

A feature of the molecular states

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王冠颖，X. Chen，李德民，E.Oset

第五届XYZ粒子学术研讨会

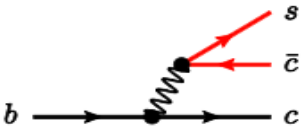
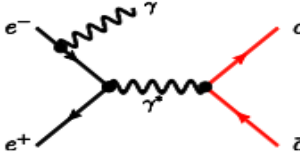
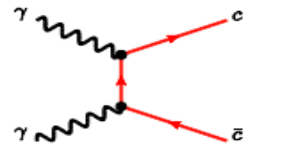
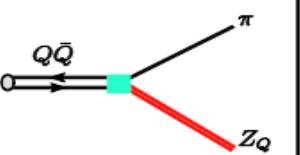
Oct. 19-23, 2018



outline

- Motivation
- LHCb: $B^+ \rightarrow J/\psi \phi K^+$
- BESIII: $e^+e^- \rightarrow \gamma J/\psi \phi$
- LHCb: $B^+ \rightarrow J/\psi \omega K^+$
- Summary

Charmonium-like states

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

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



X(4140)

- 2009, CDF Colla. PRL 102, 242002

Evidence for $X(4140)$ with sig. 3.8σ in $B^+ \rightarrow J/\psi \phi K^+$

mass : $4143.0 \pm 2.9(\text{stat}) \pm 1.2(\text{syst}) \text{ MeV}$

width : $11.7_{-5.0}^{+8.3}(\text{stat}) \pm 3.7(\text{syst}) \text{ MeV}$

- 2017, LHCb Colla., PRL 118, 022003

3 fb^{-1} pp-bar collision data, $X(4140)$ with sig. $>5 \sigma$ in

$B^+ \rightarrow J/\psi \phi K^+$, $J^{PC}=1^{++}$, with sig. $>4 \sigma$

mass : $4146.5 \pm 4.5_{-2.8}^{+4.6} \text{ MeV}$

width : $83 \pm 21_{-14}^{+21} \text{ MeV}$

- 2010, Belle Colla., PRL 104, 112004

825 fb^{-1} Y(nS) data, no evidence for $X(4140)$,

But evidence X(4350): with sig. 3.2σ in $\gamma\gamma \rightarrow J/\psi \phi$

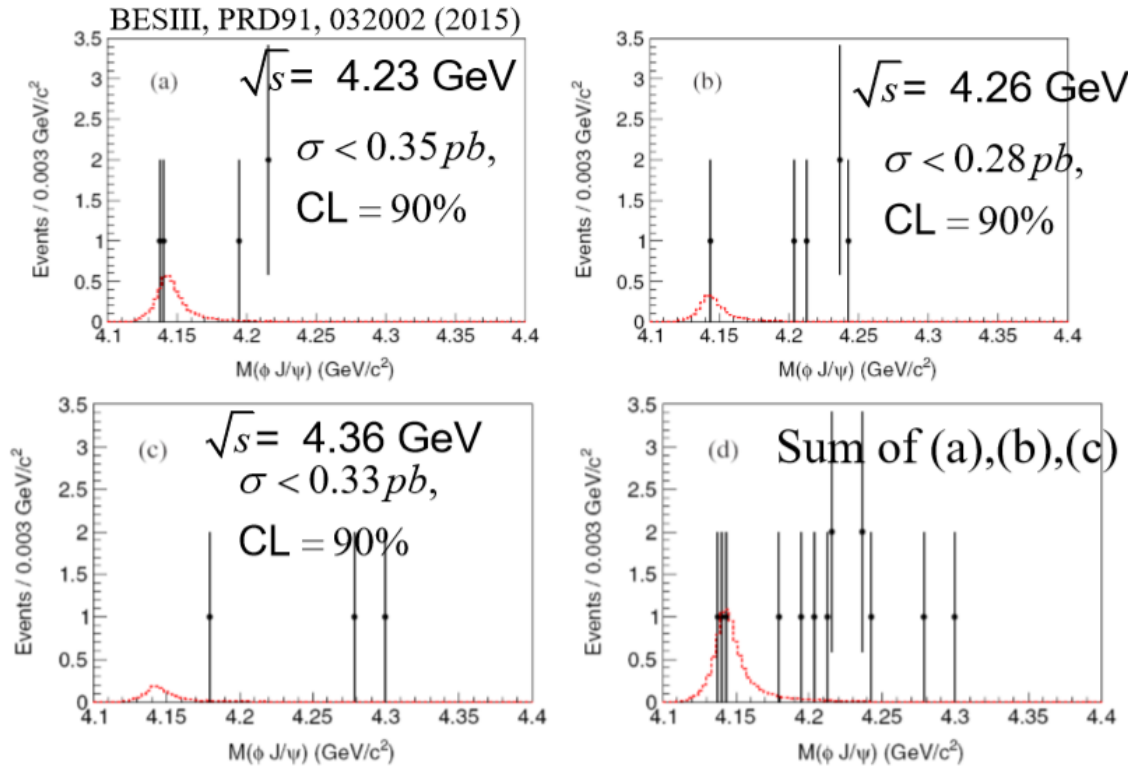
mass: $4350.6_{-5.1}^{+4.6}(\text{stat}) \pm 0.7(\text{syst})$

width: $13_{-9}^{+18}(\text{stat}) \pm 4(\text{syst})$

Silde of R.G. Ping, 2018.3.31
第一届强子与重味物理理论与实验
联合研讨会@兰州

X(4140)

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



Silde of R.G. Ping, 2018.3.31
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$$\frac{\sigma(e^+e^- \rightarrow \gamma Y(4140))}{\sigma(e^+e^- \rightarrow \gamma X(3872))} \sim 0.1 \text{ at } \sqrt{s} = 4.23, 4.26 \text{ GeV}$$

BESIII



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

Search for the $Y(4140)$ via $e^+e^- \rightarrow \gamma\phi J/\psi$ 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 $\sigma[e^+e^- \rightarrow \gamma Y(4140)] \cdot \mathcal{B}(Y(4140) \rightarrow \phi J/\psi)$ 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.

BESIII



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

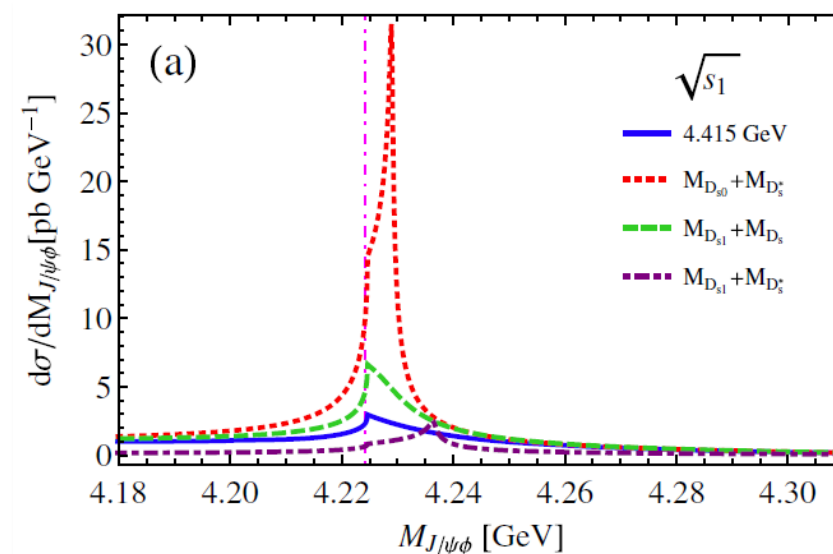
Search for the $Y(4140)$ via $e^+e^- \rightarrow \gamma\phi J/\psi$ at $\sqrt{s} = 4.23, 4.26$ and 4.36 GeV

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 $\sigma[e^+e^- \rightarrow \gamma Y(4140)] \cdot \mathcal{B}(Y(4140) \rightarrow \phi J/\psi)$ 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.

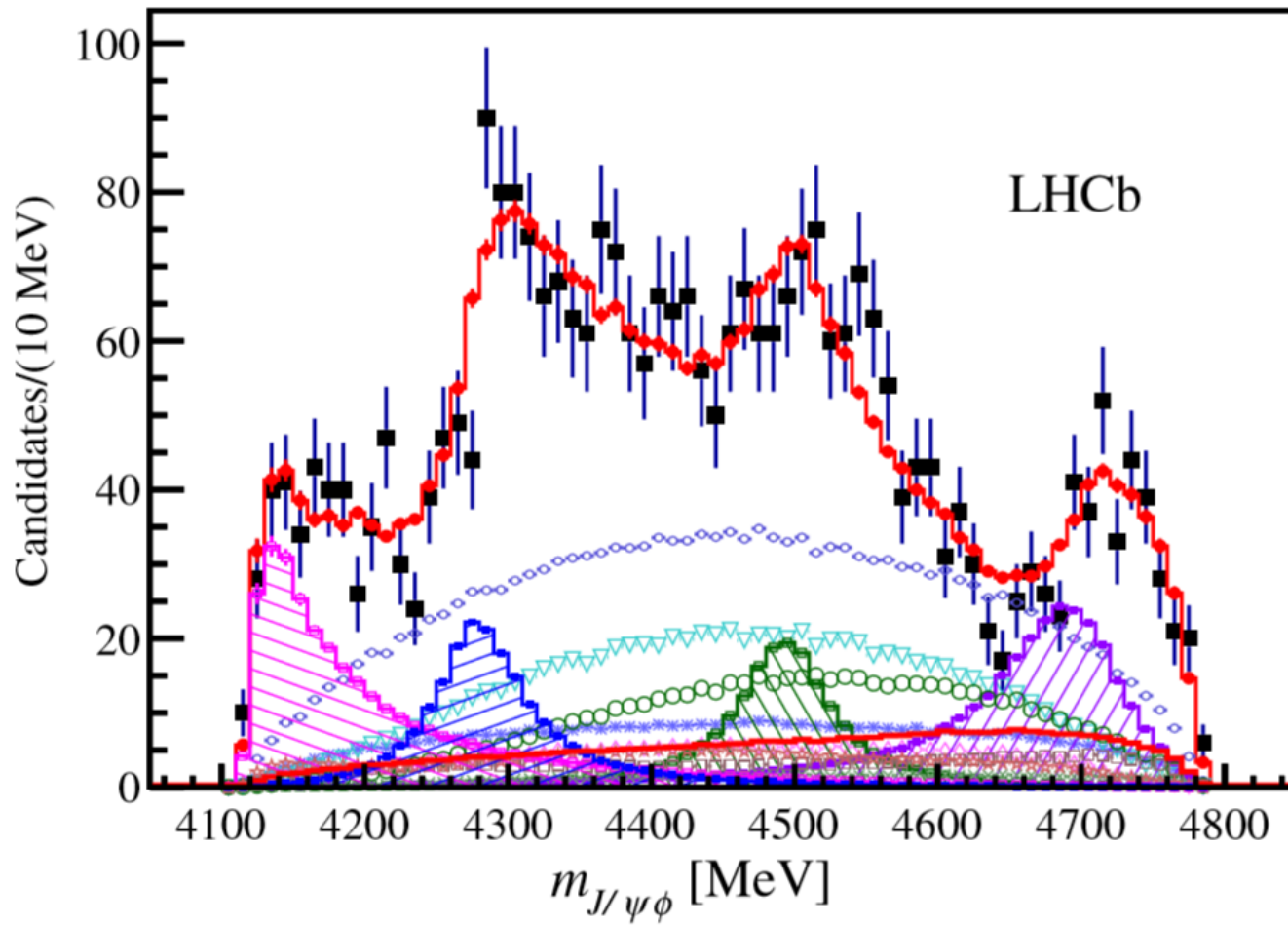
PHYSICAL REVIEW D **93**, 054032 (2016)

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

Xiao-Hai Liu^{1,*} and Makoto Oka^{1,2,†}



The LHCb measurement



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

4 X states are observed.

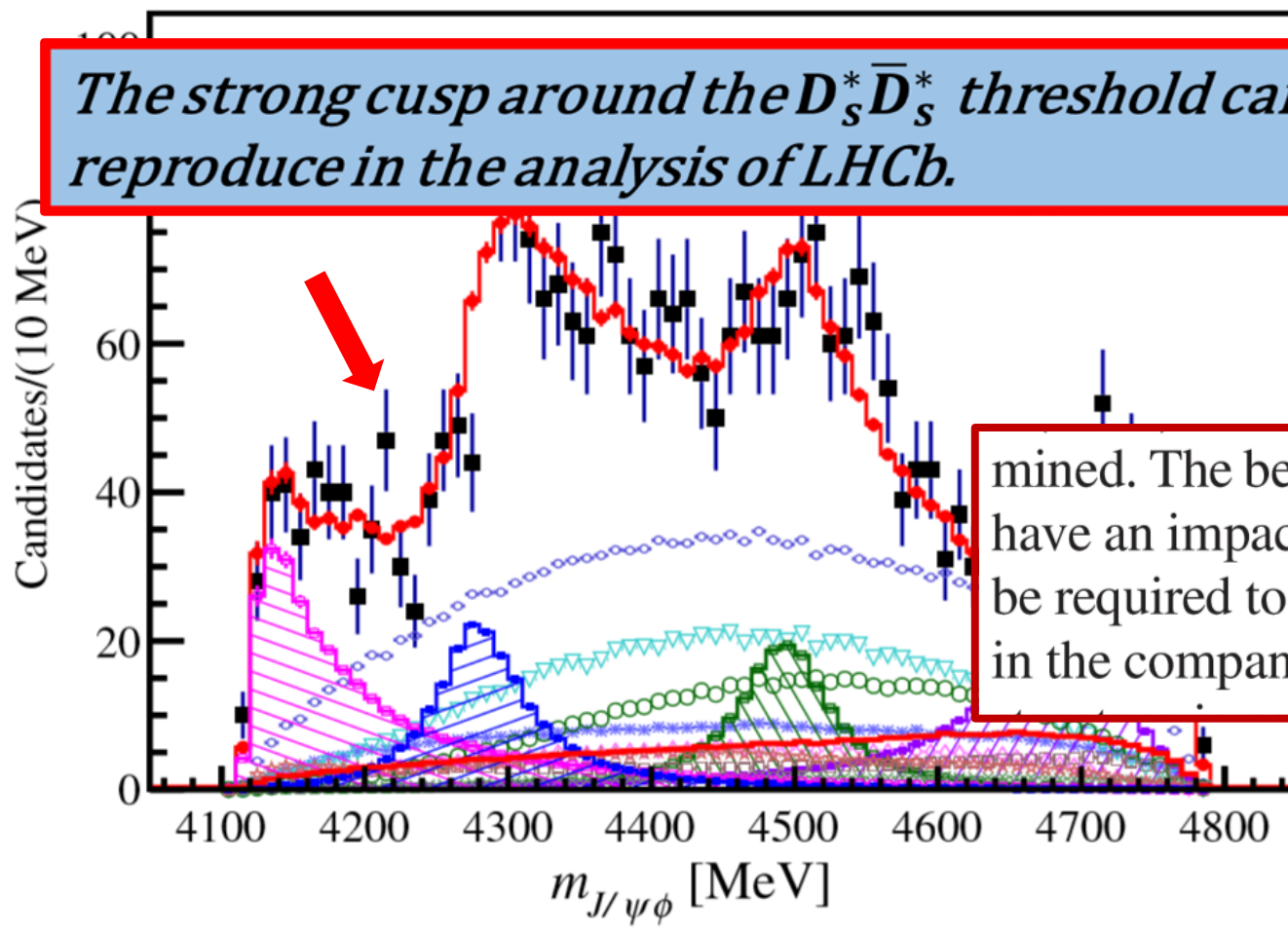
X(4140): $J^{PC}=1^{++}$

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

The LHCb measurement

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



states are observed.

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

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)

	1 ⁺⁺	1 ⁻⁺	1 ⁻	1 ⁺	1 ⁻
	10.4σ	6.4σ	6.5σ	8.3σ	9.0σ
2 ⁺⁺	7.6σ	7.2σ	5.6σ	6.8σ	9.0σ
2 ⁻⁺	9.6σ	6.4σ	6.5σ	6.3σ	9.0σ

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

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

Seen by AALTONEN 2009AH, ABAZOV 2014A, CHATRCHYAN 2014M, AAIJ 2017C in $B^+ \rightarrow XK^+$, $X \rightarrow J/\psi\phi$, and by ABAZOV 2015M separately in both prompt (4.7σ) and non-prompt (5.6σ) production in $p\bar{p} \rightarrow J/\psi\phi + \text{anything}$. Not seen by SHEN 2010 in $\gamma\gamma \rightarrow J/\psi\phi$ and ABLIKIM 2015 in $e^+e^- \rightarrow \gamma J/\psi\phi$ at $\sqrt{s} = 4.23, 4.26, 4.36$ GeV.

X(4140) MASS

4146.8 ± 2.5 MeV (S = 1.1)

X(4140) WIDTH

19^{+8}_{-7} MeV (S = 1.4)

PDG2017

The large width of X(4140)

Experiment	N_B	Mass (MeV)	Width (MeV)	σ	Fraction (%)
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CDF [26]	115	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$	5.0	$15 \pm 4 \pm 2$

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

D0 [25]	187	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$	4.7-5.7	
Average		4147.1 ± 2.4	15.7 ± 6.3		

PRL118,2017

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X(4140) MASS

4146.8 ± 2.5 MeV (S = 1.1)

X(4140) WIDTH

19^{+8}_{-7} MeV (S = 1.4)

PDG2017

Exotic states in $B^+ \rightarrow J/\psi \phi K^+$

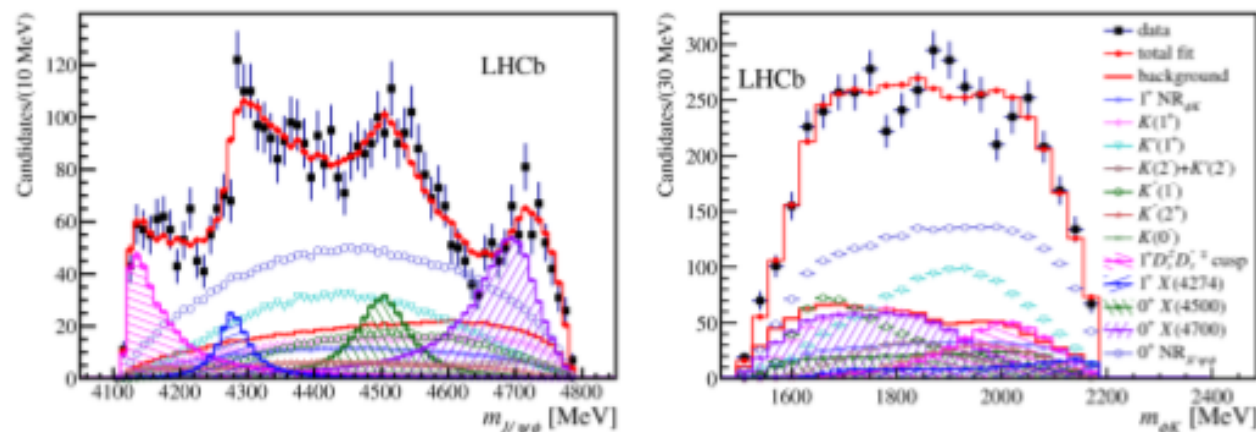
- LHCb perform full 6D amplitude analysis

LHCb-PAPER-2016-018

PRL 118 (2017)022003

LHCb-PAPER-2016-019

PRD 95 (2017) 012002



Silde of Y.N.Gao, 2018.3.31
第一届强子与重味物理理论与实验
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- 4 peaks are observed with X(4140) wider than CDF/DO/CMS

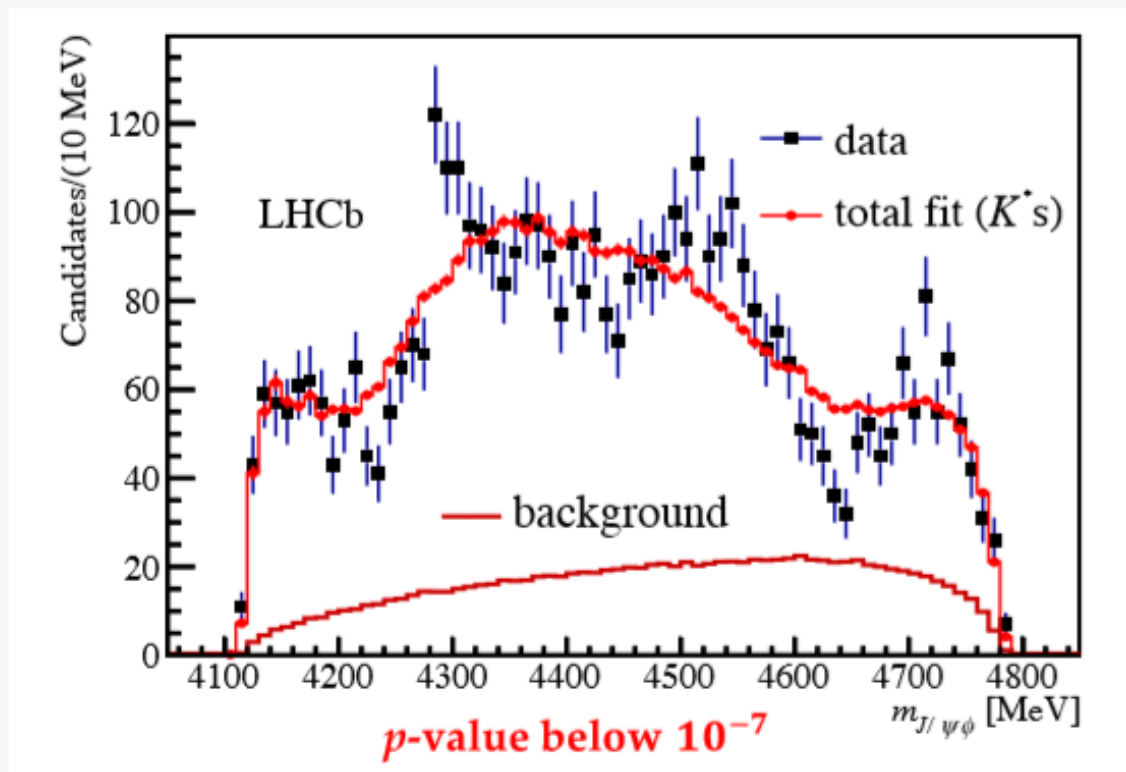
State	Signif	J^{PC}	M [MeV]	Γ [MeV]
X(4140)	8.4σ	1^{++}	$4160 \pm 4^{+5}_{-3}$	$83 \pm 21^{+21}_{-14}$
X(4274)	5.8σ	1^{++}	$4273 \pm 8^{+17}_{-4}$	$56 \pm 11^{+8}_{-11}$
X(4500)	6.1σ	0^{++}	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$
X(4700)	5.6σ	0^{++}	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$

Significant larger at LHCb
 $\Gamma_{\text{avg}}^{\text{CDF/DO/CMS}} = 15.7 \pm 6.3 \text{ MeV}$



K^{*} 's-only hypothesis fit:

- $M_{\phi K}$ and $M_{J/\psi K}$ can be described by model
- $M_{J/\psi \phi}$ is not described by fit



→ non- K^* resonances needed:

- $Z^+ \rightarrow J/\psi K^+$ - does not lead to significant improvements
- $X \rightarrow J/\psi \phi$



Decays of mesons at LHCb

Andrii Usachov
on behalf of the LHCb collaboration

Université Paris-Sud / Laboratoire de l'Accélérateur Linéaire
Orsay, France

Quarkonium 2017

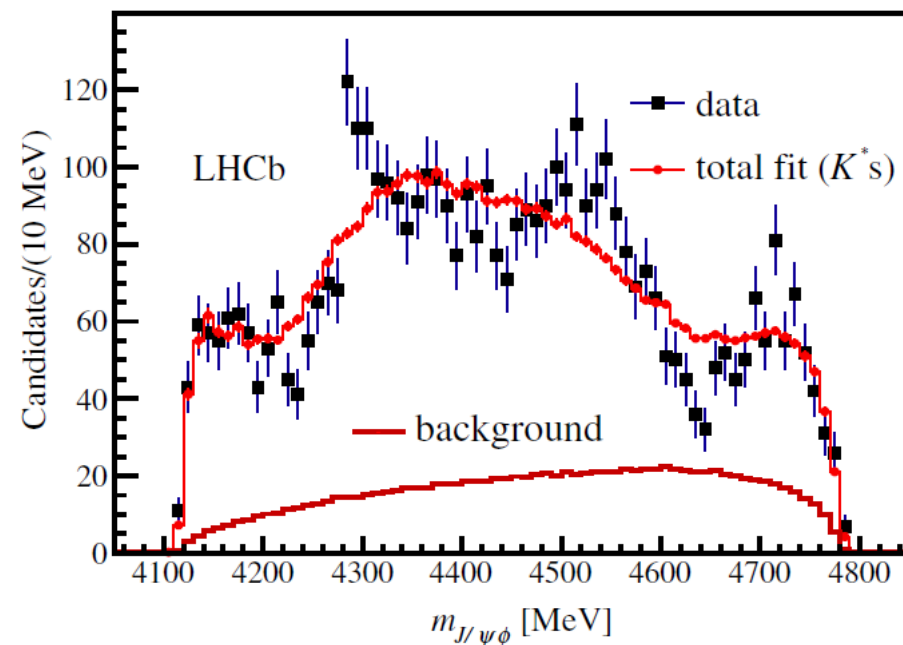
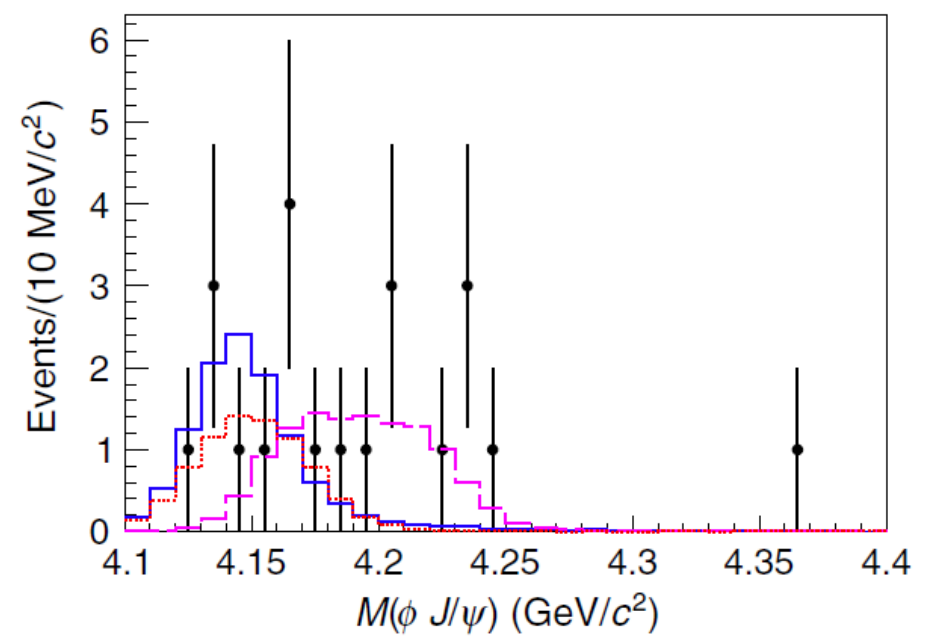
BESIII

Observation of $e^+e^- \rightarrow \phi\chi_{c1}$ 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

second systematic. **No significant signals** are observed for $e^+e^- \rightarrow \phi\chi_{c0}$ and $e^+e^- \rightarrow \gamma X(4140)$ 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:**

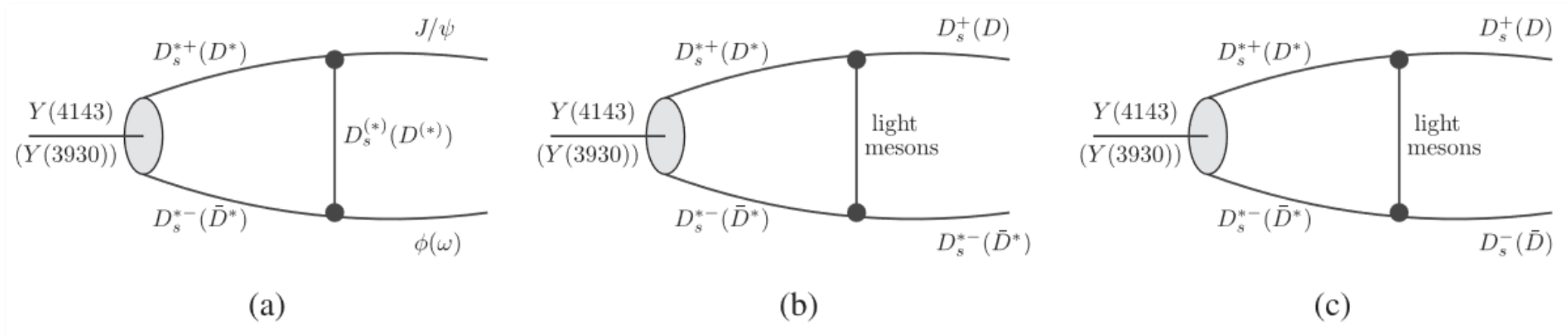
Mahajan, PLB679(2009), Z.G. Wang, EPJC63(2009)

- **Rescattering effect:**

X. Liu, PLB680(2009)

X(4140) as the $D_s^* \bar{D}_s^*$ molecule

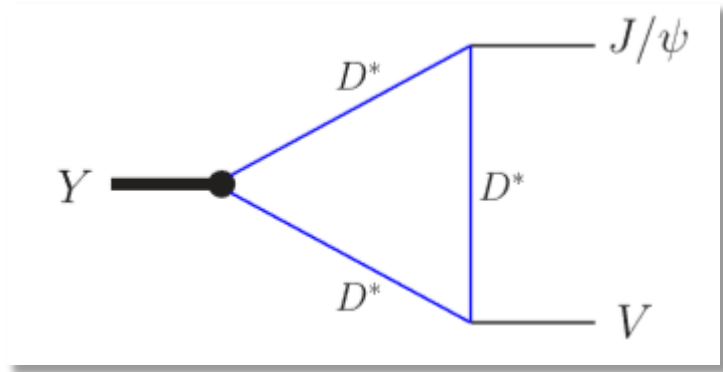
- Meson exchange model, X. Liu, S.L. Zhu, PRD80(2009)



- The X(4140) is predicted to be $J^{PC}=0^{++}, 2^{++}$

X(4140) as the $D_s^* \bar{D}_s^*$ molecule

- The meson-exchange potentials generated by the Lagrangian of heavy hadron chiral perturbation theory



$$\begin{aligned}\mathcal{L}_{D^*D^*J_\psi} &= ig_{D^*D^*J_\psi} J_\psi^\mu (D_{\mu i}^{*\dagger} \overleftrightarrow{\partial}_\nu D_i^{*\nu} + D_{\nu i}^{*\dagger} \overleftrightarrow{\partial}^\nu D_{\mu i}^* \\ &\quad - D_i^{*\dagger \nu} \overleftrightarrow{\partial}_\mu D_{\nu i}^*), \\ \mathcal{L}_{D^*D^*V} &= ig_{D^*D^*V} V_{ij}^\mu D_{\nu i}^{*\dagger} \overleftrightarrow{\partial}_\mu D_j^{*\nu} + 4if_{D^*D^*V} (\partial^\mu V_{ij}^\nu \\ &\quad - \partial^\nu V_{ij}^\mu) D_{\mu i}^* D_j^{*\dagger \nu}\end{aligned}$$

- The X(4140) with $J^{PC}=0^{++}, 2^{++}$
T. Branz, et. al, PRD80(2009)



X(4140) as the $D_S^* \bar{D}_S^*$ molecule

- **Vector meson exchange, Bethe-Salpeter equations**
X.Z.Chen, X.F.lv, R.B.Shi, X.R.Guo, 1512.06483
- **η exchange, M. Karliner, NPA954(2016)**
- **QCD sum rules**
J.R. Zhang, M.Q.Huang, JPG37(2010),
ZGWang, EPJC63(2009),
ZGWang, YF.Tian, IJMPA30(2015)
- **η , ϕ , σ exchange, G.J.Ding, EPJC64(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. Molina¹ and E. Oset¹

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

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

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

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



$D_s^* \bar{D}_s^*$ 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 $e^+ e^- \rightarrow J/\psi X$, $X \rightarrow D^* \bar{D}^*$

(Re)

• Vector-

$X(4160)$ MASS

4156_{-25}^{+29} MeV

$X(4160)$ WIDTH

139_{-60}^{+110} MeV

pole).

$D^* \bar{D}^*(4017)$, $D_s^* \bar{D}_s^*(4225)$, $K^* \bar{K}^*(1783)$,
 $\rho\rho(1551)$, $\omega\omega(1565)$,
 $\phi\phi(2039)$, $J/\psi J/\psi(6194)$, $\omega J/\psi(3880)$,
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$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$1257 + i2866$	$2681 + i940$	$-866 + i2752$	$-2617 - i5151$	$1012 + i1522$



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

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

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

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

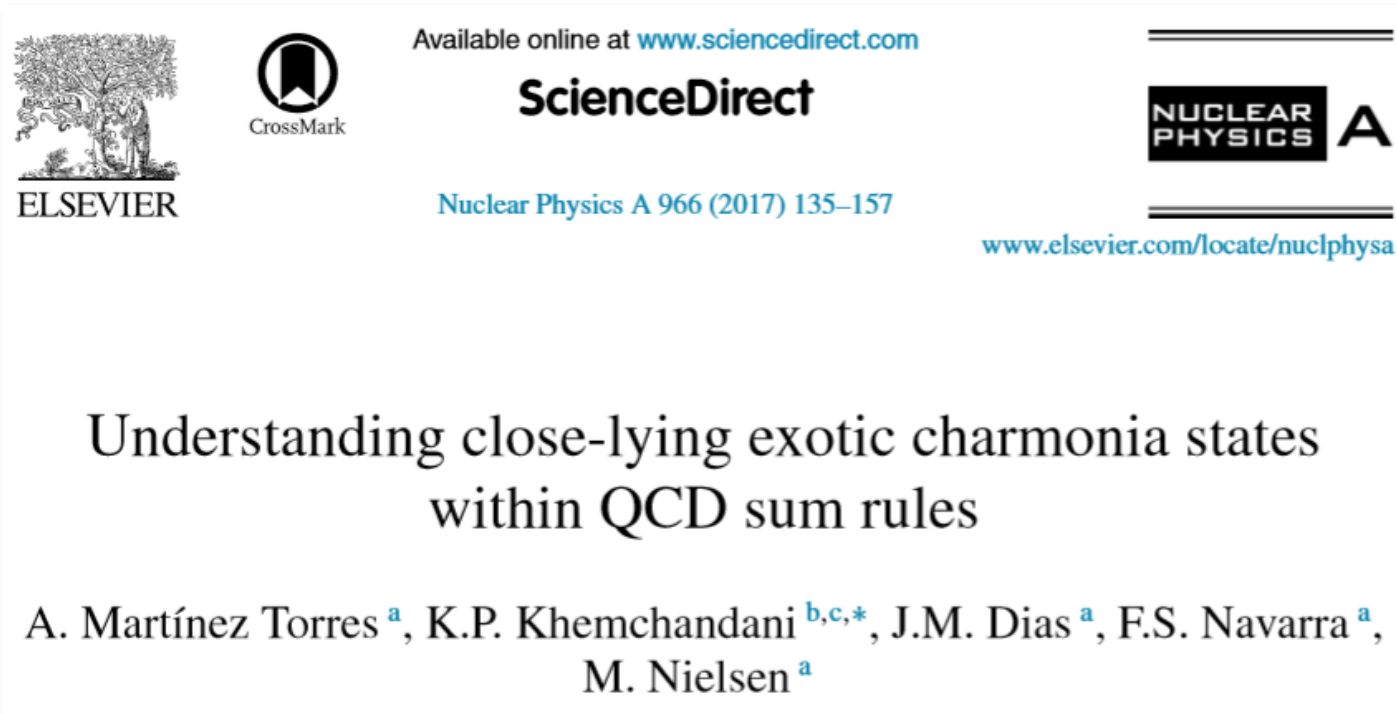
- Vector-vector exchange within local hidden gauge approach

$D^* \bar{D}^*(4017)$, $D_s^* \bar{D}_s^*(4225)$, $K^* \bar{K}^*(1783)$,
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TABLE V. Couplings g_i in units of MeV for $I = 0$, $J = 2$ (second pole).

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$1225 - i490$	$18\,927 - i5524$	$-82 + i30$	$70 + i20$	$3 - i2441$
$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$1257 + i2866$	$2681 + i940$	$-866 + i2752$	$-2617 - i5151$	$1012 + i1522$

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



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	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

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

Seen by AALTONEN 2009AH, ABAZOV 2014A, CHATRCHYAN 2014M, AAIJ 2017C in $B^+ \rightarrow XK^+$, $X \rightarrow J/\psi\phi$, and by ABAZOV 2015M separately in both prompt (4.7σ) and non-prompt (5.6σ) production in $p\bar{p} \rightarrow J/\psi\phi + \text{anything}$. Not seen by SHEN 2010 in $\gamma\gamma \rightarrow J/\psi\phi$ and ABLIKIM 2015 in $e^+e^- \rightarrow \gamma J/\psi\phi$ at $\sqrt{s} = 4.23, 4.26, 4.36$ GeV.

X(4140) MASS

4146.8 ± 2.5 MeV (S = 1.1)

X(4140) WIDTH

19^{+8}_{-7} MeV (S = 1.4)

PDG2017

$D_s^* \bar{D}_s^*$ 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	5.2σ	4.9σ
1^{-+}	10.4σ	6.4σ	6.5σ	8.2σ

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.

Seen by AALTONEN 2009AH, ABAZOV 2014A, CHATRCHYAN 2014M, AAIJ 2017C in $B^+ \rightarrow XK^+$, $X \rightarrow J/\psi\phi$, and by ABAZOV 2015M separately in both prompt (4.7σ) and non-prompt (5.6σ) production in $p\bar{p} \rightarrow J/\psi\phi + \text{anything}$. Not seen by SHEN 2010 in $\gamma\gamma \rightarrow J/\psi\phi$ and ABLIKIM 2015 in $e^+e^- \rightarrow \gamma J/\psi\phi$ at $\sqrt{s} = 4.23, 4.26, 4.36$ GeV.

X(4140) MASS

4146.8 ± 2.5 MeV (S = 1.1)

X(4140) WIDTH

19^{+8}_{-7} MeV (S = 1.4)

PDG2017

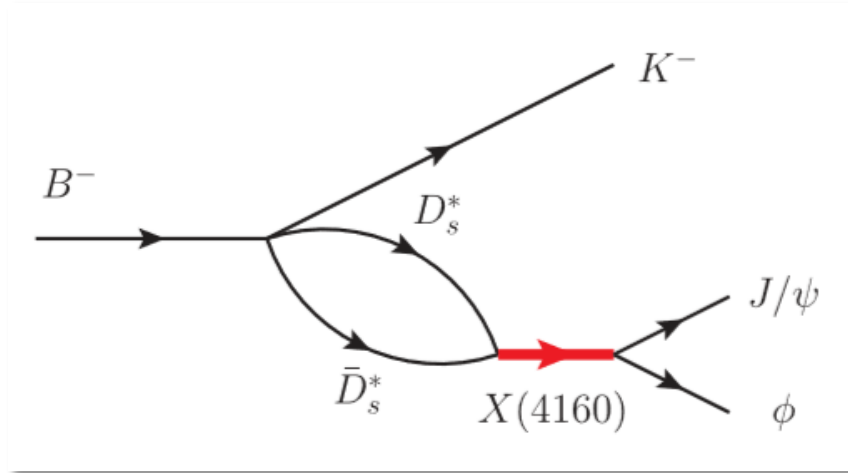


How is the molecule like?

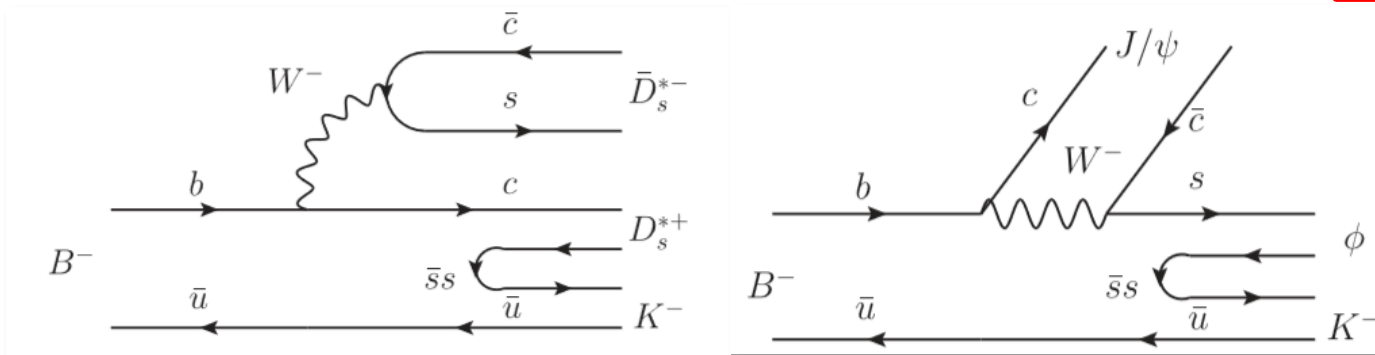
- It decays into a heavy quarkonium plus a light meson with nozero isospin, for instance, Z_c , Z_b .
- One of the defining features associated to the molecular states that couple to several hadron-hadron channels is that one can find a strong and unexpected cusp in one of the weakly coupled channels at the threshold of the channels corresponding to the main component of the molecular state.
- Dai,Dias,Oset,EPJC78(2018)
- Ewang,JJXie,LSGeng,Oset,PRD97(2019);1806.05113
- Dai,GYWang,Xchen,Ewang,DMLi,Oset,1808.10371

LHCb: $B^+ \rightarrow J/\psi \phi K^+$
PRD97(2018)014017

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



- The internal conversion is suppressed by **color factors** with respect to the external emission.
- The mechanism with the $J/\psi \phi$ 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.



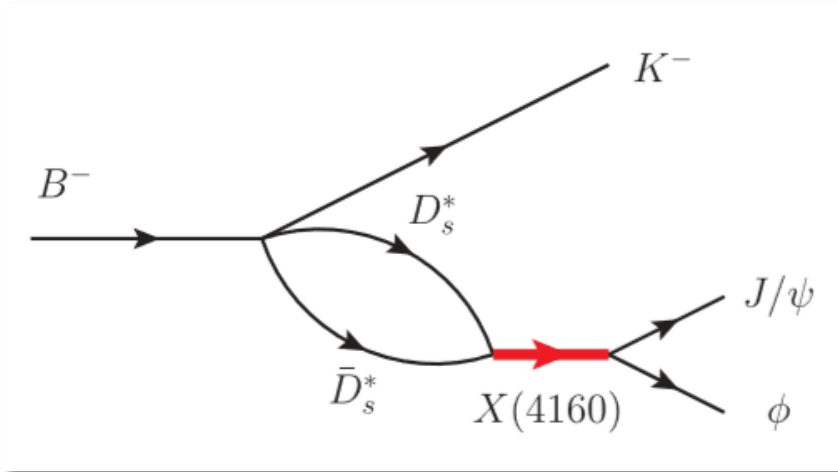
External emission

Internal conversion

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

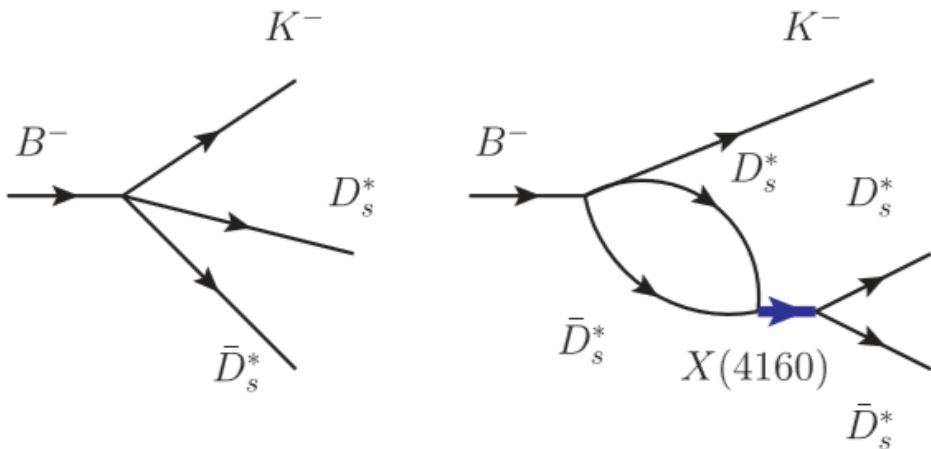
$\sqrt{s_{\text{pole}}} = 4169 + i66, I^G[J^{PC}] = 0^+[2^{++}]$				
$D^* \bar{D}^*$	$D_s^* \bar{D}_s^*$	$K^* \bar{K}^*$	$\rho \rho$	$\omega \omega$
$1225 - i490$	$18\,927 - i5524$	$-82 + i30$	$70 + i20$	$3 - i2441$
$\phi \phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega \phi$
$1257 + i2866$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

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



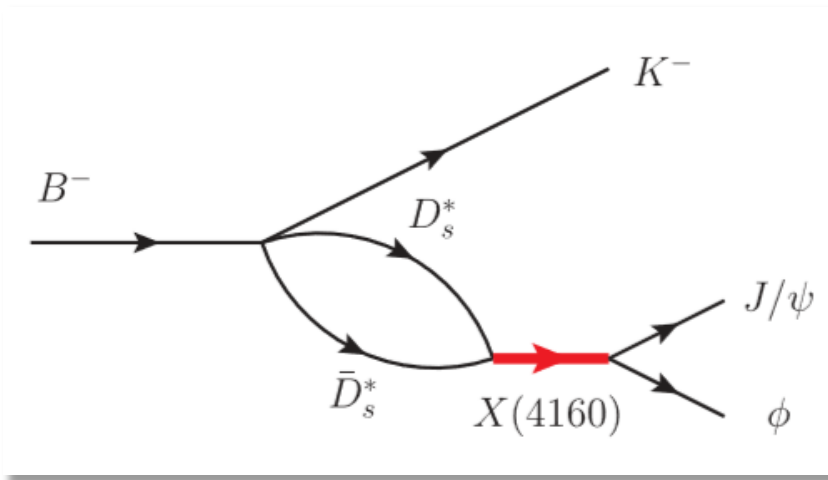
The X(4160) is $JPC=2^{++}$ state with $L=0$ in $D_s^* \bar{D}_s^*$.
We need a D-wave in the K^- to match the angular momentum in the reaction.

$$t_{B^- \rightarrow K^- D_s^* \bar{D}_s^*}^{\text{tree}} = A \left(\vec{\epsilon} \cdot \vec{k} \vec{\epsilon}' \cdot \vec{k} - \frac{1}{3} k^2 \vec{\epsilon} \cdot \vec{\epsilon}' \right),$$



where $\vec{\epsilon}, \vec{\epsilon}'$ are the polarization vectors of D_s^* and $\bar{D}_s^*$,
 $\vec{k}$ 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 $B^- \rightarrow J/\psi \phi K^-$



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.

$$t_{B^- \rightarrow K^- D_s^* \bar{D}_s^*}^{\text{tree}} = A \left(\vec{e} \cdot \vec{k} \vec{e}' \cdot \vec{k} - \frac{1}{3} \vec{k}^2 \vec{e} \cdot \vec{e}' \right),$$

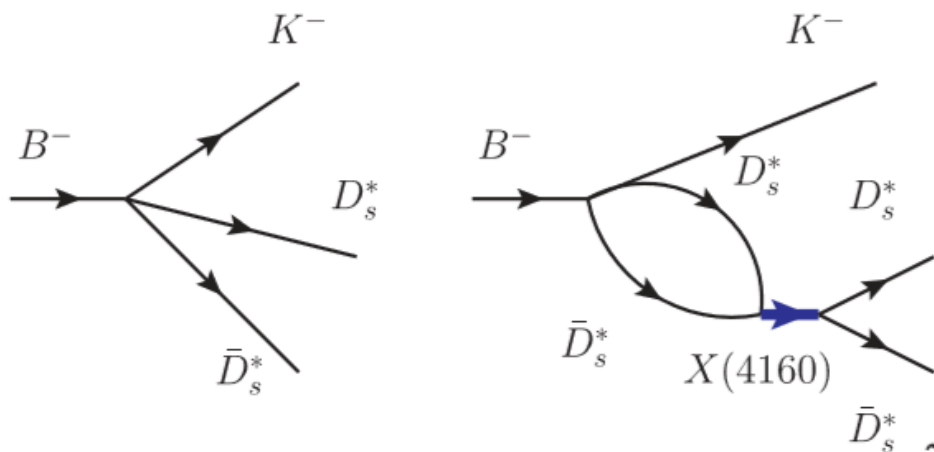
The sum over polarizations of $|t|^2$ is

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

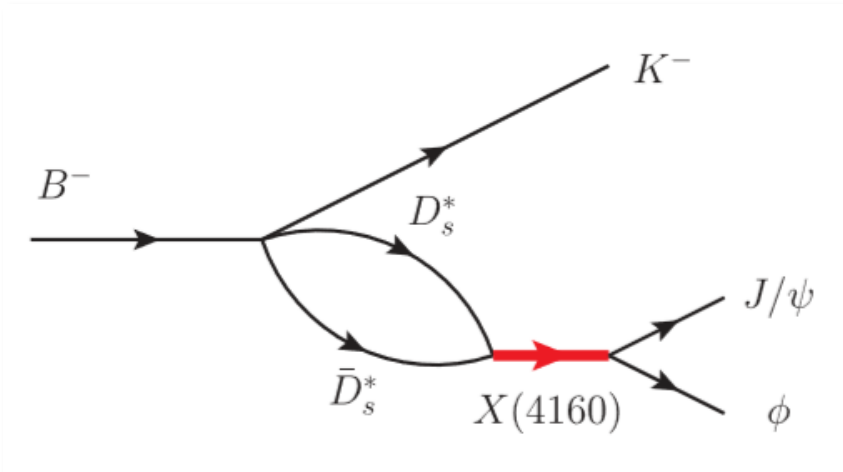
$$\frac{d\Gamma}{dM_{\text{inv}}(D_s^* \bar{D}_s^*)} = \frac{1}{(2\pi)^3} \frac{1}{4M_{B^-}^2} \frac{2}{3} |\vec{k}|^4 |\vec{k}'| \tilde{p}_{D_s^*} |A|^2$$

$\vec{k}'$ 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. 29



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



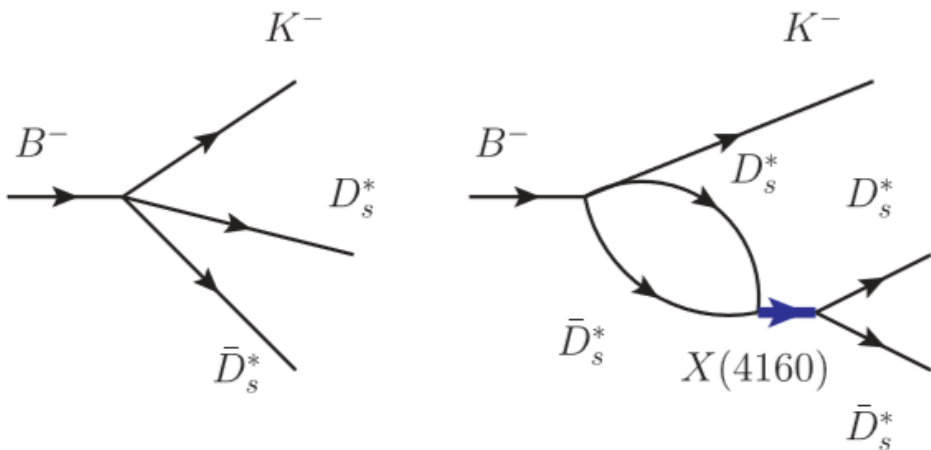
$$\frac{d\Gamma}{dM_{\text{inv}}(D_s^* \bar{D}_s^*)} = \frac{1}{(2\pi)^3} \frac{1}{4M_{B^-}^2} \frac{2}{3} |\vec{k}|^4 |\vec{k}'| \tilde{p}_{D_s^*} |A|^2,$$

For the mass distribution of $J/\psi\phi$

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

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

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



The contribution of X(4160)

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

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

- The transition amplitudes are,

$$t_{D_s^* \bar{D}_s^* \rightarrow D_s^* \bar{D}_s^*} = \frac{g_{D_s^* \bar{D}_s^*}^2}{M_{\text{inv}}^2(D_s^* \bar{D}_s^*) - M_X^2 + iM_X \Gamma_X},$$

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

$$D^* \bar{D}^*(4017), \quad D_s^* \bar{D}_s^*(4225), \quad K^* \bar{K}^*(1783),$$

$$\rho \rho(1551), \quad \omega \omega(1565),$$

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

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

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

$\sqrt{s_{\text{pole}}} = 4169 + i66, I^G[J^{\text{PC}}] = 0^+[2^{++}]$				
$D^* \bar{D}^*$	$D_s^* \bar{D}_s^*$	$K^* \bar{K}^*$	$\rho \rho$	$\omega \omega$
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 contribution of X(4160)

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

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

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

- The transition amplitudes are,

$$\begin{aligned} t_{D_s^*\bar{D}_s^* \rightarrow D_s^*\bar{D}_s^*} &= \frac{g_{D_s^*\bar{D}_s^*}^2}{M_{\text{inv}}^2(D_s^*\bar{D}_s^*) - M_X^2 + iM_X\Gamma_X}, \\ t_{D_s^*\bar{D}_s^* \rightarrow J/\psi\phi} &= \frac{g_{D_s^*\bar{D}_s^*} g_{J/\psi\phi}}{M_{\text{inv}}^2(J/\psi\phi) - M_X^2 + iM_X\Gamma_X}, \end{aligned}$$

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

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

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

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

The contribution of X(4140)

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

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



$$t_{B^- \rightarrow K^- D_s^* \bar{D}_s^*}^{\text{tree}} = A \left(\vec{\epsilon} \cdot \vec{k} \vec{\epsilon}' \cdot \vec{k} - \frac{1}{3} \vec{k}^2 \vec{\epsilon} \cdot \vec{\epsilon}' \right),$$

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

The substitution:

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

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

$$A \rightarrow \frac{BM_{X(4140)}^4}{M_{\text{inv}}^2(J/\psi \phi) - M_{X(4140)}^2 + iM_{X(4140)}\Gamma_{X(4140)}}$$

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, $\chi^2/\text{dof}=15.3/(13-3)$

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

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

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

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

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

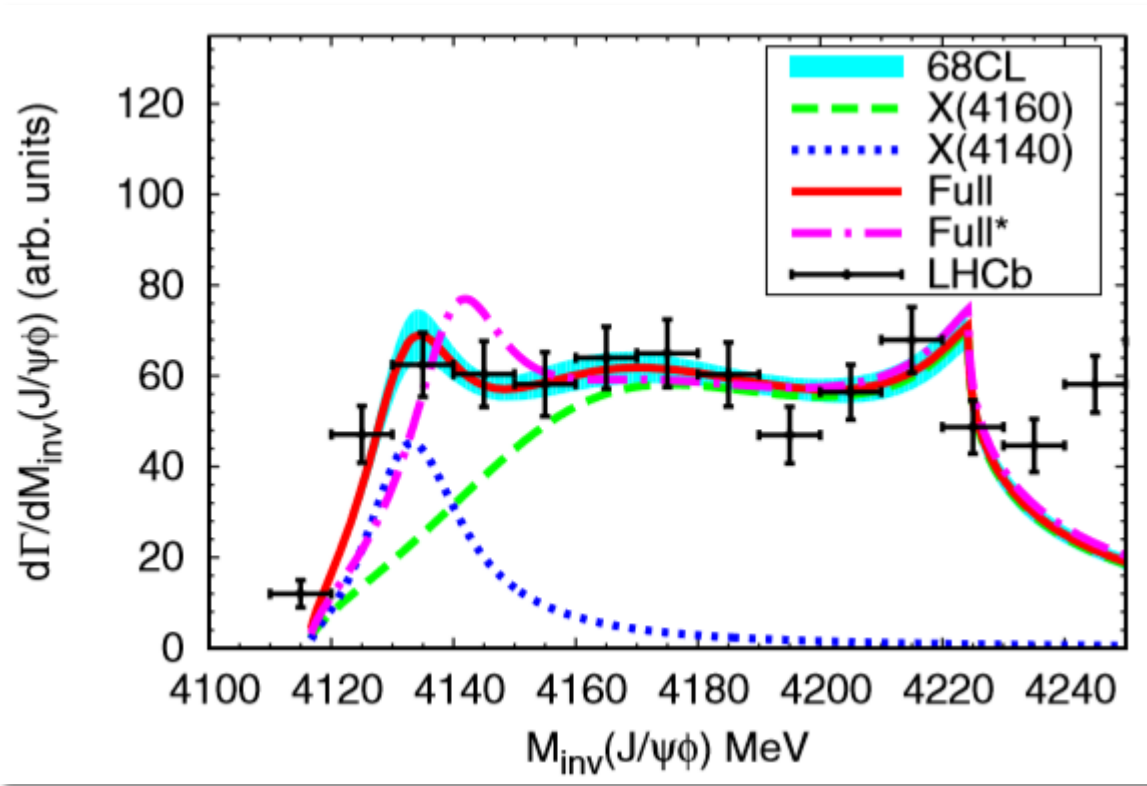
$X(4160)$ MASS

$4156^{+29}_{-25} \text{ MeV}$

$X(4160)$ WIDTH

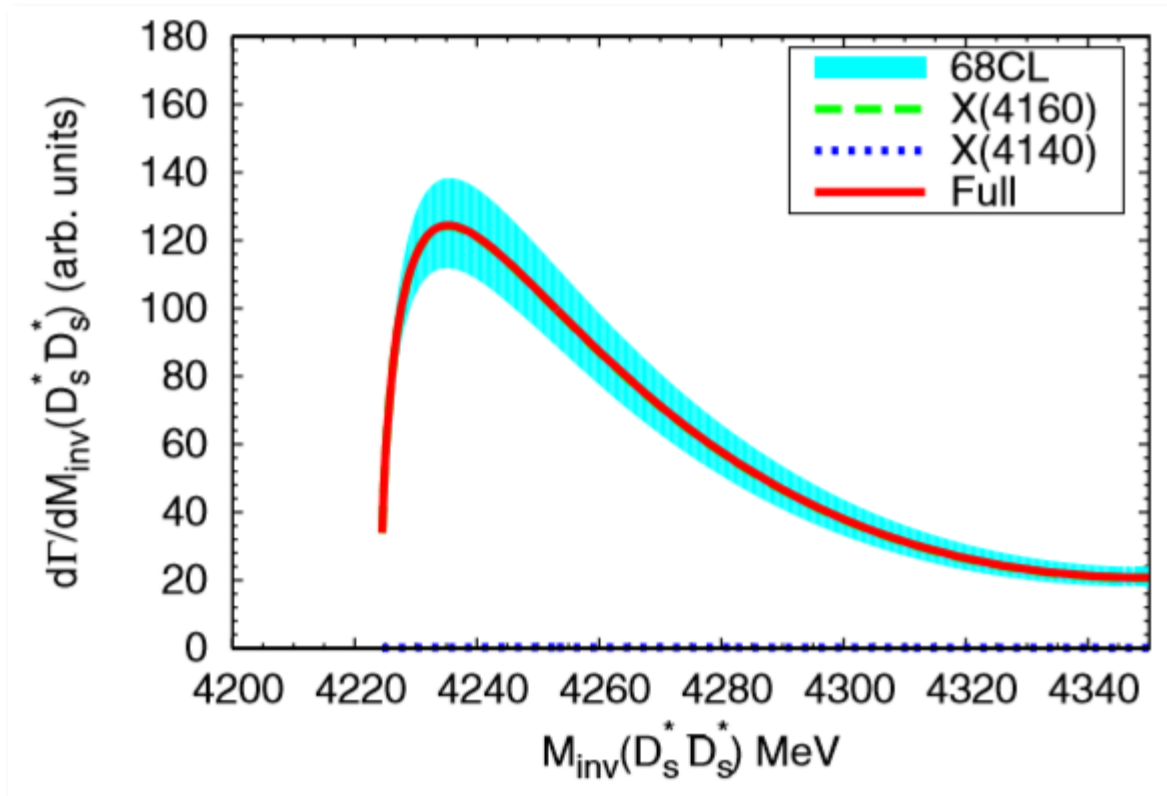
$139^{+110}_{-60} \text{ MeV}$

Results

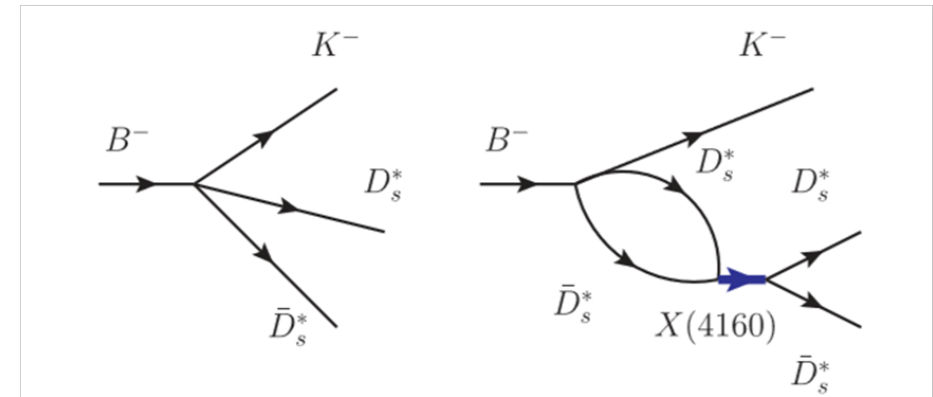


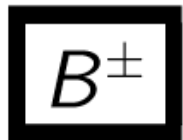
- The Flatte effect is visible, as a sharp fall down of the invariant mass distribution above the $D_s^* \bar{D}_s^*$ threshold.
- The lower part of the spectrum can be obtained from the contribution of X(4160) (2^{++}) and X(4140) (1^{++} , 19 MeV) resonances.
- The cusp of the distribution at the $D_s^* \bar{D}_s^*$ 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



- 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).





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

$$\Gamma_{169} \quad \bar{D}^*(2007)^0 D_{s1}(2536)^+ \times \quad (5.5 \pm 1.6) \times 10^{-4}$$

$$B(D_{s1}(2536)^+ \rightarrow D^*(2007)^0 K^+)$$

$$\Gamma_{196} \quad \bar{D}^*(2010)^- D^*(2010)^+ K^+ \quad (1.32 \pm 0.18) \times 10^{-3}$$

$$\Gamma_{210} \quad D_s^+ \bar{K}^0 < 8 \times 10^{-4} \text{ CL}=90\%$$

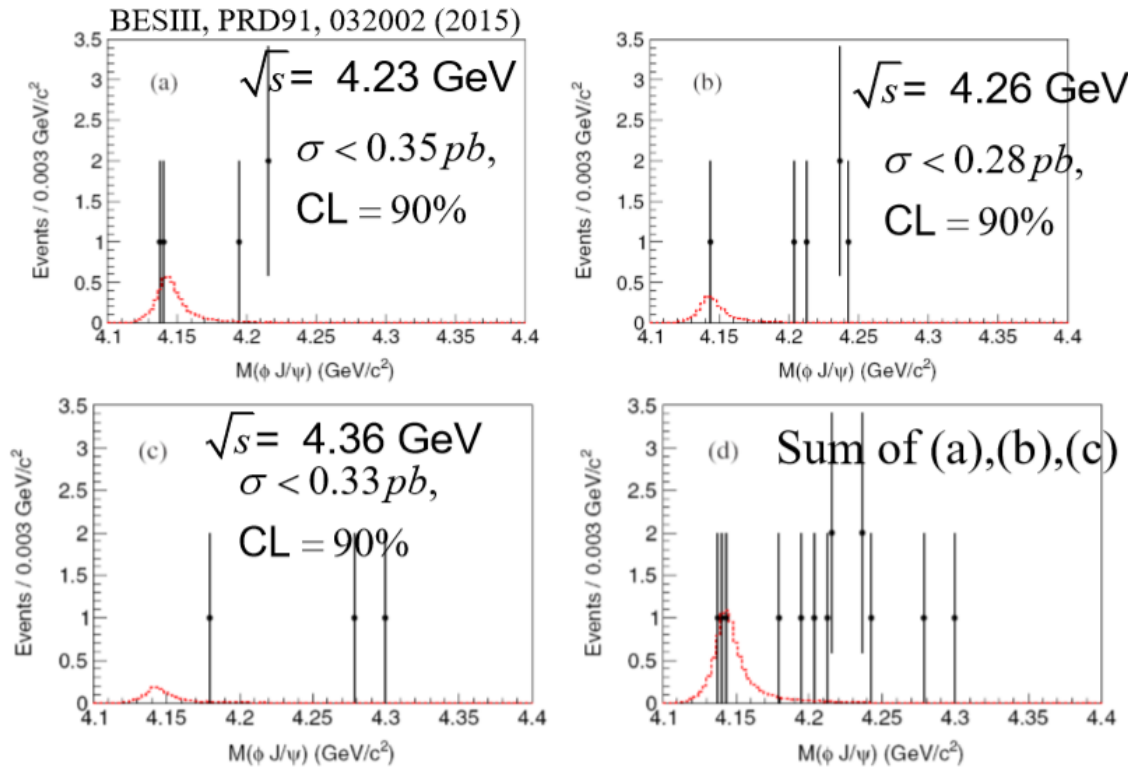
$$\Gamma_{211} \quad D_s^{*+} \bar{K}^0 < 9 \times 10^{-4} \text{ CL}=90\%$$

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

arxiv:1806.05113

X(4140)

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



Silde of R.G. Ping, 2018.3.31
 第一届强子与重味物理理论与实验
 联合研讨会@兰州

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

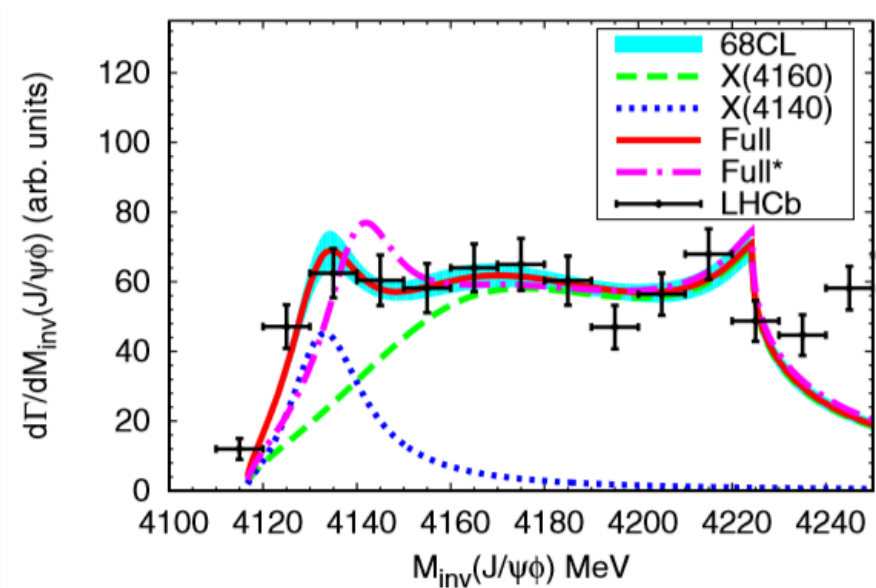
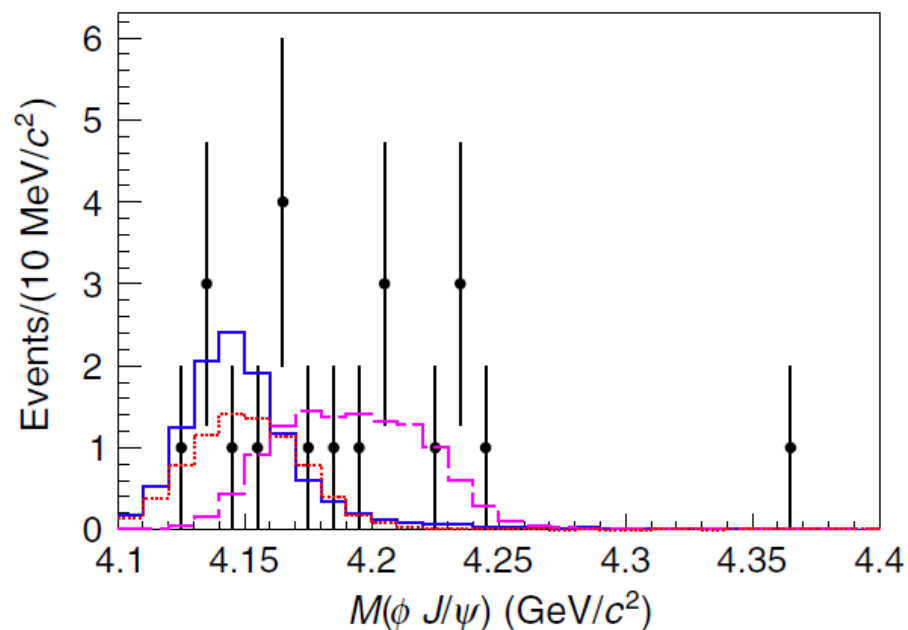
BESIII

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

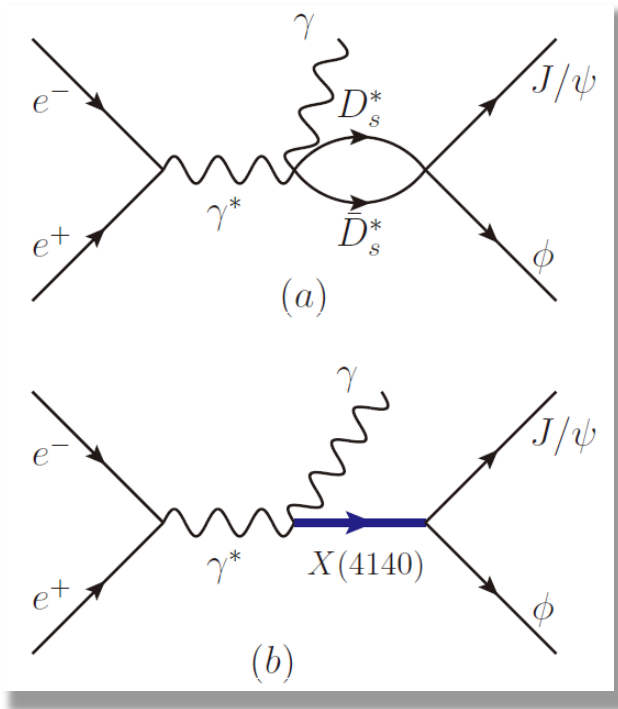
M. Ablikim *et al.* (BESIII Collaboration)

Phys. Rev. D **97**, 032008 – Published 12 February 2018

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



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



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

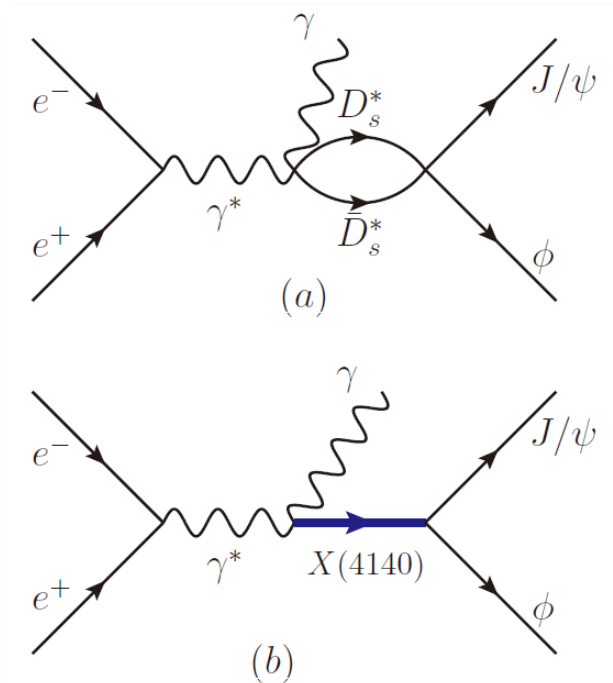
$$\begin{aligned}\mathcal{P}^{(a)} &= \left[\frac{1}{2} (\epsilon_{1i} \epsilon_{2j} + \epsilon_{1j} \epsilon_{2i}) - \frac{1}{3} \vec{\epsilon}_1 \cdot \vec{\epsilon}_2 \delta_{ij} \right] \\ &\times \left[\frac{1}{2} (\epsilon_{\phi i} \epsilon_{J/\psi j} + \epsilon_{\phi j} \epsilon_{J/\psi i}) -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

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

$$g_{D_s^* \bar{D}_s^*} = (18927 - 5524i) \text{ MeV}$$

$$g_{J/\psi\phi} = (-2617 - 5151i) \text{ MeV}$$

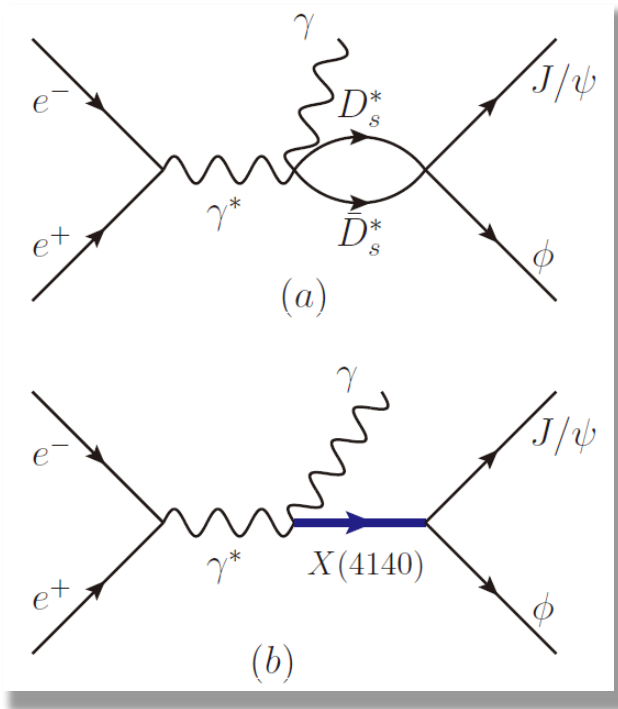
The mechanism for $J/\psi\phi$ production



$$\begin{aligned}\tilde{\mathcal{M}}_{J/\psi\phi}^{(b)} &= \frac{BM_{X_2}^2 \times \mathcal{P}^{(b)}}{M_{\text{inv}}^2(J/\psi\phi) - M_{X_2}^2 + iM_{X_2}\Gamma_{X_2}} \\ &= \mathcal{M}_{J/\psi\phi}^{(b)} \times \mathcal{P}^{(b)}, \\ \mathcal{P}^{(b)} &= \sum_{\text{pol}} [(\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot \vec{\epsilon}_{X_2}] [\vec{\epsilon}_{X_2} \cdot (\vec{\epsilon}_\phi \times \vec{\epsilon}_{J/\psi})] \\ &= (\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot (\vec{\epsilon}_\phi \times \vec{\epsilon}_{J/\psi}),\end{aligned}$$

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 $B^- \rightarrow J/\psi\phi K$ [4].

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

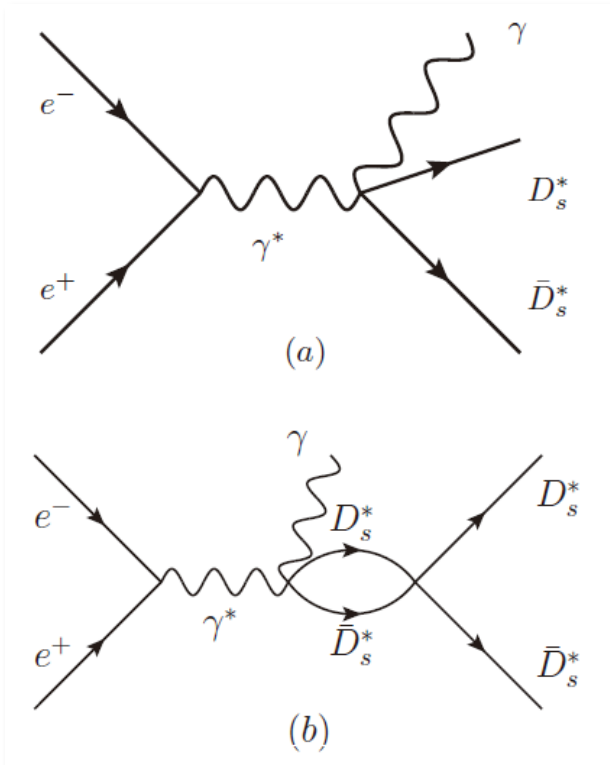


$$\frac{d\Gamma}{dM_{\text{inv}}(J/\psi\phi)} = \frac{1}{(2\pi)^3} \frac{1}{4s} k' \tilde{p}_\phi \left[|\mathcal{M}_{J/\psi\phi}^{(a)}|^2 + |\mathcal{M}_{J/\psi\phi}^{(b)}|^2 \right]$$

$$k' = \frac{\lambda^{1/2}(s, 0, M_{\text{inv}}^2(J/\psi\phi))}{2\sqrt{s}}$$

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

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

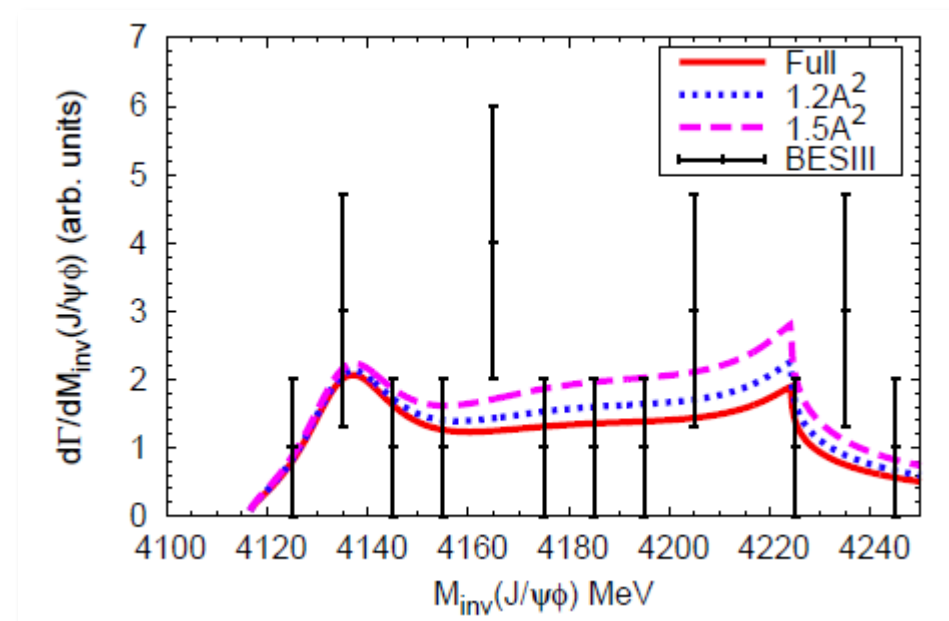
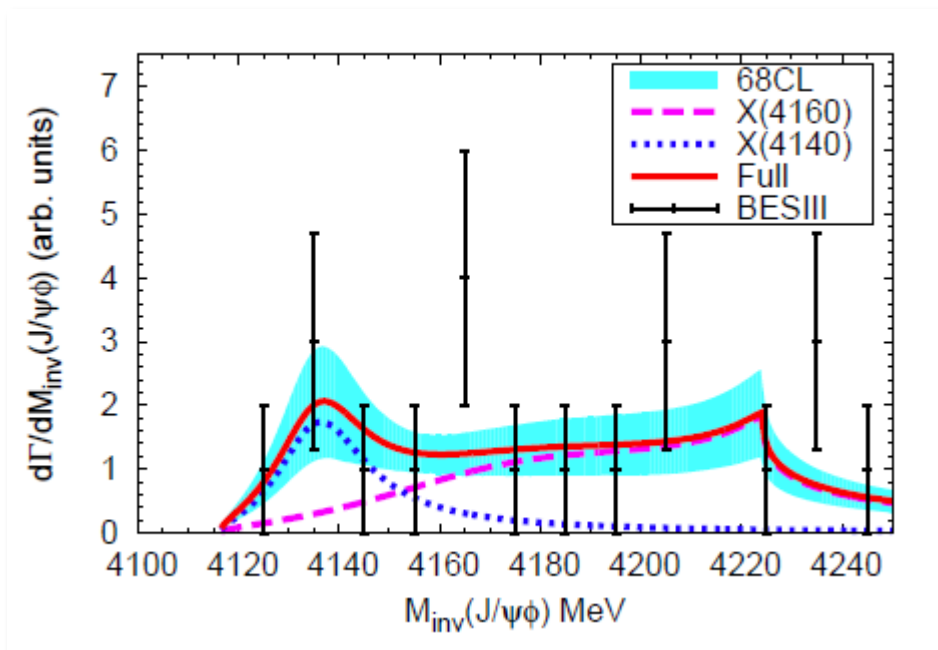


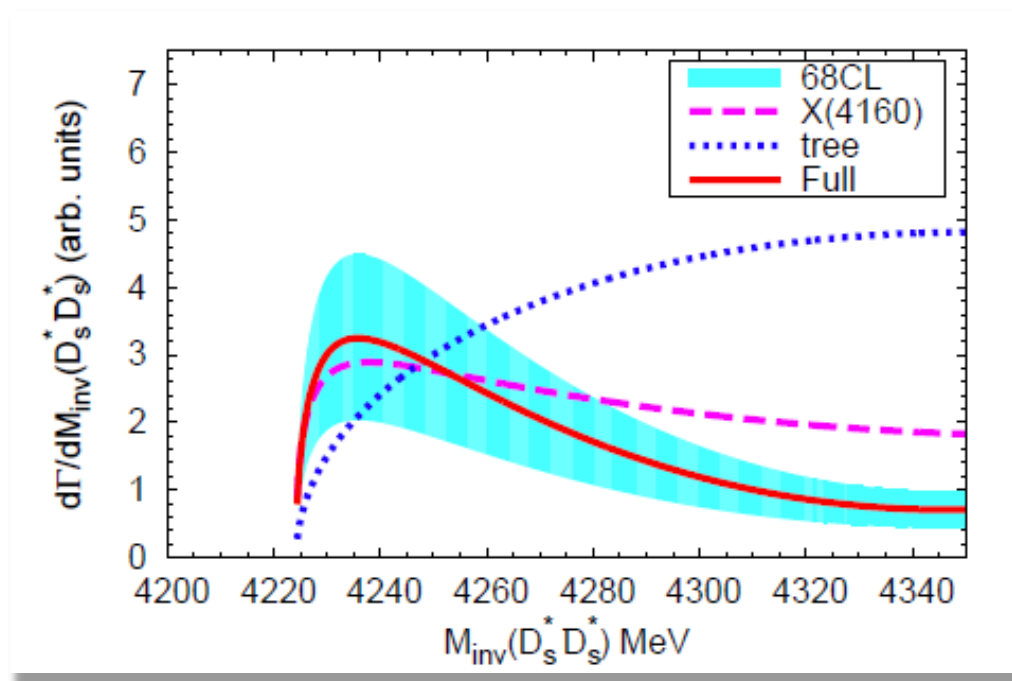
$$\frac{d\Gamma}{dM_{\text{inv}}(D_s^* \bar{D}_s^*)} = \frac{1}{(2\pi)^3} \frac{1}{4s} k' \tilde{p}_{D_s^*} |\mathcal{M}_{D_s^* \bar{D}_s^*}|^2,$$

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

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

Results

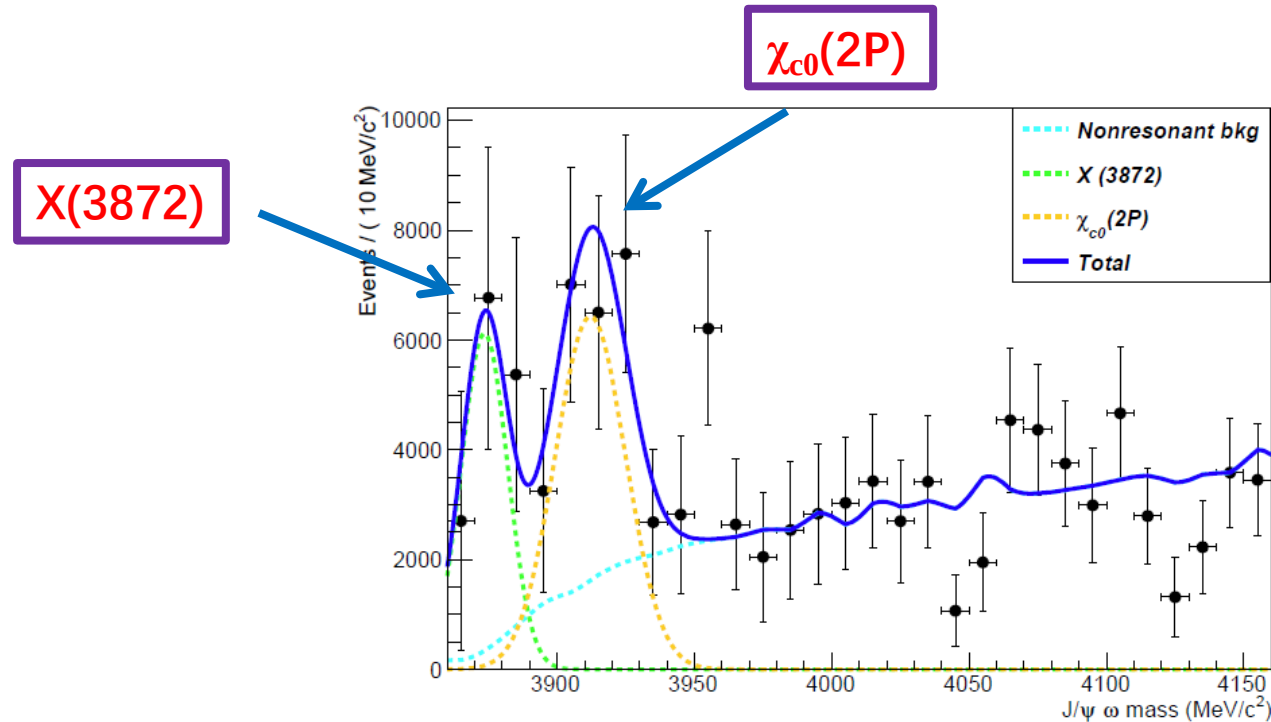




LHCb: $B^+ \rightarrow J/\psi \omega K^+$

arxiv:1808.10373

LHCb thesis 2014-243

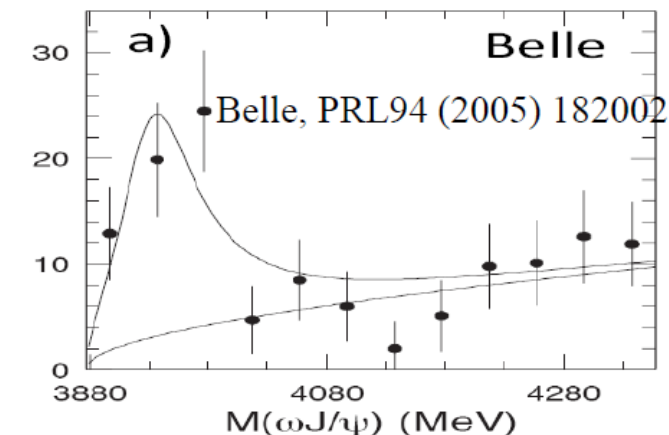


$\chi_{c0}(2P)$: X(3915)
 Is X(3915) the $\chi_{c0}(2P)$?
 HXChen, Phys.Rept. 639 (2016)
 Phys.Rev. D69 (2004) 094019

Figure 4.1: Fitted $J/\psi \omega$ efficiency-corrected invariant mass distribution.

$X(3915)$

□ $X(3915)$ in $B \rightarrow K\omega J/\psi$ observed by Belle and Babar



Belle: S-wave Breit-Wigner

$$M = 3943 \pm 17 \text{ MeV}$$

$$\Gamma = 87 \pm 24 \text{ MeV}$$

Babar:

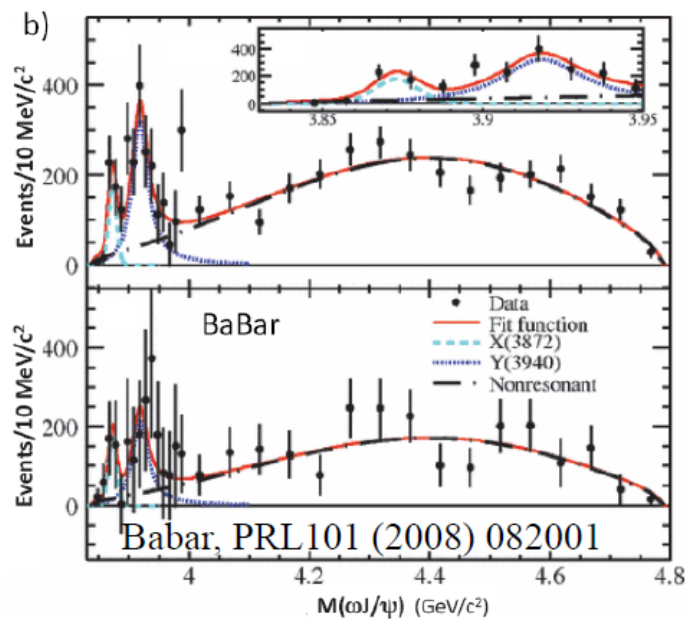
$$M = 3919 \pm 4 \text{ MeV}$$

$$\Gamma = 31 \pm 11 \text{ MeV}$$

Weighted average:

$$M = 3920 \pm 4 \text{ MeV}$$

$$\Gamma = 41 \pm 10 \text{ MeV}.$$





D*D* molecule states,X(3940),X(3930)

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

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

R. Molina¹ and E. Oset¹

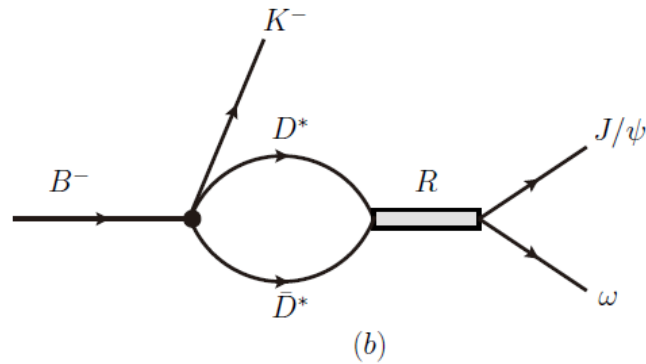
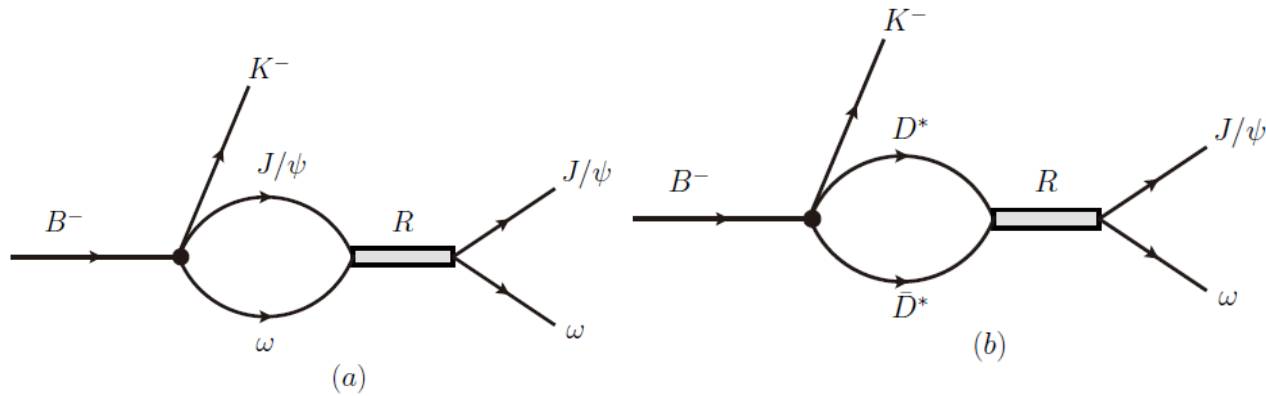
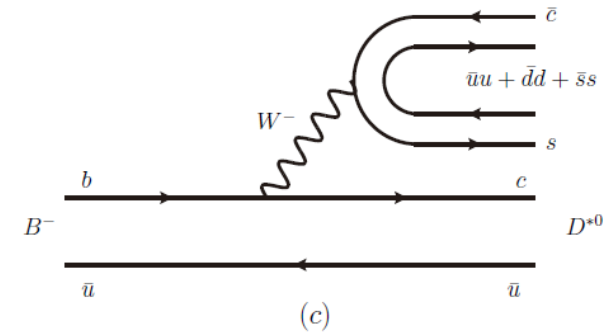
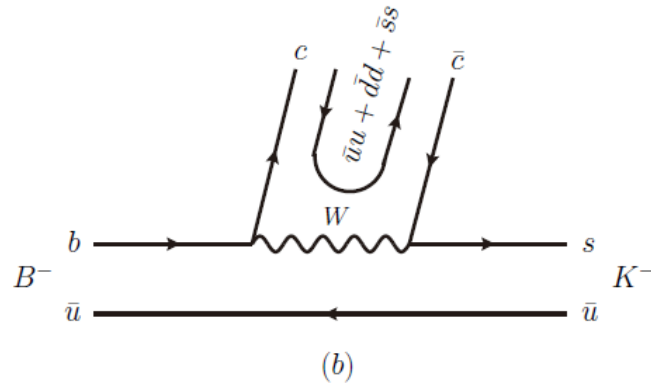
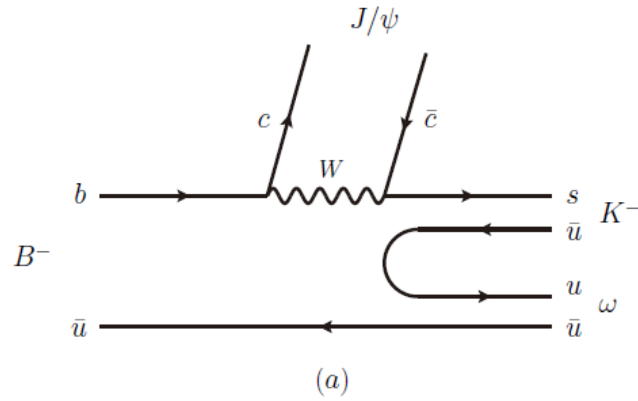
TABLE II. Couplings g_i in units of MeV for $I = 0, J = 0$.

$\sqrt{s_{\text{pole}}} = 3943 + i7.4, I^G[J^{\text{PC}}] = 0^+[0^{++}]$				
$D^*\bar{D}^*$	$D_s^*\bar{D}_s^*$	$K^*\bar{K}^*$	$\rho\rho$	$\omega\omega$
$18\,810 - i682$	$8426 + i1933$	$10 - i11$	$-22 + i47$	$1348 + i234$
$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$-1000 - i150$	$417 + i64$	$-1429 - i216$	$889 + i196$	$-215 - i107$

TABLE IV. Couplings g_i in units of MeV for $I = 0, J = 2$.

$\sqrt{s_{\text{pole}}} = 3922 + i26, I^G[J^{\text{PC}}] = 0^+[2^{++}]$				
$D^*\bar{D}^*$	$D_s^*\bar{D}_s^*$	$K^*\bar{K}^*$	$\rho\rho$	$\omega\omega$
$21\,100 - i1802$	$1633 + i6797$	$42 + i14$	$-75 + i37$	$1558 + i1821$
$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$-904 - i1783$	$1783 + i197$	$-2558 - i2289$	$918 + i2921$	$91 - i784$

The reaction



$$|H\rangle = |(D^{*0}\bar{D}^{*0} + D^{*+}\bar{D}^{*-} + D_s^{*+}\bar{D}_s^{*-} + 3C D^{*0}\bar{D}^{*0})K^- \rangle$$

$$= |[(1 + 3C)D^{*0}\bar{D}^{*0} + D^{*+}\bar{D}^{*-} + D_s^{*+}\bar{D}_s^{*-}] K^- \rangle.$$

Tree level

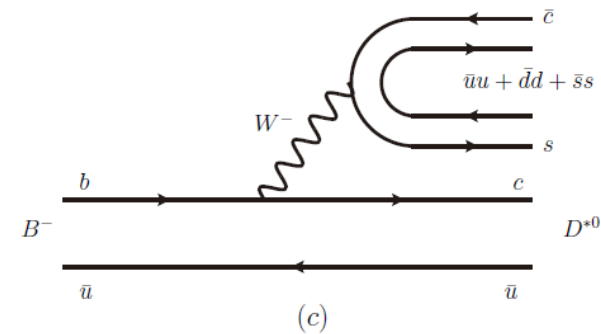
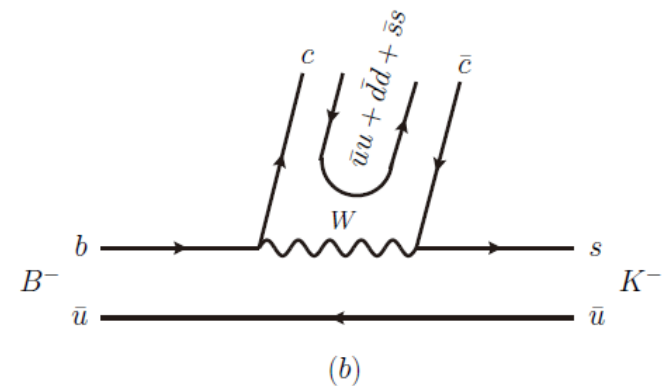
$$|H\rangle = |(D^{*0}\bar{D}^{*0} + D^{*+}\bar{D}^{*-} + D_s^{*+}\bar{D}_s^{*-} + 3C D^{*0}\bar{D}^{*0})K^{-}\rangle$$

$$= |[(1 + 3C)D^{*0}\bar{D}^{*0} + D^{*+}\bar{D}^{*-} + D_s^{*+}\bar{D}_s^{*-}] K^{-}\rangle.$$

$$t_{B^{-}\rightarrow K^{-}D^{*0}\bar{D}^{*0}}^{tree} = \left[A |\vec{k}_{av}|^2 \vec{\epsilon} \cdot \vec{\epsilon}' + B (\vec{\epsilon} \cdot \vec{k} \vec{\epsilon}' \cdot \vec{k} - \frac{1}{3} |\vec{k}|^2 \vec{\epsilon} \cdot \vec{\epsilon}') \right] (1 + 3C),$$

$$t_{B^{-}\rightarrow K^{-}D^{*+}D_s^{*-}}^{tree} = A |\vec{k}_{av}|^2 \vec{\epsilon} \cdot \vec{\epsilon}' + B (\vec{\epsilon} \cdot \vec{k} \vec{\epsilon}' \cdot \vec{k} - \frac{1}{3} |\vec{k}|^2 \vec{\epsilon} \cdot \vec{\epsilon}'),$$

$$t_{B^{-}\rightarrow K^{-}D_s^{*+}D_s^{*-}}^{tree} = A |\vec{k}_{av}|^2 \vec{\epsilon} \cdot \vec{\epsilon}' + B (\vec{\epsilon} \cdot \vec{k} \vec{\epsilon}' \cdot \vec{k} - \frac{1}{3} |\vec{k}|^2 \vec{\epsilon} \cdot \vec{\epsilon}'),$$



Final state interaction

$$\begin{aligned}
 t_1 = & G_{D^{*0}\bar{D}^{*0}}(M_{\text{inv}}) t_{D^{*0}\bar{D}^{*0} \rightarrow J/\psi \omega}^I (1 + 3C) \\
 & + G_{D^{*+}D^{*-}}(M_{\text{inv}}) t_{D^{*+}D^{*-} \rightarrow J/\psi \omega}^I \\
 & + G_{D_s^{*+}D_s^{*-}}(M_{\text{inv}}) t_{D_s^{*+}D_s^{*-} \rightarrow J/\psi \omega}^I,
 \end{aligned}$$

$$t_{D^{*0}\bar{D}^{*0}, J/\psi \omega}^i = \frac{\frac{1}{\sqrt{2}} g_{R, D^* \bar{D}^*}^{(i)} g_{R, J/\psi \omega}^{(i)}}{M_{\text{inv}}^2 - M_{R_i}^2 + i M_{R_i} \Gamma_{R_i}},$$

$$t_{D^{*+}D^{*-}, J/\psi \omega}^i = \frac{\frac{1}{\sqrt{2}} g_{R, D^* D^*}^{(i)} g_{R, J/\psi \omega}^{(i)}}{M_{\text{inv}}^2 - M_{R_i}^2 + i M_{R_i} \Gamma_{R_i}},$$

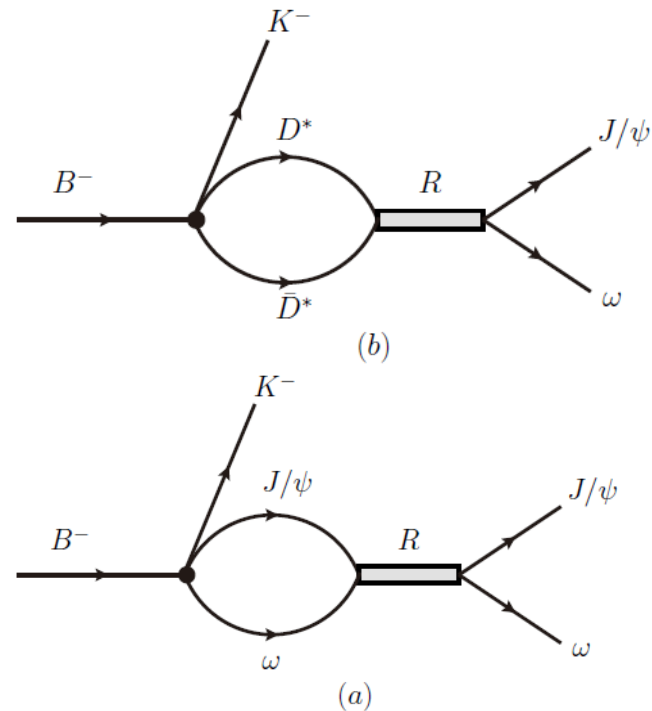
$$t_{D_s^{*+}D_s^{*-}, J/\psi \omega}^i = \frac{g_{R, D_s^{*+}D_s^{*-}}^{(i)} g_{R, J/\psi \omega}^{(i)}}{M_{\text{inv}}^2 - M_{R_i}^2 + i M_{R_i} \Gamma_{R_i}},$$

$$\begin{aligned}
 t_2 = & G_{D^{*0}\bar{D}^{*0}}(M_{\text{inv}}) t_{D^{*0}\bar{D}^{*0} \rightarrow J/\psi \omega}^{II} (1 + 3C) \\
 & + G_{D^{*+}D^{*-}}(M_{\text{inv}}) t_{D^{*+}D^{*-} \rightarrow J/\psi \omega}^{II} \\
 & + G_{D_s^{*+}D_s^{*-}}(M_{\text{inv}}) t_{D_s^{*+}D_s^{*-} \rightarrow J/\psi \omega}^{II},
 \end{aligned}$$

$$\Gamma_{R_i} = \Gamma_0^{(i)} + \Gamma_{J/\psi \omega}^{(i)} + \Gamma_{D^* \bar{D}^*}^{(i)},$$

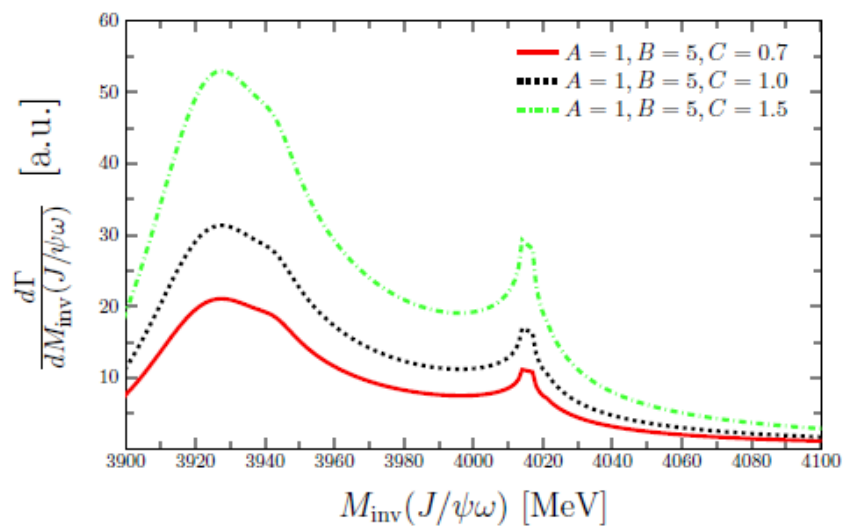
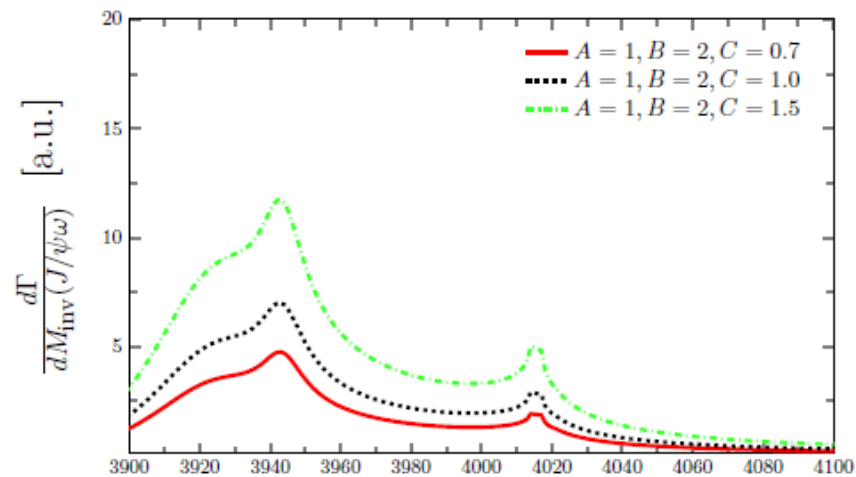
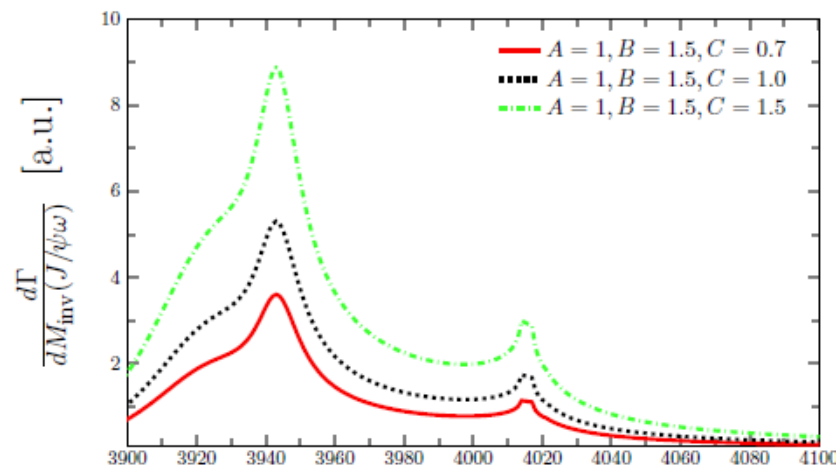
$$\Gamma_{J/\psi \omega}^{(i)} = \frac{|g_{R, J/\psi \omega}^i|^2}{8\pi M_{R_i}^2} \tilde{p}_\omega, \quad \Gamma_{D^* \bar{D}^*}^{(i)} = \frac{|g_{R, D^* \bar{D}^*}^i|^2}{8\pi M_{R_i}^2} \tilde{p}_{D^*} \Theta(M_{\text{inv}} - 2M_{D^*}),$$

$$\Gamma_0^{(i)} = \Gamma_{R_i} - \Gamma_{J/\psi \omega}^{(i)} (M_{\text{inv}}^{J/\psi \omega} = M_{R_i}).$$

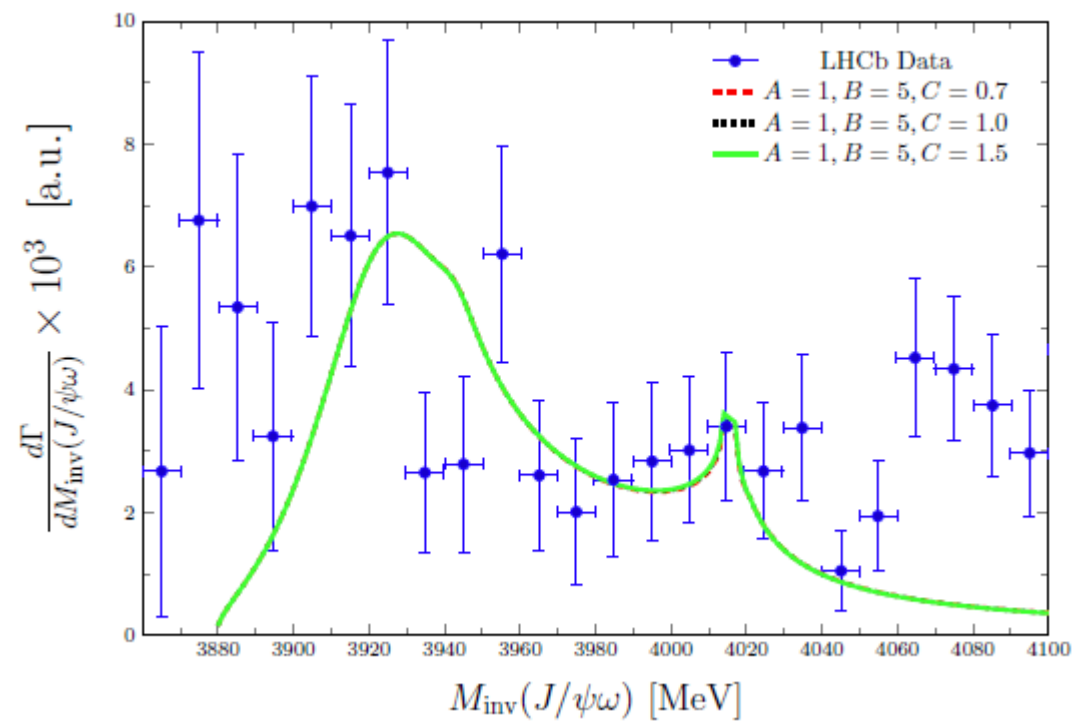


$$\begin{aligned}
 \frac{d\Gamma}{dM_{\text{inv}}^{J/\psi \omega}} = & \frac{1}{(2\pi)^3} \frac{1}{4M_B^2} k' \tilde{p}_\omega \\
 & \times \left(3|A|^2 |\vec{k}_{\text{av}}|^4 |t_1|^2 + \frac{2}{3} |B|^2 |\vec{k}|^4 |t_2|^2 \right)
 \end{aligned}$$

Results



Results



Summary

- The X(4140) deduced from the $B^+ \rightarrow J/\psi\phi K^+$ by LHCb has a large width 83 ± 21 MeV vs. 19 MeV of PDG.
- Many explanations of X(4140): molecular state, hybrid state, tetraquark state.
- X(4140) as the $D_s^* \bar{D}_s^*$ molecule, with JPC=0⁺⁺, 2⁺⁺, in contrast with the recent experimental measurement, PDG(1⁺⁺).
- X(4160) as the $D_s^* \bar{D}_s^*$ molecule, with JPC=2⁺⁺, large couplings to $D_s^* \bar{D}_s^*$, J/ $\psi\phi$ channels.

Summary

- Taking into account the contribution of X(4160) and X(4140), the lower part of the spectrum can be well reproduced.
- 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.
- We predict the $D_S^* \bar{D}_S^*$ distribution for $B^- \rightarrow K^- D_S^* \bar{D}_S^*$ reaction. There is a peak close to the threshold, and it is the reflection of the X(4160).



Summary

- We analysed the process of $e^+e^- \rightarrow \gamma J/\psi \phi$, by considering the contributions of the molecular state X(4160), and the X(4140) state.
- Our results show that some structures can be associated to the X(4160) and X(4140) states.
- The reflection effect of X(4160) is clear in the $D_s^* D_s^*$ distribution, which should not be misidentified as a new resonance.
- We strongly call for a measurement with high precision.



Summary

- We have presented a theoretical interpretation on the $B^+ \rightarrow J/\psi \omega K^+$ reaction in the range of $J/\psi \omega$ invariant mass 3930-4050 MeV, and found that two resonances X(3940) and X(3930), strongly coupled to $D^* D^*$ in $JPC=0^{++}$ and 2^{++} , give rise to a strong cusp at $D^* D^*$ threshold, which is supported by LHCb measurement.
- Our work should serve as a motivation to improve the statistic.

**Thanks for your
attention!**