Hadron-hadron molecules in the heavy hadron spectrum

Bound states and resonances in effective field theory and lattice QCD calculations

Benasque 2014

D.R. Entem

Thanks to my collaborators:

P.G. Ortega, J. Segovia, F. Fernández

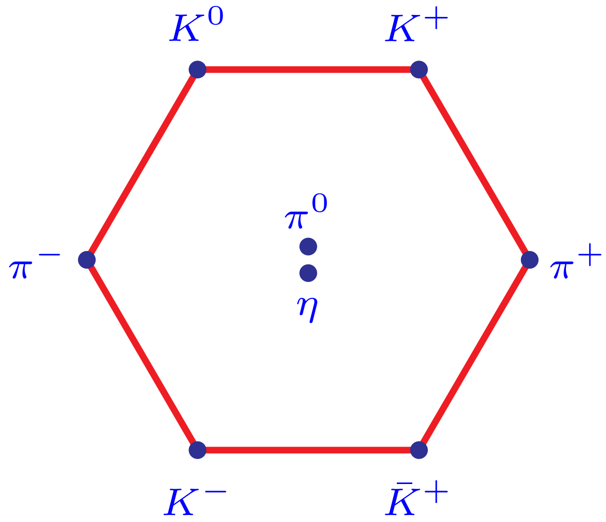
University of Salamanca

Outline

- Introduction
- hadron-hadron states
  - The two-baryon sector:
    - NN sector
    - $\Delta\Delta$ states
  - The two-meson sector:
    - The $X(3872)$
    - The 0^{++} and 1^{--} sectors
  - The baryon-meson sector:
    - The $\Lambda_c(2940)^+$
    - The $X_c(3250)$
- Summary

The Model

J. Vijande *et al.*, J. Phys. G 31



- Spontaneous Chiral Symmetry Breaking $\longrightarrow$
  - $\longrightarrow$ Golstone bosons
  - $\longrightarrow$ Goldstone bosons exchange
  - $\longrightarrow$ Scalar boson exchanges
- Gluon coupling

$$\mathcal{L}_{gqq} = i\sqrt{4\pi\alpha_s}\,\bar{\Psi}\gamma_\mu G_c^\mu \lambda^c \Psi$$

  - $\longrightarrow$ One gluon exchange
- Confinement
  Color screened confinement
- Interactions:

$$V_{q_i q_j} = \begin{cases} q_i q_j = nn \Rightarrow V_{CON} + V_{OGE} + V_{GBE} + V_{SBE} \\ q_i q_j = nQ \Rightarrow V_{CON} + V_{OGE} \\ q_i q_j = QQ \Rightarrow V_{CON} + V_{OGE} \end{cases}$$

Model Results for 1^{--} sector.

(nL)	States	QM	Exp.
(1S)	J/ψ	3096	$3096{,}916 \pm 0{,}011$
(2S)	$\psi(2S)$	3703	$3686{,}09 \pm 0{,}04$
(1D)	$\psi(3770)$	3796	$3772 \pm 1{,}1$
(3S)	$\psi(4040)$	4097	4039 ± 1
(2D)	$\psi(4160)$	4153	4153 ± 3
(4S)		4389	
(3D)	$\psi(4415)$	4426	4421 ± 4
(5S)		4614	
(4D)		4641	

Masses in MeV of $J^{PC} = 1^{--}$ $c\bar{c}$ mesons (nL) refers to the dominant partial wave and QM denotes the results of the model.

XYZ Mesons

N.Brambila et al. Eur. Phys. J. C 71, 1534 (2011)

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), *BABAR* [87] (8.6)	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \cdots$	CDF [88–90] (np), DØ [91] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), *BABAR* [93] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), *BABAR* [96] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), *BABAR* [97, 98] (3.6)		
				$B \to K(\gamma \psi(2S))$	*BABAR* [98] (3.5), Belle [99] (0.4)		
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), *BABAR* [101] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (\ldots)$	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	*BABAR* [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	$4008^{+121}_{-\ 49}$	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	$15^{+11}_{-\ 7}$	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!

XYZ Mesons

N.Brambila et al. Eur. Phys. J. C 71, 1534 (2011)

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	*BABAR* [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$	Belle [114] (5.8)	2007	NC!
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^- \Upsilon(nS))$	Belle [37, 117] (3.2)	2010	NC!

XYZ Mesons

Meson	Mass (Exp)	Candidate?	J^{PC}	Mass (Th)
$Y(4360)$	4353 ± 11	$\psi(4S)$	1^{--}	4389
$X(4630)$	4634^{+9}_{-11}	$\psi(5S)$	1^{--}	4614
$Y(4660)$	4664 ± 12	$\psi(4D)$	1^{--}	4641
$X(4160)$	4156 ± 15	η_{c2}	2^{-+}	4166

Candidates for some XYZ mesons in our CQM $c\bar{c}$ spectrum.

No $c\bar{c}$ candidates for $X(3872)$, $X(3915)$, $X(3940)$, $G(3900)$, $Y(4008)$, $Y(4140)$, $Y(4260)$, $Y(4274)$, $X(4350)$,

$^3P_0$ model

- **Pair creation Hamiltonian:**

$$\mathcal{H} = g \int d^3x \bar{\psi}(x)\psi(x)$$

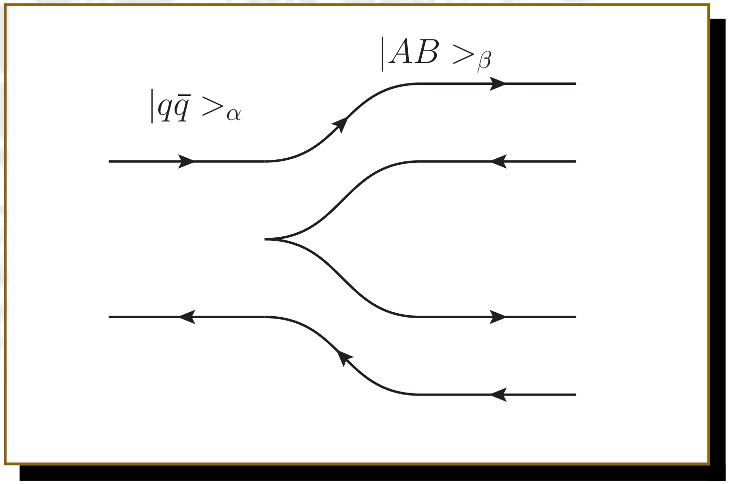
- **Non relativistic reduction:**

$$T = -3\sqrt{2}\gamma' \sum_{\mu} \int d^3p d^3p' \, \delta^{(3)}(p+p') \left[\mathcal{Y}_1 \left(\frac{p-p'}{2} \right) b^\dagger_\mu(p) d^\dagger_\nu(p') \right]^{C=1,I=0,S=1,J=0}$$

with $\gamma' = 2^{5/2}\pi^{1/2}\gamma$, $\gamma = \frac{g}{2m}$ **(in the light quark sector)**

- **Transition potential:**

$$\langle \phi_{M_1}\phi_{M_2}\beta | T | \psi_\alpha \rangle = P h_{\beta\alpha}(P)\delta^{(3)}(\vec{P}_{cm})$$



$^3P_0$ results for $c\bar{c}$ strong decays

γ **parameter fitted to** $\psi(3770) \to DD$
Phys. Rev. D 78, 114033 (2008).

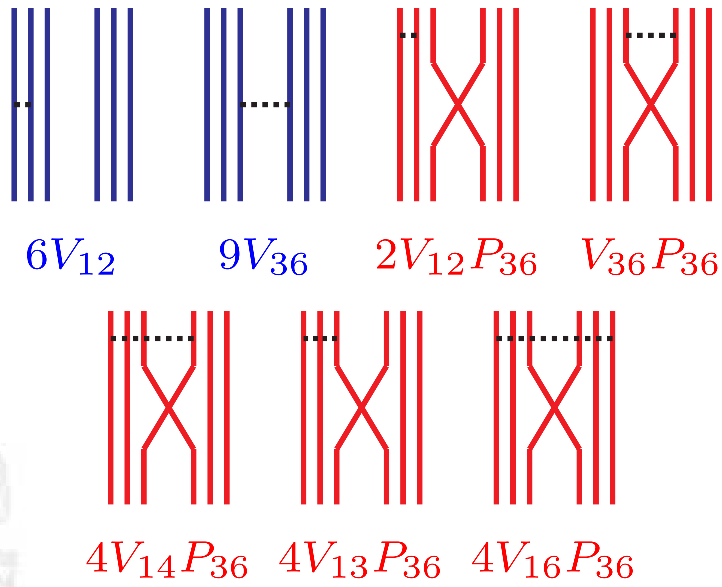
Meson	**Dominant Mode**	Γ_{QM} **(**MeV**)**	Γ_{exp} **(**MeV**)**
$\psi(3770)$	DD	22,2	$22{,}4 \pm 2{,}5$
	D^+D^-	9,5	$9{,}5 \pm 1{,}4$
	$D^0\bar{D}^0$	12,7	$12{,}8 \pm 1{,}8$
$\psi(4040)$	D^*D^*	92,9	80 ± 10
$\psi(4160)$	D^*D^*	96,8	103 ± 8
$\psi(4360)$	DD_1	89,8	103 ± 11
$\psi(4415)$	DD_1	113,1	$119 \pm 16(^*)$
$\psi(4660)$	D^*D^*	107,9	42 ± 6

The baryon-baryon sector

The NN interaction

$$\psi_B = \phi_B(\vec{p}_{\xi_1},\vec{p}_{\xi_2})\chi_B\xi_c[1^3]$$

$$\phi_B(\vec{p}_{\xi_1},\vec{p}_{\xi_2}) = \left[\frac{2b^2}{\pi}\right]^{\frac{3}{4}} e^{-b^2 p_{\xi_1}^2} \left[\frac{3b^2}{2\pi}\right]^{\frac{3}{4}} e^{-\frac{3b^2}{4}p_{\xi_2}^2}$$



$$\begin{aligned}\psi_{B_1B_2} &= \mathcal{A}\left[\chi(\vec{P})\psi^{ST}_{B_1B_2}\right]\\ &= \mathcal{A}\left[\phi_{B_1}(\vec{p}_{\xi_{B_1}})\phi_{B_2}(\vec{p}_{\xi_{B_2}})\chi(\vec{P})\chi^{ST}_{B_1B_2}\xi_c[2^3]\right]\end{aligned}$$

Rayleigh-Ritz variational principle (Resonating Group Method)

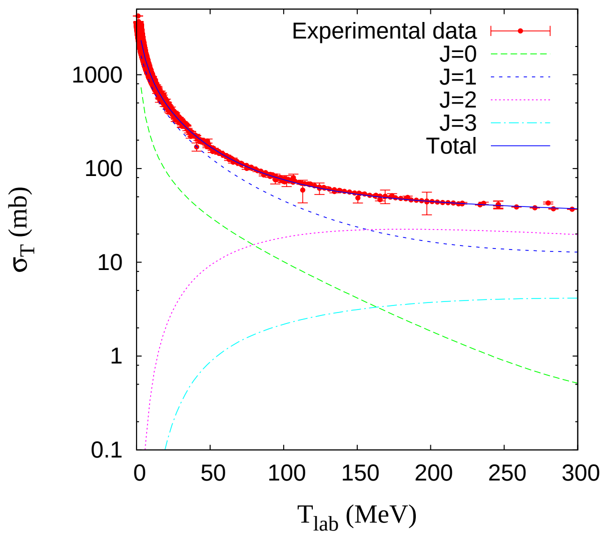
$$(\mathcal{H}-E_T)\,|\,\psi\,\rangle = 0 \quad \Rightarrow \quad \langle\,\delta\psi\,|\,(\mathcal{H}-E_T)\,|\,\psi\,\rangle = 0$$

$$\left(\frac{\vec{P}'^{\,2}}{2\mu}-E\right)\chi(\vec{P}') + \int\left({}^{\rm RGM}V_D(\vec{P}',\vec{P}_i) + {}^{\rm RGM}K(\vec{P}',\vec{P}_i)\right)\chi(\vec{P}_i)d\vec{P}_i = 0$$

$$T_\alpha^{\alpha'}(z;p',p) = V_\alpha^{\alpha'}(p',p) + \sum_{\alpha''}\int dp''\,p''^2\,V_{\alpha''}^{\alpha'}(p',p'')\frac{1}{z-E_{\alpha''}(p'')}T_\alpha^{\alpha''}(z;p'',p)$$

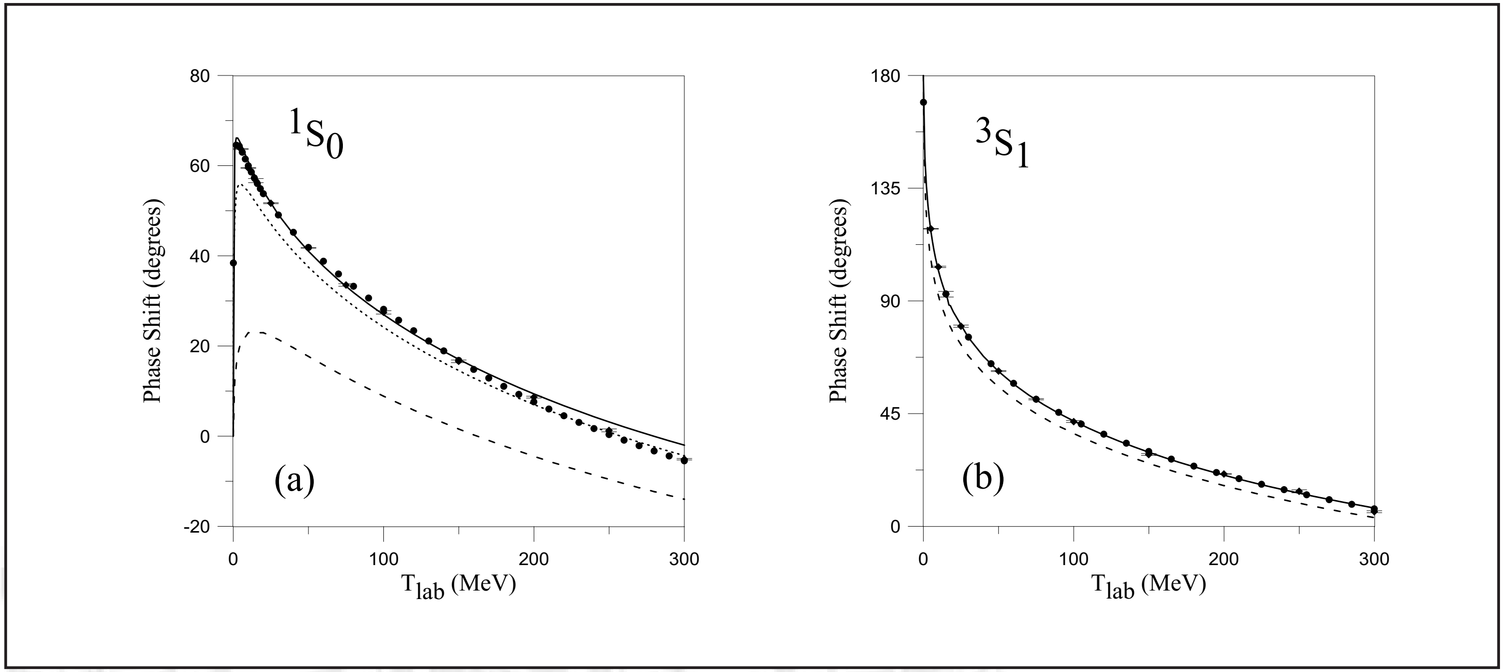
Lippmann-Schwinger Equation

NN System



- **Constituent quark model,** *Phys. Rev C 62, 034002 (2000)*

NN System



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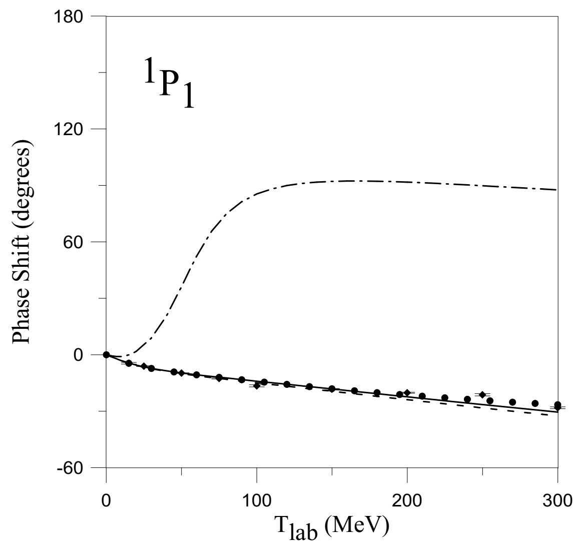

- **Constituent quark model,** *Phys. Rev C 62, 034002 (2000)*
- **Antisymmetry gives repulsion**

NN System

	Quark	χN^{3}LO	CD-Bonn	Exp.
E_D (MeV)	2.2246	2.224575	2.224575	2.224575(9)
r_m (fm)	1.985	1.978	1.970	1.97535(85)
A_S (fm$^{-1/2}$)	0.8941	0.8843	0.8846	0.8846(9)
η	0.0250	0.0256	0.0256	0.0256(4)

- **Constituent quark model,** *Phys. Rev C 62, 034002 (2000)*
- **Antisymmetry gives repulsion**
- **One bound state in NN, what happens in channels where antisymmetry is not present?**

ΔΔ states

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **27** (2001) L1–L7 www.iop.org/Journals/jg PII: S0954-3899(01)14892-9

LETTER TO THE EDITOR

ΔΔ and ΔΔΔ bound states

A Valcarce[1], H Garcilazo[2], R D Mota[2] and F Fernández[1]

Table 2. Binding energies B_2 (in MeV) of the ΔΔ states with total angular momentum j and isospin i obtained in the chiral quark cluster model using only the direct term or the direct plus exchange terms of the interaction and in the meson-exchange model.

	B_2		
(j, i)	Quark direct	Quark direct + exchange	Meson exchange
(0, 1)	188.8	108.4	2035.3
(0, 3)	6.0	0.4	Unbound
(1, 0)	193.9	138.5	2651.7
(1, 2)	70.0	5.7	Unbound
(2, 1)	76.4	30.5	43.0
(2, 3)	35.6	Unbound	Unbound
(3, 0)	17.4	29.9	8.2
(3, 2)	30.7	Unbound	Unbound

ΔΔ states

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(2, 3)	35.6	Unbound	Unbound
(3, 0)	17.4	29.9	8.2
(3, 2)	30.7	Unbound	Unbound

Also in the QDCSM the 3^+ $I = 0$ state appears

J.L. Ping *et al.*, Phys. Rev. C 78 (2009)

ΔΔ states

The ABC effect (WASA/CELSIUS Collaboration)

PRL **106**, 242302 (2011) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2011

Abashian-Booth-Crowe Effect in Basic Double-Pionic Fusion: A New Resonance?

P. Adlarson,[1] C. Adolph,[2] W. Augustyniak,[3] V. Baru,[4,5] M. Bashkanov,[6] T. Bednarski,[7] F. S. Bergmann,[8]

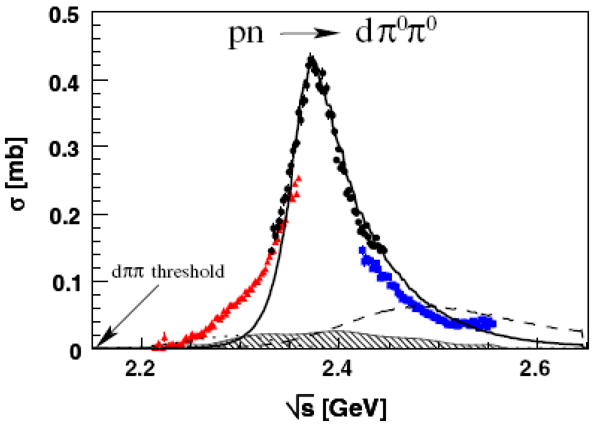

FIG. 2 (color online). Total cross sections obtained from this experiment on $pd \to d\pi^0\pi^0 + p_{\text{spectator}}$ for the beam energies $T_p = 1.0$ GeV (triangles), 1.2 GeV (dots), and 1.4 GeV (squares) normalized independently. Shown are the total cross section data after acceptance, efficiency and Fermi motion corrections. The hatched area indicates systematic uncertainties. The drawn lines represent the expected cross sections for the Roper excitation process (dotted) and the t-channel ΔΔ contribution (dashed) as well as a calculation for a s-channel resonance with $m = 2.37$ GeV and $\Gamma = 68$ MeV (solid).

- The observables are consistent with a $I(J^P) = 0(3^+)$ resonance
- Inconsistency with the NN inelastic cross section?
  - G. Faldt and C. Wilkin, Phys, Lett. B 701 for $\pi^0\pi^0$
  - M. Albaladejo and E. Oset arXiv:1304.7698 for $\pi^+\pi^-$
- A posible candidate for a ΔΔ state
  A. Pricking, M. Bashkanov and H. Clement arXiv:1310:5532
- A new proposal as a NN^* state
  D. Bugg Eur. Phys. J A50

The meson-meson sector

Measured Properties of $X(3872)$

- **Quantum Numbers** $J^{PC} = 1^{++}$ **(confirmed by LHCb)**
- **Width :** $\Gamma < 1{,}2 MeV$
- **Mass :** $M_X = 3871{,}68 \pm 0{,}17\ MeV/c^2$ $\rightarrow$ **below** $D^0 D^{*0}$ **mass threshold of** $3871{,}80 \pm 0{,}35\ MeV/c^2$
- $\frac{\mathcal{B}(X \rightarrow J/\psi \pi^+ \pi^- \pi^0)}{\mathcal{B}(X \rightarrow J/\psi \pi^+ \pi^-)} = 0{,}8 \pm 0{,}3$
- $\frac{\mathcal{B}(X \rightarrow J/\psi \gamma)}{\mathcal{B}(X \rightarrow J/\psi \pi^+ \pi^-)} = 0{,}33 \pm 0{,}12$ $\qquad \frac{\mathcal{B}(X \rightarrow \psi(2S)\gamma)}{\mathcal{B}(X \rightarrow J/\psi \gamma)} < 2{,}1$
- $\frac{\mathcal{B}(X \rightarrow \psi(2S)\gamma)}{\mathcal{B}(X \rightarrow J/\psi \pi^+ \pi^-)} = 1{,}1 \pm 0{,}4$

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- $\frac{\mathcal{B}(X \rightarrow \psi(2S)\gamma)}{\mathcal{B}(X \rightarrow J/\psi\pi^+\pi^-)} = 1{,}1 \pm 0{,}4$

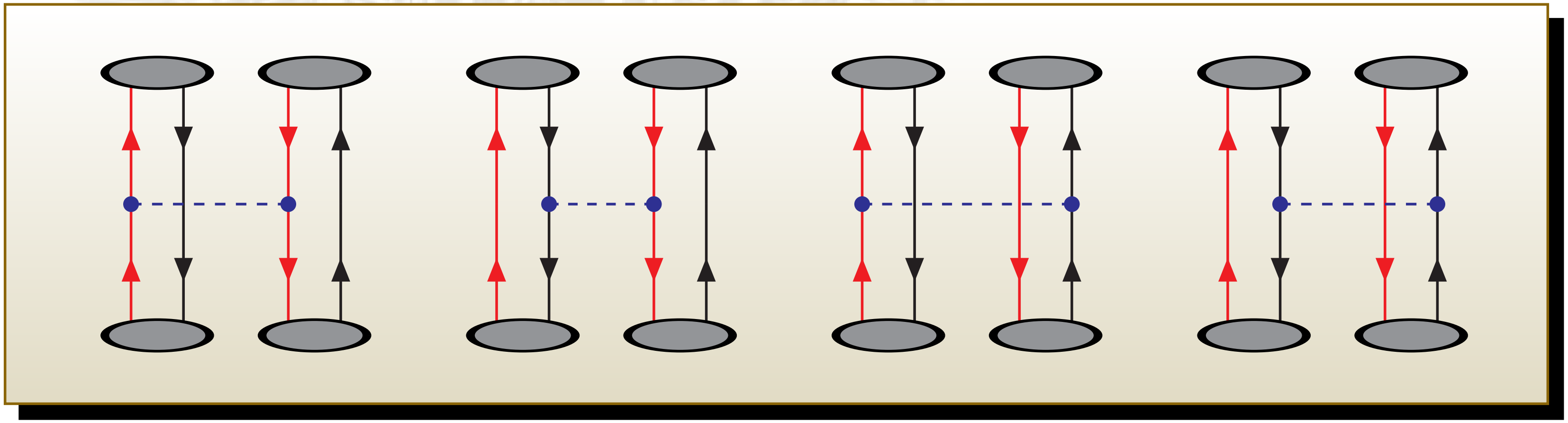
We perform a couple channel calculation with DD^* and P-wave $c\bar{c}$ states.

The M_1M_2 system

- **Quark interactions** $\rightarrow$ **Cluster interaction.**
- **For the DD^* system only direct RGM Potential:**

$$
\begin{aligned}
{}^{RGM}V_D(\vec{P}',\vec{P}_i) \quad = \quad & \sum_{i\in A,j\in B}\int d\vec{p}_{\xi'_A}\,d\vec{p}_{\xi'_B}\,d\vec{p}_{\xi_A}\,d\vec{p}_{\xi_B} \\
& \phi_A^*(\vec{p}_{\xi'_A})\phi_B^*(\vec{p}_{\xi'_B})V_{ij}(\vec{P}',\vec{P}_i)\phi_A(\vec{p}_{\xi_A})\phi_B(\vec{p}_{\xi_B})
\end{aligned}
$$

- $\phi_C(\vec{p}_C)$ **is the wave function for cluster C solution of Schrödinger's equation using Gaussian Expansion Method.**



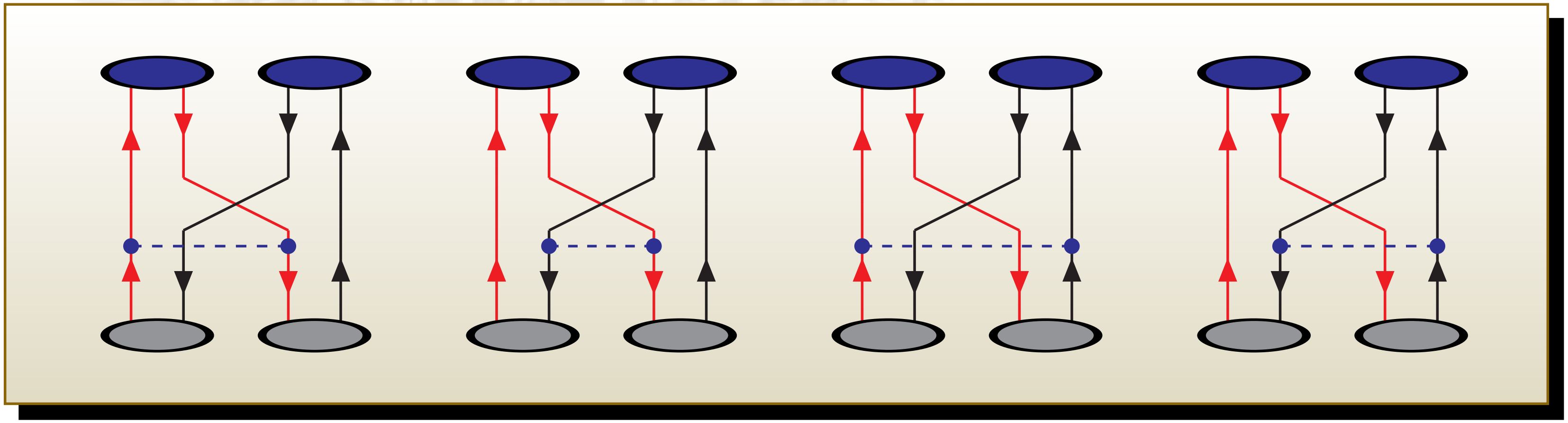
The $M_1 M_2$ system

- **Quark interactions** $\rightarrow$ **Cluster interaction.**
- **For the DD^* system only direct RGM Potential:**

$$
\begin{aligned}
{}^{RGM}V_D(\vec{P}', \vec{P}_i) \quad = \quad & \sum_{i\in A, j\in B} \int d\vec{p}_{\xi'_A} d\vec{p}_{\xi'_B} d\vec{p}_{\xi_A} d\vec{p}_{\xi_B} \\
& \phi^*_A(\vec{p}_{\xi'_A}) \phi^*_B(\vec{p}_{\xi'_B}) V_{ij}(\vec{P}', \vec{P}_i) \phi_A(\vec{p}_{\xi_A}) \phi_B(\vec{p}_{\xi_B})
\end{aligned}
$$

- $\phi_C(\vec{p}_C)$ **is the wave function for cluster** C **solution of Schrödinger's equation using Gaussian Expansion Method.**

Rearrangement processes (like $DD^* \rightarrow J/\psi\omega$)



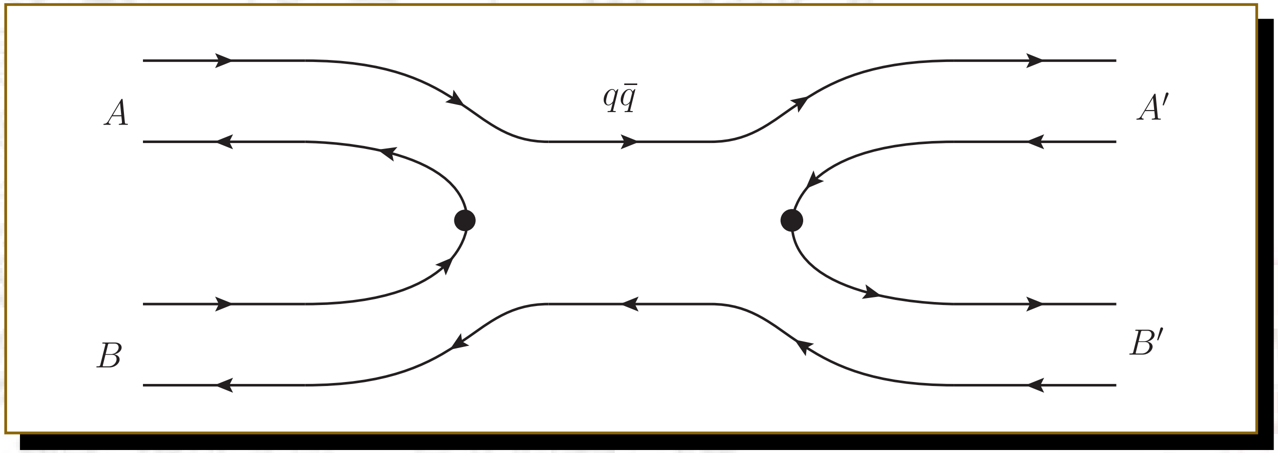
Coupling $q\bar{q}$ and $q\bar{q}\bar{q}q$ sectors

- **Hadronic state:** $|\Psi\rangle = \sum_\alpha c_\alpha \,|\psi\rangle + \sum_\beta \chi_\beta(P)\,|\phi_{M1}\phi_{M2}\beta\rangle$
- **Solving the coupling with $c\bar{c}$ states $\rightarrow$ Schrödinger type equation:**

$$\sum_\beta \int \left(H^{M_1 M_2}_{\beta'\beta}(P',P) + V^{eff}_{\beta'\beta}(P',P) \right) \chi_\beta(P) P^2 dP = E\chi_{\beta'}(P')$$

with

$$V^{eff}_{\beta'\beta}(P',P) = \sum_\alpha \frac{h_{\beta'\alpha}(P')h_{\alpha\beta}(P)}{E - M_\alpha}$$



- **The $c\bar{c}$ amplitudes are given by,**

$$c_\alpha = \frac{1}{E - M_\alpha} \sum_\beta \int h_{\alpha\beta}(P)\chi_\beta(P)P^2 dP$$

Resonance states

Lippman-Schwinger equation

$$T^{\beta'\beta}(E;P',P) = V_T^{\beta'\beta}(P',P) + \sum_{\beta''}\int dP'' P''^2 V_T^{\beta'\beta''}(P',P'')\frac{1}{E-E_{\beta''}(P'')}T^{\beta''\beta}(E;P'',P)$$

with $V_T^{\beta'\beta}(P',P) = V^{\beta'\beta}(P',P) + V_{eff}^{\beta'\beta}(P',P)$, $V_{\beta'\beta}^{eff}(P',P) = \sum_\alpha \frac{h_{\beta'\alpha}(P')h_{\alpha\beta}(P)}{E-M_\alpha}$

Resonance states

Lippman-Schwinger equation

$$T^{\beta'\beta}(E;P',P) = V_T^{\beta'\beta}(P',P) + \sum_{\beta''}\int dP''P''^2 V_T^{\beta'\beta''}(P',P'')\frac{1}{E-E_{\beta''}(P'')}T^{\beta''\beta}(E;P'',P)$$

with $V_T^{\beta'\beta}(P',P) = V^{\beta'\beta}(P',P) + V_{eff}^{\beta'\beta}(P',P)$, $V_{\beta'\beta}^{eff}(P',P) = \sum_\alpha \frac{h_{\beta'\alpha}(P')h_{\alpha\beta}(P)}{E-M_\alpha}$

Solution (Baru et al. Eur. Phys. Jour. A 44, 93 (2010))

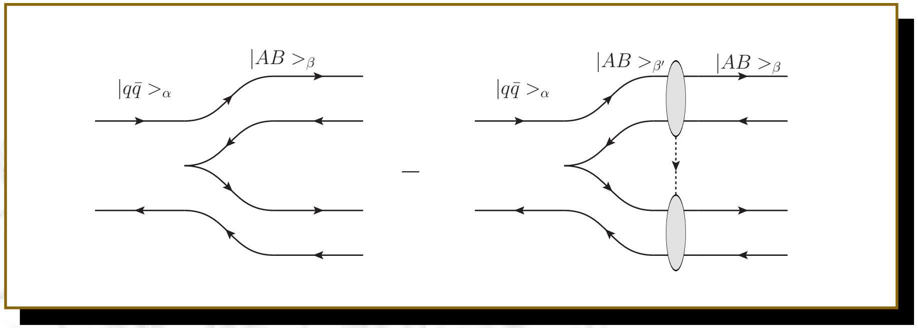
$$T^{\beta'\beta}(E;P',P) = T_V^{\beta'\beta}(E;P',P) + \sum_{\alpha,\alpha'}\phi^{\beta'\alpha'}(E;P')\Delta^{-1}_{\alpha'\alpha}(E)\bar{\phi}^{\alpha\beta}(E;P)$$

- **Non resonant contribution**
- **Resonant contribution**

with

$$T_V^{\beta'\beta}(E;P',P) = V^{\beta'\beta}(P',P) + \sum_{\beta''}\int dP''P''^2 V^{\beta'\beta''}(P',P'')\frac{1}{z-E_{\beta''}(P'')}T_V^{\beta''\beta}(E;P'',P)$$

Resonance states



Solution (Baru et al. Eur. Phys. Jour. A 44, 93 (2010))

$$T^{\beta'\beta}(E;P',P) = T_V^{\beta'\beta}(E;P',P) + \sum_{\alpha,\alpha'} \phi^{\beta'\alpha'}(E;P')\Delta^{-1}_{\alpha'\alpha}(E)\bar{\phi}^{\alpha\beta}(E;P)$$

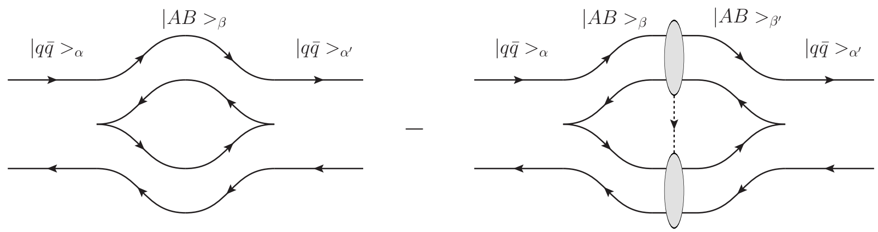
- **Non resonant contribution**
- **Resonant contribution**

with

$$\phi^{\alpha\beta'}(E;P) = h_{\alpha\beta'}(P) - \sum_\beta \int \frac{T_V^{\beta'\beta}(E;P,q)h_{\alpha\beta}(q)}{q^2/2\mu - E}\, q^2\, dq,$$

$$\bar{\phi}^{\alpha\beta}(E;P) = h_{\alpha\beta}(P) - \sum_{\beta'} \int \frac{h_{\alpha\beta'}(q)T_V^{\beta'\beta}(E;q,P)}{q^2/2\mu - E}\, q^2\, dq$$

Resonance states



Solution (Baru et al. Eur. Phys. Jour. A 44, 93 (2010))

$$T^{\beta'\beta}(E;P',P) = T_V^{\beta'\beta}(E;P',P) + \sum_{\alpha,\alpha'} \phi^{\beta'\alpha'}(E;P')\Delta^{-1}_{\alpha'\alpha}(E)\bar{\phi}^{\alpha\beta}(E;P)$$

- **Non resonant contribution**
- **Resonant contribution**

with

$$\Delta^{\alpha'\alpha}(E) = \left\{(E - M_\alpha)\delta^{\alpha'\alpha} + \mathcal{G}^{\alpha'\alpha}(E)\right\}$$

$$\mathcal{G}^{\alpha'\alpha}(E) = \sum_\beta \int dq q^2 \frac{\phi^{\alpha\beta}(q,E)h_{\beta\alpha'}(q)}{q^2/2\mu - E}$$

Resonance states

- **Resonance mass (pole position)**

$$\left|\Delta^{\alpha'\alpha}(\bar{E})\right| = \left|(\bar{E} - M_\alpha)\delta^{\alpha'\alpha} + \mathcal{G}^{\alpha'\alpha}(\bar{E})\right| = 0$$

- **Bare $c\bar{c}$ probabilities**

$$\left\{M_\alpha \delta^{\alpha\alpha'} - \mathcal{G}^{\alpha'\alpha}(\bar{E})\right\} c_{\alpha'}(\bar{E}) = \bar{E}\, c_\alpha(\bar{E})$$

- **Molecular wave function**

$$\chi_{\beta'}(P') \quad = \quad -2\mu_{\beta'} \sum_\alpha \frac{\phi_{\beta'\alpha}(E;P')c_\alpha}{P'^2 - k^2_{\beta'}}$$

- **Normalization**

$$\sum_\alpha |c_\alpha|^2 + \sum_\beta < \chi_\beta | \chi_\beta >= 1$$

Isospin symmetric calculation

- $^3S_1$ and $^3D_1$ DD^* partial waves included.
- Coupling to 1^{++} ground and first excited $c\bar{c}$ states with bare masses within the model:

$$c\bar{c}(1^3P_1) \rightarrow \quad M = 3503{,}9\ MeV$$
$$c\bar{c}(2^3P_1) \rightarrow \quad M = 3947{,}4\ MeV.$$

First results:

$M\ (MeV)$	$c\bar{c}(1^3P_1)$	$c\bar{c}(2^3P_1)$	$D^0 D^{*0}$	$D^{\pm} D^{*\mp}$	**Assignment**
3936	$0\ \%$	$79\ \%$	$10{,}5\ \%$	$10{,}5\ \%$	$\rightarrow X(3940)$
3865	$1\ \%$	$32\ \%$	$33{,}5\ \%$	$33{,}5\ \%$	$\rightarrow X(3872)$
3467	$95\ \%$	$0\ \%$	$2{,}5\ \%$	$2{,}5\ \%$	$\rightarrow \chi_{c1}(3510)$

Parameter free calculation.

Isospin breaking

Charge basis → Isospin breaking:

$$|D^{\pm}D^{*\mp}\rangle = \frac{1}{\sqrt{2}}\left(|DD^* I=0\rangle - |DD^* I=1\rangle\right)$$

$$|D^{0}D^{*0}\rangle = \frac{1}{\sqrt{2}}\left(|DD^* I=0\rangle + |DD^* I=1\rangle\right)$$

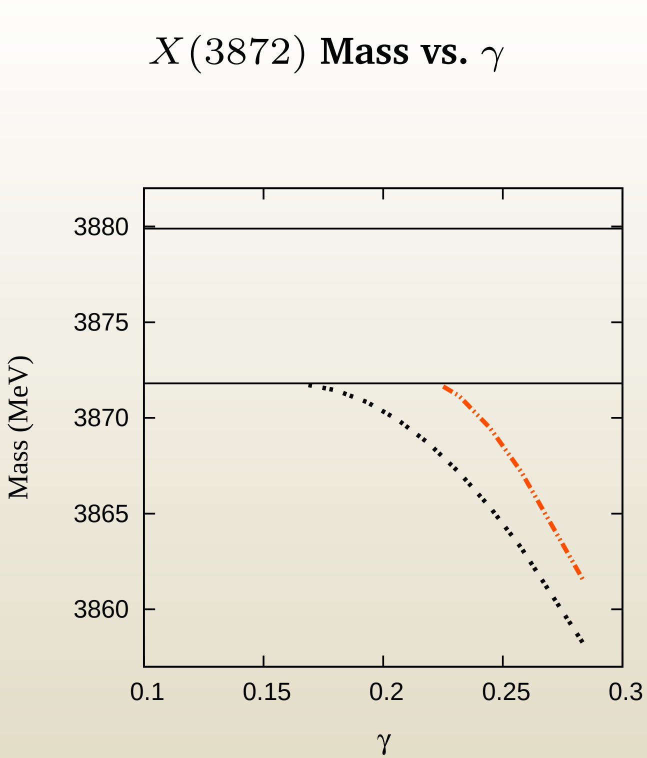
$M\ (MeV)$	$c\bar{c}(1^3P_1)$	$c\bar{c}(2^3P_1)$	D^0D^{*0}	$D^{\pm}D^{*\mp}$	**Assignment**
3937	$0\,\%$	$79\,\%$	$7\,\%$	$14\,\%$	$\to X(3940)$
3863	$1\,\%$	$30\,\%$	$46\,\%$	$23\,\%$	$\to X(3872)$
3467	$95\,\%$	$0\,\%$	$2{,}5\,\%$	$2{,}5\,\%$	$\to \chi_{c1}(3510)$

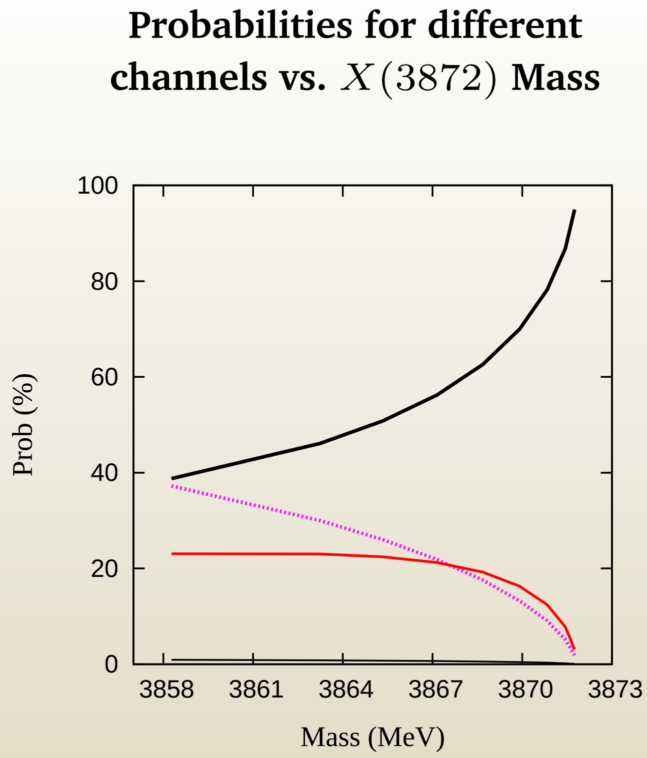
Isospin probabilities:

- $I=0 \to \mathcal{P}=66\,\%$,
- $I=1 \to \mathcal{P}=3\,\%$.

Dependence on γ

Binding energy very sensitive $\rightarrow$ Variation of γ.





No DD^* interaction included.
DD^* interaction included.

$D^0\bar{D}^{*0}$ component
D^+D^{*-} component
$c\bar{c}(2P)$ component
$c\bar{c}(1P)$ component

Final results

$^3P_0$ γ **strength parametre** $25\,\%$ **smaller** $\rightarrow E_{bind} = -0{,}6\ MeV$**.**

$M\ (MeV)$	$c\bar{c}(1^3P_1)$	$c\bar{c}(2^3P_1)$	D^0D^{*0}	$D^{\pm}D^{*\mp}$	**Assignment**
3942	$0\,\%$	$88\,\%$	$4\,\%$	$8\,\%$	$\rightarrow X(3940)$
3871	$0\,\%$	$7\,\%$	$83\,\%$	$10\,\%$	$\rightarrow X(3872)$
3484	$97\,\%$	$0\,\%$	$1{,}5\,\%$	$1{,}5\,\%$	$\rightarrow \chi_{c1}(3510)$

Isospin probabilities:

- $I = 0 \rightarrow \mathcal{P} = 70\,\%$,
- $I = 1 \rightarrow \mathcal{P} = 23\,\%$.

P.G. Ortega, J. Segovia, DRE, F. Fernández, Phys. Rev. D 81 (2010)

P.G. Ortega, DRE, F. Fernández, J. Phys. G 40 (2013)

M. Takizawa, S. Takeuchi, PTEP 9 (2013) at hadron level

Comparison with data

Flatte parametrization

Following V. Baru *et al.* Phys. Lett. B 586, 53 (2004)

$$F^{\beta}_{DD^*}(P,P;E) = -\pi\mu \sum_{\alpha} \frac{h^2_{\beta\alpha}(P)}{E - M_\alpha + g^{\alpha}_{DD^*}(E)}$$

$$g^{\alpha}_{DD^*}(E) = \sum_{\beta} \int \frac{h^2_{\beta\alpha}(P)}{\frac{P^2}{2\mu} - E - i0^+} P^2\, dP \sim \bar{E}^{\alpha}_{DD^*} + \frac{i}{2}\Gamma^{\alpha}_{DD^*} + \mathcal{O}(4\mu^2\epsilon/\Lambda^2)$$

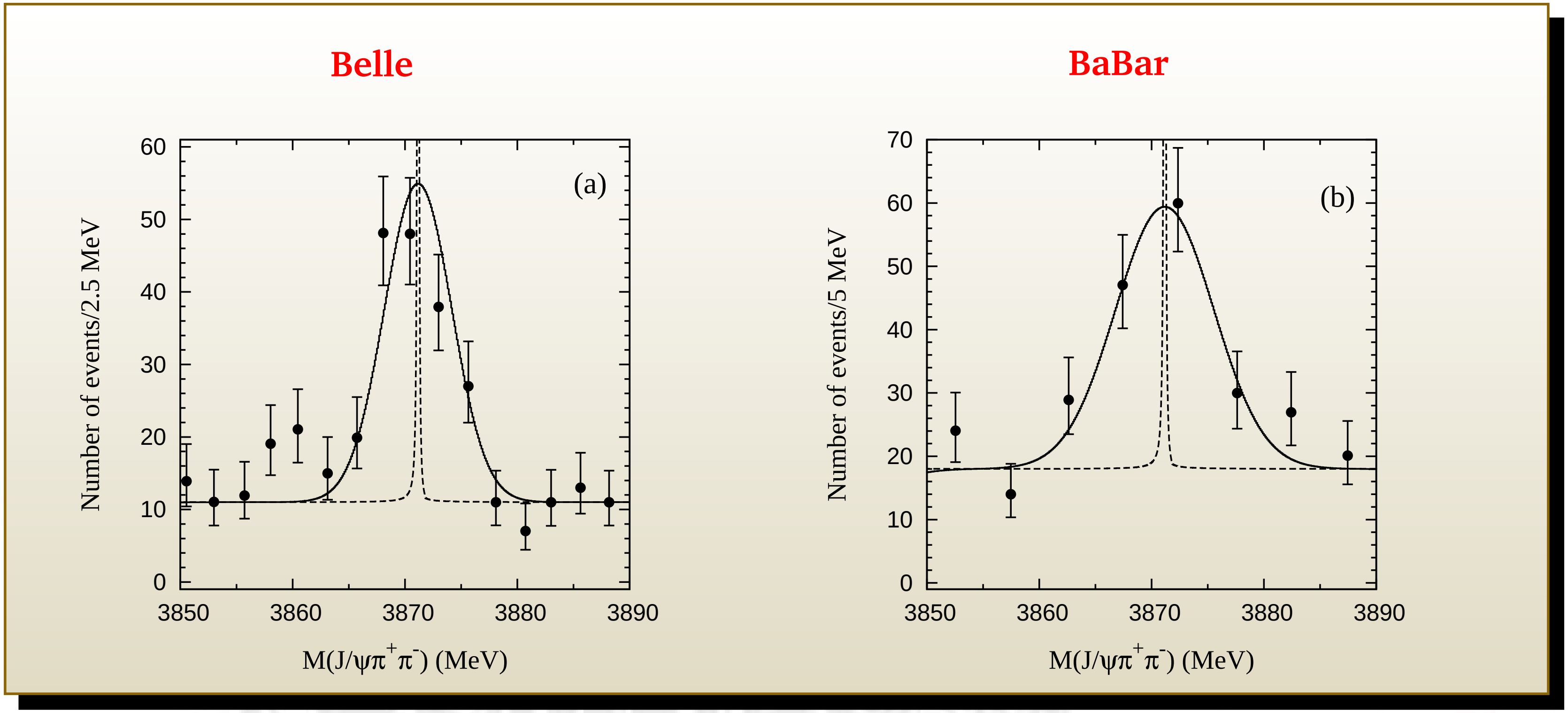
for small binding energies

$$\begin{aligned}
\frac{dBr(B \to KD^0D^{*0})}{dE} &= \mathcal{B}\frac{1}{2\pi}\frac{\Gamma_{D^0D^{*0}}(E)}{|D(E)|^2} \\
\frac{dBr(B \to K\pi^+\pi^- J/\Psi)}{dE} &= \mathcal{B}\frac{1}{2\pi}\frac{\Gamma_{\pi^+\pi^- J/\Psi}(E)}{|D(E)|^2}. \\
D(E) &= E - E_f + \frac{i}{2}(\Gamma_{D^0D^{*0}} + \Gamma_{D^+D^{*-}} + \Gamma(E)) + \mathcal{O}(4\mu^2\epsilon/\Lambda^2)
\end{aligned}$$

We calculate

$$\Gamma_{\pi^+\pi^- J/\Psi} = \sum_{JL} \int_0^{k_{max}} dk \frac{\Gamma_\rho}{(M_X - E_\rho - E_{J/\Psi})^2 + \frac{\Gamma_\rho^2}{4}} \left|\mathcal{M}^{JL}_{X\to\rho J/\Psi}(k)\right|^2.$$

Belle and BaBar data



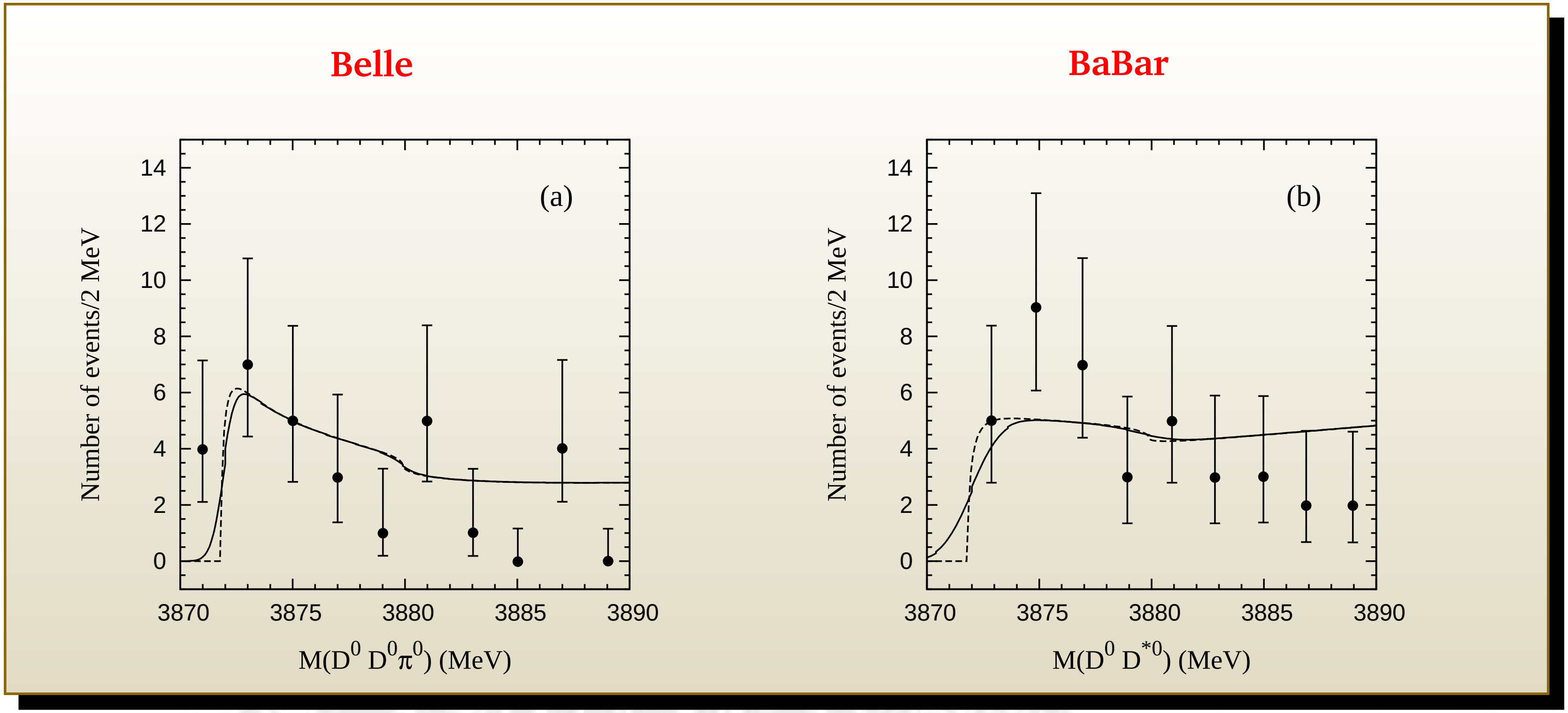
$B \to K\pi^+\pi^- J/\Psi$ **data**

solid (dashed) line with (without) resolution function

$$N^{\pi\pi J/\Psi}_{Belle}(E) \quad = \quad 2{,}5\,\textbf{[MeV]}\left(\frac{131}{8{,}3\,10^{-6}}\right)\frac{dBr(B \to K\pi^+\pi^- J/\Psi)}{dE}$$

$$N^{\pi\pi J/\Psi}_{BaBar}(E) \quad = \quad 5\,\textbf{[MeV]}\left(\frac{93{,}4}{8{,}4\,10^{-6}}\right)\frac{dBr(B \to K\pi^+\pi^- J/\Psi)}{dE}$$

Belle and BaBar data



$B \to K D^0 \bar{D}^0 \pi^0$ **data**

solid (dashed) line with (without) resolution function

$$N^{D^0\bar{D}^0\pi^0}_{Belle}(E) \;=\; 2{,}0[\textbf{MeV}]\left(\frac{48{,}3}{0{,}73\,10^{-4}}\right)\frac{dBr(B\to K D^0\bar{D}^0\pi^0)}{dE}$$

$$N^{D^0 D^{*0}}_{BaBar}(E) \;=\; 2{,}0[\textbf{MeV}]\left(\frac{33{,}1}{1{,}67\,10^{-4}}\right)\frac{dBr(B\to K D^0\bar{D}^{*0})}{dE}$$

The $X(3872)$ branching ratios

γ	E_{bind}	$c\bar{c}(2^3P_1)$	D^0D^{*0}	$D^{\pm}D^{*\mp}$	$J/\psi\rho$	$J/\psi\omega$
0,231	$-0{,}60$	12,40	79,24	7,46	0,49	0,40
0,226	$-0{,}25$	8,00	86,61	4,58	0,53	0,29

The $X(3872)$ branching ratios

E_{bind}**(MeV)**	$\Gamma_{\pi^+\pi^- J/\psi}$	$\Gamma_{\pi^+\pi^-\pi^0 J/\psi}$	R_1
$-0{,}60$	$27{,}61$	$14{,}40$	$0{,}52$
$-0{,}25$	$24{,}18$	$10{,}64$	$0{,}44$

$$R_1 = \frac{X(3872) \to \pi^+\pi^-\pi^0 J/\psi}{X(3872) \to \pi^+\pi^- J/\psi} = 0{,}8 \pm 0{,}3$$

The $X(3872)$ branching ratios

E_{bind}**(MeV)**	$\Gamma^{VMD}_{J/\psi\gamma}$	$\Gamma^{ANN}_{J/\psi\gamma}$	R_2^M	$\Gamma^{c\bar{c}}_{J/\psi\gamma}$	$R_2^{c\bar{c}}$	R_2
$-0{,}60$	0,014	0,056	0,0025	8,15	0,29	0,30
$-0{,}25$	0,011	0,045	0,0023	5,25	0,22	0,22

$$R_1 = \frac{X(3872) \to \pi^+\pi^-\pi^0 J/\psi}{X(3872) \to \pi^+\pi^- J/\psi} = 0{,}8 \pm 0{,}3$$

$$R_2 = \frac{\Gamma(X(3872) \to \gamma J/\psi)}{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)} = 0{,}14 \pm 0{,}05 \quad 0{,}33 \pm 0{,}12$$

The $X(3872)$ branching ratios

E_{bind} **(MeV)**	$\Gamma^{ANN}_{\Psi(2S)\gamma}$	R_3^M	$\Gamma^{c\bar{c}}_{\Psi(2S)\gamma}$	$R_3^{c\bar{c}}$	R_3
$-0{,}60$	0,134	0,0048	9,80	0,35	0,34
$-0{,}25$	0,101	0,0042	6,31	0,26	0,26

$$R_1 = \frac{X(3872) \to \pi^+\pi^-\pi^0 J/\psi}{X(3872) \to \pi^+\pi^- J/\psi} = 0{,}8 \pm 0{,}3$$

$$R_2 = \frac{\Gamma(X(3872) \to \gamma J/\psi)}{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)} = 0{,}14 \pm 0{,}05 \quad 0{,}33 \pm 0{,}12$$

$$R_3 = \frac{\Gamma(X(3872) \to \gamma\psi(2S))}{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)} = 1{,}1 \pm 0{,}4$$

The $X(3872)$ branching ratios

E_{bind} **(MeV)**	R_3/R_2
$-0{,}60$	$1{,}13$
$-0{,}25$	$1{,}18$

$$R_1 = \frac{X(3872) \to \pi^+\pi^-\pi^0 J/\psi}{X(3872) \to \pi^+\pi^- J/\psi} = 0{,}8 \pm 0{,}3$$

$$R_2 = \frac{\Gamma(X(3872) \to \gamma J/\psi)}{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)} = 0{,}14 \pm 0{,}05 \quad 0{,}33 \pm 0{,}12$$

$$R_3 = \frac{\Gamma(X(3872) \to \gamma\psi(2S))}{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)} = 1{,}1 \pm 0{,}4$$

$$\frac{R_3}{R_2} = \frac{\mathcal{B}(X \to \psi(2S)\gamma)}{\mathcal{B}(X \to J/\psi\gamma)} < 2{,}1$$

The 0^{++} sector

Bare $c\bar{c}\ 2^3P_0$ (3909)

Meson channels: $DD + J/\psi\omega + D_sD_s + J/\psi\phi$

Mass(MeV)	2^3P_0	DD	$J/\psi\omega$	D_sD_s	$J/\psi\phi$	Γ_{DD}	$\Gamma_{J/\psi\omega}$	$\Gamma_{D_sD_s}$
$3896{,}05 - i2{,}10$	34,22	46,67	9,41	9,67	0,03	3,37	0,83	–
$3970{,}07 - i94{,}67$	57,27	35,32	0,15	5,72	1,54	38,69	2,89	147,76
	E.J. Eichten et al. Phys. Rev. D 73 014014 (2005) (C^3)							
$3881{,}4 - i\,30{,}75$	49	34,22	–	4,41	–			

$X(3945)$ **and** $Y(3940) \rightarrow X(3915)$

Uehara et al. PRL 104, 092001 $M = 3915 \pm 3 \pm 2\ \Gamma = 17 \pm 10 \pm 3\ e^+e^- \rightarrow e^+e^-\omega J/\psi$

Choi et al. PRL 94, 182002 $M = 3943 \pm 11 \pm 13\ \Gamma = 87 \pm 22 \pm 26\ B \rightarrow \omega J/\psi K$

Assumming $\Gamma_{\gamma\gamma}(X(3915)) \sim 1$ **KeV and** $\Gamma_{\gamma\gamma}(X(3915)) \times \mathcal{B}(X(3915) \rightarrow J/\psi\omega) = 52 \pm 10 \pm 3$ **eV**
implies $\Gamma_{J\psi\omega} \sim 1$ **MeV too big for an OZI suppress decay**

F.-K. Guo, Ulf-G. Meissner, PRD86, 091501(R)

For us $\Gamma_{\gamma\gamma}(X(3915)) \times \mathcal{B}(X(3915) \rightarrow J/\psi\omega) = 125$ **eV**

The 1^{--} sector

Bare $c\bar{c}$ 3^3S_1 (4097) and 2^3D_1 (4153)

Meson channels: $DD + DD^* + D^*D^* + D_sD_s + D_sD_s^* + D_s^*D_s^*$

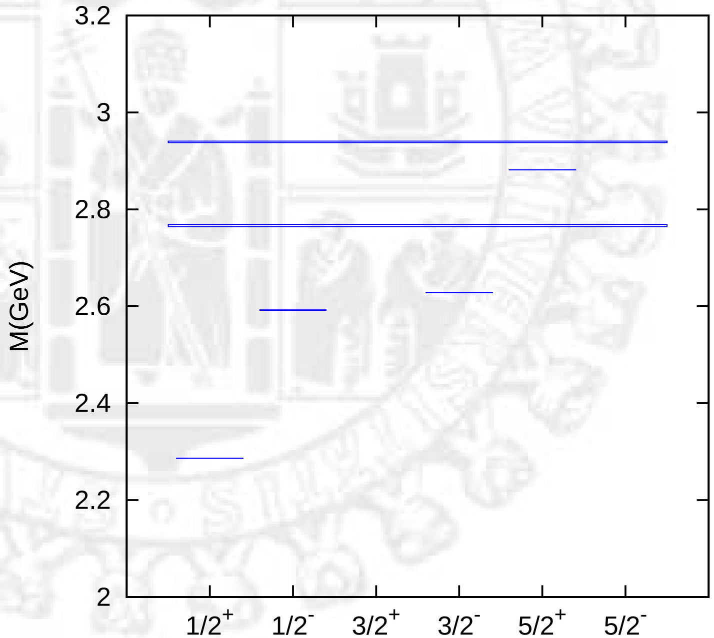
$M\ (MeV)$	3^3S_1	2^3D_1	DD	DD^*	D^*D^*	D_sD_s	$D_sD_s^*$	$D_s^*D_s^*$
$3994{,}6 - i\,11{,}60$	31,56	3,00	2,49	36,44	17,75	7,53	0,52	0,71
$4048{,}4 - i\,7{,}54$	0,92	36,15	2,99	23,49	25,81	8,86	0,92	0,85
$4123{,}9 - i\,71{,}11$	59,01	0,98	2,13	6,84	19,19	0,75	3,37	7,73
	E.J. Eichten et al. Phys. Rev. D 73 014014 (2005) (C^3)							
$4038 - i\,37$	44,89	0,16	2,87	20,36	23,10	0,98	1,58	1,08
$(4160) - i\,24{,}6$	0,09	47,61	8,37	4,24	8,87	0,55	0,96	1,31

M	Γ	$\Gamma(DD)$	$\Gamma(DD^*)$	$\Gamma(D^*D^*)$	$\Gamma(D_sD_s)$	$\Gamma(D_sD_s^*)$
3994,6	23,37	0,12	19,09	–	4,16	–
4048,4	15,09	0,51	7,24	4,42	2,92	–
4123,9	142,23	4,73	7,51	100,03	3,82	26,15

The meson-baryon sector

The Λ_c spectrum

- Λ_c^+ $I(J^P) = 0(\frac{1}{2}^+)$ $M = 2286{,}46 \pm 0{,}14$ **MeV**
- $\Lambda_c^+(2595)$ $I(J^P) = 0(\frac{1}{2}^-)$ $M = 2592{,}25 \pm 0{,}28$ **MeV** $\Gamma = 2{,}59 \pm 0{,}30 \pm 0{,}47$ **MeV**
- $\Lambda_c^+(2625)$ $I(J^P) = 0(\frac{3}{2}^-)$ $M = 2628{,}11 \pm 0{,}19$ **MeV** $\Gamma < 0{,}97$ **MeV**
- $\Lambda_c^+(2765)$ **or** $\Sigma_c(2765)$ $I(J^P) = ?(?^?)$ $M = 2766{,}6 \pm 2{,}4$ **MeV** $\Gamma = 50$ **MeV**
- $\Lambda_c^+(2880)$ $I(J^P) = 0(\frac{5}{2}^+)$ $M = 2881{,}53 \pm 0{,}35$ **MeV** $\Gamma = 5{,}8 \pm 1{,}1$ **MeV**
- $\Lambda_c^+(2940)$ $I(J^P) = 0(?^?)$ $M = 2939{,}3^{+1,4}_{-1,5}$ **MeV** $\Gamma = 17^{+8}_{-6}$ **MeV**



The Λ_c spectrum

- Λ_c^+ $I(J^P) = 0(\frac{1}{2}^+)$ $M = 2286{,}46 \pm 0{,}14$ **MeV**
- $\Lambda_c^+(2595)$ $I(J^P) = 0(\frac{1}{2}^-)$ $M = 2592{,}25 \pm 0{,}28$ **MeV** $\Gamma = 2{,}59 \pm 0{,}30 \pm 0{,}47$ **MeV**
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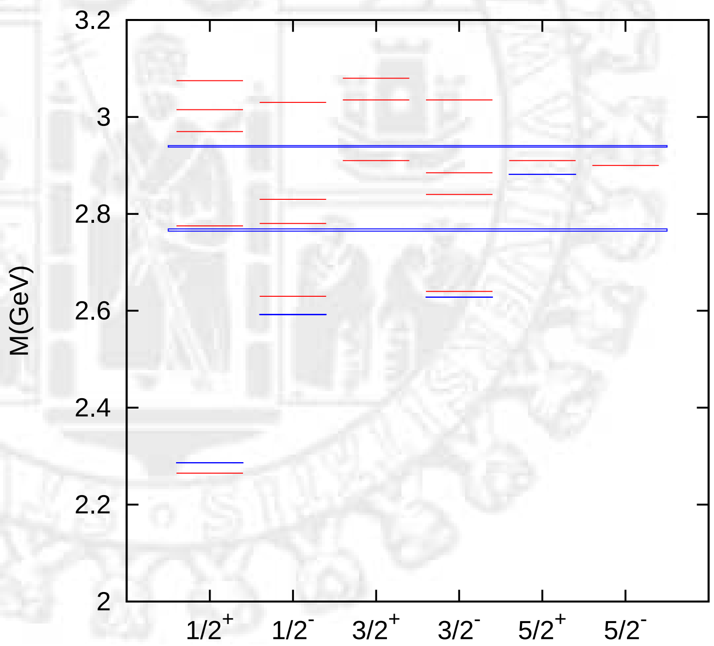

S. Capstick and N. Isgur, Phys. Rev. D 34

The Λ_c spectrum

- Λ_c^+ $I(J^P) = 0(\frac{1}{2}^+)$ $M = 2286{,}46 \pm 0{,}14$ **MeV**
- $\Lambda_c^+(2595)$ $I(J^P) = 0(\frac{1}{2}^-)$ $M = 2592{,}25 \pm 0{,}28$ **MeV** $\Gamma = 2{,}59 \pm 0{,}30 \pm 0{,}47$ **MeV**
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- $\Lambda_c^+(2765)$ **or** $\Sigma_c(2765)$ $I(J^P) = ?(?^?)$ $M = 2766{,}6 \pm 2{,}4$ **MeV** $\Gamma = 50$ **MeV**
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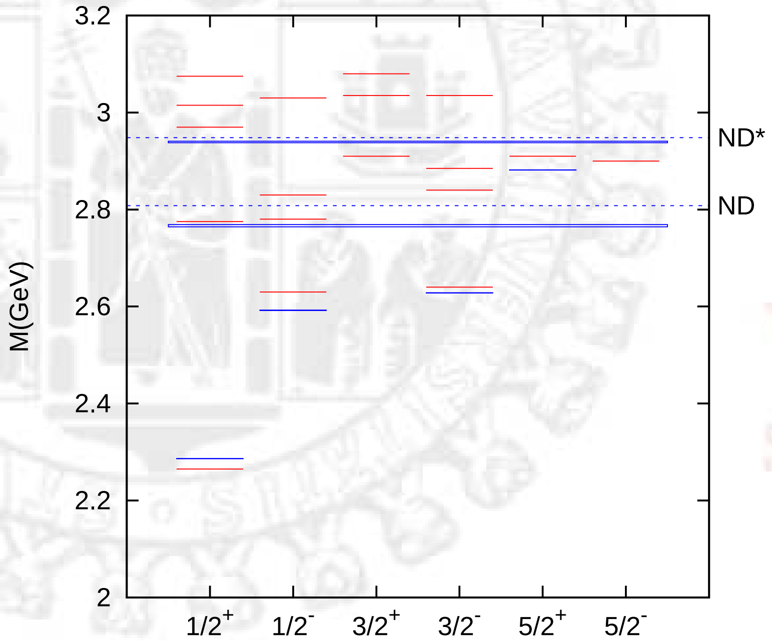


S. Capstick and N. Isgur, Phys. Rev. D 34

The $\Lambda_c(2940)^+$

B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. Lett. 98, 012001 (2007)

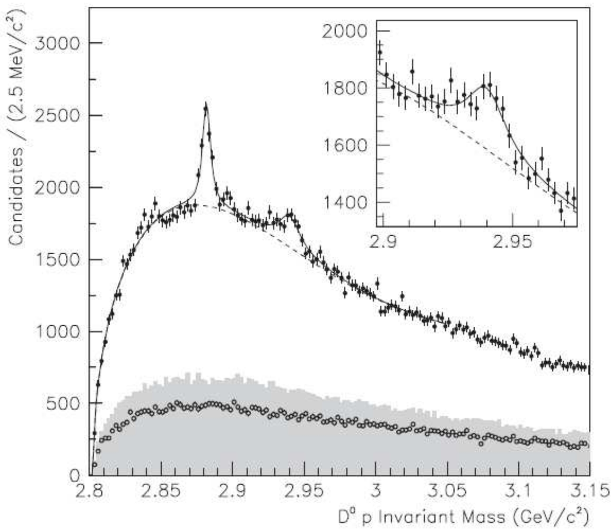


FIG. 1. The solid points are the D^0p invariant mass distribution of the final sample. Also shown are (gray) the contribution from false D^0 candidates estimated from D^0 mass sidebands and (open points) the mass distribution from wrong-sign $\bar{D}^0p$ candidates. The solid curve is the fit described in the text. The dashed curve is the portion of that fit attributed to combinatorial background.

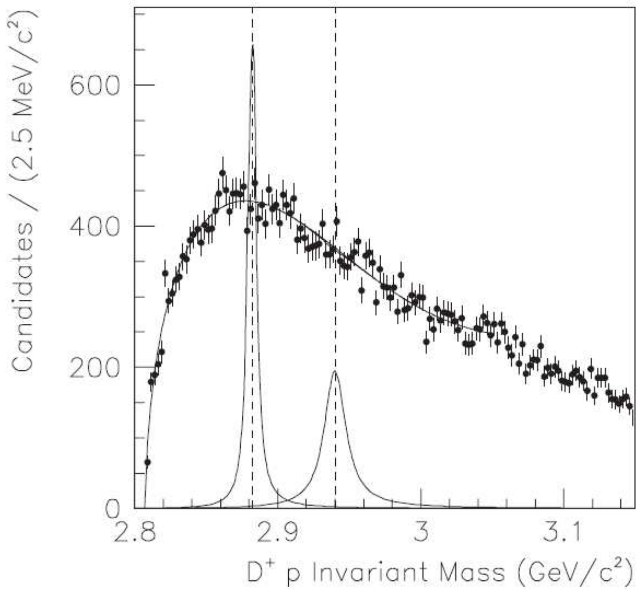


FIG. 3. The invariant mass distribution of selected D^+p candidates. The curve is the result of the fit described in the text. The curves below are the line shapes of the $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ baryons obtained from the D^0p data, drawn approximately to scale after correcting for selection efficiency and D^0 and D^+ branching fractions.

- e^+e^- **annihilation near** $\sqrt{s} = 10{,}58$ **GeV**
- D^0p **signal found**
- **No** D^+p **signal found**
- **No** $\bar{D}^0p$ **signal found**

The $\Lambda_c(2940)^+$

R. Mizuk *et al.* **(Belle Collaboration), Phys. Rev. Lett. 98, 262001 (2007)**

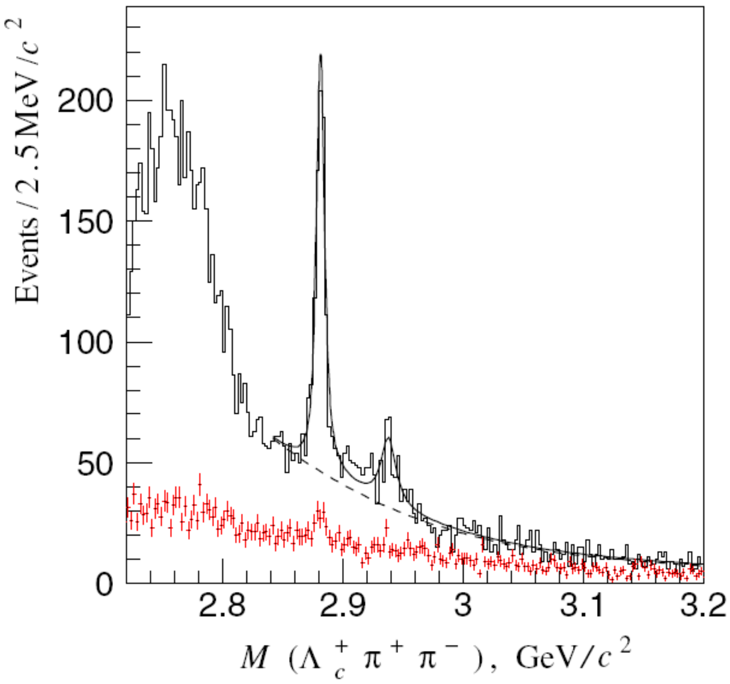


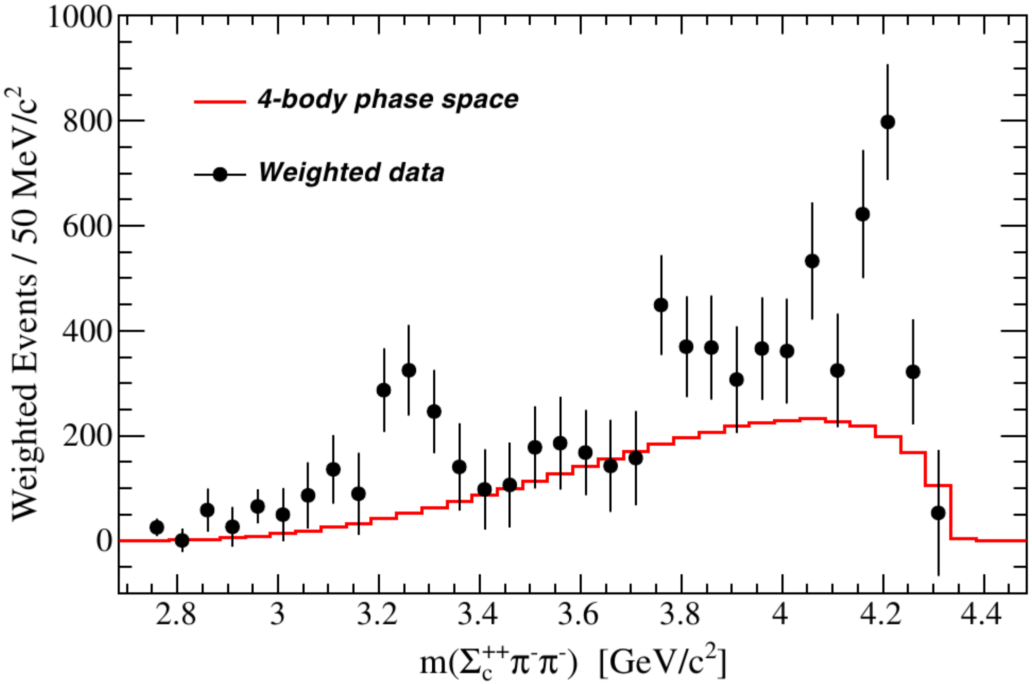
FIG. 1 (color online). The invariant mass of the $\Lambda_c^+\pi^+\pi^-$ combinations for the $\Sigma_c(2455)$ signal region (histogram) and scaled sidebands (dots with error bars). The fit result (solid curve) and its combinatorial component (dashed curve) are also presented.

The $\Lambda_c(2940)^+$

- cnn **candidates**
  - S. Capstick and N. Isgur, Phys. Rev. D 34, $3/2^+$ or $5/2^-$
  - C. Chen, Phys. Rev. 75
    - Strong decays using the $^3P_0$ model
    - Possible D-wave states in $1/2^+$ or $3/2^+$
    - First radial excitation of the $\Lambda_c(2286)^+$ fully excluded
  - X.-H. Zhong, Phys. Rev. 77
    - Chiral quark model
    - Possible D-wave in $5/2^+$ (studying strong decays)
    - Strong decays too small
- Possible ND^* molecule
  - X.-G. He *et al.*, Eur. Phys. J. C 51
    - Effective Lagrangian at hadron level
    - Possible $1/2^-$ also a possible $3/2^-$
  - Y. Dong *et al.*, Phys. Rev. D 81
    - Effective Lagrangian at hadron level
    - Rule out $1/2^-$ due to very large widths
    - Possible $1/2^+$ with an small width with dominant $\Sigma_c\pi$ decay channels
  - C. Garci-Recio *et al.*, Phys. Rev. D 79
    - Unitarized couple channel calculation
    - A possible candidate in $3/2^-$ with an small width (two meson states only in $S-$waves)
  - J. He *et al.*, Phys. Rev. D 82
    - OBE model
    - Possible $1/2^\pm$ or $3/2^\pm$

The $X_c(3250)$

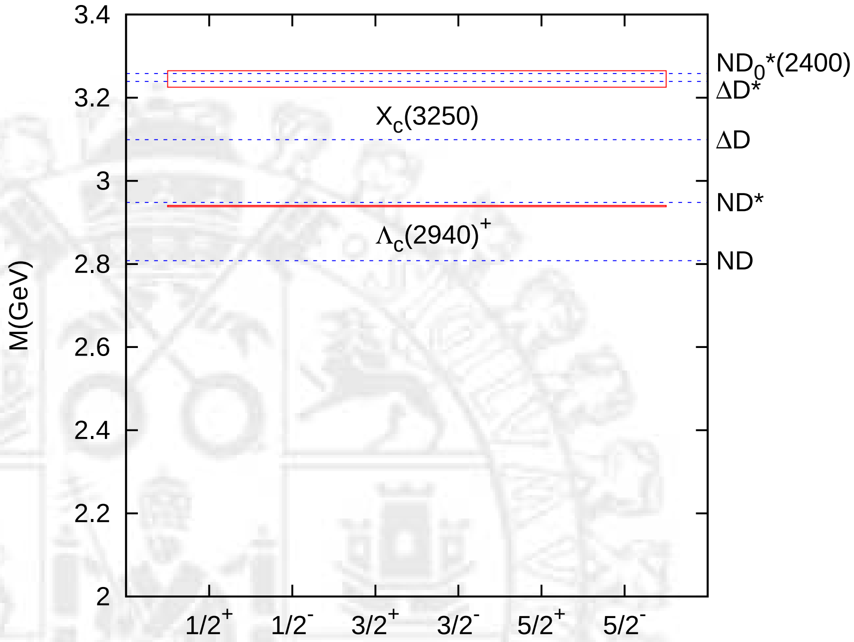
J.P.Lees *et al.* (BaBar Collaboration), Phys. Rev. D **86**, 091102 (2012)



- $B^- \to \Sigma_c^{++}\bar{p}\pi^-\pi^-$
- $\Sigma_c^{++}\pi^-\pi^-$ **invariant mass distribution with peaks at 3.25 GeV/c^2, 3.8 GeV/c^2 and 4.2 GeV/c^2**
- **Preliminary Breit-Wigner fit**

$$M = 3245 \pm 20\,\mathrm{MeV/c^2} \qquad \Gamma = 108 \pm 6\,\mathrm{MeV}$$

The $X_c(3250)$


3.4
3.2
3
2.8
2.6
2.4
2.2
2
M(GeV)
1/2+
1/2-
3/2+
3/2-
5/2+
5/2-
ND0*(2400)
ΔD*
Xc(3250)
ΔD
ND*
Λc(2940)+
ND

The $X_c(3250)$

$ND_0^*(2400)$ **molecule?**

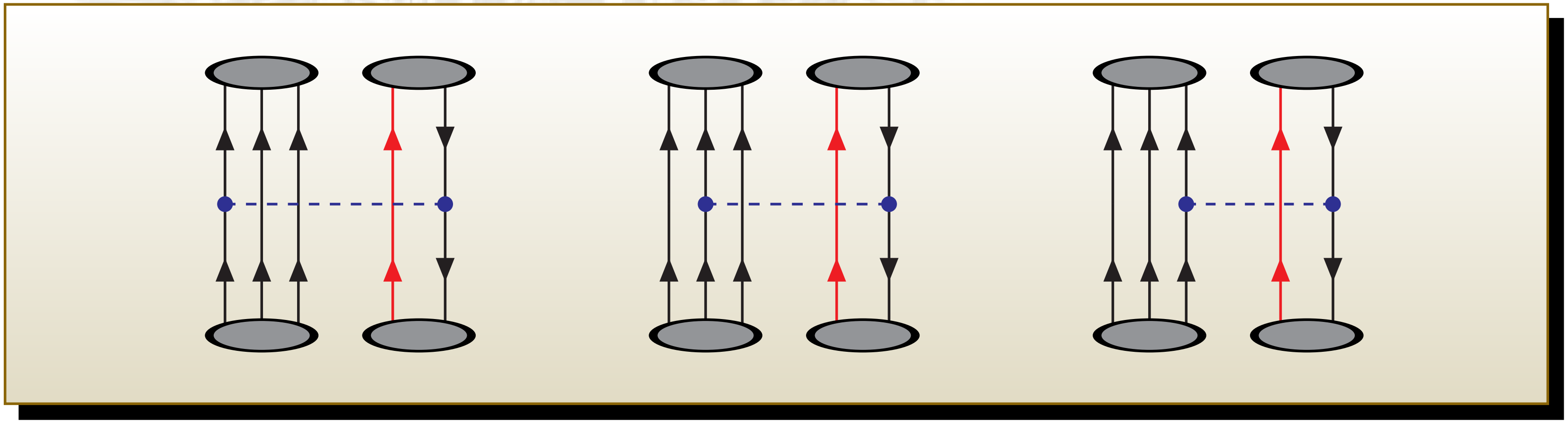
- **J. He** *et al.*, **Eur. Phys. J C 72 (2012)**
  - **Effective Lagrangian with σ, ρ and ω.**
  - $I = 1$ **and** $J^P = 1/2^+$ **with** $\Lambda \sim 1{,}2$ **GeV.**
  - $I = 0$ **with** $\Lambda \sim 4{,}2$ **GeV.**
- **J-R. Zhang, Phys. Rev. D 87 (2013)**
  - **QCD sum rules.**
  - **Realesed the OPE convergence criterion.**
  - $I = 1$ $M = 3{,}18 \pm 0{,}51$ **GeV.**
  - **Only weak conclusions can be obtained for the ND_0^* hypothesis.**

The BM system

- **Quark interactions** $\rightarrow$ **Cluster interaction.**
- **For the ND^* system only direct RGM Potential:**

$$
\begin{aligned}
{}^{RGM}V_D(\vec{P}', \vec{P}_i) \quad = \quad & \sum_{i\in N, j\in D^*} \int d\vec{p}_{\xi'_N}\, d\vec{p}_{\xi'_{D^*}}\, d\vec{p}_{\xi_N}\, d\vec{p}_{\xi_{D^*}} \\
& \phi^*_N(\vec{p}_{\xi'_N})\phi^*_{D^*}(\vec{p}_{\xi'_{D^*}}) V_{ij}(\vec{P}', \vec{P}_i)\phi_N(\vec{p}_{\xi_N})\phi_{D^*}(\vec{p}_{\xi_{D^*}})
\end{aligned}
$$

- $\phi_C(\vec{p}_C)$ **is the wave function for cluster C solution of Schrödinger's equation using Gaussian Expansion Method.**



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$$

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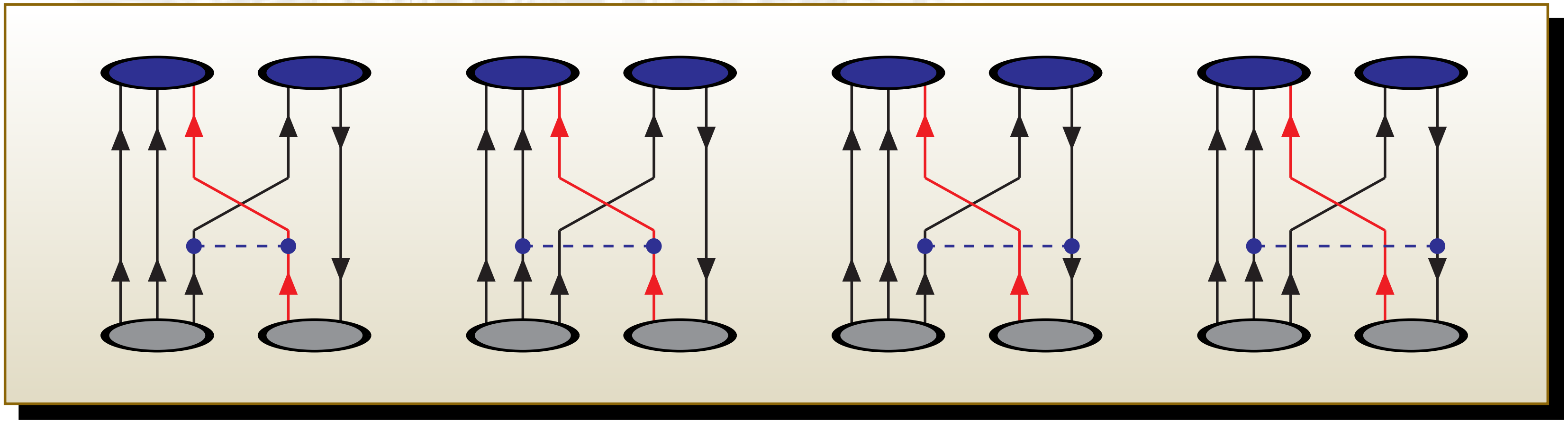
Rearrangement processes (like $ND^* \rightarrow \Sigma_c\pi$)



Charm sector $J^P = 3/2^-$

BaBar

$$M = 2939{,}8 \pm 1{,}3 \pm 1{,}0\; MeV/c^2$$
$$\Gamma = 17{,}5 \pm 5{,}2 \pm 5{,}9\; MeV/c^2$$

Belle

$$M = 2938{,}0 \pm 1{,}3^{+2,0}_{-4,0}\; MeV/c^2$$
$$\Gamma = 13^{+8}_{-5}{}^{+27}_{-7}\; MeV/c^2$$

$M\,(MeV)$	$\mathcal{P}_{^4S_{3/2}}$	$\mathcal{P}_{^2D_{3/2}}$	$\mathcal{P}_{^4D_{3/2}}$	$\mathcal{P}_{D^{*0}p}$	$\mathcal{P}_{D^{*+}n}$	$\mathcal{P}_{I=0}$	$\mathcal{P}_{I=1}$
2938.8	96.22	0.86	2.92	63.93	36.07	97.52	2.48

Decay channel	$Width\,(MeV)$	decay channel	$Width\,(keV)$
$\Lambda_c^+ \to D^0 p$	9.42	$\Lambda_c^+ \to \Sigma_c^{++}\pi^-$	29.7
$\Lambda_c^+ \to D^+ n$	10.74	$\Lambda_c^+ \to \Sigma_c^{+}\pi^0$	25.2
		$\Lambda_c^+ \to \Sigma_c^{0}\pi^+$	21.1
$\Gamma(total)$	20.2		

Bottom sector $J^P = 3/2^-$

$M\,(MeV)$	$\mathcal{P}_{{}^4S_{3/2}}$	$\mathcal{P}_{{}^2D_{3/2}}$	$\mathcal{P}_{{}^4D_{3/2}}$	$\mathcal{P}_{B^{*-}p}$	$\mathcal{P}_{\bar{B}^{*0}n}$	$\mathcal{P}_{I=0}$	$\mathcal{P}_{I=1}$
6248.3	95.15	1.08	3.77	52.56	47.44	99.91	0.09

Decay channel	$Width\,(MeV)$	Decay channel	$Width\,(keV)$
$\Lambda_b \to B^- p$	3.69	$\Lambda_b \to \Sigma_b^+ \pi^-$	40.9
$\Lambda_b \to \bar{B}^0 n$	3.75	$\Lambda_b \to \Sigma_b^0 \pi^0$	39.5
		$\Lambda_b \to \Sigma_b^- \pi^+$	38.1
$\Gamma(total)$	7.56		

$ND^{(*)}$ and $N\bar{B}^{(*)}$ states

J^P	$Isospin$	$Molecule$	$Mass(MeV)$	$E_b(MeV)$	$P_{max}(Channel)$
$\frac{1}{2}^-$	0	DN	2805,24	$-1{,}70$	$98{,}08(^2S_{1/2})$
$\frac{1}{2}^-$	1	D^*N	2947,61	$-0{,}48$	$99{,}93(^2S_{1/2})$
$\frac{3}{2}^-$	0	D^*N	2940,06	$-8{,}02$	$96{,}05(^4S_{3/2})$
$\frac{1}{2}^-$	0	$\bar{B}N$	6206,11	$-12{,}09$	$87{,}61(^2S_{1/2})$
$\frac{1}{2}^-$	1	$\bar{B}N$	6217,83	$-0{,}36$	$99{,}05(^2S_{1/2})$
$\frac{1}{2}^-$	1	$\bar{B}^*N$	6260,58	$-3{,}43$	$99{,}86(^2S_{1/2})$
$\frac{3}{2}^-$	0	$\bar{B}^*N$	6248,87	$-15{,}15$	$95{,}07(^4S_{3/2})$

$\Delta D^{(*)}$ and $\Delta \bar{B}^{(*)}$ states

J^P	$Isospin$	$Molecule$	$Mass(MeV)$	$E_b(MeV)$	$P_{max}(Channel)$
$\frac{1}{2}^-$	2	$D^*\Delta$	3232,70	$-6{,}47$	$99{,}71(^2S_{1/2})$
$\frac{3}{2}^-$	1	$D\Delta$	3097,14	$-0{,}88$	$99{,}13(^4S_{3/2})$
$\frac{3}{2}^-$	2	$D^*\Delta$	3238,19	$-0{,}98$	$99{,}69(^2S_{1/2})$
$\frac{5}{2}^-$	1	$D^*\Delta$	3226,05	$-13{,}12$	$97{,}25(^6S_{5/2})$
$\frac{1}{2}^-$	2	$\bar{B}^*\Delta$	6540,88	$-14{,}21$	$99{,}69(^2S_{1/2})$
$\frac{3}{2}^-$	1	$\bar{B}\Delta$	6498,56	$-10{,}72$	$88{,}14(^4S_{3/2})$
$\frac{3}{2}^-$	2	$\bar{B}\Delta$	6505,61	$-3{,}67$	$94{,}72(^4S_{3/2})$
$\frac{3}{2}^-$	1	$\bar{B}^*\Delta$	6554,71	$-0{,}39$	$97{,}10(^4S_{3/2})$
$\frac{3}{2}^-$	2	$\bar{B}^*\Delta$	6550,25	$-4{,}85$	$99{,}48(^4S_{3/2})$
$\frac{5}{2}^-$	1	$\bar{B}^*\Delta$	6531,94	$-23{,}16$	$96{,}76(^6S_{5/2})$

Decays of $\Delta D^{(*)}$ and $\Delta \bar{B}^{(*)}$ states

J^P	I		$\Gamma_{D\Delta}$	$\Gamma_{\Sigma_c\rho}$	$\Gamma_{\Sigma_c\pi\pi}$	Γ_{D^*N}	Γ_{DN}	$\Gamma_{D\pi\Delta}$	$\Gamma_{D^*N\pi}$	$\Gamma_{DN\pi}$
$\frac{1}{2}^-$	2	$D^*\Delta$	0,005	0,018	2,60	0	0	0	111	0
$\frac{3}{2}^-$	1	$D\Delta$	0	0	0	1,31	0,001	0	0,049	113
$\frac{3}{2}^-$	2	$D^*\Delta$	6,18	0,007	0	0	0	0,038	114	0
$\frac{5}{2}^-$	1	$D^*\Delta$	0,003	0	0	1,23	0,64	0	108	0

$$X_c(3250) \rightarrow (D^*N)\pi \rightarrow (\Sigma_c\pi)\pi$$

J^P	I		$\Gamma_{\bar{B}\Delta}$	$\Gamma_{\Sigma_b\eta}$	$\Gamma_{\bar{B}^*N}$	$\Gamma_{\bar{B}N}$	$\Gamma_{\bar{B}\pi\Delta}$	$\Gamma_{\bar{B}^*N\pi}$	$\Gamma_{\bar{B}N\pi}$
$\frac{1}{2}^-$	2	$\bar{B}^*\Delta$	0,002	0	0	0	0	111	0
$\frac{3}{2}^-$	1	$\bar{B}\Delta$	0	0,02	3,91	0,02	0	10	98
$\frac{3}{2}^-$	2	$\bar{B}\Delta$	0	0	0	0	0	5	108
$\frac{3}{2}^-$	1	$\bar{B}^*\Delta$	12,5	0,12	0,224	0,019	0,076	115	0
$\frac{3}{2}^-$	2	$\bar{B}^*\Delta$	19,9	0	0	0	0	114	0
$\frac{5}{2}^-$	1	$\bar{B}^*\Delta$	0,001	0,18	0	0,90	0	108	0

$X_c \to \pi N D^*$ decay

Decay width

$$\Gamma_{X_c^{\Delta D^*} \to (\pi N) D^*} = 2\pi \int q^2 dq |\langle \pi N D^* | \Gamma_{\pi N \Delta} | X_c^{\Delta D^*} \rangle|^2 \delta(E_f - E_i)$$
$$= \int_0^{kmax} dk k^2 |\chi^{\alpha}_{\Delta D^*}(k)|^2 \Gamma_\Delta(q)$$

with $\Gamma_\Delta(q) \sim \Gamma_\Delta$ **or** $\Gamma_\Delta(q) \sim \Gamma_\Delta \left(\frac{q}{q_\Delta}\right)^3$.

J^P	I	Mass (MeV/c^2)	$\Gamma_{D^* N\pi}$ (MeV)	$\Gamma'_{D^* N\pi}$ (MeV)	$P_{max}(Channel)$
$\frac{1}{2}^-$	2	3232.7	111	78	99.71($^2S_{1/2}$)
$\frac{3}{2}^-$	2	3238.2	114	102	99.69($^4S_{3/2}$)
$\frac{5}{2}^-$	1	3226.1	108	63	97.25($^6S_{5/2}$)

J^P	I	Mass (MeV/c^2)	$\Gamma_{\bar{B}^* N\pi}$ (MeV)	$\Gamma'_{\bar{B}^* N\pi}$ (MeV)	$P_{max}(Channel)$
$\frac{1}{2}^-$	2	6540.9	111	63	99.69($^2S_{1/2}$)
$\frac{3}{2}^-$	1	6554.7	115	109	97.10($^4S_{3/2}$)
$\frac{3}{2}^-$	2	6550.2	114	87	99.48($^4S_{3/2}$)
$\frac{5}{2}^-$	1	6531.9	108	49	96.76($^6S_{5/2}$)

Summary

- We have used a chiral constituent quark model to study possible hadron-hadron molecules.
- In the BB sector the model describes the deuteron as a NN bound state and there is candidate for the resonance found by WASA as a $\Delta\Delta$ state.
- The model describes the $X(3872)$ as a DD^* resonance state coupled to $c\bar{c}$ states.
- In the charmonium 0^{++} sector we find two resonances.
- In the ND^* sector we found a bound state with J^P $3/2^-$ which can be identified with the $\Lambda_c(2940)^+$ state. There is an analog $N\bar{B}^*$ state with the same quantum numbers which could be a possible $\Lambda_b(6248)$.
- We find several bound states in the $ND^{(*)}$ ($N\bar{B}^{(*)}$) and $\Delta D^{(*)}$ ($\Delta\bar{B}^{(*)}$) sectors.
- No $ND_0^*(2400)$ molecule found in $1/2^+$, $1/2^-$ and $3/2^-$
- Candidates for the $X_c(3250)$ as ΔD^* molecules
  - Negative parity against positive parity for ND_0^* hypothesis
  - I=2 candidate against $I = 1$ for ND_0^* hypothesis
  - Bottom partner with $M \sim 6{,}5$ GeV/c^2 against $M \sim 6{,}6$ GeV/c^2
  - Main decay channel $X_c \to D^*N\pi$ against $X_c \to DN\pi$