The charged Z_c and Z_b structures in a constituent quark model approach

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Outline

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

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4. Conclusions

The quark model (I)

André Petermann   Murray Gell-Mann   George Zweig

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A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

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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-

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

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

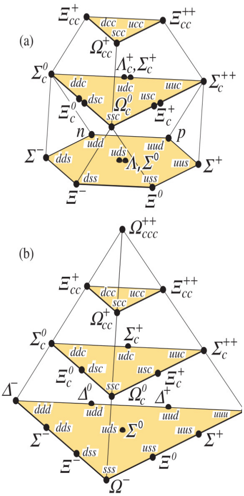
Murray Gell-Mann, 10-year-old, New York, 1939. Now, 25 years later, *Caltech*

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.

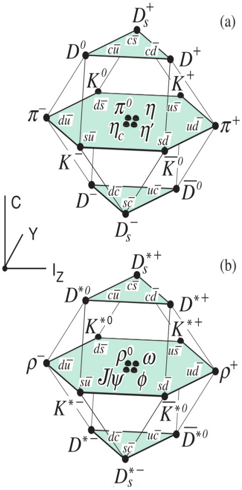
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the 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 $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowes baryon configuration $(q\,q\,q)$ 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**.

Successful classification scheme organizing the large number of **conventional hadrons**

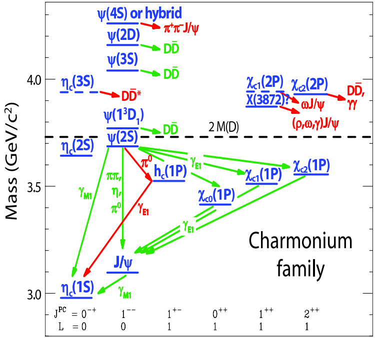
Baryons

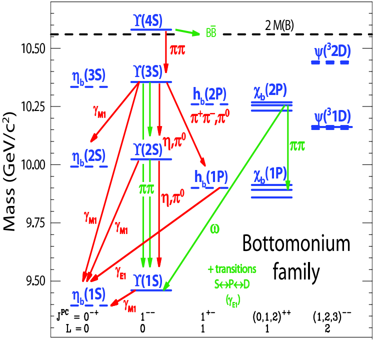


Mesons



Charmonium and bottomonium states were discovered in the 1970s.
Experimentally clear spectrum of narrow states below the open-flavor threshold





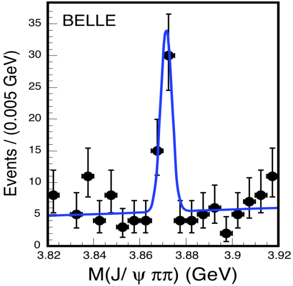
Eichten *et al.*, Rev. Mod. Phys. 80, 1161 (2008)

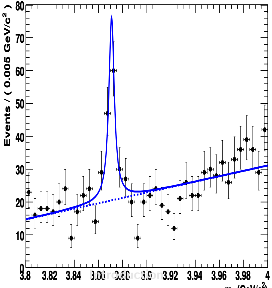
- Heavy quarkonia are bound states made of a heavy quark and its antiquark ($c\bar{c}$ charmonium and $b\bar{b}$ bottomonium).
- They can be classified in terms of the quantum numbers of a nonrelativistic bound state → Reminds positronium [(e^+e^-)-bound state] in QED.

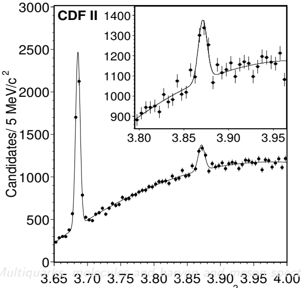
The discovery of the X(3872)

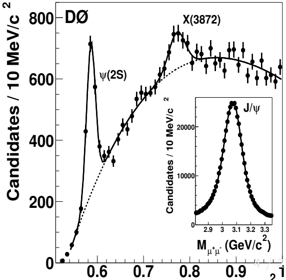
- In 2003, Belle observed an unexpected enhancement in the $\pi^+\pi^- J/\psi$ invariant mass spectrum while studying $B^+ \to K^+\pi^+\pi^- J/\psi$.
- It was later confirmed by BaBar in B-decays and by both CDF and D0 at Tevatron in prompt production from $p\bar{p}$ collisions.
- Its quantum numbers, mass, and decay patterns make it an unlikely conventional charmonium candidate.

PRL 91, 262001 (2003)



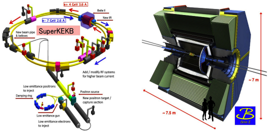




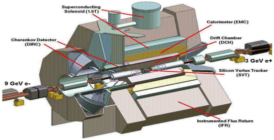


Discoveries at B-factories

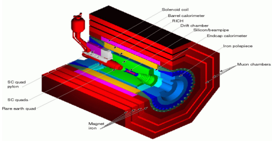
BELLE@KEK (Japan)



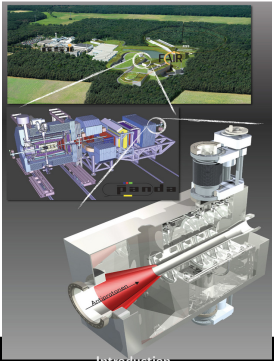
BABAR@SLAC (USA)



CLEO@CORNELL (USA)

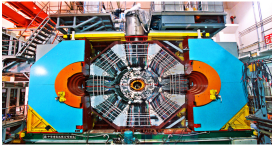


PANDA@GSI (Germany)

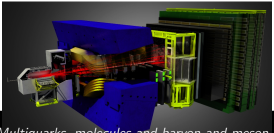


Explosion of related experimental activity:
Signals of exotic structures?
Standard $q\bar{q}$ or qqq?
Threshold cusps?

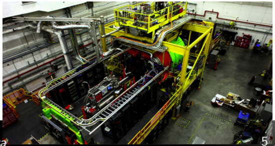
BES@IHEP (China)



LHCb@CERN (Switzerland)



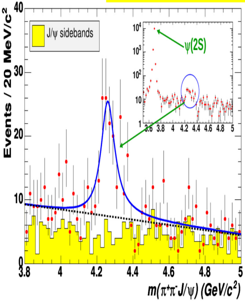
GLUEX@JLAB (USA)



The XYZ particles – A new particle zoo?

PRL95, 142001 (2005)

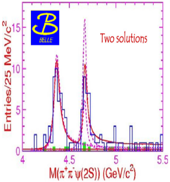
$\pi^+\pi^- J/\psi$ Mass



BaBar 232 fb⁻¹

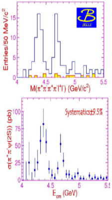
›8σ significance structure called Y(4260)

M(J/ψππ) of ψ(2S with J/ψ constrain is well described b Cauchy shape func



Parameters	Solution one	Solution two
$M(Y(4360))$	$4361 \pm 9 \pm 9$	
$\Gamma_{tot}(Y(4360))$	$74 \pm 15 \pm 10$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}(Y(4360))$	$10.4 \pm 1.7 \pm 1.5$	$11.8 \pm 1.8 \pm 1.4$
$M(Y(4660))$	$4664 \pm 11 \pm 5$	
$\Gamma_{tot}(Y(4660))$	$48 \pm 15 \pm 3$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}(Y(4660))$	$3.0 \pm 0.9 \pm 0.3$	$7.6 \pm 1.8 \pm 0.8$
ϕ	$39 \pm 30 \pm 22$	$-79 \pm 17 \pm 20$

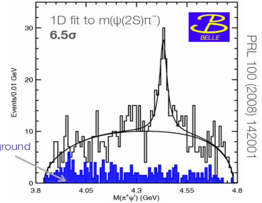
Belle: X. L. Wang *et al.*, PRL99,142002(2007)



- Y(4360) - confirmed for the first time with much better resonance parameters.
- Y(4660) - A 5.8σ narrow stat discovered.

Two solutions: constructive and destructive interference.

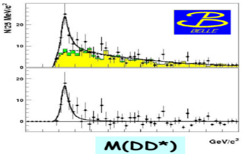
- Belle observed $Z(4430)^-$ from sample of ~2k $B^0 \longrightarrow \psi(2S)K^{+,0}\pi^-$
- Charged state ⇒ minimal quark content of $c\bar{c}u\bar{d}$



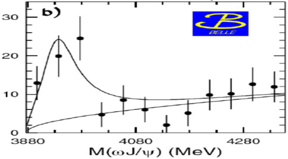
$$M = 4433 \pm 4 \pm 2 \text{ MeV}/c^2$$
$$\Gamma = 45^{+18+30}_{-13-13} \text{ MeV}/c^2$$

not seen in $\omega J/\psi$ — probably different — not seen in DD^* — Probably the χ_{c2}'

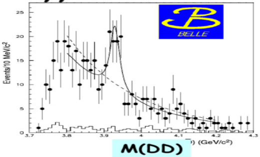
X(3940) $e^+e^- \to J/\psi\ DD^*$



Y(3940) $B \to K\ \omega J/\psi$



Z(3930) $\gamma\gamma \to DD$

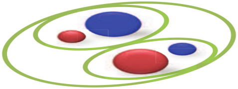


M = 3942 +7 ... ± 6 MeV

M~3943±11±13 MeV

M = 3929±5±2 MeV

In this work...

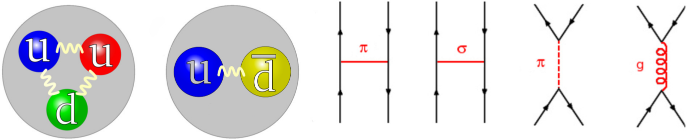


- We evaluate the molecular nature of some XYZ states using a constituent quark model

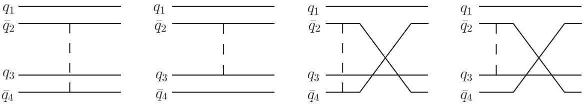
1. $X(3872)$ state:
   - Quantum numbers: $J^{PC} = 1^{++}$
   - Mass slightly below $D^0\bar{D}^{*0}$ threshold.
   - Large isospin breaking.
2. $Z_c(3900)^{\pm}$ and $Z_c(4020)^{\pm}$ states:
   - $J^{PC} = 1^{+-}$ charged states.
   - Close to $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds.
   - Absence of $D\bar{D}$ peaks $\rightarrow$ Evidence in favor of a role for pion exchange in forming molecules of open-flavor pairs.
3. $Z_b(10610)^{\pm}$ and $Z_b(10650)^{\pm}$ states:
   - Bottom partners of $Z_c(3900)^{\pm}$ and $Z_c(4020)^{\pm}$.
   - $J^{PC} = 1^{+-}$ charged states.
   - Close to $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds.
   - Absence of $B\bar{B}$ peaks.

Outline

- Meson and Baryon spectra from constituent quark models.



- Residual meson-meson interaction.



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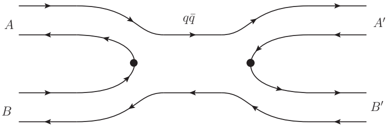
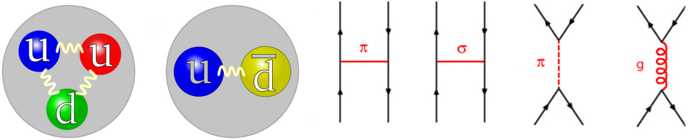


Roadmap

- Meson and Baryon spectra from constituent quark models.



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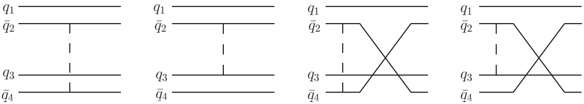

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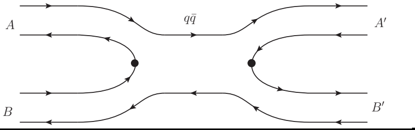

Constituent quark model

The model includes:

- Spontaneous breaking of chiral symmetry $\rightarrowtail$ Constituent mass and Pseudo-Goldstone bosons.
- QCD perturbative effects $\rightarrowtail$ Gluon exchange.
- Confinement $\rightarrowtail$ Linear screened potential.
- All parameters constrained from low-lying meson and baryon spectra.

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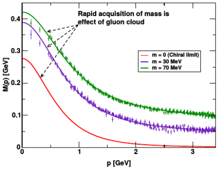
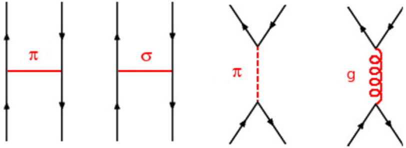


C. D. Roberts, arxiv:1109.6325v1 [nucl-th]



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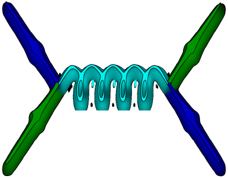

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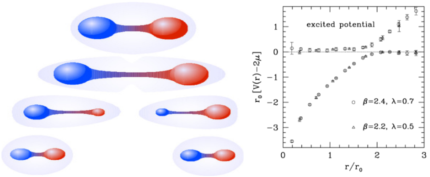

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Constituent quark model

- 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).

Roadmap

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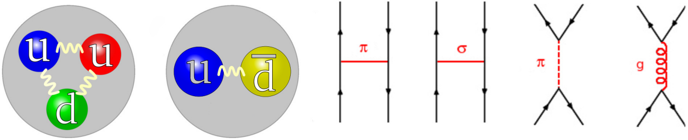

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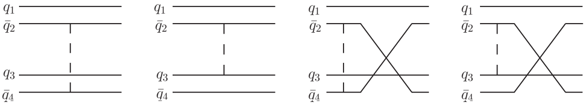

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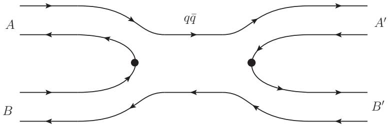
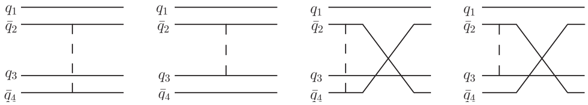


Solving the two body problem

- We want to explore meson-meson interactions.
- Meson wave function $\rightarrowtail$ 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:
    $\sum_{n'=1}^{n_{max}} \left[(T^{\alpha}_{nn'} - EN^{\alpha}_{nn'}) c^{\alpha}_{n'l} + \sum_{\alpha'}^{n^o\, chnl} V^{\alpha\alpha'}_{nn'} c^{\alpha'}_{n'l} \right] = 0$
- Resonating Group Method:
  - Interaction at quark level $\rightarrowtail$ Interaction between clusters
  - Direct and exchange potentials:



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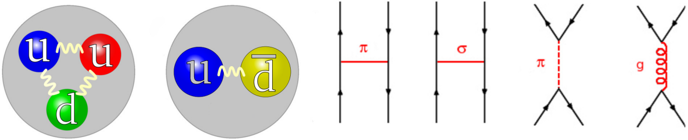

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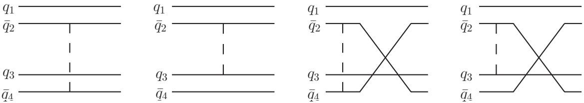

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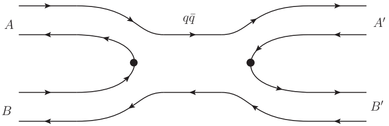
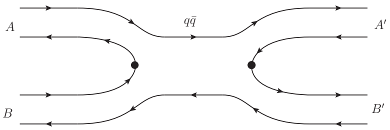


Coupling between $q\bar{q}$ and $q\bar{q} - q\bar{q}$ sectors

- Study of $\mathcal{H} = \mathcal{H}_{Q\bar{Q}} \oplus \mathcal{H}_{Q\bar{Q}q\bar{q}}$
- 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:

$$\sum_\beta \int \left(H^{M_1M_2}_{\beta'\beta}(P',P) + V^{eff}_{\beta'\beta}(E;P',P) \right) \chi_\beta(P) P^2 dP = E\chi_{\beta'}(P')$$

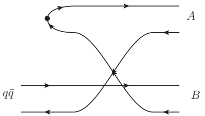
with $V^{eff}_{\beta'\beta}(E;P',P)$:



$^3P_0$ interaction

- $^3P_0$ model used as coupling mechanism.
- Pair creation hamiltonian:

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

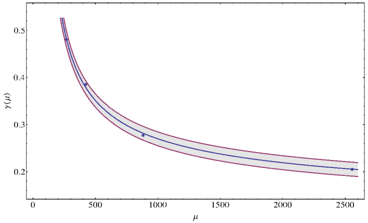


- Non relativistic reduction:

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

with $\gamma' = 2^{5/2}\pi^{1/2}\gamma$ and $\gamma = \frac{g}{2m}$

- Running of the $^3P_0$ strength $\gamma \rightarrowtail$ J. Segovia et al., arXiv:1205.2215

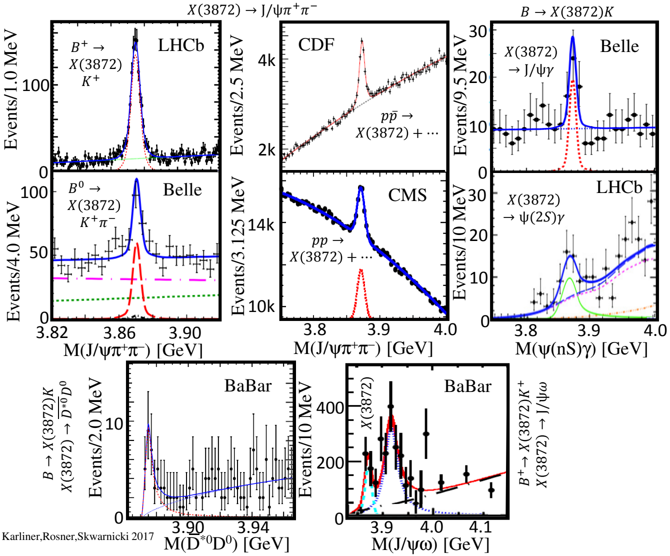


$$\gamma(\mu) = \frac{\gamma_0}{\log(\mu/\mu_\gamma)}$$

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

Outline

$X(3872)$ state



Karliner,Rosner,Skwarnicki 2017

$X(3872)$ 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 $D^0 D^{*0}$ molecule coupled to $2P$ $c\bar{c}$ states.

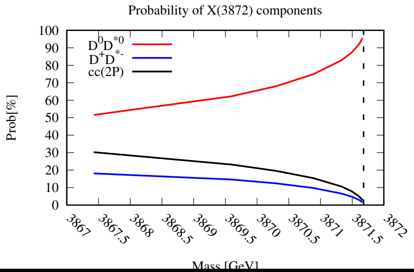
P. G. Ortega *et al.*, PRD 81, 054023 (2010).

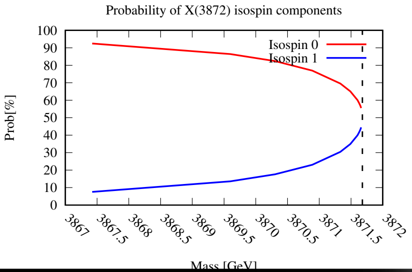
Results for the $X(3872)$ coupled calculation

- $D^0 D^{*0}$ 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
- Experimental mass of the $X(3872)$ obtained for the $^3P_0$ strength parameter γ, constrained from $Q\bar{Q}$ strong decay studies.

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

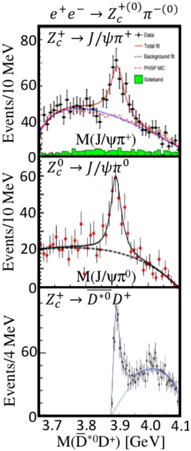
- D^0D^{*0} and $D^{\pm}D^{*\mp}$ meson-meson channels are included
- Coupled to $c\bar{c}(2^3P_1)$ meson state $\rightarrowtail$ Theoretical bare mass= 3947.4 MeV
- Inclusion of $J/\psi\rho$ y $J/\psi\omega$ channels, needed for describing the strong decays $\rightarrowtail$ Rearrangement diagrams
  Small contribution to the mass
- Experimental mass of the $X(3872)$ obtained for the $^3P_0$ strength parameter γ, constrained from $Q\bar{Q}$ strong decay studies.





$Z_c(3900)^{\pm}$ and $Z_c(4020)^{\pm}$

- $J^{PC} = 1^{+-}$ charged states.
- Close to $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds.
- $Z_c(3900)^{\pm}$, with ave. mass (3891.2 ± 3.3) MeV, seen in:
  - $e^+e^- \to \pi\pi J/\psi$ as a peak in $M(\pi J/\psi)$
  - $e^+e^- \to \pi D\bar{D}^*$ as a peak in $M(D\bar{D}^*)$.
  - $e^+e^- \to \pi\pi\psi(3868)$ as a peak in $M(\pi\psi(3868))$.
- $Z_c(4020)^{\pm}$, with ave. mass (4022.9 ± 2.8) MeV, seen in:
  - $e^+e^- \to \pi\pi h_c$ as a peak in $M(\pi h_c)$
  - $e^+e^- \to \pi D^*\bar{D}^*$ as a peak in $M(D^*\bar{D}^*)$.
  - $e^+e^- \to \pi\pi\psi(3868)$ as a peak in $M(\pi\psi(3868))$.
- Absence of $D\bar{D}$ peaks $\to$ Evidence in favor of a role for pion exchange in forming molecules of open-flavor pairs.

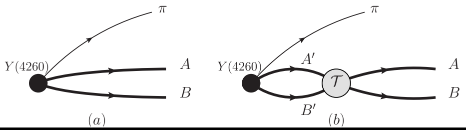


Karliner,Rosner,Skwarnicki 2017

$Z_c(3900)^{\pm}$ and $Z_c(4020)^{\pm}$

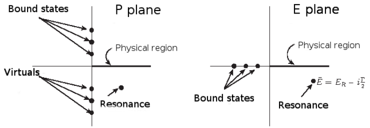
- Coupled-channels calculation of $J^{PC} = 1^{+-}$ sector with $I = 1$.
- No coupling with meson spectrum. Only direct+exchange interaction from CQM.
- Including the following thresholds:
  - $\pi J/\psi$ (3234.19 MeV)
  - $\rho\eta_c$ (3755.79 MeV)
  - $D\bar{D}^*$ (3875.85 MeV)
  - $D^*\bar{D}^*$ (4017.24 MeV)
- Poles of the S-matrix and production lineshapes.

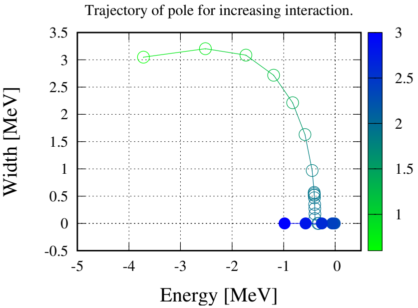
$$d\Gamma = \frac{1}{(2\pi)^3}\frac{k_{AB}k_{\pi Z_c}}{4M_Y^2}|\overline{\mathcal{M}^{\beta}(m_{AB})}|^2 dm_{AB}$$



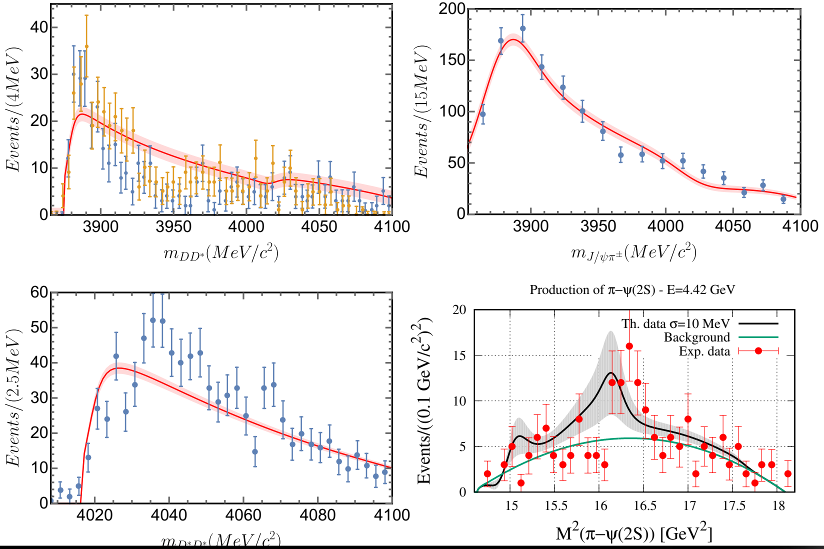
- $D^{(*)}\bar{D}^*$ attractive, but not strong enough to bind the meson pairs.
- States found as virtual poles in S-matrix.
- Poles below the $D^{(*)}\bar{D}^*$ threshold in 2$^{\text{nd}}$ Riemann sheet $\rightarrow$ Enhancement in production lineshapes.

	$Z_c(3900)$	$Z_c(4020)$
Pole position	3871.74	4013.21





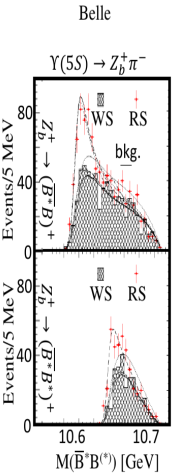
- Good description of production lineshapes.



$Events/(4MeV)$
$m_{DD^*}(MeV/c^2)$
$Events/(15MeV)$
$m_{J/\psi\pi^{\pm}}(MeV/c^2)$
$Events/(2.5MeV)$
$m_{D^*D^*}(MeV/c^2)$
Production of π−ψ(2S) - E=4.42 GeV
Th. data σ=10 MeV
Background
Exp. data
Events/((0.1 GeV/c^2)^2)
M^2(π−ψ(2S)) [GeV^2]

$Z_b(10610)^\pm$ and $Z_b(10650)^\pm$

- Bottom partners of $Z_c(3900)^\pm$ and $Z_c(4020)^\pm$.
- $J^{PC} = 1^{+-}$ charged states.
- Close to $B\bar{B}^*$ (10604 MeV) and $B^*\bar{B}^*$ (10649 MeV) thresholds.
- $Z_b(10610)^\pm$, with ave. mass (10607.2 ± 2.0) MeV, seen in:
  - $e^+e^- \to \pi\pi\Upsilon(nS)$ $(n = 1, 2, 3)$.
  - $e^+e^- \to \pi B\bar{B}^*$.
  - $e^+e^- \to \pi\pi h_b(nP)$ $(n = 1, 2)$.
- $Z_b(10650)^\pm$, with ave. mass (10652.2 ± 1.5) MeV, seen in:
  - $e^+e^- \to \pi\pi\Upsilon(nS)$ $(n = 1, 2, 3)$.
  - $e^+e^- \to \pi B^*\bar{B}^*$.
  - $e^+e^- \to \pi\pi h_b(nP)$ $(n = 1, 2)$.



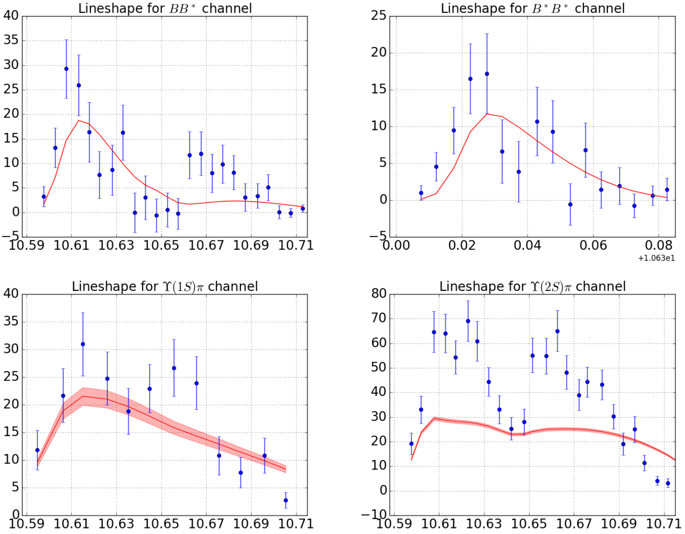
- Absence of $B\bar{B}$ peaks $\to$ Evidence in favor of a role for pion exchange in forming molecules of open-flavor pairs.

$Z_b(10610)^{\pm}$ and $Z_b(10650)^{\pm}$

- Calculation of $(I)J^{PC} = (1)1^{+-}$ analogous to that of the Z_c states.
- Including $B\bar{B}^*$, $B^*\bar{B}^*$, $\Upsilon(1S)\pi$, $\Upsilon(2S)\pi$ and $\Upsilon(3S)\pi$ channels.
- $B^{(*)}\bar{B}^*$ interaction $\sim D^{(*)}\bar{D}^*$ interaction (HFS).
- Reduction of $B^{(*)}\bar{B}^*$ kinetic energy $\rightarrow$ Bound state & Resonance

	$Z_b(10610)^{\pm}$	$Z_b(10650)^{\pm}$
Mass	10600.45	$10644.74 - 4.34\,i$
Width	2.80	8.88
$\mathcal{P}_{\max}$	95.76% (BB^*)	64.85% (B^*B^*)
Γ_{BB^*}	–	8.68
$\Gamma_{\Upsilon(1S)\pi}$	0.94	0.08
$\Gamma_{\Upsilon(2S)\pi}$	0.65	0.002
$\Gamma_{\Upsilon(3S)\pi}$	1.21	0.12

$Z_b(10610)^{\pm}$ and $Z_b(10650)^{\pm}$ production



Outline

Conclusions

- Hadron physics in heavy quark sector is indeed a Few Body Problem.
- Heavy quarkonium shows a rich phenomenology, including effects of four-quark structures near thresholds.
- Use of Constituent Quark Model plus a coupled-channels calculation explain the $Z_c(3900)^\pm$ and $Z_c(4020)^\pm$ peaks as virtual states, and $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$ ones as a bound state and a resonance.
- The Z_c's, Z_b's and $X(3872)$ can be satisfactorily explained within the same model, with no parameter tunning.

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Thanks for your attention.

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Further details at:

- *The Z_c structures in a coupled-channels model* – Eur.Phys.J. C79 (2019) no.1, 78
- *Molecular Structures in Charmonium Spectrum: The XYZ Puzzle* – JPG 40 (2013) 065107.
- *Coupled channel approach to the structure of the X(3872)* – PRD 81 (2010) 054023.

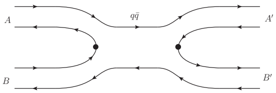
Backslides

Coupling formalism with T matrix

- But… inadequate formalism for states above the threshold
- Resonances, Virtuals, Bound states $\rightarrow$ 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:

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

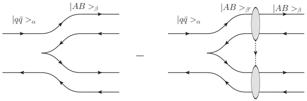
Coupling elements

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:

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

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

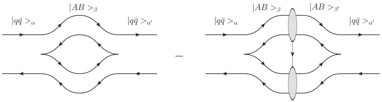


- Complete propagator:

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

- Exact mass-shift of the state:

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



$X(3872)$ strong and radiative decay results

- Experimental results

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

$$R_2 = \frac{\mathcal{B}(X \to J/\psi\gamma)}{\mathcal{B}(X \to J/\psi\pi^+\pi^-)} = \begin{cases} 0.33 \pm 0.12 \\ 0.14 \pm 0.05 \end{cases},$$

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

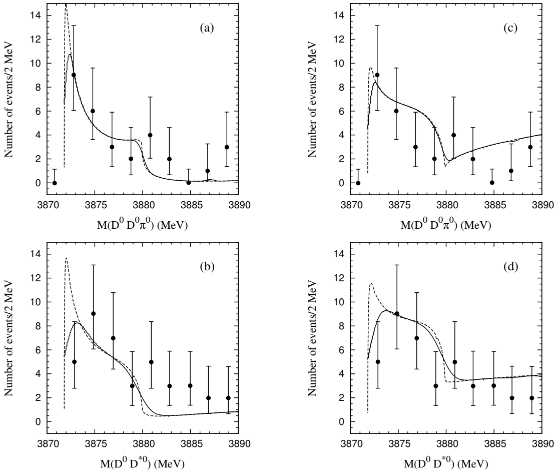
- Theoretical decays [keV]:

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

$c\bar{c}$ Production — $D\bar{D}^*$ Production

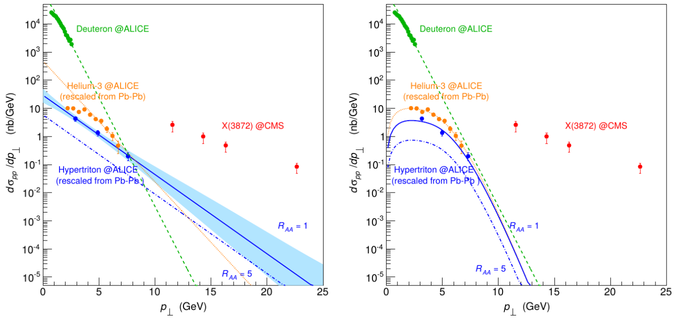


Belle
$B \to K D^0 \bar{D}^0 \pi^0$

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

$X(3872)$ pp production [arXiv:1907.01441]

- A recent paper (A. Esposito PRD 92 (2015), 034028) questioned the loosely bound nature of the $X(3872)$ based on its production in high-energy pp collisions.
- They compared with light nuclei production data by ALICE with $p_T \leq 10$GeV in Pb-Pb collisions at 2.76TeV, using Boltzmann statistics to conclude no hadronic molecule should be created with such an abunandance for large p_T.
- But pp is a non-extensive system, so we cannot use Boltzmann statistics.



$X(3872)$ pp production [arXiv:1907.01441]

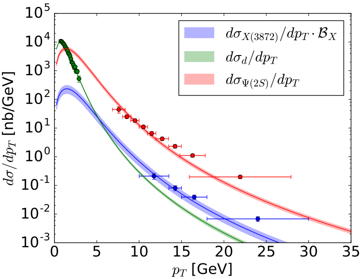
- Tsallis distribution works better for pp collisions (ALICE Coll. PRC97 (2018), 024615).
- Tsallis distribution allows to describe the deuteron and $X(3872)$ with the same q and T, and gives info on the production abundance.

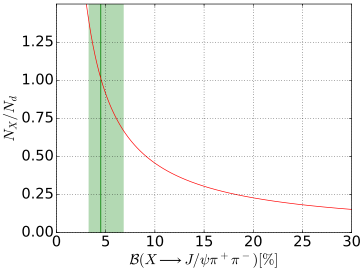
$$\frac{d^3N}{d^3p} = \frac{gV}{(2\pi)^3}\left(1+(q-1)\frac{E(p)}{T}\right)^{-\frac{q}{q-1}} \xrightarrow{q\to 1} \frac{gV}{(2\pi)^3} e^{-\frac{E(p)}{T}}$$

with $E(p_T, y) = \sqrt{p_T^2 + m^2}\cosh y$

	$X(3872) + d$	$X(3872) + \Psi(2S) + d$
$\ln(\mathcal{N}_X \mathcal{B}_X)$	41.4 ± 0.4	41.4 ± 0.4
$\ln(\mathcal{N}_d)$	40.35 ± 0.09	40.35 ± 0.09
$\ln(\mathcal{N}_\Psi)$	-	44.3 ± 0.2
q	1.122 ± 0.001	1.122 ± 0.001
T [MeV]	7.017 ± 0.07	7.018 ± 0.07

- Deuteron/X production ratio ranging between $0.3 - 1.9$ for $\mathcal{B}(X \to J/\psi\pi^+\pi^-) = 4.5^{+2.3}_{-1.2}$ % (BESIII constrains).

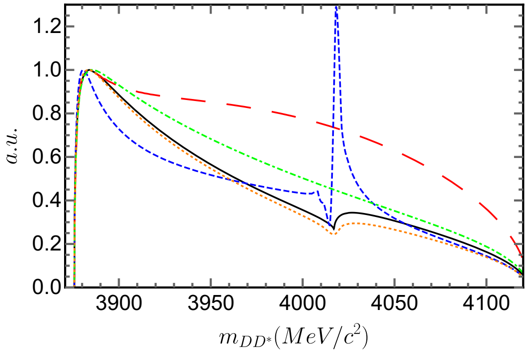




	$X(3872) + d$	$X(3872) + \Psi(2S) + d$
N_d	$(2.02 \pm 0.02) \cdot 10^{-4}$	$(2.01 \pm 0.02) \cdot 10^{-4}$
$N_X\mathcal{B}_X$	$(9 \pm 3) \cdot 10^{-6}$	$(9 \pm 3) \cdot 10^{-6}$
N_Ψ	-	$(2.2 \pm 0.3) \cdot 10^{-4}$

$Z_c(3900)^{\pm}$ and $Z_c(4020)^{\pm}$ production

- $D\bar{D}^*$ line shape for differente coupled-channels calculations.



- Red: Only $D\bar{D}^*$.
- Blue: $D\bar{D}^* + D^*\bar{D}^*$
- Green: $\rho\eta_c + D\bar{D}^*$.
- Orange: $\rho\eta_c + D\bar{D}^* + D^*\bar{D}^*$
- **Black:** $\pi J/\psi + \rho\eta_c + D\bar{D}^* + D^*\bar{D}^*$