Z_{cs}^{+} production in the B^{+} decays process

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Outline

- Introduction
- Decays of Zcs
- Productions of Zcs
- Summary

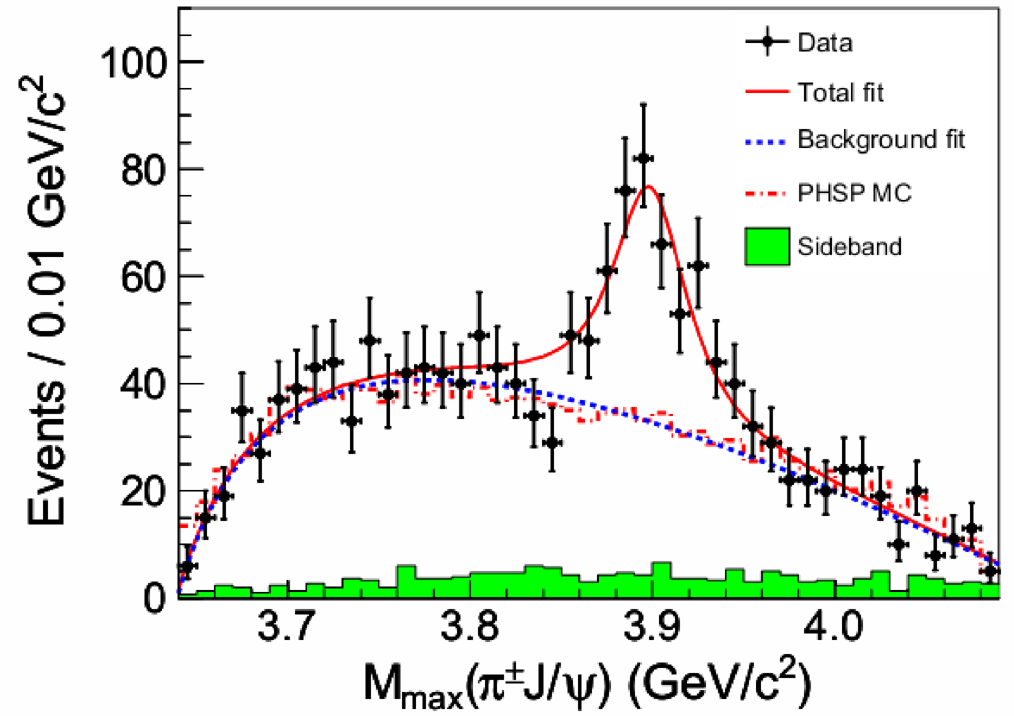
INTRODUCTION: Z_c states

Charmonium-like states: X(3872), $Z_c(3900)$, $Z_c(4020)$ ⋯

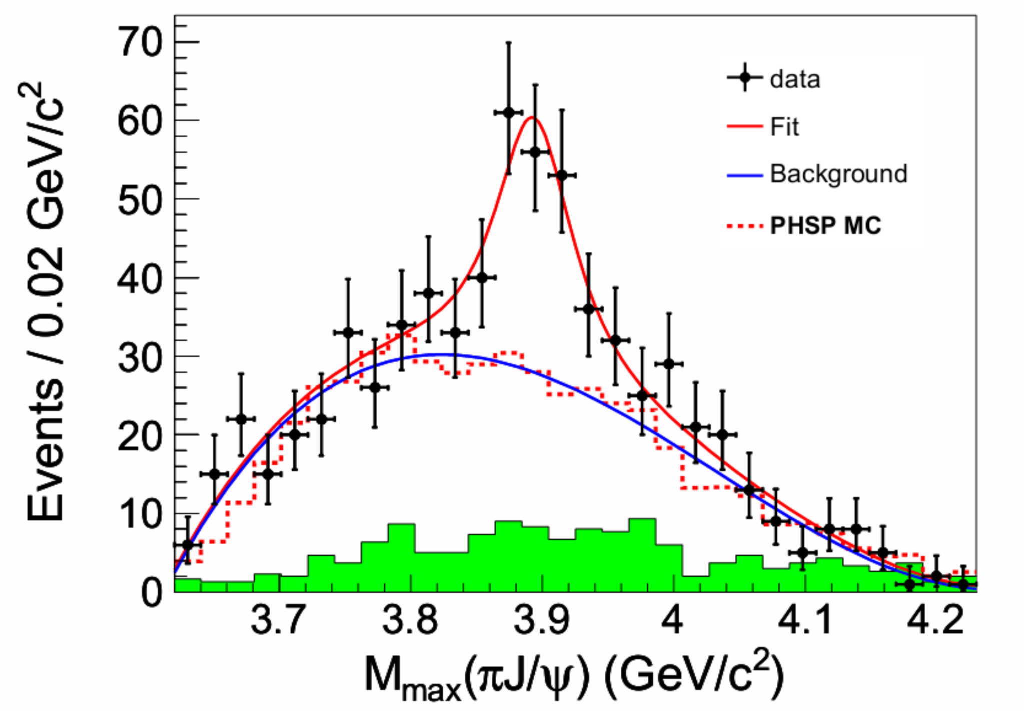
Why is $Z_c^+(3900)$ important?

- the first confirmed charged charmonium-like state.

Phys. Rev. Lett., 110:252001, 2013 (BES III)



Phys. Rev. Lett., 110:252002, 2013 (Belle)



directly exclude conventional hadron => Exotic States!!!

INTRODUCTION: from Zc to Zcs

Interpretations of Z_c

Molecular: Phys. Rev. Lett., 111(13):132003, 2013.
Phys. Rev. D, 88(1):014030, 2013.
Eur. Phys. J. C, 73(11):2621, 2013.

Tetraquark: Phys. Rev. D90,054009 (2014)
Phys. Rev. D 92(3), 034027 (2015)
Phys. Rev. D 96(11), 116003 (2017)

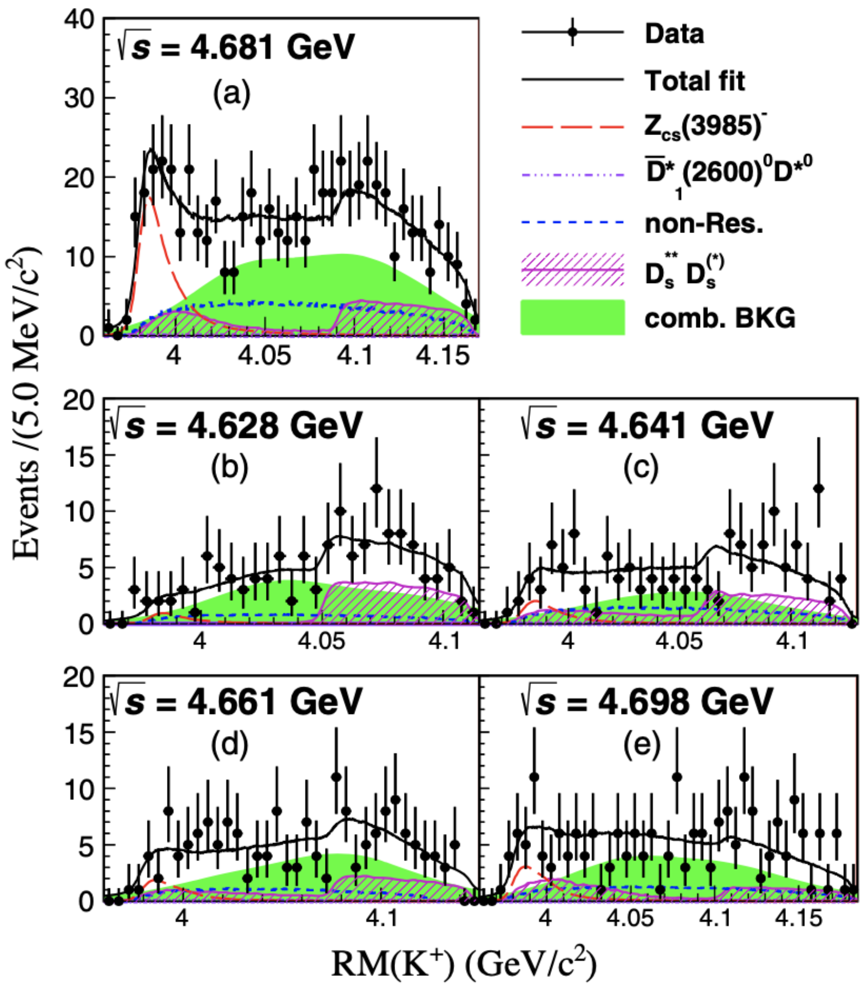
Cusp: arXiv:1504.07952

Predictions of Z_{cs}

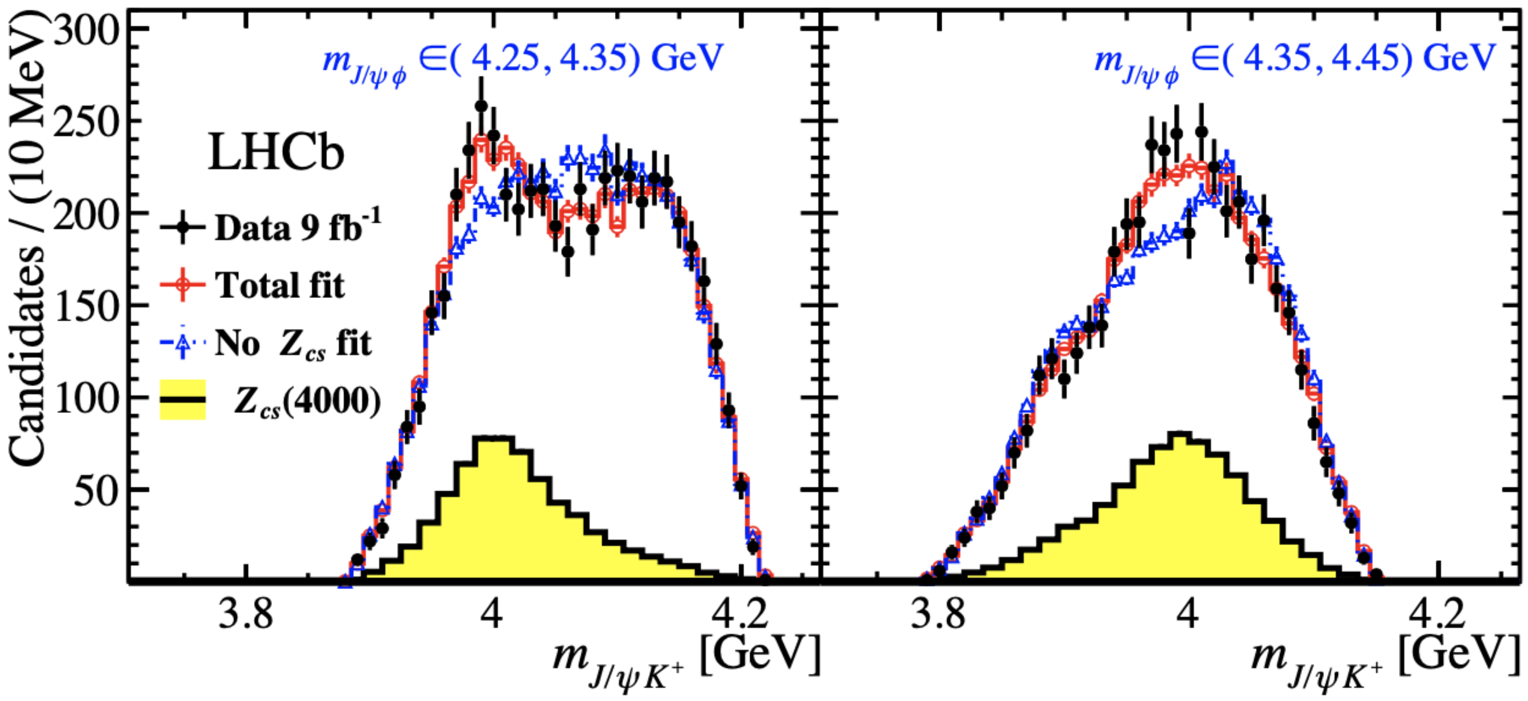
Eur. Phys. J. C, 58:399–405, 2008. **Relativistic quark model, decay**
Phys. Rev. D, 88(9):096014, 2013.). **QCD sum rule, decay**
Phys. Rev. Lett., 110(23):232001, 2013. **Effective Lagrangian approach, decay**
JHEP, 04:119, 2020. **Relativized diquark model, spectrum**

INTRODUCTION: observation of Zcs

BESIII, Phys.Rev.Lett.126, 102001 (2021)



LHCb, Phys.Rev.Lett. 127, 082001 (2021)



BES III: $e^+e^- \to K^+\left(D_s^- D^{*0} + D_s^{*-} D^0\right)$

LHCb: $B^+ \to \phi\, J/\psi\, K^+$

INTRODUCTION: observation of Zcs

Resonance parameters

Collaboration	Mass (MeV)	Width (MeV)
BES III [49]	$3982.5^{+1.8}_{-2.6} \pm 2.1$	$12.8^{+5.3}_{-4.4} \pm 3.0$
LHCb [50]	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$

The similar mass but different width, are $Z_{cs}^{+}(3985)$ and $Z_{cs}^{+}(4000)$ same state still remain a question.

Same state:

Phys. Rev. D, 103(7):074029, 2021.
Phys. Lett. B, 818:136382, 2021.
Eur. Phys. J. C, 82(6):520, 2022.

Different state

Sci. Bull. 66, 2065–2071 (2021)
Phys. Rev. D 103(7)(2021)..

Decay of Zcs in the molecular scenario

Eur. Phys. J. C, 82(6):520, 2022

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Zcs(3985)

$$|Z_{cs}^-\rangle = \frac{1}{\sqrt{2}}(|D_s^{*-}D^0\rangle + |D_s^- D^{*0}\rangle).$$

$$\mathcal{L}_{Z_{cs}} = \frac{g_{Z_{cs}}}{\sqrt{2}} Z_{cs}^{\dagger\mu}\left(\bar{D}_{s\mu}^* D + \bar{D}_s D_\mu^*\right)$$

Hidden charm decay

$Z_{cs}^- \to J/\psi K^-$, $Z_{cs}^- \to \eta_c K^{*-}$ (triangle loop)

$Z_{cs}^- \to D_s^* \bar{D}$ (directly estimated)

: The branching ratios of $Z_{cs}^- \to J/\psi K^-$, $Z_{cs}^- \to \eta_c K^{*-}$ and $Z_{cs}^- \to D^0 D_s^{*-} + c.c.$(in unites of %) depending on the model parameter α.

α	3	3.5	4	4.5	5
$\mathcal{B}[Z_{cs}^- \to J/\psi K^-]$	1.3	2.4	4.0	6.0	8.3
$\mathcal{B}[Z_{cs}^- \to \eta_c K^{*-}]$	0.9	2.1	4.2	7.6	12.5
$\mathcal{B}[Z_{cs}^- \to D^0 D_s^{*-} + c.c.]$	97.8	95.5	91.8	86.4	79.2

the decay behavior of $Z_{cs}(3985)$ is very similar to the one of $Z_c(3900)$ when we assume $Z_{cs}(3985)$ as a $D_s^{*-}D^0 + D_s^- D^{*0}$ molecular state.

Production of Zcs in B^+/B_s^0 decay

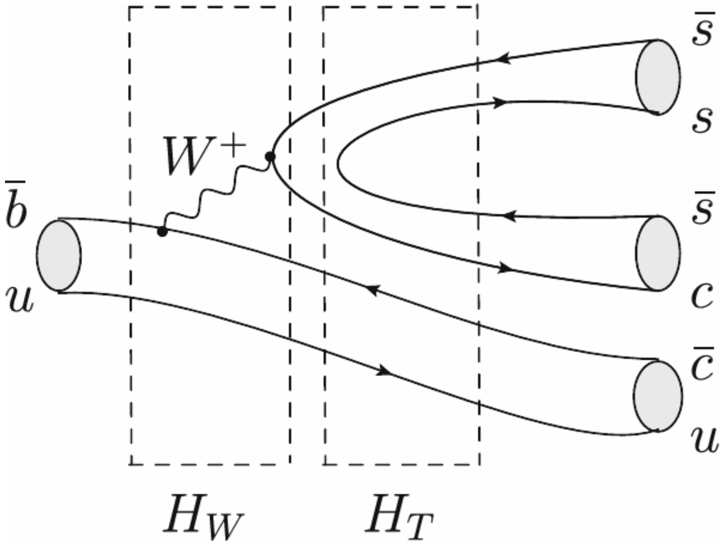
Fit fraction:

$$\frac{\mathcal{B}[B^+ \to Z_{cs}^+\phi \to J/\psi\phi K^+]}{\mathcal{B}[B^+ \to J/\psi\phi K^+]} = (9.4 \pm 2.1 \pm 3.4)\%.$$

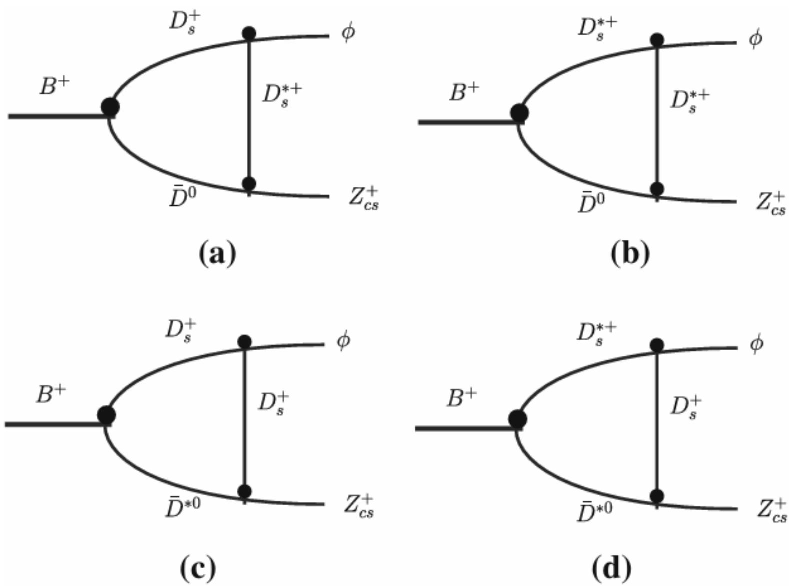
$$\mathcal{B}[B^+ \to \phi Z_{cs}^+ \to \phi(J/\psi K^+)] = (4.6 \pm 2.0) \times 10^{-6}.$$

Production Mechanism of $B^+ \to {Z_{cs}}^+\phi$

Quark level



Hadron level



Dominant contributions

$\mathcal{B}\left[B^+ \to D_s^{(*)+}\bar{D}^{(*)0}\right]$:

$(9.0 \pm 0.9) \times 10^{-3}$,
$(7.6 \pm 1.6) \times 10^{-3}$,
$(8.2 \pm 1.7) \times 10^{-3}$,
$(1.7 \pm 0.24) \times 10^{-2}$

Production of Zcs in B^+/B_s^0 decay

Weak vertex

$$\langle 0|J_\mu|P(p_1)\rangle = -if_P p_{1\mu} ,$$

$$\langle 0|J_\mu|V(p_1,\epsilon)\rangle = f_V \epsilon_\mu m_V ,$$

$$\langle P(p_2)|J_\mu|B(p)\rangle = \left[P_\mu - \frac{m_B^2 - m_P^2}{q^2} q_\mu\right] F_1\left(q^2\right) + \frac{m_B^2 - m_P^2}{q^2} q_\mu F_0\left(q^2\right)$$

$$\langle V(p_2,\epsilon)|J_\mu|B(p)\rangle = \frac{i\epsilon^\nu}{m_B + m_V}\Big\{ i\varepsilon_{\mu\nu\alpha\beta} P^\alpha q^\beta V\left(q^2\right) - (m_B+m_V)^2 g_{\mu\nu} A_1\left(q^2\right) + P_\mu P_\nu A_2\left(q^2\right) + 2m_V(m_B+m_V)\frac{P_\nu q_\mu}{q^2}\left[A_3\left(q^2\right) - A_0\left(q^2\right)\right]\Big\} ,$$

$$\mathcal{L}_{\mathcal{D}^{(*)}\mathcal{D}^{(*)}\mathcal{V}} = -ig_{\mathcal{D}\mathcal{D}\mathcal{V}} \mathcal{D}_i^\dagger \overleftrightarrow{\partial}_\mu \mathcal{D}^j (\mathcal{V}^\mu)^i_j - 2f_{\mathcal{D}^*\mathcal{D}\mathcal{V}} \varepsilon_{\mu\nu\alpha\beta} (\partial^\mu \mathcal{V}^\nu)^i_j (\mathcal{D}_i^\dagger \overleftrightarrow{\partial}^\alpha \mathcal{D}^{*\beta j} - \mathcal{D}_i^{*\beta\dagger} \overleftrightarrow{\partial}^\alpha \mathcal{D}^j) + ig_{\mathcal{D}^*\mathcal{D}^*\mathcal{V}} \mathcal{D}_i^{*\nu\dagger} \overleftrightarrow{\partial}_\mu \mathcal{D}_\nu^{*j} (\mathcal{V}^\mu)^i_j + 4if_{\mathcal{D}^*\mathcal{D}^*\mathcal{V}} \mathcal{D}_{i\mu}^{*\dagger} (\partial^\mu \mathcal{V}^\nu - \partial^\nu \mathcal{V}^\mu)^i_j \mathcal{D}_\nu^{*j} + \text{H.c.} ,$$

$$\mathcal{L}_{Z_{cs}} = \frac{g_{Z_{cs}}}{\sqrt{2}} Z^\mu_{cs} \left(D^*_{s\mu}\bar{D} + D_s \bar{D}^*_\mu\right)$$

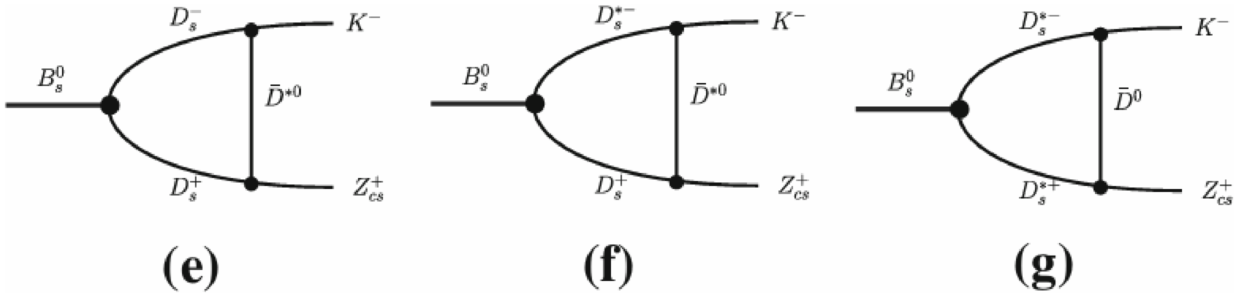
$$\mathcal{M}_a = i^3 \int \frac{d^4q}{(2\pi)^4} [\mathcal{A}^{B^+\to D_s^+\bar{D}^0}(p_1,p_2)][2f_{D^*DV}\varepsilon_{\mu_2\delta\alpha_2\beta} (ip_3^{\mu_2})(p_1+q)^{\alpha_2}][ig_{Z_{cs}D_s^*D} g_{\delta\phi}][\frac{1}{p_1^2 - m_1^2}][\frac{1}{p_2^2 - m_2^2}] [\frac{-g^{\beta\phi} + q^\beta q^\phi/m_q^2}{q^2 - m_q^2}] \mathcal{F}^2(q^2, m_q^2),$$

Form factor: $\mathcal{F}\left(q^2, m^2\right) = \frac{m^2 - \Lambda^2}{q^2 - \Lambda^2},$ ⇒ $\Lambda = m + \alpha \Lambda_{QCD}$

model parameter

Production of Zcs in B^+/B_s^0 decay

- **The branching fraction $\mathcal{B}\left[B_s^0 \to D_s^{(*)+}\overline{D_s}^{(*)0}\right]$ are also sizable, we can predict the productions of Zcs in B_s^0 decay.**



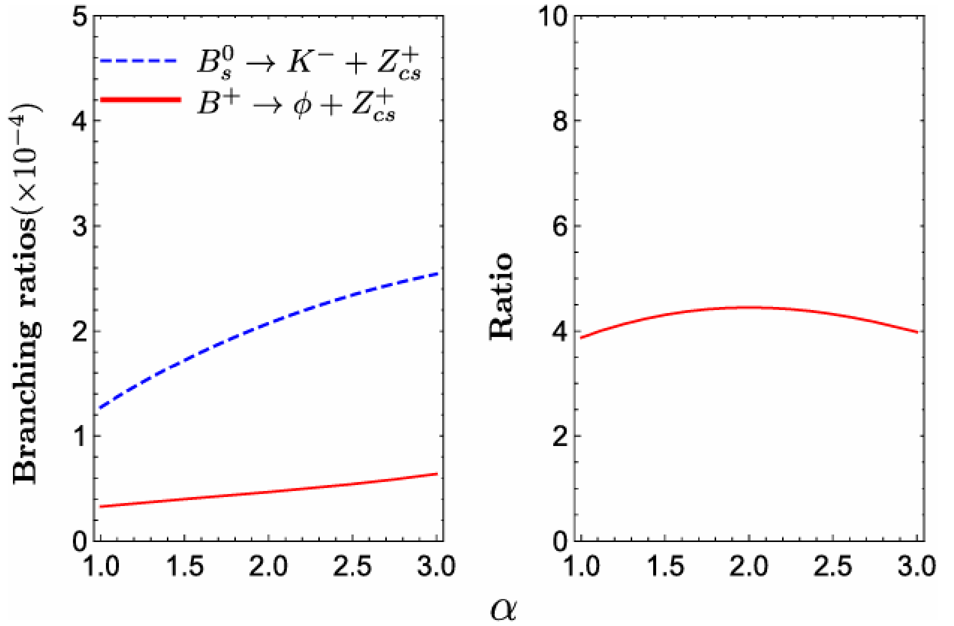


Fig. 4 Branching ratios of $B^+ \to \phi Z_{cs}^+$ and $B_s^0 \to K^- Z_{cs}^+$ (left panel) and their ratio (right panel) depending on parameter α

- **B($B^+ \to Z_{cs}^+\phi$)*B($Z_{cs}^+ \to J/\psi K^+$) = $1.86^{+2.12}_{-1.37} \times 10^{-6}$ (Present work)**
- **B($B^+ \to Z_{cs}^+\phi$)*B($Z_{cs}^+ \to J/\psi K^+$) = $4.6 \pm 2.0 \times 10^{-6}$ (LHCb)**

$$R_{B_s/B} = \frac{\mathcal{B}[B_s^0 \to K^- Z_{cs}^+]}{\mathcal{B}[B^+ \to \phi Z_{cs}^+]} = 4.17 \pm 0.28$$

Our results are comparable with the LHCb measurement.

- **Prediction:**

$$\mathcal{B}[B_s^0 \to K^\pm Z_{cs}^\mp \to J/\psi K^+K^-] = (3.83 \pm 1.69) \times 10^{-5}. \Rightarrow \frac{\mathcal{B}[B_s^0 \to Z_{cs}^\pm K^\mp \to J/\psi K^+K^-]}{\mathcal{B}[B_s^0 \to J/\psi K^+K^-]} = (4.85 \pm 2.17)\%,$$

- **The $B_s^0 \to J/\psi K^+K^-$ should be cleaner process to searching Z_{cs} .**

Production of Zcs in B^+decay(new)

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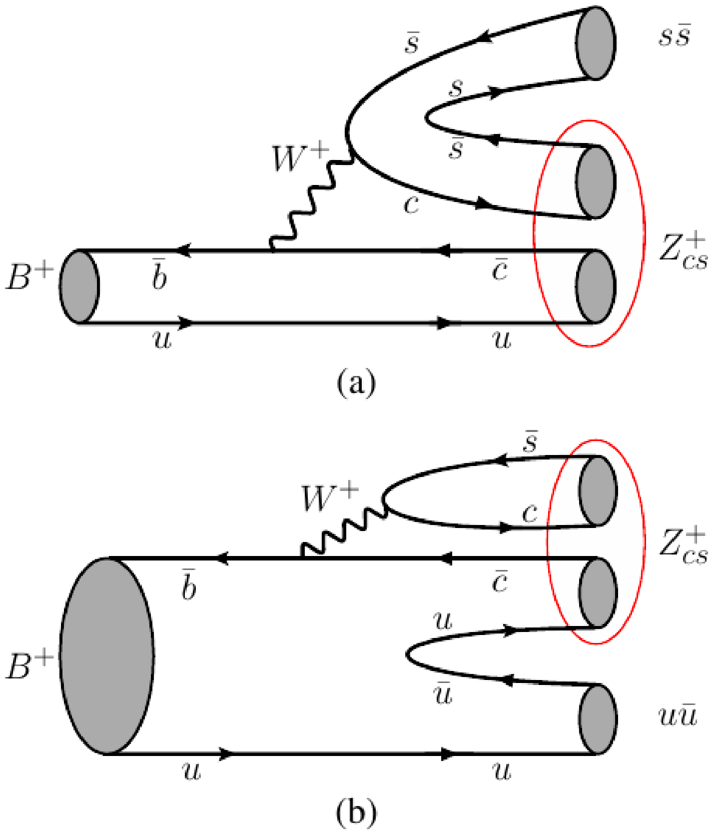
- **The final states in B^+ decay production mechanism could be $Z_{cs}{}^+$ with a $u\bar{u}$ and $s\bar{s}$ meson**

$$s\bar{s} \to \phi, \eta, \eta'$$
$$u\bar{u} \to \omega, \pi^0, \rho^0, \eta, \eta'$$

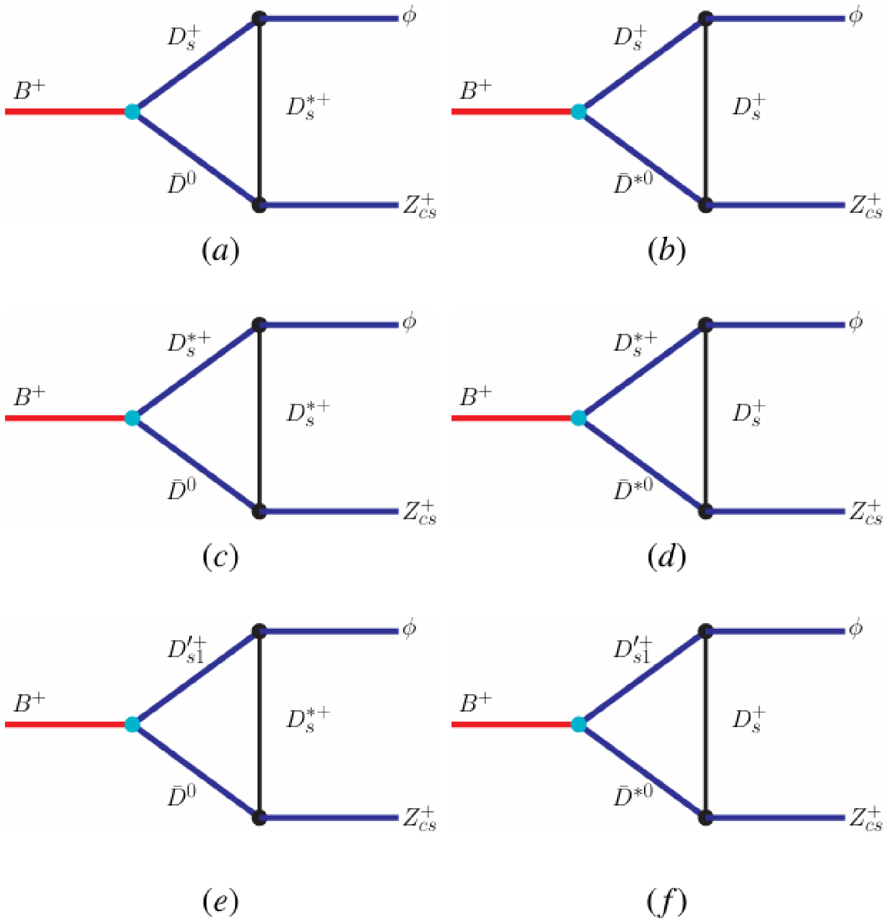


Sizable branching fraction

Process	branching fraction
$B^+ \to J/\psi K^+\phi$	$(5.0 \pm 0.4) \times 10^{-5}$
$B^+ \to J/\psi K^+\omega$	$(3.2^{+0.60}_{-0.32}) \times 10^{-4}$
$B^+ \to J/\psi K^+\eta$	$(1.24 \pm 0.14) \times 10^{-4}$
$B^+ \to J/\psi K^+\eta'$	$(3.1 \pm 0.4) \times 10^{-5}$
$B^+ \to J/\psi K^+\pi^0$	$(1.14 \pm 0.1) \times 10^{-3}$
$B^+ \to J/\psi K^+\rho^0$	–

Production of Zcs in B^+decay(new)

Considered diagrams of $B^+ \to Z_{cs}{}^+\phi$ in the present work

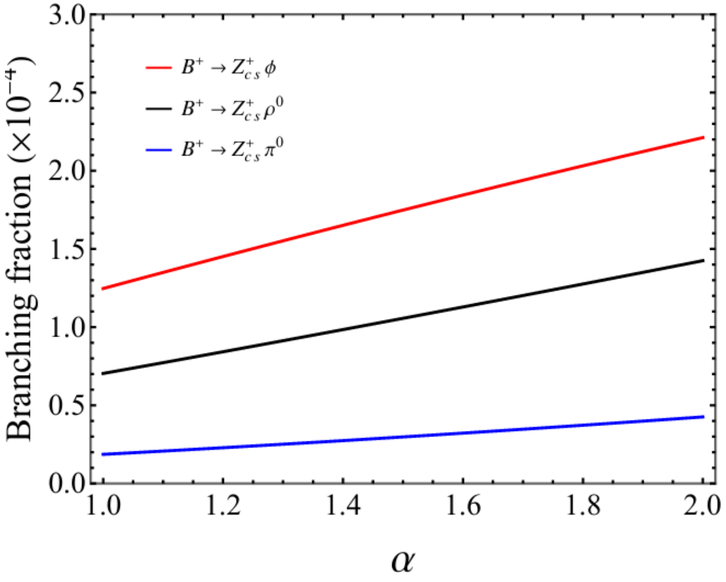


- **more final states, more immediate states**
  $\mathcal{B}[B^+ \to D'^+_{s1}\bar{D}^0] = (3.1 \pm 0.9) \times 10^{-3}$,
  $\mathcal{B}[B^+ \to D'^+_{s1}\bar{D}^{(*)0}] = (1.2 \pm 0.3) \times 10^{-2}$.

- **The D'_{s1} couplings to $D_s^{(*)}\phi$ via S-wave**

Process	Loops
$B^+ \to Z_{cs}^+\phi$	$D_s^+\bar{D}^0 D_s^{*+}$, $D_s^+\bar{D}^{*0} D_s^+$, $D_s^{*+}\bar{D}^0 D_s^{*+}$ $D_s^{*+}\bar{D}^{*0} D_s^+$, $D'^+_{s1}\bar{D}^0 D_s^{*+}$, $D'^+_{s1}\bar{D}^{*0} D_s^+$,
$B^+ \to Z_{cs}^+\omega/\rho^0$	$\bar{D}^0 D_s^+ \bar{D}^{*0}$, $\bar{D}^{*0} D_s^+ \bar{D}^{*0}$, $\bar{D}^0 D_s^{*+} \bar{D}^0$, $\bar{D}^{*0} D_s^{*+} \bar{D}^0$,
$B^+ \to Z_{cs}^+\eta/\eta'$	$D_s^+\bar{D}^0 D_s^{*+}$, $D_s^{*+}\bar{D}^0 D_s^{*+}$, $D_s^{*+}\bar{D}^{*0} D_s^+$, $D'^+_{s1}\bar{D}^0 D_s^{*+}$ $\bar{D}^0 D_s^+ \bar{D}^{*0}$, $\bar{D}^{*0} D_s^+ \bar{D}^{*0}$, $\bar{D}^{*0} D_s^{*+} \bar{D}^0$
$B^+ \to Z_{cs}^+\pi^0$	$\bar{D}^0 D_s^+ \bar{D}^{*0}$, $\bar{D}^{*0} D_s^+ \bar{D}^{*0}$, $\bar{D}^{*0} D_s^{*+} \bar{D}^0$

Result



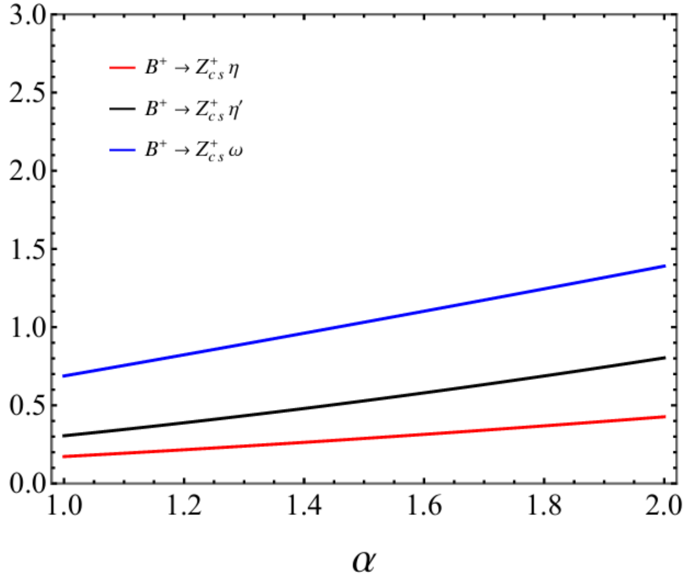


TABLE V: The estimated branching fractions for all processes (in order of 10^{-4}).

Process	branching fraction
$B^+ \to Z_{cs}^+ \phi$	$1.75^{+0.46}_{-0.50}$
$B^+ \to Z_{cs}^+ \omega$	$1.03^{+0.36}_{-0.34}$
$B^+ \to Z_{cs}^+ \rho^0$	$1.06^{+0.36}_{-0.36}$
$B^+ \to Z_{cs}^+ \eta$	$0.29^{+0.14}_{-0.12}$
$B^+ \to Z_{cs}^+ \eta'$	$0.53^{+0.27}_{-0.22}$
$B^+ \to Z_{cs}^+ \pi^0$	$0.30^{+0.13}_{-0.12}$

Phys. Rev. D, 104(7):074011, 2021.
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$\mathcal{B}[Z_{cs}{}^+ \to J/\psi K^+]$ was estimated to be around 4%

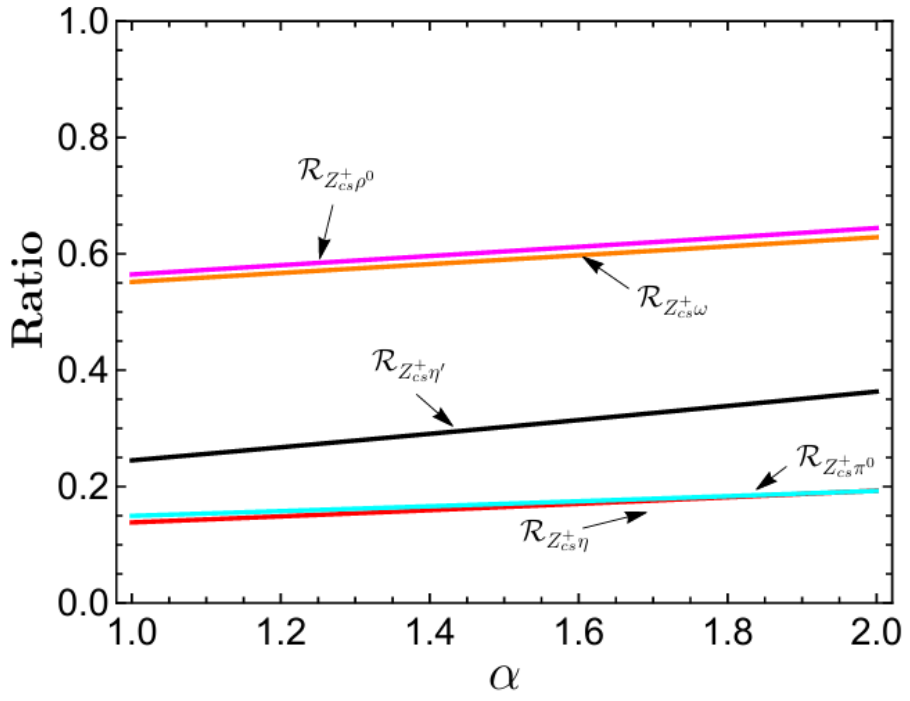
- **Our estimation** Zhuo Yu, Qi Wu and DianYong Chen

$$\mathcal{B}[B^+ \to Z_{cs}^+ \phi \to J/\psi K^+ \phi]$$
$$= \mathcal{B}[B^+ \to Z_{cs}^+ \phi] \times \mathcal{B}[Z_{cs}^+ \to J/\psi K^+]$$
$$= (7.0^{+11.3}_{-5.37}) \times 10^{-6},$$

- **Experiment(LHCb)**

$$\mathcal{B}[B^+ \to Z_{cs}^+ \phi \to J/\psi K^+ \phi] = (4.6 \pm 2.0) \times 10^{-6}.$$

Result



$$\mathcal{R}_{Z_{cs}^+\mathbb{M}} = \frac{\mathcal{B}[B^+ \to Z_{cs}^+\mathbb{M}]}{\mathcal{B}[B^+ \to Z_{cs}^+\phi]},$$

- **The ratio between these branching ratios indicate our estimation is weakly dependent on the model parameter.**

$$\frac{FF[B^+ \to Z_{cs}^+\mathbb{M} \to J/\psi K^+\mathbb{M}]}{FF[B^+ \to Z_{cs}^+\phi \to J/\psi K^+\phi]} = \frac{\mathcal{B}[B^+ \to J/\psi K^+\phi]}{\mathcal{B}[B^+ \to J/\psi K^+\mathbb{M}]}\mathcal{R}_{Z_{cs}^+\mathbb{M}}.$$

Process	Ratio	FF
$B^+ \to J/\psi K^+\phi$	...	$(9.4 \pm 2.1 \pm 3.4)$
$B^+ \to J/\psi K^+\omega$	$0.59^{+0.04}_{-0.04}$	$0.87^{+0.24}_{-0.24}$
$B^+ \to J/\psi K^+\rho^0$	$0.60^{+0.04}_{-0.03}$	...
$B^+ \to J/\psi K^+\eta$	$0.16^{+0.03}_{-0.02}$	$0.61^{+0.27}_{-0.17}$
$B^+ \to J/\psi K^+\eta'$	$0.30^{+0.06}_{-0.05}$	$4.55^{+2.22}_{-1.46}$
$B^+ \to J/\psi K^+\pi^0$	$0.17^{+0.02}_{-0.02}$	$0.07^{+0.02}_{-0.01}$

- **The fit fraction of Z_{cs} in $B^+ \to J/\psi K^+\eta'$ is comparable with $B^+ \to J/\psi K^+\phi$(the largest one), it is accessible for future experiment.**

Summary

- $\boldsymbol{Z_{cs}}^+$ could be assigned as a $D_s^*\overline{D} + D_s\overline{D^*}$ molecular state.
- We considered more finals states and immediate states to investigate the $\boldsymbol{Z_{cs}}^+$ production in $\boldsymbol{B}^+$ decay process.
- The fit fractions of $\boldsymbol{Z_{cs}}^+$ in different three-body decay process of $\boldsymbol{B}^+$ meson are predicted.
- **We propose to search $Z_{cs}{}^+$ in the process $B^+ \to J/\psi K^+\eta'$.**

Thanks!