The strange partners of the Zc in a chiral quark model

The Xvth Quark confinement and the Hadron spectrum conference

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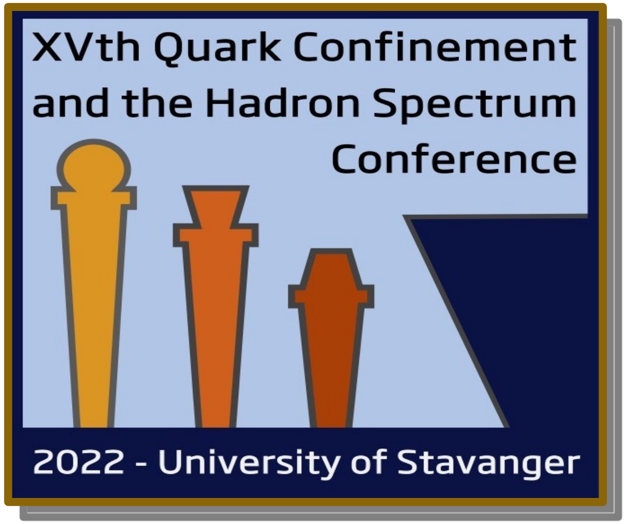
in collaboration with P.G. Ortega and F. Fernández



Overview

- *Introduction*
- *The Zcs states*
- *Theoretical framework of the present work*
- *Results*
- *Conclusions*

Introduction

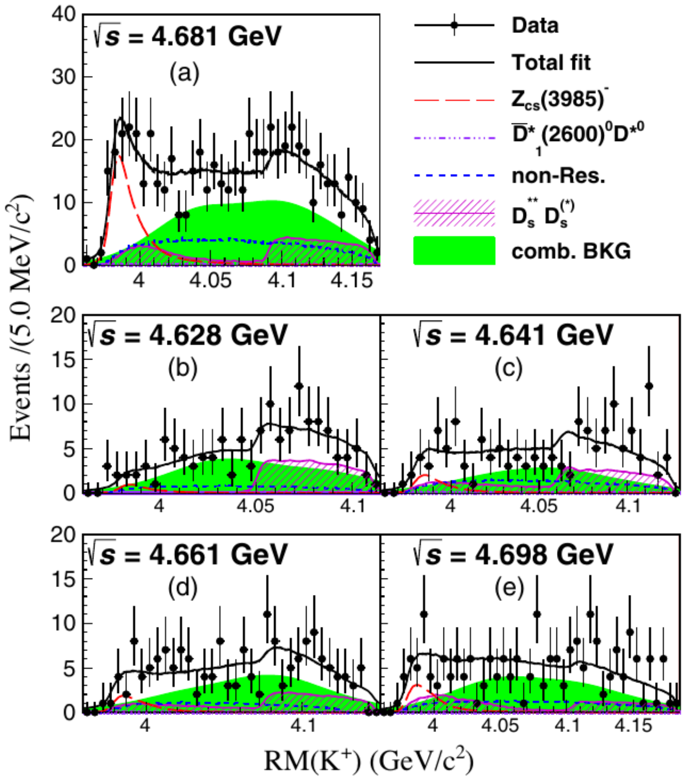
- *In 1974 the November revolution started heavy hadron spectroscopy*
- *Three years later the* Υ*(1S) state was discovered at Fermilab*
- *The naive quark model was successful describing the spectra up to the discovery of the X(3872) in 2003 by Belle.*
- *After 2003 many states that are not accommodated in the quark model have been observed*
- *A clear indication of states beyond the quark model are pentaquarks and charged states in the charmonium or bottomonium energy regions (Zc and Zb)*
- *The first charged states measured were the Zb(10610) and Zb(10650) from Belle*
- *The charmonium analogs are the Zc(3900) and Zc(4020)*
- *Last year BESIII (Zcs(3985)) and LHCb (Zcs(4000) and Zcs(4220)) discovered charged states with strangeness*

The Zcs states

PHYSICAL REVIEW LETTERS **126**, 102001 (2021)

Editors' Suggestion   Featured in Physics

Observation of a Near-Threshold Structure in the K^+ Recoil-Mass Spectra in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$



(BESIII Collaboration)

$$m_{\rm pole}[Z_{cs}(3985)^-] = (3982.5^{+1.8}_{-2.6} \pm 2.1)\ \mathrm{MeV}/c^2,$$

$$\Gamma_{\rm pole}[Z_{cs}(3985)^-] = (12.8^{+5.3}_{-4.4} \pm 3.0)\ \mathrm{MeV}.$$

Significance: $5.3\ \sigma$

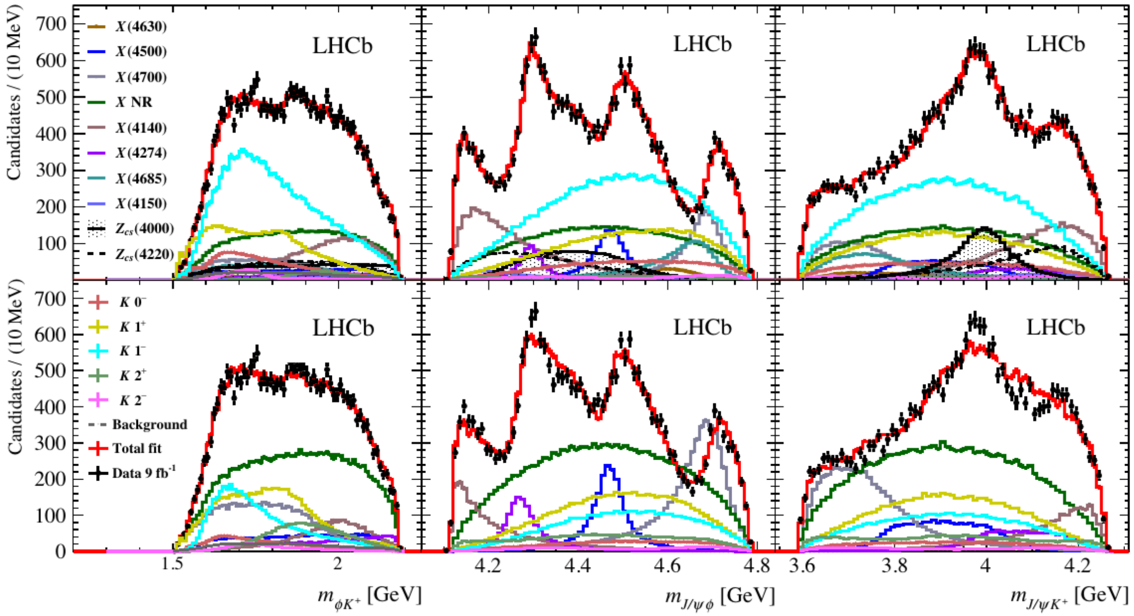
The Zcs states

PHYSICAL REVIEW LETTERS **127**, 082001 (2021)

Editors' Suggestion

Observation of New Resonances Decaying to $J/\psi K^+$ and $J/\psi\phi$

	Significance	m	Γ
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$

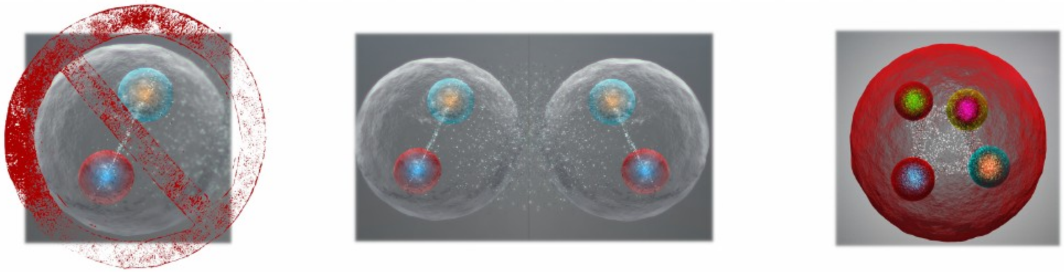


(LHCb Collaboration)

Two states

Is the Zcs(3985) the Zcs(4000)?

Popular explanations



- Tetraquarks

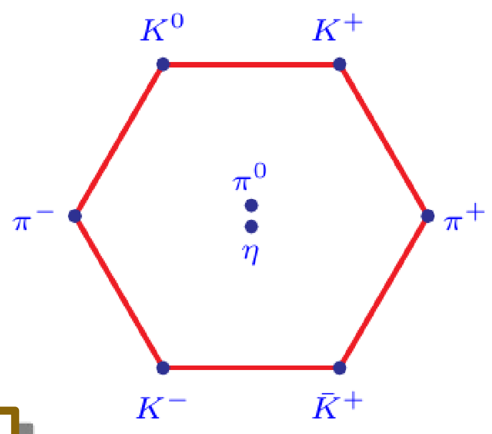
  A. Esposito et al, IJMPA30, 1530002.
  J.M. Dias et al, PRD 88, 016004 (2013).
  S.S. Agaev et al, PRD 96, 034026 (2017).
  Z.-G. Wang et al, PRD 89, 054019 (2014).
  C.-F. Qiao et al, EPJC 74, 3122 (2014).
  C. Deng et al, PRD 90, 054009 (2014).
  A. Ali et al, PRD 85, 054011 (2012).
  L. Maiani et al, PLB 778, 247 (2018).
  ...

- Molecules

  A. Bondar et al, PRD 84, 054010 (2011).
  F.-K. Guo et al, PRD 88, 054007 (2013).
  T. Mehen et al, PRD 88, 034017 (2013).
  J. He et al, EPJC 73, 2635 (2013).
  X.-H. Liu et al, PRD 90, 074020 (2014).
  J. Nieves et al, PRD 84, 056015 (2011).
  J.-R. Zhang et al, PLB 704, 312 (2011).
  J. M. Dias et al, PRD 91, 076001 (2015).
  ...

The Chiral Quark Model

- *Spontaneous Chiral Symmetry Breaking*
  Pseudo-goldstone boson exchange
- *One gluon exchange*
- *Confinement*



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

A. Manohar and H. Georgi, Nucl. Phys. B 324 (1984)

F. Fernández et al., J. Phys. G 19 (1993)

Theoretical framework

Resonanting Group Method (RGM)

$$\left(\frac{P'^2}{2\mu}-E\right)\chi_\alpha(P')+\sum_{\alpha'}\int\left[{}^{\rm RGM}V_D^{\alpha\alpha'}(P',P_i)+{}^{\rm RGM}V_R^{\alpha\alpha'}(P',P_i)\right]\chi_{\alpha'}(P_i)\,P_i^2\,dP_i=0$$

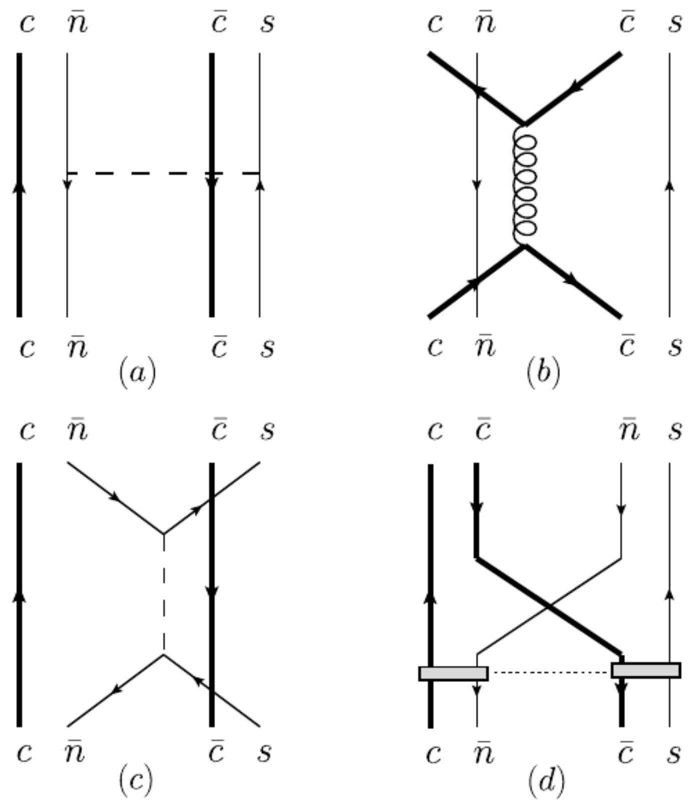
$$\begin{aligned}{}^{\rm RGM}V_D^{\alpha\alpha'}(\vec{P}',\vec{P}_i) &= \sum_{i\in A,j\in B}\int d\vec{p}_{A'}d\vec{p}_{B'}d\vec{p}_A d\vec{p}_B\phi^*(\vec{p}_{A'})\phi^*(\vec{p}_{B'})V_{ij}^{\alpha\alpha'}(\vec{P}',\vec{P}_i)\phi(\vec{p}_A)\phi(\vec{p}_B)\\ {}^{\rm RGM}V_R^{\alpha\alpha'}(\vec{P}',\vec{P}_i) &= \sum_{i\in A,j\in B}\int d\vec{p}_{A'}d\vec{p}_{B'}d\vec{p}_A d\vec{p}_B\phi^*(\vec{p}_{A'})\phi^*(\vec{p}_{B'})V_{ij}^{\alpha\alpha'}(\vec{P}',\vec{P}_i)P_{mn}\left[\phi(\vec{p}_A)\phi(\vec{p}_B)\right]\end{aligned}$$

Coupled-channels Lippman-Schwinger equation

$$\begin{aligned}T_\alpha^{\alpha'}(E;p',p) &= V_\alpha^{\alpha'}(p',p)+\sum_{\alpha''}\int dp''p''^2V_{\alpha''}^{\alpha'}(p',p'')\frac{1}{E-\epsilon_{\alpha''}(p'')}T_\alpha^{\alpha''}(E;p',p)\\ \epsilon_\alpha(p) &= \frac{p^2}{2\mu_\alpha}+\Delta M_\alpha\\ S_\alpha^{\alpha'} &= 1-2\pi i\sqrt{\mu_\alpha\mu_{\alpha'}k_\alpha k_{\alpha'}}T_\alpha^{'})e+i0^+;k_{\alpha'},k_\alpha)\end{aligned}$$

Theoretical framework

Direct diagrams



Annihilation of heavy q

Annihilation of light q

Rearrengement diagrams

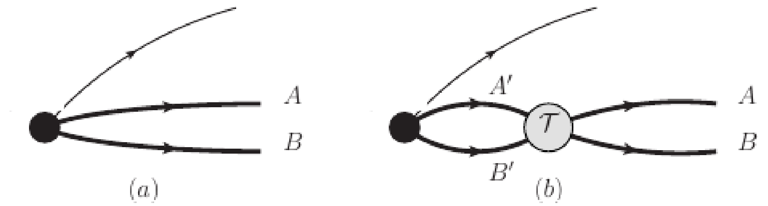
Theoretical framework

Decay width

$$\frac{d\Gamma_{Z_{cs}\to AB}}{dm_{AB}} = \frac{1}{(2\pi)^3}\frac{k_{AB}k_{KZ_{cs}}}{4s}\left|\mathcal{M}^{\beta}(m_{AB})\right|^2$$

Production amplitude

$$\mathcal{M}^{\beta}(m_{AB}) = \left(\mathcal{A}^{\beta}e^{i\theta_{\beta}} - \sum_{\beta'}\mathcal{A}^{\beta'}e^{i\theta_{\beta'}}\int d^3p\frac{T^{\beta}_{\beta'}(E,k_{\beta},p)}{p^2/2\mu - E - i0}\right)$$



Invariant mass distribution

$$N(m_{AB}) = \mathcal{N}_{AB} \times \frac{d\Gamma_{Z_{cs}\to AB}}{dm_{AB}}$$

$\{\mathcal{A}_{\beta},\theta_{\beta},\mathcal{N}_{AB}\}$ *Fitted to the experimental data*

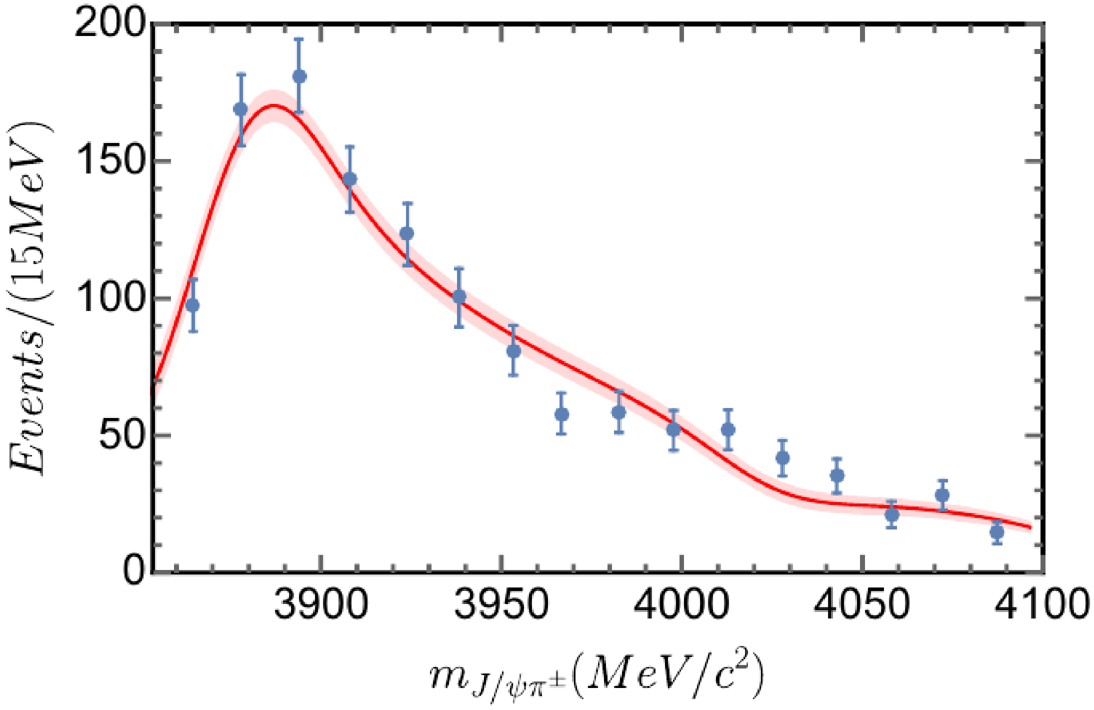
$$\chi^2(\{\mathcal{A}_{\beta},\theta_{\beta},\mathcal{N}_{AB}\}) = \sum_i\left(\frac{N^{\rm the}(x_i)-N^{\rm exp}(x_i)}{\sigma_i^{\rm exp}}\right)^2$$

Zc states in the CQM

P.G. Ortega et al, Eur.Phys.J. C79 (2019) no.1, 78

$$e^+e^- \to \pi^+\pi^- J/\psi$$

$\sqrt{s} = 4.26$ GeV



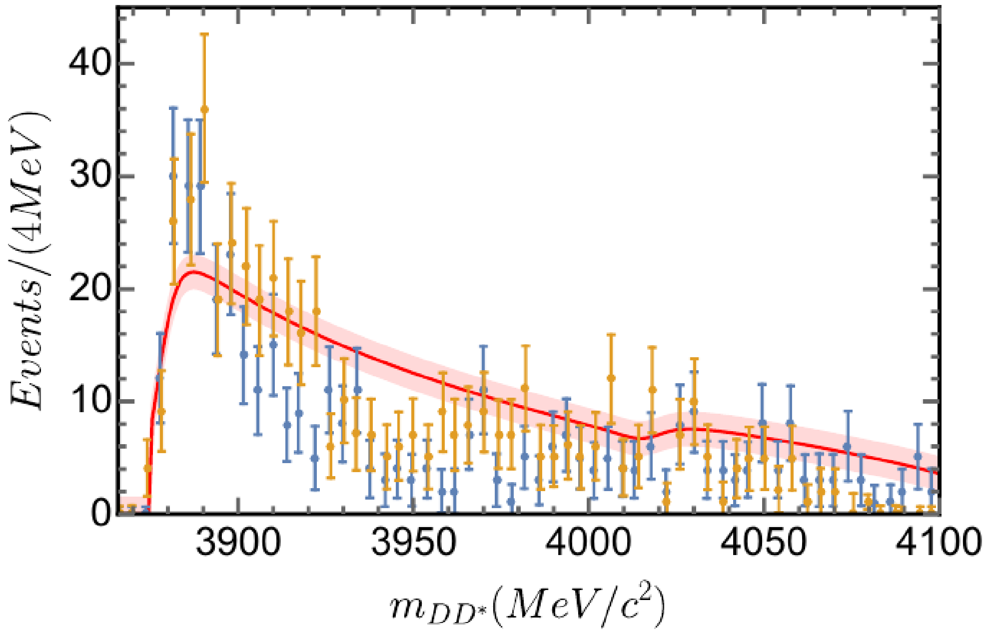
Data from BESIII Phys. Rev. Lett. 119, 072001 (2017)

Zc states in the CQM

P.G. Ortega et al, Eur.Phys.J. C79 (2019) no.1, 78

$$e^+e^- \to \pi^\pm (D\bar{D}^*)^\mp$$

$\sqrt{s} = 4.26$ GeV



Data from BESIII Phys. Rev. D 92, 092006 (2015)

Zc states in the CQM

P.G. Ortega et al, Eur.Phys.J. C79 (2019) no.1, 78

Calculation	$Z_c(3900)$ pole	RS	$Z_c(4020)$ pole	RS
$D\bar{D}^*$	$3871.37 - 2.17\,i$	(S)	-	-
$D\bar{D}^* + D^*\bar{D}^*$	$3872.27 - 1.85\,i$	(S,F)	$4014.16 - 0.10\,i$	(S,S)
$\rho\eta_c + D\bar{D}^*$	$3871.32 - 0.00\,i$	(S,S)	-	-
$\rho\eta_c + D\bar{D}^* + D^*\bar{D}^*$	$3872.07 - 0.00\,i$	(S,S,F)	$4013.10 - 0.00\,i$	(S,S,S)
$\pi J/\psi + \rho\eta_c + D\bar{D}^* + D^*\bar{D}^*$	$3871.74 - 0.00\,i$	(S,S,S,F)	$4013.21 - 0.00\,i$	(S,S,S,S)

Calculation	$Z_c(3900)$	type
This work	3871.74	virtual
F. Aceti et al.	$3878 - 23\,i$	resonance
M. Albaladejo et al.	$3894 \pm 6 \pm 1 - 30 \pm 12 \pm 6\,i$	resonance
	$3886 \pm 4 \pm 1 - 22 \pm 6 \pm 4\,i$	resonance
	$3831 \pm 26^{+7}_{-28}$	virtual
	$3844 \pm 19^{+12}_{-21}$	virtual
Y. Ikeda et al.	$3709 \pm 94 - 183(46)\,i$	virtual
	$3748 \pm 76 - 157(32)\,i$	virtual
	$3686 \pm 56 - 44(27)\,i$	virtual
J. He et al.	$3876 - 5\,i$	resonance
Calculation	**$Z_c(4020)$**	**type**
This work	4013.21	virtual
F. Aceti et al.	$(3990 - 4000) - 50\,i$	bound/virtual

Results

$$J/\psi K^- \; (3592\,\mathrm{MeV/c^2})$$
$$\eta_c K^{*-} \; (3877\,\mathrm{MeV/c^2})$$
$$D_s^- D^{*0} \; (3976\,\mathrm{MeV/c^2})$$
$$D^0 D_s^{*-} \; (3979\,\mathrm{MeV/c^2})$$
$$J/\psi K^{*-} \; (3990\,\mathrm{MeV/c^2})$$
$$D^{*0} D_s^{*-} \; (4120\,\mathrm{MeV/c^2})$$

$$I(J^P) = \tfrac{1}{2}(1^+)$$

a) Without annihilation

$$\begin{pmatrix} V^{\sigma}_{D_s D^* \to D_s D^*} & 0 & 0 \\ 0 & V^{\sigma}_{D_s^* D \to D_s^* D} & 0 \\ 0 & 0 & V^{\sigma}_{D_s^* D^* \to D_s^* D^*} \end{pmatrix}$$

b) With annihilation

$$\begin{pmatrix} V^{\sigma}_{D_s D^* \to D_s D^*} & V^{K}_{D_s D^* \to D_s^* D} & V^{K}_{D_s D^* \to D_s * D^*} \\ V^{K}_{D_s^* D \to D_s D^*} & V^{\sigma}_{D_s^* D \to D_s^* D} & V^{K}_{D_s^* D \to D_s^* D^*} \\ V^{K}_{D_s^* D^* \to D_s D^*} & V^{K}_{D_s^* D^* \to D_s^* D} & V^{\sigma}_{D_s^* D^* \to D_s^* D^*} \end{pmatrix}$$

Two poles (virtual states):

$D_s^- D^{*0}$ $\quad$ $D^{*0} D_s^{*-}$

a) 3970 and 4110

b) 3961-3i and 4106-5i

Two fits (with the same t-matrix)

1) BESSIII data

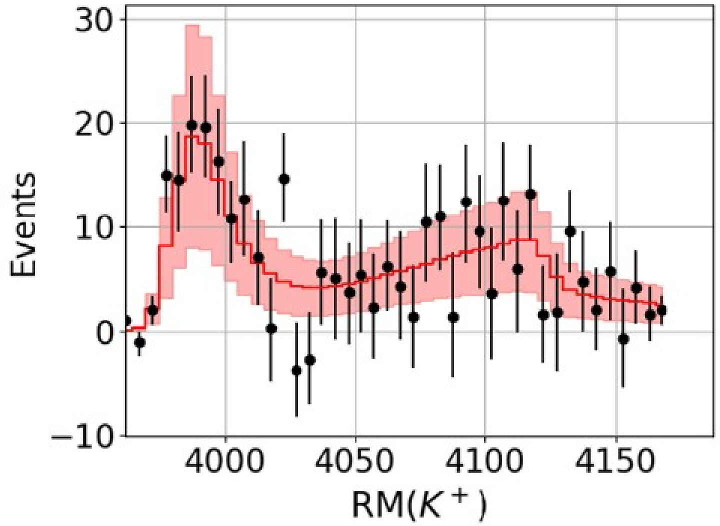
2) LHCb data

Results

Parameters	BESIII data		LHCb data	
	Model a	Model b	Model a	Model b
χ^2/d.o.f.	1.00	1.02	2.65	2.04
$\ln(\mathcal{N}_{D_sD^*+DD_s^*})$	25.4(5)	24.6(6)	-	-
$\ln(\mathcal{N}_{J/\psi K})$	-	-	25.22(6)	25.43(8)
$\mathcal{A}_{J/\psi K}$	0.71(4)	1.0(9)	0.026(1)	0.028(2)
$\mathcal{A}_{\eta_c K^*}$	0.31(3)	0.33(2)	0.39(2)	0.35(3)
$\mathcal{A}_{D_sD^*}$	0.028(2)	0.052(5)	0.140(4)	0.02(1)
$\mathcal{A}_{DD_s^*}$	0.030(2)	0.04(1)	0.00(2)	0.10(1)
$\mathcal{A}_{J/\psi K^*}$	0.01(1)	0.01(2)	0.9(1)	0.52(7)
$\mathcal{A}_{D^*D_s^*}$	0.17(5)	0.29(2)	0.143(4)	0.15(1)
$\theta_{J/\psi K}$	-1.42(3)	-2.65(8)	-2.43(2)	-0.39(13)
$\theta_{\eta_c K^*}$	-0.53(5)	-1.8(2)	1.43(4)	-3.19(6)
$\theta_{D_sD^*}$	-2.33(7)	3.2(4)	-3.19(3)	-1.25(3)
$\theta_{DD_s^*}$	-2.39(7)	2.4(2)	1(6)	-0.96(11)
$\theta_{J/\psi K^*}$	-1.1(9)	-3(5)	-0.4(1)	1.15(13)
$\theta_{D^*D_s^*}$	-2.5(3)	-2.7(2)	0.67(2)	2.80(11)

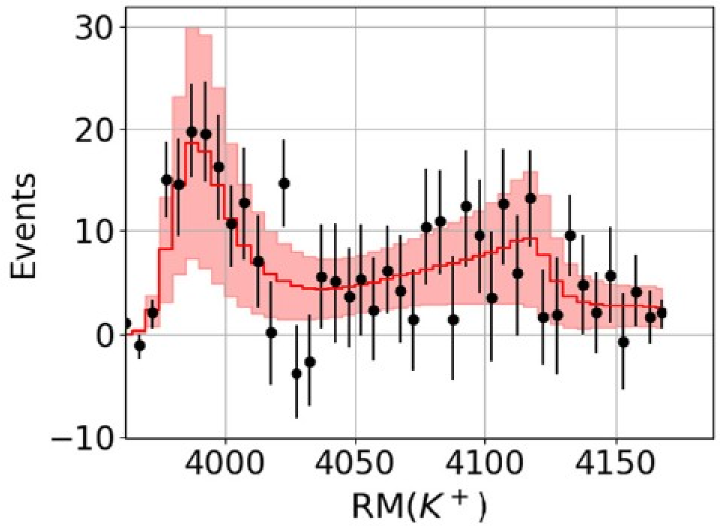
Results

$$\chi^2/\mathrm{d.o.f} = 1.00$$



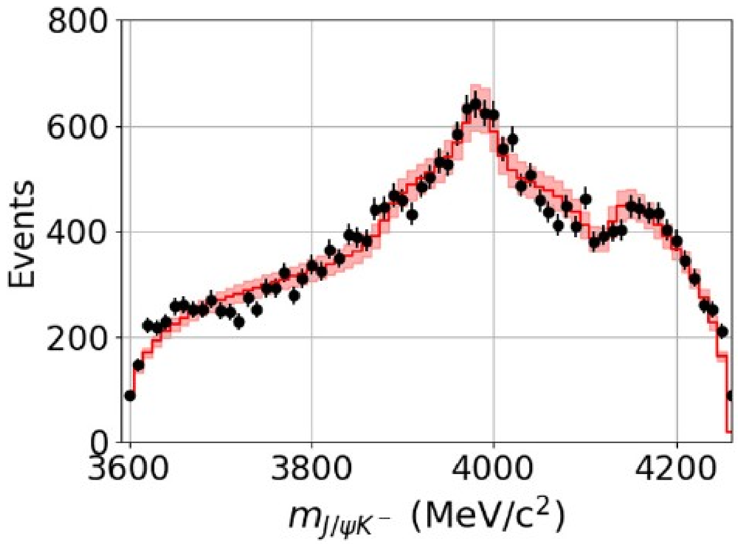
BESSIII data well reproduced

$$\chi^2/\mathrm{d.o.f} = 1.02$$



Results

$$\chi^2/\mathrm{d.o.f} = 2.65$$

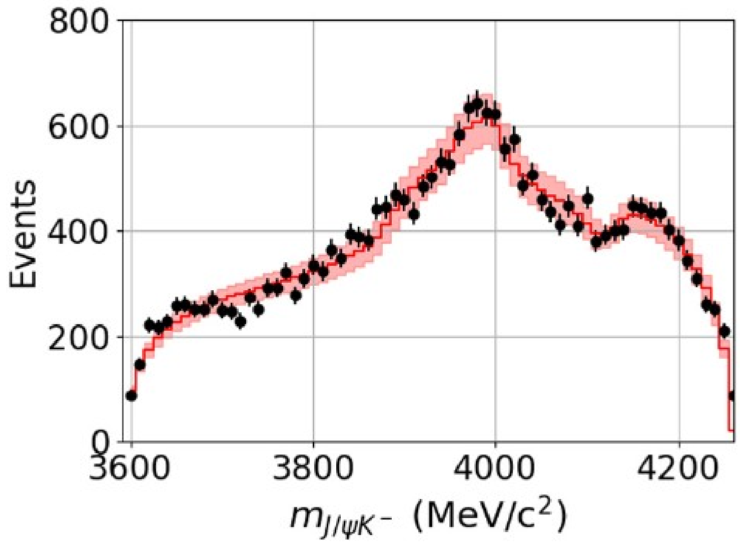


LHCb data:

- The Zcs(4000) might be the Zcs(3985)

- The data can be explained with the Zcs(4110)

$$\chi^2/\mathrm{d.o.f} = 2.04$$



Conclusions

- *We use the Chiral Quark Model plus a coupled channels calculation to explain the Zcs(3985), Zcs(4000) and Zcs(4220) as virtual states*
- *The same model reproduces the Zc(3900) and Zc(4020) also as virtual states*
- *Two virtual states below DsD* and D*Ds**

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

- *The Zcs(3985) and Zcs(4000) peaks are compatible with the same state*
- *Two virtual states below B*Bs and B*Bs**

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