UNIVERSIDAD DE MURCIA

Hadronic particles made of many vector mesons

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(in collaboration with J.Yamagata-Sekihara and E.Oset)

L.R., E.Oset, Phys.Rev.D82 (2010) 054013

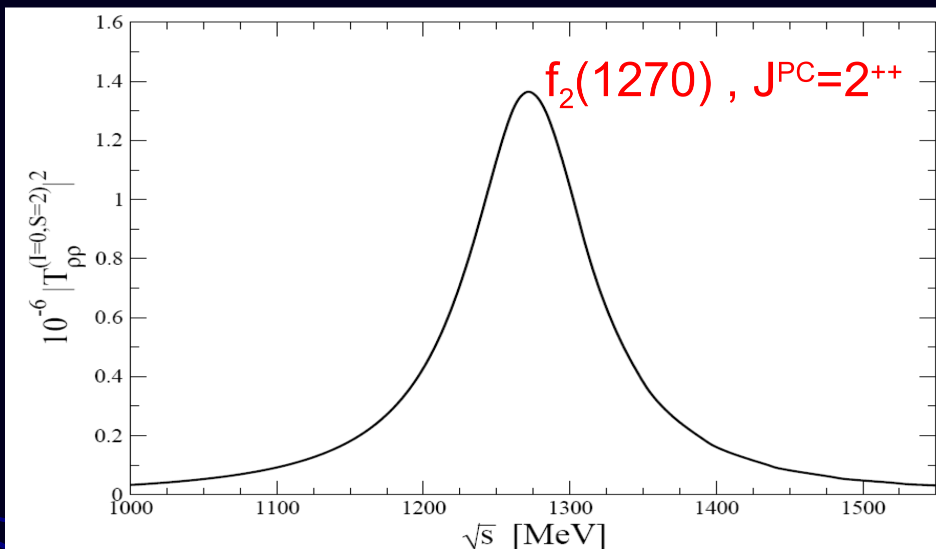
J. Yamagata-Sekihara, L.R., E.Oset, Phys.Rev.D82 (2010) 094017

HADRON'11, Munich, June 17, 2011

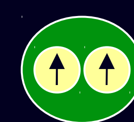
Introduction

ρρ interaction in isospin 0 and spin 2 is very strong

(UChPT) **R.Molina, D.Nicmorus, E.Oset, PRD78,114018(2008)**

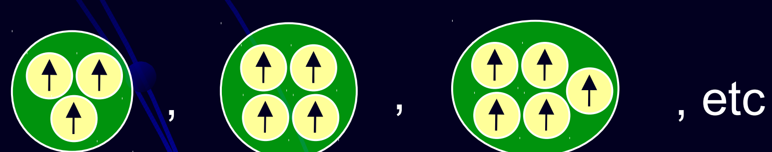


$f_2(1270)$ is a molecule of two *ρ*(770)



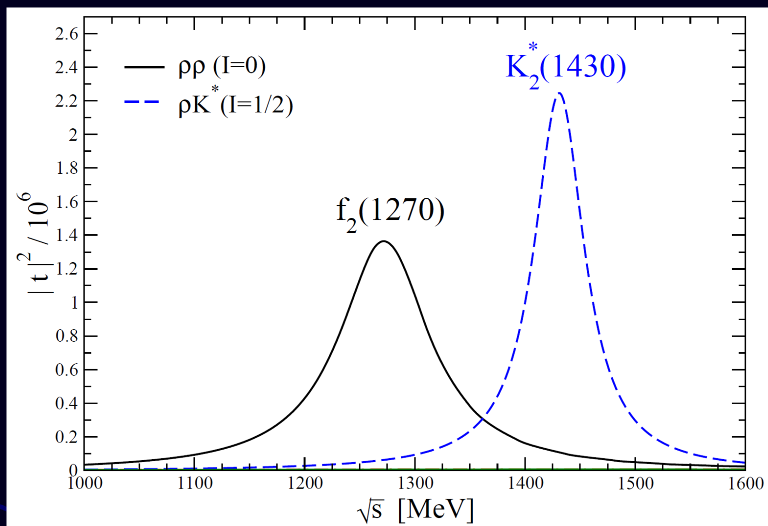
Binding energy very strong ~140 MeV/ρ = ¡20% of the ρ mass, only with two particles!

Is it possible to obain states with larger number of ρ(770) mesons?



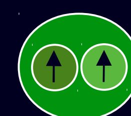
What about other vector mesons? K*(892)

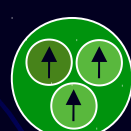
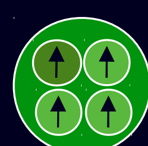
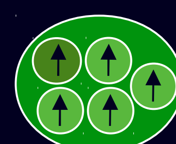
$K^*\rho$ interaction in isospin 0 and spin 2 is also very strong



K^*_2(1430) is a molecule of $K^*\rho$

L.Geng, E.Oset, PRD79,074009(2009)

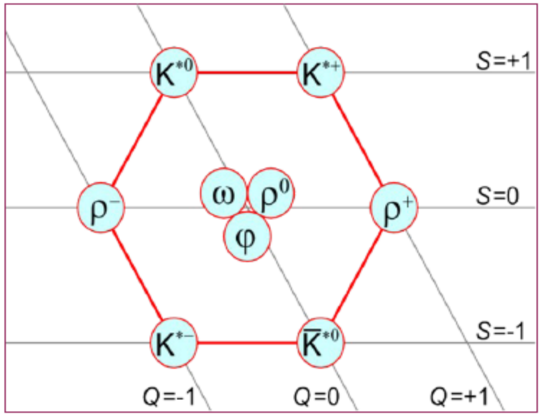


 ,  ,  , etc ?

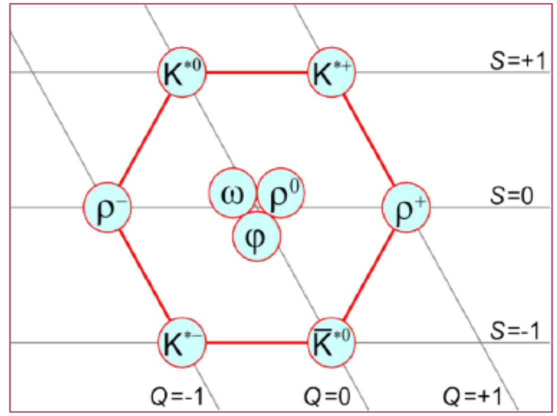
Vector-vector interaction

R.Molina, D.Nicmorus, E.Oset, PRD78,114018(2008)

L.Geng, E.Oset, PRD79,074009(2009)



+



21 strangeness, Isospin, spin channels

Interaction kernel provided by the hidden gauge symmetry Lagrangians

M. Bando et al.'1985,'1988

$$\mathcal{L} = -\frac{1}{4}\langle \bar{V}_{\mu\nu}\bar{V}^{\mu\nu}\rangle + \frac{1}{2}M_v^2\langle [V_\mu - (i/g)\Gamma_\mu]^2\rangle$$

$$V_\mu = \begin{pmatrix} \frac{\omega+\rho^0}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & \frac{\omega-\rho^0}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_\mu$$

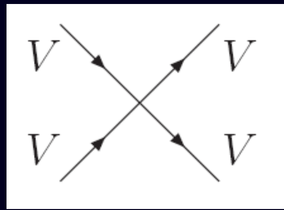
$$\Phi = \begin{pmatrix} \frac{\eta}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

$$\bar{V}_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu]$$

$$\Gamma_\mu = \frac{1}{2}\{u^\dagger[\partial_\mu - i(v_\mu + a_\mu)]u + u[\partial_\mu - i(v_\mu - a_\mu)]u^\dagger\}$$

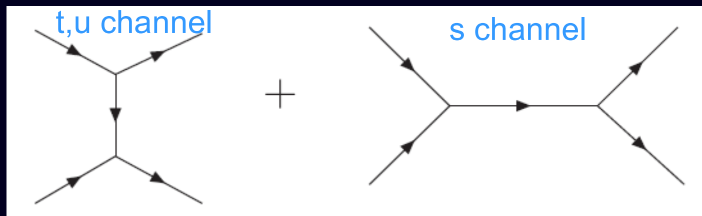
$$u^2 = U = \exp\left(\frac{i\sqrt{2}\Phi}{f}\right)$$

V



contact term

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

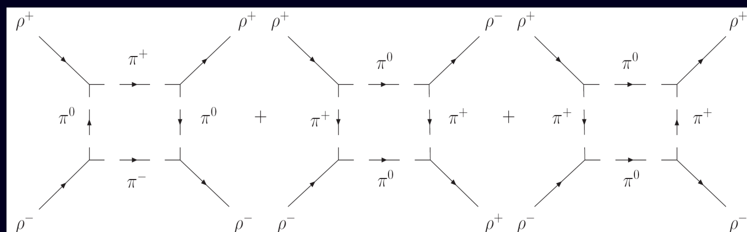


t,u channel V exchange

(s channel basically p-wave → small)

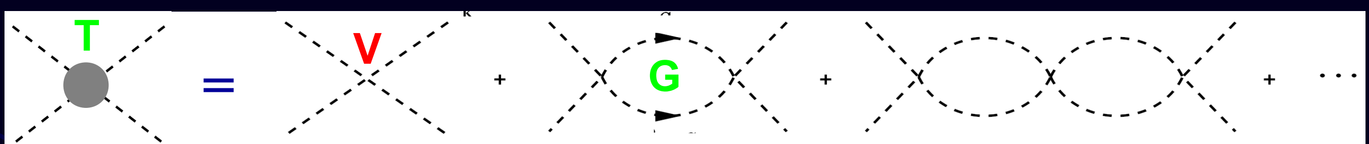
$$\mathcal{L}^{(3V)}_{III} = ig\langle (\partial_\mu V_\nu - \partial_\nu V_\mu) V^\mu V^\nu \rangle$$

dominant



box ⟶ provides $\pi\pi$ decay

Kernel of Bethe-Salpeter



$$T = \frac{V}{1 - VG}$$

I	S	Contact	Exchange	$\sim Total[I^G(J^{PG})]$
1	1	$6g^2$	$-4g^2(\frac{3s}{4M_\rho^2} - 1)$	$-2g^2[1^+(1^{+-})]$
0	0	$8g^2$	$-8g^2(\frac{3s}{4M_\rho^2} - 1)$	$-8g^2[0^+(0^{++})]$
0	2	$-4g^2$	$-8g^2(\frac{3s}{4M_\rho^2} - 1)$	$-20g^2[0^+(2^{++})]$
2	0	$-4g^2$	$4g^2(\frac{3s}{4M_\rho^2} - 1)$	$4g^2[0^+(2^{++})]$
2	2	$2g^2$	$4g^2(\frac{3s}{4M_\rho^2} - 1)$	$10g^2[0^+(2^{++})]$

strong attraction

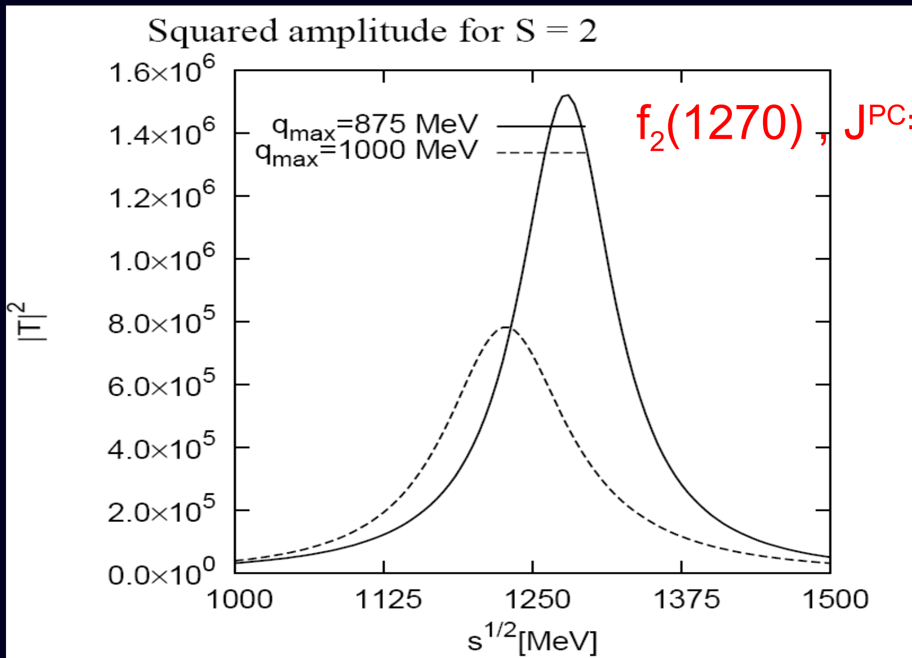
Notation: (mass, width) in MeV

$I^G(J^{PC})$	Theory			PDG data		
	pole position	real axis		name	mass	width
		$\Lambda_b = 1.4$ GeV	$\Lambda_b = 1.5$ GeV			
$0^+(0^{++})$	(1512,51)	(1523,257)	(1517,396)	$f_0(1370)$	1200∼1500	200∼500
$0^+(0^{++})$	(1726,28)	(1721,133)	(1717,151)	$f_0(1710)$	1724 ± 7	137 ± 8
$0^+(1^{++})$	(1802,78)	(1802,49)		f_1		
$0^+(2^{++})$	(1275,2)	(1276,97)	(1275,111)	$f_2(1270)$	1275.1 ± 1.2	$185.0^{+2.9}_{-2.4}$
$0^+(2^{++})$	(1525,6)	(1525,45)	(1525,51)	$f'_2(1525)$	1525 ± 5	73^{+6}_{-5}
$1^-(0^{++})$	(1780,133)	(1777,148)	(1777,172)	a_0		
$1^+(1^{+-})$	(1679,235)	(1703,188)		b_1		
$1^-(2^{++})$	(1569,32)	(1567,47)	(1566,51)	$a_2(1700)$??		
$1/2(0^+)$	(1643,47)	(1639,139)	(1637,162)	K		
$1/2(1^+)$	(1737,165)	(1743,126)		$K_1(1650)$?		
$1/2(2^+)$	(1431,1)	(1431,56)	(1431,63)	$K_2^*(1430)$	1429 ± 1.4	104 ± 4

- 11 dynamically generated states in 9 strangeness-isospin-spin channels
- 5 states clearly identified and 6 more predicted

$$f_0(1370), f_0(1710), f_2(1270), f_2'(1525), K_2^*(1430)$$

$\rho\rho$ I=0, S=2

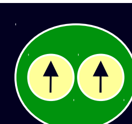


$f_2(1270)$, $J^{PC}=2^{++}$

Cutoff set to get the peak at the $f_2(1270)$ mass

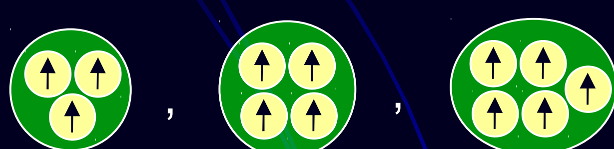
And that's all the freedom for the rest of the work !

$f_2(1270)$ is a molecule of two $\rho(770)$

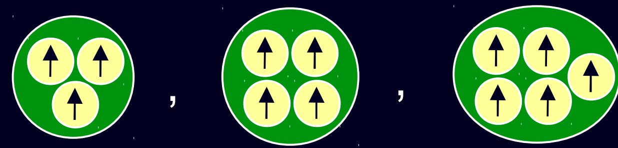


Is it possible to obain states with larger number of ρ(770) mesons?

Binding energy very strong ~140 MeV/ρ = ¡20% of the ρ mass, only with two particles!



, etc



, , , etc ?

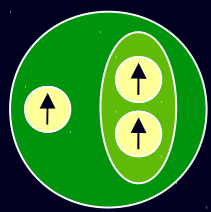
Possible candidates for multi-$\rho(770)$ states in the PDG:

$n\,^{2s+1}\ell_J$	J^{PC}	I = 1 $u\bar{d}$, $\bar{u}d$, $\frac{1}{\sqrt{2}}(d\bar{d}-u\bar{u})$	I = $\frac{1}{2}$ $u\bar{s}$, $d\bar{s}$; $\bar{d}s$, $-\bar{u}s$	I = 0 f'	I = 0 f	$\theta_{\rm quad}$ [°]	$\theta_{\rm lin}$ [°]
$1\,^1S_0$	0^{-+}	π	K	η	$\eta'(958)$	-11.5	-24.6
$1\,^3S_1$	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$	38.7	36.0
$1\,^1P_1$	1^{+-}	$b_1(1235)$	$K_{1B}{}^{\dagger}$	$h_1(1380)$	$h_1(1170)$		
$1\,^3P_0$	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$		
$1\,^3P_1$	1^{++}	$a_1(1260)$	$K_{1A}{}^{\dagger}$	$f_1(1420)$	$f_1(1285)$		
$1\,^3P_2$	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$	29.6	28.0
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$K_2(1770)^{\dagger}$	$\eta_2(1870)$	$\eta_2(1645)$		
$1\,^3D_1$	1^{--}	$\rho(1700)$	$K^*(1680)$		$\omega(1650)$		
$1\,^3D_2$	2^{--}		$K_2(1820)$				
$1\,^3D_3$	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\phi_3(1850)$	$\omega_3(1670)$	32.0	31.0
$1\,^3F_4$	4^{++}	$a_4(2040)$	$K_4^*(2045)$		$f_4(2050)$		
$1\,^3G_5$	5^{--}	$\rho_5(2350)$					
$1\,^3H_6$	6^{++}	$a_6(2450)$			$f_6(2510)$		
$2\,^1S_0$	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1475)$	$\eta(1295)$		
$2\,^3S_1$	1^{--}	$\rho(1450)$	$K^*(1410)$	$\phi(1680)$	$\omega(1420)$		

Interaction of several $\rho(770)$

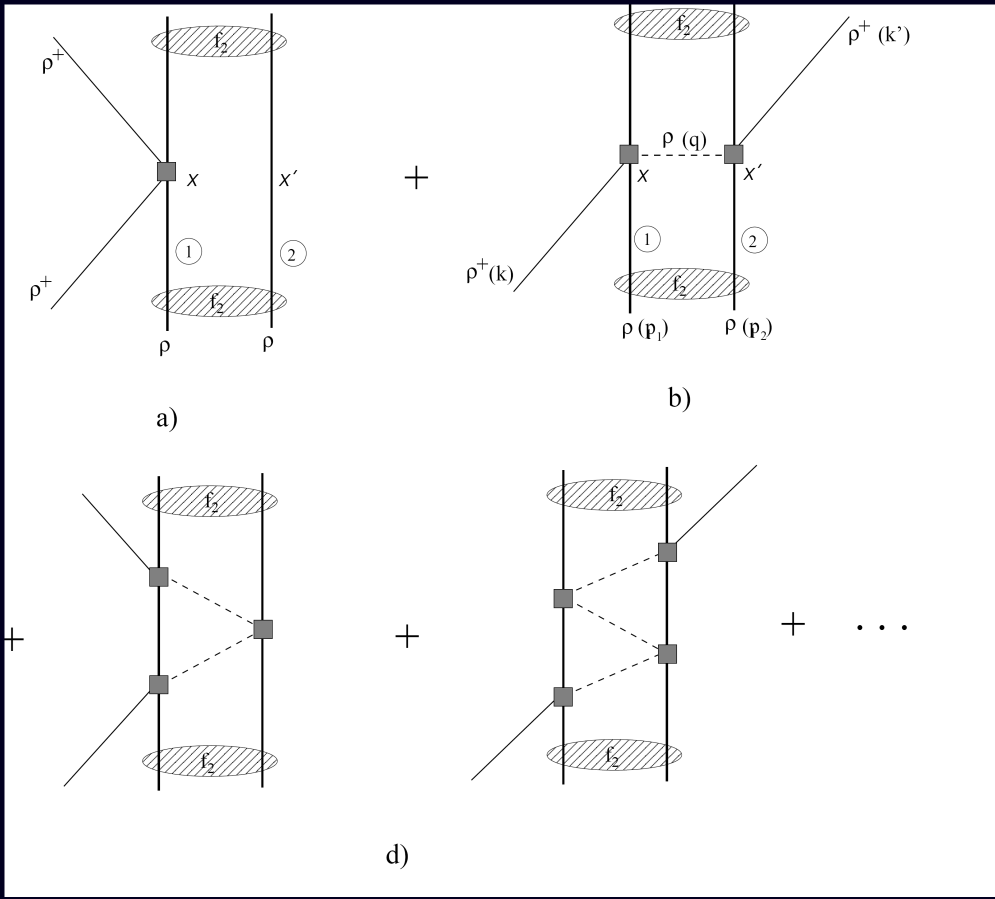
Three $\boldsymbol{\rho}$'s:

Since two $\boldsymbol{\rho}$ tend to clusterize, we study the interaction of one $\boldsymbol{\rho}$ with the other two $\boldsymbol{\rho}$ clusterized building up a $f_2(1270)$



Fixed center approximation to Faddeev equations:

$$T_1 = t_1 + t_1 G_0 T_2$$
$$T_2 = t_2 + t_2 G_0 T_1$$
$$T = T_1 + T_2$$



(similar to kaon-deuteron, **Kamalov, Oset, Ramos '01**)

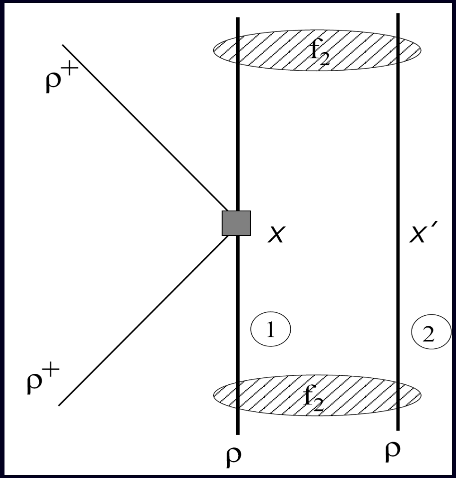
Single scattering:

S-matrix:

$$S^{(1)} = \int d^4x \frac{1}{\sqrt{2\omega_{p_1}}} e^{-ip_1^0 x^0} \varphi_1(\vec{x}) \frac{1}{\sqrt{2\omega_{p'_1}}} e^{ip'^0_1 x^0} \varphi_1(\vec{x}) \frac{1}{\sqrt{2\omega_k \mathcal{V}}} e^{-ikx} \frac{1}{\sqrt{2\omega'_k \mathcal{V}}} e^{ik'x} (-it_1)$$

$$t_1 = \frac{2}{9}\left(5t_{\rho\rho}^{(I=2)} + t_{\rho\rho}^{(I=0)}\right)$$

$\rho\rho$ unitarized amplitude



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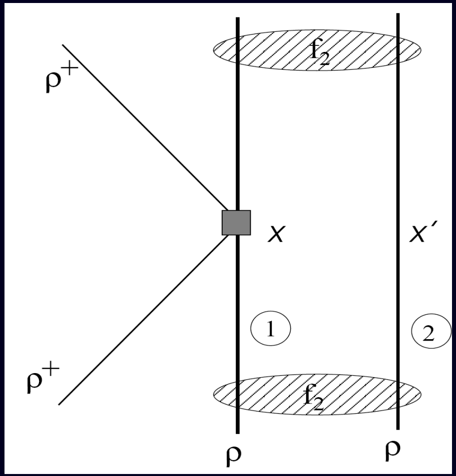
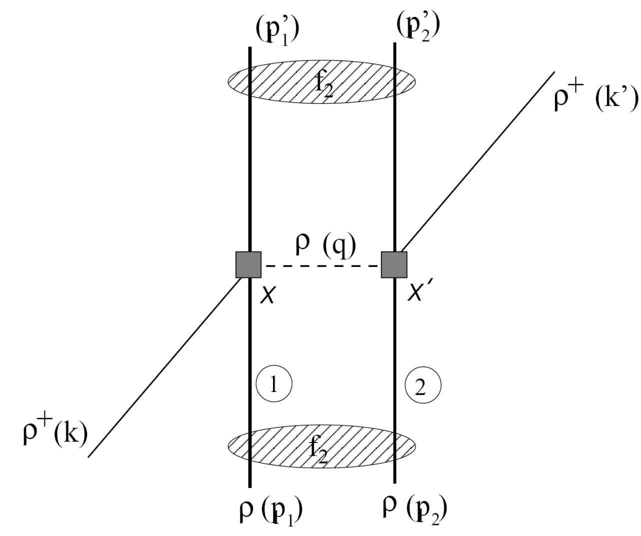


Double scattering:



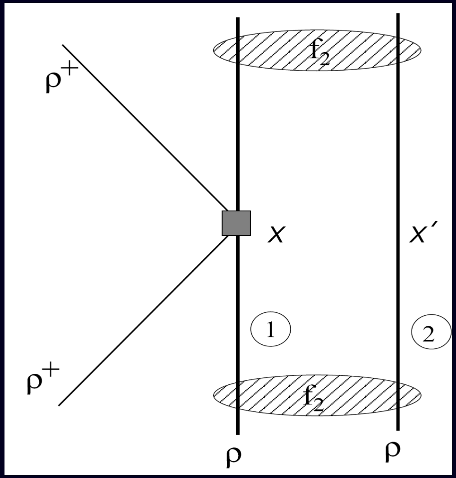
Single scattering:

S-matrix:

$$S^{(1)} = \int d^4x \frac{1}{\sqrt{2\omega_{p_1}}} e^{-ip_1^0 x^0} \varphi_1(\vec{x}) \frac{1}{\sqrt{2\omega_{p'_1}}} e^{ip'^0_1 x^0} \varphi_1(\vec{x}) \frac{1}{\sqrt{2\omega_k \mathcal{V}}} e^{-ikx} \frac{1}{\sqrt{2\omega'_k \mathcal{V}}} e^{ik'x} (-it_1)$$

$$t_1 = \frac{2}{9}\left(5t^{(I=2)}_{\rho\rho} + t^{(I=0)}_{\rho\rho}\right)$$

$\rho\rho$ unitarized amplitude



Double scattering:

$$S^{(2)} = -i(2\pi)^4 \delta(k + K_{f_2} - k' - K'_{f_2}) \frac{1}{\mathcal{V}^2} \frac{1}{\sqrt{2\omega_k}} \frac{1}{\sqrt{2\omega'_k}} \frac{1}{\sqrt{2\omega_{p_1}}} \frac{1}{\sqrt{2\omega_{p'_1}}} \frac{1}{\sqrt{2\omega_{p_2}}} \frac{1}{\sqrt{2\omega_{p'_2}}} \times \int \frac{d^3q}{(2\pi)^3} F_{f_2}(q) \frac{1}{q^{02} - \vec{q}^{\,2} - m_\rho^2 + i\epsilon} t_1 t_1.$$

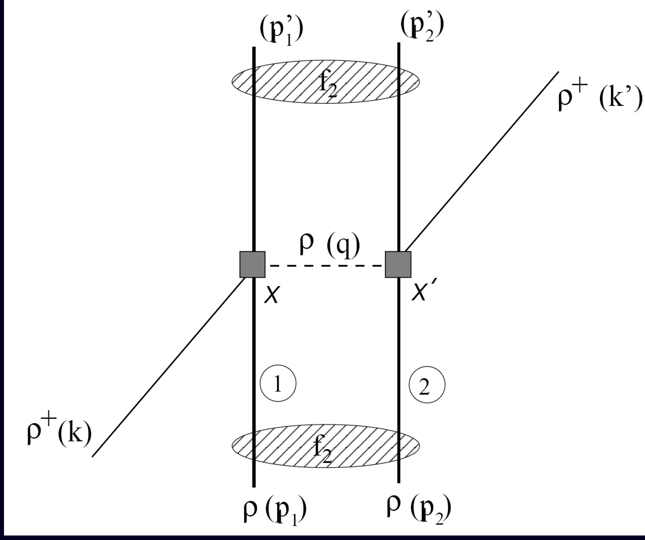
$$\varphi_1(x)\varphi_2(x') = \frac{1}{\sqrt{\mathcal{V}}} e^{i\vec{K}_{f_2}\cdot\vec{R}} \Psi_{f_2}(\vec{r})$$

$f_2(1270)$ form factor

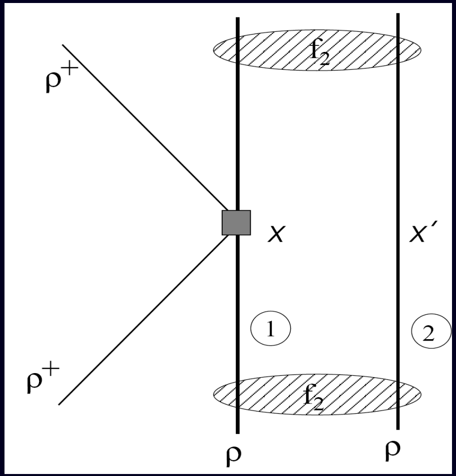
$$F_{f_2}\left(\vec{q} - \frac{\vec{k} + \vec{k}'}{2}\right) \equiv \int d^3r\, e^{-i\left(\vec{q} - \frac{\vec{k}+\vec{k}'}{2}\right)\cdot\vec{r}}\, \Psi_{f_2}(\vec{r})^2$$

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

Same cutoff as in the scattering of two particles



L.Geng, E.Oset, PRD79,074009(2009)



Single scattering:

S-matrix:

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$$t_1 = \frac{2}{9}\left(5t_{\rho\rho}^{(I=2)} + t_{\rho\rho}^{(I=0)}\right)$$

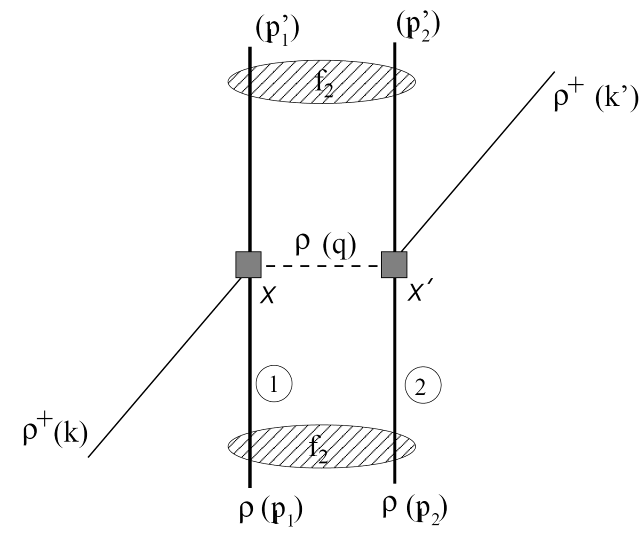
$\rho\rho$ unitarized amplitude

Double scattering:

Full scattering amplitude:

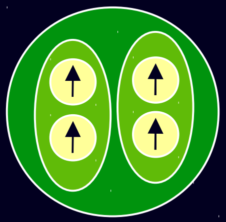
$$T_{\rho f_2} = 4(t_1 + t_1 t_1 G_0)$$

$$G_0 \equiv \frac{1}{M_{f_2}} \int \frac{d^3q}{(2\pi)^3} F_{f_2}(q) \frac{1}{q^{0\,2} - \vec{q}^{\,2} - m_\rho^2 + i\epsilon}$$

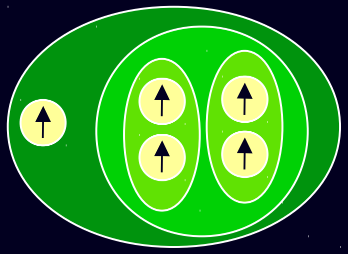


Larger number of ρ mesons:

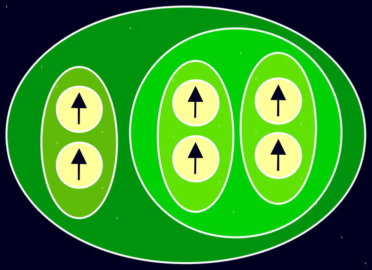
4 ρ's (f_4): interaction of two f_2



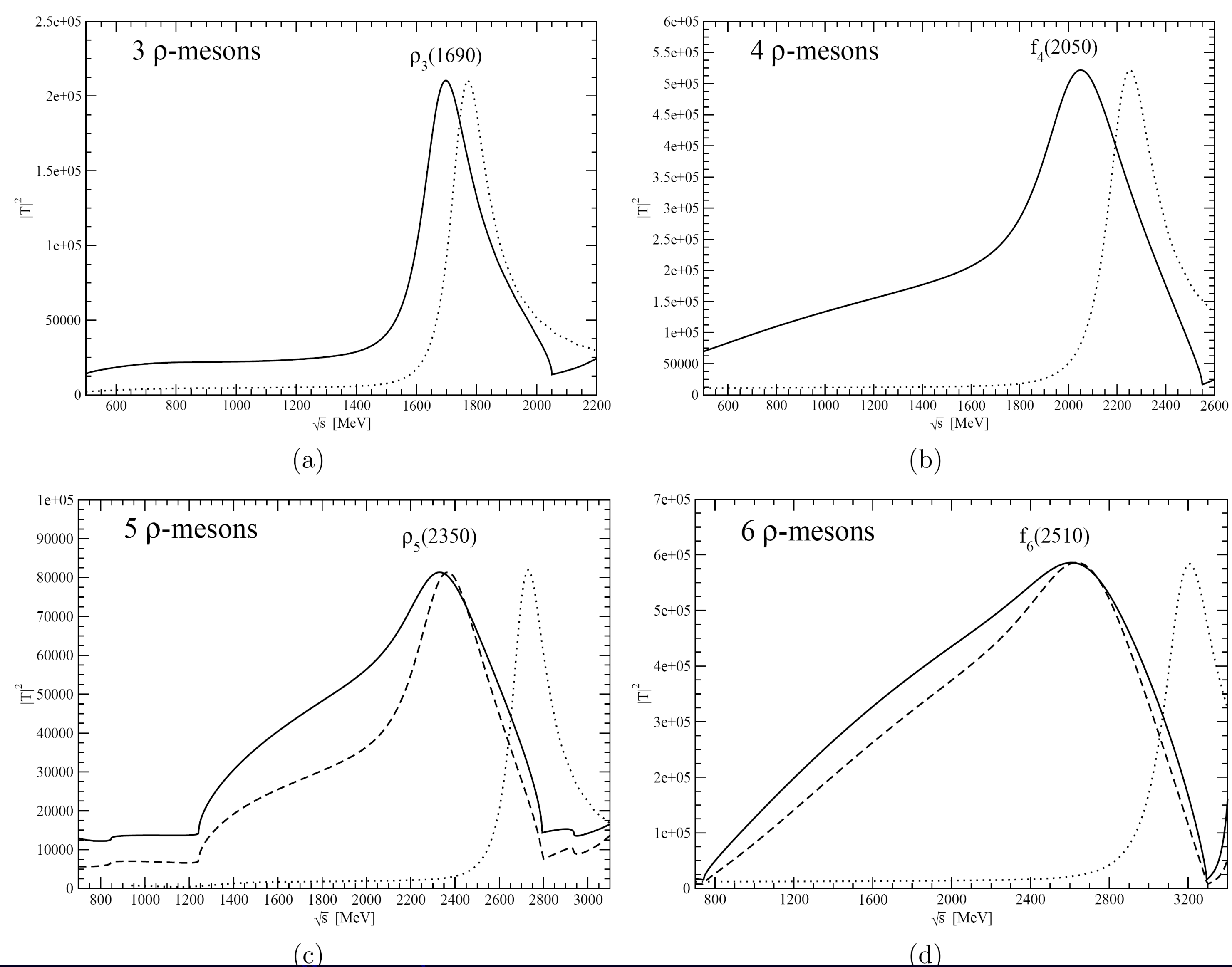
5 ρ's (ρ_5): interaction of ρ-f_4



6 ρ's (f_6): interaction of f_2-f_4



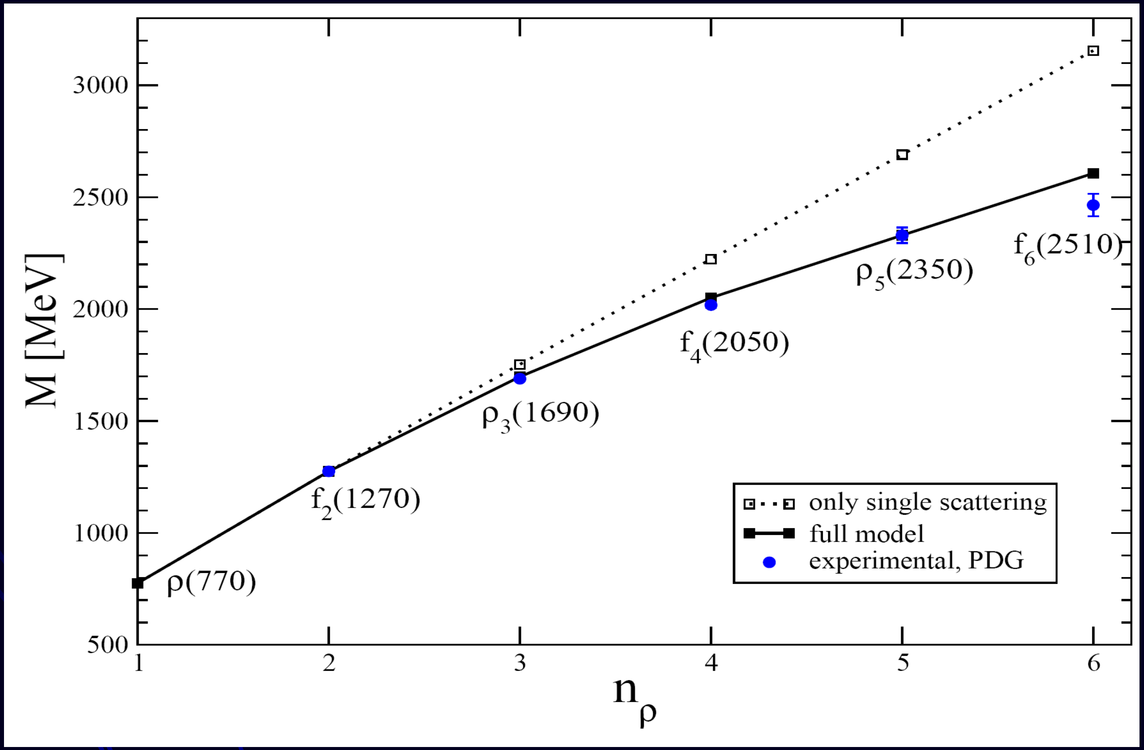
Results



(dotted: only single scattering)

(masses: from position of the maximum)

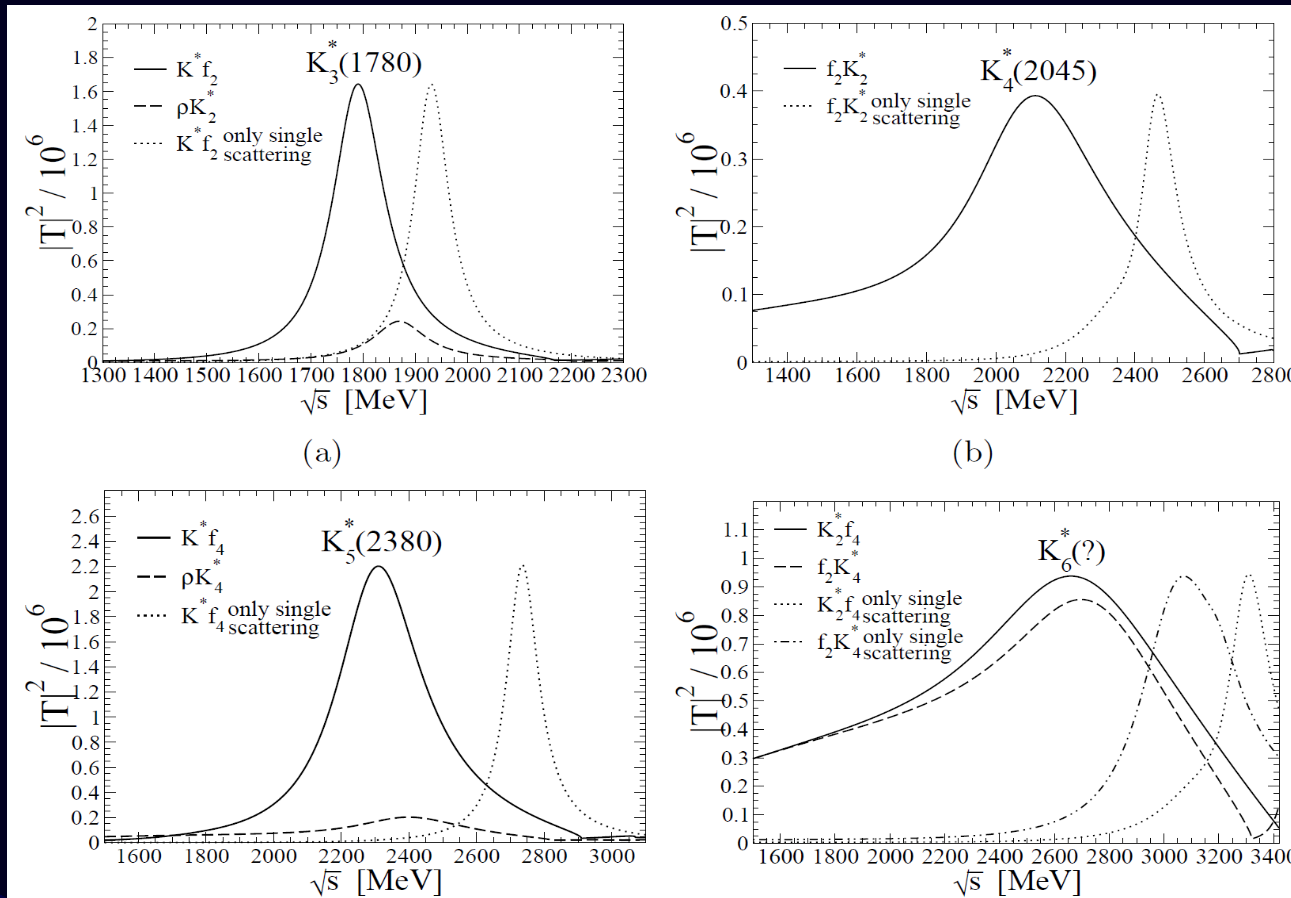
n_ρ		mass, PDG [25]	mass, only single scatt.	mass, full model	$E(n_\rho)$
2	$f_2(1270)$	1275 ± 1	1275	1285	133
3	$\rho_3(1690)$	1689 ± 2	1753	1698	209
4	$f_4(2050)$	2018 ± 11	2224	2051	263
5	$\rho_5(2350)$	2330 ± 35	2690	2330-2366	302-309
6	$f_6(2510)$	2465 ± 50	3155	2607-2633	337-341



Inclusion of K*(892)

Possible candidates for K* multi-ρ states in the PDG:

$n\,^{2s+1}\ell_J$	J^{PC}	I = 1 $u\bar{d},\ \bar{u}d,\ \frac{1}{\sqrt{2}}(d\bar{d}-u\bar{u})$	I = $\frac{1}{2}$ $u\bar{s},\ d\bar{s};\ \bar{d}s,\ -\bar{u}s$	I = 0 f'	I = 0 f
$1\,^1S_0$	0^{-+}	π	K	η	$\eta'(958)$
$1\,^3S_1$	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$
$1\,^1P_1$	1^{+-}	$b_1(1235)$	$K_{1B}{}^\dagger$	$h_1(1380)$	$h_1(1170)$
$1\,^3P_0$	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$
$1\,^3P_1$	1^{++}	$a_1(1260)$	$K_{1A}{}^\dagger$	$f_1(1420)$	$f_1(1285)$
$1\,^3P_2$	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$K_2(1770)^\dagger$	$\eta_2(1870)$	$\eta_2(1645)$
$1\,^3D_1$	1^{--}	$\rho(1700)$	$K^*(1680)$		$\omega(1650)$
$1\,^3D_2$	2^{--}		$K_2(1820)$		
$1\,^3D_3$	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\phi_3(1850)$	$\omega_3(1670)$
$1\,^3F_4$	4^{++}	$a_4(2040)$	$K_4^*(2045)$		$f_4(2050)$
$1\,^3G_5$	5^{--}	$\rho_5(2350)$	$K^*{}_5(2380)$		
$1\,^3H_6$	6^{++}	$a_6(2450)$	$K^*{}_6$???		$f_6(2510)$
$2\,^1S_0$	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1475)$	$\eta(1295)$
$2\,^3S_1$	1^{--}	$\rho(1450)$	$K^*(1410)$	$\phi(1680)$	$\omega(1420)$



generated resonance	amplitude	mass, PDG [21]	mass only single scatt.	mass full model
$K_2^*(1430)$	ρK^*	1429 ± 1.4	–	1430
$K_3^*(1780)$	$K^* f_2$	1776 ± 7	1930	1790
$K_4^*(2045)$	$f_2 K_2^*$	2045 ± 9	2466	2114
$K_5^*(2380)$	$K^* f_4$	$2382 \pm 14 \pm 19$	2736	2310
K_6^*	$K_2^* f_4$-$f_2 K_4^*$	–	3073-3310	2661-2698

(masses: from position of the maximum)

Summary

- $\rho\rho$ and $K^*\rho$ interaction in I=0, S=2 is very strong (kernel: VV interaction from HGS)

→ $f_2(1270)$ and $K^*_2(1430)$ dynamically generated (UChPT)

- Many-particle interaction from fixed center Faddeev equations

- Prominent shapes for the multi-body scattering amplitudes

- Maxima in very good agreement with the masses of

$\rho_3(1690)$, $f_4(2050)$, $\rho_5(2350)$ and $f_6(2510)$

→ dynamically generated from multiple ρ interaction (3, 4, 5 and 6 ρ's respectively)

- Inclusion of K*:

$K^*_3(1430)$, $K^*_4(2045)$, $K^*_5(2380)$ and $K^*_6(2510)$

dynamically generated from K^*-multiple ρ interaction

EXTRA

UChPT (unitary extensions of chiral perturbation theory)

ChPT very sucessful to describe a large amount of phenomenology at low energies

Problems (limitations) of ChPT:

- The number of parameters increases a lot with the order of the expansion

- The energy range of applicability is restricted to low energies

Typically till the energies where the first resonances appear

→ A resonance implies a pole, which a perturbative expansion can never produce

ChPT cannot be applied to the region of intermediate energies where the hadronic spectrum is very rich

Basic idea of UChPT:

Oller, Oset, Dobado, Pelaez, Meissner, Kaiser, Weise, Ramos, Vicente-Vacas, Nieves, Ruiz-Arriola, Lutz,...

Input:

lowest order chiral Lagrangian
+ implementation of **unitarity** in coupled channels
+ exploitation of analytic properties

} Extended range of applicability of ChPT to higher energies

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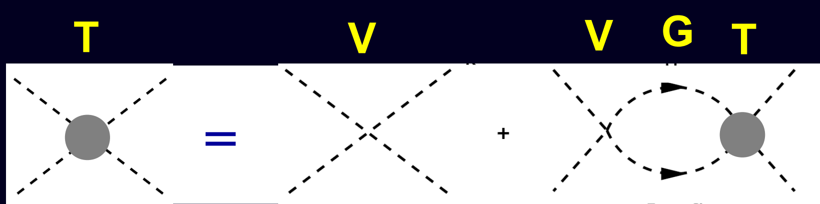
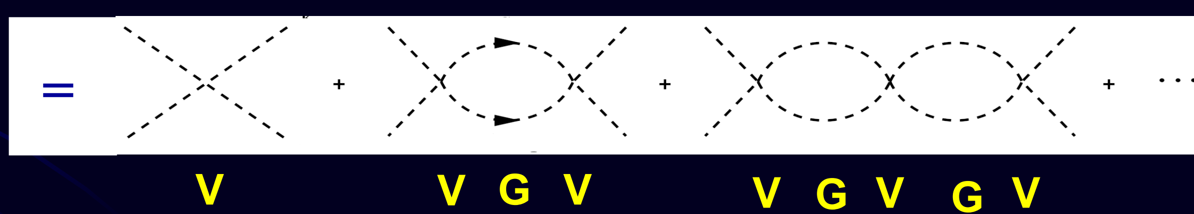
Unitarity of the S-matrix implies:





(Bethe-Salpeter eq.)

The kernel of the BS equation, **V**, is the lowest order ChPT Lagrangian

Effectively, one is summing this infinite series of diagrams

$$G = \frac{1}{16\pi^2}\left(\alpha + Log\frac{m_1^2}{\mu^2} + \frac{m_2^2 - m_1^2 + s}{2s}Log\frac{m_2^2}{m_1^2} + \frac{p}{\sqrt{s}}\left(Log\frac{s - m_2^2 + m_1^2 + 2p\sqrt{s}}{-s + m_2^2 - m_1^2 + 2p\sqrt{s}} + Log\frac{s + m_2^2 - m_1^2 + 2p\sqrt{s}}{-s - m_2^2 + m_1^2 + 2p\sqrt{s}}\right)\right)$$

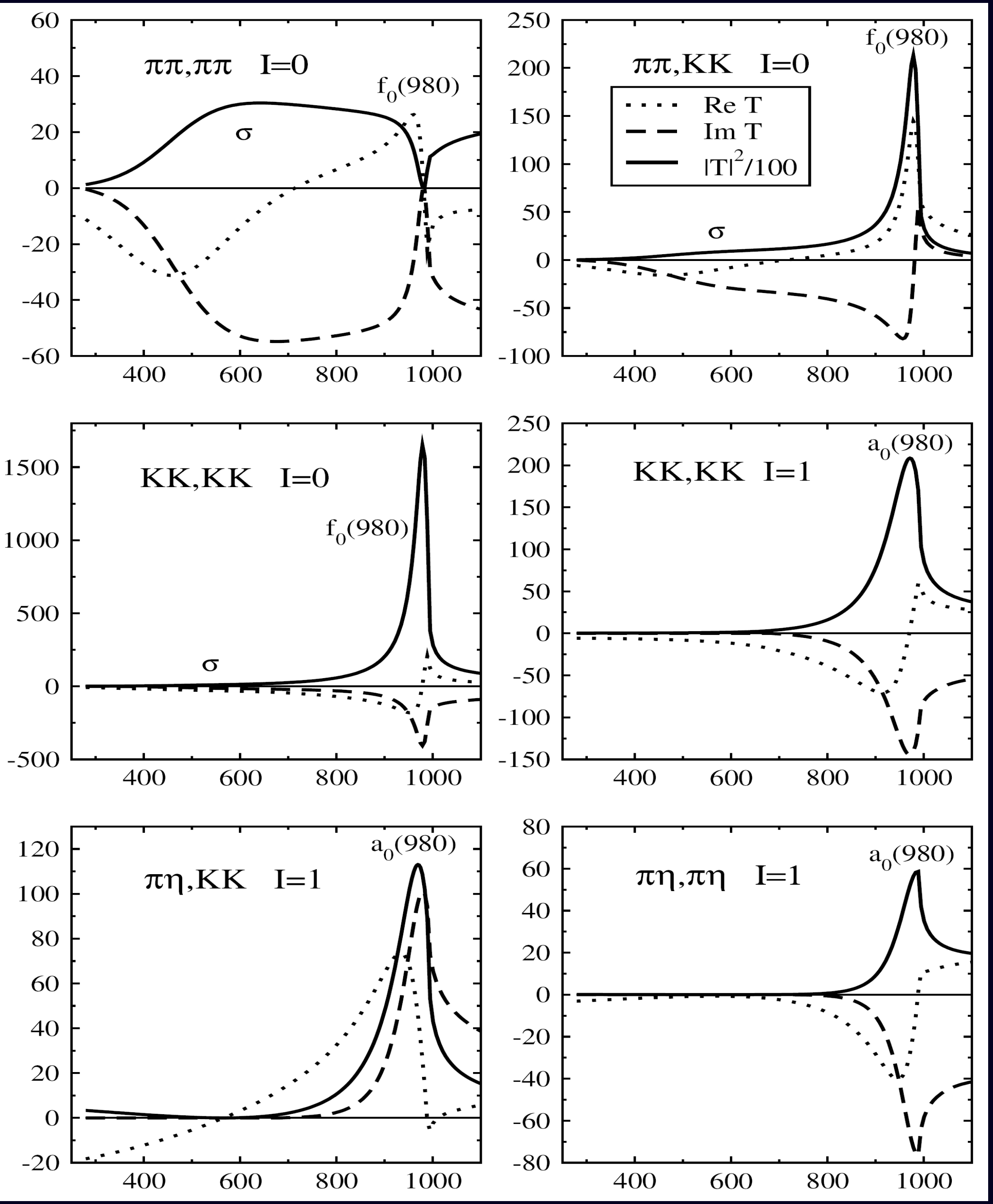
$$G = \int_0^{q_{max}} \frac{q^2 dq}{(2\pi)^2} \frac{\omega_1 + \omega_2}{\omega_1\omega_2[(P^0)^2 - (\omega_1 + \omega_2)^2 + i\epsilon]}$$

Example: MM in s-wave

Prominent shapes for the resonances

Many resonances appear without including them explicitly

"dynamically generated" resonances



Important:

UChPT not only gives spectroscopy (masses and widths) but the shape of the scattering amplitude out of the resonance position