The charmonium-like states X(4140) and X(4160)

王恩 郑州大学

合作者：耿立升，谢聚军，李德民，E.Oset，郝伟，刘文颖

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EPJC80(2020)626, CPC43(2019)113101,
RPD97(2018)014017,103(2021)034019

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

$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$	$2.0 \pm 0.5\,^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+18}_{-110}$	$174 \pm 27\,^{+134}_{-73}$	$2.6 \pm 0.5\,^{+2.9}_{-1.5}$
All $X(0^+)$				$20 \pm 5\,^{+14}_{-7}$
$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6\,^{+10}_{-8}$	$5.6 \pm 0.7\,^{+2.4}_{-0.6}$
$X(4700)$	17 (18)	$4694 \pm 4\,^{+16}_{-3}$	$87 \pm 8\,^{+16}_{-6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
$\mathrm{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8\,^{+19}_{-11}$
All $X(1^+)$				$26 \pm 3\,^{+8}_{-10}$
$X(4140)$	13 (16)	$4118 \pm 11\,^{+19}_{-36}$	$162 \pm 21\,^{+24}_{-49}$	$17 \pm 3\,^{+19}_{-6}$
$X(4274)$	18 (18)	$4294 \pm 4\,^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5\,^{+0.8}_{-0.4}$
$X(4685)$	15 (15)	$4684 \pm 7\,^{+13}_{-16}$	$126 \pm 15\,^{+37}_{-41}$	$7.2 \pm 1.0\,^{+4.0}_{-2.0}$
All $Z_{cs}(1^+)$				$25 \pm 5\,^{+11}_{-12}$
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6\,^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-7}$

LHCb:2103.01803

X.~D.~Yang, F.~L.~Wang, Z.~W.~Liu and X.~Liu, arXiv:2103.03127

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reported four X states are confirmed with high significance. A 1^+ assignment is favoured for the new $X(4685)$ state with also high significance, but the quantum numbers of the $X(4150)$ and $X(4630)$ are less well determined. The best hypothesis for the $X(4630)$ state is 1^- over 2^- at a 3σ level. The other hypotheses are ruled out by more than 5σ. The fit prefers 2^- for the $X(4150)$ state by more than 4σ. The narrower $Z_{cs}(4000)^+$ state is determined to be 1^+ with high significance. The broader $Z_{cs}(4220)^+$ state could be 1^+ or

X.~D.~Yang, F.~L.~Wang, Z.~W.~Liu and X.~Liu, arXiv:2103.03127

X(4140)

- **LHCb2021:** $4118 \pm 11 {}^{+19}_{-36}$ $162 \pm 21 {}^{+24}_{-49}$

EWang,EPJC80(2020)626

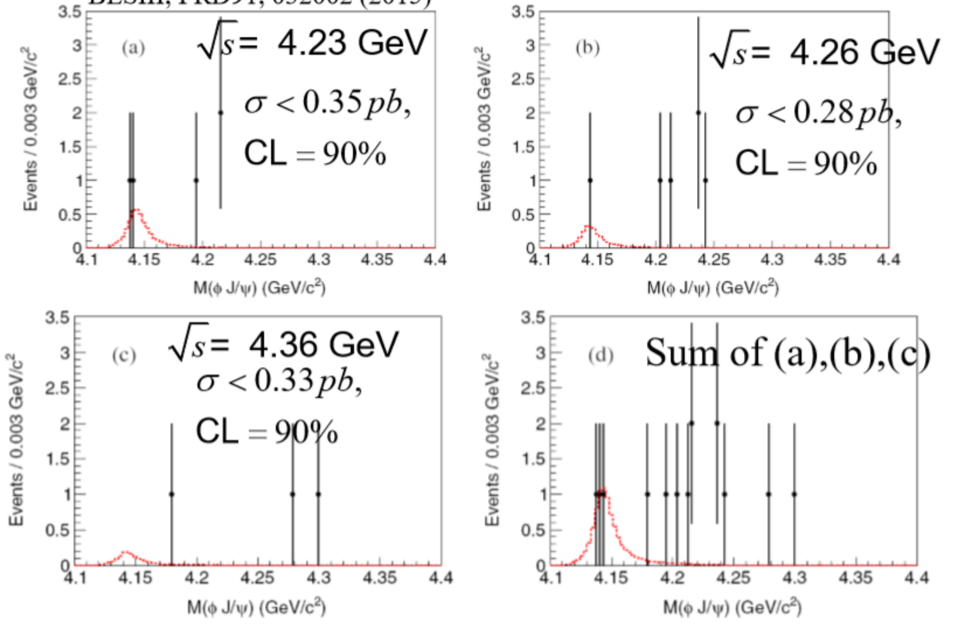
Exp.	Mass	Width	Sig.	Year
CDF [7]	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$	3.8σ	2009
CMS [8]	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$	5.0σ	2014
D0 [9]	$4159.0 \pm 4.3 \pm 6.6$	$20 \pm 13^{+3}_{-8}$	3.0σ	2014
D0 [10]	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$	4.7σ	2015
CDF [11]	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$	5.0σ	2011
LHCb [17]	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	8.4σ	2017
PDG [2]	4146.8 ± 2.4	22^{+8}_{-7}		2019

X(4140) width reported by LHCb is substantially larger than previously determined

Search for X(4140) in BESIII

Search for the Y(4140) via $e^+e^- \to \gamma\phi J/\psi$ at $\sqrt{s}=$ 4.23, 4.26 and 4.36 Ge

BESIII, PRD91, 032002 (2015)

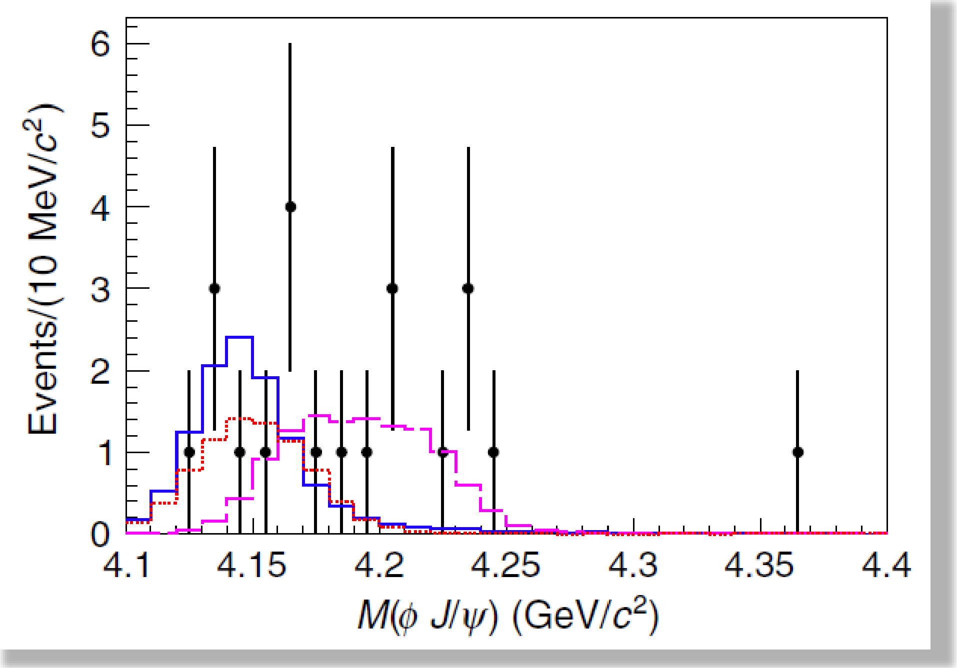


$$\frac{\sigma(e^+e^- \to \gamma Y(4140))}{\sigma(e^+e^- \to \gamma X(3872))} \sim 0.1 \text{ at } \sqrt{s} = 4.23, 4.26 \text{ GeV}$$

13

Observation of $e^+e^- \to \phi\chi_{c1}$ and $\phi\chi_{c2}$ at $\sqrt{s} = 4.600$ GeV

M. Ablikim *et al.* (BESIII Collaboration)
Phys. Rev. D **97**, 032008 – Published 12 February 2018



X(4140): $\chi_{c1}(3P)$ or tetraquark

Eur. Phys. J. C (2020) 80:626
https://doi.org/10.1140/epjc/s10052-020-8187-0

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Canonical interpretation of the $X(4140)$ state within the $^3P_0$ model

Wei Hao, Guan-Ying Wang, En Wang[a], Guan-Nan Li, De-Min Li

School of Physics and Microelectronics, Zhengzhou University, Zhengzhou 450001, Henan, China

and $\chi_{c2}(3P)$. Our results show that the $X(4140)$ state with the small width given in PDG can be explained as the charmonium state $\chi_{c1}(3P)$ in the $^3P_0$ model, and high precision measurement of the width of the $X(4140)$ is crucial to understand its nature.

Eur. Phys. J. C (2016) 76:671
DOI 10.1140/epjc/s10052-016-4531-9

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Where are $\chi_{cJ}(3P)$?

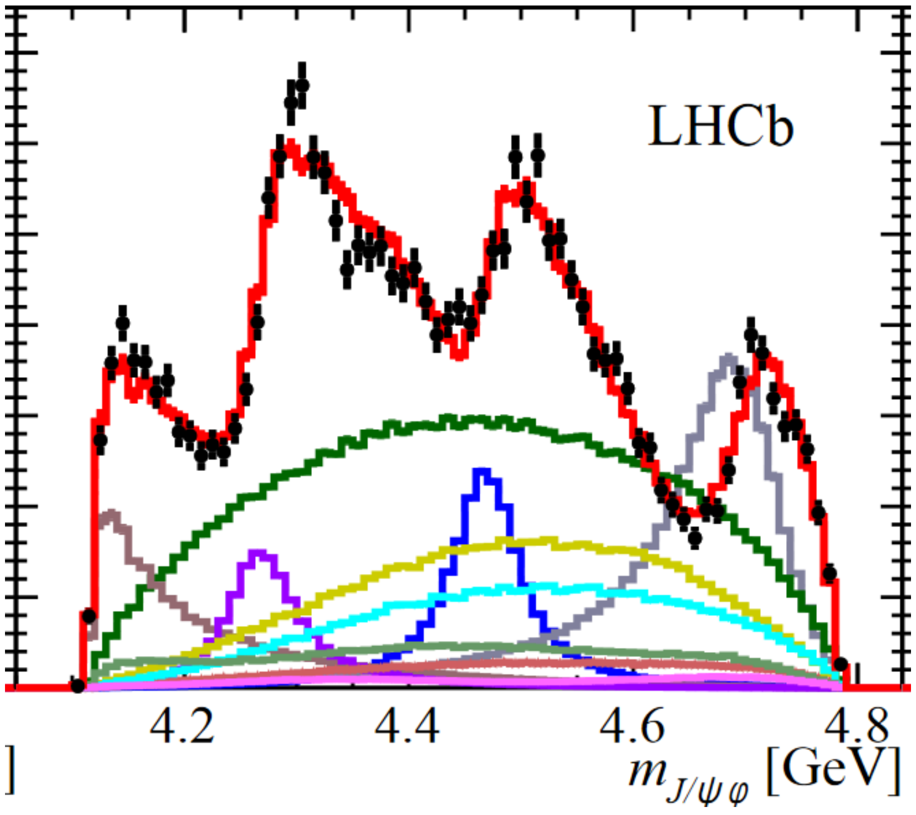
Dian-Yong Chen[a]

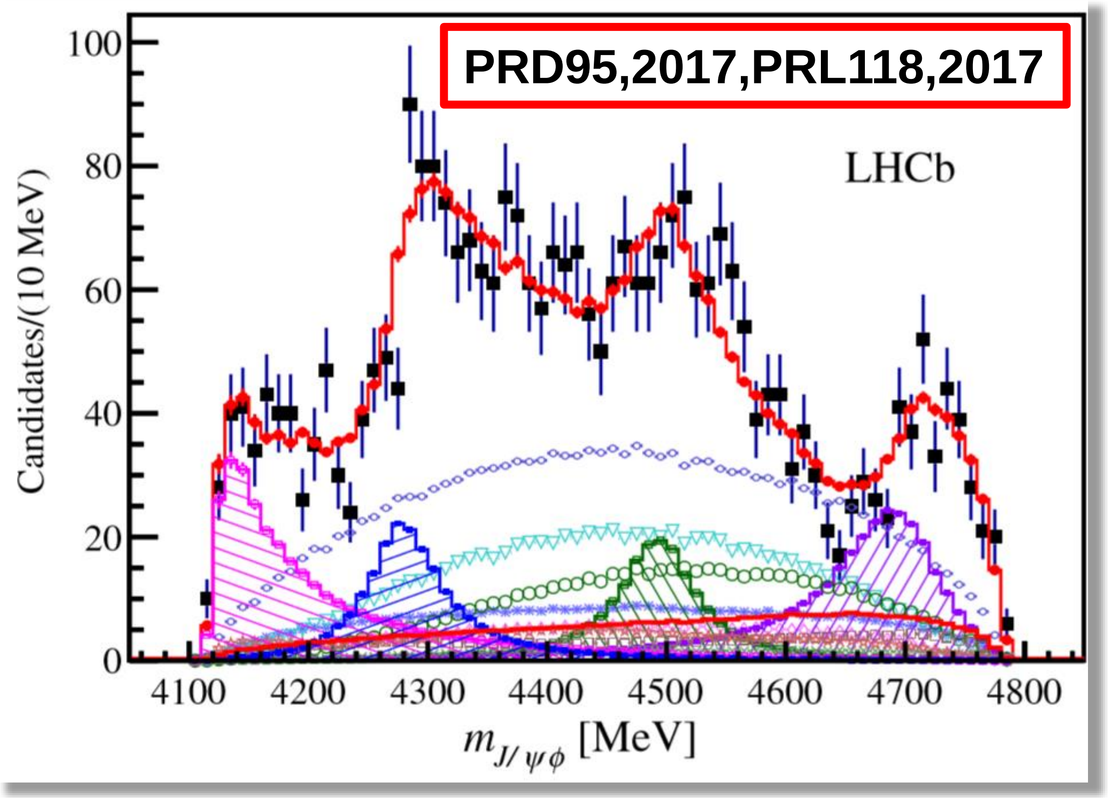
Department of Physics, Southeast University, Nanjing 210094, People's Republic of China

$$\Gamma(X(4140) \to J/\psi\phi) = 86.9 \pm 22.6\,\mathrm{MeV}$$

- *ZGWang, Eur.Phys.J.C* 79 (2019) 1, 72
- $80 \pm 29 MeV$,*Agaev,Phys.Rev.D* 95 (2017)114003
- *Tetraquark, JingWu, Phys.Rev.D* 94 (2016) 094031
- *HXChen, Eur.Phys.J.C* 77 (2017)160
- *Diquark-antidiquark, Turkan, Nucl.Phys.A* 985 (2019) 38
- $D_s^* D_s$ *cusp effect, XHLiu, Phys.Lett.B* 766 (2017) 117

LHCb $J/\psi\phi$: 2021 & 2017





X(4150) & X(4160)

- **X(4150):**

$X(2^-)$			
$X(4150)$	$4.8\ (8.7)$	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$

- **X(4160)**

$c\bar{c}$ MESONS
(including possibly non-$q\bar{q}$ states)

$\boldsymbol{X}(4160)$ $I^G(J^{PC}) = ?^?(?^{??})$

Seen by PAKHLOV 2008 in $e^+ e^- \to J/\psi X$, $X \to D^* \overline{D}^*$

$X(4160)$ MASS	4156^{+29}_{-25} MeV
$X(4160)$ WIDTH	139^{+110}_{-60} MeV

$D_s^*\bar{D}_s^*$ molecule

PHYSICAL REVIEW D **80,** 114013 (2009)

$Y(3940)$, $Z(3930)$, and the $X(4160)$ as dynamically generated resonances from the vector-vector interaction

R. Molina[1] and E. Oset[1]

[1]*Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Apartado 22085, 46071 Valencia, Spain*

(Received 24 July 2009; revised manuscript received 28 October 2009; published 15 December 2009)

- **Vector-vector exchange within local hidden gauge approach**

$D^*\bar{D}^*(4017)$, $D_s^*\bar{D}_s^*(4225)$, $K^*\bar{K}^*(1783)$, $\rho\rho(1551)$, $\omega\omega(1565)$,

$\phi\phi(2039)$, $J/\psi J/\psi(6194)$, $\omega J/\psi(3880)$, $\phi J/\psi(4116)$, $\omega\phi(1802)$,

TABLE V. Couplings g_i in units of MeV for $I = 0$, $J = 2$ (second pole).

$\sqrt{s_{\rm pole}} = 4169 + i66$, $I^G[J^{PC}] = 0^+[2^{++}]$				
$D^*\bar{D}^*$	$D_s^*\bar{D}_s^*$	$K^*\bar{K}^*$	$\rho\rho$	$\omega\omega$
$1225 - i490$	$18\,927 - i5524$	$-82 + i30$	$70 + i20$	$3 - i2441$
$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$1257 + i2866$	$2681 + i940$	$-866 + i2752$	$-2617 - i5151$	$1012 + i1522$

$D_s^* \bar{D}_s^*$ molecule

PHYSICAL REVIEW D **80**, 114013 (2009)

$Y(3940)$, $Z(3930)$, and the $X(4160)$ as dynamically generated resonances from the vector-vector interaction

$X(4160)$ $\quad I^G(J^{PC}) = ?^?(?^{??})$

Seen by PAKHLOV 2008 in $e^+ e^- \to J/\psi X$, $X \to D^* \bar{D}^*$

(Re

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- **Vector-**

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$\phi J/\psi(4116)$, $\omega\phi(1802)$,

pole).

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$D_s^* \bar{D}_s^*$ molecule, X(4160)

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Nuclear Physics A 966 (2017) 135–157

NUCLEAR PHYSICS A

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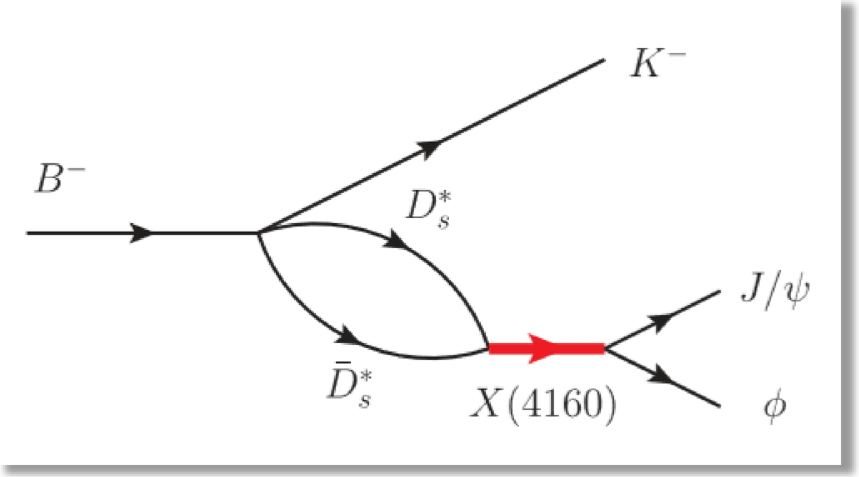
Understanding close-lying exotic charmonia states within QCD sum rules

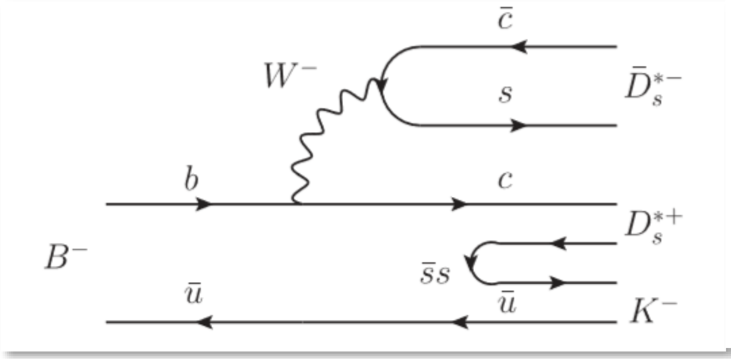
A. Martínez Torres [a], K.P. Khemchandani [b,c,*], J.M. Dias [a], F.S. Navarra [a], M. Nielsen [a]

The comparison made above hints a possible $D_s^* \bar{D}_s^*$ molecule-like nature with quantum numbers $J^{PC} = 2^{++}$ for $X(4160)$. However, our work also implies the existence of a $J^{PC} = 0^{++}$

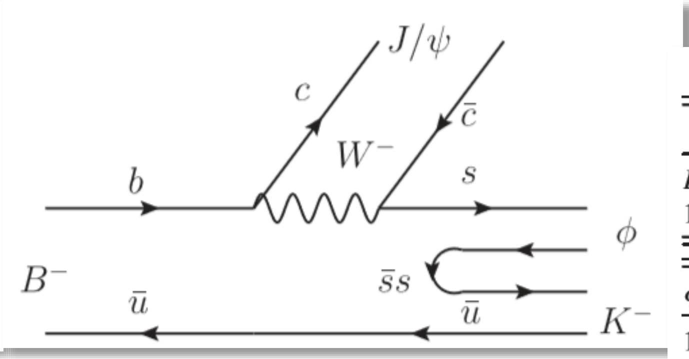
The reaction of $B^- \to J/\psi\,\phi K^-$



- The internal conversion is suppressed by **color factors** with respect to the external emission.
- The mechanism with the J/ψϕ intermediate state instead of $D_s^*\bar{D}_s^*$ would involve the extra factor $g_{J/\psi\phi}/g_{D_s^*\bar{D}_s^*}$, and can be safely neglected.



External emission



Internal conversion

TABLE V. Couplings g_i in units of MeV for $I = 0$, $J = 2$ (second pole).

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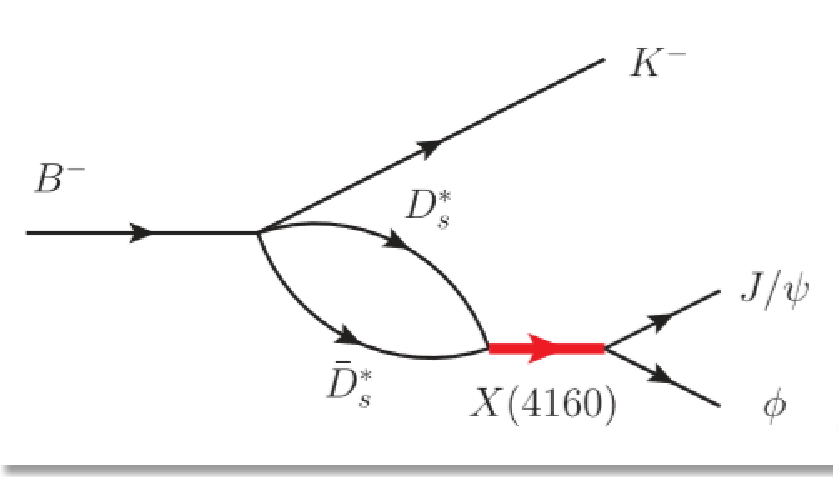
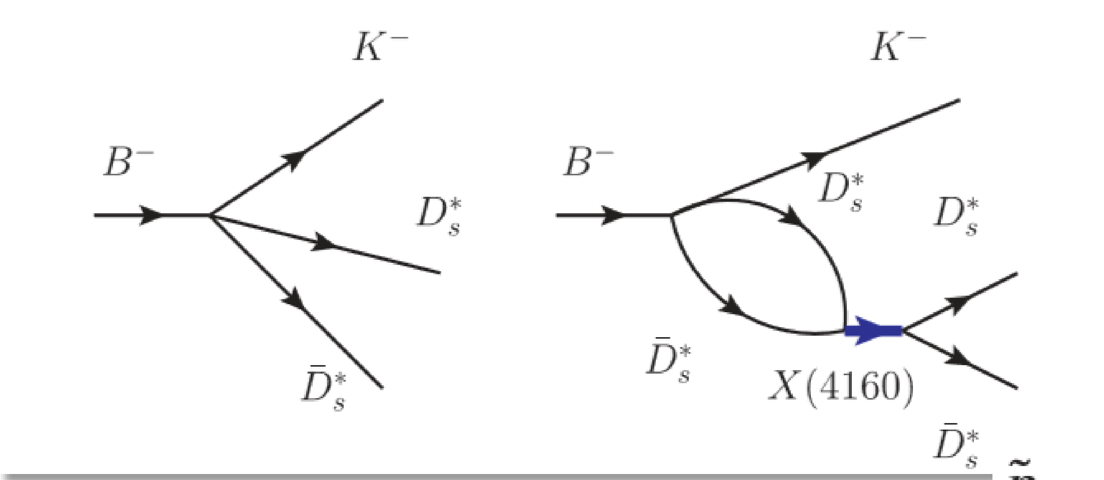
The reaction of $B^- \to J/\psi\,\phi K^-$



The X(4160) is JPC=2⁺⁺ state with L=0 in $D_s^*\bar{D}_s^*$. We need a D-wave in the K- to match the angular momentum in the reaction.

$$t^{\text{tree}}_{B^-\to K^- D_s^* \bar{D}_s^*} = A\left(\vec{\epsilon}\cdot\vec{k}\vec{\epsilon}\,'\cdot\vec{k} - \frac{1}{3}\vec{k}^2\vec{\epsilon}\cdot\vec{\epsilon}\,'\right),$$

The sum over polarizations of $|t|^2$ is



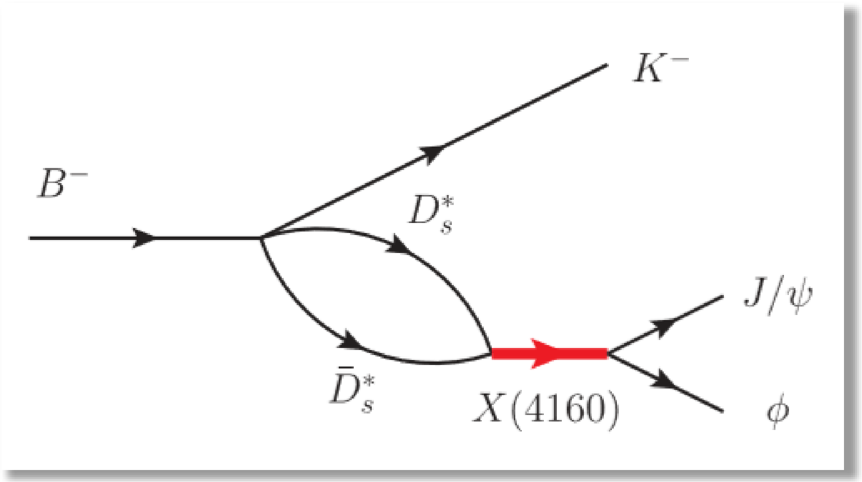
$$\sum_{\text{pol}} |t^{\text{tree}}_{B^-\to K^- D_s^* \bar{D}_s^*}|^2 = \frac{2}{3}|\vec{k}|^4,$$

$$\frac{d\Gamma}{dM_{\text{inv}}(D_s^*\bar{D}_s^*)} = \frac{1}{(2\pi)^3}\frac{1}{4M_{B^-}^2}\frac{2}{3}|\vec{k}|^4|\vec{k}\,'|\tilde{p}_{D_s^*}|A|^2$$

$\vec{k}\,'$ the K^- momentum in the B^- rest frame

$\tilde{p}_{D_s^*}$ the D_s^* momentum in the $D_s^*\bar{D}_s^*$ rest frame.

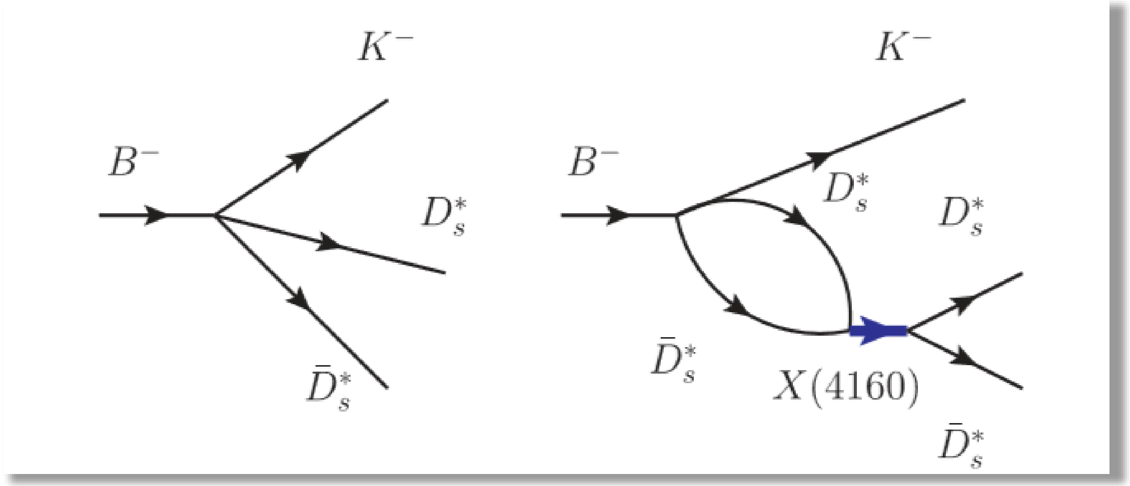
The reaction of $B^- \to J/\psi\,\phi K^-$



$$\frac{d\Gamma}{dM_{\rm inv}(D_s^*\bar{D}_s^*)} = \frac{1}{(2\pi)^3}\frac{1}{4M_{B^-}^2}\frac{2}{3}|\vec{k}|^4|\vec{k}'||\tilde{p}_{D_s^*}||A|^2,$$

For the mass distribution of J/ψϕ

$$A \to A \times G_{D_s^*\bar{D}_s^*}(M_{\rm inv}(J/\psi\phi)) \times t_{D_s^*\bar{D}_s^* \to J/\psi\phi}(M_{\rm inv}(J/\psi\phi)),$$



For the mass distribution of $D_s^*\bar{D}_s^*$

$$A \to A[1 + G_{D_s^*\bar{D}_s^*}(M_{\rm inv}(D_s^*\bar{D}_s^*)) \times t_{D_s^*\bar{D}_s^* \to D_s^*\bar{D}_s^*}(M_{\rm inv}(D_s^*\bar{D}_s^*))].$$

The contribution of X(4160)

- **G is the loop function, with the cut off method,**

$$G_l = \int \frac{d^3q}{(2\pi)^3} \frac{M_l}{2\omega_l(q)E_l(q)} \frac{1}{k^0 + p^0 - q^0 - E_l(q) + i\epsilon}$$

$D^*\bar{D}^*(4017)$, $D_s^*\bar{D}_s^*(4225)$, $K^*\bar{K}^*(1783)$, $\rho\rho(1551)$, $\omega\omega(1565)$,

$\phi\phi(2039)$, $J/\psi J/\psi(6194)$, $\omega J/\psi(3880)$, $\phi J/\psi(4116)$, $\omega\phi(1802)$,

- **The transition amplitudes are,**

$$t_{D_s^*\bar{D}_s^* \to D_s^*\bar{D}_s^*} = \frac{g^2_{D_s^*\bar{D}_s^*}}{M^2_{\text{inv}}(D_s^*\bar{D}_s^*) - M_X^2 + iM_X\Gamma_X},$$

$$t_{D_s^*\bar{D}_s^* \to J/\psi\phi} = \frac{g_{D_s^*\bar{D}_s^*}\, g_{J/\psi\phi}}{M^2_{\text{inv}}(J/\psi\phi) - M_X^2 + iM_X\Gamma_X},$$

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The contribution of X(4140)

- **Since X(4140) is 1^{++}, the kaon should be in P-wave, and the operator for P-wave is,**

$$(\vec{\epsilon}_{J/\psi} \times \vec{\epsilon}_{\phi}) \cdot \vec{k}, \quad \Longleftrightarrow \quad t^{\text{tree}}_{B^- \to K^- D_s^* \bar{D}_s^*} = A\left(\vec{\epsilon} \cdot \vec{k} \vec{\epsilon}' \cdot \vec{k} - \frac{1}{3} \vec{k}^2 \vec{\epsilon} \cdot \vec{\epsilon}'\right),$$

$$\frac{d\Gamma}{dM_{\text{inv}}(D_s^* \bar{D}_s^*)} = \frac{1}{(2\pi)^3} \frac{1}{4M_{B^-}^2} \frac{2}{3} |\vec{k}|^4 |\vec{k}'| \tilde{p}_{D_s^*} |A|^2,$$

The substitution:

$$M_{\text{inv}}(D_s^* \bar{D}_s^*) \to M_{\text{inv}}(J/\psi \phi), \qquad \frac{2}{3} |\vec{k}|^4 \to 2|\vec{k}|^2, \qquad \tilde{p}_{D_s^*} \to \tilde{p}_{\phi},$$

$$A \to \frac{B M^4_{X(4140)}}{M^2_{\text{inv}}(J/\psi \phi) - M^2_{X(4140)} + i M_{X(4140)} \Gamma_{X(4140)}}$$

with B a parameter to be fitted to the data.

$$M_{X(4140)} = 4132 \text{ MeV},$$

Results

- **We fit the data from threshold up to about 4250 MeV.**
- **13 data, chi^2/dof=15.3/(13-3)**

$$\Gamma_0 = 65.0 \pm 7.1 \text{ MeV} \quad (\text{at } 68\% \text{ confidence level}),$$

$$\Gamma_{J/\psi\phi} \simeq 22.0 \text{ MeV}$$

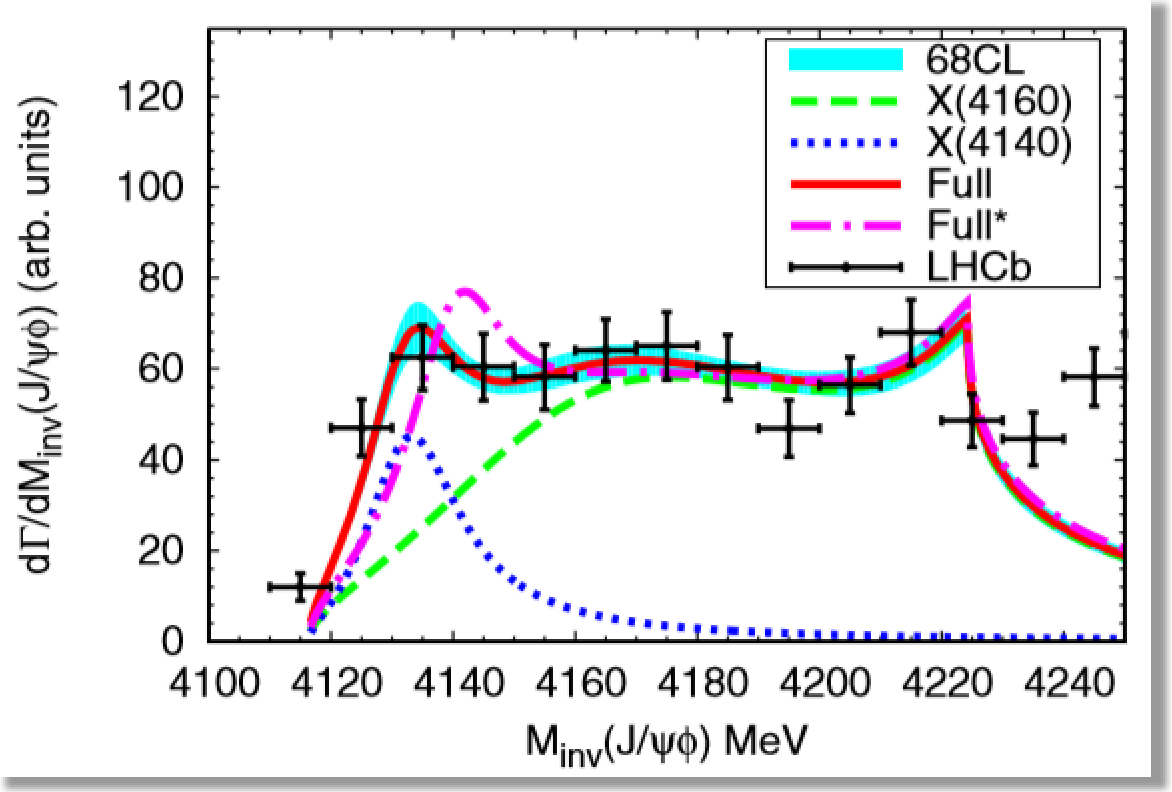
$$\Gamma_{X(4160)} \simeq 87.0 \pm 7.1 \text{ MeV}$$

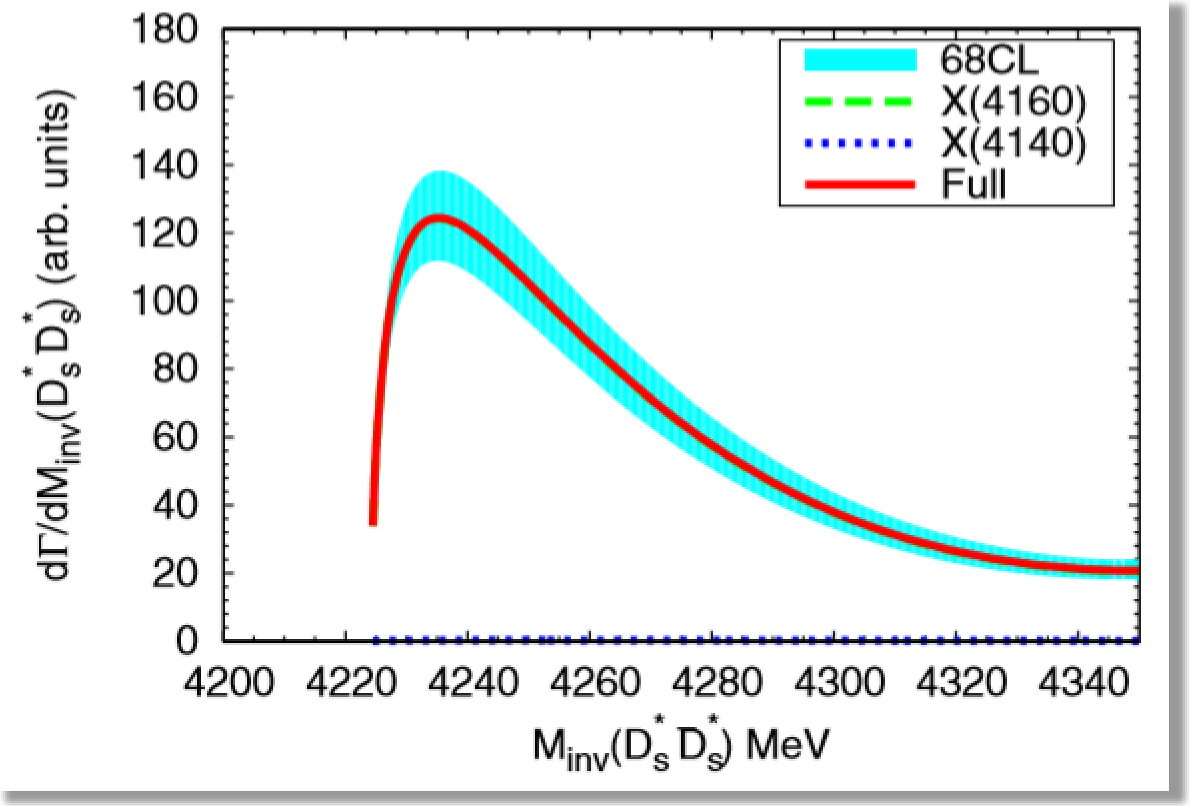
$X(4160)$ $I^G(J^{PC}) = ?^?(?^{??})$

Seen by PAKHLOV 2008 in $e^+ e^- \to J/\psi X$, $X \to D^* \overline{D}^*$

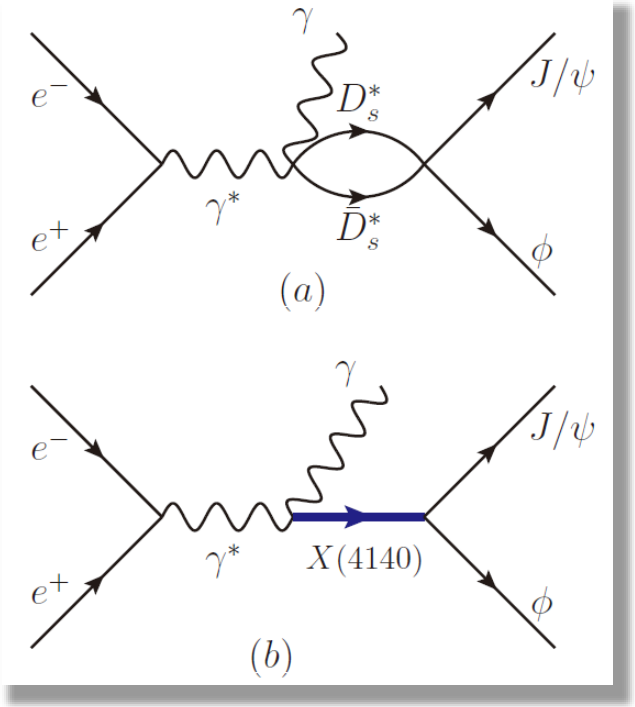
$X(4160)$ MASS	4156^{+29}_{-25} MeV
$X(4160)$ WIDTH	139^{+110}_{-60} MeV

Results


68CL
X(4160)
X(4140)
Full
Full*
LHCb
dΓ/dM_inv(J/ψφ) (arb. units)
M_inv(J/ψφ) MeV
0
20
40
60
80
100
120
4100
4120
4140
4160
4180
4200
4220
4240


68CL
X(4160)
X(4140)
Full
dΓ/dM_inv(D*_s D*_s) (arb. units)
M_inv(D*_s D*_s) MeV
0
20
40
60
80
100
120
140
160
180
4200
4220
4240
4260
4280
4300
4320
4340

$e^+e^- \to \gamma J/\psi\phi$



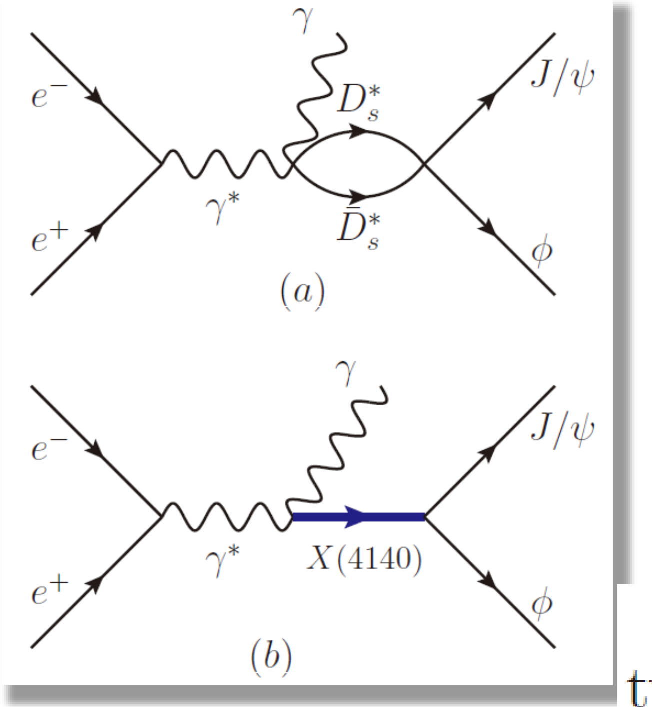
$$\tilde{\mathcal{M}}^{(a)}_{J/\psi\phi} = A \times G_{D_s^*\bar{D}_s^*} t_{D_s^*\bar{D}_s^*, J/\psi\phi} \times \mathcal{P}^{(a)}$$
$$= \mathcal{M}^{(a)}_{J/\psi\phi} \times \mathcal{P}^{(a)},$$

$$\mathcal{P}^{(a)} = \left[\frac{1}{2}\left(\epsilon_{1i}\epsilon_{2j} + \epsilon_{1j}\epsilon_{2i}\right) - \frac{1}{3}\vec{\epsilon}_1 \cdot \vec{\epsilon}_2 \delta_{ij}\right]$$
$$\times \left[\frac{1}{2}\left(\epsilon_{\phi i}\epsilon_{J/\psi j} + \epsilon_{\phi j}\epsilon_{J/\psi i}\right) - \frac{1}{3}\vec{\epsilon}_\phi \cdot \vec{\epsilon}_{J/\psi}\delta_{ij}\right]$$

$$t_{D_s^*\bar{D}_s^*, J/\psi\phi} = \frac{g_{D_s^*\bar{D}_s^*} g_{J/\psi\phi}}{M^2_{\text{inv}}(J/\psi\phi) - M^2_{X_1} + i\Gamma_{X_1} M_{X_1}},$$

$$g_{D_s^*\bar{D}_s^*} = (18927 - 5524i)\ \text{MeV}$$
$$g_{J/\psi\phi} = (-2617 - 5151i)\ \text{MeV}$$

$e^+e^- \to \gamma J/\psi\phi$



$$\tilde{\mathcal{M}}^{(b)}_{J/\psi\phi} = \frac{BM^2_{X_2} \times \mathcal{P}^{(b)}}{M^2_{\rm inv}(J/\psi\phi) - M^2_{X_2} + iM_{X_2}\Gamma_{X_2}}$$

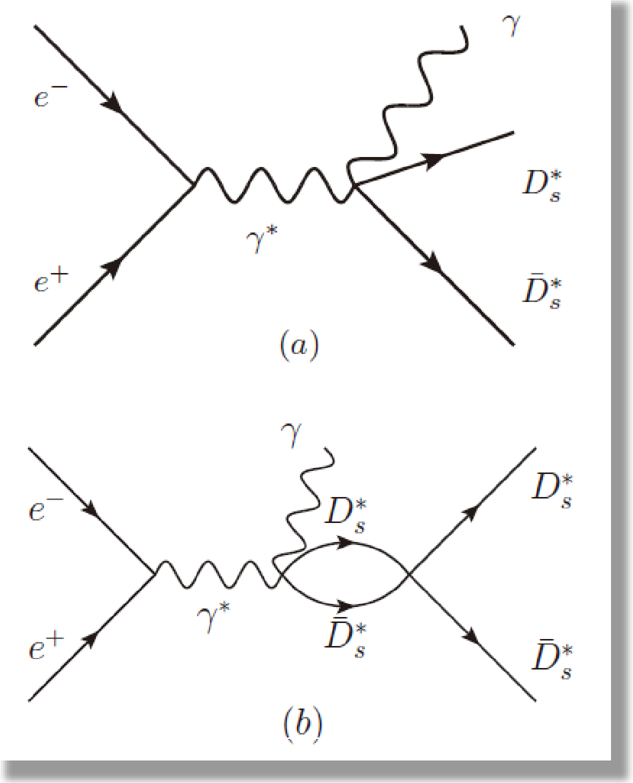
$$= \mathcal{M}^{(b)}_{J/\psi\phi} \times \mathcal{P}^{(b)},$$

$$\mathcal{P}^{(b)} = \sum_{\rm pol} [(\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot \vec{\epsilon}_{X_2}] \, [\vec{\epsilon}_{X_2} \cdot (\vec{\epsilon}_\phi \times \vec{\epsilon}_{J/\psi})]$$

$$= (\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot (\vec{\epsilon}_\phi \times \vec{\epsilon}_{J/\psi}) \, ,$$

In the present work, the only relevant thing is that the two structures $\mathcal{P}^{(a)}$ and $\mathcal{P}^{(b)}$ do not interfere, and there are no momenta involved, unlike in the decay $B^- \to J/\psi\phi K$ [4].

The mechanism for $D_s^*\bar{D}_s^*$ production

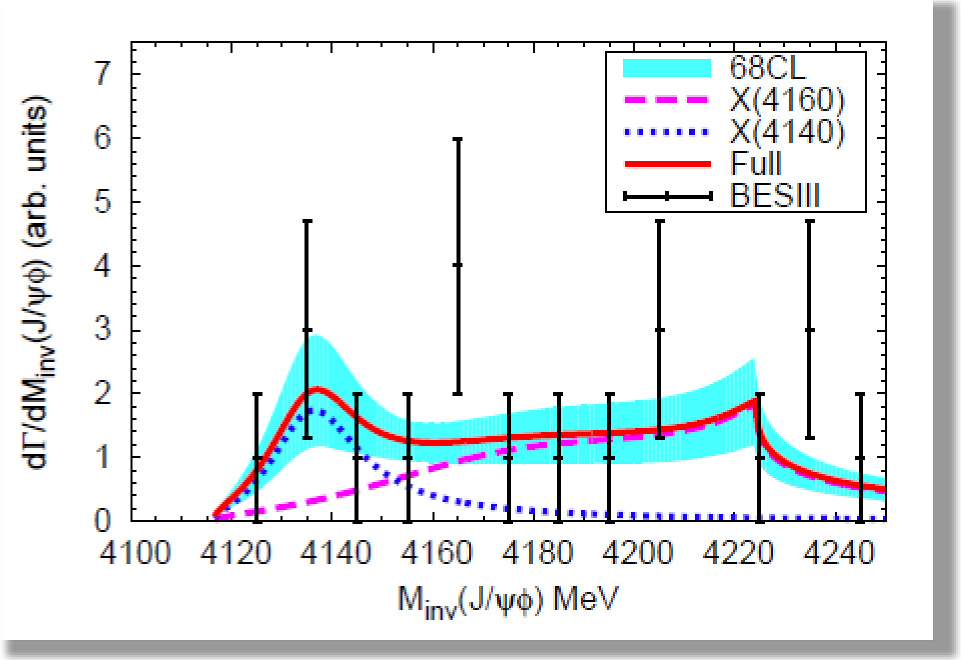


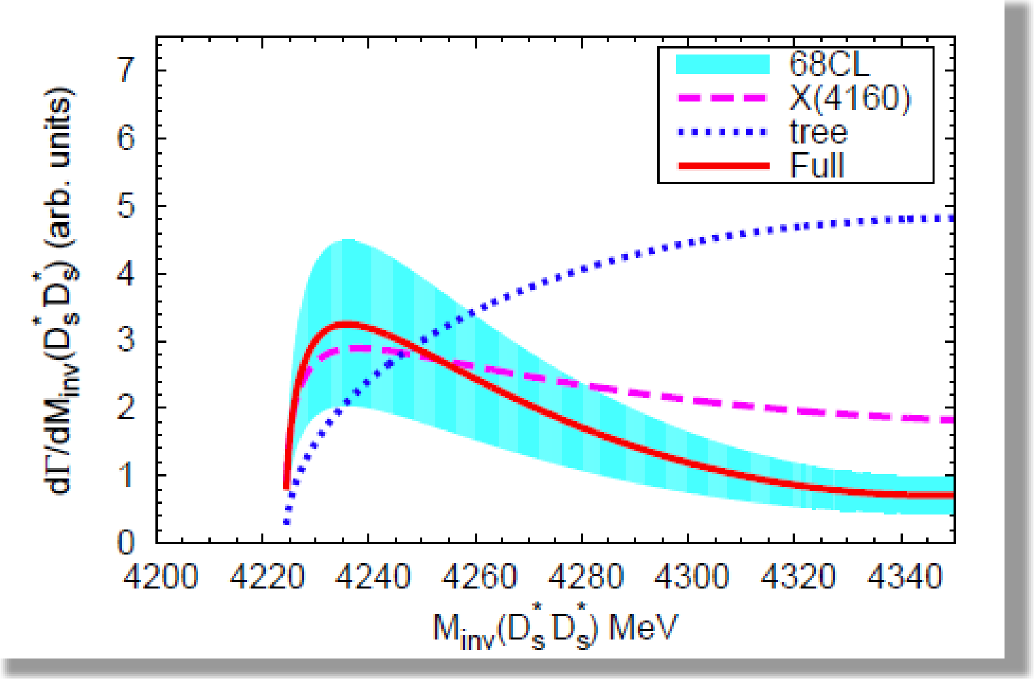
$$\frac{d\Gamma}{dM_{\rm inv}(D_s^*\bar{D}_s^*)} = \frac{1}{(2\pi)^3}\frac{1}{4s}k'\tilde{p}_{D_s^*}|\mathcal{M}_{D_s^*\bar{D}_s^*}|^2,$$

$$\begin{aligned}\mathcal{M}_{D_s^*\bar{D}_s^*} &= A\left[T^{\rm tree}+T^{X(4160)}\right]\\ &= A\Big[1+G_{D_s^*\bar{D}_s^*}\left(M_{\rm inv}(D_s^*\bar{D}_s^*)\right)\\ &\quad \times t_{D_s^*\bar{D}_s^*,D_s^*\bar{D}_s^*}\left(M_{\rm inv}(D_s^*\bar{D}_s^*)\right)\Big]\end{aligned}$$

$$t_{D_s^*\bar{D}_s^*,D_s^*\bar{D}_s^*} = \frac{g^2_{D_s^*\bar{D}_s^*}}{M^2_{\rm inv}(D_s^*\bar{D}_s^*)-M^2_{X_1}+i\Gamma_{X_1}M_{X_1}}$$

Results


68CL
X(4160)
X(4140)
Full
BESIII
dΓ/dM$_{inv}$(J/ψφ) (arb. units)
M$_{inv}$(J/ψφ) MeV


68CL
X(4160)
tree
Full
dΓ/dM$_{inv}$($D_s^* D_s^*$) (arb. units)
M$_{inv}$($D_s^* D_s^*$) MeV

$\Lambda_b \to J/\psi\Lambda\phi$

- **First observed by CMS** PLB802, 135203(2020)
- **$J/\psi\phi$ final state interaction, X(4140) &X(4160)**
- **$\Lambda\phi$ final state interactions, no information about Λ^***
- **$J/\psi\Lambda$ final state interaction, P_{cs}**

Recent results on exotic hadrons at LHCb

Mengzhen Wang
Center of High Energy Physics, Tsinghua University
(On behalf of the LHCb collaboration)

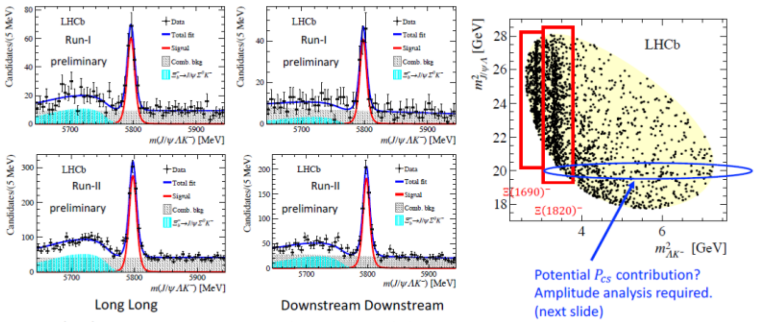
Implications of LHCb measurements and future prospects
28 Oct. – 30 Oct. 2020

10/29/20 Implications workshop 2020 1

LHCb-PAPER-2020-039 LHCb preliminary

The $\Xi_b^- \to J/\psi K^-\Lambda$ data sample

- Used to search for predicted $[uds c\bar{c}]$ pentaquark P_{cs} PRC93(2016)065203
- Run-I + Run-II data: $\sim$1750 signals, purity $\sim$80%



Potential P_{cs} contribution? Amplitude analysis required. (next slide)

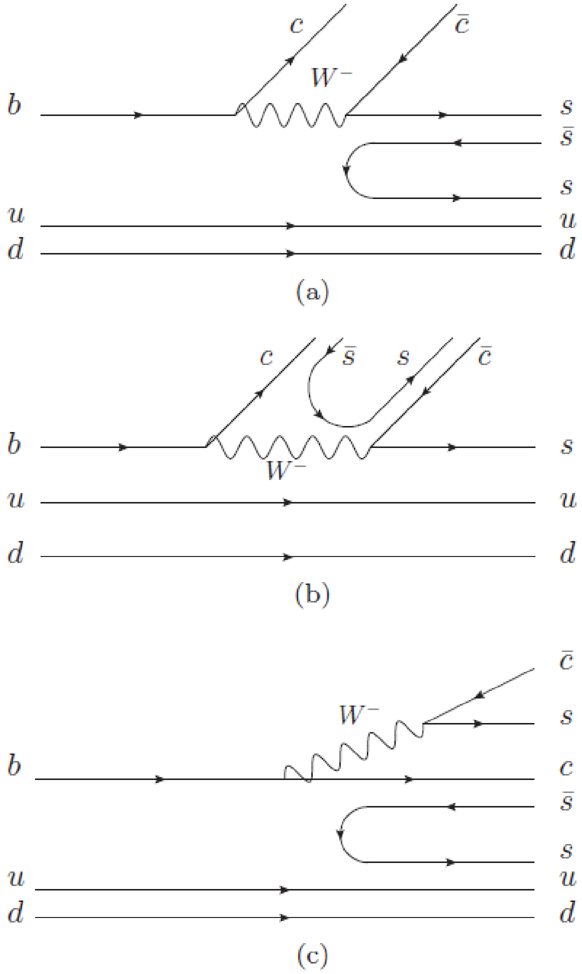
10/29/20 Implications workshop 2020 14

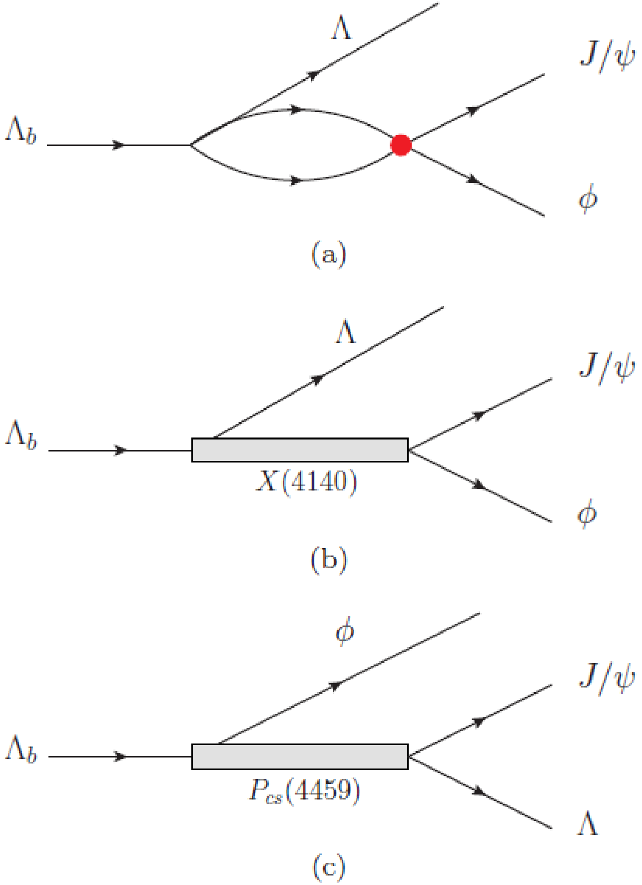
PHYSICAL REVIEW C
covering nuclear physics
Highlights Recent Accepted Authors Referees Search Press About Staff

Looking for a hidden-charm pentaquark state with strangeness $S=-1$ from Ξ_b^- decay into $J/\psi K^-\Lambda$

Hua-Xing Chen, Li-Sheng Geng, Wei-Hong Liang, Eulogio Oset, En Wang, and Ju-Jun Xie
Phys. Rev. C **93**, 065203 – Published 14 June 2016

The mechanism





$$\mathcal{M}^{P} = A\left(\vec{\epsilon}_{J/\psi} \times \vec{\epsilon}_{\phi}\right) \cdot \vec{k}\, G_{D_s^* \bar{D}_s^*}\, t_{D_s^* \bar{D}_s^* \to J/\psi \phi},$$

$$\mathcal{M}^{S} = B \times \frac{M^3_{X(4140)}\, \vec{\epsilon}_{J/\psi} \cdot \vec{\epsilon}_{\phi}}{M^2_{\mathrm{inv}} - M^2_{X(4140)} + i M_{X(4140)} \Gamma_{X(4140)}},$$

$$\mathcal{M}^{P_{cs}} = C \times \frac{M^3_{P_{cs}}\, \vec{\epsilon}_{J/\psi} \cdot \vec{\epsilon}_{\phi}}{M^2_{J/\psi\Lambda} - M^2_{P_{cs}} + i M_{P_{cs}} \Gamma_{P_{cs}}},$$

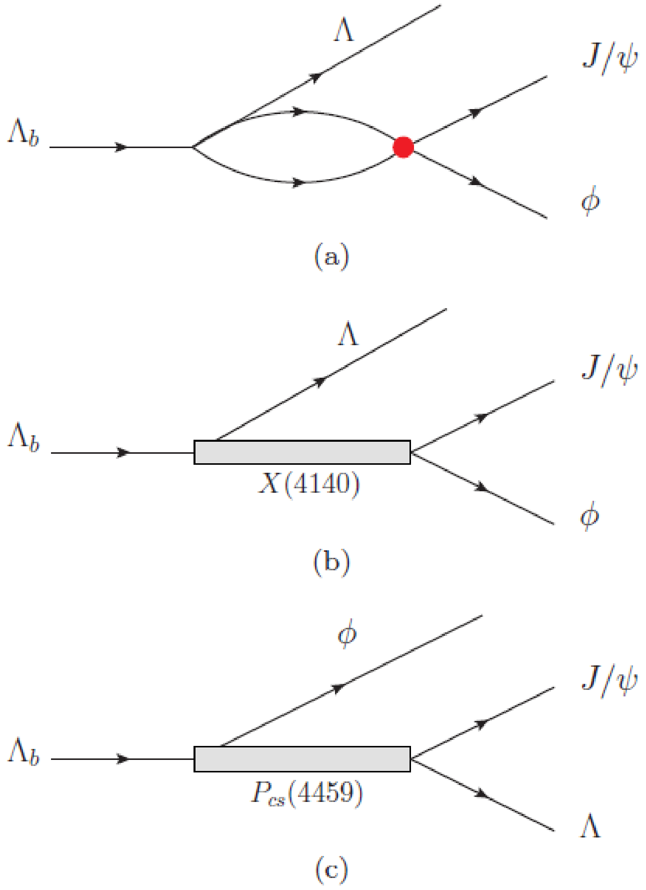
$$\frac{d^2\Gamma}{dM^2_{J/\psi\phi}dM^2_{J/\psi\Lambda}} = \frac{1}{(2\pi)^3}\frac{1}{32M^3_{\Lambda_b}}\sum|\mathcal{M}|^2,$$

$$\sum|\mathcal{M}|^2 = \sum\left(|\mathcal{M}^S|^2 + |\mathcal{M}^P|^2\right) \quad (17)$$

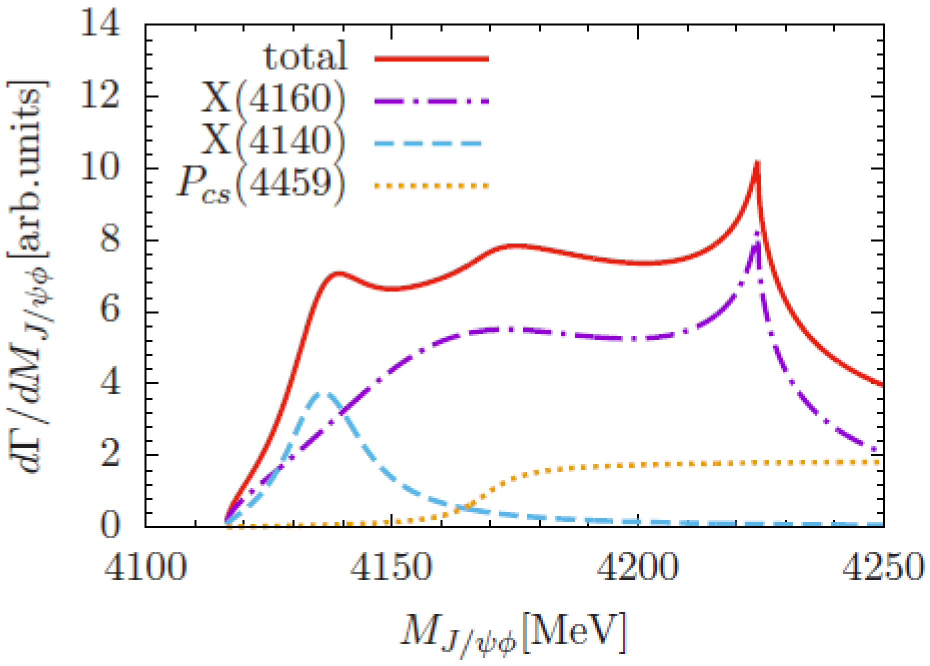
$$= B^2\left(3|\tilde{\mathcal{M}}^S|^2 + 2|\vec{k}|^2|\tilde{\mathcal{M}}^P|^2\right), \quad (18)$$

$$\tilde{\mathcal{M}}^P = \alpha G_{D_s^*\bar{D}_s^*}\, t_{D_s^*\bar{D}_s^*\to J/\psi\phi}, \quad (19)$$

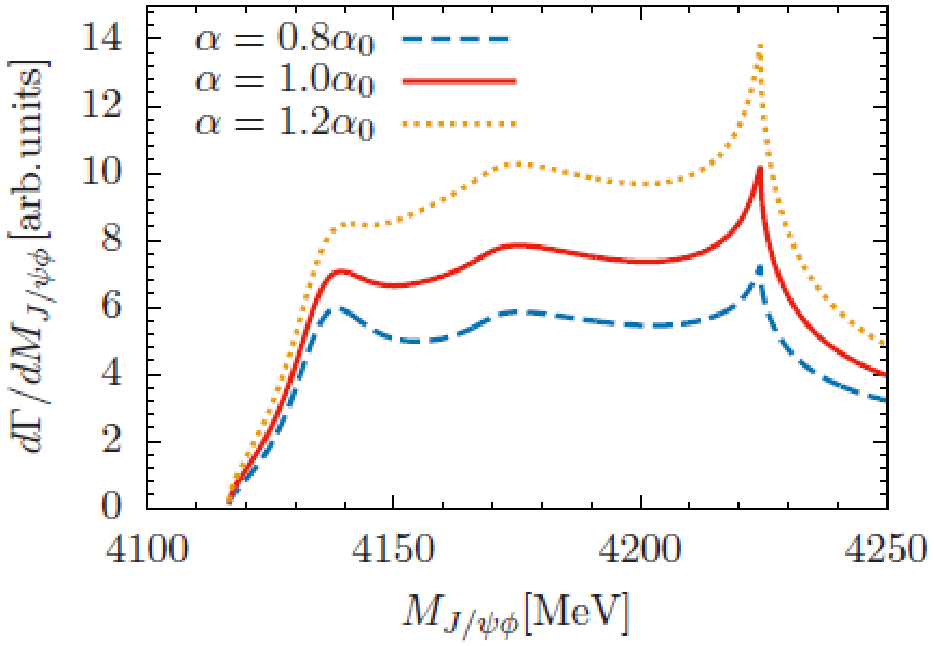
$$\tilde{\mathcal{M}}^S = \frac{M^3_{X(4140)}}{M^2_{J/\psi\phi} - M^2_{X(4140)} + iM_{X(4140)}\Gamma_{X(4140)}} + \frac{\beta M^3_{P_{cs}}}{M^2_{J/\psi\Lambda} - M^2_{P_{cs}} + iM_{P_{cs}}\Gamma_{P_{cs}}}, \quad (20)$$



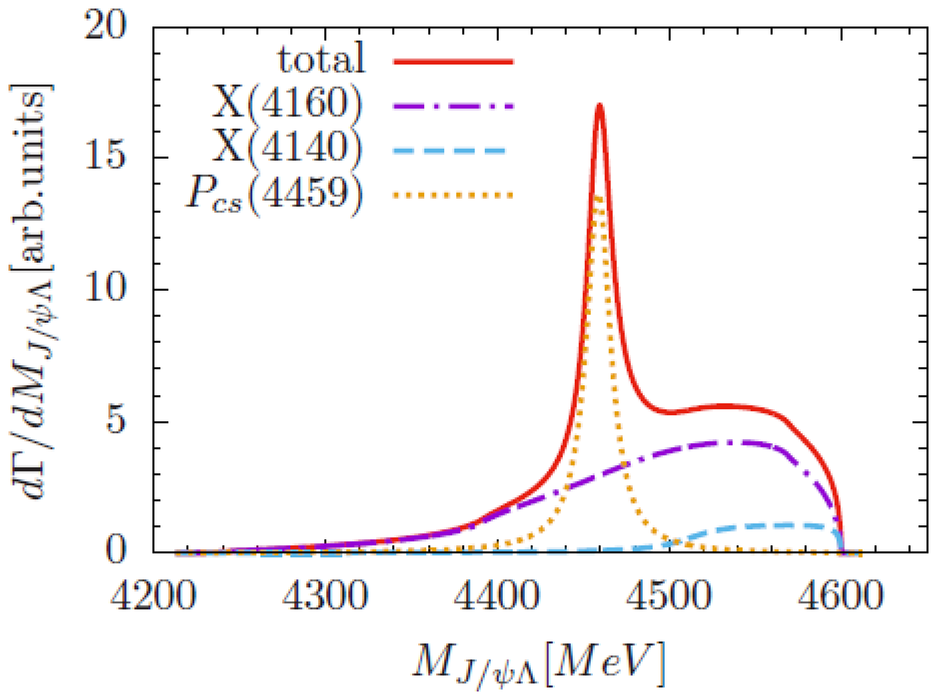
Results



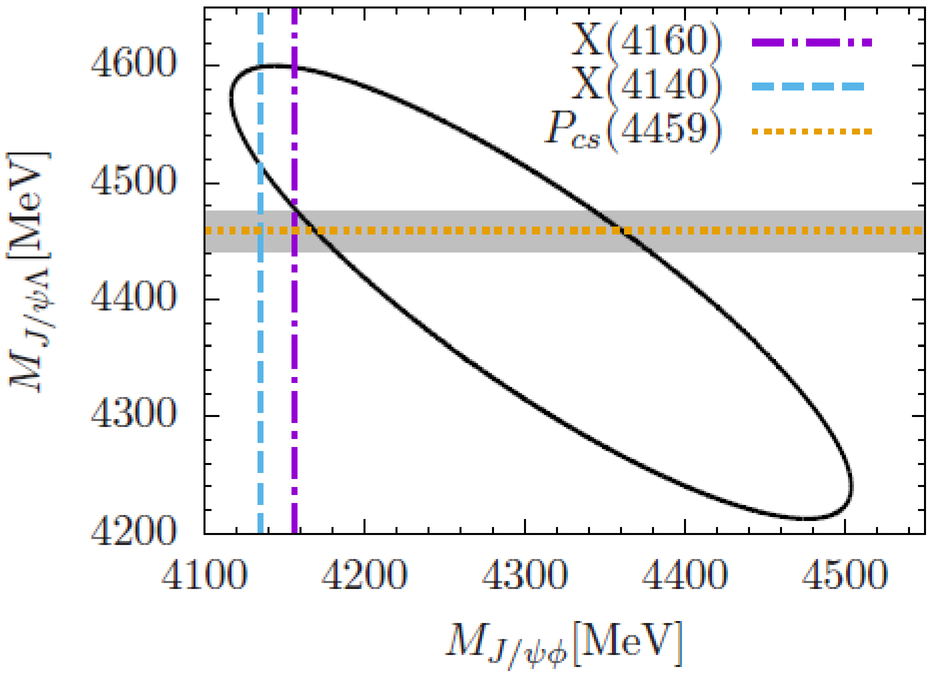
total
X(4160)
X(4140)
$P_{cs}(4459)$
$d\Gamma/dM_{J/\psi\phi}$[arb.units]
$M_{J/\psi\phi}$[MeV]



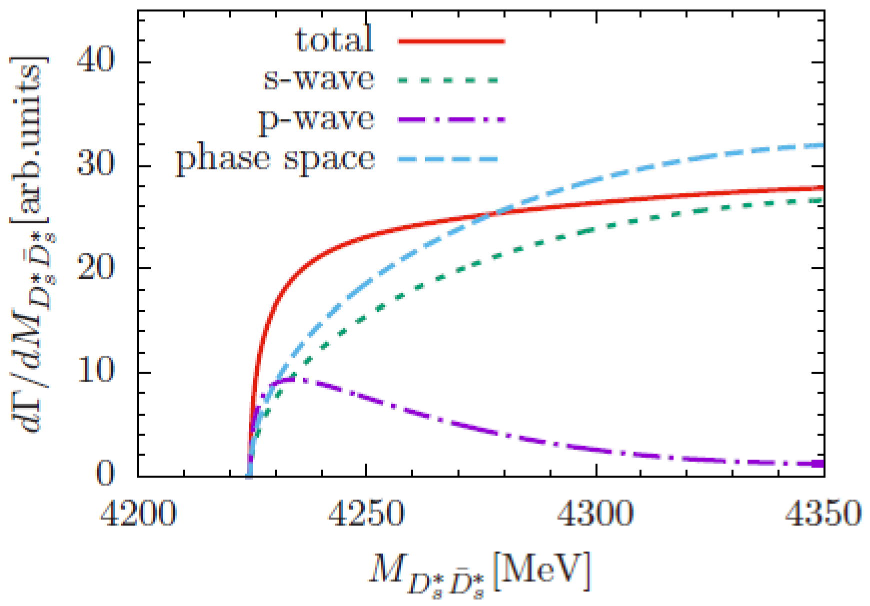
$\alpha = 0.8\alpha_0$
$\alpha = 1.0\alpha_0$
$\alpha = 1.2\alpha_0$
$d\Gamma/dM_{J/\psi\phi}$[arb.units]
$M_{J/\psi\phi}$[MeV]



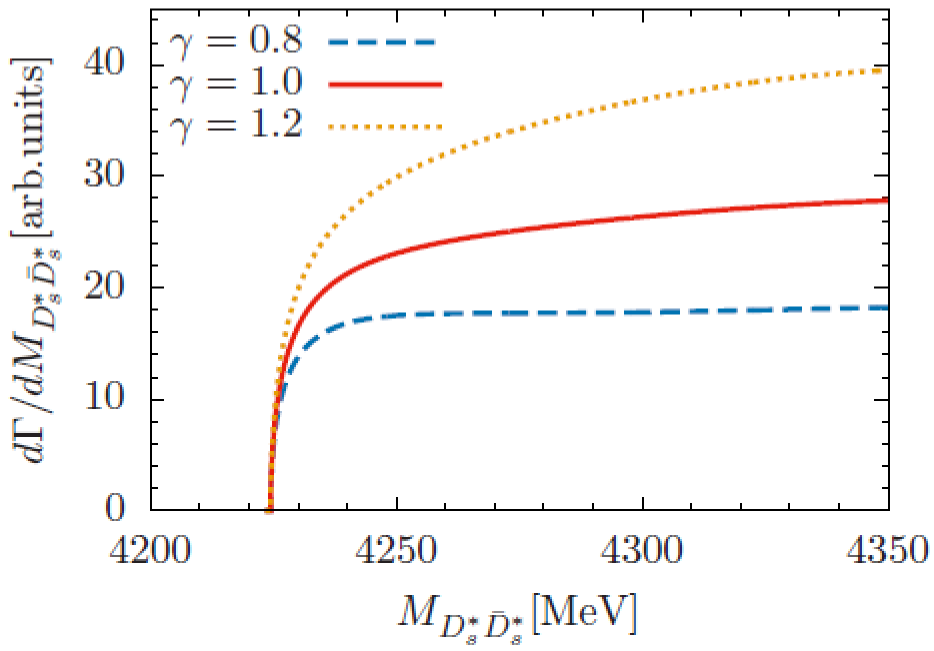
$d\Gamma/dM_{J/\psi\Lambda}$[arb.units]
total
X(4160)
X(4140)
$P_{cs}(4459)$
20
15
10
5
0
4200
4300
4400
4500
4600
$M_{J/\psi\Lambda}[MeV]$



$M_{J/\psi\Lambda}$[MeV]
X(4160)
X(4140)
$P_{cs}(4459)$
4600
4500
4400
4300
4200
4100
4200
4300
4400
4500
$M_{J/\psi\phi}$[MeV]



total
s-wave
p-wave
phase space
$d\Gamma/dM_{D_s^*\bar{D}_s^*}$[arb.units]
$M_{D_s^*\bar{D}_s^*}$[MeV]



$\gamma = 0.8$
$\gamma = 1.0$
$\gamma = 1.2$
$d\Gamma/dM_{D_s^*\bar{D}_s^*}$[arb.units]
$M_{D_s^*\bar{D}_s^*}$[MeV]

Summary

- The width of X(4140) is important.
- With a narrow X(4140) and the $D_s^* \bar{D}_s^*$ molecular state X(4160), we can provide an good explanation of the LHCb2017 measurements for $B^+ \to J/\psi \phi K^+$.
- Our model is also compatible with the BESIII measurements about $e^+ e^- \to \gamma J/\psi \phi$.
- The process $\Lambda_b \to J/\psi \Lambda \phi$ can be used to learn X(4140), X(4160), and the newly observed Pcs.

Thanks for your attention!