The $Z_{cs}(3985)^-$ structure in a coupled-channels model

P. G. Ortega, D. R. Entem and F. Fernández

Departamento de Física Fundamental and IUFFyM, Universidad de Salamanca

HADRON 2021

19TH INTERNATIONAL CONFERENCE ON HADRON SPECTROSCOPY AND STRUCTURE

Outline

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

Outline

1. Introduction

2. The model

3. Results

4. Conclusions



André Petermann *Murray Gell-Mann* *George Zweig*

Volume 8, number 3 PHYSICS LETTERS

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

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-

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

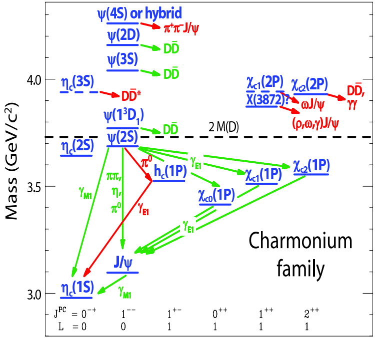
$3\times 3\times 3 = 27, \ldots$ $\quad 3\otimes 3\otimes 3 = 10\oplus 8\oplus 8\oplus 1$

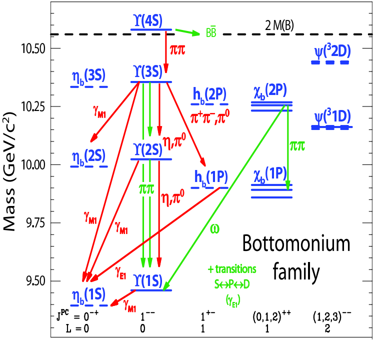

Murray Gell-Mann, 10-year-old, New York, 1939. Now, 25 years later, *Caltech*

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 $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, 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**.

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





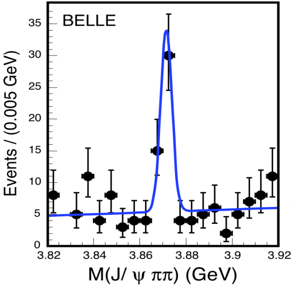
Eichten *et al.*, Rev. Mod. Phys. 80, 1161 (2008)

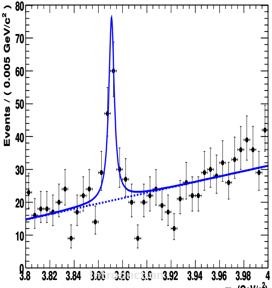
- Heavy quarkonia are bound states made of a heavy quark and its antiquark ($c\bar{c}$ charmonium and $b\bar{b}$ bottomonium).
- They can be classified in terms of the quantum numbers of a nonrelativistic bound state $\rightarrow$ Reminds positronium [(e^+e^-)-bound state] in QED.

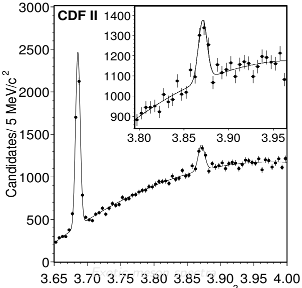
The discovery of the X(3872)

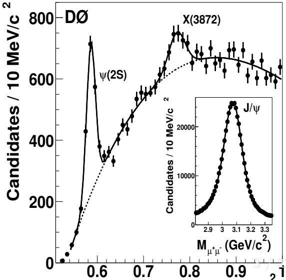
- In 2003, Belle observed an unexpected enhancement in the $\pi^+\pi^- J/\psi$ invariant mass spectrum while studying $B^+ \to K^+\pi^+\pi^- J/\psi$.
- It was later confirmed by BaBar in B-decays and by both CDF and D0 at Tevatron in prompt production from $p\bar{p}$ collisions.
- Its quantum numbers,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

PRL 91, 262001 (2003)



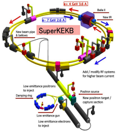


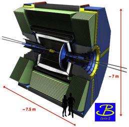




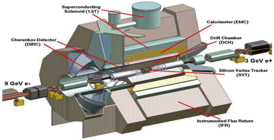
Discoveries at B-factories

BELLE@KEK (Japan)

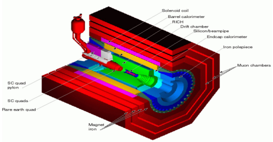




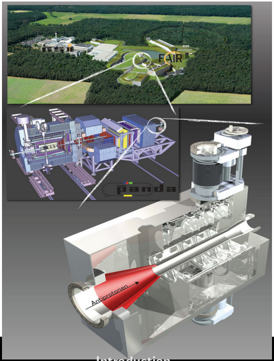
BABAR@SLAC (USA)



CLEO@CORNELL (USA)

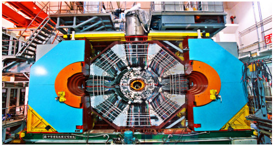


PANDA@GSI (Germany)

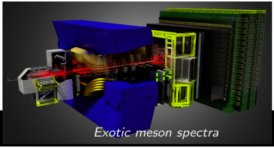


Explosion of related experimental activity:
Signals of exotic structures?
Standard $q\bar{q}$ or qqq?
Threshold cusps?

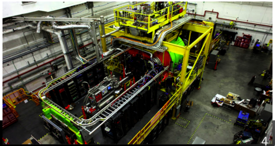
BES@IHEP (China)



LHCb@CERN (Switzerland)

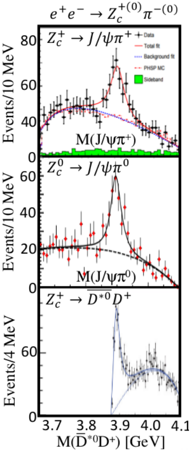


GLUEX@JLAB (USA)



$Z_c(3900)^{\pm}$ 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.

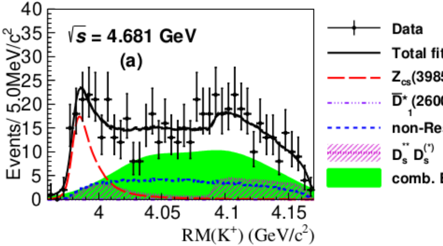


Karliner,Rosner,Skwarnicki 2017

$Z_{cs}(3985)^-$ state

- Seen in BESIII in the K^+ recoil-mass spectrum of $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$.
- Quantum numbers: $I(J^P) = \frac{1}{2}(1^+)$.
- Minimum quark content: $c\bar{c}s\bar{u}$.
- Mass close to $D_s^- D^{*0}/D_s^{*-} D^0$ thresholds:

$$M_{Z_{cs}(3985)} = (3982.5^{+1.8}_{-2.6} \pm 2.1)\mathrm{MeV}/c^2,$$
$$\Gamma_{Z_{cs}(3985)} = (12.8^{+5.3}_{-4.4} \pm 3.0)\mathrm{MeV},$$



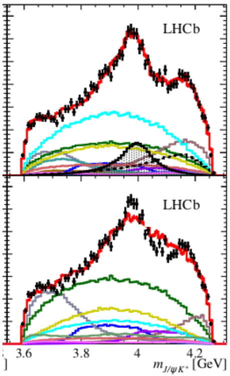
$Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$

- Discovered at LHCb in $J/\psi K^-$ invariant mass spectrum of $B^+ \to J/\psi \phi K^+$.
- Quantum numbers: $I(J^P) = \frac{1}{2}(1^+)$ (but 1^- not ruled out for $Z_{cs}(4220)^+$).
- Minimum quark content: $c\bar{c}u\bar{s}$.
- Masses and widths of $Z_{cs}(4000)^+$:

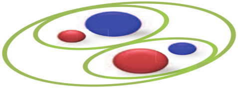
$$M_{Z_{cs}(4000)} = (4003 \pm 6^{+4}_{-14})\mathrm{MeV}/c^2,$$
$$\Gamma_{Z_{cs}(4000)} = (131 \pm 15 \pm 26)\mathrm{MeV},$$

- Masses and widths of $Z_{cs}(4220)^+$:

$$M_{Z_{cs}(4220)} = (4216 \pm 24^{+43}_{-30})\mathrm{MeV}/c^2,$$
$$\Gamma_{Z_{cs}(4220)} = (233 \pm 52^{+97}_{-73})\mathrm{MeV},$$



In this work...



- We evaluate the molecular nature of charged Z states using a constituent quark model

1. $Z_c(3900)^{\pm}$ and $Z_c(4020)^{\pm}$ states.
2. $Z_{cs}(3985)^{-}$ state.
3. $Z_{cs}(4000)^{+}$ and $Z_{cs}(4220)^{+}$ states.

Outline

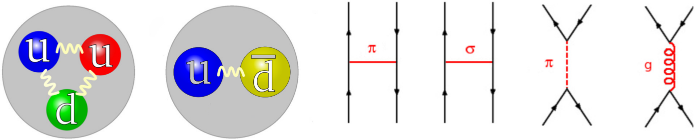
1. Introduction

2. The model

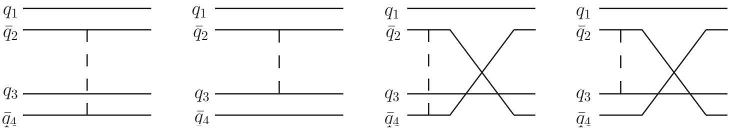
3. Results

4. Conclusions

- Meson and Baryon spectra from constituent quark models.

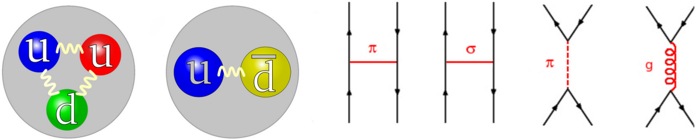


- Residual meson-meson interaction.

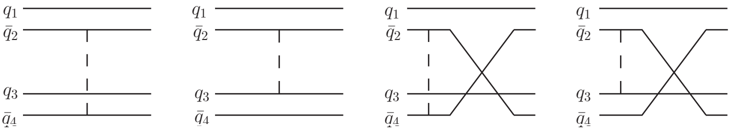


Roadmap

- Meson and Baryon spectra from constituent quark models.



- Residual meson-meson interaction.



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.

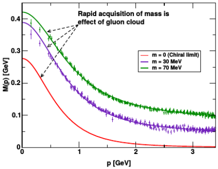
$$\mathcal{L} = \bar{\psi}(i\,\partial\!\!\!/ - M(q^2)U^{\gamma_5})\,\psi\,,$$

$$U^{\gamma_5} = e^{i\lambda_a\phi^a\gamma_5/f_\pi}\,,$$
$$\phi^a = \{\vec{\pi}, K_i, \eta_8\}.$$

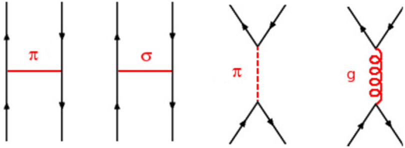
Constituent quark model

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.



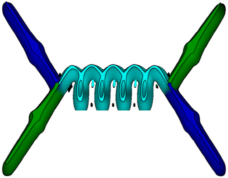
C. D. Roberts, arxiv:1109.6325v1 [nucl-th]



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.

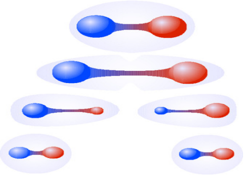


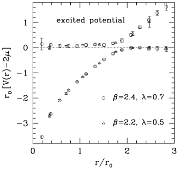
$$\mathcal{L}_{qqg} = i\sqrt{4\pi\alpha_s}\,\bar{\psi}\gamma_\mu G_a^\mu \lambda^a \psi,$$

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.





$$V_{\mathrm{CON}}(\vec{r}) = \left[-a_c(1-e^{-\mu_c r}) + \Delta\right](\vec{\lambda}^c_q \cdot \vec{\lambda}^c_{\bar{q}})\,.$$

Constituent quark model

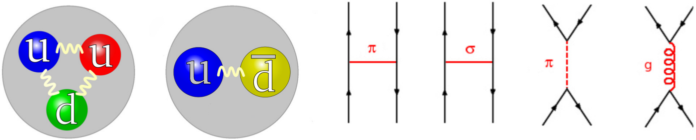
The model includes:

- 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.

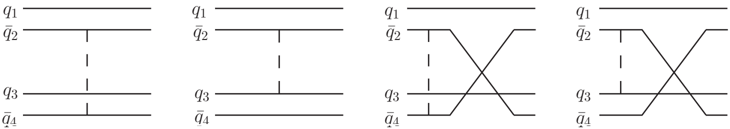
Constituent quark model

- 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).
- Exotic Meson and Baryon spectrum:
  - P. G. Ortega, J. Segovia, D. R. Entem, F. Fernández, **PRD81**, 054023 (2010).
  - P. G. Ortega, J. Segovia, D. R. Entem, F. Fernández, **PLB778**, 1 (2018).
  - P. G. Ortega, J. Segovia, D. R. Entem, F. Fernández, **EPJC80**, 223 (2020).
  - P. G. Ortega, D. R. Entem, F. Fernández, **PLB718**, 1381 (2013).
  - P. G. Ortega, D. R. Entem, F. Fernández, **PLB764**, 207 (2017).

- Meson and Baryon spectra from constituent quark models.

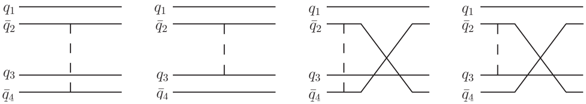


- Residual meson-meson interaction.



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 $\phi_{nl}(p) = (-i)^l \frac{N_{nl}}{(2\eta_n)^{l+3/2}} p^l e^{-\frac{p^2}{4\eta_n}}$
  - 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:



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

Outline

1. Introduction

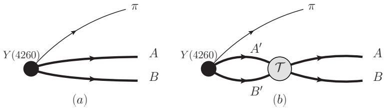
2. The model

3. Results

4. Conclusions

- Coupled-channels calculation of $J^{PC} = 1^{+-}$ sector with $I = 1$.
- Including $\pi J/\psi$, $\rho\eta_c$, $D\bar{D}^*$, $D^*\bar{D}^*$.
- Calculation of poles of the S-matrix and production lineshapes.

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



$$\mathrm{M}^{\beta}(m_{AB}) = \left(\mathcal{A}^{\beta}e^{i\,\theta_{\beta}} - \sum_{\beta'}\mathcal{A}^{\beta'}e^{i\,\theta_{\beta'}}\int d^3p\frac{t^{\beta'\beta}(p,k^{\beta},E)}{p^2/2\mu - E - i\,0}\right).$$

- Fit on parameters affecting only the production vertex.

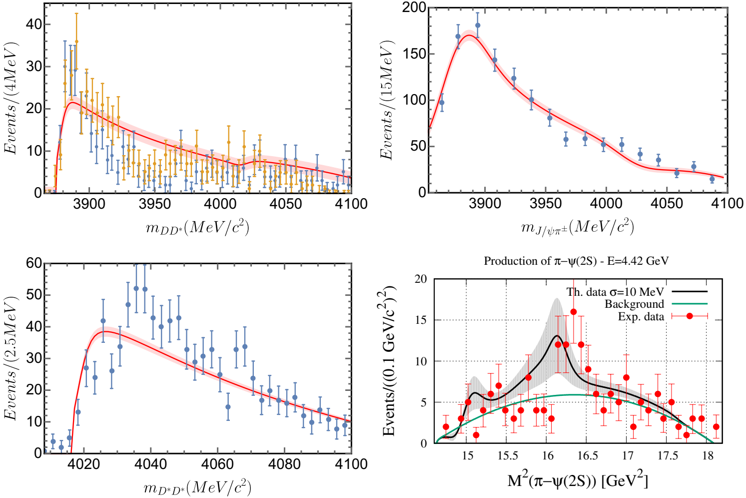
$Z_c(3900)^{\pm}$ and $Z_c(4020)^{\pm}$ poles

- $D^{(*)}\bar{D}^{*}$ 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^{nd} Riemann sheet $\rightarrow$ Enhancement in production lineshapes.

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

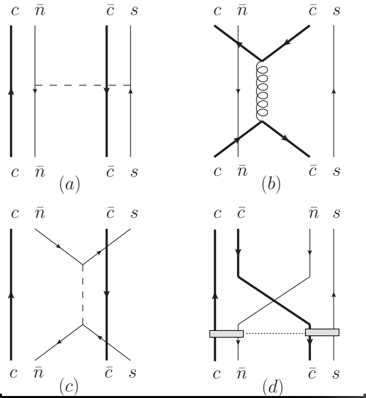
- Good description of production lineshapes.

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



- Strange partners of the $Z_c(3900)^{\pm}$ and $Z_c(4020)^{\pm}$.
- Coupled-channels calculation of $J^{PC} = 1^{+-}$ sector with $I = \frac{1}{2}$.
- Including $D^{*0}D_s^-$, $D^0D_s^{*-}$, $D^{*0}D_s^{*-}$, $J/\psi K^{*-}(892)$, $\eta_c K^{*-}(892)$ and $J/\psi K^-$

- Unlike the Z_c case, no π exchange is allowed.
- Only direct interation through a scalar σ.
- Annihilation diagrams through g and K.
- Two possibilities: annihilation off (model (a)) or on (model (b)).



$Z_{cs}(3985)^{\pm}/Z_{cs}(4000)^{\pm}$ and $Z_{cs}(4220)^{\pm}$ poles

- We find two virtual states below the $D_s^- D^{*0}$ and $D^{*0} D_s^{*-}$ thresholds $\rightarrow$ Candidate to $Z_{cs}(4220)^{\pm}$.

	$Z_{cs}(3985)$	$Z_{cs}(4220)$
Model a	3970	4110
Model b	$3961 - 3\,i$	$4106 - 5\,i$

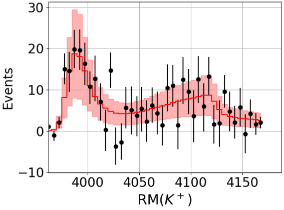
- In the bottom sector, we find two virtual states below the $B^{*-} B_s^0$ and $B^{*-} B_s^{*0}$ thresholds.

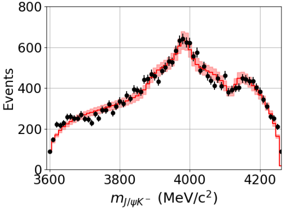
	$Z_{bs}(10691)$	$Z_{bs}(10739)$
Model b	10691	10739

$Z_{cs}(3985)^{\pm}/Z_{cs}(4000)^{\pm}$ and $Z_{cs}(4220)^{\pm}$ production

Model (a)

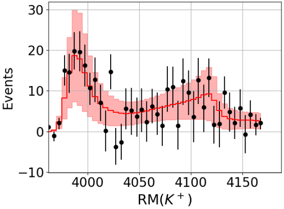
	BESIII	LHCb
$\frac{\chi^2}{\text{d.o.f.}}$	1.00	2.65

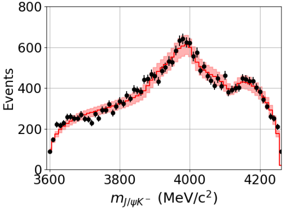




Model (b)

	BESIII	LHCb
$\frac{\chi^2}{\text{d.o.f.}}$	1.02	2.04





$Z_{cs}(3985)^-$ and $Z_{cs}(4000)^+$ peaks compatible with the same pole structure

Outline

1. Introduction

2. The model

3. Results

4. Conclusions

Conclusions

- Use of Constituent Quark Model plus a coupled-channels calculation explain the $Z_{cs}(3985)^-$, $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$ as virtual states, with no parameter tunning.
- The same model reproduces the $Z_c(3900)^\pm$, $Z_c(4020)^\pm$ structures as virtual states.
- The $Z_{cs}(3985)^-$ and $Z_{cs}(4000)^+$ peaks are compatible with the same virtual state.
- Bottom partners of the Z_{cs} structures are predicted at 10.69 GeV/c^2 and 10.74 GeV/c^2.

Thanks for your attention.

portega@usal.es

Further details at:

- *The strange partner of the Z_c structures in a coupled-channels model* – Phys.Lett.B 818 (2021), 136382.
- *The Z_c structures in a coupled-channels model* – Eur.Phys.J. C79 (2019) no.1, 78
- *The Z_b structures in a constituent quark model coupled-channels calculation* – Arxiv:2107.02544