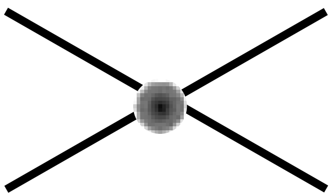
Resonance or
Bound state => ***Hadronic composite***

Interaction *V*



Chiral symmetry

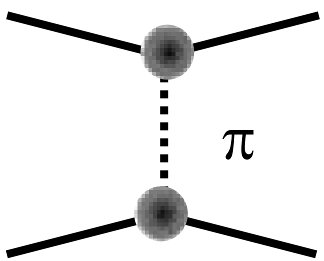
ρ-exchange (***short range***) ~ Weinberg+Tomozawa



$\sim \delta(x)$ or typical hadron size ~ 0.5 fm

This has been the input in many cases

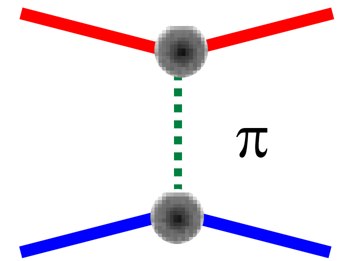
Pion exchange (***long range***) ~ tensor force in NN (deuteron)



$$\frac{1}{q^2 + m_\pi^2} \sim 1.4 \text{ fm}$$

Revised study in
Nuclear Physics
Hadrons with heavy Q

Pion Dominance (*long range*)



For the system of $\bar{Q}q$-qqq, $\bar{Q}q$- $Q\bar{q}$ etc..

Heavy Q symmetry for $\bar{D}$ $\bar{D}^*$ --> Coupled channel of $\bar{D}N$ and $\bar{D}^*N$

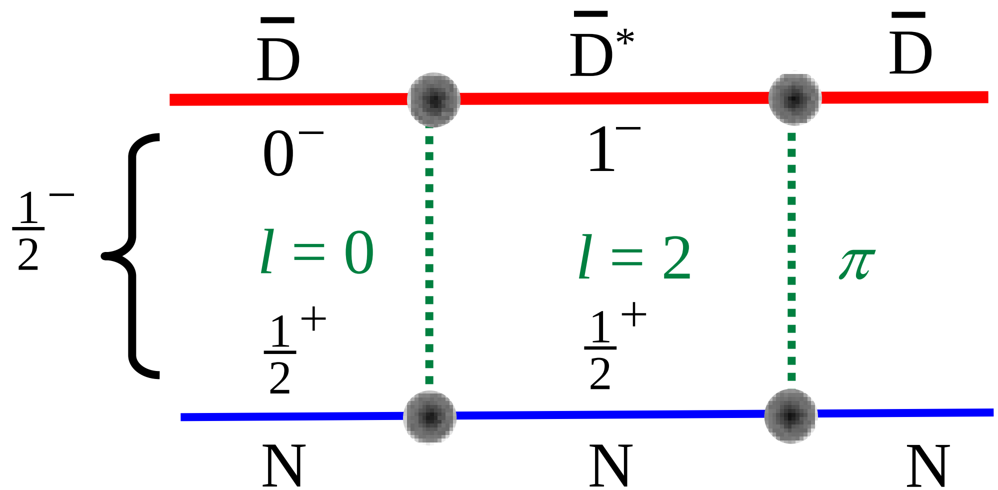
Yasui-Sudoh, PRD80, 034008, 2009
Yamaguchi-Ohkoda-Yasui-Hosaka, arXiv:1105.0734 [hep-ph] 2011

Tensor of OPEP

$m_{K^*} - m_K \sim 400\ MeV$

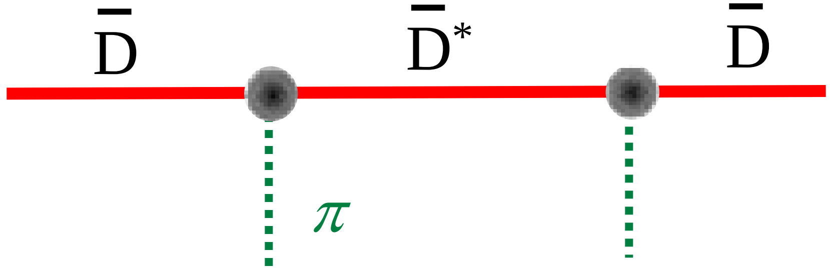
$m_{D^*} - m_D \sim 140\ MeV$

$m_{B^*} - m_B \sim 35\ MeV$



Providing sufficient attraction when $M_P \sim M_{P*}$

$\bar{D}N$ interaction



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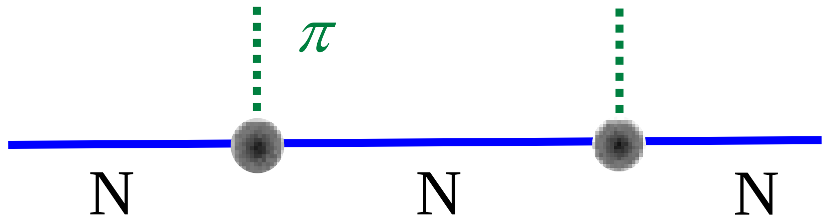
πN interaction



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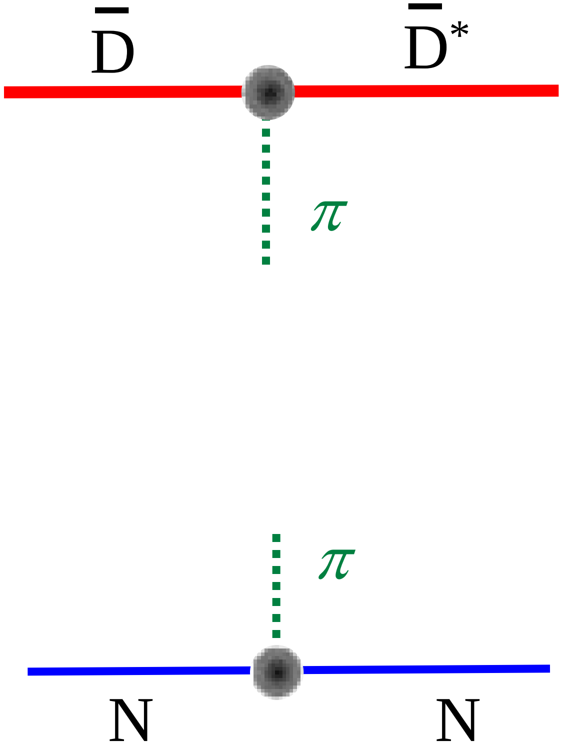
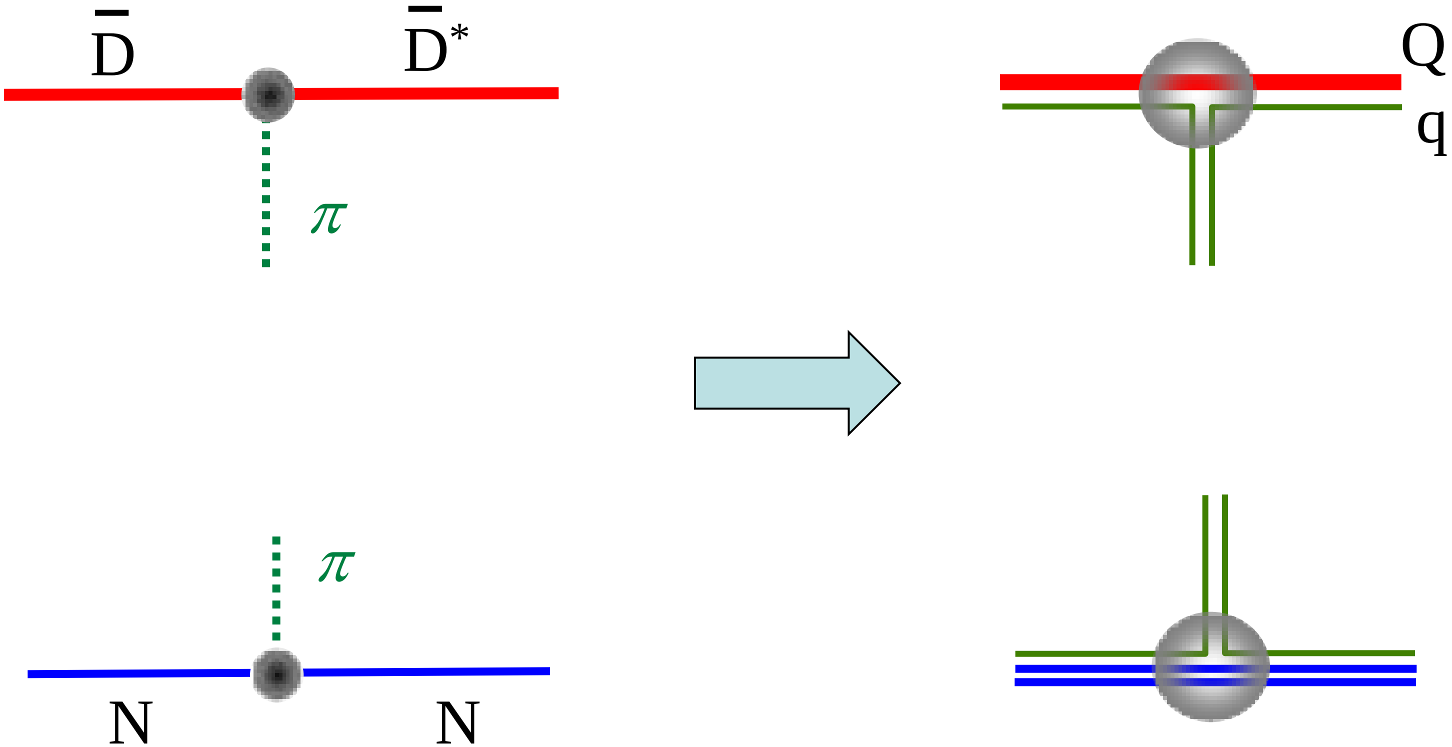


D̄
D̄*
π
π
N
N


$\bar{D}$
$\bar{D}^*$
π
π
N
N
Q
q

Bound states: $I, J^P = 0, 1/2^-$

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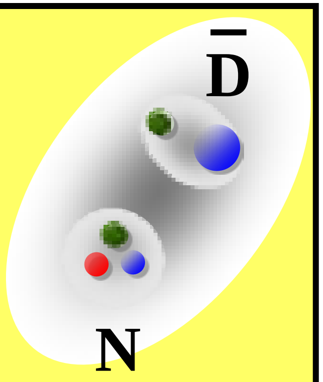

Weakly vs Strongly bound

$\bar{D}N$ ***Three coupled-channels*** BN

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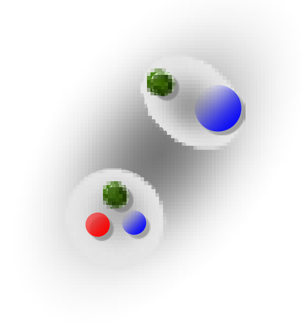
Bound states: $I, J^P = 0, 1/2^-$

$\bar{Q}q$-qqq



More stronly bound for heavier quark

charm

Bottom regions

m_{D*}

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m_{B*}

Large m_Q ←

Small m_Q →

$\bar{D}$N, BN resonant states $3/2^-$

$\bar{Q}q$-qqq

$\bar{D}$N

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$$M_R = 113 - i\,\frac{17}{2}\ \mathrm{MeV}$$

BN

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$$M_R = 8 - i\,\frac{0.13}{2}\ \mathrm{MeV}$$

Feschbach resonance
of $\bar{D}^*$N

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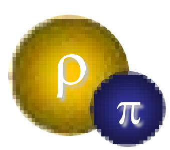
3. Recent analysis for a_1

Hideko Nagahiro[1], Kanabu Nawa[2],
Sho Ozaki[2], Daisuke Jido[3], and Atsushi Hosaka[2]

arXiv:1101.3623[hep-ph]

[1] Department of Physics, Nara Women's University,
[2] RCNP, Osaka University,
[3] YITP, Kyoto University

$|\boldsymbol{a_1}\rangle_{\textbf{phys}} = c_1 |$ 

$\rangle_{\textbf{composite}} + c_2 |$ 

$\rangle_{q\bar{q}\ldots} + \ldots$

Reasonably truncated model space

Maskawa’s Dr. thesis

Maskawa Toshihide

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Nagoya Univ. Physics Dept.

… handwritten 19 pages

Maskawa’s Dr. thesis

Published in PTP38, 190 (1967)

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A model for π, ρ and a_1

A good model for the ***elementary*** *and* ***composites***

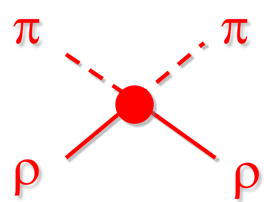
Hidden Local Symmetry or *Holographic* model

Bando-Kugo-Yamawaki
Phys. Rept., 164 (1988) 217

Sakai-Sugimoto
PTP113(05)843; PTP114(05)1083

Nawa, Suganuma, Kojo
PRD75(07)086003 etc

$$\mathcal{L}_{\rm WT} = -\frac{g_4}{4f_\pi^2}\mathrm{tr}\left([\rho^\mu, \partial^\nu \rho_\mu][\pi, \partial_\nu \pi]\right)$$

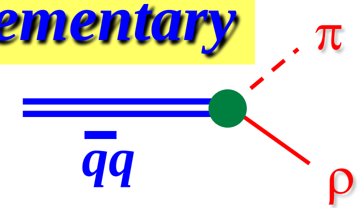


Dynamical Generation of

composite

$$\mathcal{L}_{a_1\pi\rho} = -g_{a_1\pi\rho}\frac{\sqrt{2}}{f_\pi}\left\{\mathrm{tr}\left[(\underline{\partial_\mu} a_{1\nu} - \underline{\partial_\nu} a_{1\mu})[\partial^\mu \pi, \rho^\nu]\right] + \mathrm{tr}\left[(\partial_\mu \rho_\nu - \partial_\nu \rho_\mu)[\partial^\mu \pi, \underline{a_1^\nu}]\right]\right\}$$

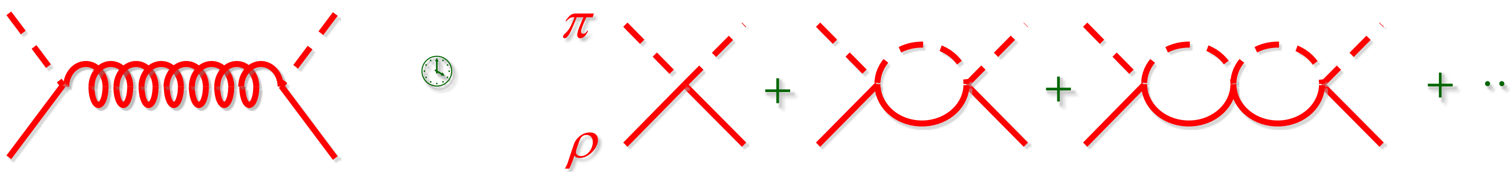
elementary



Mixing

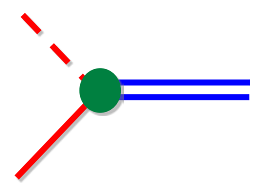
Solving the problem

(a) Composite, dynamically generated



(b) Bare, $\bar{q}q$

(c) Mixing



mixing with the strength ***x***

$$0 < x < 1$$

Hamiltonian

$$H = \begin{pmatrix} H_{\pi\rho} + v_{WT} & v \\ v & M_{a_1} \end{pmatrix}$$

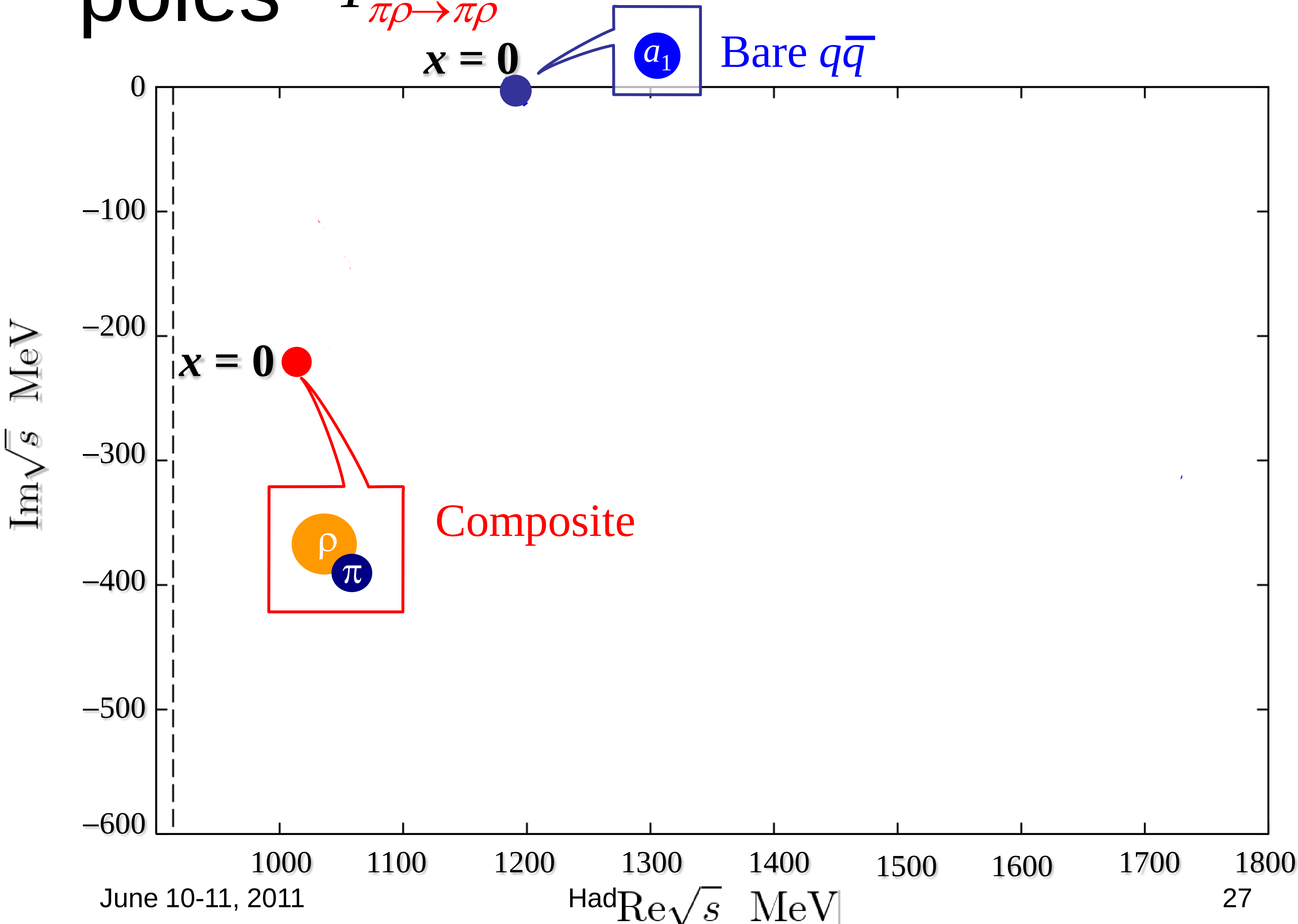
LS-equation

$$\rightarrow$$

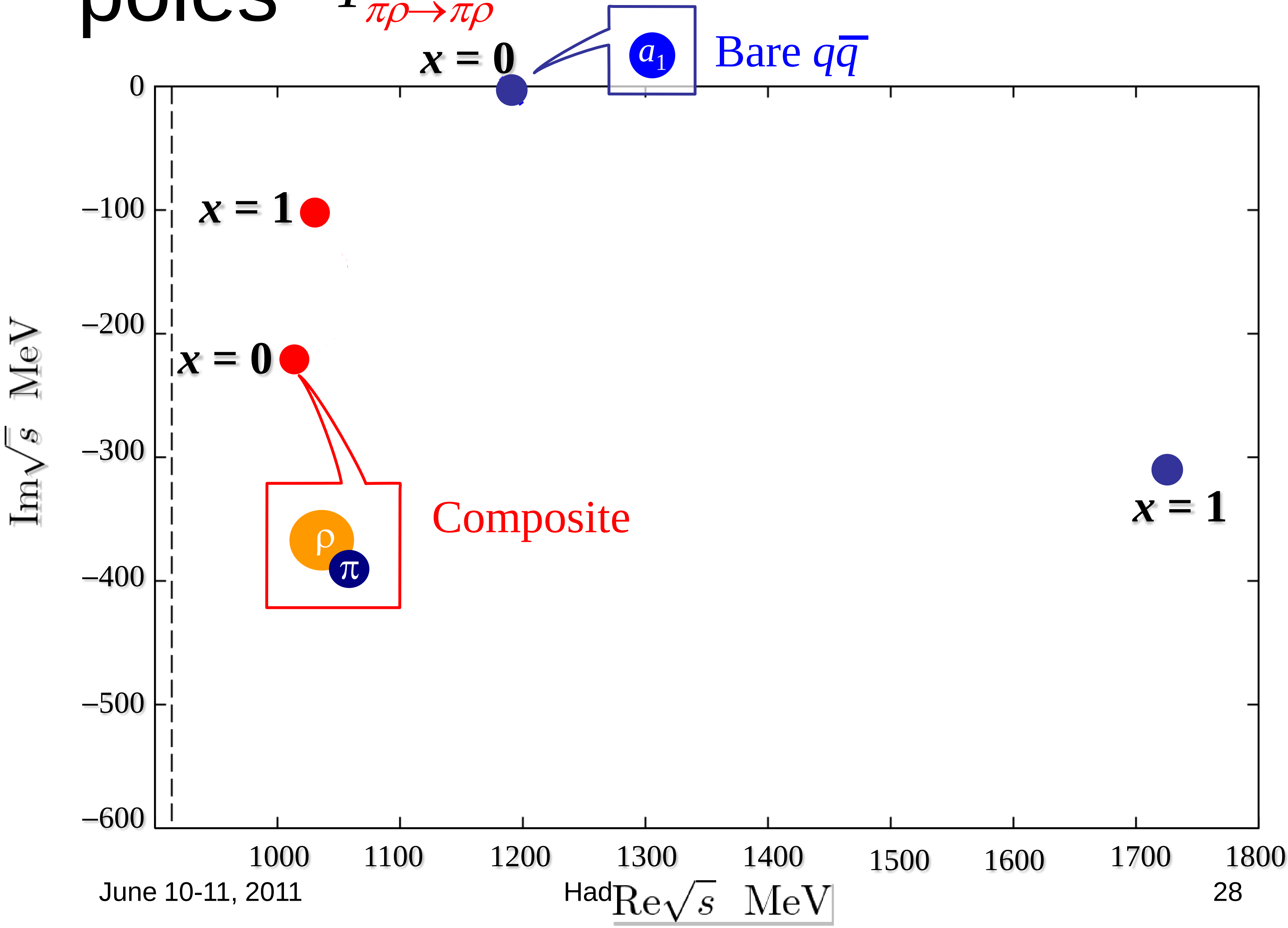
T-matrix

$$T = \begin{pmatrix} T_{\pi\rho\to\pi\rho} & T_{\pi\rho\to a_1} \\ T_{a_1\to\pi\rho} & T_{a_1\to a_1} \end{pmatrix}$$

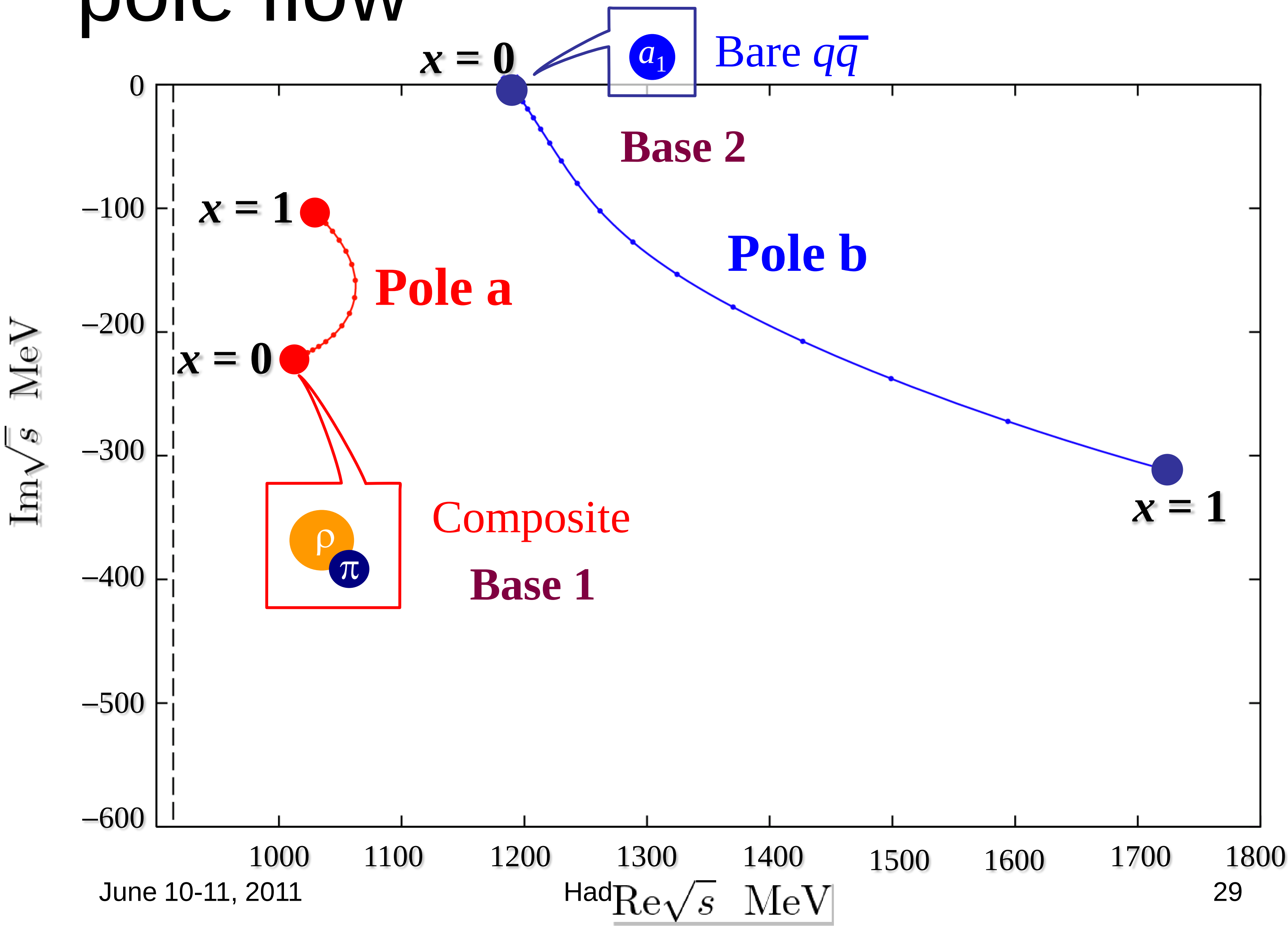
poles $T_{\pi\rho\to\pi\rho}$



poles $T_{\pi\rho\to\pi\rho}$



pole flow



x = 0
Bare $q\bar{q}$
a_1
0
Base 2
−100
x = 1
Pole b
Pole a
−200
x = 0
−300
x = 1
ρ
π
Composite
−400
Base 1
−500
−600
1000
1100
1200
1300
1400
1500
1600
1700
1800
Im$\sqrt{s}$ MeV
Re$\sqrt{s}$ MeV

To know better the nature of the poles

Extract one-particle propagators in the T matrix

$$T = \begin{pmatrix} T_{\pi\rho\to\pi\rho} & T_{\pi\rho\to a_1} \\ T_{a_1\to\pi\rho} & T_{a_1\to a_1} \end{pmatrix}$$

Base 1

$$T_{\pi\rho\to\pi\rho} = (g_R, g)\begin{pmatrix} G^{11} & G^{12} \\ G^{21} & G^{22} \end{pmatrix}\begin{pmatrix} g_R \\ g \end{pmatrix}$$

Base 2

$$[\hat{G}_{\rm full}]^{11} \sim \frac{z_a^{11}}{E - E_a} + \frac{z_b^{11}}{E - E_b}$$

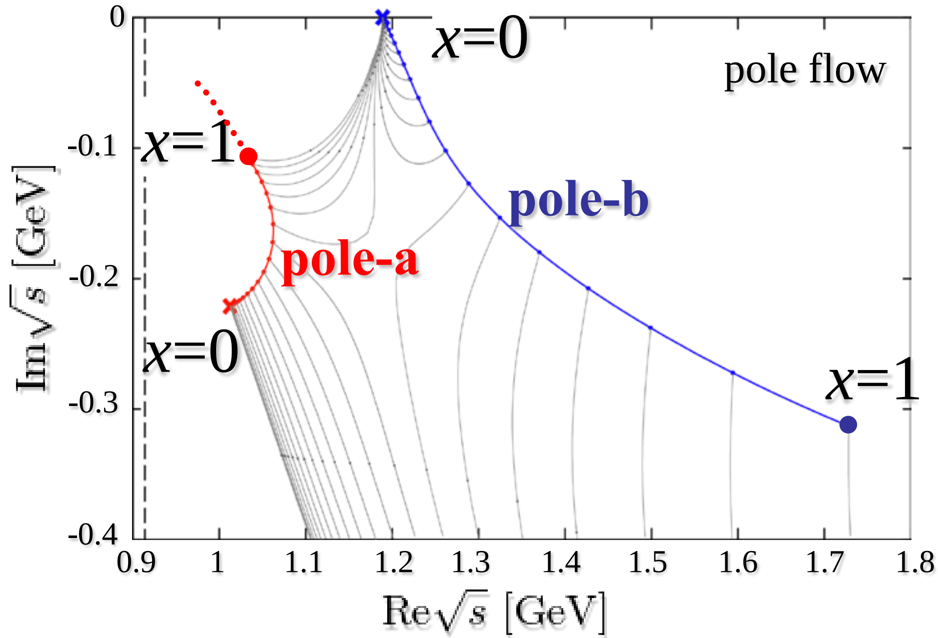
$$[\hat{G}_{\rm full}]^{22} \sim \frac{z_a^{22}}{E - E_a} + \frac{z_b^{22}}{E - E_b}$$

Full solution

-> Two level problem

$$|\,\mathbf{Pole}\,\rangle_{\rm \mathbf{phys}} = c_1 \,|\, \rho\,\pi \,\rangle_{\rm \mathbf{composite}} + c_2 \,|\, a \,\rangle_{\rm \mathbf{elementar}}$$

mixing properties



$$[\hat{G}_{\mathrm{full}}]^{11} = \frac{z_a^{11}}{E - E_a} + \frac{z_b^{11}}{E - E_b}$$

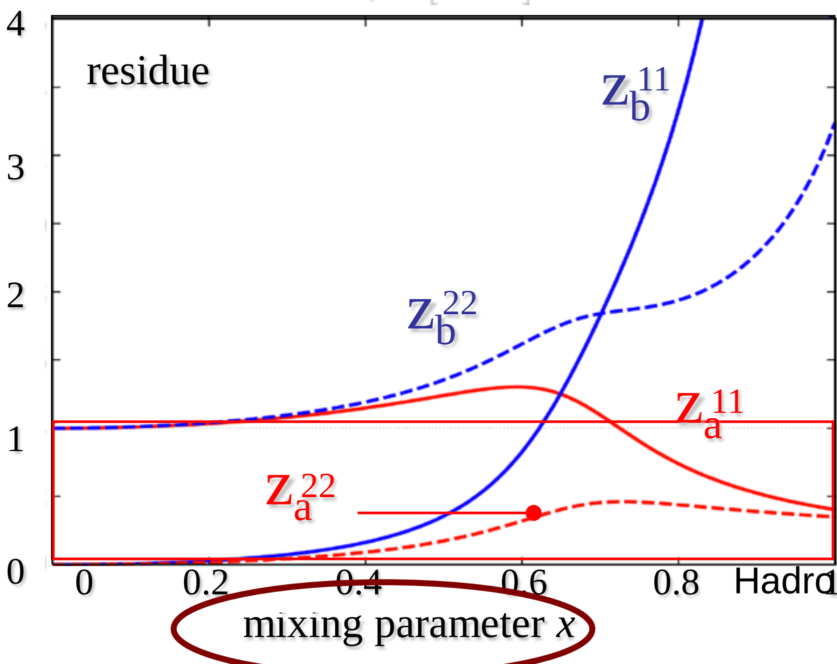
$$[\hat{G}_{\mathrm{full}}]^{22} = \frac{z_a^{22}}{E - E_a} + \frac{z_b^{22}}{E - E_b}$$

Z_a^{11} … composite

Z_a^{22} … bare

Z_b^{11} … composite

Z_b^{22} … bare



at physical point (*x*=1)

- pole-a remains as a "*molecule*"
- pole-b changes into a "*molecule*"

→ **both poles have molecule comp.**

Summary

- Exotics may have *correlations*, $q\bar{q}$, qq, qqq
  We have focused on hadronic correlation
- Heavy quark baryons are likely to exist
  For ***DN*, *BN***, predicted a ***bound*** and ***resonant*** states
  Pion exchange is the key ***SSB of Chiral symmetry***
- Studied a system of ***composite+elementary*** $\boldsymbol{a_1}$
  Mixing interaction makes hadron structure nontrivial
  Large-N_c limit should be taken with care

Subtraction constants

$\Lambda(1405)$

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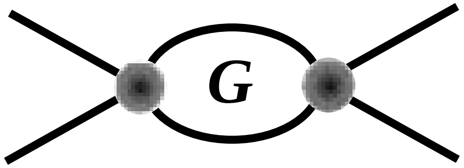
$N^{*}(1535)$

For S =-1 (~Λ(1405)), a_{pheno} and a_{natural} are similar but
For S = 0 (~*N*(1535)), they are very much different

ρ-exchange (***short range***) ~ WT

Natural condition ***for hadronic composite***

corresponding to hadron size ~ 0.5 fm



Cut-off

$$G(E) \sim i \int \frac{d^4 q}{(2\pi)^4} \frac{2M}{(P-q)^2 - M^2 + i\varepsilon} \frac{1}{q^2 - m^2 + i\varepsilon} \sim \sum_n^{\Lambda} \frac{1}{E - E_n}$$

$$\Lambda \sim 0.5 - 1\,\text{GeV}$$

Dimensional regularization

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$$a_{natural} \sim -2$$

for $\Lambda(1405)$

T. Hyodo, D. Jido, A. Hosaka,
Phys.Rev.C78:025203,2008;
arXiv:0803.2550 [nucl-th]

$\bar{K}N$ dynamics and $\Lambda(1405)$

Oset and Ramos, NPA635, 99 (1998)

K-p scattering

$\pi\Sigma$ mass distribution

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Ç™Ç±ÇÃÉsÉNÉ`ÉÉÇ¾å©ÇÈÇžÇ½Ç…ÇÕïKóvÇ-ÇÅB

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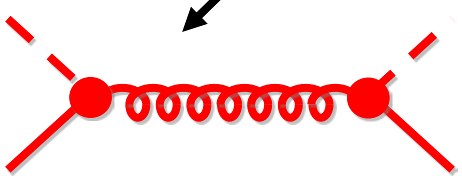
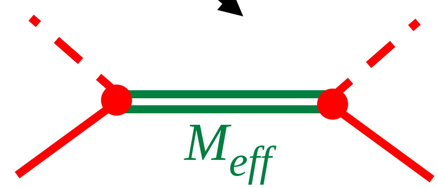
If experiments prefer a_{pheno} rather than $a_{natural}$, the difference can be

$$T(\sqrt{s})_{pheno} = \frac{1}{V_{WT}{}^{-1} - G(\sqrt{s}, a_{pheno})} = \frac{1}{V_{WT}{}^{-1} + \Delta A - G(\sqrt{s}, a_{natural})}$$

$$V_{eff} = V_{WT} + \frac{C}{2f^2} \frac{\left(\sqrt{s} - M\right)^2}{\sqrt{s} - M_{eff}}$$





Hadronic composite

Non-hadronic composite
Quark originated

$$T_{\pi\rho\to\pi\rho} = V + VG_{\pi\rho}V + VG_{\pi\rho}VG_{\pi\rho}V + \ldots$$

$$= (g_R, g)\begin{pmatrix} w & 0 \\ 0 & G_{a1} \end{pmatrix}\begin{pmatrix} g_R \\ g \end{pmatrix}$$

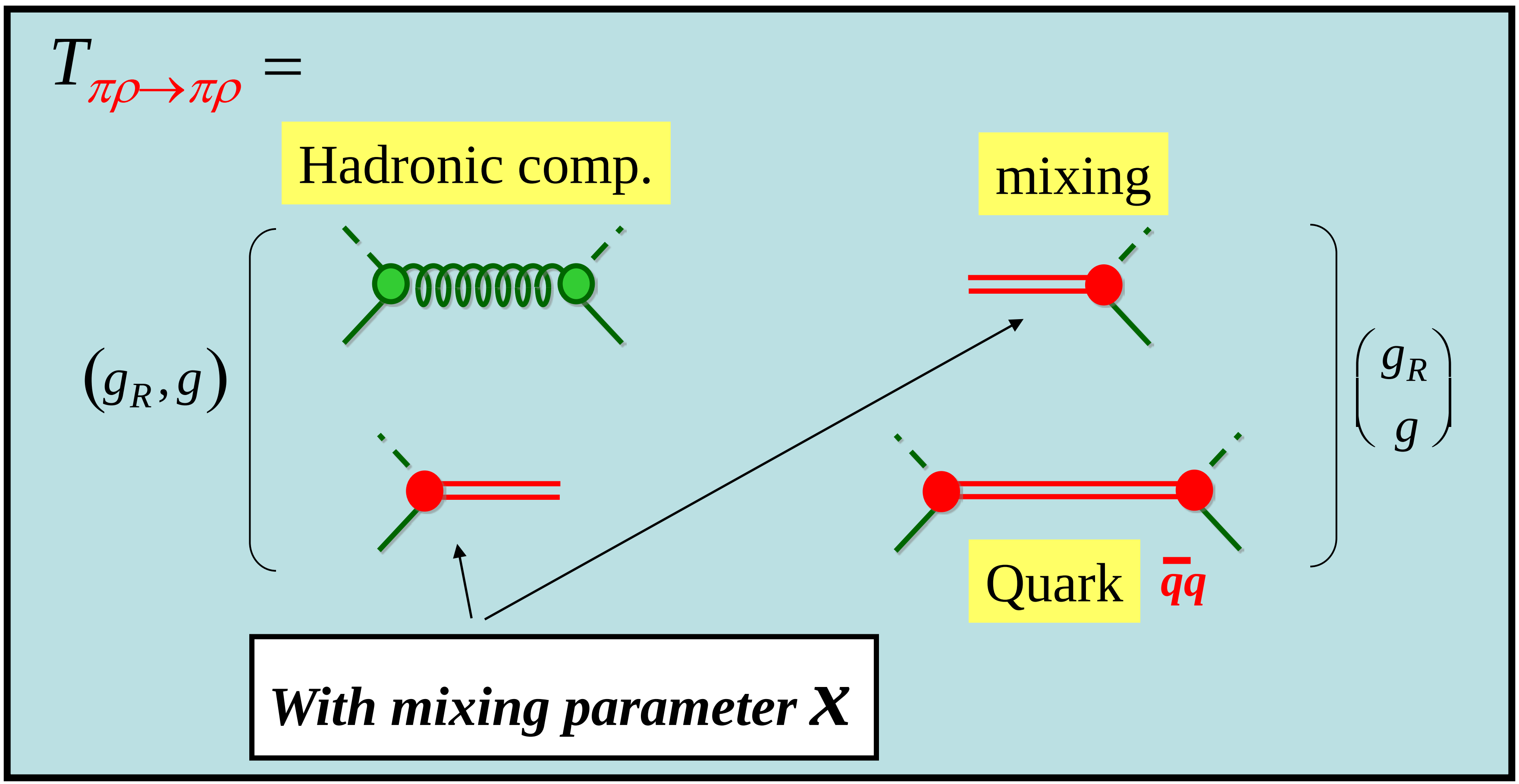
$$+(g_R, g)\begin{pmatrix} w & 0 \\ 0 & G_{a1} \end{pmatrix}\begin{pmatrix} g_R \\ g \end{pmatrix} G_{\pi\rho}\,(g_R, g)\begin{pmatrix} w & 0 \\ 0 & G_{a1} \end{pmatrix}\begin{pmatrix} g_R \\ g \end{pmatrix} + \ldots$$

$$= (g_R, g)\left[\begin{pmatrix} w & 0 \\ 0 & G_{a1} \end{pmatrix} + \begin{pmatrix} w & 0 \\ 0 & G_{a1} \end{pmatrix}\begin{pmatrix} g_R G_{\pi\rho} g_R & g_R G_{\pi\rho} g \\ g G_{\pi\rho} g_R & g G_{\pi\rho} g \end{pmatrix}\begin{pmatrix} w & 0 \\ 0 & G_{a1} \end{pmatrix} + \ldots\right]\begin{pmatrix} g_R \\ g \end{pmatrix}$$

$$= (g_R, g)\frac{1}{\begin{pmatrix} w & 0 \\ 0 & G_{a1} \end{pmatrix}^{-1} - \begin{pmatrix} g_R G_{\pi\rho} g_R & g_R G_{\pi\rho} g \\ g G_{\pi\rho} g_R & g G_{\pi\rho} g \end{pmatrix}}\begin{pmatrix} g_R \\ g \end{pmatrix}$$

$$= (g_R, g)\frac{1}{\begin{pmatrix} w^{-1} - g_R G_{\pi\rho} g_R & 0 \\ 0 & G_{a1}{}^{-1} - g G_{\pi\rho} g \end{pmatrix}^{-1} - \begin{pmatrix} 0 & g_R G_{\pi\rho} g \\ g G_{\pi\rho} g_R & 0 \end{pmatrix}}\begin{pmatrix} g_R \\ g \end{pmatrix}$$

$$T_{\pi\rho\to\pi\rho} = (g_R, g)\frac{1}{\begin{pmatrix} w^{-1} - g_R G_{\pi\rho} g_R & 0 \\ 0 & G_{a1}{}^{-1} - g G_{\pi\rho} g \end{pmatrix}^{-1} - \begin{pmatrix} 0 & g_R G_{\pi\rho} g \\ g G_{\pi\rho} g_R & 0 \end{pmatrix}} \begin{pmatrix} g_R \\ g \end{pmatrix}$$



Solving the problem

$$\begin{cases} (H_{\pi\rho} + v_{WT})\psi_{\pi\rho} + v\psi_{a1} = E\psi_{\pi\rho} \\ v\psi_{\pi\rho} + M_{a1}\psi_{a1} = E\psi_{a1} \end{cases} \longrightarrow \psi_{a1} = \frac{1}{E - M_{a1}} v\psi_{\pi\rho}$$

$$\downarrow$$

$$(H_{\pi\rho} + \underbrace{v_{WT} + v\frac{1}{E - M_{a1}}v}) \psi_{\pi\rho} = E\psi_{\pi\rho}$$

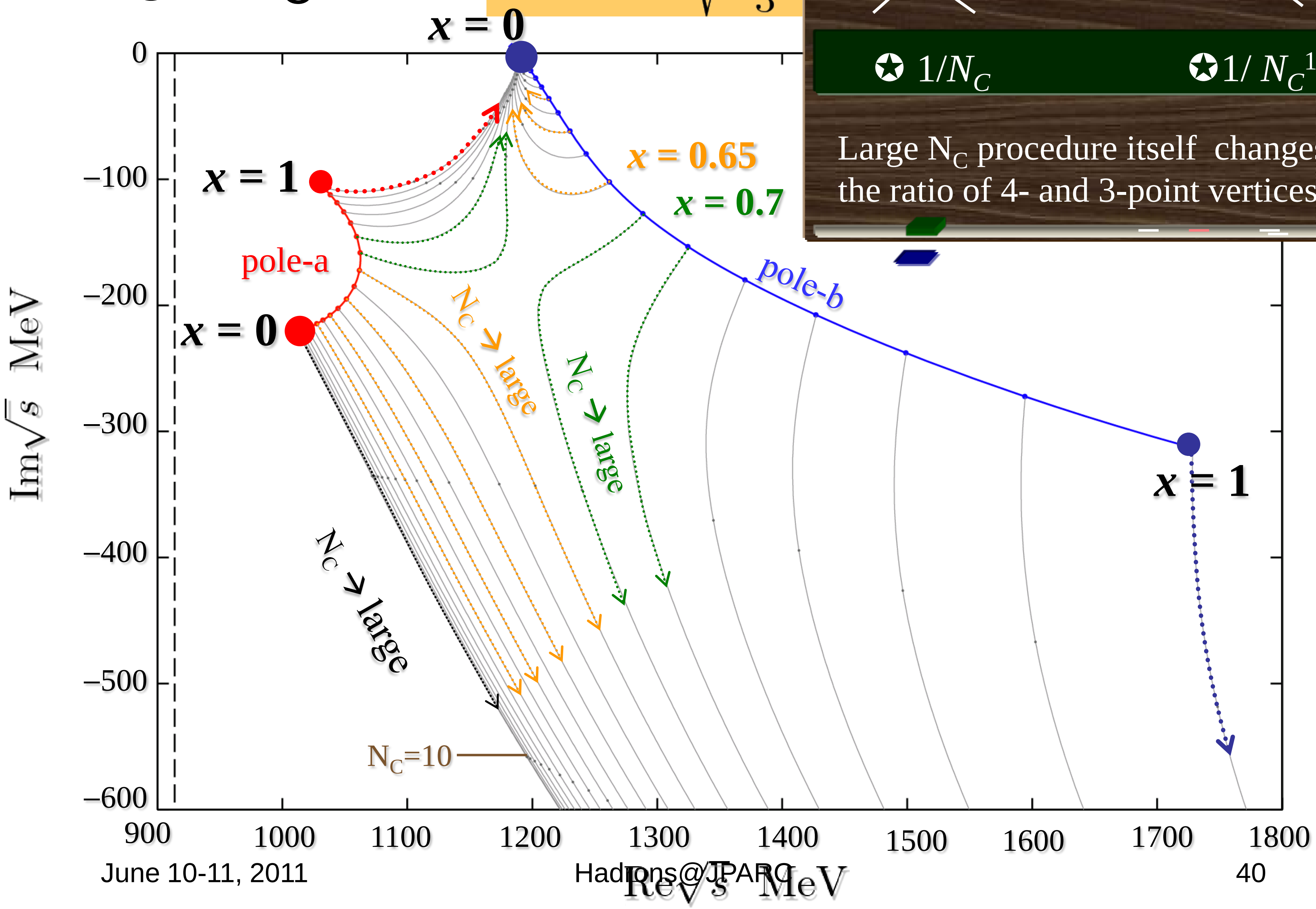
$$(\underline{H_{\pi\rho}} + \underbrace{g_R w g_R + g G_{a1} g}) \psi_{\pi\rho} = \underline{E\psi_{\pi\rho}} \qquad G_{\pi\rho} = \frac{1}{E - H_{\pi\rho}}$$

$$\|$$

$$(g_R, g)\begin{pmatrix} w & 0 \\ 0 & G_{a1} \end{pmatrix}\begin{pmatrix} g_R \\ g \end{pmatrix} \equiv V$$

large N_C flow

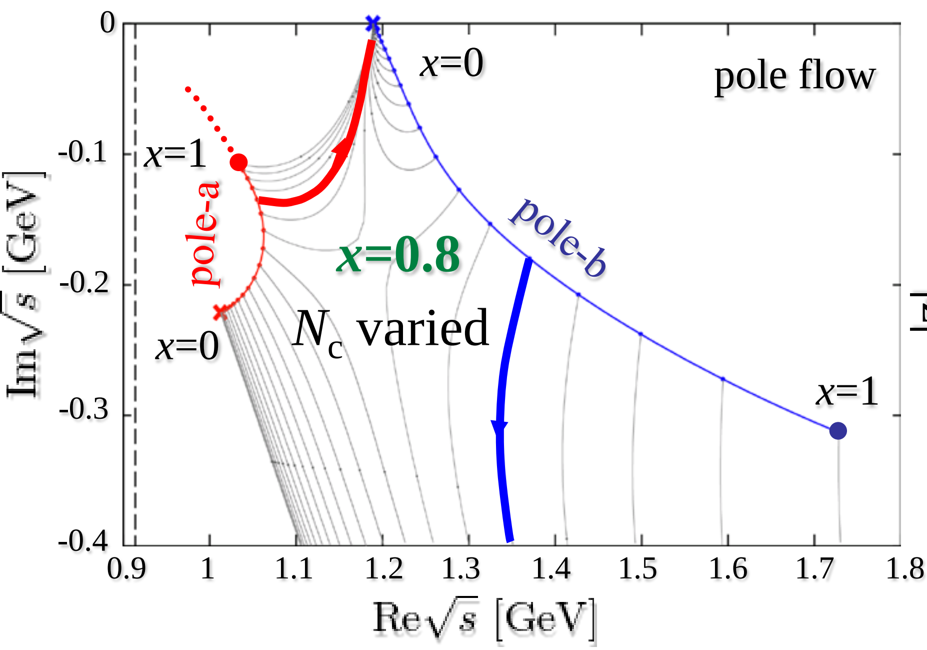
$$f_\pi \to f_\pi \times \sqrt{\frac{N_C}{3}}$$

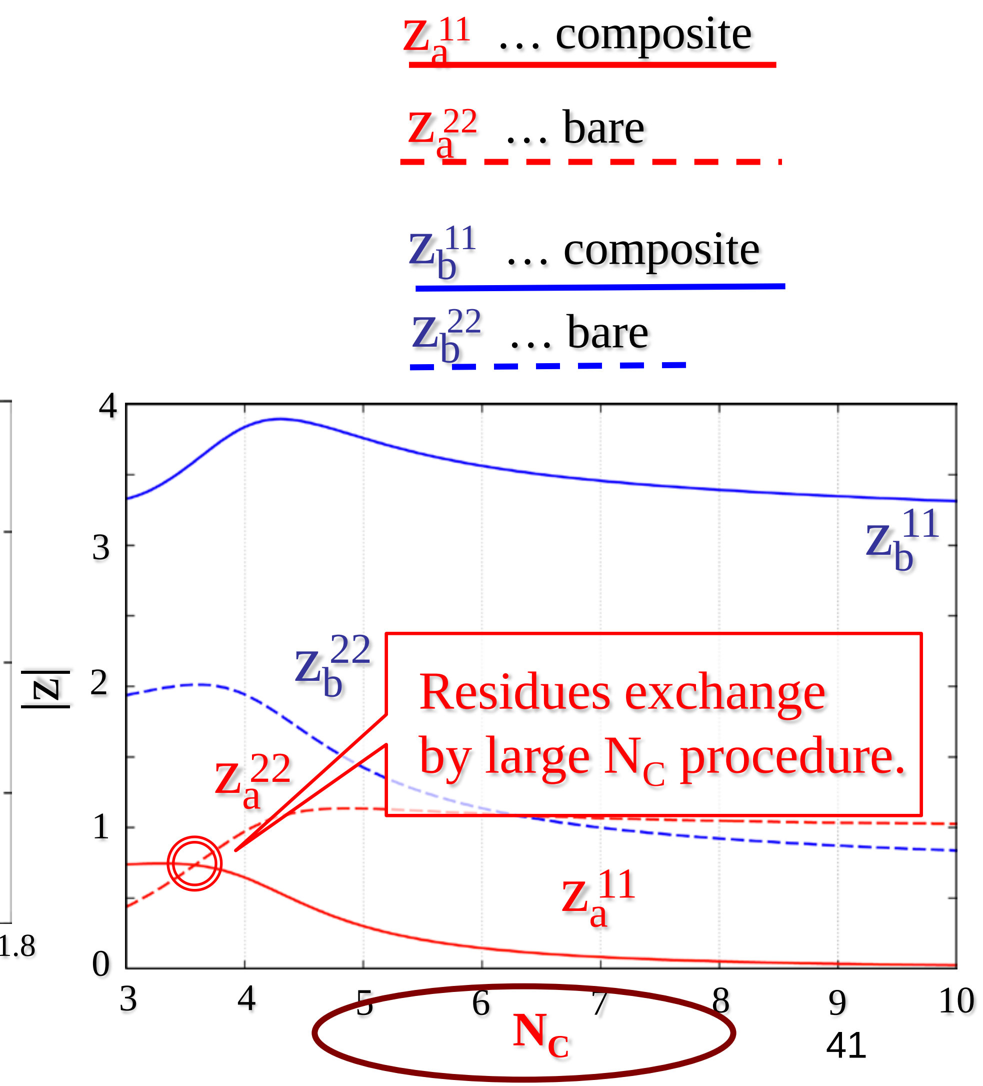


Large N_C procedure itself changes the ratio of 4- and 3-point vertices.

large N_C

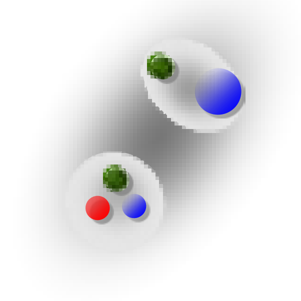
For realistic mixing
pole-b stays similar
pole-a changes its nature
molecule-> bare





Bound states: $I, J^P = 0, 1/2^-$

$\bar{Q}q\text{-}qqq$



Phase shift of DN scattering starts at $\delta = \pi$

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