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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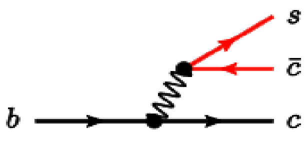
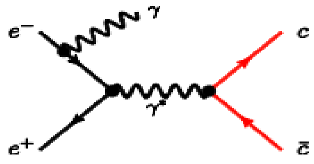
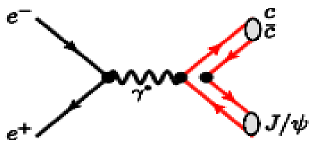
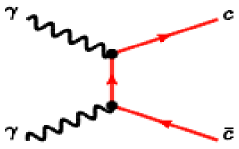
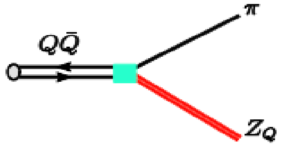
RPD97(2018)014017，arXiv:2012.01804

outline

- Motivation
- $B^+ \to J/\psi\phi K^+$
- $e^+e^- \to \gamma J/\psi\phi$
- $\Lambda_b \to J/\psi\Lambda\phi$
- Summary

Charmonium-like states

				
$X(3872)$	$Y(4008)$	$X(3940)$	$X(3915)$	$Z_c(3885)$
$Y(3940)$	$Y(4260)$	$X(4160)$	$Z(3930)$	$Z_c(3900)$
$Z^+(4430)$	$Y(4220)$		$X(4350)$	$Z_c(4020)$
$Z^+(4050)$	$Y(4320)$			$Z_c(4025)$
$Z^+(4250)$	$Y(4360)$			$Z_b(10610)$
$Y(4140)$	$Y(4390)$			$Z_b(10650)$
$Y(4274)$	$Y(4630)$			
$Z^+(4200)$	$Y(4660)$			
$Z^+(4240)$				
$X(3823)$				
$X_c(3250)$				
$P_c(4380)$				
$P_c(4450)$				

H.X.Chen,W. Chen,X.Liu, S.L. Zhu, Phys.Rept. 639 (2016) 1-121

X(4140)

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

EWang,EPJC80(2020)626

- **No signals in Belle**(PRL**104**,112004 (2010)), **LHCb**(**PRD85, 091103 (2012)**), **BaBar**(**PRD 91, 012003 (2015)**)
- **The signal of X(4140) is only observed in the process $B^+ \to J/\psi\phi K^+$**

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

INSPIRE search

$\chi_{c1}(4140)$ $I^G(J^{PC}) = 0^+(1^{++})$
was $X(4140)$

This state shows properties different from a conventional $q\bar{q}$ state. A candidate for an exotic structure. See the review on non- $q\bar{q}$ states. Seen by AALTONEN 2009AH, ABAZOV 2014A, CHATRCHYAN 2014M, AAIJ 2017C in $B^+ \to \chi_{c1} K^+$, $\chi_{c1} \to J/\psi\phi$, and by ABAZOV 2015M separately in both prompt (4.7 σ) and non-prompt (5.6 σ) production in $p\bar{p} \to J/\psi\phi+$ anything. Not seen by SHEN 2010 in $\gamma\gamma \to J/\psi\phi$ and ABLIKIM 2015 in $e^+ e^- \to \gamma J/\psi\phi$ at $\sqrt{s}$ = 4.23, 4.26, 4.36 GeV.

$\chi_{c1}(4140)$ MASS	4146.8 ± 2.4 MeV (S = 1.1)
$\chi_{c1}(4140)$ WIDTH	22^{+8}_{-7} MeV (S = 1.3)

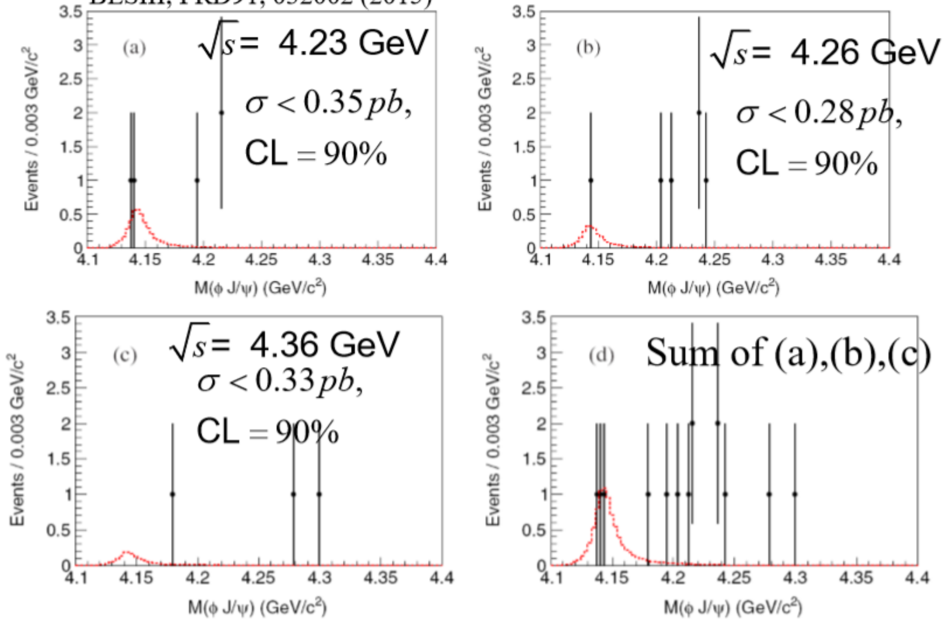
Decay Modes

Mode		Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P (MeV/c)
Γ_1	$J/\psi\phi$	seen		217
Γ_2	$\gamma\gamma$	not seen		2073

X(4140)

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)

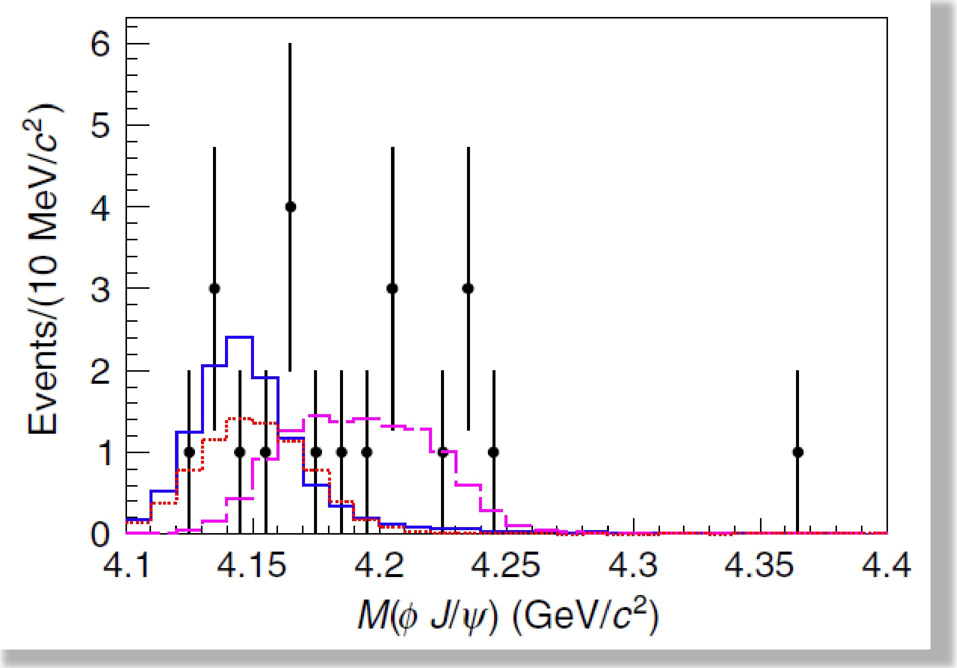


$$\frac{\sigma(e^+e^- \to \gamma Y(4140))}{\sigma(e^+e^- \to \gamma X(3872))} \sim 0.1 \text{ at } \sqrt{s} = 4.23, 4.26 \text{ GeV}$$

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



BESIII

PHYSICAL REVIEW D **91,** 032002 (2015)

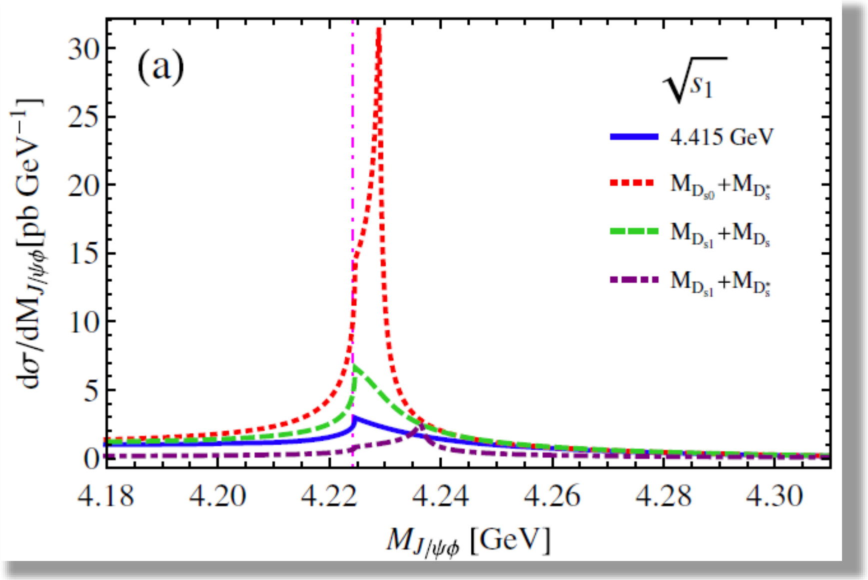
Search for the $Y(4140)$ via $e^+e^- \to \gamma\phi J/\psi$ at $\sqrt{s} = 4.23$, 4.26 and 4.36 GeV

Using data samples collected at center-of-mass energies $\sqrt{s} = 4.23$, 4.26, and 4.36 GeV with the BESIII detector operating at the BEPCII storage ring, we search for the production of the charmoniumlike state $Y(4140)$ through a radiative transition followed by its decay to $\phi J/\psi$. No significant signal is observed and upper limits on $\sigma[e^+e^- \to \gamma Y(4140)] \cdot \mathcal{B}(Y(4140) \to \phi J/\psi)$ at the 90% confidence level are estimated as 0.35, 0.28, and 0.33 pb at $\sqrt{s} = 4.23$, 4.26, and 4.36 GeV, respectively.

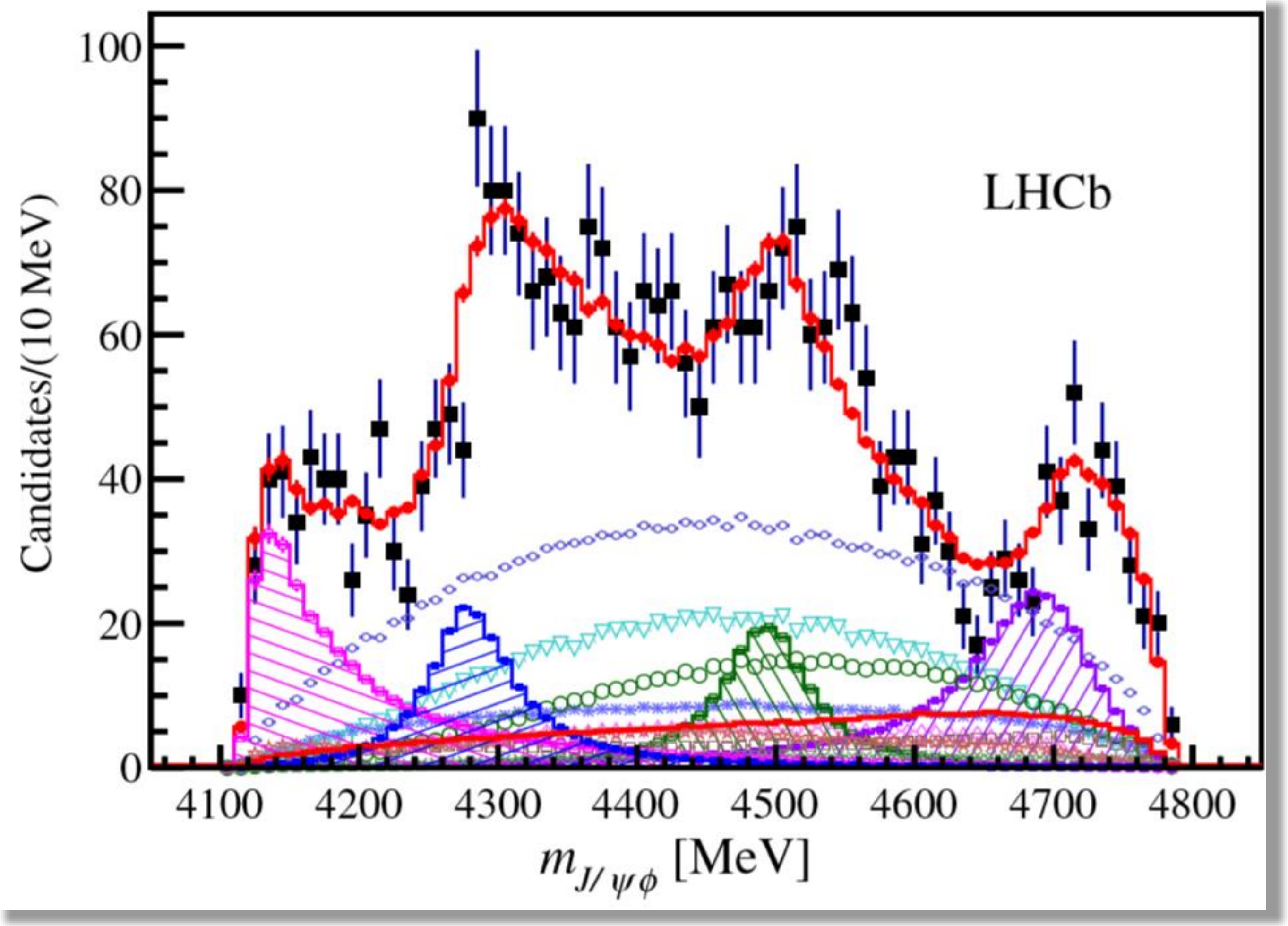
PHYSICAL REVIEW D **93,** 054032 (2016)

Searching for charmoniumlike states with hidden $s\bar{s}$

Xiao-Hai Liu[1,*] and Makoto Oka[1,2,†]



The LHCb measurement



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

4 X states are observed.

X(4140): $J^{PC}=1^{++}$

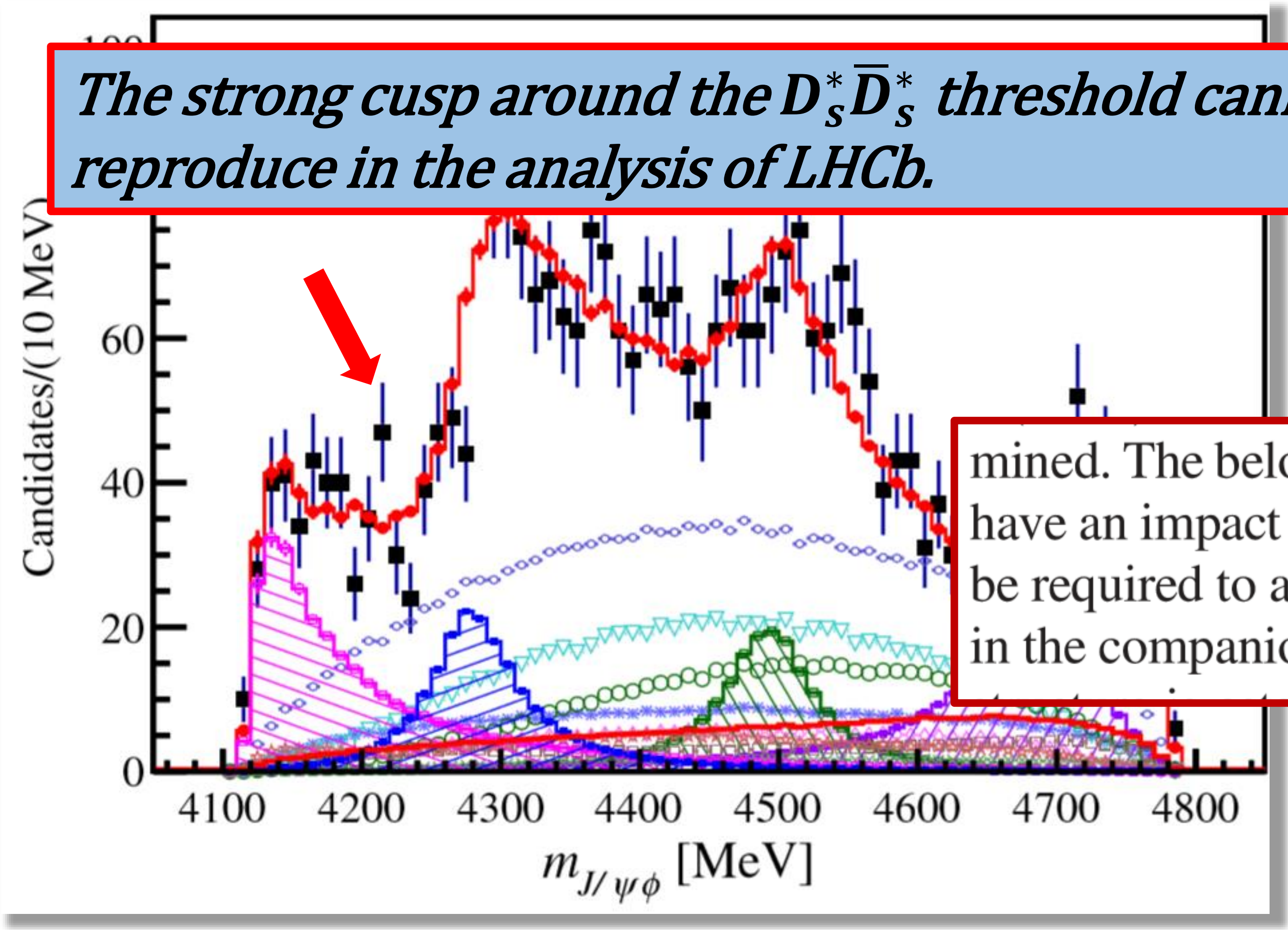
Width=83±21 MeV

J^{PC}	$X(4140)$	$X(4274)$	$X(4500)$	$X(4700)$
0^{++}	10.3σ	7.8σ	Preferred	Preferred
0^{-+}	12.5σ	7.0σ	8.1σ	8.2σ
1^{++}	Preferred	Preferred	**5.2σ**	**4.9σ**
1^{-+}	10.4σ	**6.4σ**	6.5σ	8.3σ
2^{++}	**7.6σ**	7.2σ	5.6σ	6.8σ
2^{-+}	9.6σ	**6.4σ**	6.5σ	6.3σ

PRD95,2017,PRL118,2017

The LHCb measurement

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



The strong cusp around the $D_s^*\bar{D}_s^*$ threshold cannot be reproduce in the analysis of LHCb.

... states are observed.

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Width=83±21 MeV

mined. The below-$J/\psi\phi$-threshold $D_s^\pm D_s^{*\mp}$ cusp [9,18] may have an impact on the $X(4140)$ structure, but more data will be required to address this issue, as discussed in more detail in the companion article [30]. The existence of the $X(4274)$

2^{++}	**7.6σ**	7.2σ	5.6σ	6.8σ
2^{-+}	9.6σ	**6.4σ**	6.5σ	6.3σ

PRD95,2017,PRL118,2017

The large width of X(4140)

Experiment	N_B	Mass (MeV)	Width (MeV)	σ	Fraction (%)
CDF [1]	58	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$	3.8	
Belle [19]	*325*	*4143.0 fixed*	*11.7 fixed*	*1.9*	
CDF [26]	*115*	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$	*5.0*	$15 \pm 4 \pm 2$
LHCb [21]	346	4143.4 fixed	15.3 fixed	1.4	<7
CMS [23]	2480	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$	5.0	10 ± 3
D0 [24]	215	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$	3.1	$21 \pm 8 \pm 4$
BABAR [22]	189	4143.4 fixed	15.3 fixed	1.6	<13
D0 [25]		$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$	4.7–5.7	
Average		4147.1 ± 2.4	15.7 ± 6.3		

PRL118,2017

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

INSPIRE sea

$\chi_{c1}(4140)$ $I^G(J^{PC}) = 0^+(1^{++})$
was $X(4140)$

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PDG2020

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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
D0 [25]		$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$	4.7–5.7	
Average		4147.1 ± 2.4	15.7 ± 6.3		

The deduced width of X(4140), 83±21 MeV, larger than the former experimental measurements, and also the average of the PDG.

PRL118,2017

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PDG2020

BESIII

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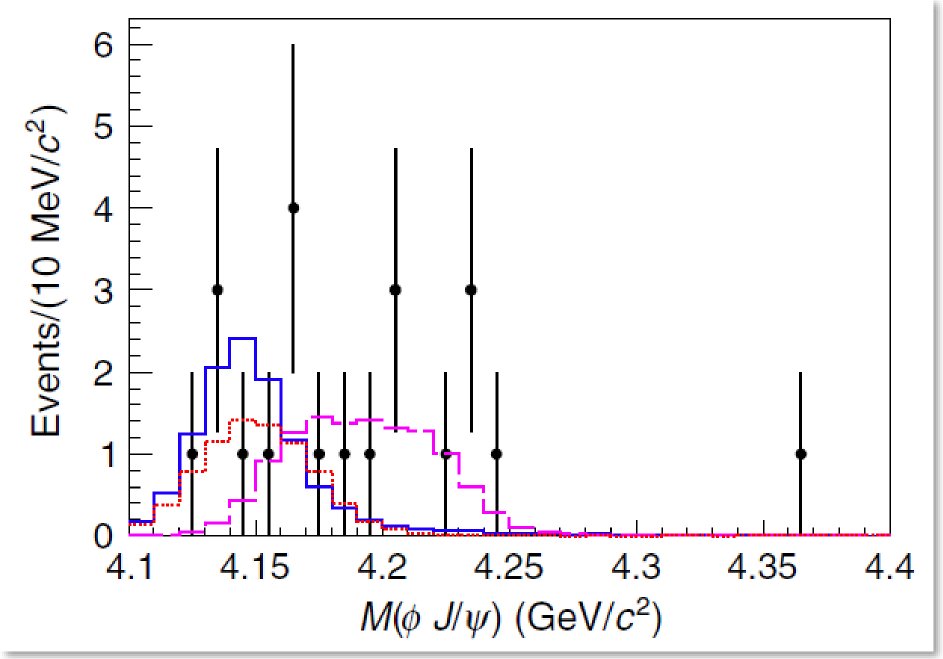
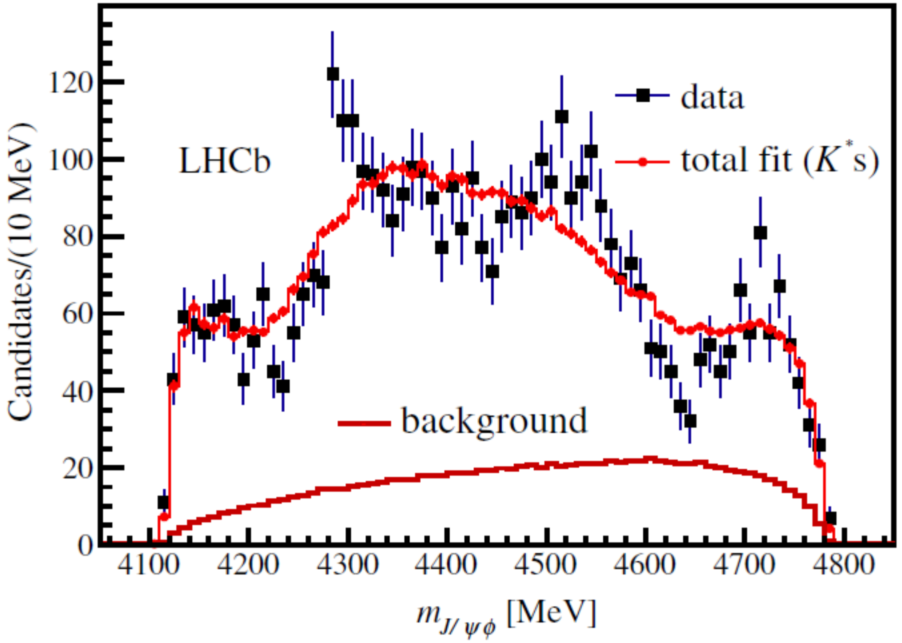
M. Ablikim *et al.* (BESIII Collaboration)
Phys. Rev. D **97**, 032008 – Published 12 February 2018

second systematic. No significant signals are observed for $e^+e^- \to \phi\chi_{c0}$ and $e^+e^- \to \gamma X(4140)$ and upper limits on the Born cross sections at 90% C.L. are provided at $\sqrt{s} = 4.600$ GeV.





X(4140)

- Many explanations:

➢ Molecular state:

X. Liu, S.L. Zhu, PRD80(2009), G.J. Ding,EPJC64(2009),J.R. Zhang, M.Q.Huang,JPG37(2010),

➢ Tetraquark:

F.Stancu,JPG37(2010),Z.G.Wang,IJMPA30(2015)

➢ Hybrid state:

Mahajan,PLB679(2009),Z.G.Wang,EPJC63(2009)

➢ Rescattering effect:

X. Liu,PLB680(2009)

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

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

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

(Re

- **Vector-**

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

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

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

pole).

$\sqrt{s_{pole}} = 4169 + i66$, $I^G[J^{PC}] = 0^+[2^{++}]$

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$1225 - i490$	$18\,927 - i5524$	$-82 + i30$	$70 + i20$	$3 - i2441$

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$1257 + i2866$	$2681 + i940$	$-866 + i2752$	$-2617 - i5151$	$1012 + i1522$

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

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

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

The $D_s^*\bar{D}_s^*$ molecule with 2^{++} was associated to the X(4160), not the X(4140).

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

$D^*\bar{D}^*(4017)$, $D_s^*\bar{D}_s^*(4225)$, $K^*\bar{K}^*(1783)$,
$\rho\rho(1551)$, $\omega\omega(1565)$,
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$D_s^* \bar{D}_s^*$ molecule, X(4160)

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Nuclear Physics A 966 (2017) 135–157

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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 $J^{PC} = 0^{++}$

$D_s^* \bar{D}_s^*$ molecule, X(4140) or X(4160)

- **The quantum numbers of X(4140) established to be 0+(1++)**

J^{PC}	$X(4140)$	$X(4274)$	$X(4500)$	$X(4700)$
0^{++}	10.3σ	7.8σ	Preferred	Preferred
0^{-+}	12.5σ	7.0σ	8.1σ	8.2σ
1^{++}	Preferred	Preferred	$\mathbf{5.2}\sigma$	$\mathbf{4.9}\sigma$
1^{-+}	10.4σ	$\mathbf{6.4}\sigma$	6.5σ	8.3σ
2^{++}	$\mathbf{7.6}\sigma$	7.2σ	5.6σ	6.8σ
2^{-+}	9.6σ	$\mathbf{6.4}\sigma$	6.5σ	6.3σ

PRD95,2017,PRL118,2017

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

INSPIRE sea

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PDG2020

$D_s^*\bar{D}_s^*$ molecule, X(4140) or X(4160)

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0^{++}	10.3σ	7.8σ	Preferred	Preferred
0^{-+}	12.5σ	7.0σ	8.1σ	8.2σ
1^{++}	Preferred	Preferred	5.2σ	4.9σ

PRD95,2017,PRL118,2017

The association of the $D_s^*\bar{D}_s^*$ molecule with 0^{++}/ 2^{++} to X(4140) can no longer be supported, and the association of the $D_s^*\bar{D}_s^*$ molecule to X(4160) has much weight.

was $X(4140)$

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PDG2020

X(4140)

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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

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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

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.

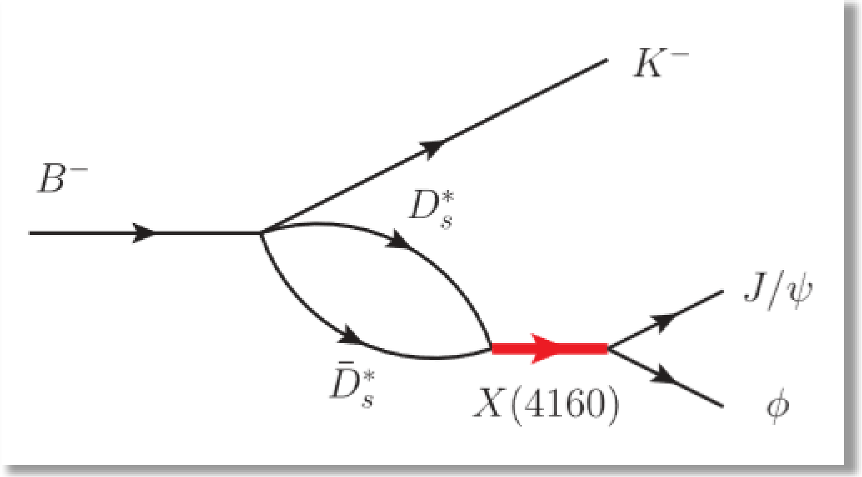
$$\Gamma(X(4140) \to J/\psi\phi) = 86.9 \pm 22.6\,\mathrm{MeV}$$

- *ZGWang, Eur.Phys.J.C* 79 (2019) 1, 72
- *80+-29MeV,Agaev,Phys.Rev.D* 95 (2017) 11, 114003
- *Tetraquark, JingWu, Phys.Rev.D* 94 (2016) 9, 094031
- *HXChen, Eur.Phys.J.C* 77 (2017) 3, 160
- *Diquark-antidiquark, Turkan, Nucl.Phys.A* 985 (2019) 38-65
- $D_s^* D_s$ *cusp effect, XHLiu, Phys.Lett.B* 766 (2017) 117-124

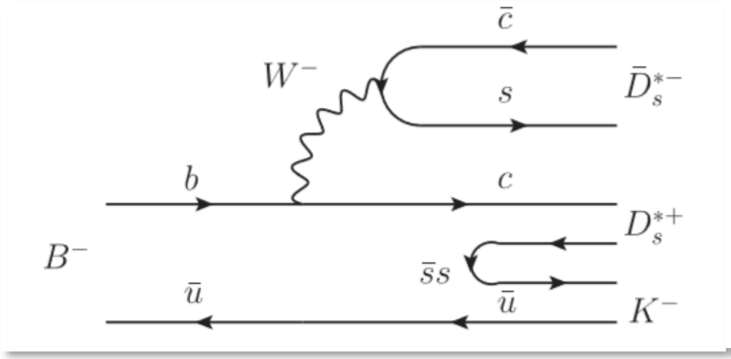
LHCb: $B^+ \to J/\psi\phi K^+$

PRD97(2018)014017

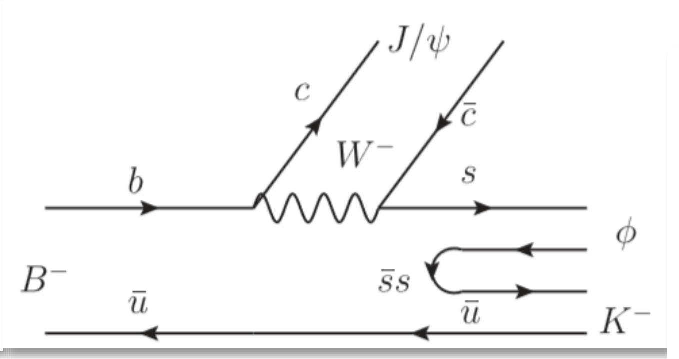
The reaction of $B^- \to J/\psi\, \phi K^-$



- 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

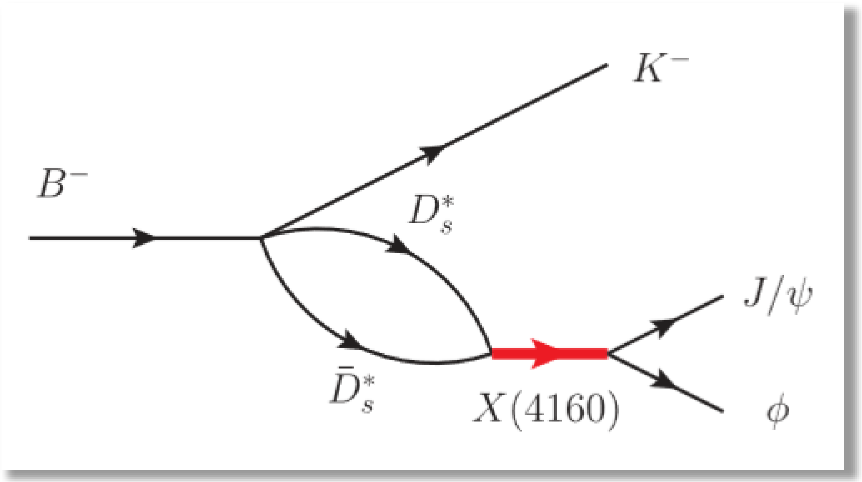


Internal conversion

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

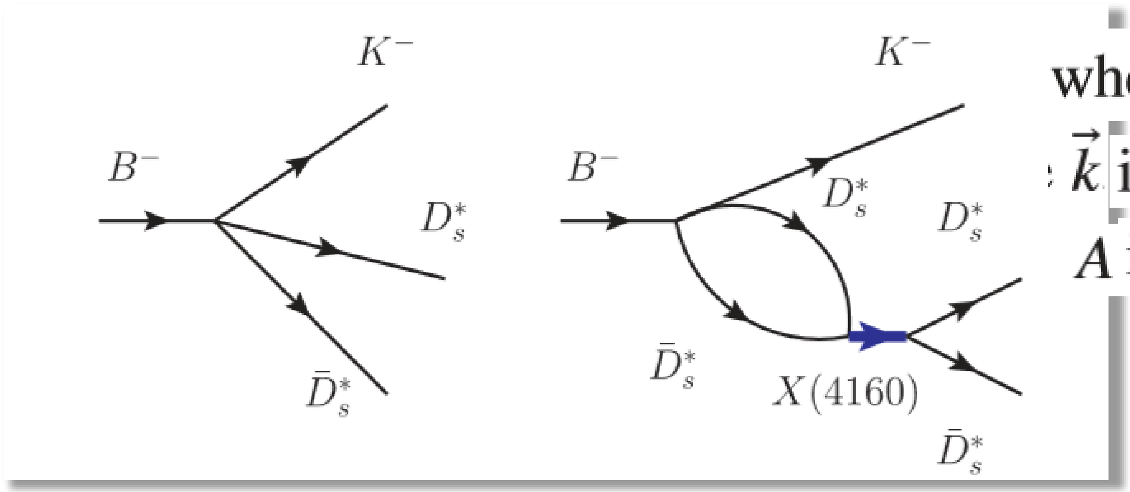
$\sqrt{s_{\rm pole}} = 4169 + i66$, $I^G[J^{PC}] = 0^+[2^{++}]$				
$D^*\bar{D}^*$	$D_s^*\bar{D}_s^*$	$K^*\bar{K}^*$	$\rho\rho$	$\omega\omega$
$1225 - i490$	$18\,927 - i5524$	$-82 + i30$	$70 + i20$	$3 - i2441$
$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$1257 + i2866$	$2681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

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.

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

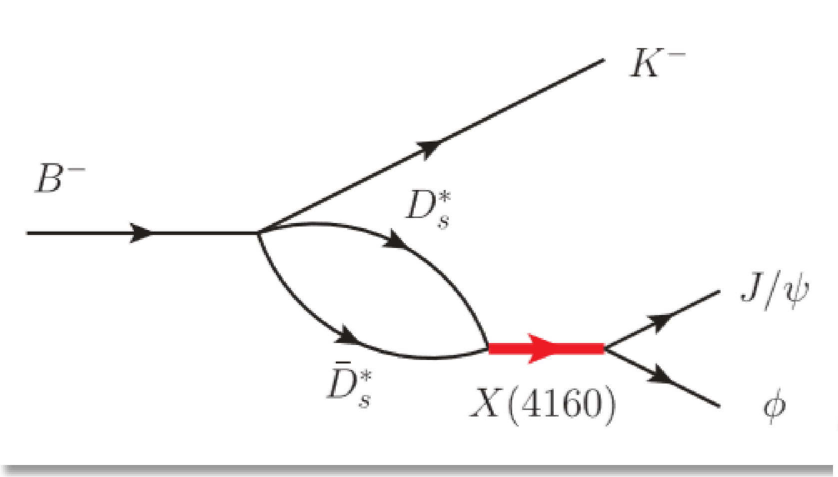


where $\vec{\epsilon}$, $\vec{\epsilon}\,'$ are the polarization vectors of D_s^* and $\vec{D}_s^*$,

$\vec{k}$ is the K^- momentum in the $D_s^*\bar{D}_s^*$ rest frame,

A is an unknown factor that will be fitted to the data.

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



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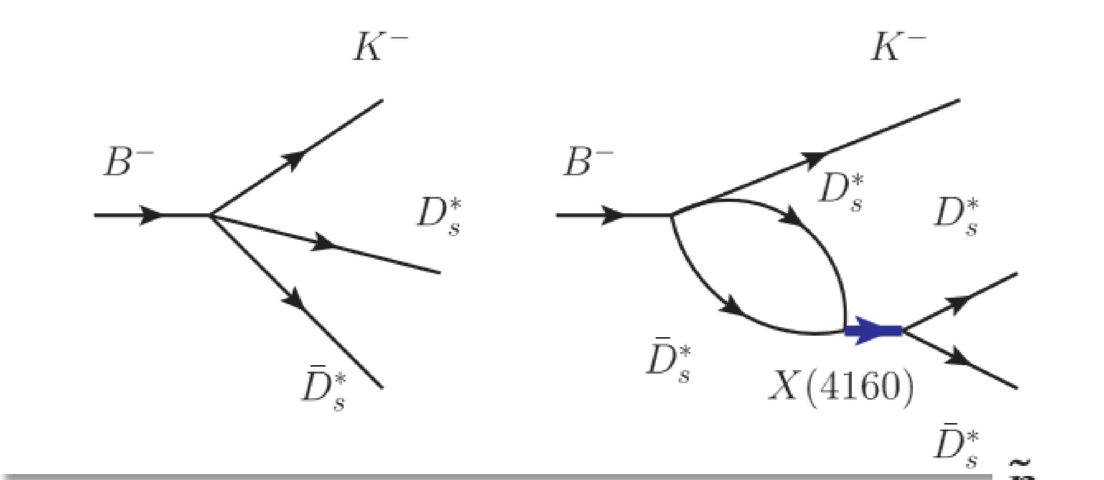
The sum over polarizations of $|t|^2$ is

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

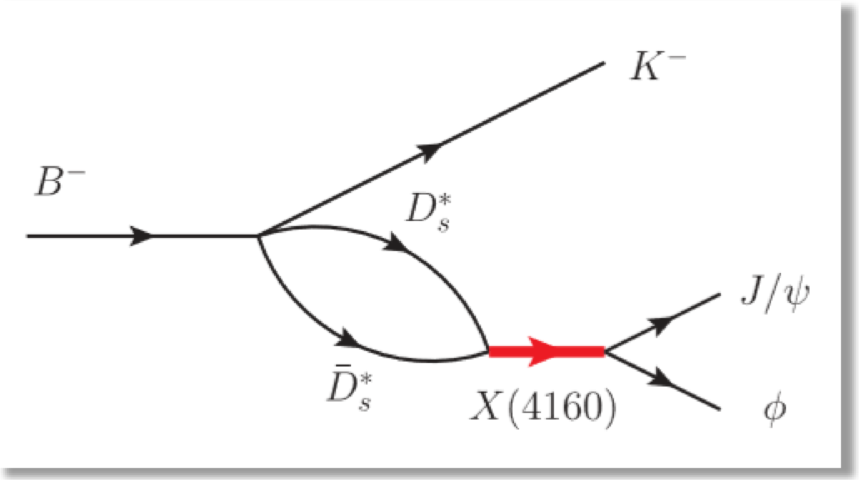


$$\frac{d\Gamma}{dM_{\rm inv}(D_s^* \bar{D}_s^*)} = \frac{1}{(2\pi)^3}\frac{1}{4M_{B^-}^2}\frac{2}{3}|\vec{k}|^4|\vec{k}'||\tilde{p}_{D_s^*}||A|^2$$

$\vec{k}'$ 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 $B^- \to J/\psi\,\phi K^-$



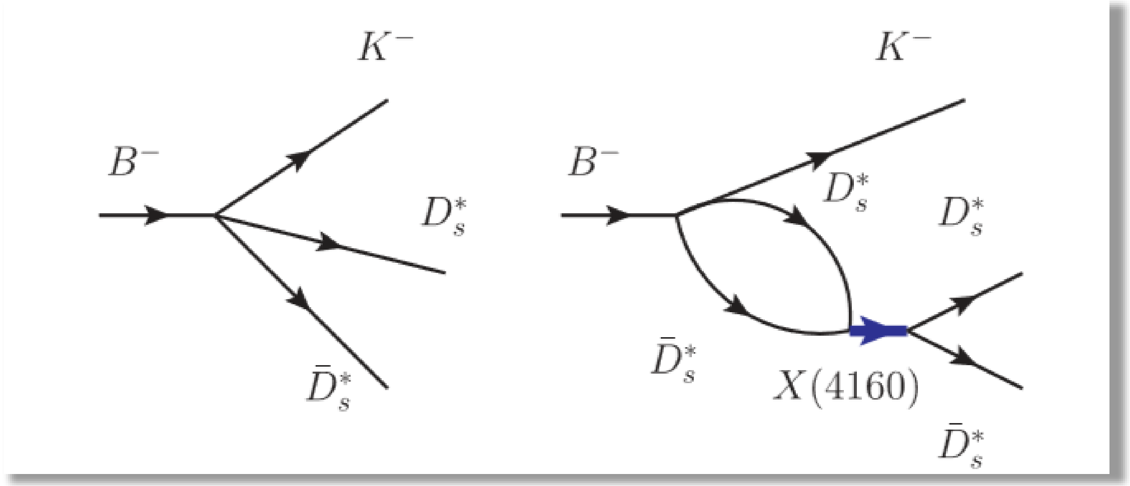
$$\frac{d\Gamma}{dM_{\rm inv}(D_s^*\bar{D}_s^*)} = \frac{1}{(2\pi)^3}\frac{1}{4M_{B^-}^2}\frac{2}{3}|\vec{k}|^4|\vec{k}'||\tilde{p}_{D_s^*}||A|^2,$$

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,

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

$$D^*\bar{D}^*(4017), \quad D_s^*\bar{D}_s^*(4225), \quad K^*\bar{K}^*(1783),$$
$$\rho\rho(1551), \quad \omega\omega(1565),$$
$$\phi\phi(2039), \quad J/\psi J/\psi(6194), \quad \omega J/\psi(3880),$$
$$\phi J/\psi(4116), \quad \omega\phi(1802),$$

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

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

$$\Gamma_X = \Gamma_0 + \Gamma_{J/\psi\phi} + \Gamma_{D_s^*\bar{D}_s^*},$$

with Γ_0 accounting for the channels of Ref. [23] not explicitly considered here (we shall fit that to the data as discussed above), and

Flatté effect

$$\Gamma_{J/\psi\phi} = \frac{|g_{J/\psi\phi}|^2}{8\pi M_X^2} \tilde{p}_\phi,$$

$$\Gamma_{D_s^*\bar{D}_s^*} = \frac{|g_{D_s^*\bar{D}_s^*}|^2}{8\pi M_X^2} \tilde{p}_{D_s^*} \Theta(M_{\rm inv}(D_s^*\bar{D}_s^*) - 2M_{D_s^*}).$$

The contribution of X(4140)

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

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

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

The substitution:

$$M_{\text{inv}}(D_s^* \bar{D}_s^*) \to M_{\text{inv}}(J/\psi \phi),$$

$$\frac{2}{3}|\vec{k}|^4 \to 2|\vec{k}|^2, \qquad \tilde{p}_{D_s^*} \to \tilde{p}_{\phi},$$

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

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)

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

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

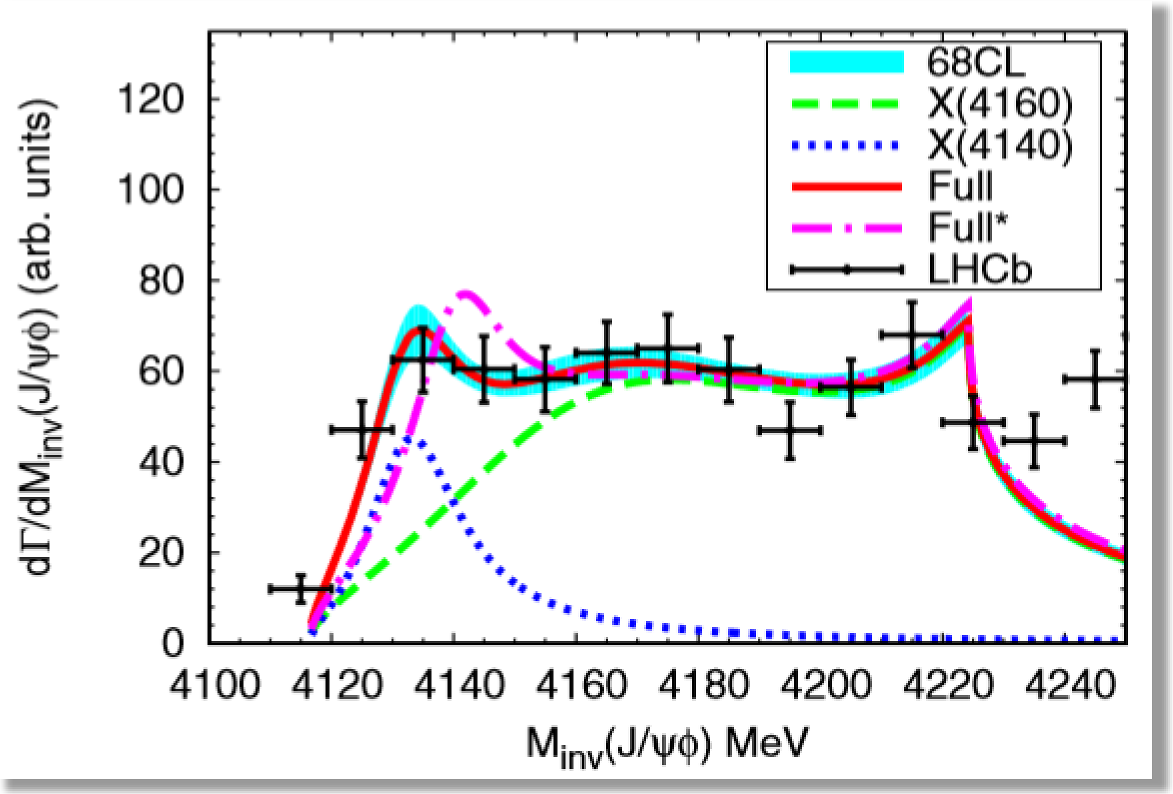
$$\Gamma_{X(4160)} \simeq 87.0 \pm 7.1 \text{ MeV}$$

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

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

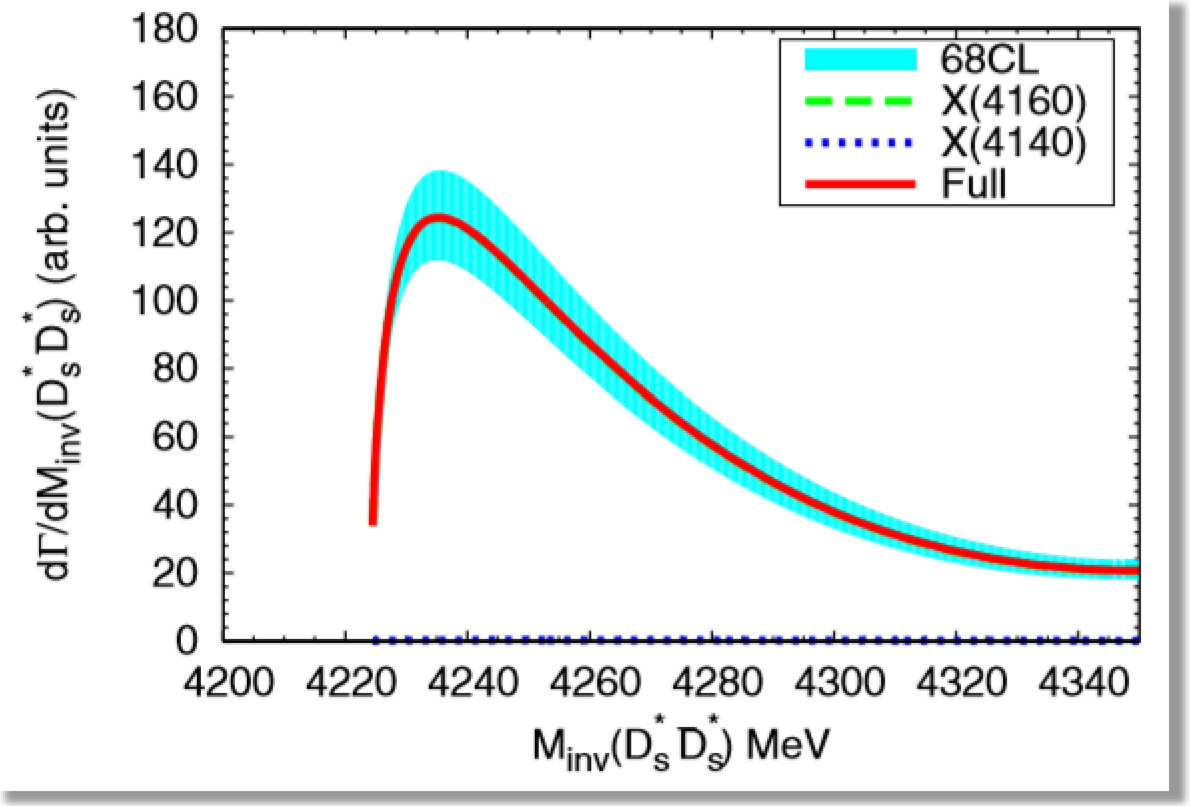
$X(4160)$ MASS	4156^{+29}_{-25} MeV
$X(4160)$ WIDTH	139^{+110}_{-60} MeV

Results



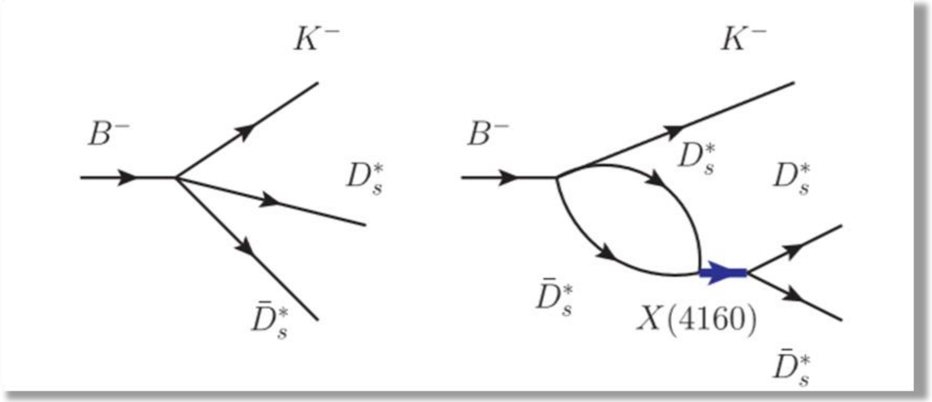
- **The Flatte effect is visable, as a sharp fall down of the invariant mass distribution above the $D_s^* \bar{D}_s^*$ threshold.**
- **The lower part of the spectrum can be obtain from the contribution of X(4160)(2++) and X(4140)(1++, 19 MeV) resonances.**
- **The cusp of the distribution at the $D_s^* \bar{D}_s^*$ threshold, cannot be accommodated by a Breit-Wigner amplitude, and it indicates that the resonance in that region is tied to the $D_s^* \bar{D}_s^*$ channel.**

Results



$$B^- \to K^- D_s^* \bar{D}_s^*$$

- There is a peak close to the threshold, which should not be misidentified with a new state, but it is the reflection of the X(4160).
- The strength of the peak is the twice of the one of the X(4140).



$B^{\pm}$

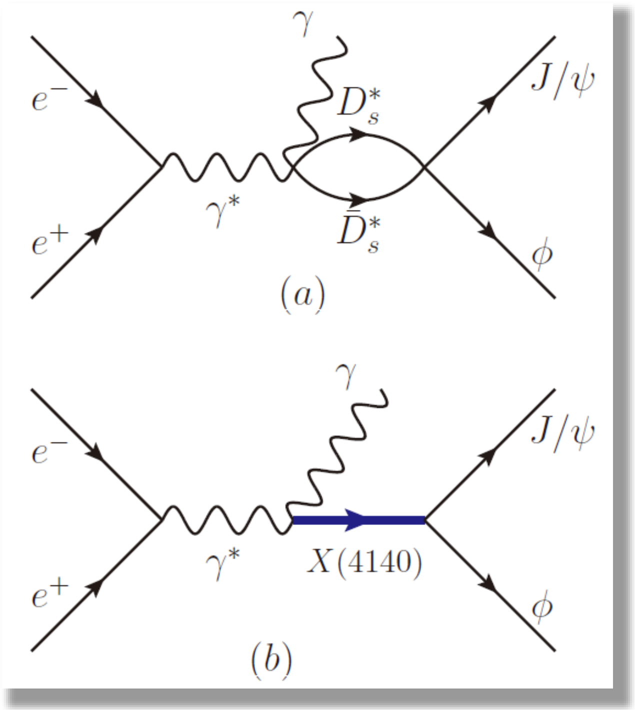
$I(J^P) = \frac{1}{2}(0^-)$

Γ_{169}	$\overline{D}^*(2007)^0 D_{s1}(2536)^+ \times$ B$(D_{s1}(2536)^+ \to D^*(2007)^0 K^+)$	$(5.5 \pm 1.6) \times 10^{-4}$
Γ_{196}	$D^*(2010)^- D^*(2010)^+ K^+$	$(1.32 \pm 0.18) \times 10^{-3}$
Γ_{210}	$D_s^+ \overline{K}^0$	$< 8 \times 10^{-4}$ CL=90%
Γ_{211}	$D_s^{*+} \overline{K}^0$	$< 9 \times 10^{-4}$ CL=90%

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

CPC43(2019)113101

The mechanism for $J/\psi\phi$ production



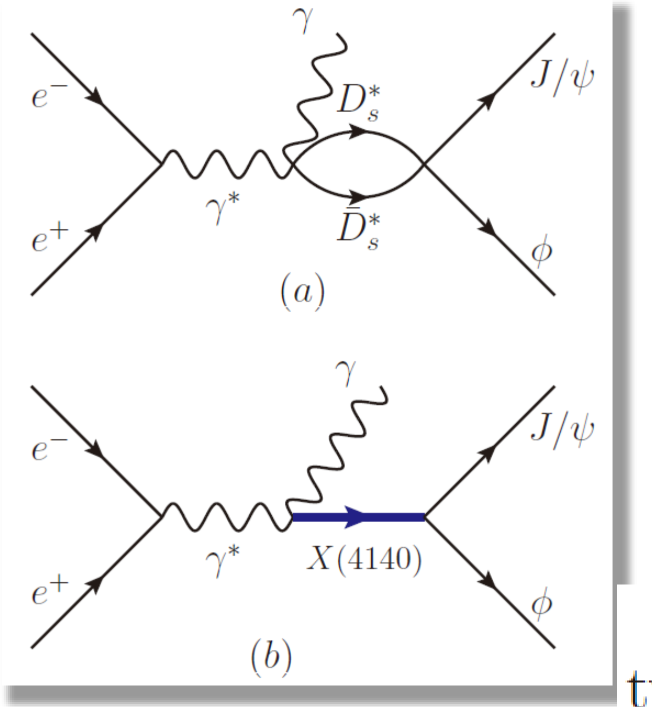
$$\tilde{\mathcal{M}}^{(a)}_{J/\psi\phi} = A \times G_{D_s^*\bar{D}_s^*} t_{D_s^*\bar{D}_s^*,J/\psi\phi} \times \mathcal{P}^{(a)}$$
$$= \mathcal{M}^{(a)}_{J/\psi\phi} \times \mathcal{P}^{(a)},$$

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

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

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

The mechanism for $J/\psi\phi$ production

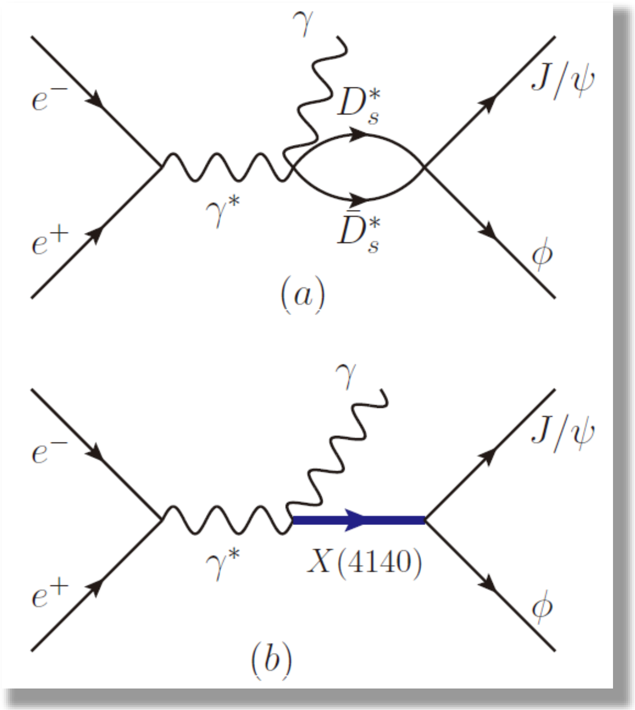


$$\tilde{\mathcal{M}}^{(b)}_{J/\psi\phi} = \frac{BM^2_{X_2} \times \mathcal{P}^{(b)}}{M^2_{\text{inv}}(J/\psi\phi) - M^2_{X_2} + iM_{X_2}\Gamma_{X_2}} = \mathcal{M}^{(b)}_{J/\psi\phi} \times \mathcal{P}^{(b)},$$

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

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 $J/\psi\phi$ production

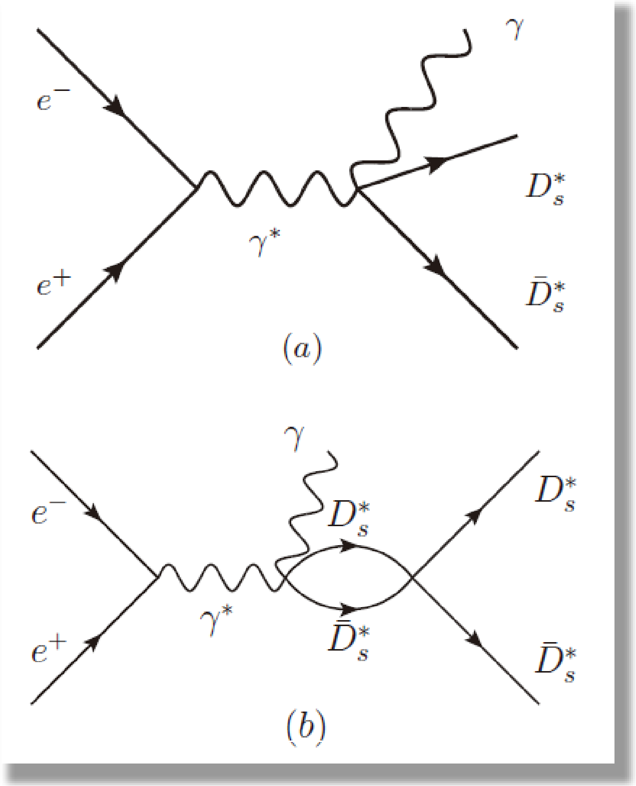


$$\frac{d\Gamma}{dM_{\rm inv}(J/\psi\phi)} = \frac{1}{(2\pi)^3}\frac{1}{4s}k'\tilde{p}_\phi\left[|\mathcal{M}^{(a)}_{J/\psi\phi}|^2 + |\mathcal{M}^{(b)}_{J/\psi\phi}|^2\right]$$

$$k' = \frac{\lambda^{1/2}\left(s, 0, M^2_{\rm inv}(J/\psi\phi)\right)}{2\sqrt{s}}$$

$$\tilde{p}_\phi = \frac{\lambda^{1/2}(M^2_{\rm inv}(J/\psi\phi), m^2_{J/\psi}, m^2_\phi)}{2M_{\rm inv}(J/\psi\phi)}$$

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

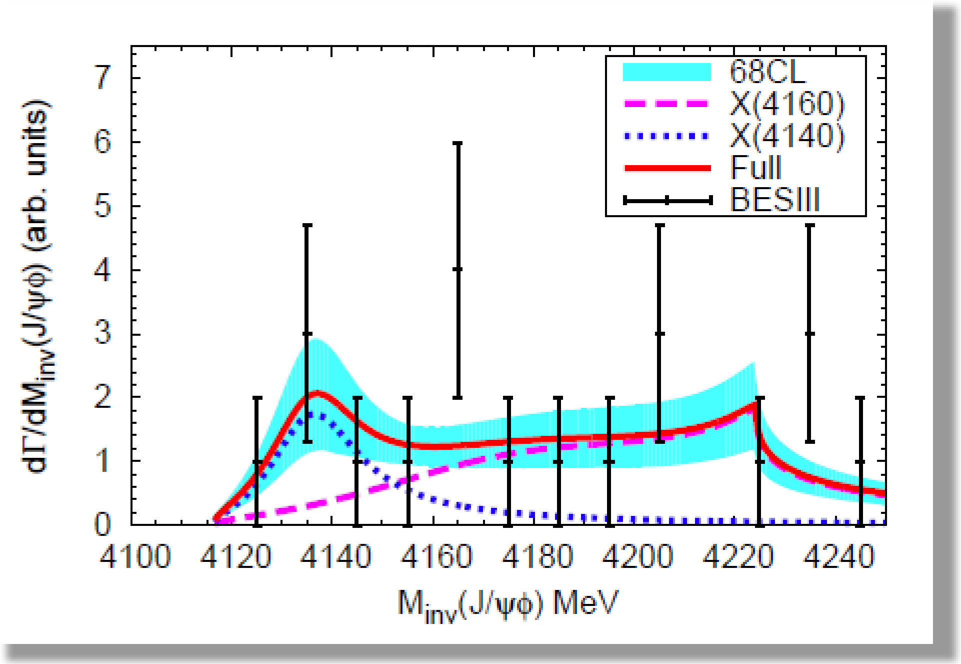


$$\frac{d\Gamma}{dM_{\rm inv}(D_s^*\bar{D}_s^*)} = \frac{1}{(2\pi)^3}\frac{1}{4s}k'\tilde{p}_{D_s^*}|\mathcal{M}_{D_s^*\bar{D}_s^*}|^2,$$

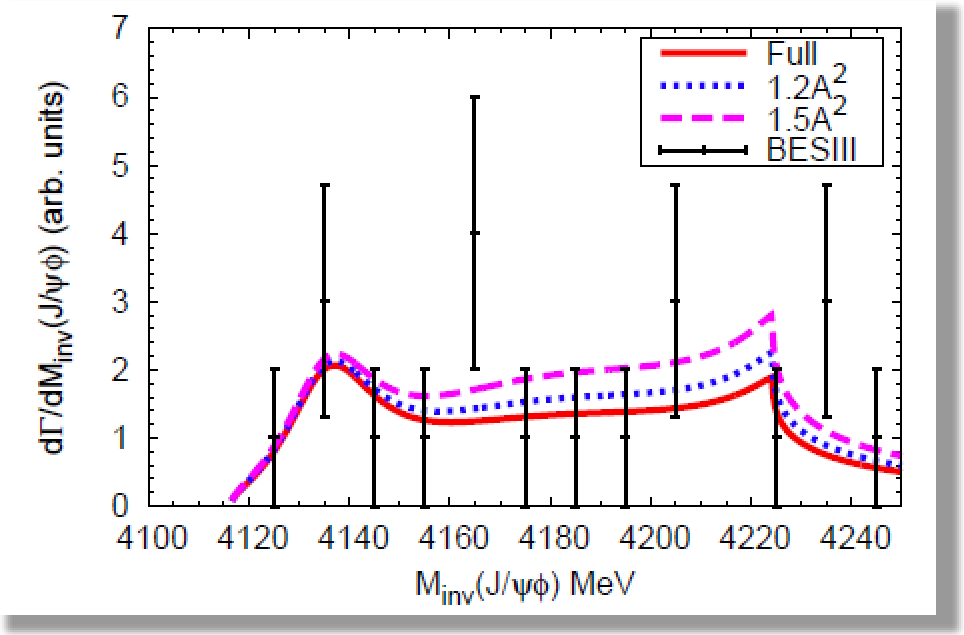
$$\begin{aligned}\mathcal{M}_{D_s^*\bar{D}_s^*} &= A\left[T^{\rm tree} + T^{X(4160)}\right] \\ &= A\left[1 + G_{D_s^*\bar{D}_s^*}\left(M_{\rm inv}(D_s^*\bar{D}_s^*)\right)\right. \\ &\quad \left.\times t_{D_s^*\bar{D}_s^*,D_s^*\bar{D}_s^*}\left(M_{\rm inv}(D_s^*\bar{D}_s^*)\right)\right]\end{aligned}$$

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

Results

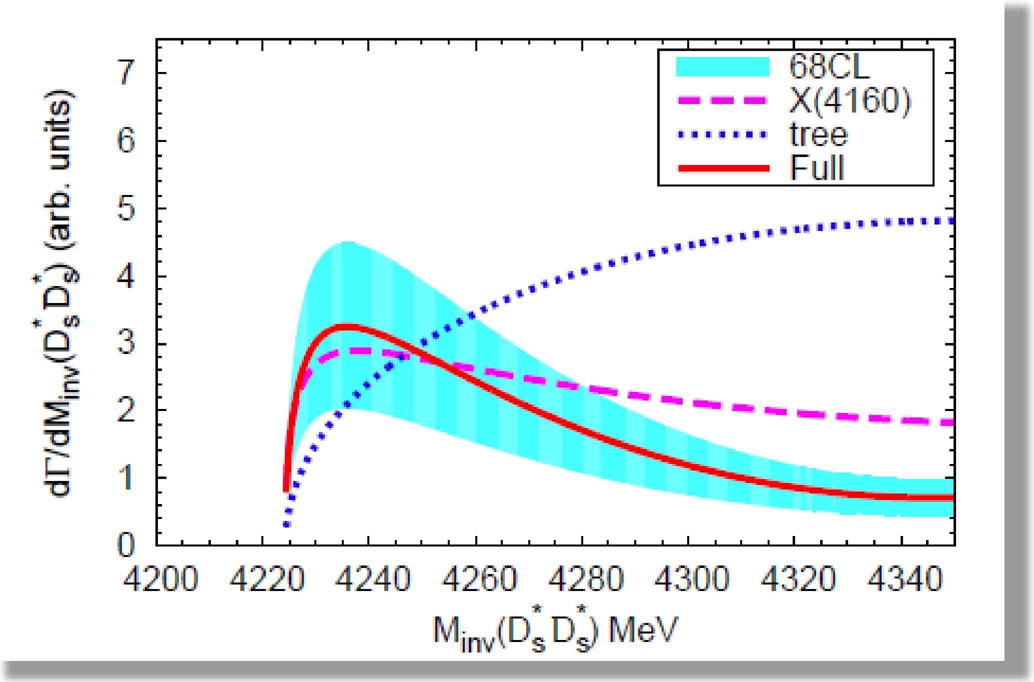


68CL
X(4160)
X(4140)
Full
BESIII
dΓ/dM$_{inv}$(J/ψφ) (arb. units)
M$_{inv}$(J/ψφ) MeV



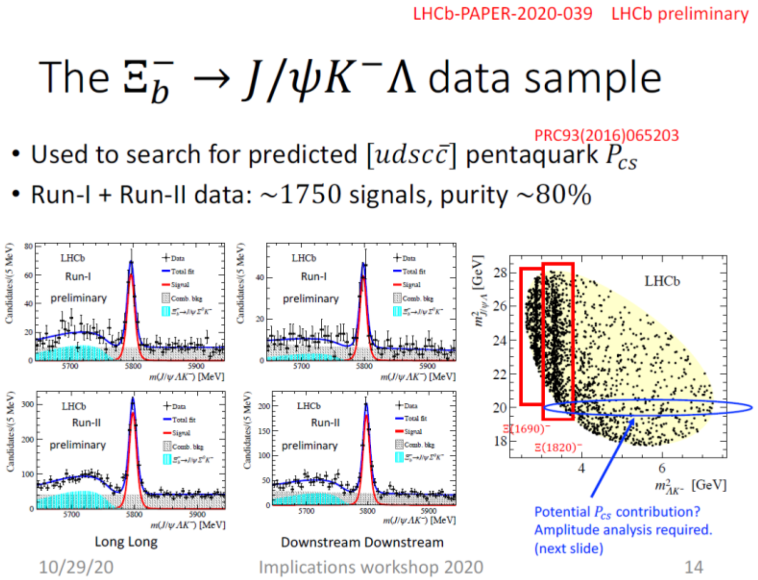
Full
1.2A^2
1.5A^2
BESIII
dΓ/dM$_{inv}$(J/ψφ) (arb. units)
M$_{inv}$(J/ψφ) MeV

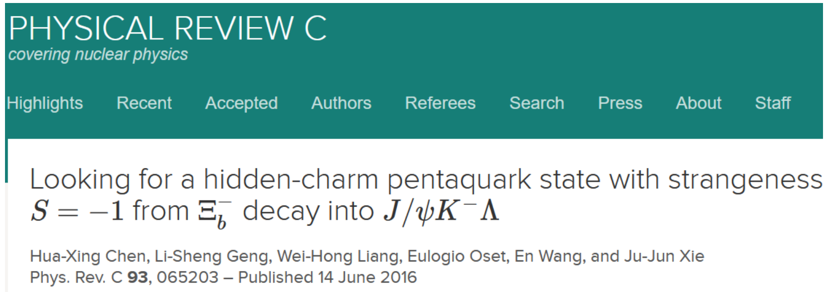
$e^+e^- \to D_s^*\bar{D}_s^*\gamma$



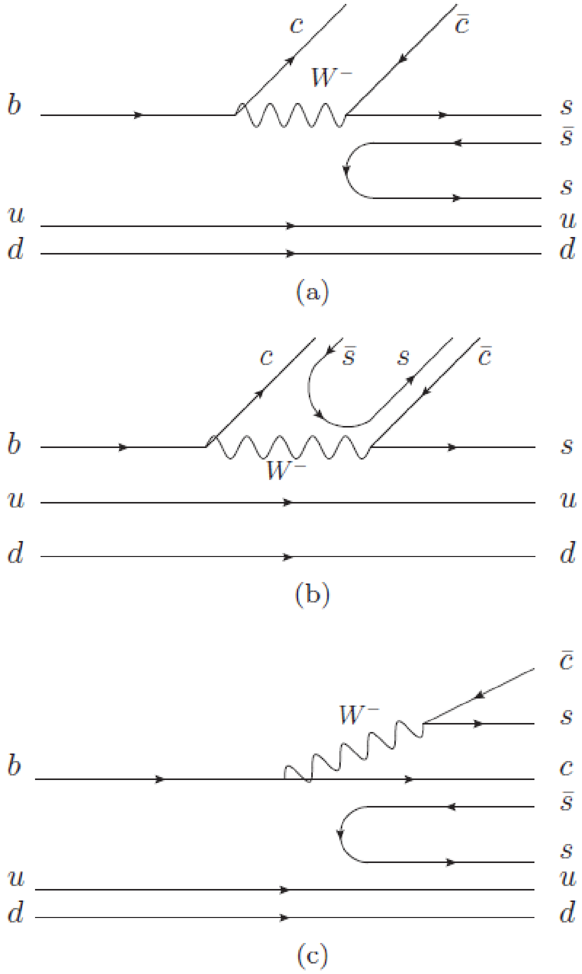
$\Lambda_b \to J/\psi\Lambda\phi$

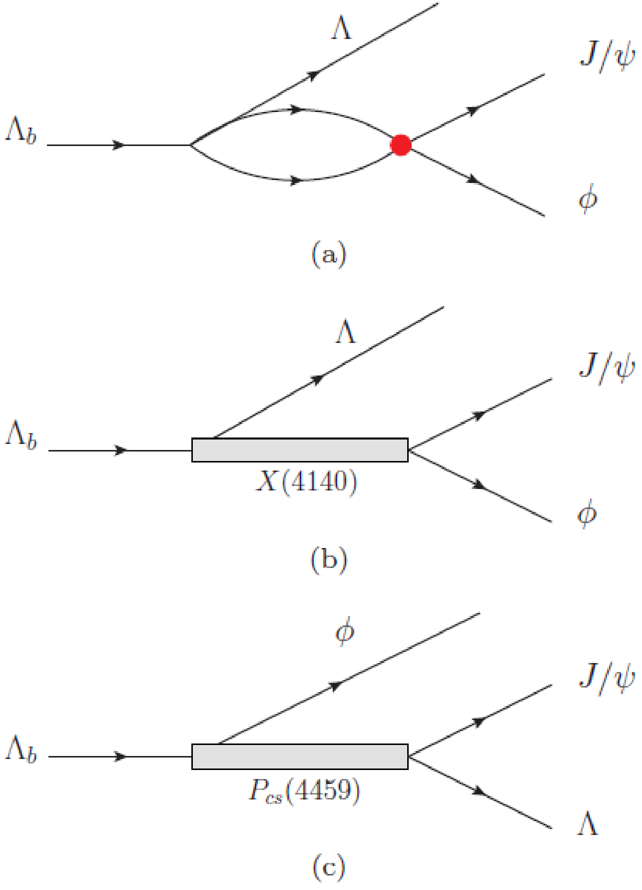
- **First observed by CMS** PLB802, 135203(2020)
- **$J/\psi\phi$ final state interaction, X(4140) &X(4160)**
- **$\Lambda\phi$ final state interactions, no information about Λ^***
- **$J/\psi\Lambda$ final state interaction, P_{cs}**





The mechanism





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

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

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

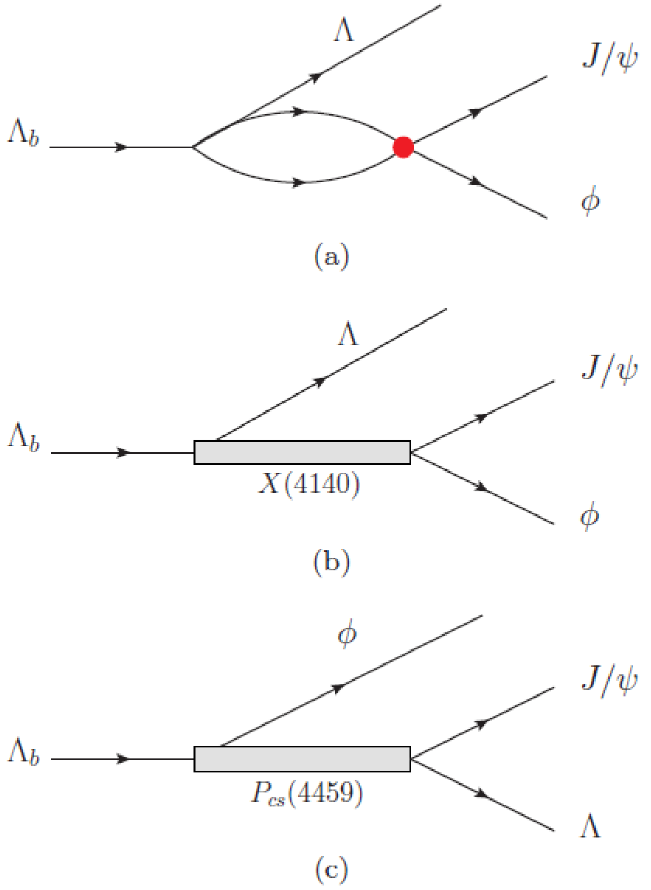
$$\frac{d^2\Gamma}{dM^2_{J/\psi\phi}dM^2_{J/\psi\Lambda}} = \frac{1}{(2\pi)^3}\frac{1}{32M^3_{\Lambda_b}}\sum|\mathcal{M}|^2,$$

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

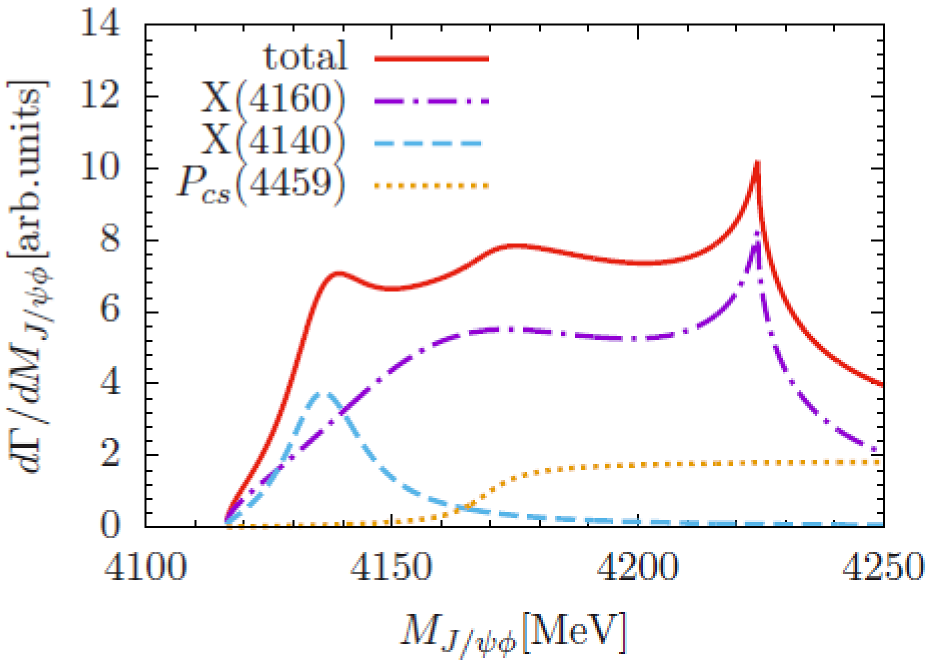
$$= B^2\left(3|\tilde{\mathcal{M}}^S|^2 + 2|\vec{k}|^2|\tilde{\mathcal{M}}^P|^2\right), \quad (18)$$

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

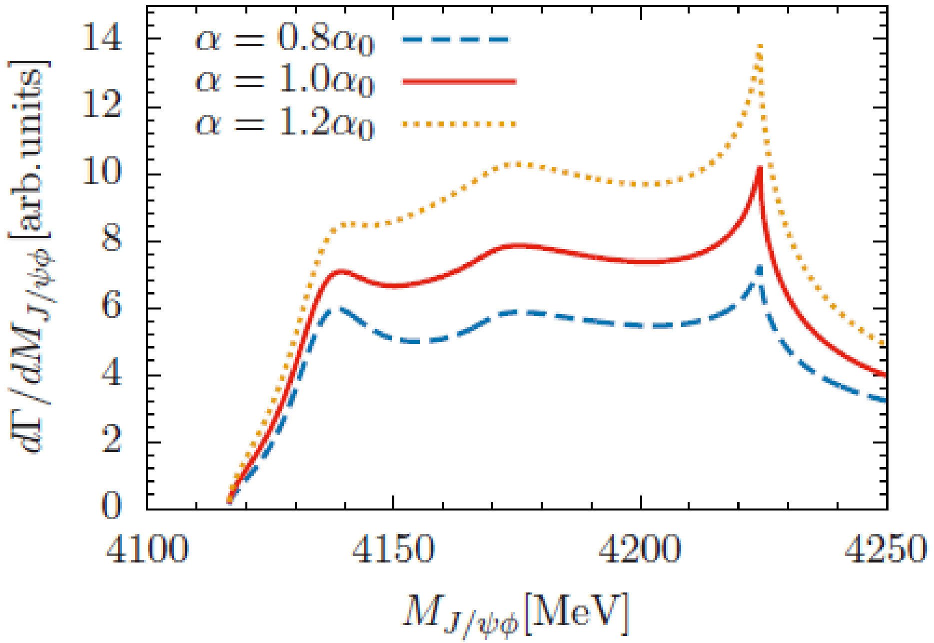
$$\tilde{\mathcal{M}}^S = \frac{M^3_{X(4140)}}{M^2_{J/\psi\phi} - M^2_{X(4140)} + iM_{X(4140)}\Gamma_{X(4140)}} + \frac{\beta M^3_{P_{cs}}}{M^2_{J/\psi\Lambda} - M^2_{P_{cs}} + iM_{P_{cs}}\Gamma_{P_{cs}}}, \quad (20)$$



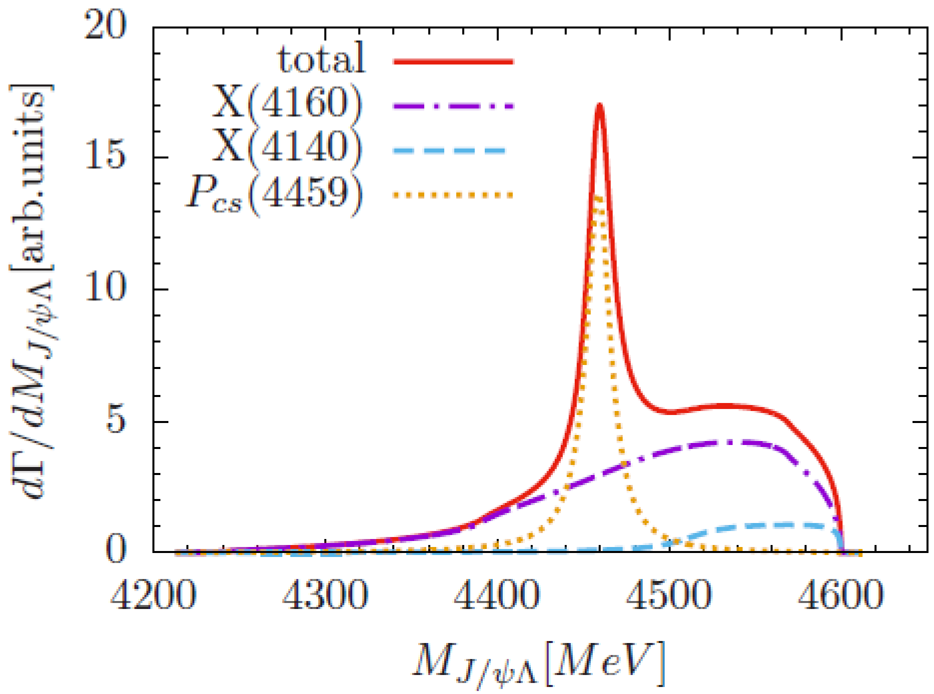
Results

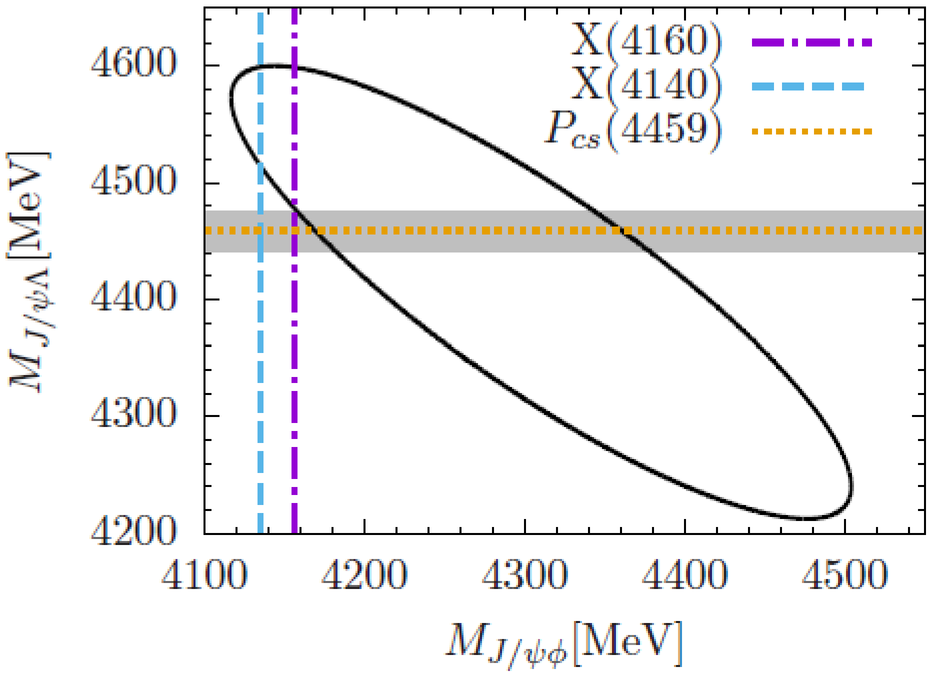


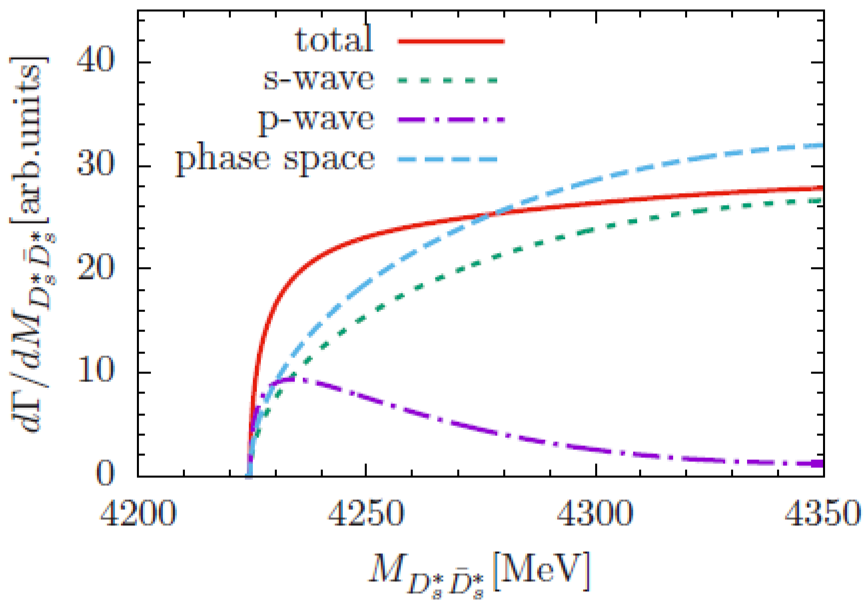
total
X(4160)
X(4140)
$P_{cs}(4459)$
$d\Gamma/dM_{J/\psi\phi}$[arb.units]
$M_{J/\psi\phi}$[MeV]
0
2
4
6
8
10
12
14
4100
4150
4200
4250

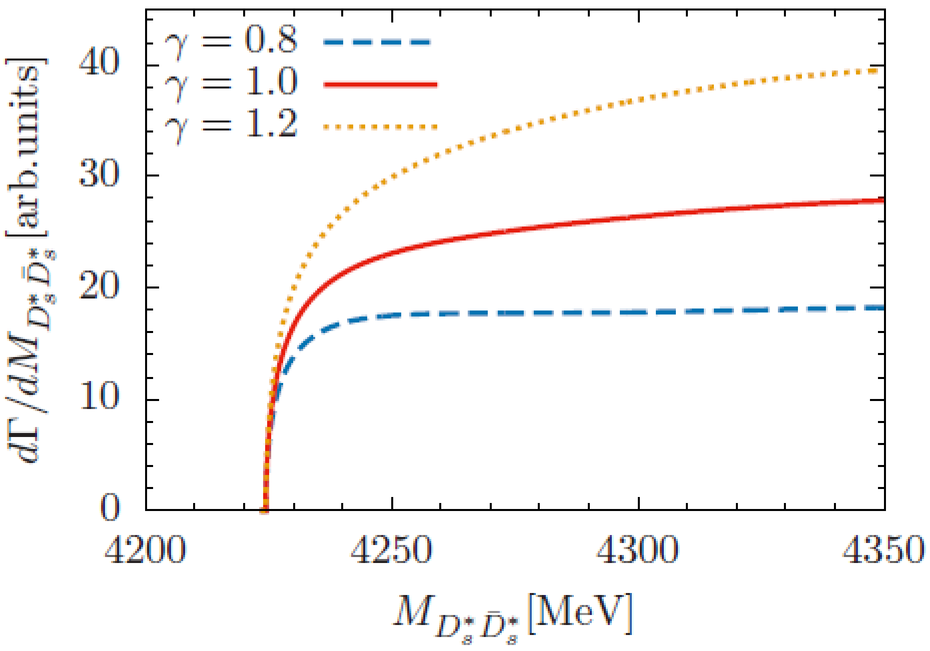


$\alpha = 0.8\alpha_0$
$\alpha = 1.0\alpha_0$
$\alpha = 1.2\alpha_0$
$d\Gamma/dM_{J/\psi\phi}$[arb.units]
$M_{J/\psi\phi}$[MeV]
0
2
4
6
8
10
12
14
4100
4150
4200
4250


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


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


total
s-wave
p-wave
phase space
$d\Gamma/dM_{D_s^*\bar{D}_s^*}$[arb.units]
$M_{D_s^*\bar{D}_s^*}$[MeV]
0
10
20
30
40
4200
4250
4300
4350


$\gamma = 0.8$
$\gamma = 1.0$
$\gamma = 1.2$
$d\Gamma/dM_{D_s^*\bar{D}_s^*}$[arb.units]
$M_{D_s^*\bar{D}_s^*}$[MeV]
0
10
20
30
40
4200
4250
4300
4350

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 LHCb measurements for $B^+ \to J/\psi\phi K^+$.**
- **Our model is also compatible with the BESIII measurments 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.**
- **The signal of X(4160) in $D_s^*\bar{D}_s^*$ spectrum is important to confirm the molecular nature.**

Thanks for your attention!