Hadronic Molecules in the Heavy Baryon Spectrum

XIth Quark Confinement and the Hadron Spectrum

September 8-12, 2014

Saint-Petersburg State University, Russia

D.R. Entem, P.G. Ortega, F. Fernández

VNIVERSITAS STVDII SALAMANTINI

University of Salamanca

Outline

- Motivation: the $\Lambda_c(2940)^+$ and the $X_c(3250)$.
- The Chiral Quark model
- hadron-hadron states
  - The two-baryon sector:
    - NN sector
    - $\Delta\Delta$ states
  - The two-meson sector:
    - The $X(3872)$
  - The baryon-meson sector:
    - The $\Lambda_c(2940)^+$
    - The $X_c(3250)$
    - Other states and bottom analogs.
- Summary

The $\Lambda_c(2940)^+$

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

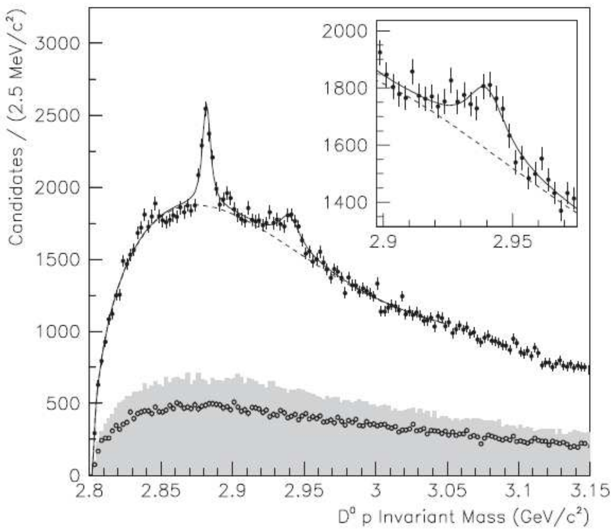


FIG. 1. The solid points are the D^0p invariant mass distribution of the final sample. Also shown are (gray) the contribution from false D^0 candidates estimated from D^0 mass sidebands and (open points) the mass distribution from wrong-sign $\bar{D}^0p$ candidates. The solid curve is the fit described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

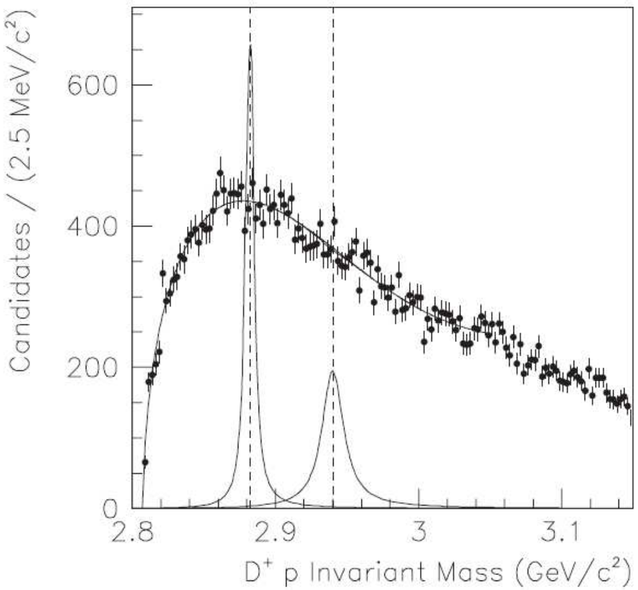


FIG. 3. The invariant mass distribution of selected D^+p candidates. The curve is the result of the fit described in the text. The curves below are the line shapes of the $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ baryons obtained from the D^0p data, drawn approximately to scale after correcting for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

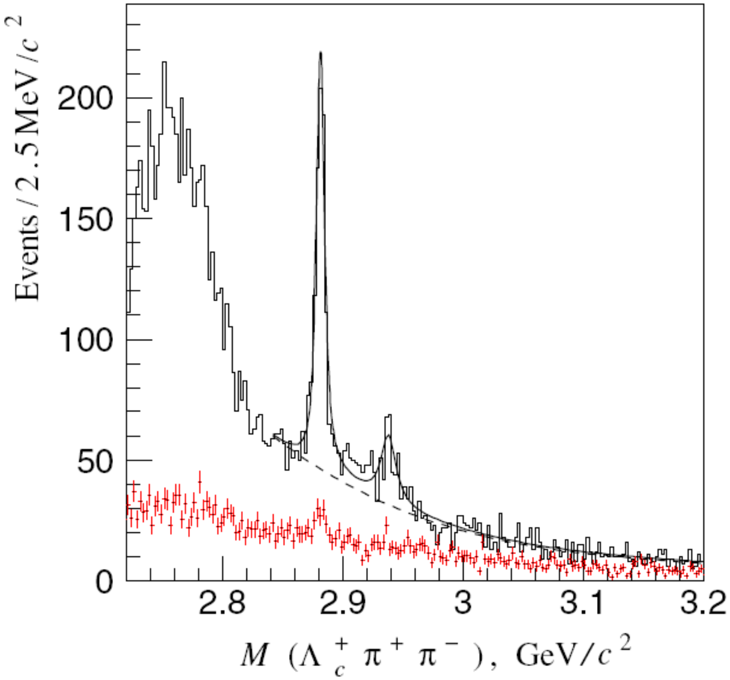
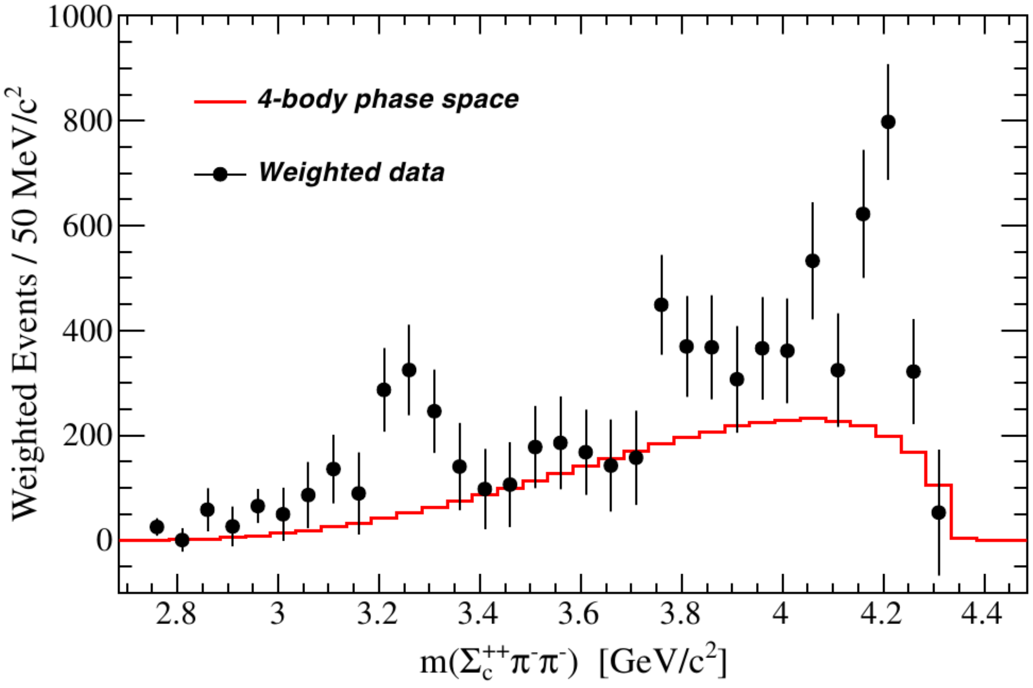


FIG. 1 (color online). The invariant mass of the $\Lambda_c^+\pi^+\pi^-$ combinations for the $\Sigma_c(2455)$ signal region (histogram) and scaled sidebands (dots with error bars). The fit result (solid curve) and its combinatorial component (dashed curve) are also presented.

The $X_c(3250)$

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

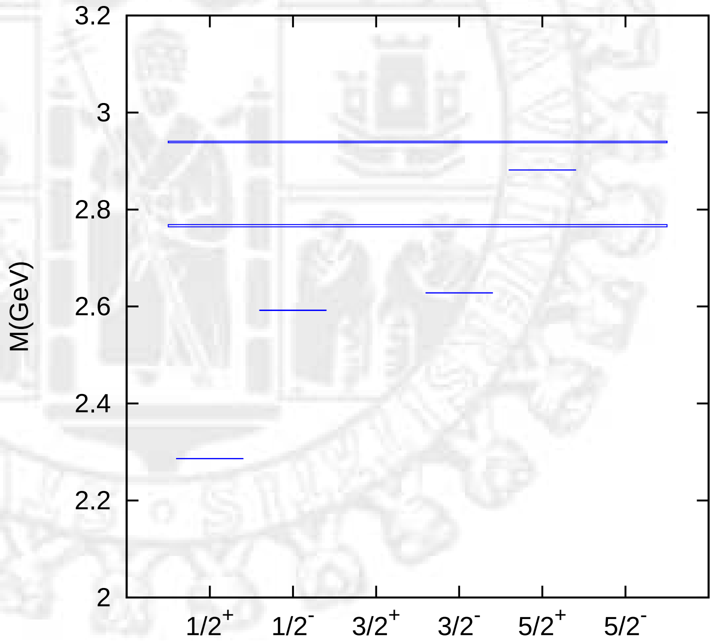


- $B^- \to \Sigma_c^{++}\bar{p}\pi^-\pi^-$
- $\Sigma_c^{++}\pi^-\pi^-$ **invariant mass distribution with peaks at 3.25 GeV/c^2, 3.8 GeV/c^2 and 4.2 GeV/c^2**
- **Preliminary Breit-Wigner fit**

$$M = 3245 \pm 20\,\mathrm{MeV/c^2} \qquad \Gamma = 108 \pm 60\,\mathrm{MeV}$$

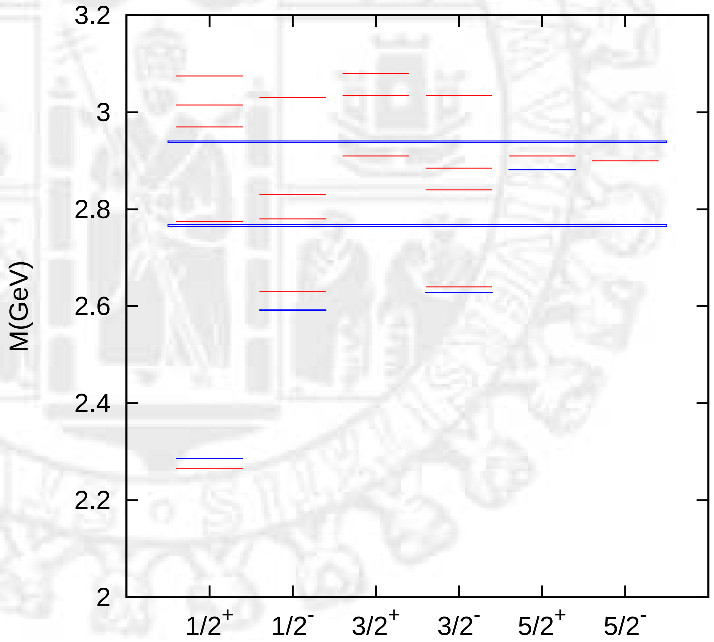
The Λ_c spectrum

- 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**
- $\Lambda_c^+(2625)$ $I(J^P) = 0(\frac{3}{2}^-)$ $M = 2628{,}11 \pm 0{,}19$ **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

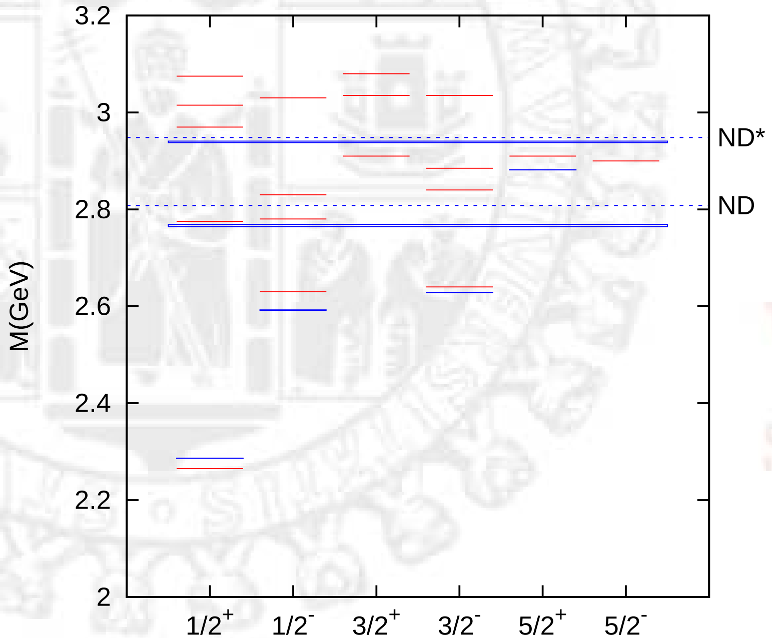
- Λ_c^+ $I(J^P) = 0(\frac{1}{2}^+)$ $M = 2286{,}46 \pm 0{,}14$ **MeV**
- $\Lambda_c^+(2595)$ $I(J^P) = 0(\frac{1}{2}^-)$ $M = 2592{,}25 \pm 0{,}28$ **MeV** $\Gamma = 2{,}59 \pm 0{,}30 \pm 0{,}47$ **MeV**
- $\Lambda_c^+(2625)$ $I(J^P) = 0(\frac{3}{2}^-)$ $M = 2628{,}11 \pm 0{,}19$ **MeV** $\Gamma < 0{,}97$ **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**



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

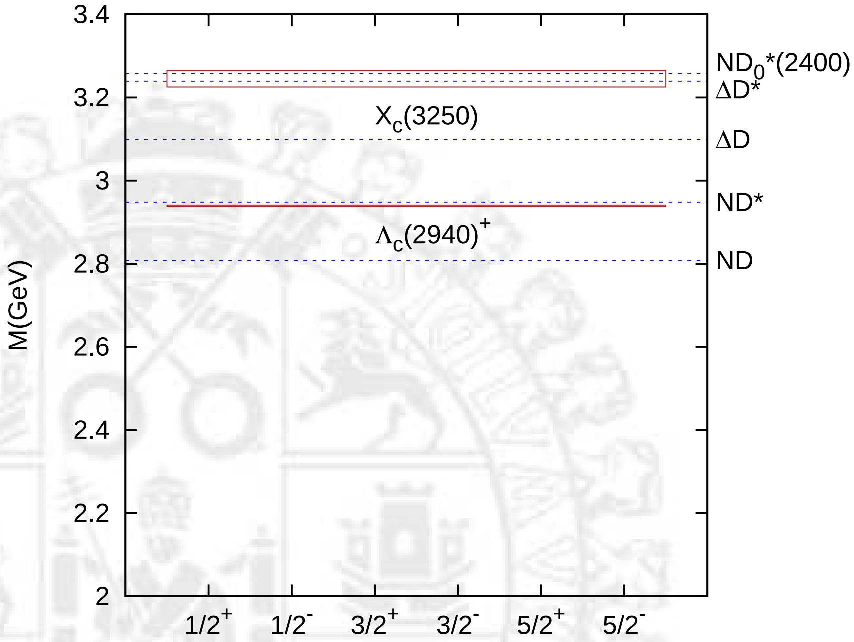
The Λ_c spectrum

- 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**
- $\Lambda_c^+(2625)$ $I(J^P) = 0(\frac{3}{2}^-)$ $M = 2628{,}11 \pm 0{,}19$ **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**



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

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 $\Lambda_c(2940)^+$

- 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 $3/2^\pm$

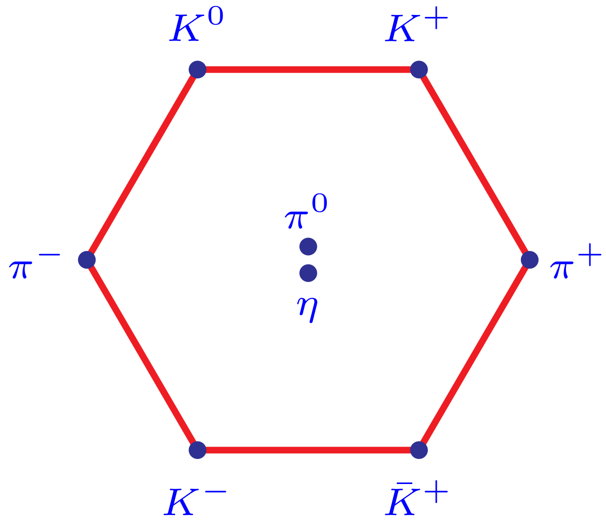
The $X_c(3250)$

$ND_0^*(2400)$ **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 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

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

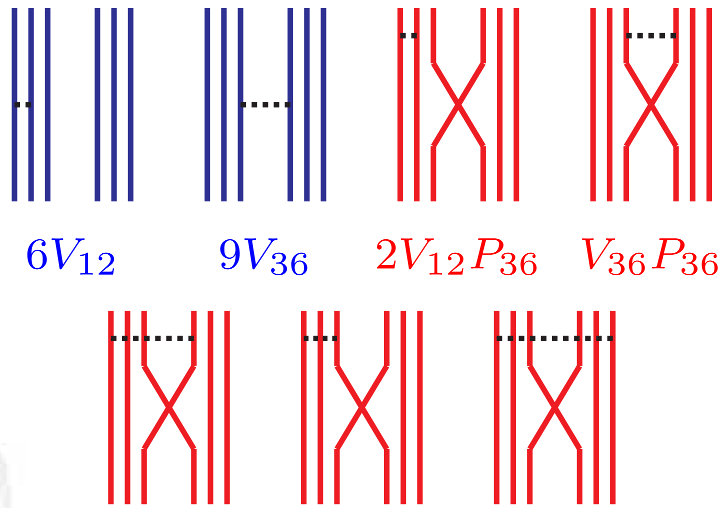
  $\longrightarrow$ One gluon exchange
- Confinement
  Color screened confinement
- Interactions:

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

The NN interaction

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

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



$$\psi_{B_1 B_2} = \mathcal{A}\left[\chi(\vec{P})\psi^{ST}_{B_1 B_2}\right]$$

$$= \mathcal{A}\left[\phi_{B_1}(\vec{p}_{\xi_{B_1}})\phi_{B_2}(\vec{p}_{\xi_{B_2}})\chi(\vec{P})\chi^{ST}_{B_1 B_2}\xi_c[2^3]\right]$$

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

	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 is not present in ND^* and ΔD^***
- **One bound state in NN, what happens in ND^* and ΔD^*?**

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]

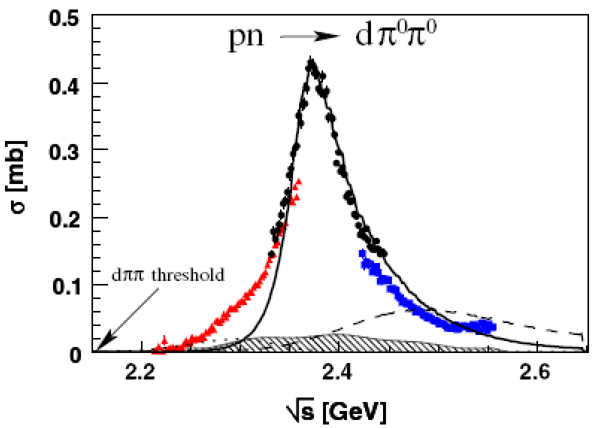


FIG. 2 (color online). Total cross sections obtained from this experiment on $pd \to d\pi^0\pi^0 + p_{\mathrm{spectator}}$ for the beam energies $T_p = 1.0$ GeV (triangles), 1.2 GeV (dots), and 1.4 GeV (squares) normalized independently. Shown are the total cross section data after acceptance, efficiency 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 $\Delta\Delta$ 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 $\Delta\Delta$ state**
  A. Pricking, M. Bashkanov and H. Clement arXiv:1310:5532
- **A new proposal as a NN^* state**
  D. Bugg Eur. Phys. J A50

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

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

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

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

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** $3871{,}80 \pm 0{,}35\ MeV/c^2$
- $\frac{\mathcal{B}(X \to J/\psi \pi^+ \pi^- \pi^0)}{\mathcal{B}(X \to J/\psi \pi^+ \pi^-)} = 0{,}8 \pm 0{,}3$
- $\frac{\mathcal{B}(X \to J/\psi \gamma)}{\mathcal{B}(X \to J/\psi \pi^+ \pi^-)} = 0{,}33 \pm 0{,}12$ $\frac{\mathcal{B}(X \to \psi(2S)\gamma)}{\mathcal{B}(X \to J/\psi \gamma)} < 2{,}1$
- $\frac{\mathcal{B}(X \to \psi(2S)\gamma)}{\mathcal{B}(X \to J/\psi \pi^+ \pi^-)} = 1{,}1 \pm 0{,}4$

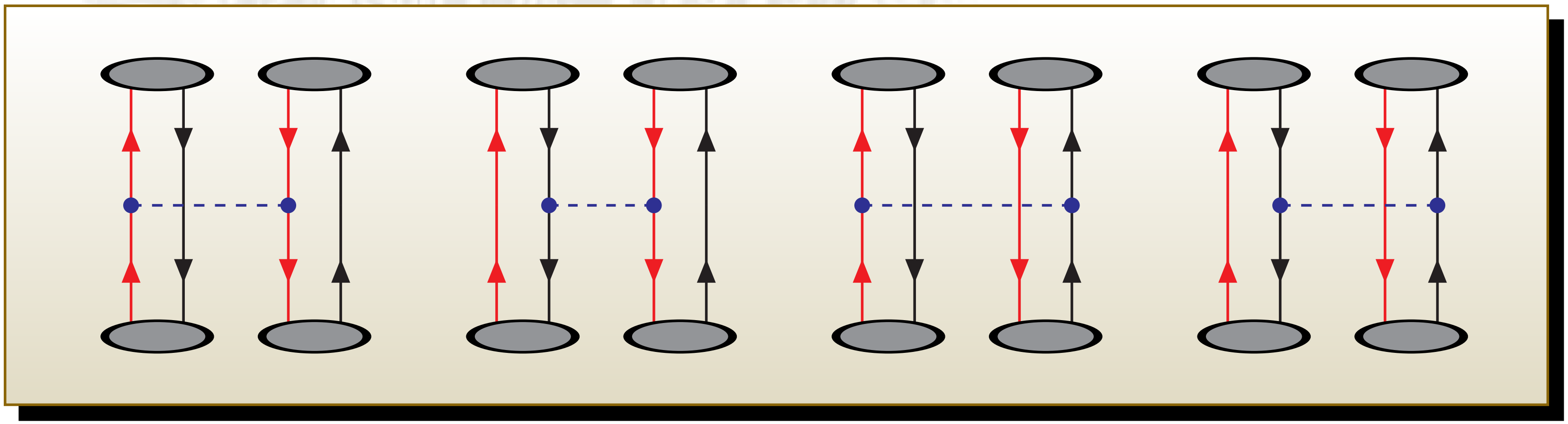
We perform a couple channel calculation with DD^* and P-wave $c\bar{c}$ states.

The $M_1 M_2$ system

- **Quark interactions** $\longrightarrow$ **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.**



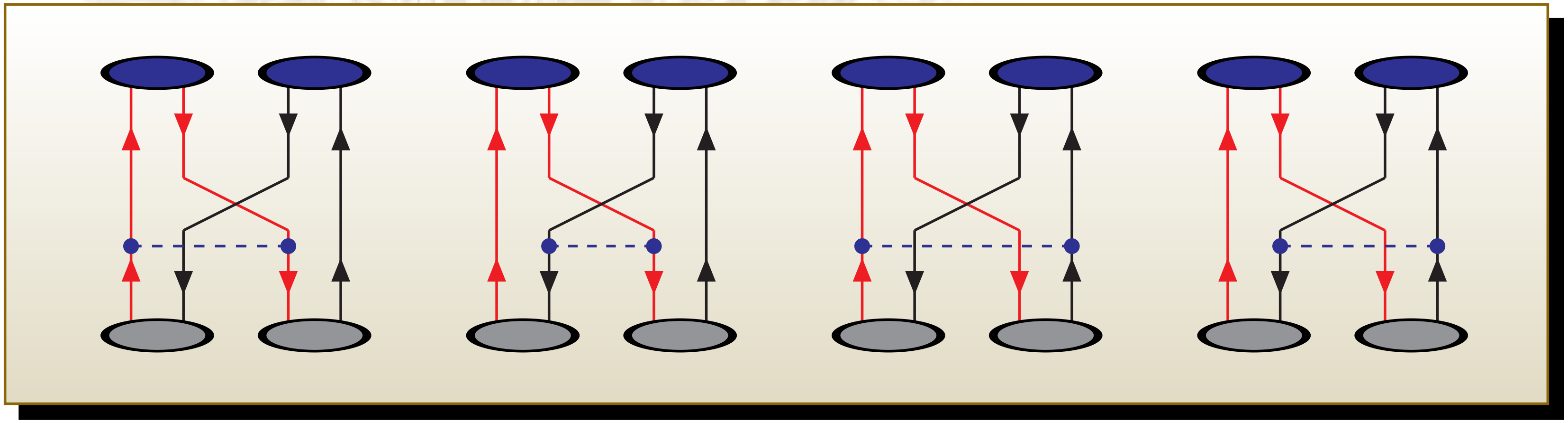
The $M_1 M_2$ system

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

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

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

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



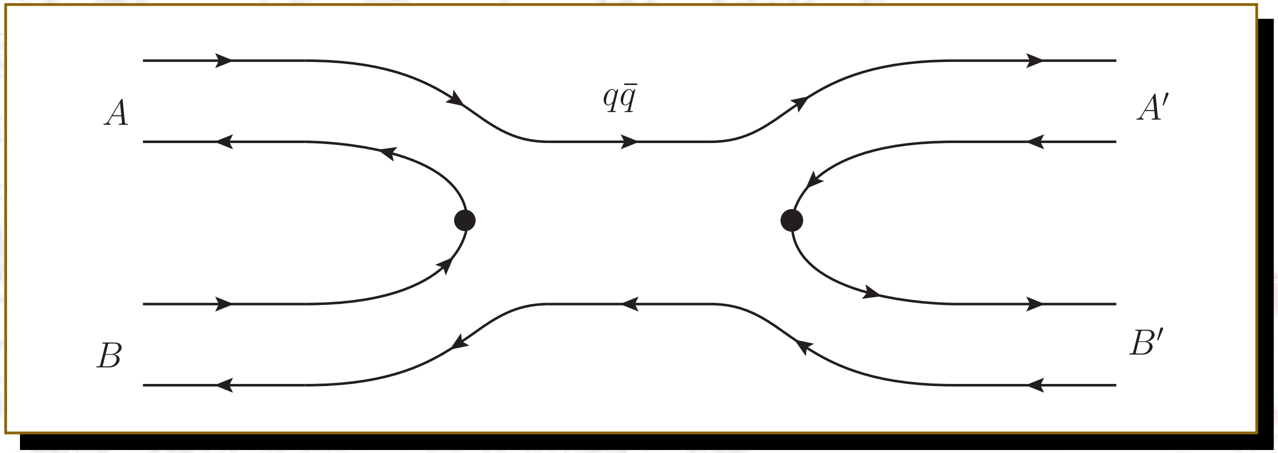
Coupling $q\bar{q}$ and $q\bar{q}\bar{q}q$ sectors

- **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,**

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

The $X(3872)$

- $^3S_1$ **and** $^3D_1$ DD^* **partial waves included.**
- **Coupling to** 1^{++} **ground and first excited** $c\bar{c}$ **states with bare masses within the model:** $c\bar{c}(1^3P_1) \rightarrow M = 3503{,}9\ MeV$ $c\bar{c}(2^3P_1) \rightarrow M = 3947{,}4\ MeV$ **and**
- **Isospin breaking** $M_{D^\pm} + M_{D^{*\pm}} \neq M_{D^0} + M_{D^{*0}}$

Parameter free calculation.

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

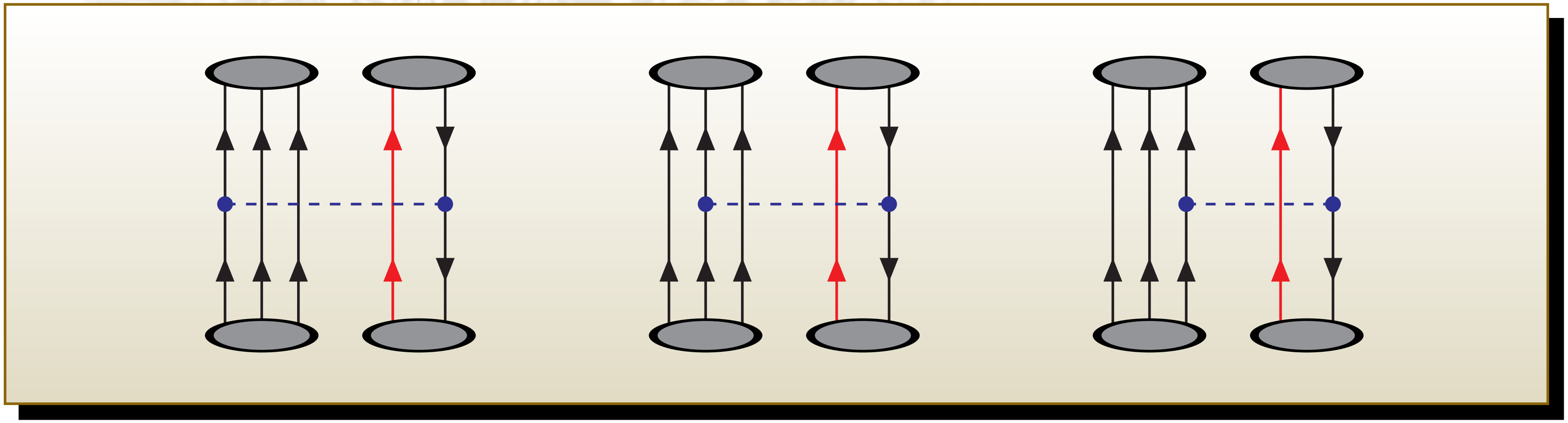
- **Isospin probabilities**: $\mathcal{P}_{I=0} = 66\,\%$, $\mathcal{P}_{I=1} = 3\,\%$, $\mathcal{P}_{c\bar{c}} = 30\,\%$.
- **Fine tune** $^3P_0$ γ **strength parameter to** E_{bind}. $\mathcal{P}_{I=0} \sim 70\,\%$, $\mathcal{P}_{I=1} \sim 23\,\%$, $\mathcal{P}_{c\bar{c}} \sim 7\,\%$
- **P.G. Ortega, 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**

The BM system

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

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

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



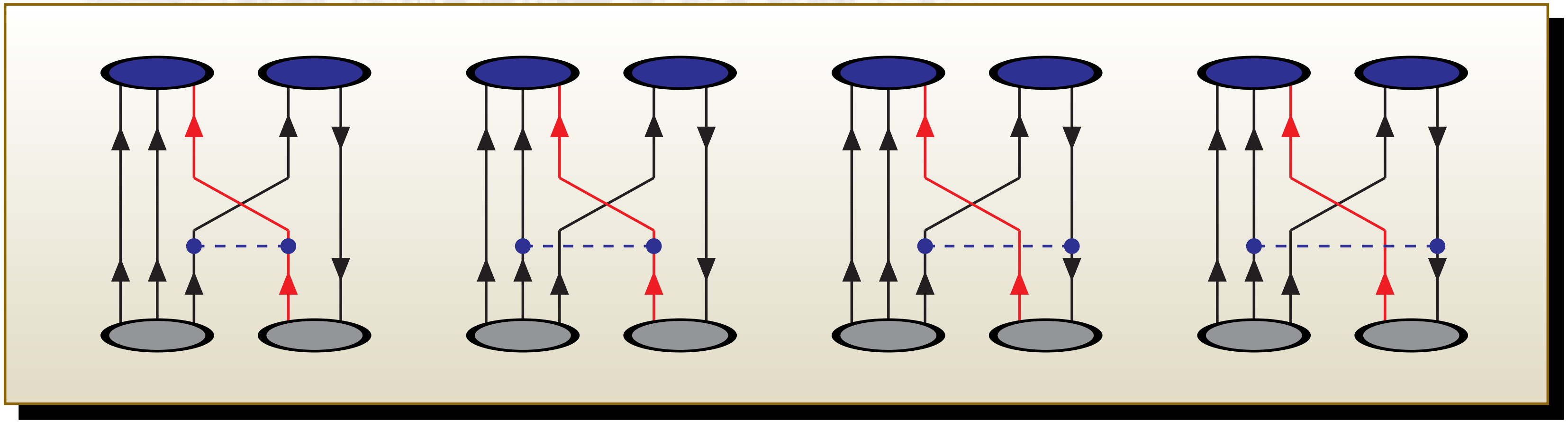
The BM system

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

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

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

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		

P.G. Ortega, D.R.E., F. Fernández, PLB 718, 1381 (2013)

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	$-1,70$	$98,08(^2S_{1/2})$
$\frac{1}{2}^-$	1	D^*N	2948	$-0,48$	$99,93(^2S_{1/2})$
$\frac{3}{2}^-$	0	D^*N	2939	$-8,02$	$96,05(^4S_{3/2})$
$\frac{1}{2}^-$	0	$\bar{B}N$	6206	$-12,09$	$87,61(^2S_{1/2})$
$\frac{1}{2}^-$	1	$\bar{B}N$	6218	$-0,36$	$99,05(^2S_{1/2})$
$\frac{1}{2}^-$	1	$\bar{B}^*N$	6261	$-3,43$	$99,86(^2S_{1/2})$
$\frac{3}{2}^-$	0	$\bar{B}^*N$	6248	$-15,15$	$95,07(^4S_{3/2})$

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

J^P	$Isospin$	$Molecule$	$Mass(MeV)$	$E_b(MeV)$	$P_{max}(Channel)$
$\frac{1}{2}^-$	2	$D^*\Delta$	3233	$-6{,}47$	$99{,}71(^2S_{1/2})$
$\frac{3}{2}^-$	1	$D\Delta$	3097	$-0{,}88$	$99{,}13(^4S_{3/2})$
$\frac{3}{2}^-$	2	$D^*\Delta$	3238	$-0{,}98$	$99{,}69(^2S_{1/2})$
$\frac{5}{2}^-$	1	$D^*\Delta$	3226	$-13{,}12$	$97{,}25(^6S_{5/2})$
$\frac{1}{2}^-$	2	$\bar{B}^*\Delta$	6541	$-14{,}21$	$99{,}69(^2S_{1/2})$
$\frac{3}{2}^-$	1	$\bar{B}\Delta$	6499	$-10{,}72$	$88{,}14(^4S_{3/2})$
$\frac{3}{2}^-$	2	$\bar{B}\Delta$	6506	$-3{,}67$	$94{,}72(^4S_{3/2})$
$\frac{3}{2}^-$	1	$\bar{B}^*\Delta$	6555	$-0{,}39$	$97{,}10(^4S_{3/2})$
$\frac{3}{2}^-$	2	$\bar{B}^*\Delta$	6550	$-4{,}85$	$99{,}48(^4S_{3/2})$
$\frac{5}{2}^-$	1	$\bar{B}^*\Delta$	6532	$-23{,}16$	$96{,}76(^6S_{5/2})$

Three possible candidates for the $X_c(3250)$

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

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

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

P.G. Ortega, D.R.E., F. Fernández, PLB 729, 24 (2014)

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 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 $3/2^-$
- $I = 2$ $J^P = 1/2^-$ candidate 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 $X_c \to DN\pi$