Threshold effects in hadron spectrum: a new spectroscopy?

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Outline

1. Motivation
2. The model
3. Results
4. Conclusions

Outline

Quark model

André Petermann

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A SCHEMATIC MODEL OF BARYONS AND MESONS *

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Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" $^{1-3)}$, we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dy-

$3 \times 3 = 9,$ $\quad 3 \otimes \bar{3} = 8 \oplus 1,$

$3 \times 3 \times 3 = 27, \ldots$ $\quad 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

Murray Gell-Mann, 10-year-old, New York, 1939.

Now, 25 years later, Caltech

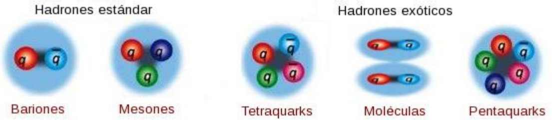
ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" $^{6)}$ q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowes baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly give just **1** and **8**.

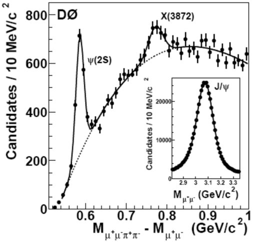
Discoveries at B-factories

- Exotic Mesons: $X(3872)$, $D_{s0}^{*}(2317)$, $D_{s1}(2460)$, $X(4140)$,...
- Exotic Baryons: $\Lambda_c(2940)$, $P_c(4380)$, $P_c(4450)$,...

  Signals of exotic structures? Standard $q\bar{q}$ or qqq? Threshold cusps?



- Possibility to study the coupling with higher Fock spaces.
- Some of them may be naive $q\bar{q}$ or qqq structures.
- Others are more elusive: $X(3872) \rightarrowtail$



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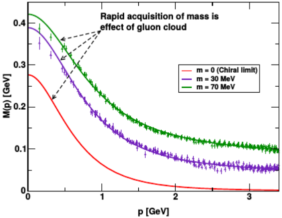
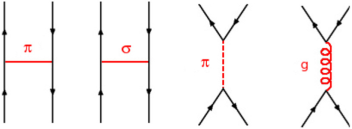
Ingredients of constituent quark model

The model includes:

- Spontaneous breaking of chiral symmetry ↣ Constituent mass and Pseudo-Goldstone bosons.



C. D. Roberts, arxiv:1109.6325v1 [nucl-th]



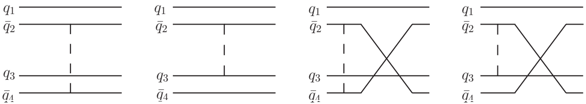
- QCD perturbative effects ↣ Gluon exchange.
- Confinement ↣ Screened potential.
- All parameters constrained from low-lying meson and baryon spectra.

Constituent quark model

- Nucleon-Nucleon interaction:
  - D. R. Entem, F. Fernández, A. Valcarce, **PRC62**, 034002 (2000).
  - A. Valcarce, A. Faessler, F. Fernández, **PLB345**, 367 (1995).
  - F. Fernández, A. Valcarce, U. Straub, A. Faessler, **JPG19**, 2013 (1993).
- Baryon spectrum:
  - A. Valcarce, H. Garcilazo, and J. Vijande, **PRC72**, 025206 (2005).
  - H. Garcilazo, A. Valcarce, F. Fernández, **PRC64**, 058201 (2001).
- Meson spectrum:
  - J. Vijande, F. Fernández y A. Valcarce, **JPG31**, 481 (2005).
  - J. Segovia, A. M. Yasser, D. R. Entem, F. Fernández, **PRD78**, 114033 (2008).
  - J. Segovia, P. G. Ortega, D. R. Entem, F. Fernández, **PRD90**, 074027 (2016).

Solving the two body problem

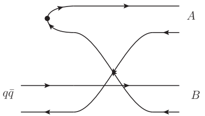
- We want to explore meson-meson and meson-baryon interactions.
- Meson wave function ↣ Gaussian Expansion Method:
  - $\psi_{lm}(\vec{p}) = \sum_{n=1}^{n_{max}} C_{nl} Y_{lm}(\hat{p}) \phi_{nl}(p)$, with $\phi_{nl}(p) = (-i)^l \frac{N_{nl}}{(2\eta_n)^{l+3/2}} p^l e^{-\frac{p^2}{4\eta_n}}$
  - GEM free parameters: $\{n_{max}, r_1, a\}$
  - Rayleigh-Ritz variational principle:
    $\sum_{n'=1}^{n_{max}} \left[(T^{\alpha}_{nn'} - E N^{\alpha}_{nn'}) c^{\alpha}_{n'l} + \sum_{\alpha'}^{n^o\, chnl} V^{\alpha\alpha'}_{nn'} c^{\alpha'}_{n'l} \right] = 0$
- Baryon wave functions ↣ Gaussian with scaled range.
- Resonating Group Method:
  - Interaction at quark level ↣ Interaction between clusters
  - Direct and exchange potentials:



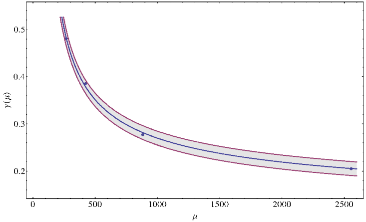
$^3P_0$ interaction

- $^3P_0$ model used as coupling mechanism.
- 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 $\gamma' = 2^{5/2}\pi^{1/2}\gamma$ and $\gamma = \frac{g}{2m}$
- Running of the $^3P_0$ strength $\gamma \longrightarrow$ J. Segovia et al., arXiv:1205.2215



$$\gamma(\mu) = \frac{\gamma_0}{\log(\mu/\mu_\gamma)}$$

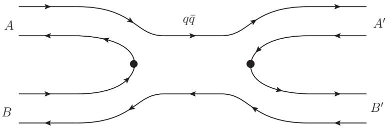
- $\gamma_0 = 0.81 \pm 0.02$
- $\mu_\gamma = 49.84 \pm 2.58$ MeV
- Solid line is the fit
- Shaded area → 90% C.L.

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

- Effect of $q\bar{q}$ on meson-meson states $\rightarrowtail$ Molecular states, mass-shifts, threshold cusps,...
- Mixed states: $|\Psi\rangle = \sum_\alpha c_\alpha |\psi\rangle + \sum_\beta \chi_\beta(P)\,|\phi_{M1}\phi_{M2}\beta\rangle$
- Solving the coupling with the $q\bar{q}$ meson spectrum $\rightarrowtail$ Schrödinger-type equation:

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

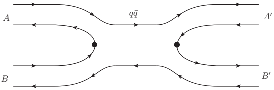
with $V^{eff}_{\beta'\beta}(E;P',P)$:



Coupling formalism with T matrix

- Resonances → Poles of the Scattering Matrix:
  $S_{\alpha}^{\alpha'} = 1 - 2\pi i \sqrt{\mu_{\alpha}\mu_{\alpha'} k_{\alpha} k_{\alpha'}}\, T_{\alpha}^{\alpha'}(E + i0; k_{\alpha'}, k_{\alpha})$
- T matrix obtained with Lippmann-Schwinger:
  $T^{\beta'\beta}(E; P', P) = V_T^{\beta'\beta}(P', P) + \sum_{\beta''} \int dP'' P''^2 V_T^{\beta'\beta''}(P', P'') \frac{1}{E - E_{\beta''}(P'')} T^{\beta''\beta}(E; P'', P)$
- With $V_T^{\beta'\beta}(P', P) = V^{\beta'\beta}(P', P) + V_{eff}^{\beta'\beta}(P', P)$

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



The complete T matrix factorizes like V_T:

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

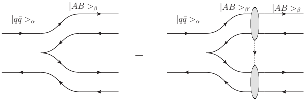
Coupling elements

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

- Modified vertex:

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

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

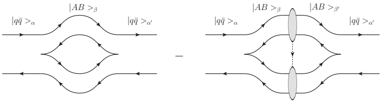


- Complete propagator:

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

- Exact mass-shift of the state:

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



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$X(3872)$ state

- Quantum numbers: $J^{PC} = 1^{++}$
- Width : $\Gamma < 1.2$ (90% C.L.)
- Mass : $M_X = 3871.69 \pm 0.17\, MeV/c^2 \rightarrowtail$
  Close & slightly below $D^0\bar{D}^{*0}$ threshold.
- $R_1 = \frac{\mathcal{B}(X \to J/\psi\pi^+\pi^-\pi^0)}{\mathcal{B}(X \to J/\psi\pi^+\pi^-)} = \begin{cases} 1.0 \pm 0.4 \pm 0.3 \text{ (Belle)} \\ 0.8 \pm 0.3 \text{ (BaBar)} \end{cases}$,
- $R_2 = \frac{\mathcal{B}(X \to J/\psi\gamma)}{\mathcal{B}(X \to J/\psi\pi^+\pi^-)} = \begin{cases} 0.33 \pm 0.12 \text{ (BaBar)} \\ 0.14 \pm 0.05 \text{ (Belle)} \end{cases}$,
- $R_3 = \frac{\mathcal{B}(X \to \psi(2S)\gamma)}{\mathcal{B}(X \to J/\psi\gamma)} = 2.6 \pm 0.6$ (LHCb).

Experimental data suggest a loosely-bound D^0D^{*0} molecule coupled to $2P$ $c\bar{c}$ states.

P. G. Ortega *et al.*, `PRD 81, 054023 (2010).`

Results for the $X(3872)$ coupled calculation

- $D^0 D^{*0}$ and $D^{\pm} D^{*\mp}$ meson-meson channels are included
- Coupled to $c\bar{c}(2^3P_1)$ meson state $\rightarrowtail$ Theoretical bare mass$=$ 3947.4 MeV
- Inclusion of $J/\psi\rho$ y $J/\psi\omega$ channels, needed for describing the strong decays $\rightarrowtail$ Rearrangement diagrams
  Small contribution to the mass
- The value of γ is fine-tuned to obtain the $X(3872)$ experimental mass

γ	E_{bind}	$c\bar{c}(2^3P_1)$	$D^0 D^{*0}$	$D^{\pm} D^{*\mp}$	$J/\psi\rho$	$J/\psi\omega$
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

$X(3872)$ strong and radiative decay results

- Experimental results

$$R_1 = \frac{\mathcal{B}(X \to J/\psi\pi^+\pi^-\pi^0)}{\mathcal{B}(X \to J/\psi\pi^+\pi^-)} = \begin{cases} 1.0 \pm 0.4 \pm 0.3 \\ 0.8 \pm 0.3 \end{cases},$$

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$$R_3 = \frac{\mathcal{B}(X \to \psi(2S)\gamma)}{\mathcal{B}(X \to J/\psi\gamma)} = 2.6 \pm 0.6$$

- Theoretical decays [keV]:

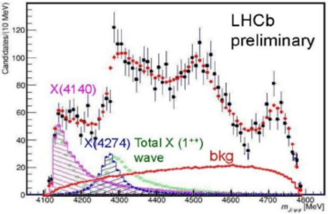
E_{bind}	$\Gamma_{\pi^+\pi^- J/\psi}$	$\Gamma_{\pi^+\pi^-\pi^0 J/\psi}$	$\Gamma^{M}_{J/\psi\gamma}$	$\Gamma^{c\bar{c}}_{J/\psi\gamma}$	$\Gamma^{c\bar{c}}_{\Psi(2S)\gamma}$
-0.60	27.61	14.40	0.070	8.15	9.80
-0.25	24.18	10.64	0.056	5.25	6.31

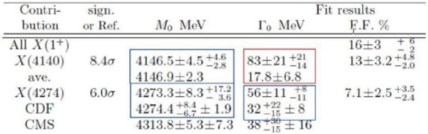
- Theoretical ratios:

E_{bind}	R_1	R_2	R_3
-0.60	0.52	0.30	1.20
-0.25	0.44	0.22	1.20

LHCb Resonances

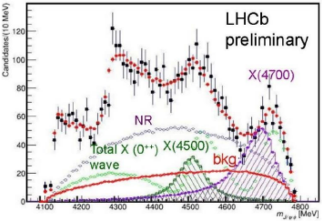
$X(1^{++})$

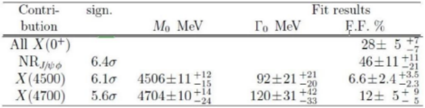




Contri-bution	sign. or Ref.	M_0 MeV	Γ_0 MeV	F.F. %
				Fit results
All $X(1^+)$				$16\pm3\ ^{+\ 6}_{-\ 2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$	$13\pm3.2\,^{+4.8}_{-2.0}$
ave.		4146.9 ± 2.3	17.8 ± 6.8	
$X(4274)$	6.0σ	$4273.3\pm8.3\,^{+17.2}_{-\ 3.6}$	$56\pm11\,^{+8}_{-11}$	$7.1\pm2.5\,^{+3.5}_{-2.4}$
CDF		$4274.4\,^{+8.4}_{-6.7}\pm1.9$	$32\,^{+22}_{-15}\pm8$	
CMS		$4313.8\pm5.3\pm7.3$	$38\,^{+30}_{-15}\pm16$	

$X(0^{++})$





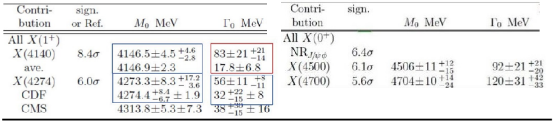
Contri-bution	sign.	M_0 MeV	Γ_0 MeV	F.F. %
				Fit results
All $X(0^+)$				$28\pm\ 5\,^{+7}_{-7}$
$\mathrm{NR}_{J/\psi\phi}$	6.4σ			$46\pm11\,^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\,^{+12}_{-15}$	$92\pm21\,^{+21}_{-20}$	$6.6\pm2.4\,^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$	$12\pm\ 5\,^{+\ 9}_{-\ 5}$

LHCb Resonances: $X(4274)$, $X(4500)$ and $X(4700)$

- States fit naive QM predictions! $\rightarrowtail$ non-$q\bar{q}$ part not important.
- Quark model predictions:

State	J^{PC}	nL	Mass (MeV/c^2)	Width (MeV)	Exp. (MeV/c^2)
χ_{c0}	0^{++}	$3P$	4261.7		
		$4P$	4497.7	115.40	$4506 \pm 11^{+12}_{-15}$
		$5P$	4697.6	112.02	$4704 \pm 10^{+14}_{-24}$
		$6P$	4855.6		
χ_{c1}	1^{++}	$3P$	4271.5	29.80	4273.3 ± 8.3
		$4P$	4520.8		

- LHCb results:



Contri- bution	sign. or Ref.	M_0 MeV	Γ_0 MeV
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ave.		4146.9 ± 2.3	17.8 ± 6.8
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CDF		$4274.4\,^{+8.4}_{-6.7}\pm1.9$	$32\,^{+22}_{-15}\pm8$
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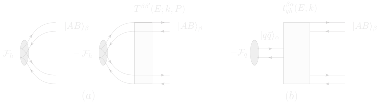
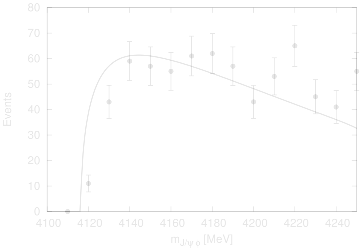
$X(4700)$	5.6σ	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$

LHCb Resonances: Searching for $X(4140)$

- Coupling channel calculation for the $J^{PC} = 1^{++}$ sector: $D_s^{(*)} D_s^{(*)}$ and $J/\psi\phi$ channels.
- Any signal of $X(4140)$ neither bound nor virtual





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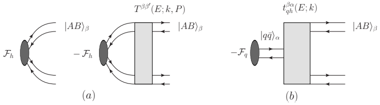

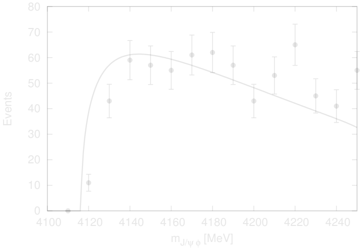

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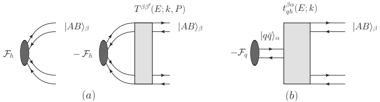
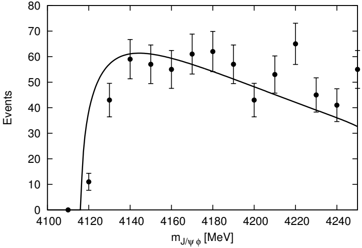


- The $X(4140)$ appears as a threshold cusp



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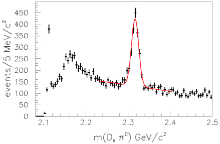
More details at:

P. G. Ortega *et al.*, `PRD 94, 114018 (2016) -- arxiv:1608.01325`

$D_{s0}^*(2317)$ and $D_{s1}(2460)$ open-charm mesons

- $D_{s0}^*(2317)$ $[0^+]$ $\rightarrowtail$ Discovered in 2003 in $D_s^+\pi^0$ by CLEO.
- $D_{s1}(2460)$ $[1^+]$ $\rightarrowtail$ Discovered in 2003 in $D_s^{*\,+}\pi^0$ by BaBar.
- Very narrow states below the $D^{(*)}K$ thresholds.
- States far from naive quark models and heavy quark symmetry expectations $\rightarrowtail$ $\sim 100\,\mathrm{MeV}$ above thresholds
- $D_{s1}(2536)$ $[1^+]$ width: $0.92 \pm 0.05\,MeV$ $\rightarrowtail$ $j_q = \frac{3}{2}$ HQS state?

- $c\bar{s}$ system $\rightarrowtail$ *Heavy Quark Symmetry*
- $D^{(*)}K$ molecular states? Renormalized $c\bar{s}$?

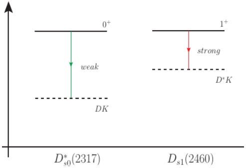


Good agreement with experiments when DK operators are included.

D. Mohler *et al.* PRL 111, 222001; C. B. Lang *et al.* PRD90, 034510; G. S. Bali *et al.* arXiv:1706.01247.

$D_{s0}^*(2317)$ and $D_{s1}(2460)$ open-charm mesons

- Potential mass shift depend only on energy difference between $c\bar{s}$ state and the open-flavored threshold.

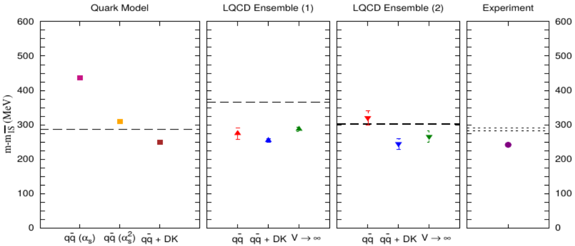


- Similar dynamics for 0^+ and 1^+ $\rightarrowtail$ $j_q^P = 1/2^+$ HQS doublet.
- The states should be degenerated.
- They should couple equally to DK and D^*K.

- *Addition of the one-loop QCD correction to the spin-dependent term of the potential.* S.N. Gupta and S.F. Radford, PRD24, 2309 (1981).
- *There is a spin-dependent term which affects only to mesons with different flavor quarks.* O. Lakhina and E.S.Swanson, PLB650, 159 (2007).
- The 0^+ is more sensitive to the inclusion of the one-loop corrections.

	$j_q^P = 1/2^-$		$j_q^P = 1/2^+$		$j_q^P = 3/2^+$	
	0^-	1^-	0^+	1^+	1^+	2^+
This work (α_s)	1984	2110	2510	2593	2554	2591
This work (α_s^2)	1984	2104	2383	2570	2560	2609
Exp.	1969.0 ± 1.4	2112.3 ± 0.5	2318.0 ± 1.0	2459.6 ± 0.9	2535.12 ± 0.25	2572.6 ± 0.9

The $D_{s0}^*(2317)$ meson



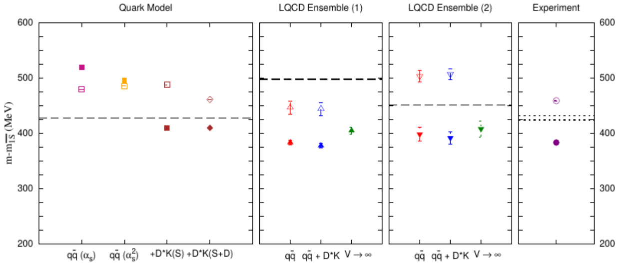
P.G. Ortega *et al.*, arXiv: 1603.07000 [hep-ph]

LQCD data: C. B. Lang *et al.* PRD90, 034510 (2014).

- Input: Bare $c\bar{s}$ (1^3P_0) state + DK threshold.
- Mass much higher using naive quark model and no 1-loop correction.
- Mass due to α_s^2-corrections allows the 0^+ to be closer to DK threshold $\longrightarrow$ DK coupling becomes a relevant dynamic mechanism.
- When we couple the 0^+ $c\bar{s}$ ground state with the DK threshold the mass is in good agreement with experiment.

State	Mass	$\mathcal{P}[q\bar{q}\,(^3P_0)]$	$\mathcal{P}[DK(S-wave)]$
$D_{s0}^*(2317)$	2323.7	66.3%	33.7%

The $D_{s1}(2460)$ and $D_{s1}(2536)$ mesons (I)



P.G. Ortega *et al.*, arXiv: 1603.07000 [hep-ph]

LQCD data: C. B. Lang *et al.* PRD90, 034510 (2014).

- Input: Bare $c\bar{s}$ (1^1P_1) and (1^3P_1) states + D^*K threshold (S & D waves).
- Naive quark model predicts states almost degenerated, with masses close to the experimentally observed mass of the $D_{s1}(2536)$.
- The inclussion of the 1-loop corrections to the OGE potential does not improve the situation, making the splitting between the two states even smaller.

The $D_{s1}(2460)$ and $D_{s1}(2536)$ mesons (II)

State	Mass	Width	$\mathcal{P}[q\bar{q}\,(^1P_1)]$	$\mathcal{P}[q\bar{q}\,(^3P_1)]$	$\mathcal{P}[D^*K(S)]$	$\mathcal{P}[D^*K(D)]$
$D_{s1}(2460)$	2484.0	0.00	12.9%	32.8%	54.3%	-
$D_{s1}(2536)$	2562.1	0.22	34.4%	15.8%	49.8%	-
$D_{s1}(2460)$	2484.0	0.00	12.1%	33.6%	54.1%	0.2%
$D_{s1}(2536)$	2535.2	0.56	31.9%	14.5%	16.8%	36.8%

The $q\bar{q}$ component in the wave function of the $D_{s1}(2536)$ meson holds quite well the $^1P_1$ and $^3P_1$ composition predicted by HQS $\rightarrowtail$ $j_q^P = 3/2^+$ doublet.

Crucial in order to have a very narrow state and describe well its decays.

$$R_1 = \frac{\Gamma(D_{s1}(2536)^+ \to D^{*0}K^+)}{\Gamma(D_{s1}(2536)^+ \to D^{*+}K^0)},$$

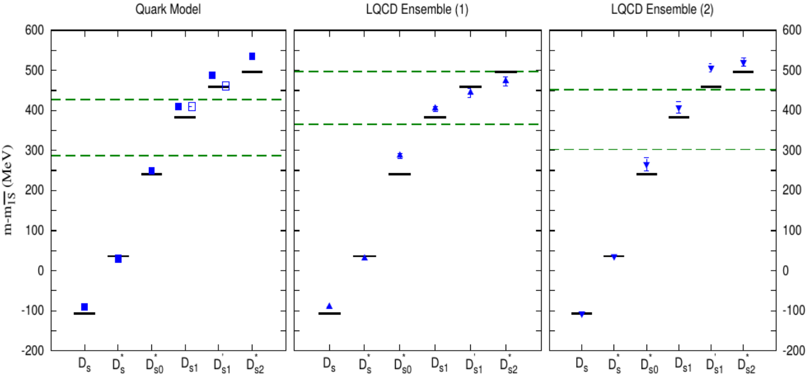
$$R_2 = \frac{\Gamma_S(D_{s1}(2536)^+ \to D^{*+}K^0)}{\Gamma(D_{s1}(2536)^+ \to D^{*+}K^0)},$$

$$R_3 = \frac{\Gamma(D_{s1}(2536)^+ \to D^+\pi^-K^+)}{\Gamma(D_{s1}(2536)^+ \to D^{*+}K^0)},$$

	This work	Experiment
Γ [MeV]	0.56	$0.92 \pm 0.03 \pm 0.04$
R_1	1.15	1.18 ± 0.16
R_2	0.52	$0.72 \pm 0.05 \pm 0.01$
R_3 [%]	14.5	$3.27 \pm 0.18 \pm 0.37$

Low-lying charmed-strange mesons

Overall agreement between quark model, lattice QCD and experimental data

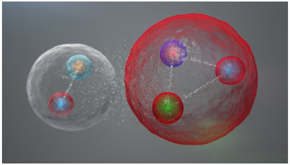


Theoretical results on $D_{s1}^*(2700)$, $D_{sJ}^*(2860)$ and $D_{sJ}(3040)$ in PRD91, 094020 (2015).

P. G. Ortega *et al.*, `PRD94, 074037 (2016) -- arxiv:1603.07000`

$\Lambda_c(2940)^+$ baryon

- Discovered in D^0p and $\Sigma_c(2455)^{0,++}\pi^\pm$ channels
- Mass: $2939.8 \pm 1.3 \pm 1.0\, MeV/c^2$ Width: $17.5 \pm 5.2 \pm 5.9\, MeV$ (BaBar)
- Mass: $2938.0 \pm 1.3^{+2.0}_{-4.0}\, MeV/c^2$ Width: $13^{+8}_{-5}{}^{+27}_{-7}\, MeV$ (Belle)
- Mass: $2944.8 \pm 0.4^{+3.5}_{-2.5}\, MeV/c^2$ Width: $27.7 \pm 0.9^{+8.2}_{-6.0}\, MeV$ (LHCb)
- $D^{*0}p$ molecule in S-wave? $\rightarrowtail$ Possible quantum numbers:



J^P	$^{2S+1}L_J$		
$\frac{1}{2}^-$	$^2S_{\frac{1}{2}}$	$^4D_{\frac{1}{2}}$	
$\frac{1}{2}^+$	$^2P_{\frac{1}{2}}$	$^4P_{\frac{1}{2}}$	
$\frac{3}{2}^-$	$^4S_{\frac{3}{2}}$	$^2D_{\frac{3}{2}}$	$^4D_{\frac{3}{2}}$
$\frac{3}{2}^+$	$^2P_{\frac{3}{2}}$	$^4P_{\frac{3}{2}}$	$^4F_{\frac{3}{2}}$

- $J^P = \frac{3}{2}^-$ Similar scenario as the $X(3872)$ state

$\Lambda_c(2940)^+$ **baryon:** D^*N **in** $J^P = \frac{3}{2}^-$ **sector**

- Only quark-quark interaction $\rightarrowtail$ Pure D^*-N interaction
- D^*N molecule in S-wave with $J^P = \frac{3}{2}^-$
- Results including charged molecular states:

$Mass$	$\mathcal{P}_{^4S_{3/2}}$	$\mathcal{P}_{^2D_{3/2}}$	$\mathcal{P}_{^4D_{3/2}}$	$\mathcal{P}_{D^{0*}p}$	$\mathcal{P}_{D^{+*}n}$	$\mathcal{P}_{I=0}$	$\mathcal{P}_{I=1}$
2938.80	96.22	0.86	2.92	63.93	36.07	97.52	2.48

- Decays:

Decay channel	$Width\,(MeV)$	decay channel	$Width\,(keV)$
$\Lambda_c^+ \to D^0 p$	9.42	$\Lambda_c^+ \to \Sigma_c^{++}\pi^-$	4.19
$\Lambda_c^+ \to D^+ n$	10.74	$\Lambda_c^+ \to \Sigma_c^{+}\pi^0$	4.35
		$\Lambda_c^+ \to \Sigma_c^{0}\pi^+$	4.51

- Total width: $\Gamma = 20.2$ MeV
- Experimental width: $\Gamma = 17^{+8}_{-6}$ MeV

$\Lambda_c(2940)^+$ baryon: D^*N in $J^P = \frac{3}{2}^-$ sector

- Only quark-quark interaction $\rightarrowtail$ Pure D^*-N interaction
- D^*N molecule in S-wave with $J^P = \frac{3}{2}^-$ $\rightarrowtail$ **favoured by recent LHCb analysis!**
- Results including charged molecular states:

Mass	$\mathcal{P}_{^4S_{3/2}}$	$\mathcal{P}_{^2D_{3/2}}$	$\mathcal{P}_{^4D_{3/2}}$	$\mathcal{P}_{D^{0*}p}$	$\mathcal{P}_{D^{+*}n}$	$\mathcal{P}_{I=0}$	$\mathcal{P}_{I=1}$
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		$\Lambda_c^+ \to \Sigma_c^{0}\pi^+$	4.51

- Total width: $\Gamma = 20.2$ MeV
- Experimental width: $\Gamma = 17^{+8}_{-6}$ MeV

Partner in b sector: $\Lambda_b(6248)^0$

- Possibility existence of a partner of $\Lambda_b(2940)^+$ in b sector
- Description as a B^*N molecule in $J^P = \frac{3}{2}^-$ sector.
- Results including charged molecular states:

$M\,(MeV)$	$\mathcal{P}_{^4S_{3/2}}$	$\mathcal{P}_{^2D_{3/2}}$	$\mathcal{P}_{^4D_{3/2}}$	$\mathcal{P}_{B^{*-}p}$	$\mathcal{P}_{B^{*0}n}$	$\mathcal{P}_{I=0}$	$\mathcal{P}_{I=1}$
6248.34	95.15	1.08	3.77	52.56	47.44	99.91	0.09

- Decays:

Decay channel	$Width\,(MeV)$	Decay channel	$Width\,(keV)$
$\Lambda_b^0 \to B^- p$	3.69	$\Lambda_b^0 \to \Sigma_b^+ \pi^-$	6.30
$\Lambda_b^0 \to B^0 n$	3.75	$\Lambda_b^0 \to \Sigma_b^0 \pi^0$	6.34
		$\Lambda_b^0 \to \Sigma_b^- \pi^+$	6.38

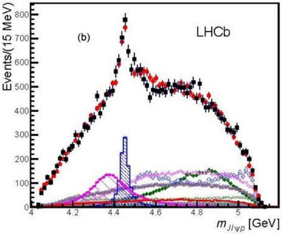
More details at:

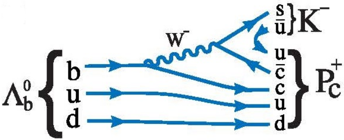
P. G. Ortega *et al.*, `Physics Letters B 718, 1381-1384 (2013)`

LHCb Pentaquarks: $P_c(4380)$ and $P_c(4450)$

R. Aaij et al, *Phys. Rev. Lett.* **115**, 072001 (2015).

- Discovered in 2015 in $\Lambda_b^0 \to J/\psi K^- p$ decay.
- Preferred quantum numbers: $(\frac{3}{2}^{\mp}, \frac{5}{2}^{\pm})$
- But other combinations such as $(\frac{3}{2}^{-}, \frac{3}{2}^{-})$ not excluded (L. Roca, arxiv:1602.06791)
- Masses close to $D\Sigma_c^*$ and $D^*\Sigma_c$ channel thresholds.





$$
\begin{aligned}
M_{P_c(4380)} &= 4380 \pm 8 \pm 29\, MeV, \\
M_{P_c(4450)} &= 4449.8 \pm 1.7 \pm 2.5\, MeV, \\
\Gamma_{P_c(4380)} &= 205 \pm 18 \pm 86\, MeV, \\
\Gamma_{P_c(4450)} &= 39 \pm 5 \pm 19\, MeV.
\end{aligned}
$$

LHCb pentaquarks: $P_c(4380)$ and $P_c(4450)$

- $\bar{D}^{(*)}\Sigma_c^{(*)}$ molecules in S-wave and P-wave.
- We obtain the following candidates:

$$\begin{aligned} M_{P_c(4380)} &= 4380 \pm 8 \pm 29\ MeV, \\ M_{P_c(4450)} &= 4449.8 \pm 1.7 \pm 2.5\ MeV, \\ \Gamma_{P_c(4380)} &= 205 \pm 18 \pm 86\ MeV, \\ \Gamma_{P_c(4450)} &= 39 \pm 5 \pm 19\ MeV. \end{aligned}$$

Molecule	J^P	I	$Mass(MeV/c^2)$	$B_E(MeV/c^2)$	Width $J/\psi p$	Width $\bar{D}^*\Lambda_c$
$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	$\frac{1}{2}$	4320.8	0.8	2.4	1.1
$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	$\frac{1}{2}$	4385.0	1.0	10.0	14.7
$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	$\frac{1}{2}$	4458.9	3.8	5.3	63.6
$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	$\frac{1}{2}$	4461.3	1.4	0.8	21.2
$\bar{D}^*\Sigma_c$	$\frac{3}{2}^+$	$\frac{1}{2}$	4462.7	0.01	0.2	6.3
$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	$\frac{1}{2}$	4519.8	7.3	0.9	9.9
$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	$\frac{1}{2}$	4523.3	3.9	22.9	4.0
$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	$\frac{1}{2}$	4524.5	2.6	0.05	3.0
$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^+$	$\frac{1}{2}$	4526.2	1.0	0.05	0.8

P. G. Ortega *et al.*, `PLB 764, 207 (2017) -- arxiv:1606.06148`

Outline

1. Motivation
2. The model
3. Results
4. Conclusions

Conclusions

- Heavy quark sector shows a rich phenomenology, including four and five quark structures depending on the dynamics.
- The effect of nearby thresholds may generate non-trivial states (molecules) and structures (mass-shifts, threshold cusps) which modifies naive QM predictions, so they must be incorporated to the models.
- Use of Constituent Quark Model plus a coupled channels calculation can account for this phenomenology in an unified way from naive meson and baryon spectrum to the recently pentaquark signals (and beyond).

Further details for results presented here...

- X(3872):
  - *Coupled channel approach to the structure of the X(3872)* – PRD 81 (2010) 054023.
  - *Molecular Structures in Charmonium Spectrum: The XYZ Puzzle* – JPG 40 (2013) 065107.
  - *Partners of the $X(3872)$ and HQSS breaking* – arXiv:1601.03901.
  - *Counting states and the Hadron Resonance Gas: Does X(3872) count?* – arXiv:1707.01915.
- XYZ in charmonium and bottomonium sector:
  - *Canonical description of the new LHCb resonances* – PRD 94 (2016), 114018.
  - *Charmonium resonances in the 3.9 GeV/c^2 energy region and the $X(3915)/X(3930)$ puzzle* – arXiv:1706.02639.
- XYZ in open-charm and open-bottom meson spectra:
  - *Molecular components in P-wave charmed-strange mesons* – PRD 94 (2016), 074037.
  - *Threshold effects in P-wave bottom-strange mesons* – PRD 95 (2017), 034010.
- XYZ in baryon spectra:
  - *Quark model description of the $\Lambda_c(2940)^+$ as a molecular D^*N state and the possible existence of the $\Lambda_b(6248)$* – PLB 718 (2013) 1381-1384.
  - *LHCb pentaquarks in constituent quark models* – PLB 764 (2017) 207-211.
  - *Hadronic molecules in the open charm and open bottom baryon spectrum* – PRD 90 (2014), 114013.
  - *$D^*\Delta$ molecular interpretation for the $X_c(3250)$* – PLB 729 (2014) 24-26.

Thanks for your attention.

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$X(3915)/X(3930)$ **controversy**

- $X(3915)$ seen in $\gamma\gamma \to \omega J/\psi$ process
- Consistent with $0^{++} \rightarrowtail$ assigned to $\chi_{c0}(2P)$.
- But... $J^{PC} = 0^{++}$ assignment challenged by Guo and Meissner [arxiv:1208.1134] and Olsen [arxiv:1410.6534] because:
  - $X(3915) \to \omega J/\psi$ too large for OZI-suppressed decay.
  - No signal for $X(3915) \to D\bar{D}$ decay.
  - If $X(3930)$ is $\chi_{c2}(2P)$, $\chi_{c2}(2P) - \chi_{c0}(2P)$ mass splitting too small.
- Z.-Y. Zhou [arxiv:1501.00879] points to a $J^P = 2^+$ assignment! $\rightarrowtail$ Implies $X(3915)$ might not be a pure $c\bar{c}$ state.
- Besides, $X(3860)$, decaying to $D\bar{D}$, reported by Belle
- Mass: $3862^{+26}_{-32}{}^{+40}_{-13}$ MeV$/c^2$, Width: $201^{+154}_{-67}{}^{+88}_{-82}$ MeV
- $J^{PC} = 0^{++}$ option is favored over the 2^{++} hypothesis.$\rightarrowtail$ Is this the $\chi_{c0}(2P)$?

$X(3915)/X(3930)$ **controversy**

- Aim: Analyze if the 0^{++} assignment for $X(3915)$ is reasonable.
- Effect of the thresholds over the theoretical bare state?
- Two calculations for $J^{PC} = 0^{++}$ and $J^{PC} = 2^{++}$ sectors.
- Closest $c\bar{c}$ states and thresholds (mass in MeV in parenthesis):
  - $J^{PC} = 0^{++}$: 2^3P_0 $c\bar{c}$ (3909), $D\bar{D}$ (3734), $\omega J/\psi$ (3880), D_sD_s (3937) and $D^*\bar{D}^*$ (4017)
  - $J^{PC} = 2^{++}$: 2^3P_2 $c\bar{c}$ (3969), $D\bar{D}$, $\omega J/\psi$, D_sD_s, $D\bar{D}^*$ (3877) and $D^*\bar{D}^*$

Results for $J^{PC} = 0^{++}$ - 2^{++} (I)

- Mass and decay width, in MeV, and probabilities of the different Fock components.

J^{PC}	Mass	Width	$\mathcal{P}[c\bar{c}]$	$\mathcal{P}[D\bar{D}]$	$\mathcal{P}[D\bar{D}^*]$	$\mathcal{P}[\omega J/\psi]$	$\mathcal{P}[D_s\bar{D}_s]$	$\mathcal{P}[D^*\bar{D}^*]$
0^{++}	3890.3	6.7	44.1%	21.6%	–	28.4%	2.6%	3.3%
0^{++}	3927.4	229.8	19.2%	66.3%	–	5.3%	3.7%	5.5%
2^{++}	3925.6	19.0	42.2%	11.3%	37.0%	4.0%	0.4%	5.1%

- Mass and width of the 2^{++} state compatible with the $X(3930)$.
- The 0^{++} resonances - First guess:
  - Mass of first 0^{++} compatible with $X(3860)$, but width smaller $\rightarrowtail$ Position of node in 2^3P_0 bare wave function?
  - Mass of second 0^{++} state $\rightarrowtail$ Elusive $Y(3940)$ resonance? But width far from experimental value, and controversial state.

Results for $J^{PC} = 0^{++}$ - 2^{++} (I)

- Mass and decay width, in MeV, and probabilities of the different Fock components.

J^{PC}	Mass	Width	$\mathcal{P}[c\bar{c}]$	$\mathcal{P}[D\bar{D}]$	$\mathcal{P}[D\bar{D}^*]$	$\mathcal{P}[\omega J/\psi]$	$\mathcal{P}[D_s\bar{D}_s]$	$\mathcal{P}[D^*\bar{D}^*]$
0^{++}	3890.3	6.7	44.1%	21.6%	–	28.4%	2.6%	3.3%
0^{++}	3927.4	229.8	19.2%	66.3%	–	5.3%	3.7%	5.5%
2^{++}	3925.6	19.0	42.2%	11.3%	37.0%	4.0%	0.4%	5.1%

- Mass and width of the 2^{++} state compatible with the $X(3930)$.
- The 0^{++} resonances - Second guess:
  - First 0^{++} $\rightarrowtail$ Too narrow to be observed? Or X(3915)?
  - Second 0^{++} state $\rightarrowtail$ $X(3860)$ resonance. Width OK, but mass a bit high.

Results for $J^{PC} = 0^{++}$ - 2^{++} (II)

- Now, if $X(3915)$ is 0^{++}, $\omega J/\psi$ branching far from experiments.
- Let's calculate for the $J^{PC} = 2^{++}$ state the product of the two-photon decay width and the branching fraction to $\omega J/\psi$ and $D\bar{D}$ channels (in eV), assuming the $X(3915)$ and $X(3930)$ are the same 2^{++} resonance.

	Belle	BaBar	model A
$\Gamma_{\gamma\gamma} \times \mathcal{B}(2^{++} \to \omega J/\psi)$	$18 \pm 5 \pm 2$	$10.5 \pm 1.9 \pm 0.6$	20.9
$\Gamma_{\gamma\gamma} \times \mathcal{B}(2^{++} \to D\bar{D})$	$180 \pm 50 \pm 30$	$249 \pm 50 \pm 40$	75.4
$\Gamma_{\gamma\gamma} \times \mathcal{B}(2^{++} \to D\bar{D}^{*})$	-	-	196.0

- Results not far from the experimental data.
- DD branching ratio a bit small, but crossed contribution from DD^* not considered.
- This suggest that the $X(3915)/X(3930)$ resonances are the same 2^{++} state.

More details at:

P. G. Ortega *et al.*, `arxiv:1706.02639`

Results for the $X(3940)$ coupled calculation

- $X(3940) \rightarrowtail$ Seen on the J/ψ invariant mass spectrum
- Mass: $3943 \pm 6 \pm 6\,MeV$ Width: $52\,MeV$ to $90\% C.L.$
- Decays to DD^* channel $\rightarrowtail$ Good candidate for $\chi_{c1}(2P)$
- Masses and probabilities:

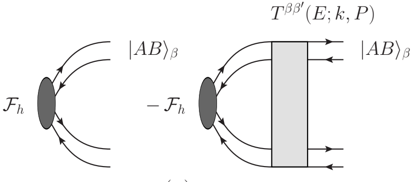
γ	$Masa$	Γ	$c\bar{c}(2^3P_1)$	D^0D^{*0}	$D^{\pm}D^{*\mp}$	$J/\psi\rho$	$J/\psi\omega$
0.231	3942.5	93.8	61.02	18.57	16.86	0.01	3.54
0.226	3941.8	89.9	61.09	18.53	16.85	0.01	3.52

- Partial widths

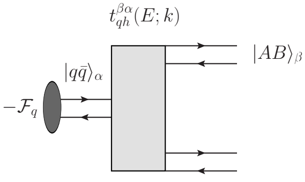
γ	D^0D^{*0}	$D^{\pm}D^{*\mp}$	$J/\psi\rho$	$J/\psi\omega$
0.231	41.82	41.91	0.04	10.01
0.226	40.15	40.28	0.03	9.45

Lineshapes

- Molecular contribution $\rightarrowtail$ $\frac{dB_{r_h}((AB)^{\beta})}{dE} = \text{const} \times k|\mathcal{M}_h^{\beta}(E)|^2\Theta(E)$
  with $\mathcal{M}_h^{\beta}(E) = \mathcal{F}_h\left(1 - \sum_{\beta'}\int dP\, T^{\beta\beta'}(E;k_\beta,P)\frac{2\mu_{\beta'}P^2}{P^2-k_{\beta'}^2}\right)_{\textit{on shell}}$
- Mesonic contribution $\rightarrowtail$ $\frac{dB_{r_q}((AB)^{\beta})}{dE} = \text{const} \times k\left|\mathcal{M}_q^{\beta}(E)\right|^2\Theta(E)$
  with $\mathcal{M}_q^{\beta} = -\mathcal{F}_q\sum_{\alpha,\alpha'}\phi_{\alpha'\beta}(E;k)\Delta_{\alpha'\alpha}(E)^{-1}$



(a)

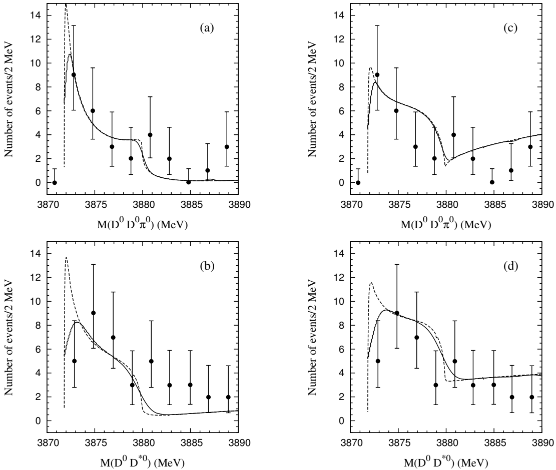


(b)

Lineshapes for $X(3872)$ with $E_b = -0.25\,MeV$

$c\bar{c}$ Production

$D\bar{D}^*$ Production



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

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