Experimental support for a new h_1 resonance around 1830 MeV and theoretical backing from the vector-vector interaction; Prediction of I=1 molecular states of *DD**bar and *D***D**bar and relationship to the Z_c(3900) and the claimed Z_c(4025).

E. Oset , IFIC and Theory Department, Valencia

Hidden gauge formalism for vector mesons, pseudoscalars and photons

Vector-vector interaction. Meson resonances, f_0, f_2, ….

Experimental evidence for a new h_1(1830) predicted theoretically

I=1, Z states made from D D*bar and D* D*bar around 3900MeV and 4000MeV

Hidden gauge formalism for vector mesons, pseudoscalars and photons

Bando et al. PRL, 112 (85); Phys. Rep. 164, 217 (88); U. G: Meissner Phys Rep 161 (88)

$$\mathcal{L} = \mathcal{L}^{(2)} + \mathcal{L}_{III} \tag{1}$$

with

$$\mathcal{L}^{(2)} = \frac{1}{4} f^2 \langle D_\mu U D^\mu U^\dagger + \chi U^\dagger + \chi^\dagger U \rangle \tag{2}$$

$$\mathcal{L}_{III} = -\frac{1}{4}\langle V_{\mu\nu} V^{\mu\nu}\rangle + \frac{1}{2} M_V^2 \langle [V_\mu - \frac{i}{g}\Gamma_\mu]^2\rangle, \tag{3}$$

where $\langle ... \rangle$ represents a trace over $SU(3)$ matrices. The covariant derivative is defined by

$$D_\mu U = \partial_\mu U - ieQA_\mu U + ieUQA_\mu, \tag{4}$$

with $Q = diag(2, -1, -1)/3$, $e = -|e|$ the electron charge, and A_μ the photon field. The chiral matrix U is given by

$$U = e^{i\sqrt{2}\phi/f} \tag{5}$$

$$\phi \equiv \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 \end{pmatrix}, \quad V_\mu \equiv \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_\mu . \tag{6}$$

In $\mathcal{L}_{III}$, $V_{\mu\nu}$ is defined as

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu] \tag{9}$$

and

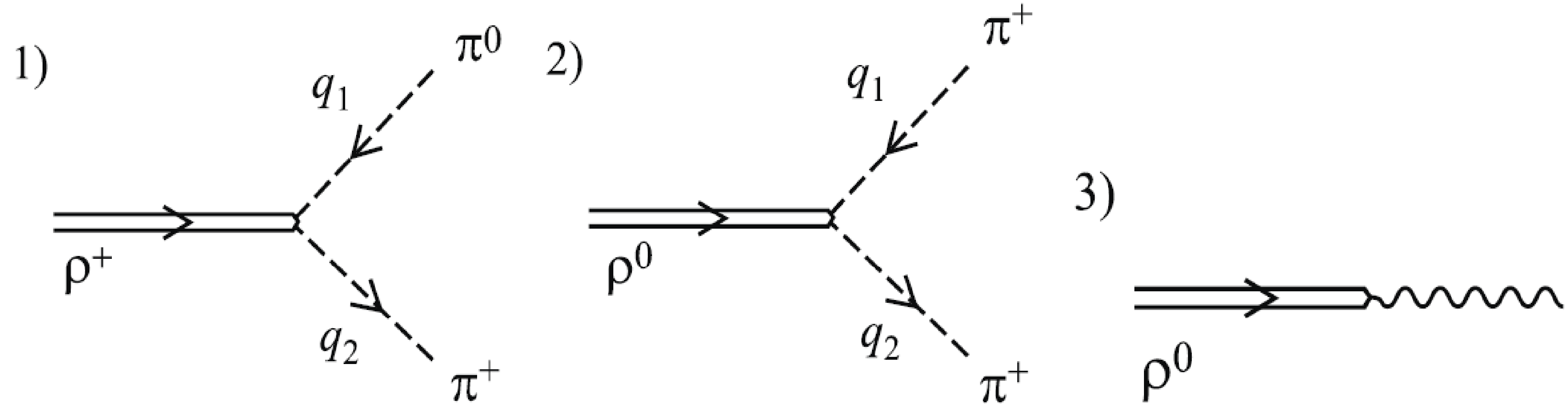
$$\Gamma_\mu = \frac{1}{2}[u^\dagger(\partial_\mu - ieQA_\mu)u + u(\partial_\mu - ieQA_\mu)u^\dagger] \tag{10}$$

with $u^2 = U$. The hidden gauge coupling constant g is related to f and the vector meson mass (M_V) through

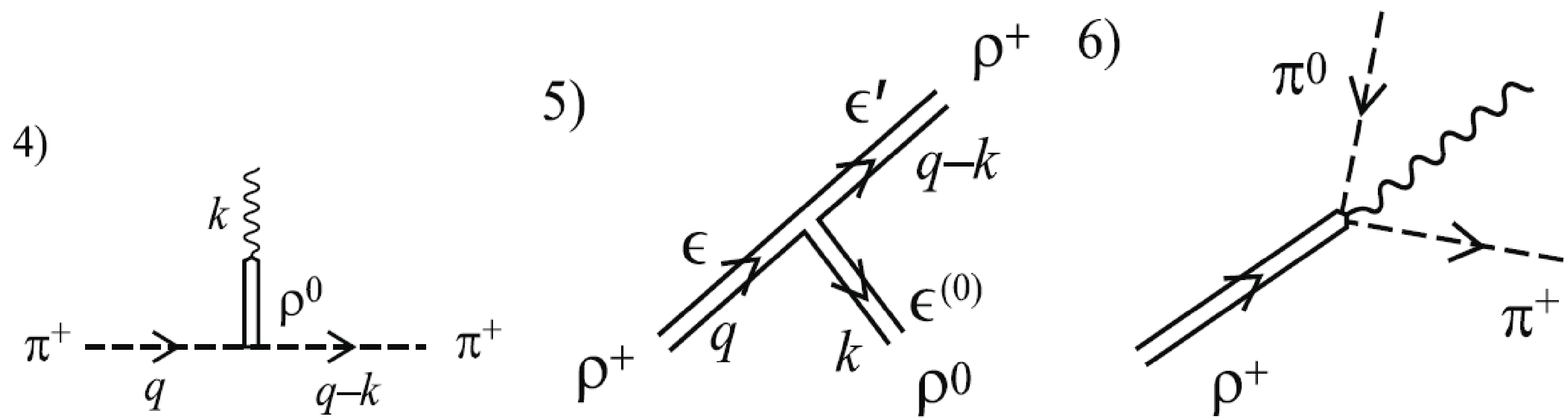
$$g = \frac{M_V}{2f}, \tag{11}$$

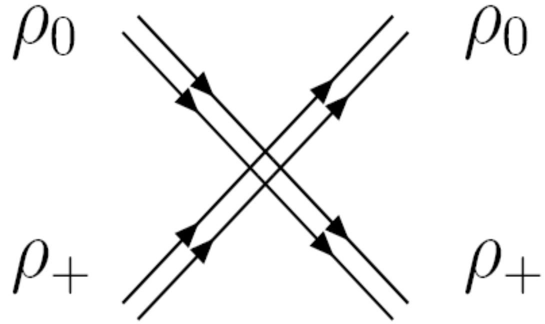
$$\mathcal{L}_{V\gamma} = -M_V^2 \frac{e}{g} A_\mu \langle V^\mu Q \rangle$$
$$\mathcal{L}_{V\gamma PP} = e\frac{M_V^2}{4gf^2} A_\mu \langle V^\mu (Q\phi^2 + \phi^2 Q - 2\phi Q \phi) \rangle$$
$$\mathcal{L}_{VPP} = -i\frac{M_V^2}{4gf^2} \langle V^\mu [\phi, \partial_\mu \phi] \rangle$$

$$\mathcal{L}_{III}^{(c)} = \frac{g^2}{2} \langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu \rangle \ , \qquad \mathcal{L}_{III}^{(3V)} = ig \langle (\partial_\mu V_\nu - \partial_\nu V_\mu) V^\mu V^\nu \rangle \ ,$$

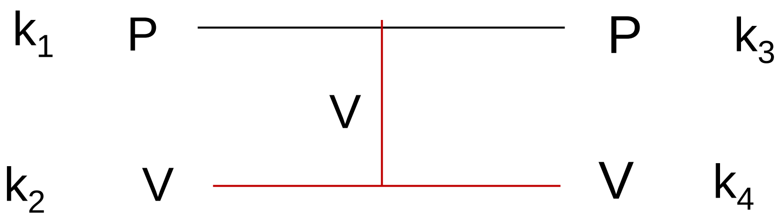

1)
π0
q1
q2
π+
ρ+
2)
π+
q1
q2
π+
ρ0
3)
ρ0

(a) (b) (c)


4)
k
ρ0
π+
q
q–k
π+
5)
ρ+
ϵ′
q–k
ϵ
ϵ(0)
ρ+
q
k
ρ0
6)
π0
π+
ρ+


ρ0
ρ0
ρ+
ρ+

Pseudoscalar-vector interaction



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

$$\mathcal{L}_{VPP} = -ig\langle [P, \partial_\nu P] V^\nu \rangle$$

We take the approximation that the three momentum of the external vectors is small Compared to the mass of the vector mesons.

V^ν cannot correspond to an external vector.
Indeed, external vectors have only spatial components in the approximation of neglecting three momenta, $\varepsilon^0 = k/M$ for longitudinal vectors, $\varepsilon^0 = 0$ for transverse vectors. Then ∂_ν becomes three momentum which is neglected. →
V^ν corresponds to the exchanged vector. → complete analogy to VPP
Extra $\varepsilon_\mu \varepsilon^\mu = -\varepsilon_i \varepsilon_i$ but the interaction is formally identical to the case of PP→PP

We obtain the effective Lagrangian

$$\mathcal{L}_{VVPP} = -\frac{1}{4f^2} \mathrm{Tr}([V^\mu, \partial^\nu V_\mu][P, \partial_\nu P]),$$

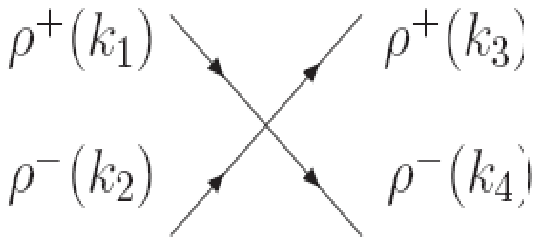
Which is the chiral Lagrangian of Birse, Z.P. 1996

The interaction becomes $g^2 (k_1+k_3).(k_2+k_4)$ up to some SU(3) coefficient

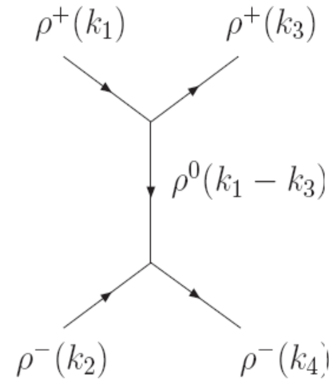
Rho-rho interaction in the hidden gauge approach

R.Molina, D. Nicmorus, E. O. PRD (08)

V= -



+



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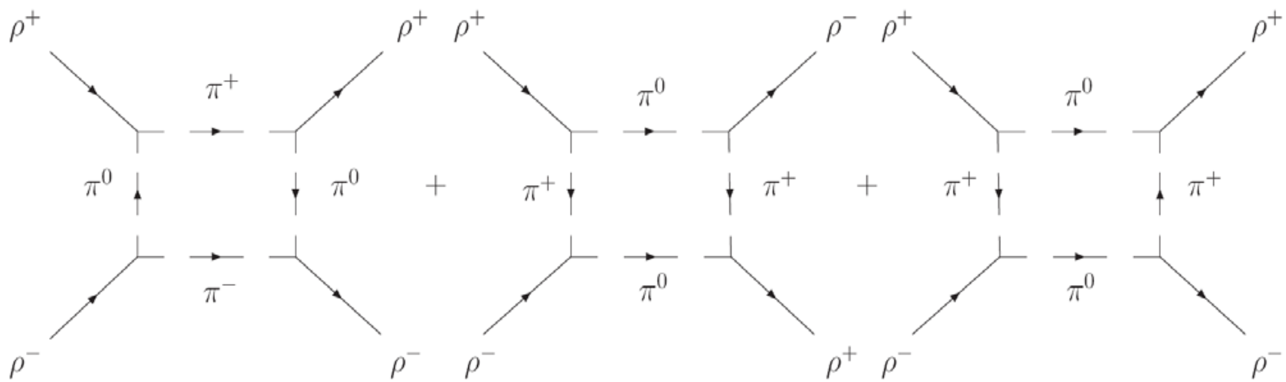


Spin projectors neglecting q/M_V, in L=0

$$\mathcal{P}^{(0)} = \frac{1}{3}\epsilon_\mu\epsilon^\mu\epsilon_\nu\epsilon^\nu$$

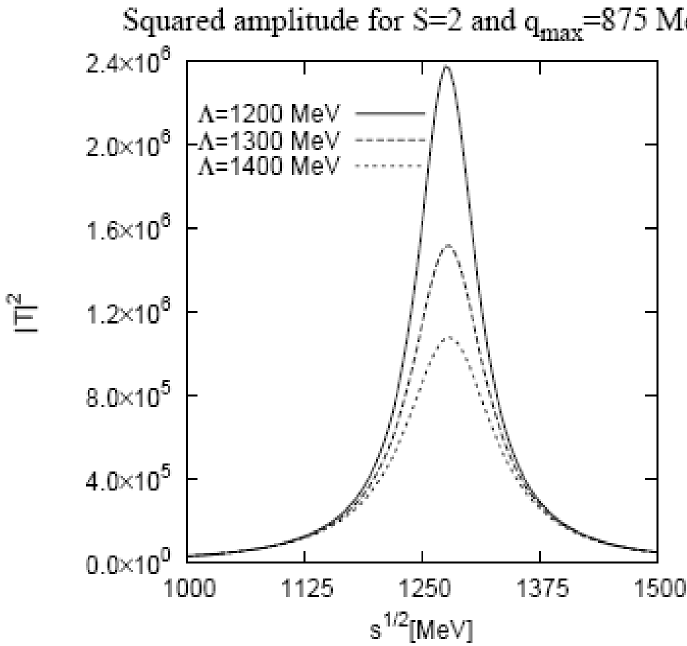
$$\mathcal{P}^{(1)} = \frac{1}{2}(\epsilon_\mu\epsilon_\nu\epsilon^\mu\epsilon^\nu - \epsilon_\mu\epsilon_\nu\epsilon^\nu\epsilon^\mu)$$

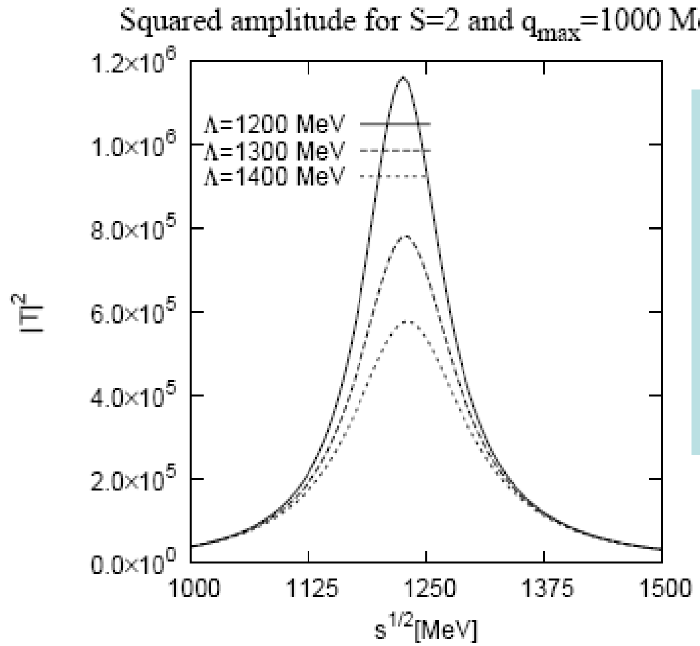
$$\mathcal{P}^{(2)} = \{\frac{1}{2}(\epsilon_\mu\epsilon_\nu\epsilon^\mu\epsilon^\nu + \epsilon_\mu\epsilon_\nu\epsilon^\nu\epsilon^\mu) - \frac{1}{3}\epsilon_\alpha\epsilon^\alpha\epsilon_\beta\epsilon^\beta\}$$

Bethe Salpeter eqn.

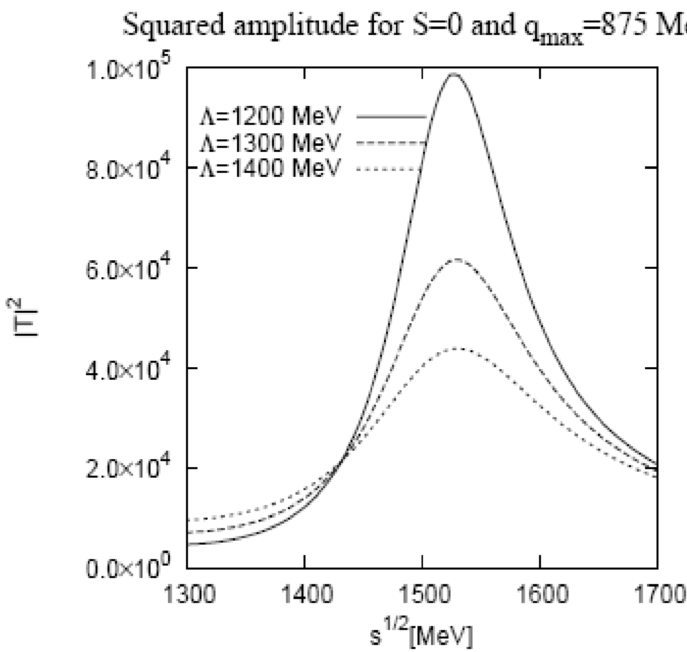
$$T = \frac{V}{1-VG}$$

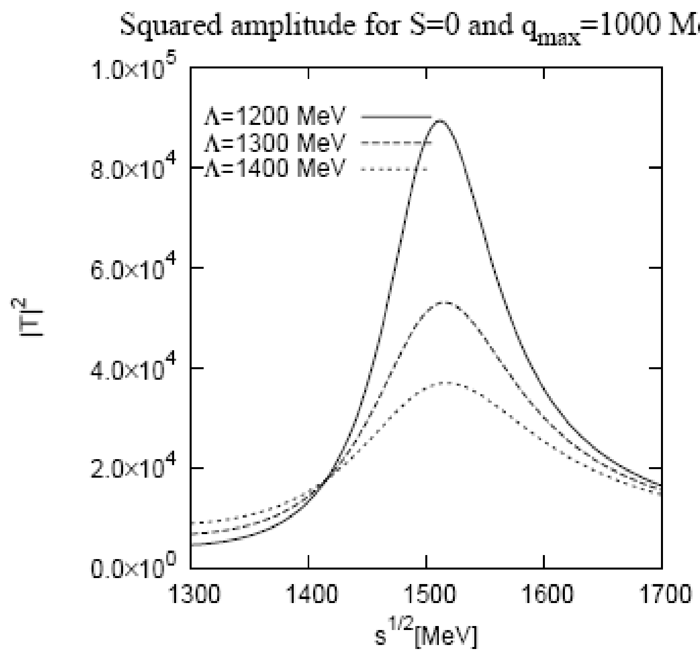
G is the ρρ propagator





Two I=0 states generated f_0, f_2 that we associate to $f_0(1370)$ and $f_2(1270)$

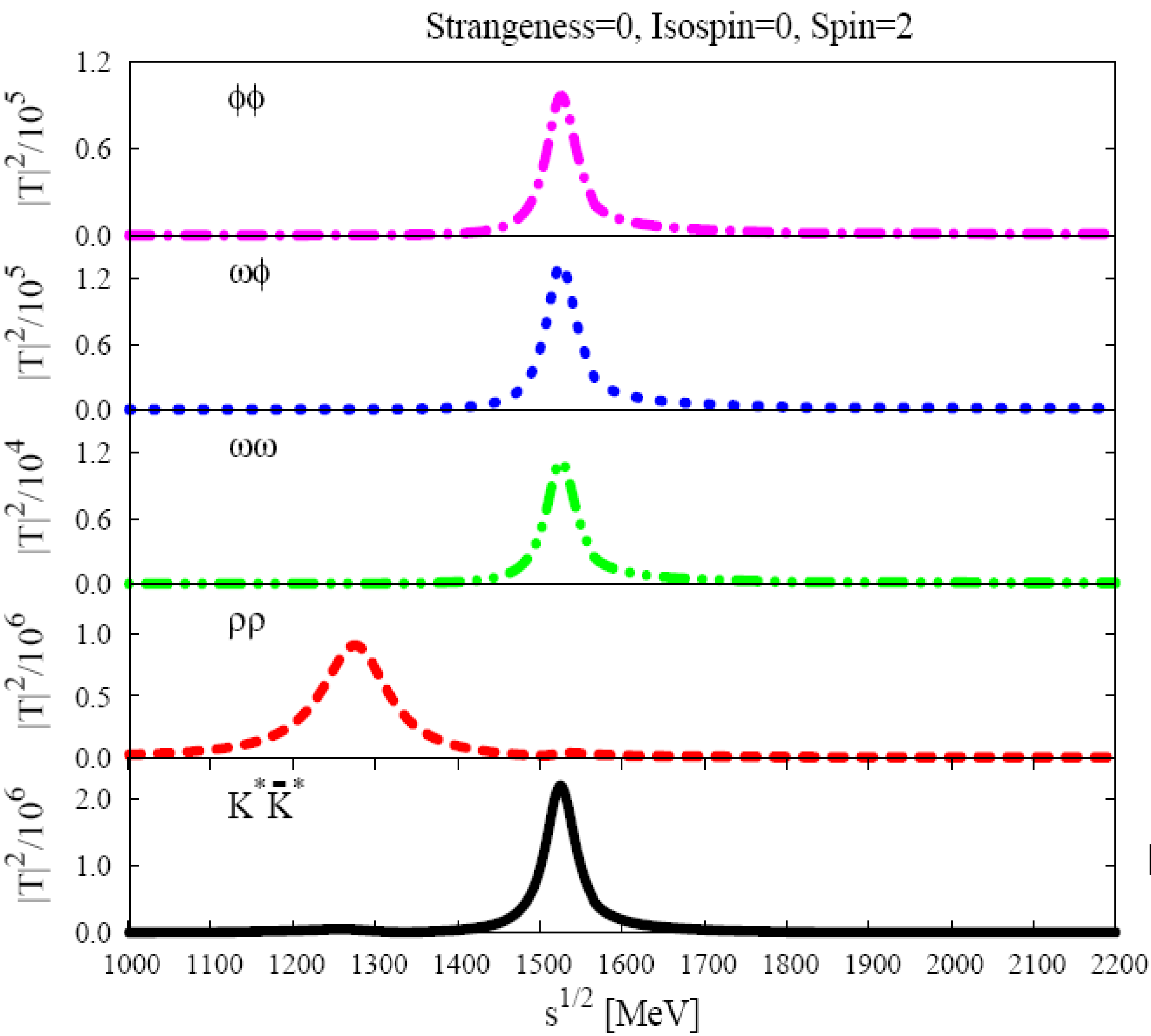




Belle finds the $f_0(1370)$ around 1470 MeV

Generalization to coupled channels: L. S. Geng , E.O, Phys Rev D 09

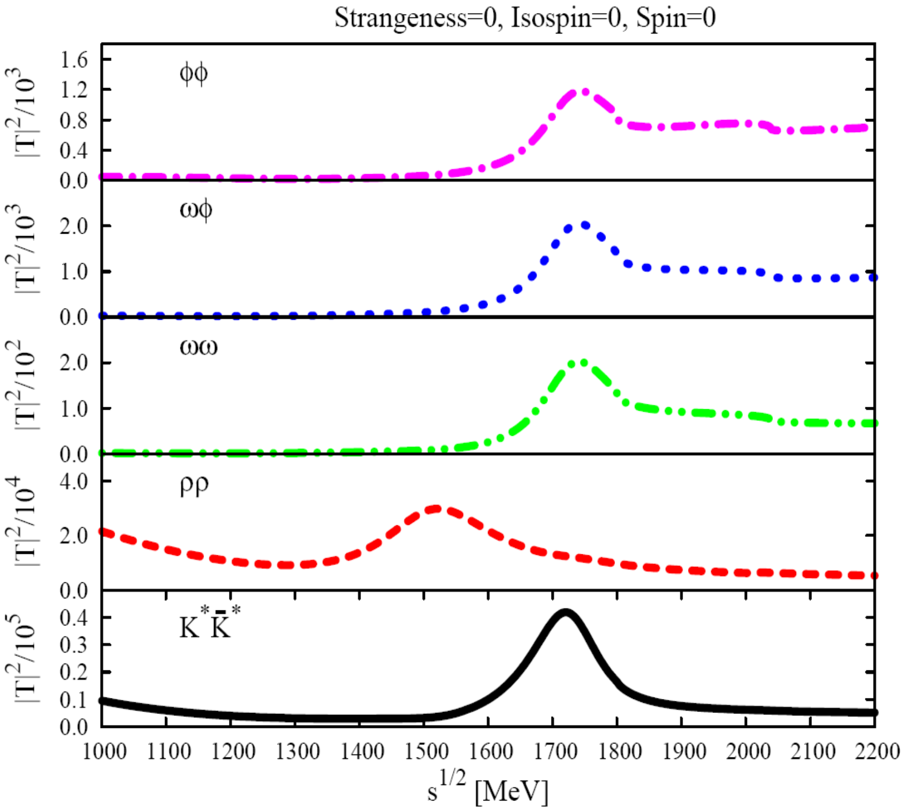
Attraction found in many channels

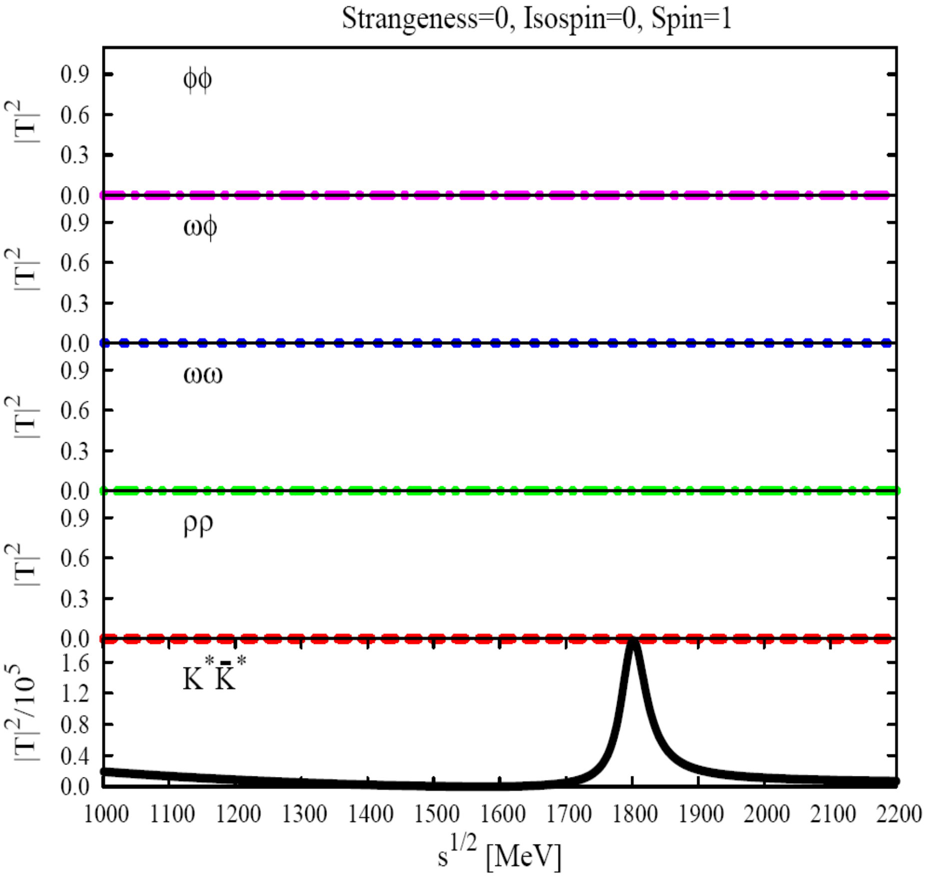


The $f_2(1270)$ is not changed by the addition of new channels, but a new resonance appears can be associated to $f'_2(1525)$

Exp :$\Gamma(f_2(1270))$= 185 MeV

Exp: $\Gamma (f'_2(1525))$ = 76 MeV





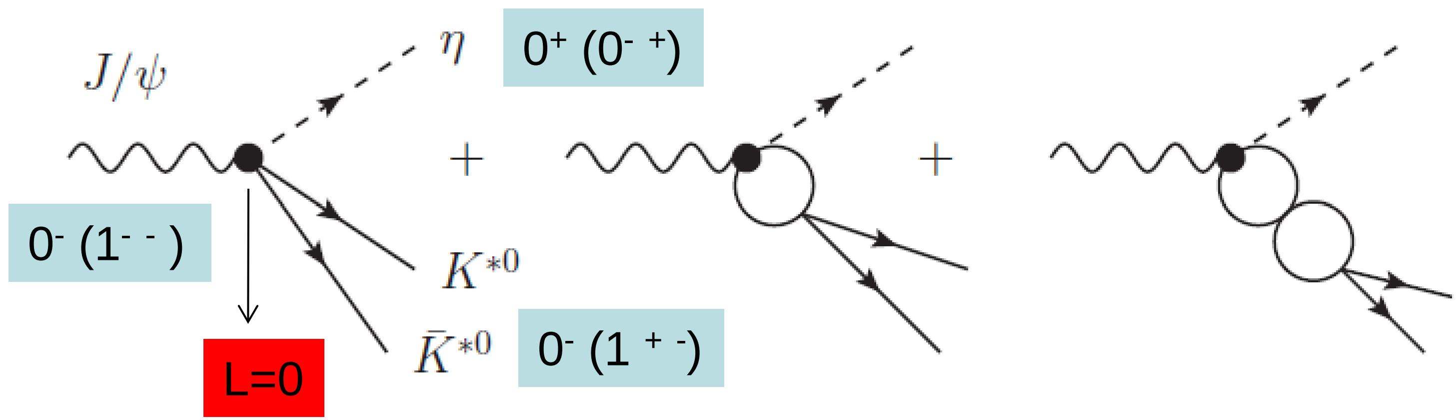
For S=1 there is no decay into pseudoscar-pseudoscalar. Indeed, V V in L=0 has P=+. J=S=1
PP needs L=1 to match J=1, but then P=-1. → The width is small
it comes only from K* K*bar (a convolution over the mass distribution of the K*'s is made)

Predicted meson states from V V interaction

$I^G(J^{PC})$	M , Γ [MeV] Theory			PDG data		
	Pole position	Real axis $\Lambda_b = 1.4$ GeV	Real axis $\Lambda_b = 1.5$ GeV	Name	Mass	Width
$0^+(0^{++})$	(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)		h_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)	$a_2(1700)$??	a_2(1320) Nagahiro PRD 11	
$1/2(0^+)$	(1643,47)	(1639,139)	(1637,162)	K_0^*		
$1/2(1^+)$	(1737,165)	(1743,126)		$K_1(1650)$?		
$1/2(2^+)$	(1431,1)	(1431,56)	(1431,63)	$K_2^*(1430)$	1429 ± 1.4	104 ± 4

Signature of an h_1 state in the $J/\psi \to \eta h_1 \to \eta K^{*0}\bar{K}^{*0}$ decay

Xie Ju Jun, M. Albaladejo and E. O, PLB 2014



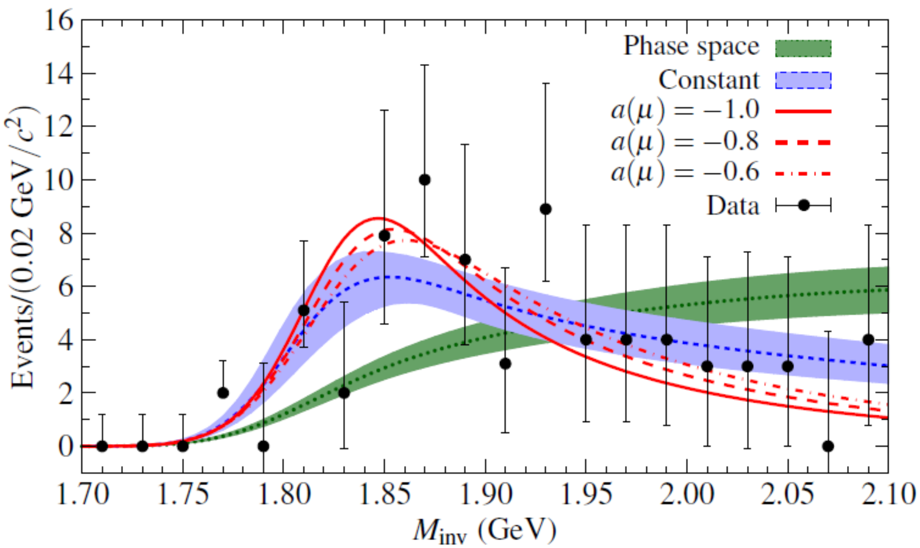
$I^G(J^{PC})$			
$0^-(1^{+-})$	(1802,78)	(1802,49)	h_1

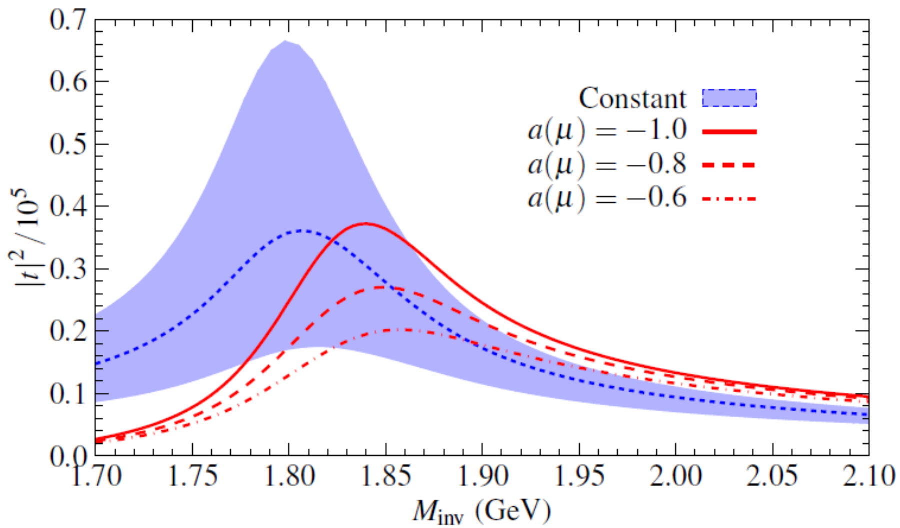
Pole positions and residues in the strangeness=0 and isospin=0 channel. All quantities are in units of MeV.

(1802, −i39) [spin=1]					
	$K^*\bar{K}^*$	$\rho\rho$	$\omega\omega$	$\omega\phi$	$\phi\phi$
g	(8034, −i2542)	0	0	0	0

does not go to VV because of C-parity
It cannot go to PP , because J=1 requires L=1 in PP -> negative parity
Thus K* K*bar is the only open channel

M.Ablikim *et al.* [BES Collaboration], Phys. Lett. B **685**, 27 (2010).





$$t = v + v\widetilde{G}t = v(1+\widetilde{G}t) = (1-v\widetilde{G})^{-1}v = (v^{-1}-\widetilde{G})^{-1}$$

$$v = \left(9 + b\left(1 - \frac{3M_{\rm inv}^2}{4m_{K^*}^2}\right)\right) g^2$$

$$t_P = V_P\left(1+\widetilde{G}(M_{\rm inv}^2)t(M_{\rm inv}^2)\right) = V_P\frac{t(M_{\rm inv}^2)}{v(M_{\rm inv}^2)}$$

$$g = m_\rho/2f$$

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

μ= 1000 MeV
a(μ) = α

$$\frac{d\Gamma}{dM_{\rm inv}} = \frac{C}{|v(M_{\rm inv}^2)|^2}\frac{p_1\widetilde{p}_2}{M_{J/\psi}}\left|t(M_{\rm inv}^2)\right|^2$$

A fit to data is made changing a(μ)

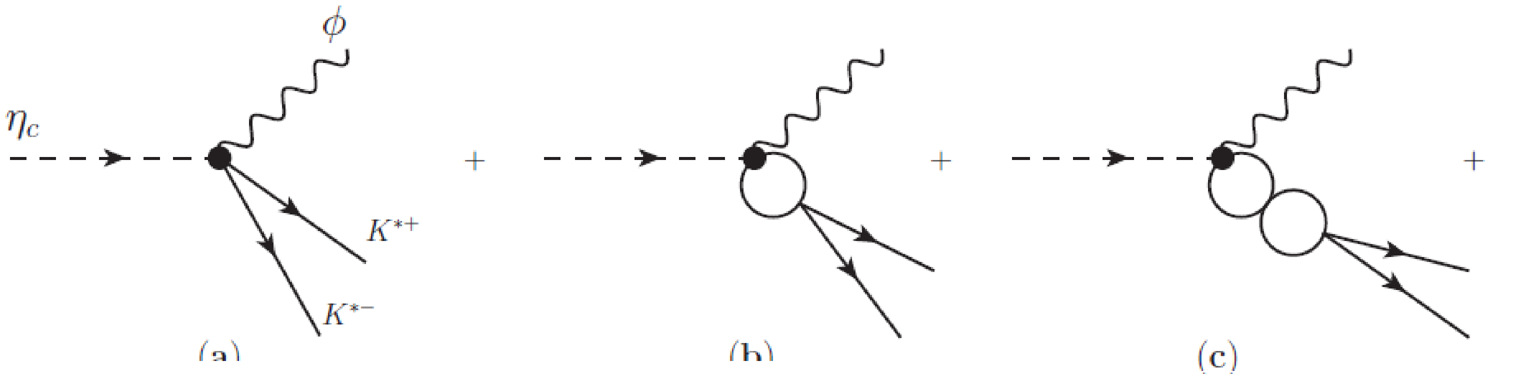
$M_{h_1} = 1830 \pm 20$ MeV and $\Gamma_{h_1} = 110 \pm 10$ MeV

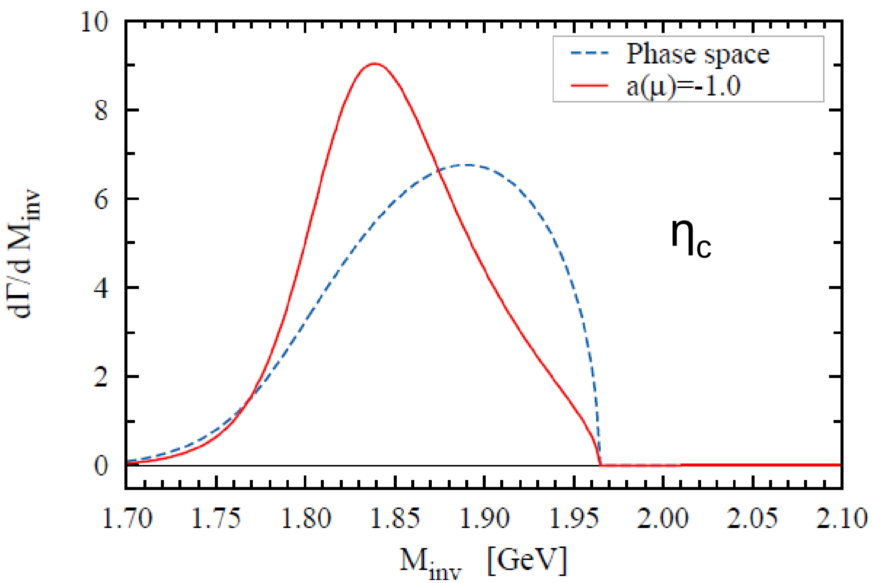
Predictions:

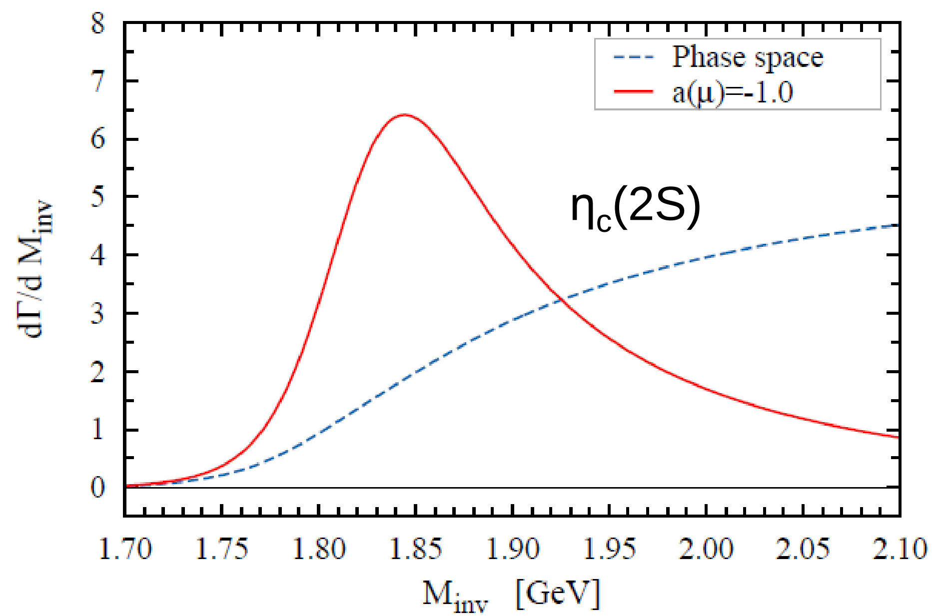
Test of the $h_1(1830)$ made of $K^*\bar{K}^*$ with the $\eta_c \to \phi K^{*+}K^{*-}$

X.-L. Ren,[1] L. S. Geng,[1,*] E. Oset,[1,2,†] and J. Meng[1,3,4]

Arxiv 2014







Z_c states: They are I=1 states, cannot be c cbar → exotic states!

BESIII Ablikim PRL 2013

$Z_c(3900)$ from the invariant mass of $\pi J/\psi$ in the $e^+e^- \to \pi^+\pi^- J/\psi$ reaction

Belle a peak is also seen in $\pi J/\psi$ around 3894 MeV Liu PRL 2013

CLEO reported a peak at 3886 MeV $I = 1$ and $J^P = 1^+$ Xiao PLB 2013

BESIII $e^+e^- \to \pi^\pm (D\bar{D}^*)^\mp$ resonance with mass around 3885 MeV

Ablikim PRL 2014

Are all these signals the same state?

Theoretical interpretations:
Voloshin discussion on possible structures, PRD 2013
Wilbring … PLB 2013, Wang ….PLB2013, Dong …PRD2013, Ke …EPJC2013
claim a D D*bar molecule
Dias … PRD2013, Qiao Arkix2013 claim pentaquark ….

More Z_c states

BESIII in $e^+e^- \to \pi^+\pi^- h_c$ reaction, looking at the invariant mass of $\pi^\pm h_c$.

$Z_c(4020)$ and a width of about 8 MeV Ablikim 2013

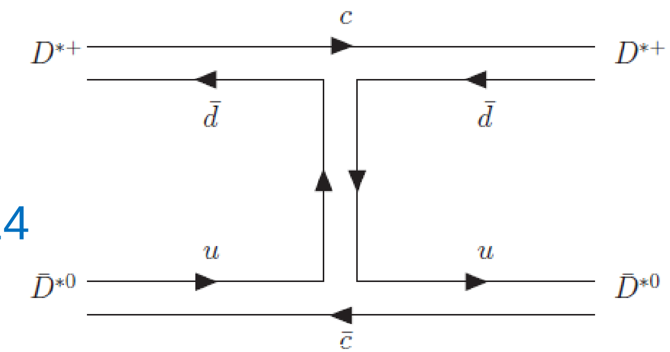
BESIII $(D^*\bar{D}^*)^\pm$ spectrum close to threshold

mass around 4025 MeV and width about 25 MeV Ablikim 2013

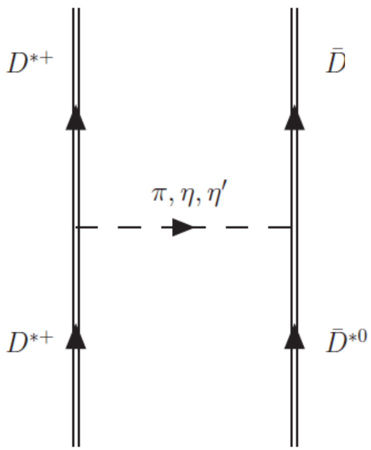
Are they the same state? Can one get different results from the reanalysis of the D* D*bar spectrum at threshold?

Theoretical approach
General observations

Aceti, Dias, Bayar, E. O, EPJA2014

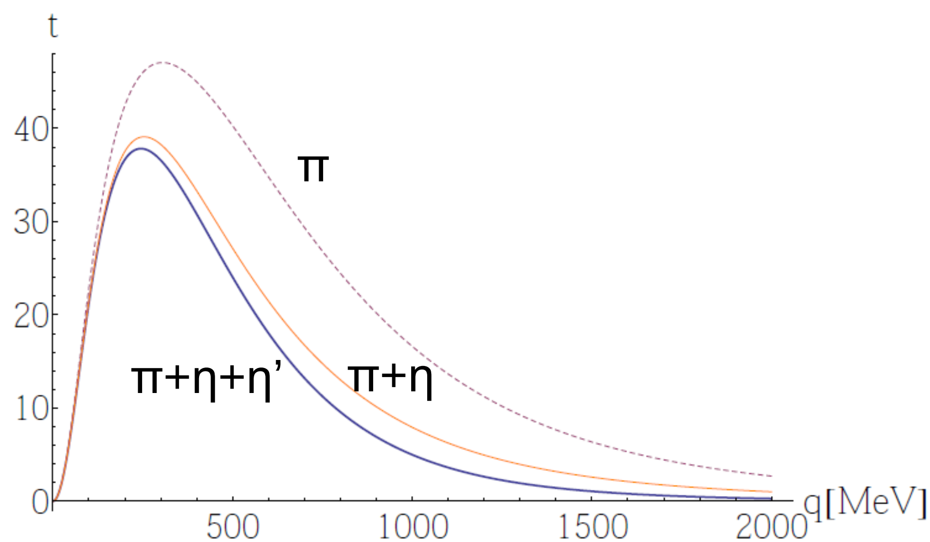


Light meson exchange is OZI forbidden

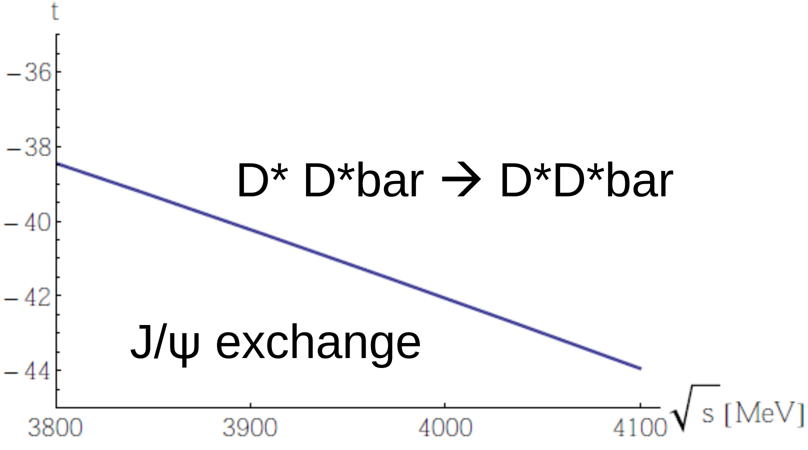


$$\mathcal{L} = \frac{G}{\sqrt{2}} \epsilon^{\mu\nu\alpha\beta} \langle \partial_\mu V_\nu \partial_\alpha V_\beta P \rangle \qquad P = \begin{pmatrix} \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 & D^- \\ K^- & \bar{K}^0 & -\frac{\eta}{\sqrt{3}} + \sqrt{\frac{2}{3}}\eta' & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix}$$

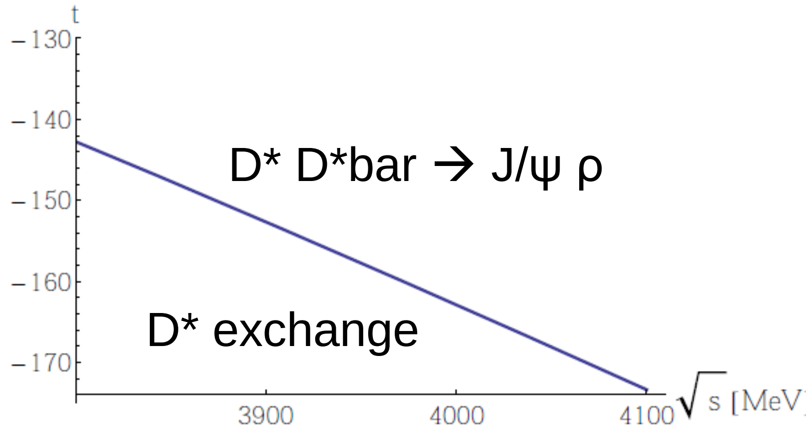
$$t \simeq -\frac{G^2}{2} m_{D^*}^2 \; \vec{q} \cdot (\vec{\epsilon}_1 \times \vec{\epsilon}_3) \; \vec{q} \cdot (\vec{\epsilon}_2 \times \vec{\epsilon}_4) \left(-\frac{1}{2} \frac{1}{q^2 - m_\pi^2} + \frac{1}{3} \frac{1}{q^2 - m_\eta^2} + \frac{1}{6} \frac{1}{q^2 - m_{\eta'}^2} \right)$$



Similarly, ρ+ω also cancels: Only heavy quark exchange is allowed:
But one must take into account coupled channels: D* D*bar, J/ψ ρ,
the strength is largest in J=2.

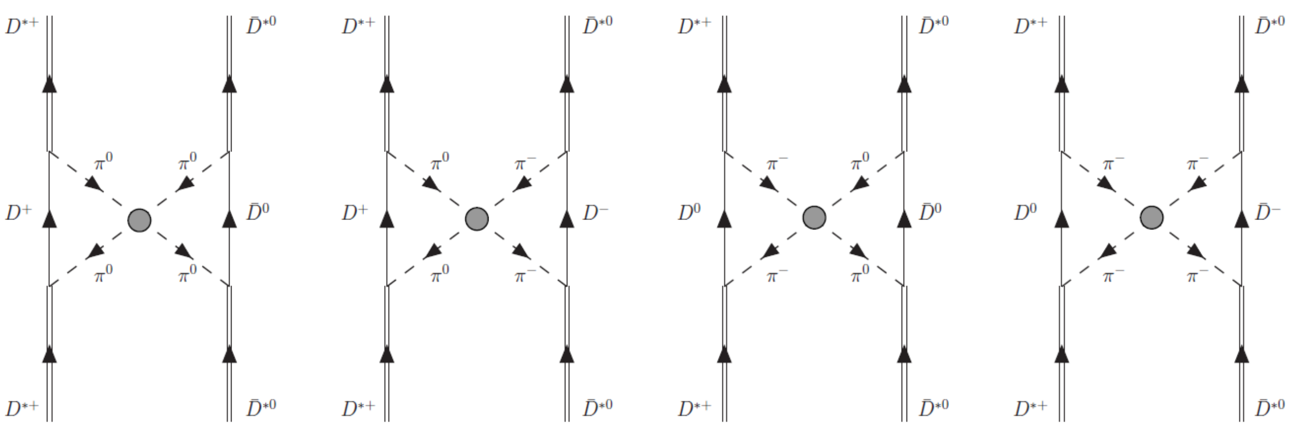


(a)

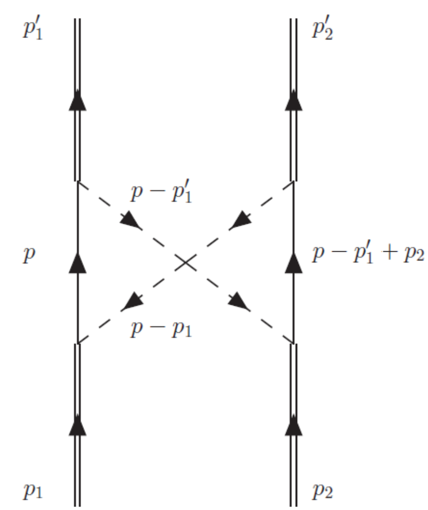


(b)

Two pion exchange is not OZI forbidden: We have evaluated correlated an uncorrelated two pion exchange. Vector exchange is dominant



a) b) c) d)



Theoretical results from vector exchange and coupled channels

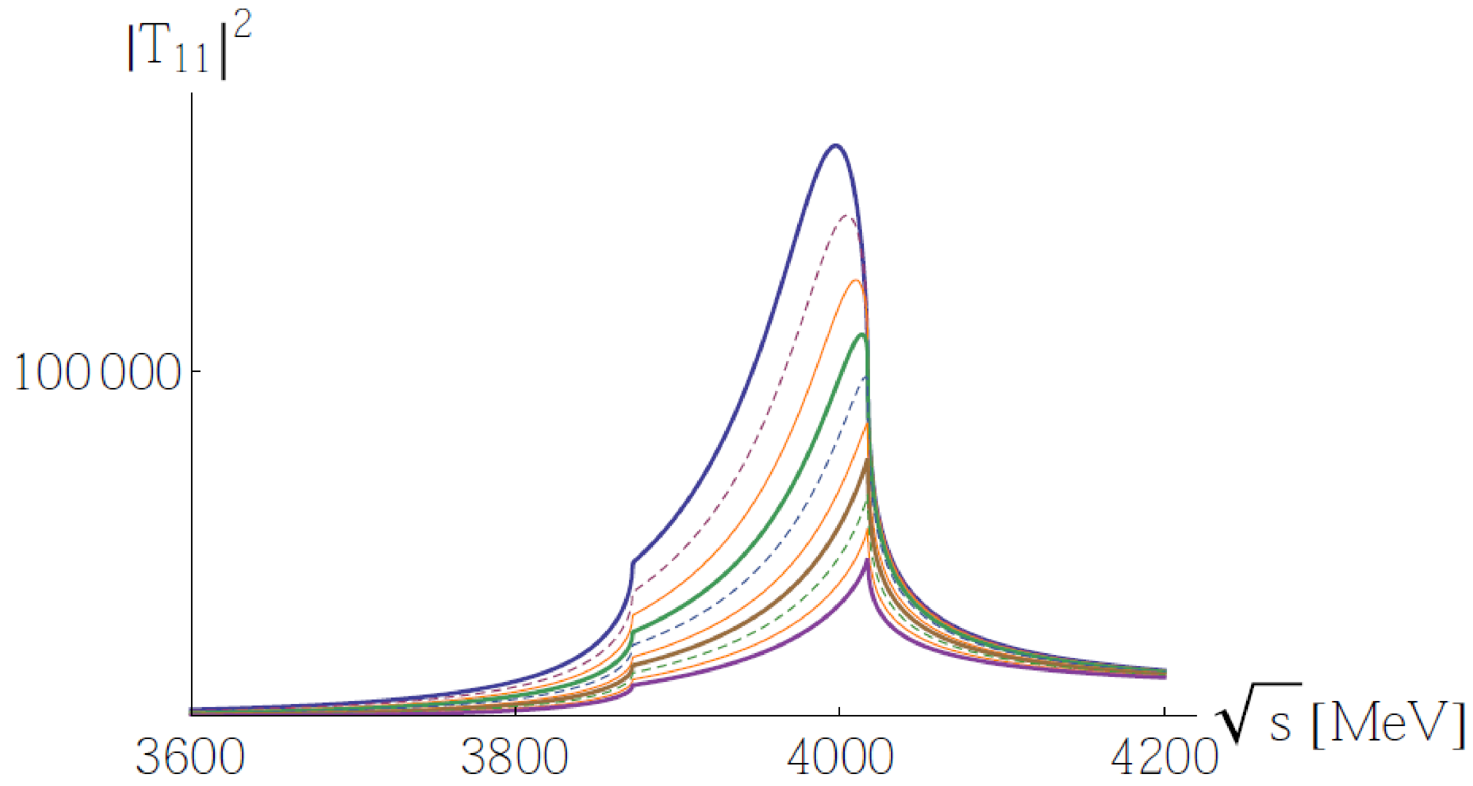
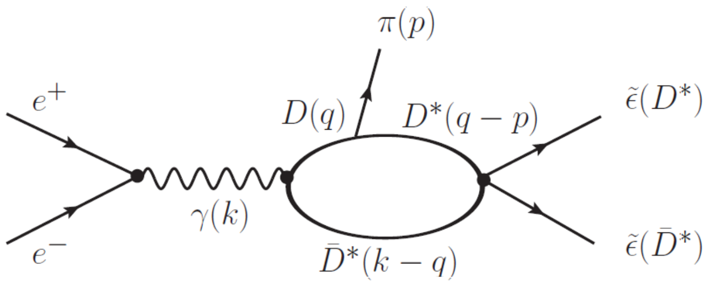


FIG. 16. $|T_{11}|^2$ as a function of $\sqrt{s}$, for different values of the cutoff q_{max}. From up down, $q_{max} = 960, 900, 850, 800, 750, 700, 650, 600, 550, 500$ MeV.

We get a clear signal in the scattering matrix, close to threshold or a few MeV below it, around 3990-4010 MeV. Smaller mass than 4025 claimed in experiment!. Also Γ around 160 MeV, bigger than claimed in exp. (35 MeV).

Is there really a contradiction??

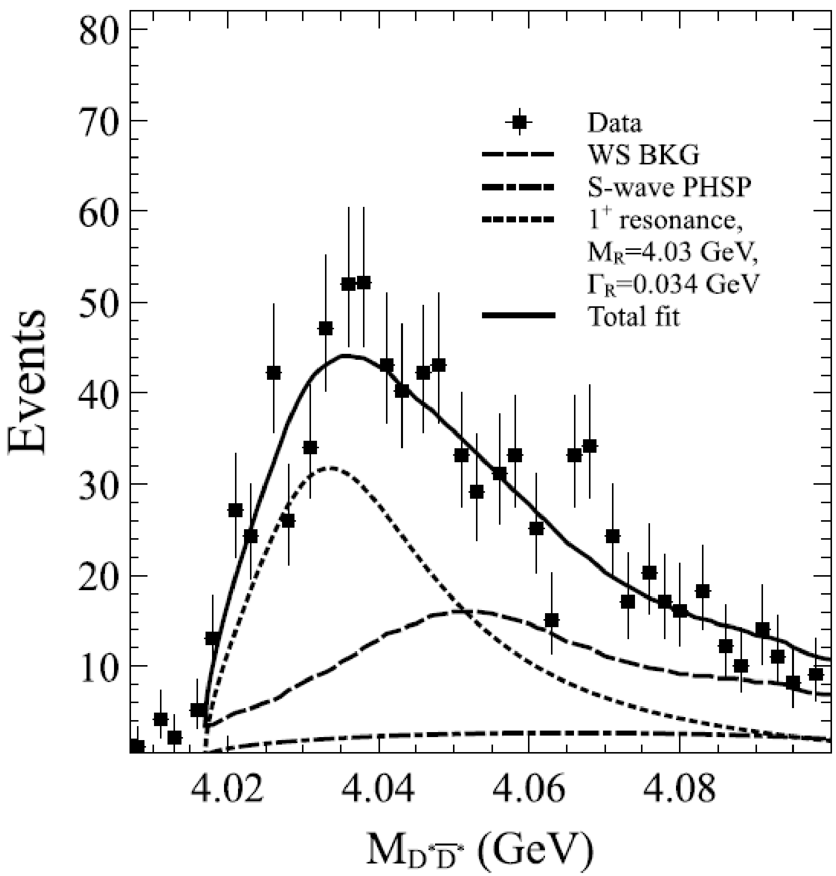
Reanalysis of the experiment. We use the dynamics of the mechanism:

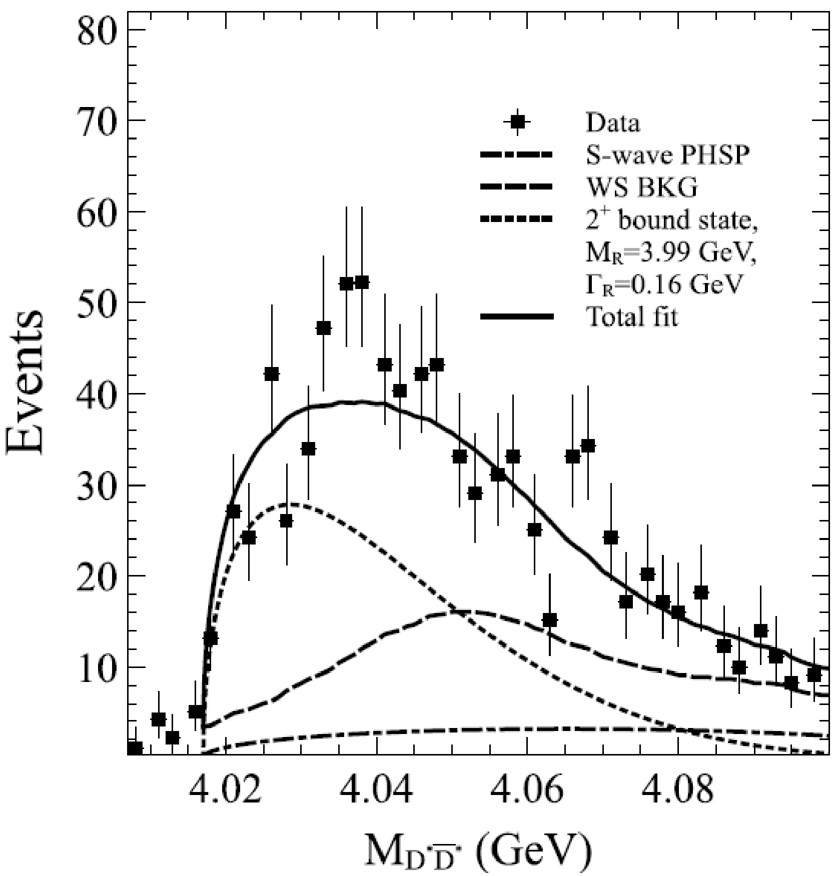


The conclusion is that while a fit like the one suggested in the exp. is OK, other fits, with J=2, more bound and with bigger width are possible.

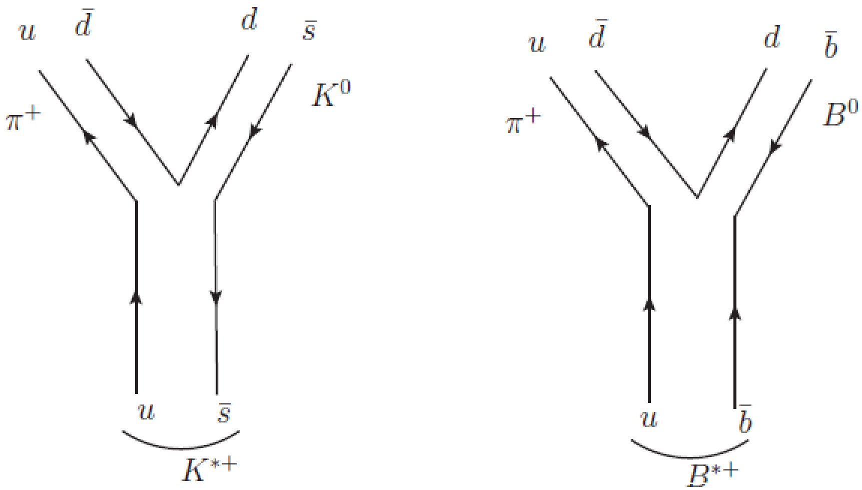
Martinez Torres, Khemchandani, Navarra Nielsen, E.O. PRD2014

DETERMINE J FOR THIS STATE





Heavy quark spin symmetry made simple, W.H. Liang, C.W. Xiao, E.O. PRD 14



$$S^{mic} = 1 - it\sqrt{\frac{2m_L}{2E_L}}\sqrt{\frac{2m'_L}{2E'_L}}\sqrt{\frac{1}{2\omega_\pi}}\frac{1}{\mathcal{V}^{3/2}}(2\pi)^4\delta(P_{in}-P_{out})$$

$$S^{mac}_{K^*} = 1 - it_{K^*}\frac{1}{\sqrt{2\omega_{K^*}}}\frac{1}{\sqrt{2\omega_K}}\frac{1}{\sqrt{2\omega_\pi}}\frac{1}{\mathcal{V}^{3/2}}(2\pi)^4\delta(P_{in}-P_{out}),$$

$$S^{mac}_{B^*} = 1 - it_{B^*}\frac{1}{\sqrt{2\omega_{B^*}}}\frac{1}{\sqrt{2\omega_B}}\frac{1}{\sqrt{2\omega_\pi}}\frac{1}{\mathcal{V}^{3/2}}(2\pi)^4\delta(P_{in}-P_{out}).$$

$$\frac{t_{B^*}}{t_{K^*}} \equiv \frac{\sqrt{m_{B^*}m_B}}{\sqrt{m_{K^*}m_K}} \simeq \frac{m_{B^*}}{m_{K^*}}.$$

Agreement with lattice QCD for B* and with experimental D* decay width to D π

In the exchange of vector mesons the dominant term in the vertex PPV is proportional to (p^0+p'^0) leading to the Weinberg Tomozawa term of the chiral Lagrangians. → The correcting factor demanded by the HQSS is automatically implemented.

This justifies a posteriori the plain extrapolation of the WT interaction to the heavy sector done in many works:

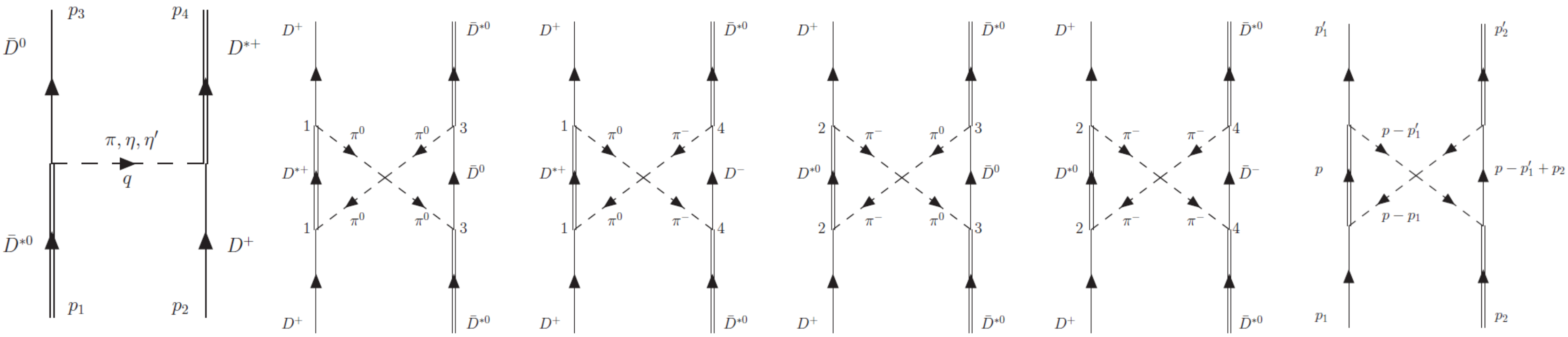
Wu and Zou
Ramos et al
Kolomeitsev et al
Gamermann et al…
Hosaka et al
Nieves et al ……………….

The D D*bar states

$$(I^G(J^{PC}) = 1^+(1^{+-}))$$

$$\pi\omega\ \eta\rho,\ (\bar{K}K^* + c.c.)/\sqrt{2},\ (\bar{D}D^* + c.c.)/\sqrt{2},\ \eta_c\rho \text{ and } \pi J/\Psi$$

Aceti, Bayar, Dias, E.O., Martinez Torres, Khemchandani, Navarra, Nielsen 2014



Once again heavy vector exchange is dominant and all the pseudoscalar exchanges are smaller. We exchange J/ψ in the diagonal channels and D* In the non diagonal. The vector interaction is also weaker here than in D*D*bar

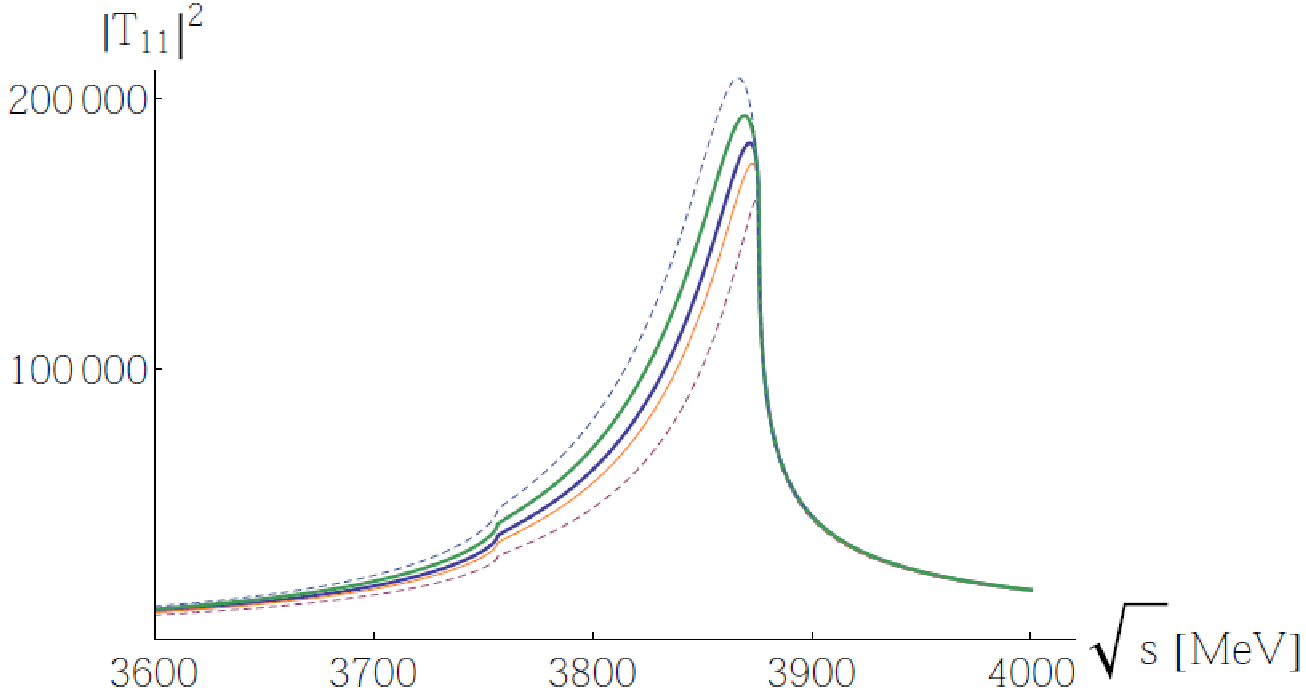
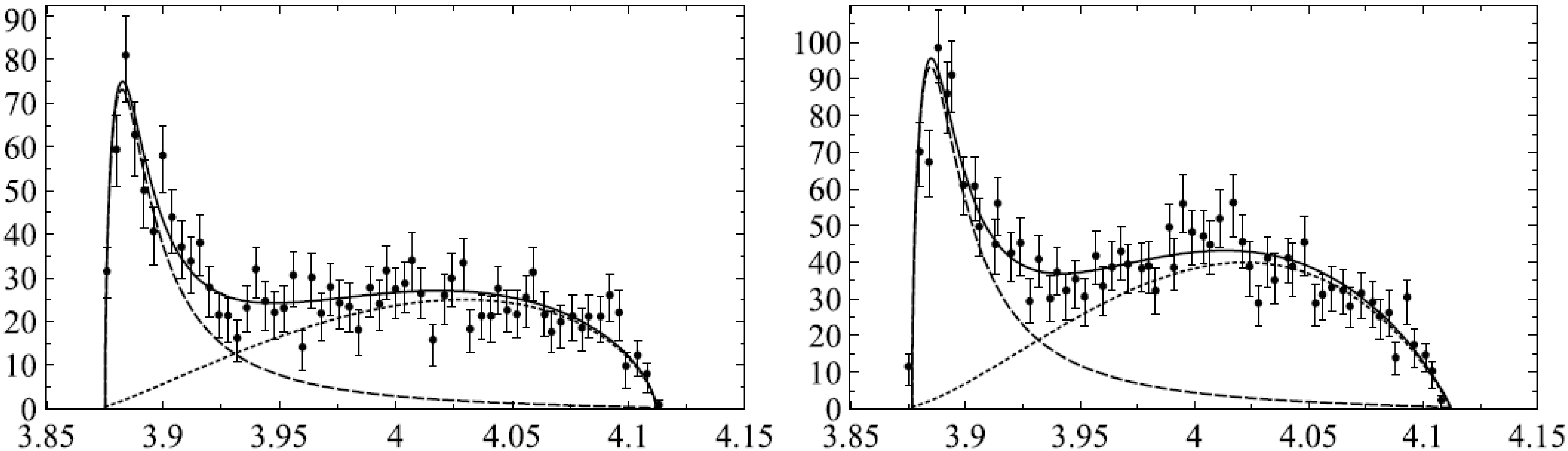


FIG. 12. $|T|^2$ as a function of $\sqrt{s}$ for values of the cutoff q_{max} equal to 850, 800, 770, 750 and 700 MeV. The peak moves to the left as the cutoff increases.

We get results between 3865-3875 MeV and Γ around 30 MeV.
Mass lower than 3885 MeV of exp. Γ is compatible with exp. 25+-14 MeV

Can a reanalysis give smaller masses? YES

$M_R = 3875.62$ MeV, width $\Gamma_R = 30$ MeV (right panel)



$M_R = 3874.15$ MeV, width $\Gamma_R = 27$ MeV (left panel)

The reanalysis can accommodate 3862-3884 MeV, but Chisquare too big above this.

Conclusions

Chiral dynamics plays an important role in hadron physics. The local hidden gauge extends it and allows to deal with vector mesons

Their combination with nonperturbative unitary techniques allows to study the interaction of hadrons. Poles in amplitudes correspond to dynamically generated resonances. Many of the known meson and baryon resonances can be described in this way.

One of the predictions, h_1 state around 1830 MeV is confirmed by BES data

The exotic Z_c states, around Z_c(3900) or Z_c(4000) can be understood as D D*bar or D* D*bar with coupled channels, respectively.
Very little bound, Z_c(4000) with J=2.
Reanalysis of data allows for different masses and widths compatible with theoretical predictions.

Experimental challenges to test the nature of these resonances looking for quantum numbers, new decay channels or production modes.