The role of X(4140) and X(4160) in the reaction of $B \to J/\psi \phi K$

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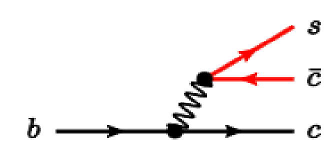
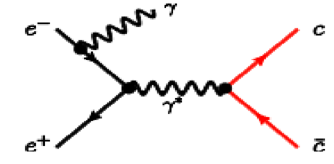
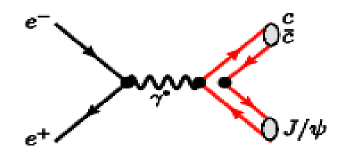
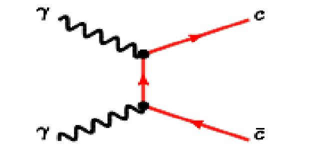
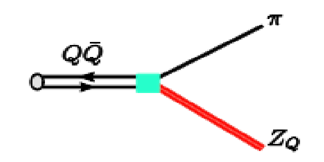
GuiLin@Aug. 20, 2018

outline

- Motivation
- The reaction of $B^+ \to J/\psi\varphi K^+$
- 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)

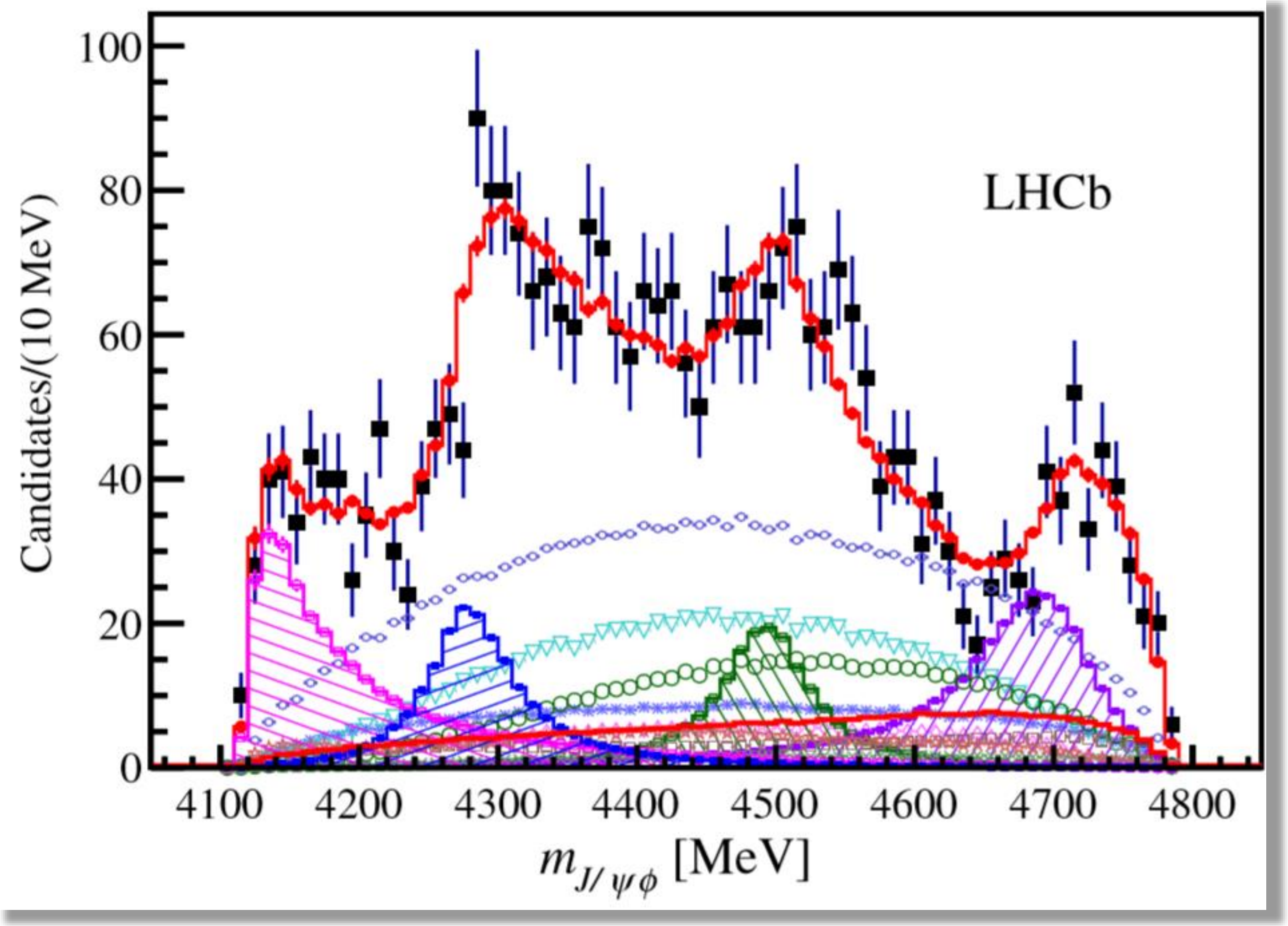
TABLE I: The experimental measurement of the $X(4140)$.

Experment	Mass	Width	Significance	Year
CDF [1]	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$	3.8σ	2009
CMS [2]	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$	5.0σ	2014
D0 [3]	$4159.0 \pm 4.3 \pm 6.6$	$20 \pm 13^{+3}_{-8}$	3.0σ	2014
D0 [4]	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$	4.7σ	2015
CDF [5]	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$	5.0σ	2011
LHCb [12]	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	8.4σ	2017

Before 2015, LHCb and Babar have not confirmed this state.

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

The LHCb measurement



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

4 X states are observed.

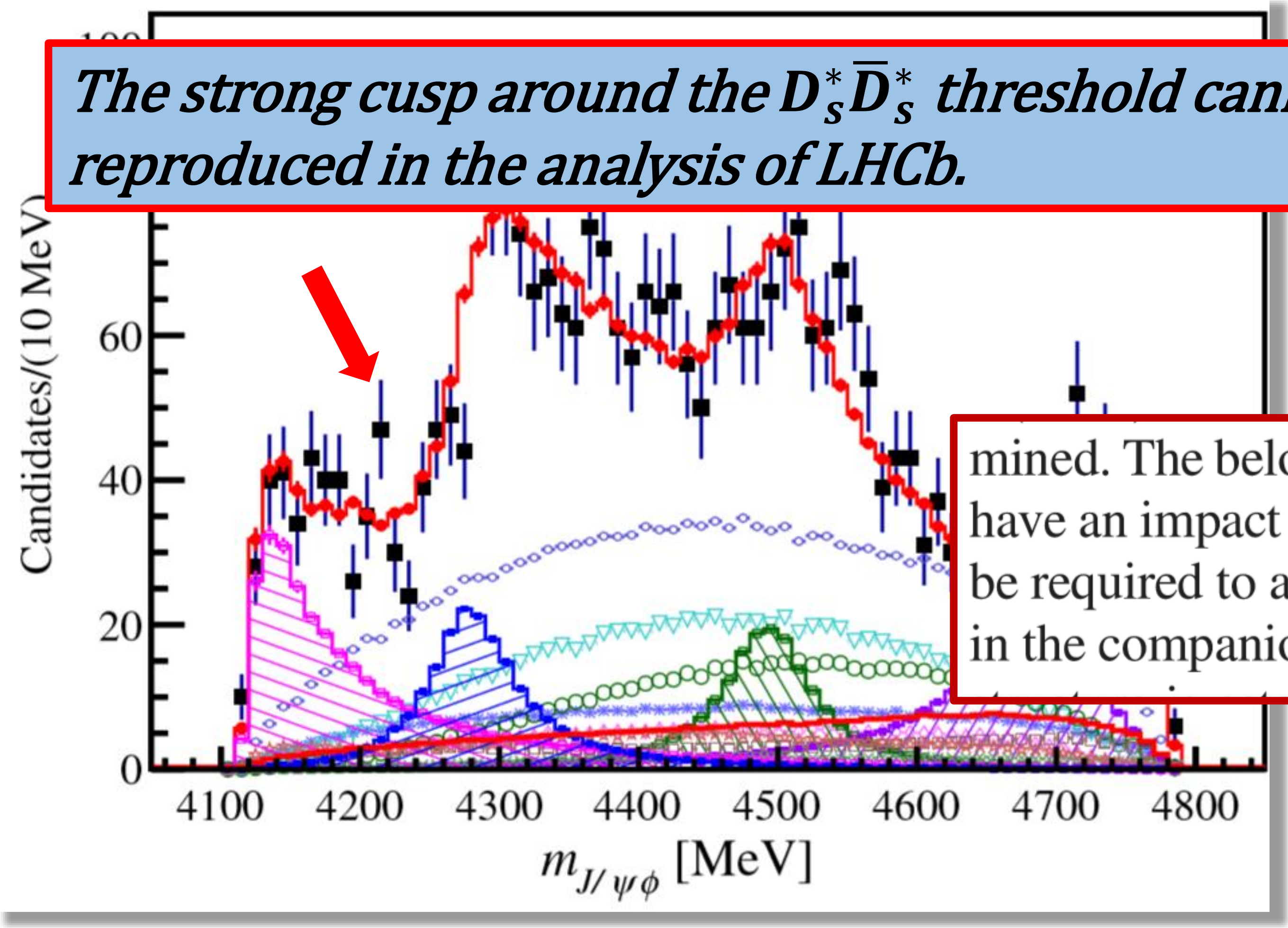
X(4140): $J^{PC}=1^{++}$

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



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

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

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 $X(4274)$

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

PRD95,2017,PRL118,2017

X(4140) structure

- **Molecular state:** 0^{++} or 2^{++}

  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),EPJC79,72(2019)

- **Hybrid state:**

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

- **Rescattering effect:**

  X. Liu,PLB680(2009)

- **X_{c1}(3P):** (with a small width~20 MeV)

  D.Y. Chen, EPJC76,671(2016)， Poster by En Wang,

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

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

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

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(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

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

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

pole).

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

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www.elsevier.com/locate/nuclphysa

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

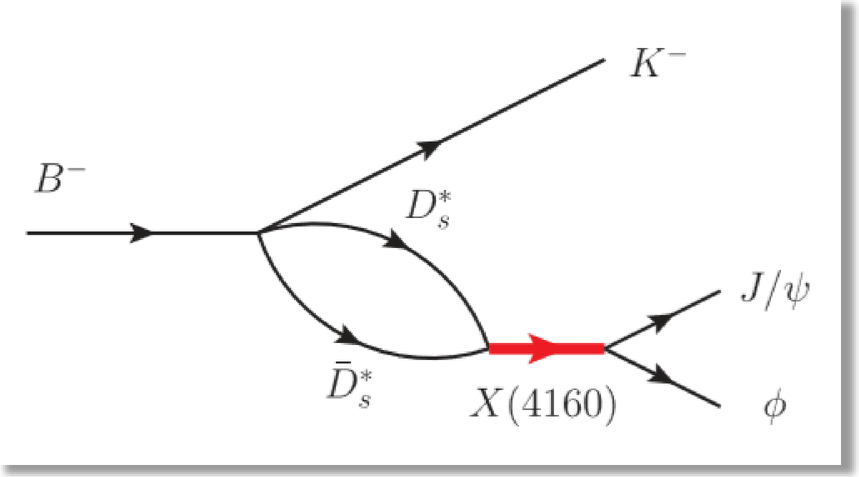
How to distinguish the molecule state?

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

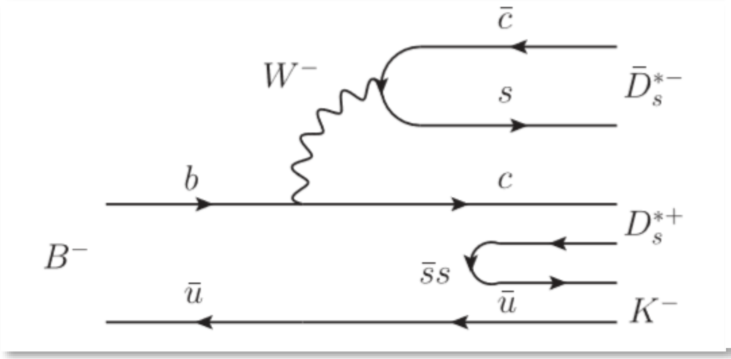
The reaction of $B^+ \to J/\psi\phi K^+$

PRD97(2018)014017

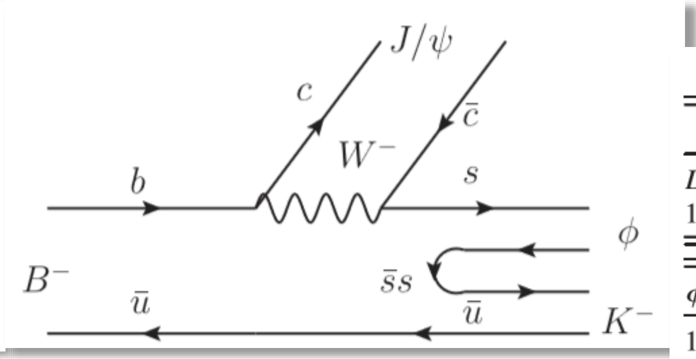
The reaction of $B^- \to J/\psi\, \phi K^-$



- **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

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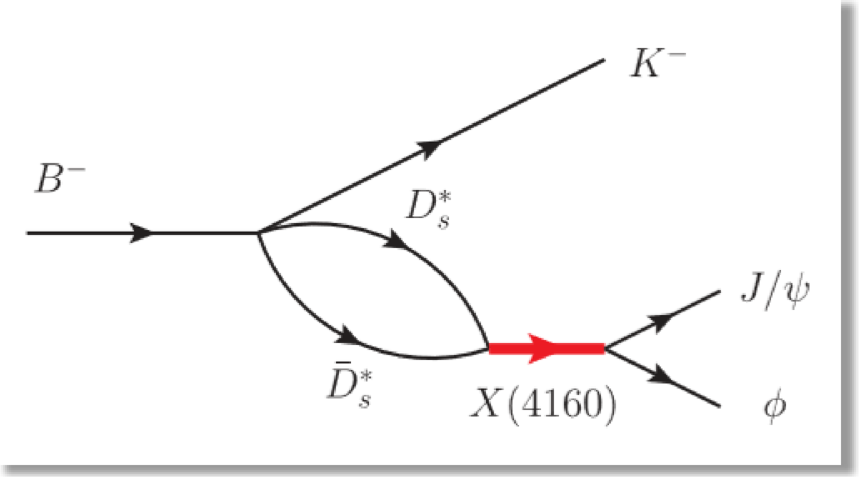
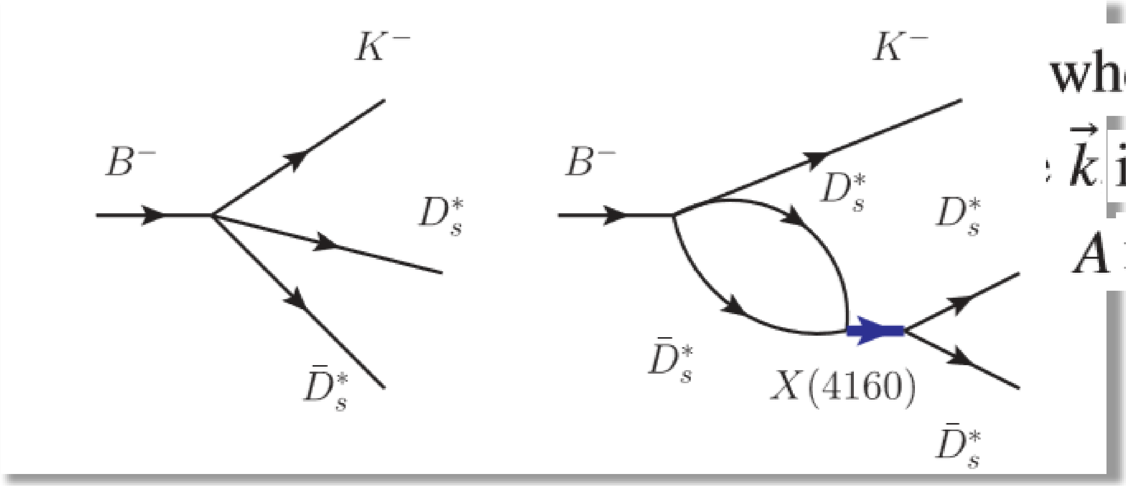
The reaction of $B^- \to J/\psi\, \phi K^-$



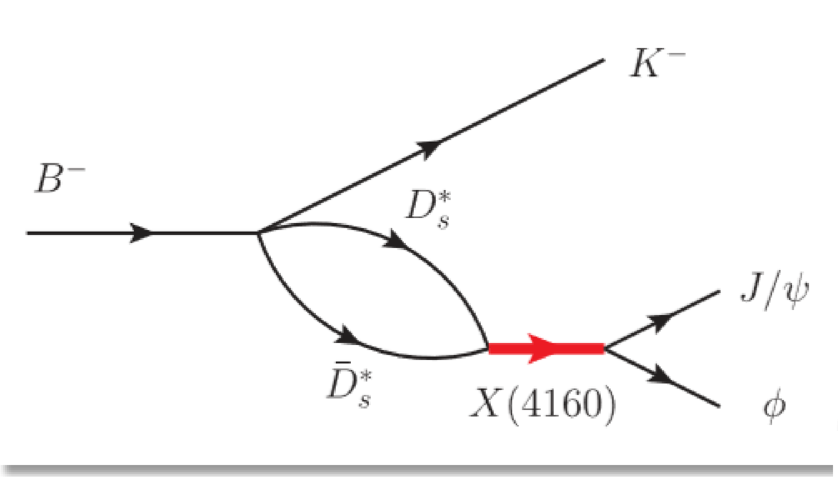
The X(4160) is JPC=2^{++} state with L=0 in $D_s^*\bar{D}_s^*$. We need a D-wave in the K$^-$ to match the angular momentum in the reaction.

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



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

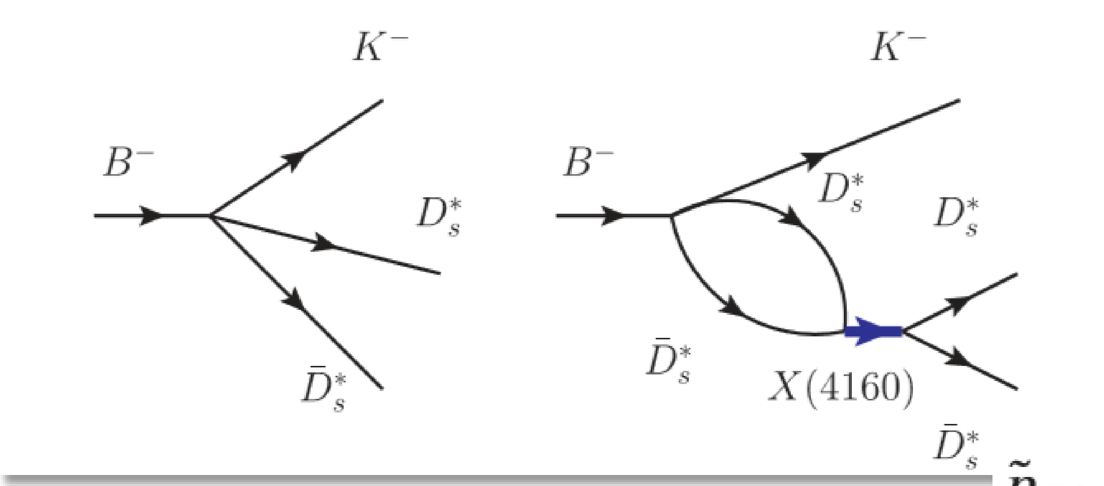


The X(4160) is $J^{PC}=2^{++}$ state with L=0 in $D_s^* \bar{D}_s^*$. We need a D-wave in the K^- to match the angular momentum in the reaction.

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

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

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

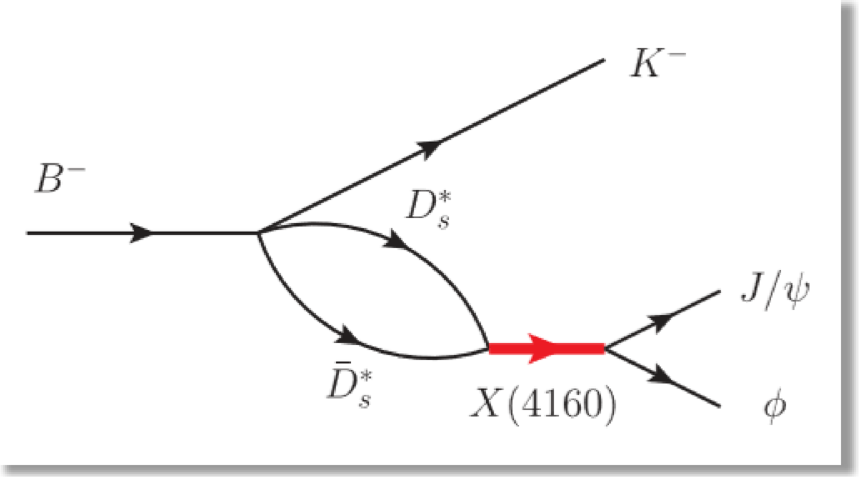


$$\frac{d\Gamma}{dM_{\text{inv}}(D_s^* \bar{D}_s^*)} = \frac{1}{(2\pi)^3}\frac{1}{4M_{B^-}^2}\frac{2}{3}|\vec{k}|^4|\vec{k}'||\tilde{p}_{D_s^*}||A|^2$$

$\vec{k}'$ 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.

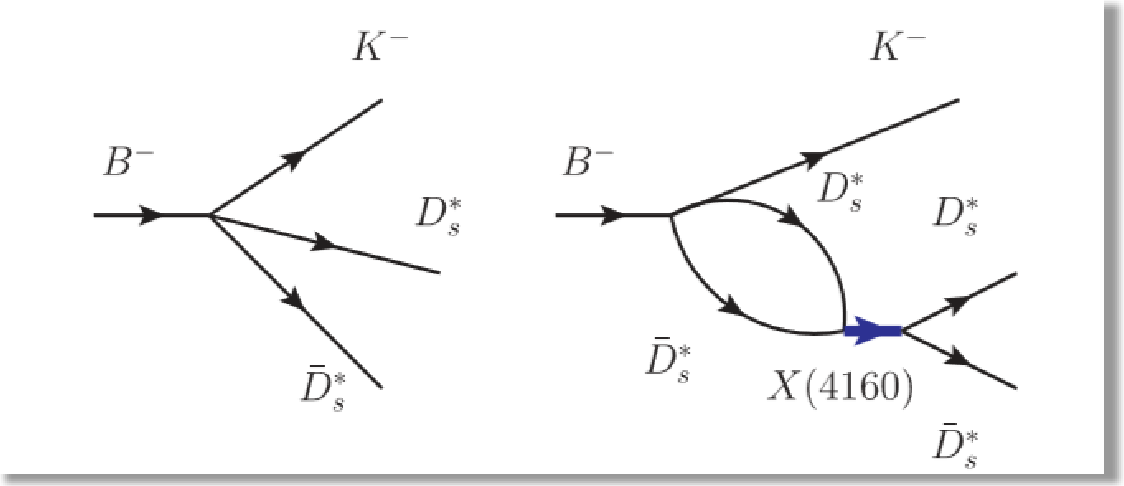
The reaction of $B^- \to J/\psi\,\phi K^-$



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

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,

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

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

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

- The transition amplitudes are,

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

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

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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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- **The transition amplitudes are,**

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

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

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

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,

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

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

The substitution:

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

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

with B a parameter to be fitted to the data.

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

Results

- We fit the LHCb data from threshold up to about 4250 MeV.
- 13 data, χ^2/dof=15.3/(13-3)=1.39

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

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

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

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

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

$X(4160)$ MASS	4156^{+29}_{-25} MeV
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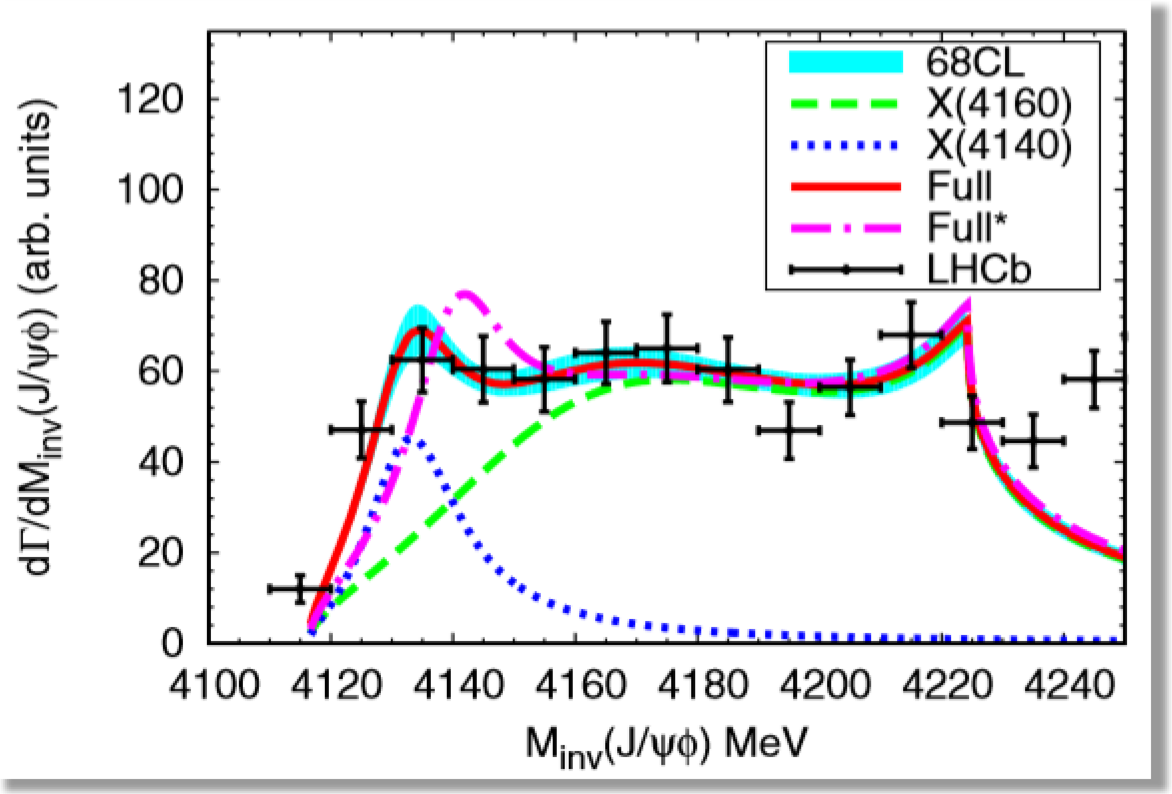
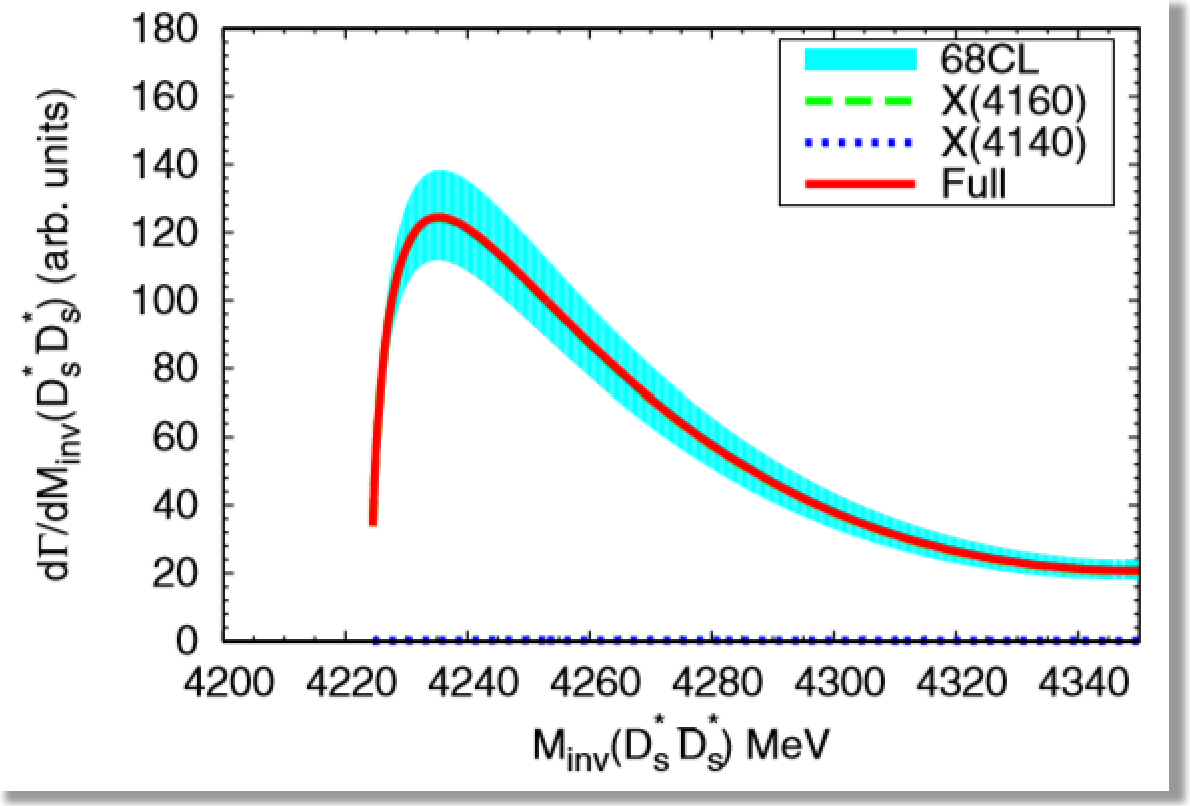
Results



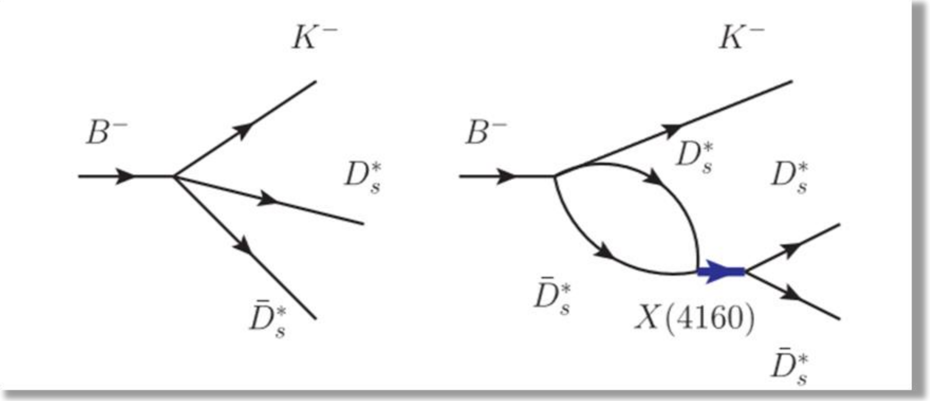
- **The Flatte effect is visable, as a sharp fall down of the invariant mass distribution above the $D_s^* \overline{D}_s^*$ threshold.**
- **The lower part of the spectrum can be obtained from the contribution of X(4160) (2^{++}) and X(4140)(1^{++}, 19 MeV) resonances.**
- **The cusp of the distribution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



Summary

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

Summary

- Taking into account the contribution of X(4160) and X(4140), the lower part of the spectrum of LHCb 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 $B^- \to K^- D_s^* \bar{D}_s^*$ reaction. There is a peak close to the threshold, which is the reflection of the X(4160).

Thanks for your attention!