The Interaction between Vector Mesons and Baryons in a Chiral Unitary Approach

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Hadron-China 2012, KITPC

2012-7-19

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   A. N-rho-rho system
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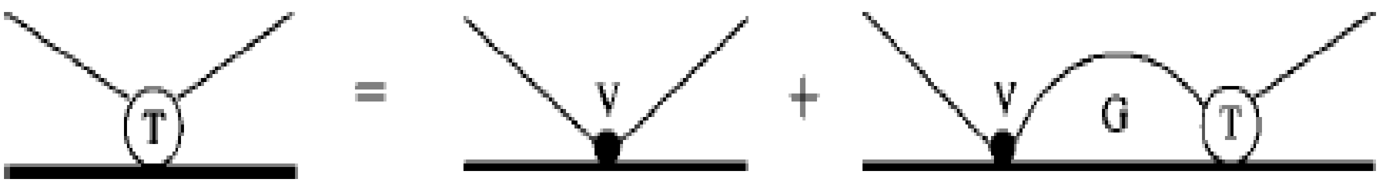
Bethe-Salpeter Eqution

With a kernel of effective interaction, we can solve the BS equation. The amplitude satisfies the unitary relation exactly, and the properties of hadron resonances generated dynamically can be obained. These resonances do not appear in the effective Lagrangian density.

$$T = V + VGT = [1 - VG]^{-1} V$$



Hidden-gauge symmetry

- In orde to construct the vector meson-baryon octet interaction Lagrangian density, we consider the SU(3) flavor local gauge symmetry neglecting the mass term, and then we obtain

$$L = -g\left\{\left\langle \overline{B}\gamma_{\mu}\left[V^{\mu}, B\right]\right\rangle + \left\langle \overline{B}\gamma_{\mu}B\right\rangle\left\langle V^{\mu}\right\rangle\right\}$$

$$B = \begin{pmatrix} \frac{1}{\sqrt{6}}\Lambda + \frac{1}{\sqrt{2}}\Sigma^0 & \Sigma^+ & p \\ \Sigma^- & \frac{1}{\sqrt{6}}\Lambda - \frac{1}{\sqrt{2}}\Sigma^0 & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix} \quad V_\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_\mu$$

Vector-vector Interaction

$$V^{\mu\nu} = \partial^\mu V^\nu - \partial^\nu V^\mu + ig[V^\mu, V^\nu],$$

$$\mathcal{L}_{III}^{(3V)} = ig\langle(\partial_\mu V_\nu - \partial_\nu V_\mu)V^\mu V^\nu\rangle$$

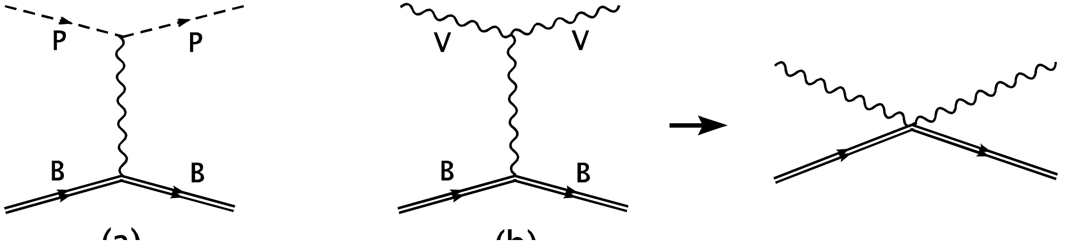
$$\mathcal{L}_{III}^{(c)} = \frac{g^2}{2}\langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu\rangle$$

Vector octet-baryon decuplet interaction

- Now I will discuss the interaction between vector mesons and baryon decuplet in the chiral unitary approach. Because the interaction Lagrangian is not known, we will try to obtain the vector octet –baryon decuplet interaction potentials by comparing the pseudoscalar meson – baryon decuplet interaction.

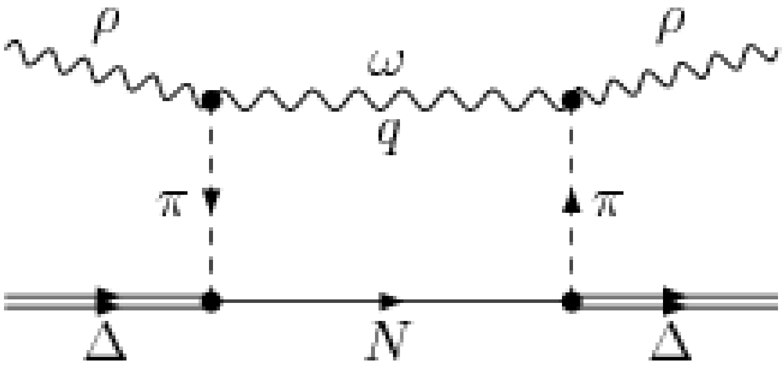
Interaction Vertex

- When the momentum transfer is far less than the mass of the vector meson in the propagator, we can neglect the square of the momentum in the propagator. Therefore the t-channel interaction between vector meson and baryon is obtained:

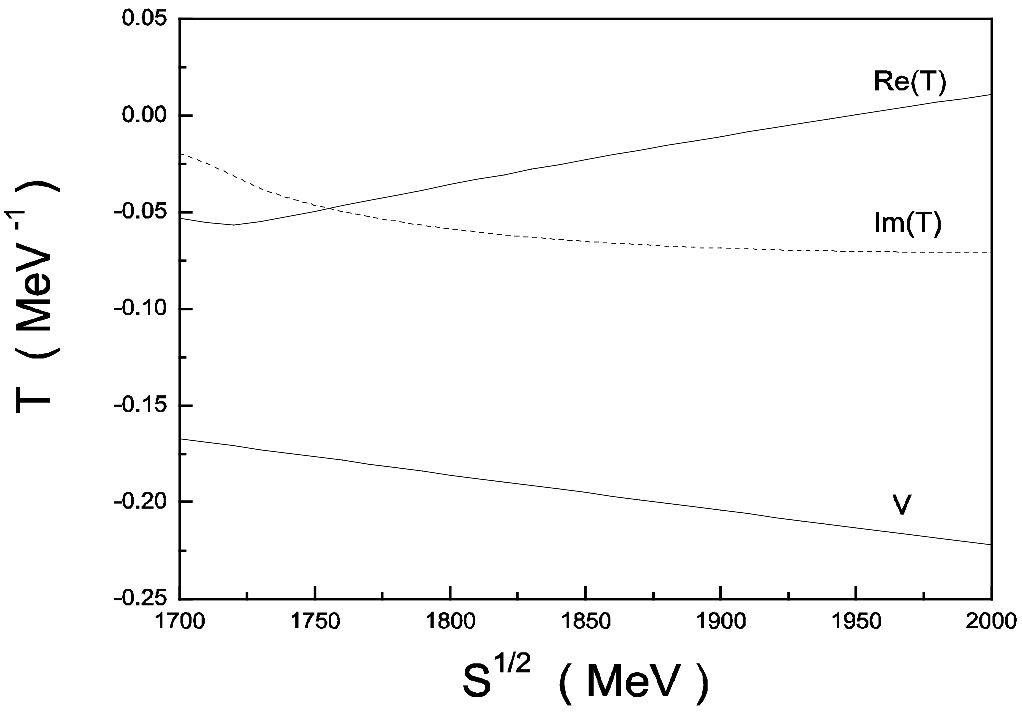


$$V_{ij} = -C_{ij}\,\frac{1}{4f^2}\left(k^0 + k'^0\right)\,\vec{\epsilon}\cdot\vec{\epsilon}'\,;$$

Anomalous Term

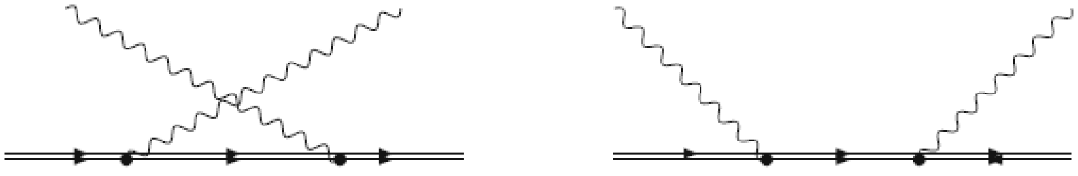


Anomalous Term



u-channel and s-channel

- In addition to the anomalous term, we also neglected the contribution from s-channel and u-channel interaction since we thought their effects are small.



Vector meson – baryon loop function in the dimensional regularization scheme

$$
\begin{aligned}
G_i(\sqrt{s}) = \frac{2M_i}{(4\pi)^2}\Bigg\{ & a_i(\mu) + \ln\frac{m_i^2}{\mu^2} + \frac{M_i^2 - m_i^2 + s}{2s}\ln\frac{M_i^2}{m_i^2} \\
& + \frac{Q_i(\sqrt{s})}{\sqrt{s}}[\ln(s-(M_i^2-m_i^2)+2\sqrt{s}Q_i(\sqrt{s})) \\
& + \ln(s+(M_i^2-m_i^2)+2\sqrt{s}Q_i(\sqrt{s})) \\
& - \ln(-s+(M_i^2-m_i^2)+2\sqrt{s}Q_i(\sqrt{s})) \\
& - \ln(-s-(M_i^2-m_i^2)+2\sqrt{s}Q_i(\sqrt{s}))]\Bigg\},
\end{aligned}
$$

Vector meson-baryon loop function accounting for the width of the intermediate states

$$\tilde{G}(s) = \frac{1}{N_\rho N_\Delta} \int_{m_\Delta - 2\Gamma_\Delta}^{m_\Delta + 2\Gamma_\Delta} d\tilde{M} \left(-\frac{1}{\pi}\right) \mathcal{I}m \frac{1}{\tilde{M} - M_\Delta + i\frac{\Gamma_1(\tilde{M})}{2}}$$

$$\times \int_{(m_\rho - 2\Gamma_\rho)^2}^{(m_\rho + 2\Gamma_\rho)^2} d\tilde{m}^2 \left(-\frac{1}{\pi}\right) \mathcal{I}m \frac{1}{\tilde{m}^2 - m_\rho^2 + i\tilde{m}\Gamma_2(\tilde{m})}$$

$$\times G(s, \tilde{M}, \tilde{m}^2),$$

$$N_\rho = \int_{(m_\rho - 2\Gamma_\rho)^2}^{(m_\rho + 2\Gamma_\rho)^2} d\tilde{m}^2 \left(-\frac{1}{\pi}\right) \mathcal{I}m \frac{1}{\tilde{m}^2 - m_\rho^2 + i\tilde{m}\Gamma_2(\tilde{m})},$$

$$N_\Delta = \int_{m_\Delta - 2\Gamma_\Delta}^{m_\Delta + 2\Gamma_\Delta} d\tilde{M} \left(-\frac{1}{\pi}\right) \mathcal{I}m \frac{1}{\tilde{M} - M_\Delta + i\frac{\Gamma_1(\tilde{M})}{2}},$$

$$\Delta \rightarrow N\pi$$

$$\Gamma_1(\tilde{M}) = \Gamma_\Delta \left(\frac{\lambda^{1/2}(\tilde{M}^2, M_N^2, m_\pi^2) 2M_\Delta}{\lambda^{1/2}(M_\Delta^2, M_N^2, m_\pi^2) 2\tilde{M}} \right)^3 \theta(\tilde{M} - M_N - m_\pi)$$

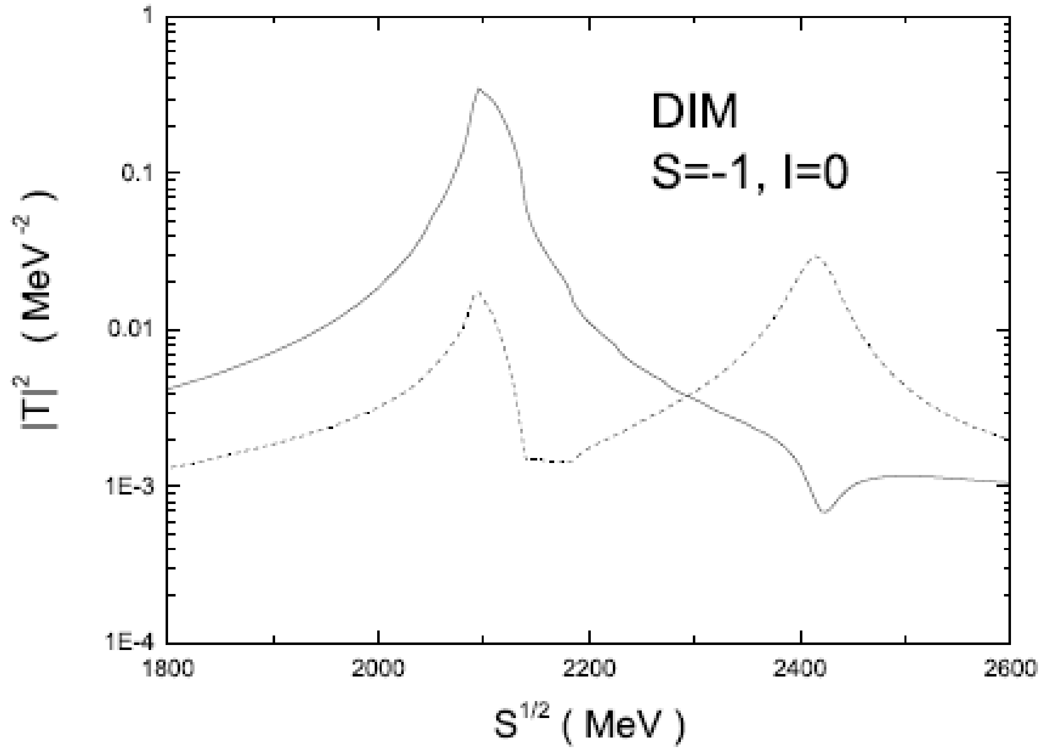
$$\rho \rightarrow \pi\pi$$

$$\Gamma_2(\tilde{m}) = \Gamma_\rho \left(\frac{\tilde{m}^2 - 4m_\pi^2}{m_\rho^2 - 4m_\pi^2} \right)^{3/2} \theta(\tilde{m} - 2m_\pi)$$

Decay modes

	Mass (MeV)	Width (MeV)	Decay mode	Fraction ($\frac{\Gamma_i}{\Gamma}$)
$\rho(770)$	770	150	$\pi\pi$	100%
$\omega(782)$	782	8.49	$\pi^+\pi^-\pi^0$	89.1%
$\phi(1020)$	1020	4.26		
$K^*(892)$	892	50	$K\pi$	100%
$\Delta(1232)$	1232	120	$N\pi$	100%
$\Sigma(1385)^0$	1385	37	$\Lambda\pi(\Sigma\pi)$	88%(12%)
$\Xi(1530)$	1530	9.5	$\Xi\pi$	100%
Ω	1672			

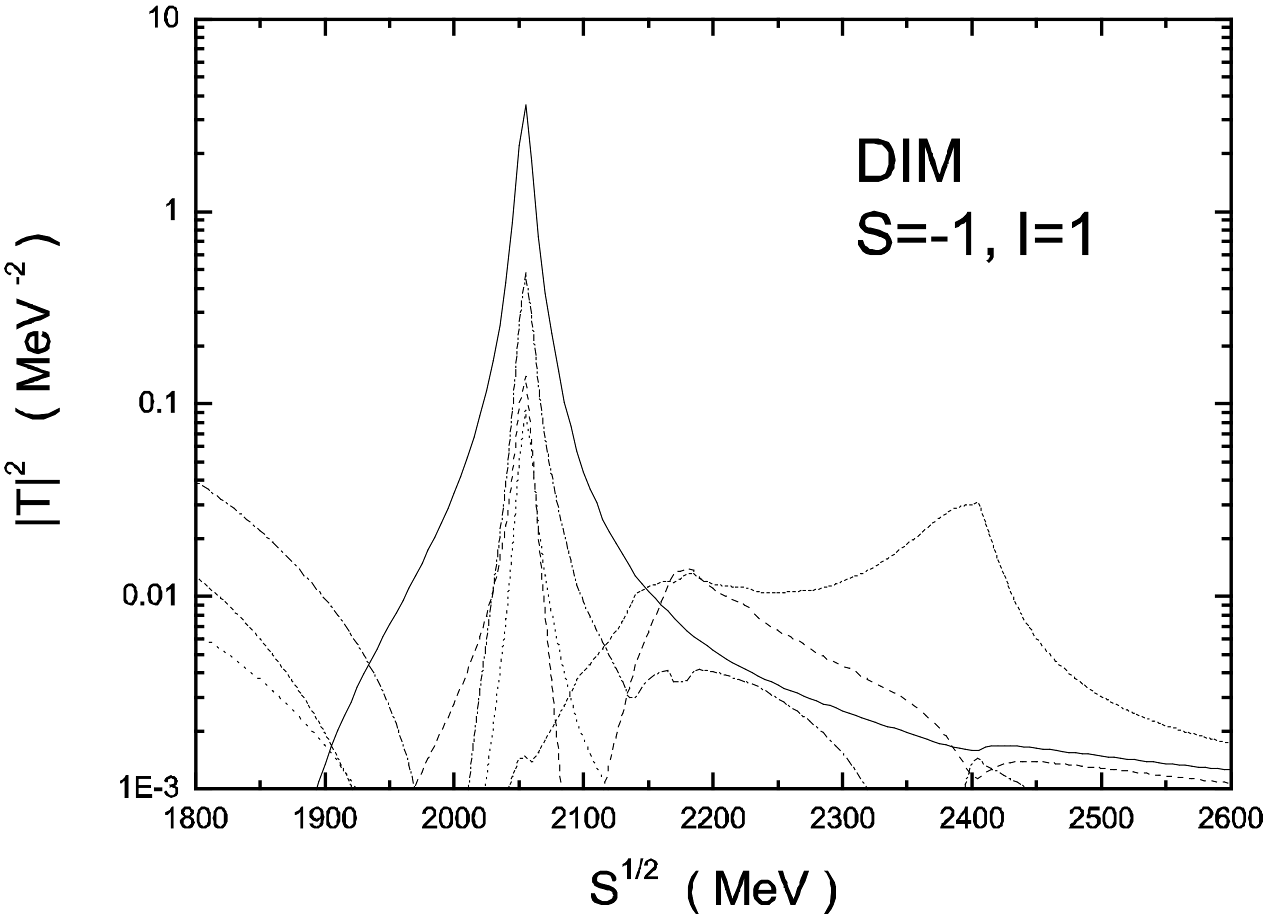
S=-1，I=0 Channel



S=-1， I=0 Channel

z_R	$2052 + i10$	
	g_i	$\lvert g_i \rvert$
$\Sigma^*\rho$	$4.2 + i0.1$	4.2
$\Xi^* K^*$	$2.0 + i0.1$	2.0

S=-1，I=1Channel



Resonance for S=-1,I=1 channel

z_R	$1987 + i1$		$2144 + i58$		$2385 + i75$	
	g_i	$\|g_i\|$	g_i	$\|g_i\|$	g_i	$\|g_i\|$
ΔK^*	$4.2 + i0.038$	4.2	$-0.68 - i0.11$	0.69	$-0.44 - i0.37$	0.58
$\Sigma^* \rho$	$1.4 + i0.0030$	1.4	$4.3 + i0.75$	4.4	$-0.41 - i1.1$	1.2
$\Sigma^* \omega$	$1.4 + i0.018$	1.4	$-1.3 + i0.41$	1.4	$1.4 + i0.39$	1.5
$\Sigma^* \phi$	$-2.1 - i0.027$	2.1	$1.9 - i0.63$	2.0	$-2.2 - i0.56$	2.2
$\Xi^* K^*$	$0.070 - i0.011$	0.071	$4.0 + i0.12$	4.0	$3.5 - i1.5$	3.8

S. Sarkar, B. X. Sun, E.Oset et al., EPJA 44, 431 (2010)

S, I	Theory			PDG data				
	pole position	real axis		name	J^P	status	mass	width
		mass	width					
$0, 1/2$	$1850 + i5$	1850	11	$N(2090)$	$1/2^-$	$\star$	1880-2180	95-414
				$N(2080)$	$3/2^-$	$\star\star$	1804-2081	180-450
		2270(*bump*)		$N(2200)$	$5/2^-$	$\star\star$	1900-2228	130-400
$0, 3/2$	$1972 + i49$	1971	52	$\Delta(1900)$	$1/2^-$	$\star\star$	1850-1950	140-240
				$\Delta(1940)$	$3/2^-$	$\star$	1940-2057	198-460
				$\Delta(1930)$	$5/2^-$	$\star\star\star$	1900-2020	220-500
		2200(*bump*)		$\Delta(2150)$	$1/2^-$	$\star$	2050-2200	120-200
$-1, 0$	$2052 + i10$	2050	19	$\Lambda(2000)$	$?^?$	$\star$	1935-2030	73-180
$-1, 1$	$1987 + i1$	1985	10	$\Sigma(1940)$	$3/2^-$	$\star\star\star$	1900-1950	150-300
	$2145 + i58$	2144	57	$\Sigma(2000)$	$1/2^-$	$\star$	1944-2004	116-413
	$2383 + i73$	2370	99	$\Sigma(2250)$	$?^?$	$\star\star\star$	2210-2280	60-150
				$\Sigma(2455)$	$?^?$	$\star\star$	2455±10	100-140
$-2, 1/2$	$2214 + i4$	2215	9	$\Xi(2250)$	$?^?$	$\star\star$	2189-2295	30-130
	$2305 + i66$	2308	66	$\Xi(2370)$	$?^?$	$\star\star$	2356-2392	75-80
	$2522 + i38$	2512	60	$\Xi(2500)$	$?^?$	$\star$	2430-2505	59-150
$-3, 1$	$2449 + i7$	2445	13	$\Omega(2470)$	$?^?$	$\star\star$	2474±12	72±33

Table 1: The properties of the 10 dynamically generated resonances and their possible PDG counterparts. We also include the N^* bump around 2270 MeV and the Δ^* bump around 2200 MeV.

S. Sarkar, B. X. Sun, E.Oset et al., EPJA 44, 431 (2010)

- Ten resonances in the different strangeness and isospin channels. Degenerate in JP=1/2-, 3/2-, 5/2-.

Vector-baryon octet interaction

- E. Oset and A. Ramos, EPJA 44, 445 (2010).

I, S	Theory			PDG data				
	pole position	real axis mass	real axis width	name	J^P	status	mass	width
$1/2, 0$	—	1696	92	$N(1650)$	$1/2^-$	$\star\star\star\star$	1645-1670	145-185
				$N(1700)$	$3/2^-$	$\star\star\star$	1650-1750	50-150
	$1977+i53$	1972	64	$N(2080)$	$3/2^-$	$\star\star$	≈ 2080	180-450
				$N(2090)$	$1/2^-$	$\star$	≈ 2090	100-400
$0, -1$	$1784+i4$	1783	9	$\Lambda(1690)$	$3/2^-$	$\star\star\star\star$	1685-1695	50-70
				$\Lambda(1800)$	$1/2^-$	$\star\star\star$	1720-1850	200-400
	$1907+i70$	1900	54	$\Lambda(2000)$	$?^?$	$\star$	≈ 2000	73-240
	$2158+i13$	2158	23					
$1, -1$	—	1830	42	$\Sigma(1750)$	$1/2^-$	$\star\star\star$	1730-1800	60-160
	—	1987	240	$\Sigma(1940)$	$3/2^-$	$\star\star\star$	1900-1950	150-300
				$\Sigma(2000)$	$1/2^-$	$\star$	≈ 2000	100-450
$1/2, -2$	$2039+i67$	2039	64	$\Xi(1950)$	$?^?$	$\star\star\star$	1950 ± 15	60 ± 20
	$2083+i31$	2077	29	$\Xi(2120)$	$?^?$	$\star$	≈ 2120	25

Table 5: The properties of the 9 dynamically generated resonances and their possible PDG counterparts.

Tensor coupling between vector meson and baryon octet

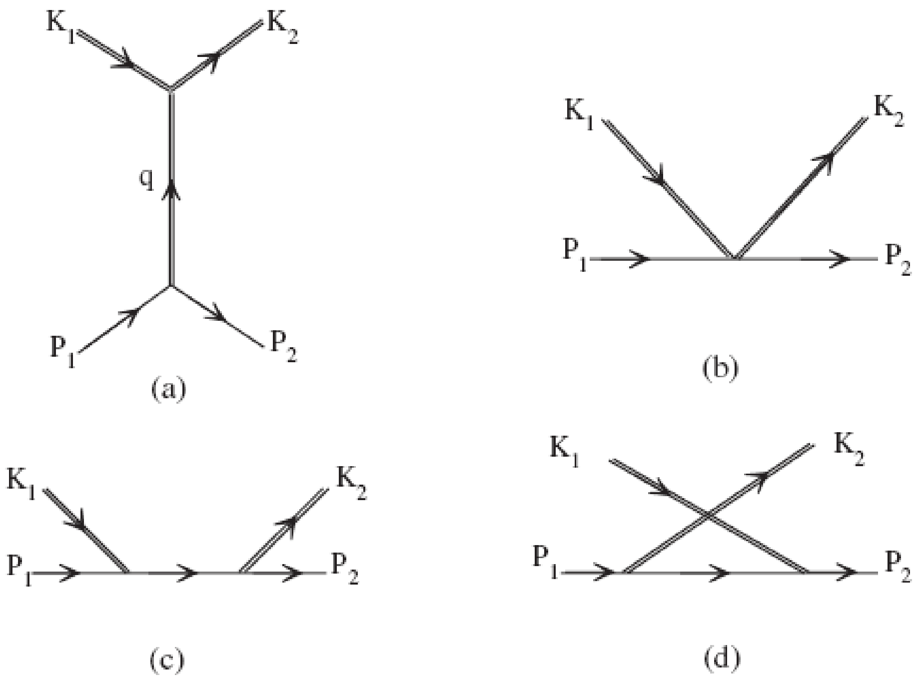
- K. P. Khemchandani, H. Kaneko, H. Nagahiro and A. Hosaka,

  PRD 83, 114041 (2011).

  In this article, a tensor coupling term between vector meson and baryon octet is added, which is relevant to the magnetic moments of the baroyns, and is also gauge invariant.

$$\mathcal{L}_{\rm VB} = -g\Big\{\langle \bar{B}\gamma_\mu[V^\mu, B]\rangle + \langle \bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle + \frac{1}{4M}\big(F\langle \bar{B}\sigma_{\mu\nu}[V^{\mu\nu}, B]\rangle + D\langle \bar{B}\sigma_{\mu\nu}\{V^{\mu\nu}, B\}\rangle\big)\Big\},$$

K. P. Khemchandani et al.,PRD 83, 114041 (2011)



K. P. Khemchandani et al.,PRD 83, 114041 (2011)

- In addition to t-channel, the s-channel,u-channel and contact interaction are taken into account, and a non-relativistic interaction potential between vector meson and baryon octet with strangeness S=0 is obtained.
- When u-channel and s-channel are taken into account, the hadronic resonances generated dynamically with different spins are not degenerate again.

Results for Strangeness S=0

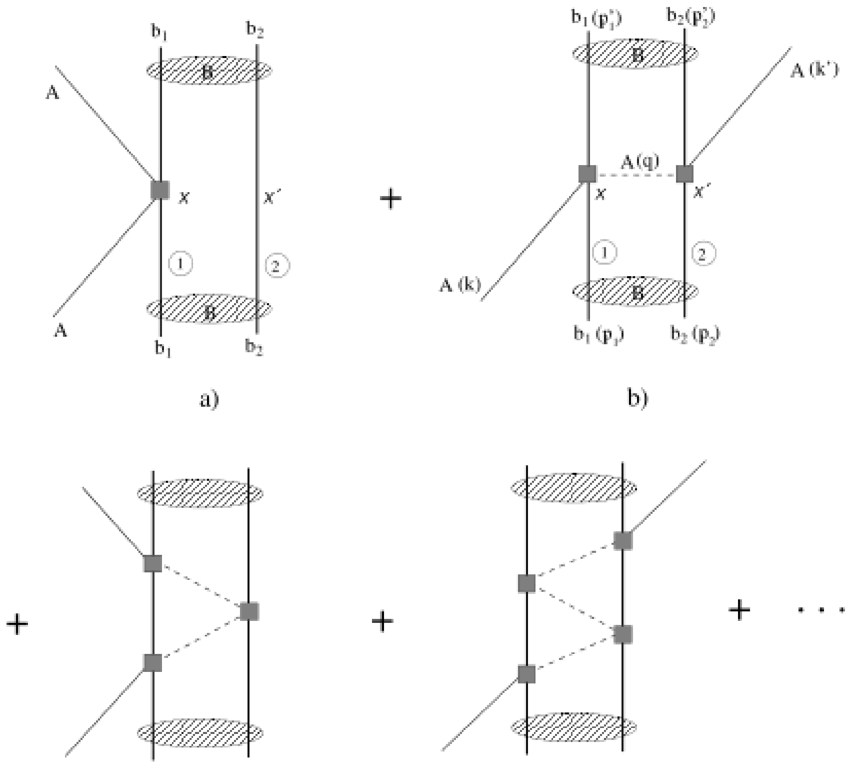
- S=0 K. P. Khemchandani et al.,PRD 83, 114041 (2011)

Pole positions	Corresponding known states
$1637 - i35$ MeV	$N^*(1700)D_{13}$
$2071 - i70$ MeV	$N^*(2080)D_{13}$
$1977 - i22$ MeV	$N^*(2090)S_{11}$
$2006 - i112$ MeV	$\Delta(1900)S_{31}$

- I=1/2, S=0, E. Oset and A. Ramos, EPJA 44, 445 (2010).

I, S	Theory			PDG data				
	pole position	real axis mass	real axis width	name	J^P	status	mass	width
$1/2, 0$	—	1696	92	$N(1650)$	$1/2^-$	$\star\star\star\star$	1645-1670	145-185
				$N(1700)$	$3/2^-$	$\star\star\star$	1650-1750	50-150
	$1977 + i53$	1972	64	$N(2080)$	$3/2^-$	$\star\star$	≈ 2080	180-450
				$N(2090)$	$1/2^-$	$\star$	≈ 2090	100-400

Fixed Center Approximation of Faddeev Equation



Fixed Center Approximation of Faddeev Equation

$$T_1 = t_1 + t_1 G_0 T_2$$

$$T_2 = t_2 + t_2 G_0 T_1$$

$$T = T_1 + T_2$$

$$\Downarrow$$

$$T_1 = t_1 + t_1 G_0 T_1$$

$$T = 2T_1$$

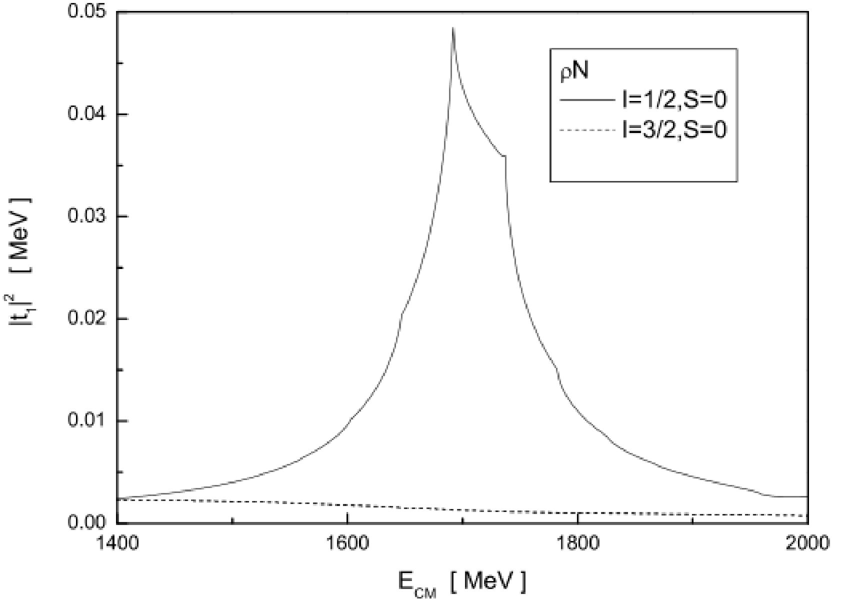
N-rho-rho system

$$|\rho\rho\rangle_{I=0} = -\frac{1}{\sqrt{3}}|\rho^+\rho^- + \rho^-\rho^+ + \rho^0\rho^0\rangle = \frac{1}{\sqrt{3}}\Big(|(1,-1)\rangle + |(-1,1)\rangle - |(0,0)\rangle\Big)$$

$$|p\rangle = |(\frac{1}{2})\rangle$$

Two-body N-rho interaction

$$t_1 = \frac{1}{3}\left(2t_{N\rho}^{(I=3/2)} + t_{N\rho}^{(I=1/2)}\right)$$



S-Matrix

- Single scattering

$$S^{(1)} = -it_1 \frac{1}{\mathcal{V}^2} \frac{1}{\sqrt{2\omega_{p_1}}} \frac{1}{\sqrt{2\omega_{p_1'}}} \sqrt{\frac{M_N}{E_N(k)}} \sqrt{\frac{M_N}{E_N(k')}} (2\pi)^4 \, \delta(k + K_{f_2} - k' - K'_{f_2})$$

- Double scattering

$$S^{(2)} = -i(2\pi)^4 \delta(k + K_{f_2} - k' - K'_{f_2}) \frac{1}{\mathcal{V}^2} \sqrt{\frac{M_N}{E_N(k)}} \sqrt{\frac{M_N}{E_N(k')}} \frac{1}{\sqrt{2\omega_{p_1}}} \frac{1}{\sqrt{2\omega_{p_1'}}} \frac{1}{\sqrt{2\omega_{p_2}}} \frac{1}{\sqrt{2\omega_{p_2'}}}$$
$$\times \int \frac{d^3 q}{(2\pi)^3} F_{f_2}(q) \frac{2M_N}{q^{0\,2} - \vec{q}^{\,2} - M_N^2 + i\epsilon} t_1 t_1.$$

- General form

$$S = -iT_{Nf_2}(s) \frac{1}{\mathcal{V}^2} \sqrt{\frac{M_N}{E(k)}} \sqrt{\frac{M_N}{E(k')}} \frac{1}{\sqrt{2\omega_{f_2}}} \frac{1}{\sqrt{2\omega_{f_2'}}} (2\pi)^4 \, \delta(k + K_{f_2} - k' - K'_{f_2})$$

Three-body Amplitude

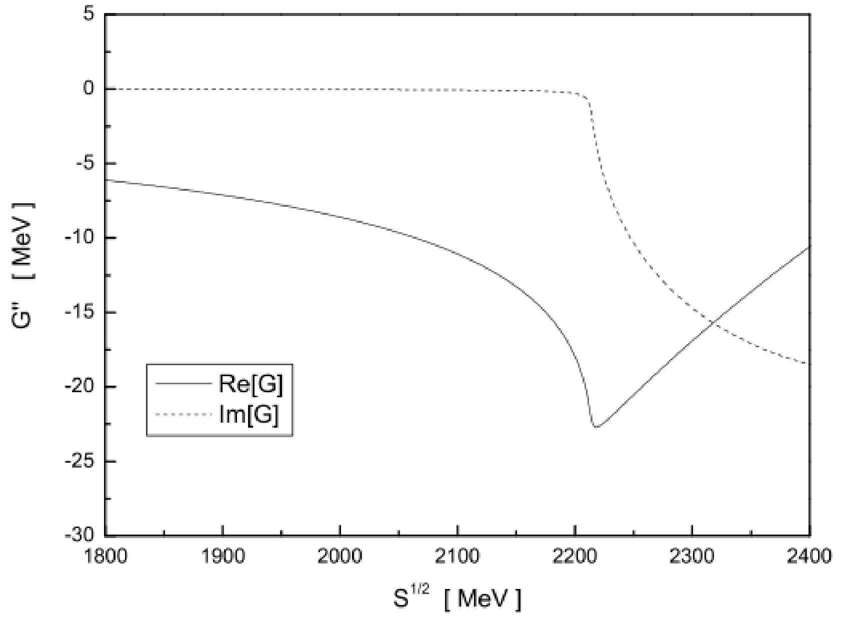
$$T_{Nf_2}(s) = 2\left(t_1' + t_1' G_0''(s) t_1'\right)$$

$$t_1' = t_1 \sqrt{\frac{2\omega_{f_2(1270)}}{2\omega_\rho}} \sqrt{\frac{2{\omega'}_{f_2(1270)}}{2\omega'_\rho}},$$

$$G_0''(s) = \frac{1}{\sqrt{2\omega_{f_2(1270)} 2{\omega'}_{f_2(1270)}}} \times$$

$$\int \frac{d^3\vec{q}}{(2\pi)^3} F_{f_2(1270)}(q) \frac{M_N}{E_N(\vec{q}^{\,2})} \frac{1}{q^0 - E_N(\vec{q}^{\,2}) + i\epsilon}$$

G function with Λ=875MeV

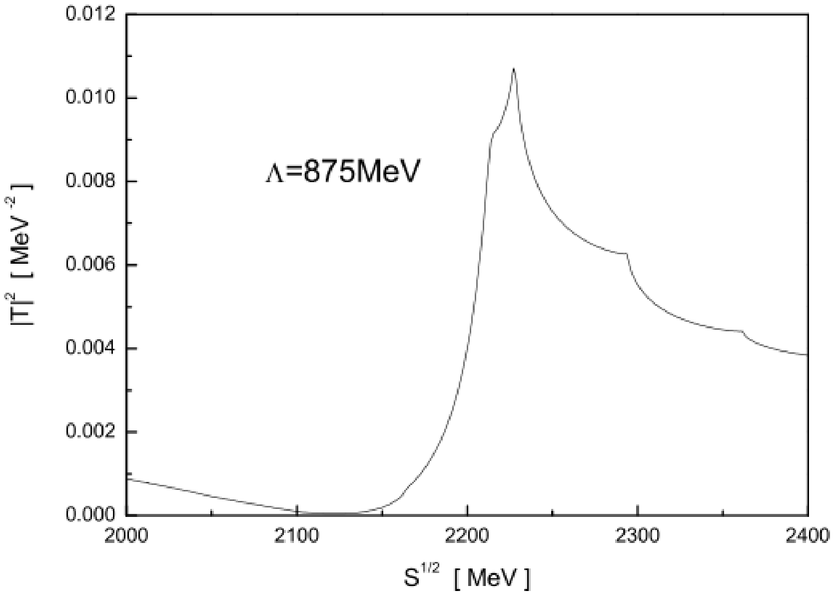


Three-body Amplitude

$$T_{Nf_2}(s) \;=\; \frac{2t_1'}{1 - G_0'' t_1'} \;=\; \frac{2}{t'^{-1}(s')_1 - G_0''(s)}$$

$$s' = s_{N\rho} = \frac{1}{2}\left(s + 2m_\rho^2 + M_N^2 - M_{f_2}^2\right)$$

$$M = 2227 MeV, \qquad I = \frac{1}{2}, J = \frac{3}{2} \, or \, \frac{5}{2}, Parity = +$$

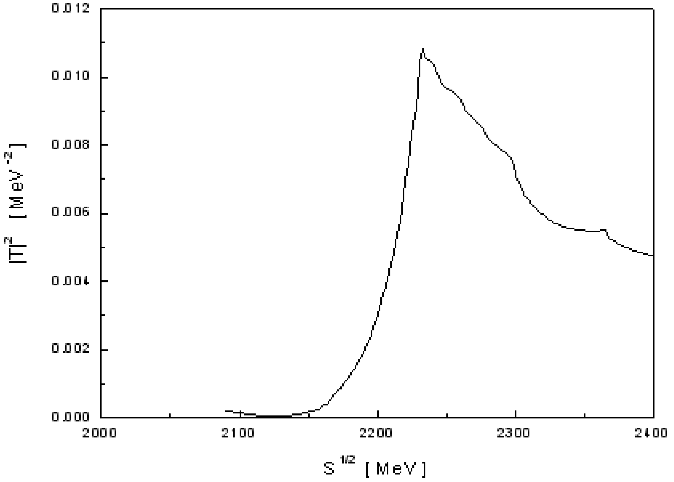


Decay width of $f_2(1270)\to\pi\pi$

$$T_{Nf_2}(s) = \frac{1}{N_{f_2}} \int_{(M_{f_2}-2\Gamma_{f_2})^2}^{(M_{f_2}+2\Gamma_{f_2})^2} d\tilde{M}^2 \left(-\frac{1}{\pi}\right) \mathrm{Im}\left[\frac{1}{\tilde{M}^2 - M_{f_2}^2 + i\tilde{M}\Gamma_1(\tilde{M})}\right] T_{Nf_2}(s,\tilde{M}^2),$$

$$N_{f_2} = \int_{(M_{f_2}-2\Gamma_{f_2})^2}^{(M_{f_2}+2\Gamma_{f_2})^2} d\tilde{M}^2 \left(-\frac{1}{\pi}\right) \mathrm{Im}\left[\frac{1}{\tilde{M}^2 - M_{f_2}^2 + i\tilde{M}\Gamma_1(\tilde{M})}\right]$$

N-rho-rho Amplitude with f_2 width

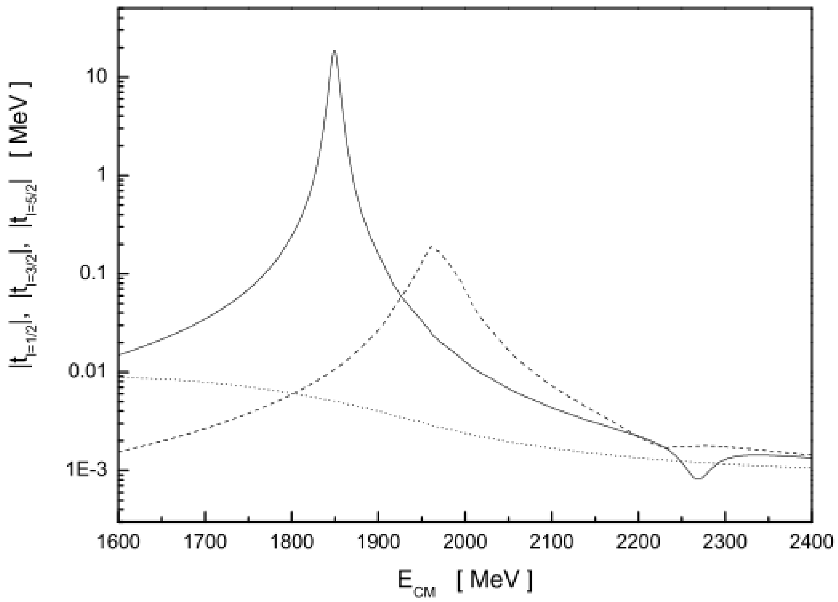


Delta-rho-rho

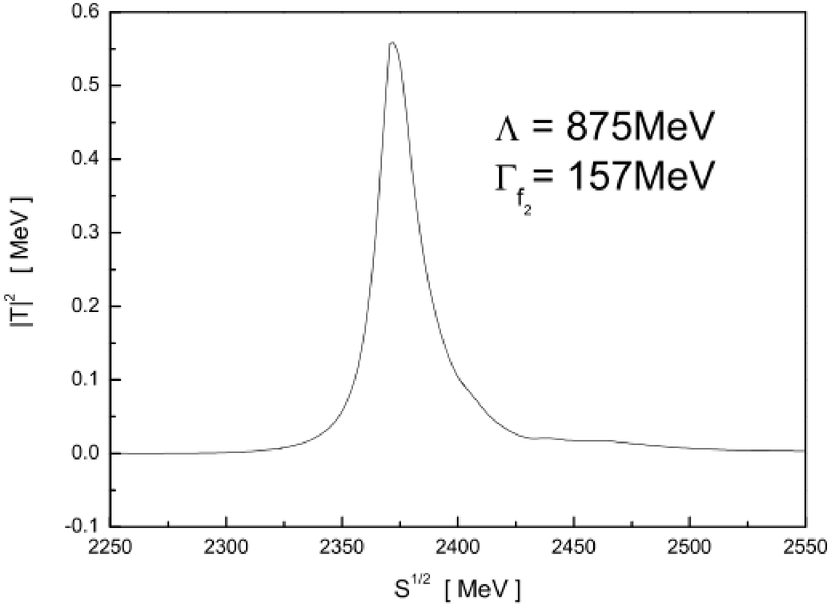
$$t_1 = \frac{1}{3}\left(3/2 t_{\Delta\rho}^{I=5/2} + t_{\Delta\rho}^{I=3/2} + 1/2 t_{\Delta\rho}^{I=1/2}\right)$$

$$M_N \to M_\Delta$$

Two-body Delta-rho Amplitudes



3-body Amplitudes of Delta-rho-rho with decay width of $f_2(1270)$



B. X. Sun, H. X. Chen and E.Oset,EPJA 47 (2011) 127

- Peak around 2227MeV for N-rho-rho
- Peak around 2372MeV for Δ-rho-rho

$$\Delta\left(2390\right), \quad J^{p} = \frac{7}{2}^{+}$$

Form factor of $f_2(1270)$

$$\varphi_1{}^*(x)\,\varphi_2(x') = \frac{1}{\sqrt{V}}\, e^{i\vec{K}_{f_2}\cdot\vec{R}}\, \Psi_{f_2}(\vec{r})$$

$$\vec{R} = \frac{\vec{x}+\vec{x}\,'}{2}, \qquad \vec{r} = \vec{x}-\vec{x}\,',$$

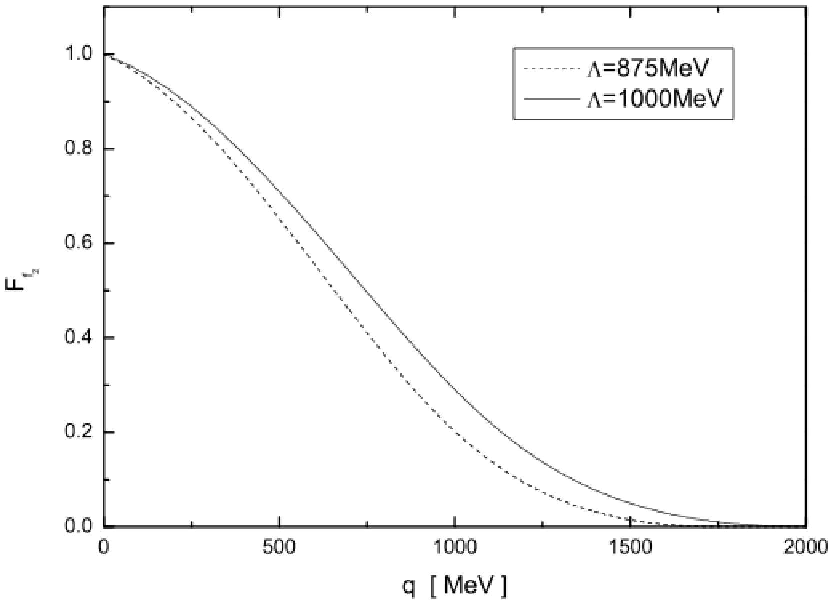
$$F_{f_2}(\vec{q}) = \int \Psi^*_{f_2}(\vec{r})\,\Psi_{f_2}(\vec{r})\, e^{-i\vec{q}\cdot\vec{r}}\, d^3r$$

Form factor of $f_2(1270)$

$$F_{f_2}(q) = \frac{1}{\mathcal{N}} \int_{\substack{p<\Lambda \\ |\vec{p}-\vec{q}|<\Lambda}} d^3p \, \frac{1}{M_{f_2} - 2\omega_\rho(\vec{p})} \, \frac{1}{M_{f_2} - 2\omega_\rho(\vec{p}-\vec{q})}$$

$$\mathcal{N} = \int_{p<\Lambda} d^3p \frac{1}{\left(M_{f_2} - 2\omega_\rho(\vec{p})\right)^2}$$

Form factor of $f_2(1270)$



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- Thanks