Theoretical aspects of Hadron Spectroscopy and Phenomenology

Valencia, Spain

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Exotic hadrons in $\Lambda_b \to J/\psi\ \phi\ \Lambda$ decay

In collaboration with

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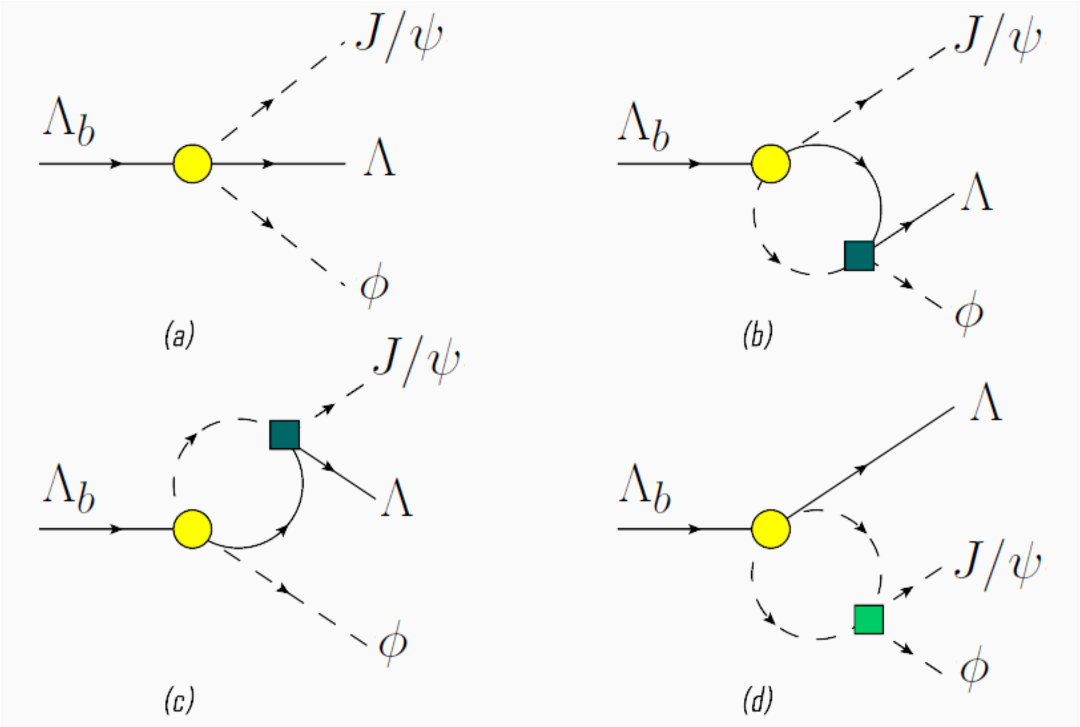
Phys. Rev. D102 (2020) 054027

University of Barcelona, Spain

Motivation

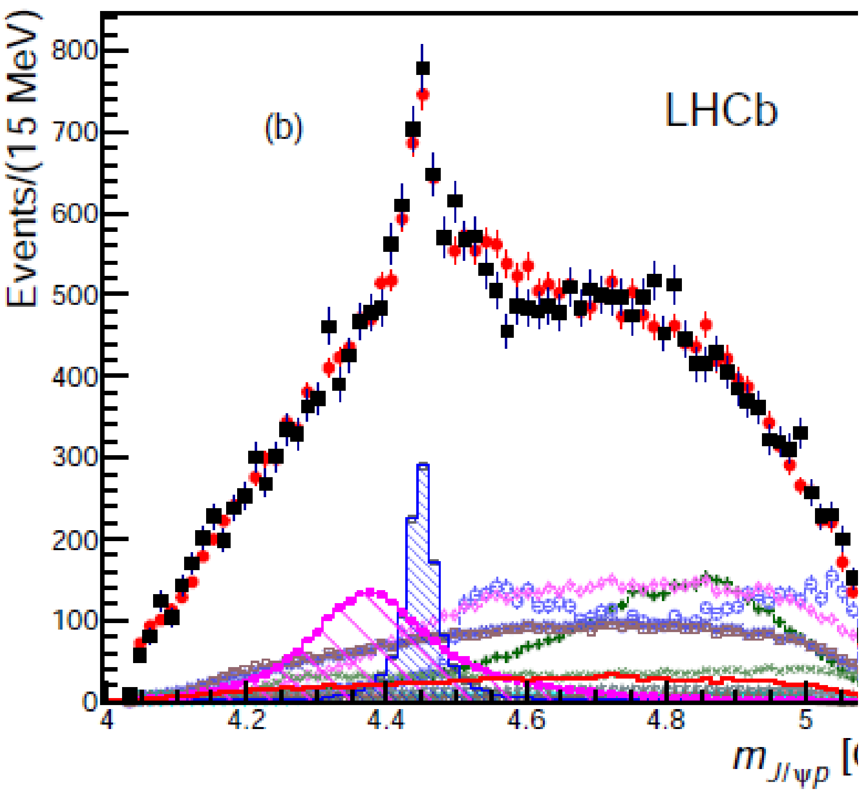
The $\boldsymbol{\Lambda_b \to J/\psi\ \phi\ \Lambda}$ decay + final state interactions



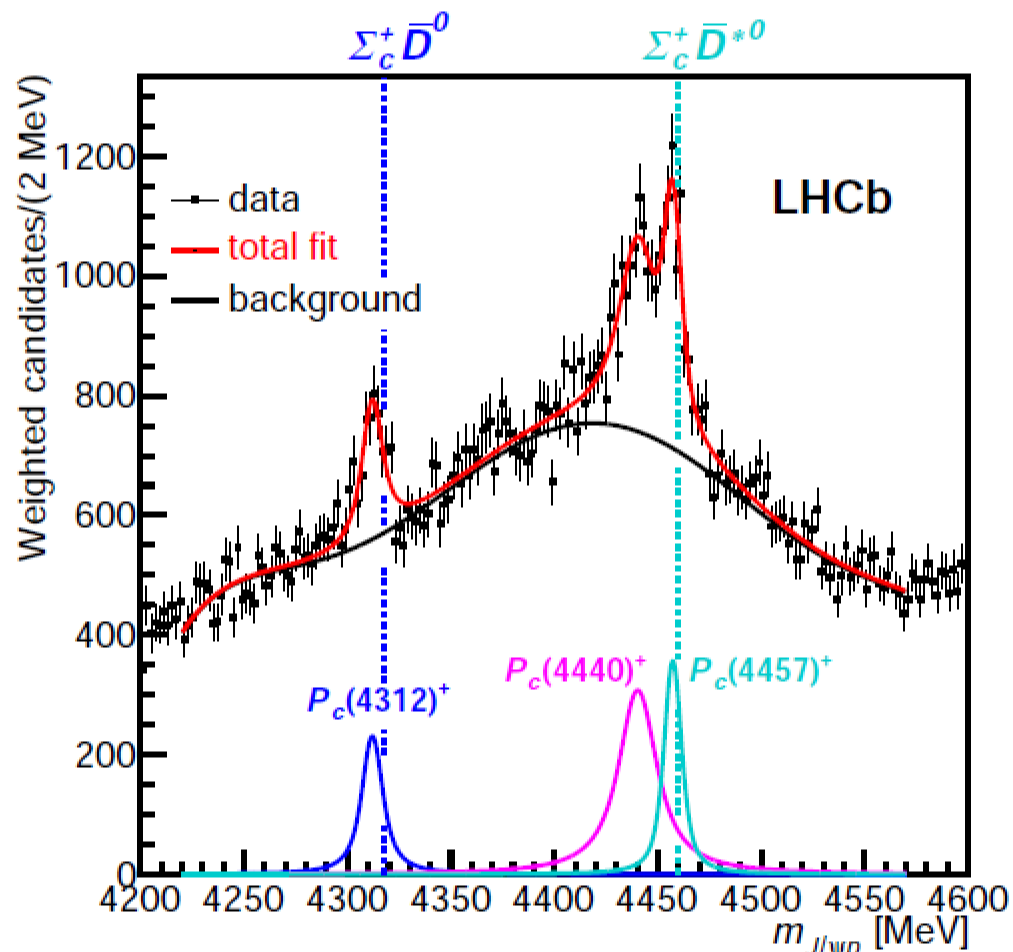
In all 3 two-body channels we can see something "exotic"

Observation of $J/\Psi p$ resonances consistent with pentaquark states in $\Lambda_b \to J/\psi\ K^-\ p$ decays

LHCb Coll., **Phys.Rev.Lett. 115 (2015) 072001**

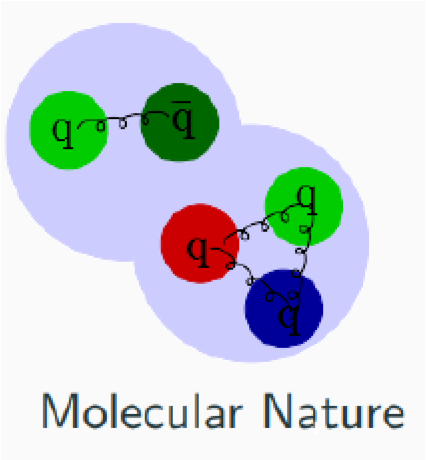


LHCb Coll., **Phys.Rev.Lett. 122 (2019) 222001**



Dynamically generated hidden charm resonances around 4.3 GeV

Similar states have been predicted theoretically!

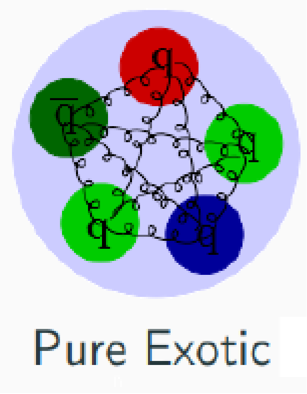


Molecular models

- Wu, Molina, Oset, Zou,
PRL 105, 232001 (2010); PRC 84, 015202 (2011)
- Yang, Sun, He, Liu, Zhu,
Chin. Phys. C 36, 6 (2012)
- Xiao, Nieves, Oset, PRD 88, 056012 (2013)
- Karliner, Rosner, PRL 115, 122001 (2015)

Quark models

- Wang, Huang, Zhang, Zou, PRC 84, 015203 (2011)
- Yuan, Wei, He, Xu, Zou, EPJA 48, 61 (2012)



Dynamically generated hidden charm resonances around 4.3 GeV

Jia-Jun Wu, R. Molina, E. Oset & B. S. Zou,
Phys. Rev. Lett. 105 (2010) 232001;
Phys. Rev. C84 (2011) 015202

(I,S)	z_R	Real axis		Γ_i
		M	Γ	
$(1/2,0)$				$J/\psi N$
	$4415-9.5i$	4412	47.3	19.2
$(0,-1)$				$J/\psi\Lambda$
	$4368-2.8i$	4368	28.0	5.4
	$4547-6.4i$	4544	36.6	13.8

(I,S)	z_R	g_a			
$(1/2,0)$		$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c^+$	$J/\psi N$	
	$4415-9.5i$	$2.83-0.19i$	$-0.07+0.05i$	$-0.85+0.02i$	
		2.83	0.08	0.85	
$(0,-1)$		$\bar{D}_s^*\Lambda_c^+$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi'_c$	$J/\psi\Lambda$
	$4368-2.8i$	$1.27-0.04i$	$3.16-0.02i$	$-0.10+0.13i$	$0.47+0.04i$
		1.27	3.16	0.16	0.47
	$4547-6.4i$	$0.01+0.004i$	$0.05-0.02i$	$2.61-0.13i$	$-0.61-0.06i$
		0.01	0.05	2.61	0.61

TABLE IX: Pole position (z_R) and coupling constants (g_a) to various channels for the states from $PB\to PB$ including the $J/\psi N$ and $J/\psi\Lambda$ channels.

The S=-1 pentaquarks are molecular states, mostly made of $\bar{D}^*\Xi_c$ or $\bar{D}^*\Xi'_c$, and decaying into $J/\psi\Lambda$

How to observe strange hidden charm pentaquarks?

$$\Xi_b \to J/\psi\ K^-\ \Lambda$$

Chen et al., PRC 93, 065203 (2016)

$$\Lambda_b \to J/\psi\ K^0\ \Lambda$$

Lu, Wang, Xie, Geng, Oset, PRD 93 (2016) 094009

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

Feijoo, Magas, Ramos, Oset, EPJ C76 (2016) no.8, 446

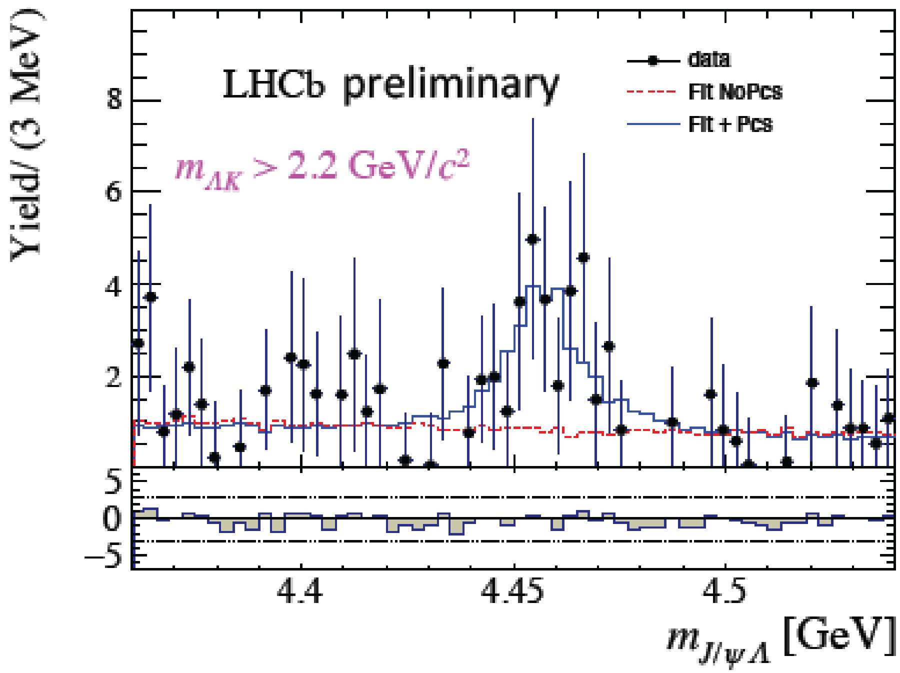
$$\Lambda_b \to J/\psi\ \phi\ \Lambda$$

Magas, Ramos, Somasundaram, Tena Vidal, PRD102 (2020) 054027

W. Y. Liu et al., [arXiv:2012.01804 [hep-ph]].

Although the statistics of the production of Ξ_b^- is much smaller than that of Λ_b

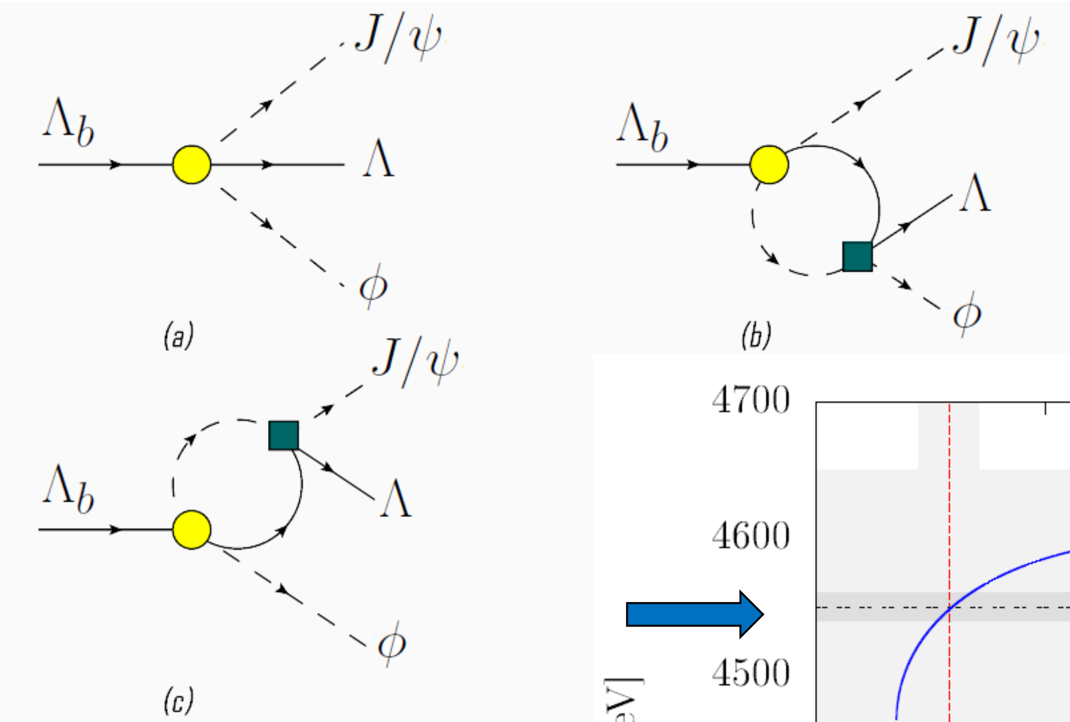
$\Xi_b \to J/\psi\, K^-\, \Lambda$



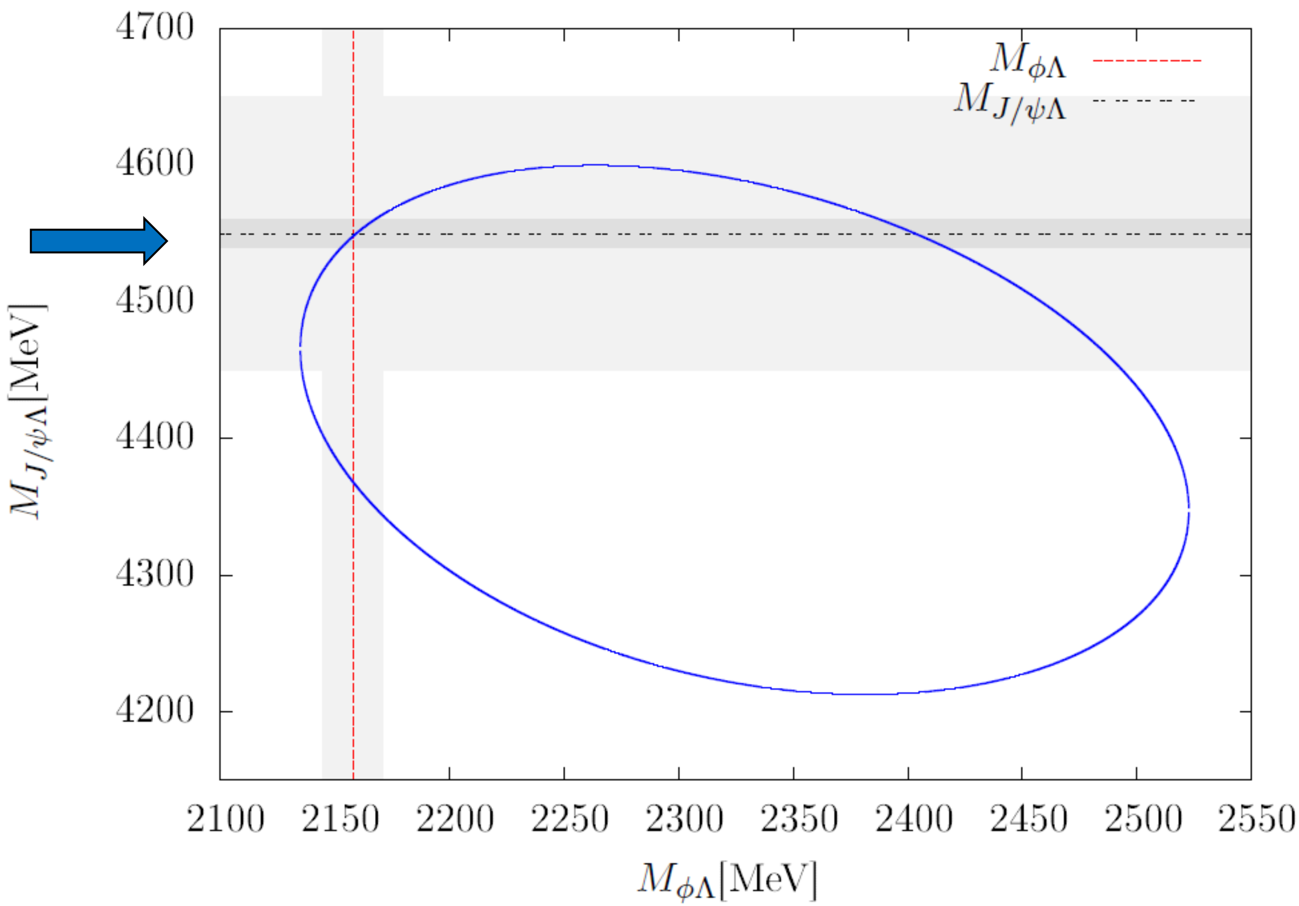
State	M_0 [MeV]	Γ [MeV]
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$

3.1σ significance

The $\Lambda_b \to J/\psi\ \phi\ \Lambda$ decay: Dalitz plots



Strange tentaquark
can be observed if
$M_R \leq 4550 MeV$



Dynamically generated resonances from the vector octet-baryon octet interaction

Oset, Ramos, **Eur. Phys. J. A44 (2010) 445**

z_R	$1784 + i4$		$1906 + i70$		$2158 + i13$	
	g_i	$\mid g_i \mid$	g_i	$\mid g_i \mid$	g_i	$\mid g_i \mid$
$\bar{K}^*N(1833)$	$3.3 + i0.07$	3.3	$0.1 + i0.2$	0.3	$0.2 + i0.3$	0.3
$\omega\Lambda(1898)$	$1.4 + i0.03$	1.4	$0.4 + i0.2$	0.5	$-0.3 - i0.2$	0.4
$\rho\Sigma(1964)$	$-1.5 + i0.03$	1.5	$3.1 + i0.7$	3.2	$0.01 - i0.08$	0.08
$\phi\Lambda(2135)$	$-1.9 - i0.04$	1.9	$-0.6 - i0.3$	0.6	$0.5 + i0.3$	0.5
$K^*\Xi(2212)$	$0.1 + i0.003$	0.1	$0.3 + i0.1$	0.3	$3.2 - i0.1$	3.2

Table 2: Pole position and coupling constants to various channels of the resonances found in the $I = 0, S = -1$ sector.

Resonance is dynamically generated with
$M_R = 2158$ MeV and $\Gamma = 23$ MeV
main channel is ΞK^*, but it also couples to $\Lambda\phi$

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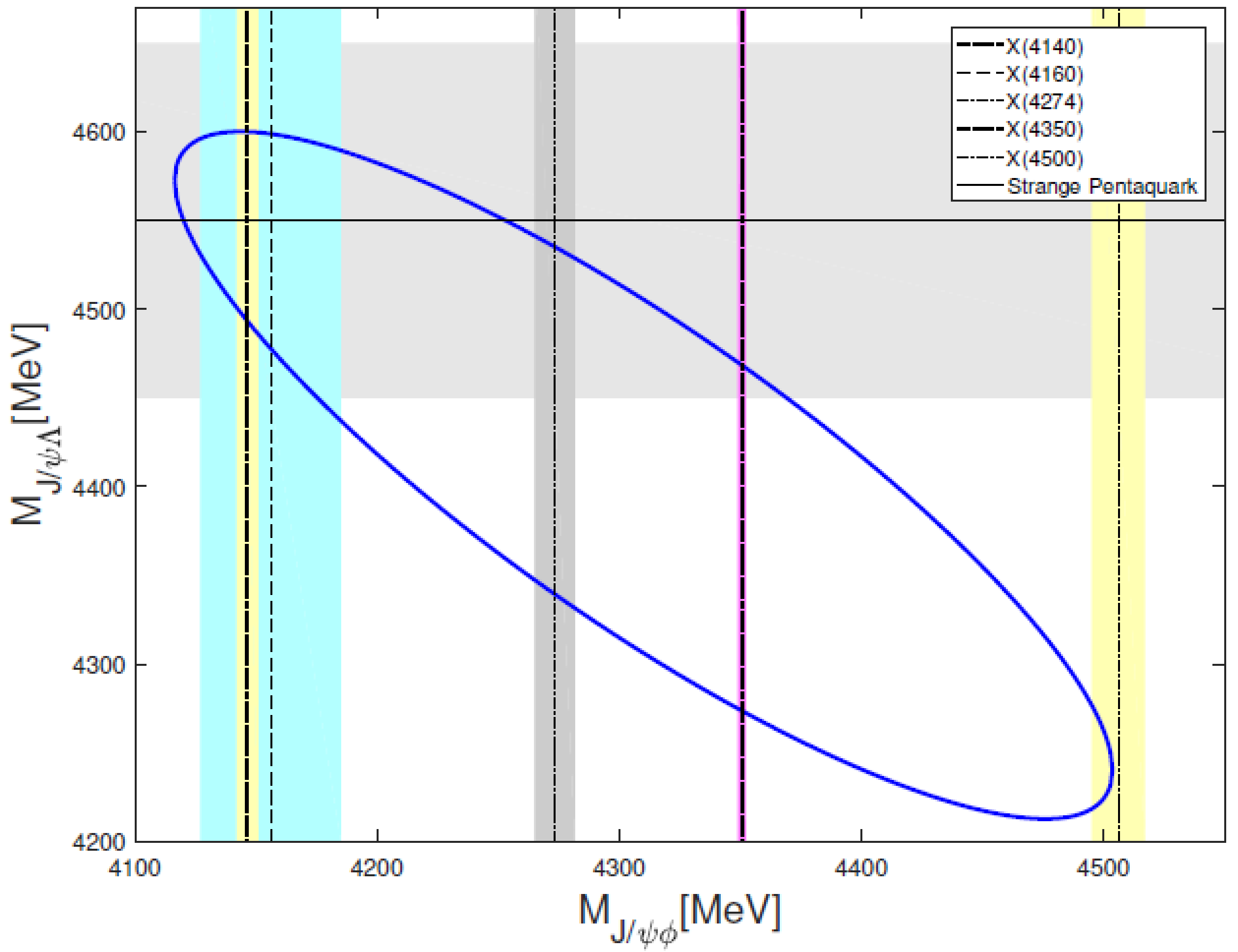
main channel is ΞK^*, but it also couples to $\Lambda\phi$

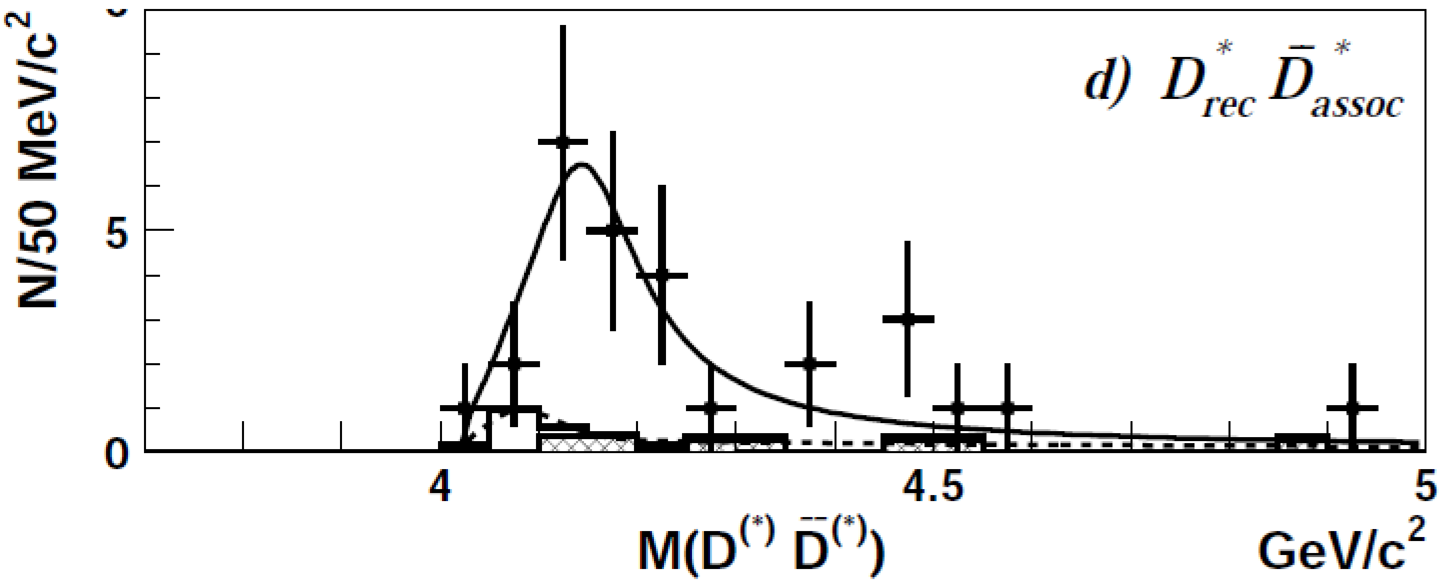
With the current model parameters
it is unlikely to observe it
in this reaction

The $\Lambda_b \to J/\psi\ \phi\ \Lambda$ decay: Dalitz plots



The $\Lambda_b \to J/\psi\ \phi\ \Lambda$ decay: Dalitz plots

Belle Coll., *Phys. Rev .Lett.* 100 (2008) 202001

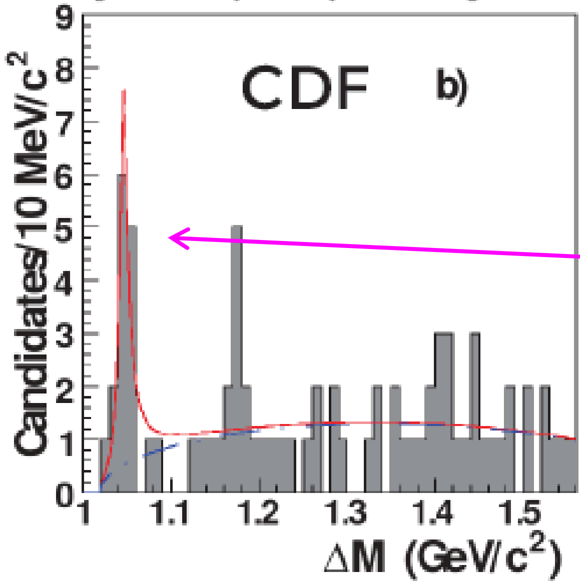


State	N_{events}	M	Γ	$\mathcal{N}_\sigma$
$X(3880)(D_{\rm rec}\overline{D}_{\rm assoc})$	63^{+31}_{-25}	3878 ± 48	347^{+316}_{-143}	3.8
$X(3940)(D_{\rm rec}\overline{D}^*_{\rm assoc})$	52^{+24}_{-16}	3942^{+7}_{-6}	37^{+26}_{-15}	6.0
$X(3940)(D^*_{\rm rec}\overline{D}_{\rm assoc})$	$5.2^{+3.4}_{-2.7}$	3934^{+23}_{-17}	57^{+62}_{-34}	2.8
$X(4160)(D^*_{\rm rec}\overline{D}^*_{\rm assoc})$	$23.8^{+12.3}_{-8.0}$	4156^{+25}_{-20}	139^{+111}_{-61}	5.5

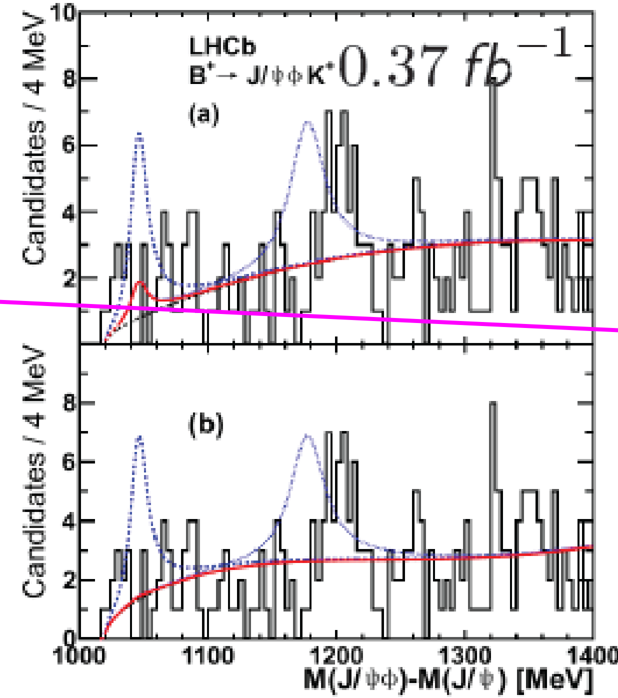
X(4160)
wide resonance

Resonances decaying into $J/\psi\ \phi$

[PRL102(2009)242002]

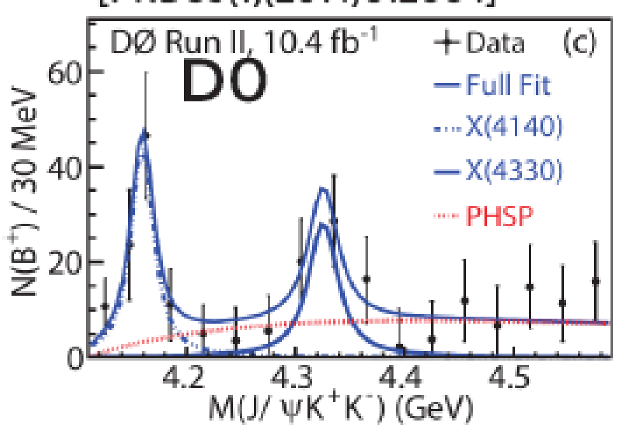


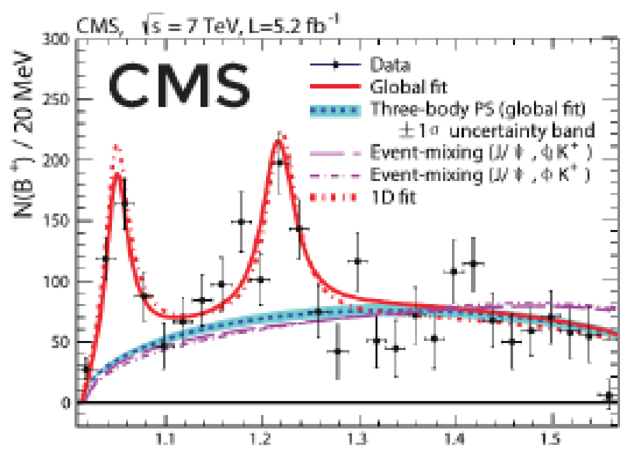
LHCb [PRD85(2012)091103]



Narrow structures in $J/\psi\phi$ discovered by CDF in 2008

[PRD89(1)(2014)012004]





[PLB734(2014)261]

X(4140)
narrow resonance

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

Resonances decaying into $J/\psi\ \phi$

X(4140)

Particle Data Group
***Phys. Rev. D* 98 (2018) 3, 030001**

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

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.

$\chi_{c1}(4140)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN
4146.8±2.4 OUR AVERAGE	Error includes scale factor of 1		

$\chi_{c1}(4140)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TE
$22\ ^{+8}_{-7}$ OUR AVERAGE	Error includes scale factor of		

X(4160)

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

OMITTED FROM SUMMARY TABLE

Seen by PAKHLOV 08 in $e^+e^- \to J/\psi X$, $X \to D^*\overline{D}^*$

X(4160) MASS

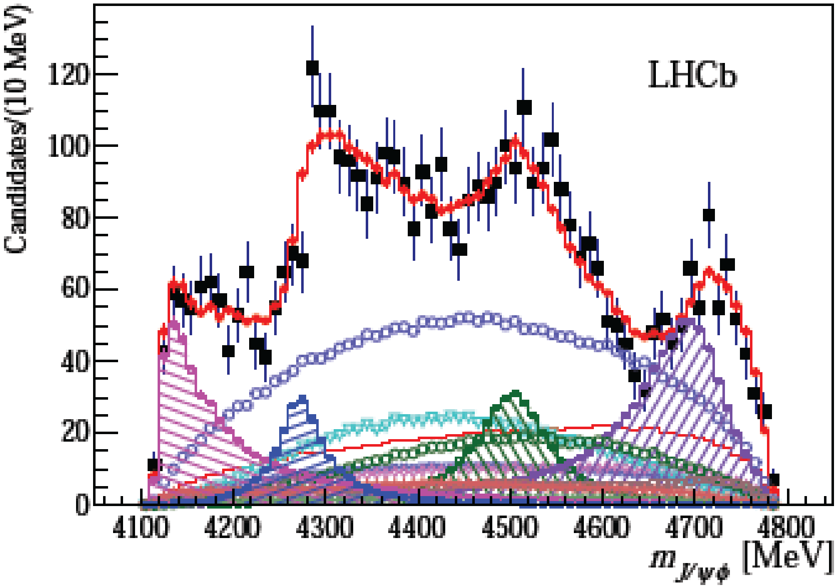
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{4156^{+25}_{-20}\pm15}$	24	PAKHLOV	08	BELL	$e^+e^- \to J/\psi X$

X(4160) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{139^{+111}_{-61}\pm21}$	24	PAKHLOV	08	BELL	$e^+e^- \to J/\psi X$

Resonances decaying into $J/\psi\ \phi$

LHCb [PRL118(2017)022003]



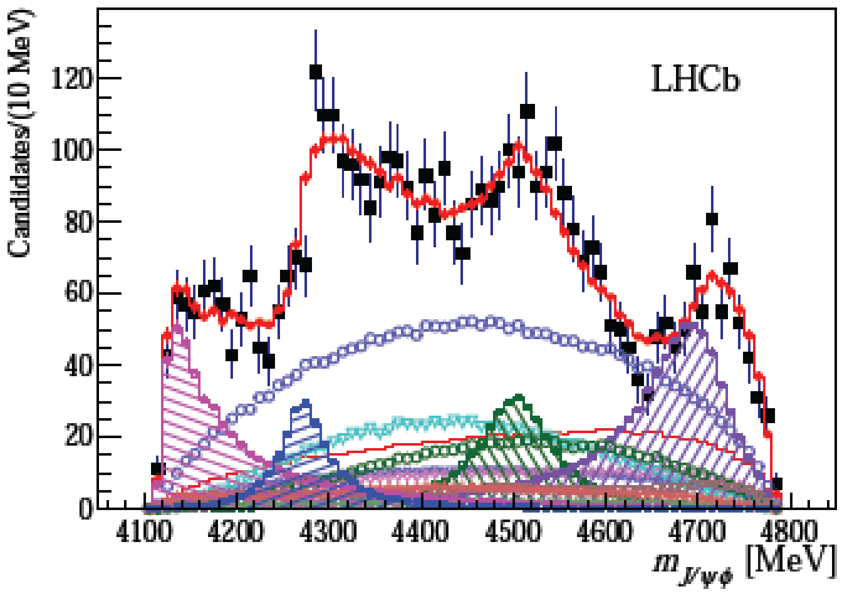
Wide X(4140)

Contri-bution	Sign. or Ref.	Fit results M_0 [MeV]	Γ_0 [MeV]	FF %
All $X(1^+)$				$16\pm3\ ^{+\ 6}_{-\ 2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$	$13.0\pm3.2\,^{+4.7}_{-2.0}$
ave.	Table 1	4147.1 ± 2.4	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\,^{+17.2}_{-\ 3.6}$	$56\pm11\,^{+\ 8}_{-11}$	$7.1\pm2.5\,^{+3.5}_{-2.4}$
CDF	[26]	$4274.4\,^{+8.4}_{-6.7}\pm1.9$	$32\,^{+22}_{-15}\pm8$	
CMS	[23]	$4313.8\pm5.3\pm7.3$	$38\,^{+30}_{-15}\pm16$	
All $X(0^+)$				$28\pm\ 5\pm\ 7$
$NR_{J/\psi\phi}$	6.4σ			$46\pm11\ ^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\,^{+12}_{-15}$	$92\pm21\,^{+21}_{-20}$	$6.6\pm2.4\,^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$	$12\pm\ 5\ ^{+\ 9}_{-\ 5}$

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

Resonances decaying into $J/\psi\ \phi$

LHCb [PRL118(2017)022003]



Wide X(4140) !

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$X(4700)$	5.6σ	$4704 \pm 10\ {}^{+14}_{-24}$	$120 \pm 31\ {}^{+42}_{-33}$	$12 \pm\ 5\ {}^{+\ 9}_{-\ 5}$

No X(4160) !

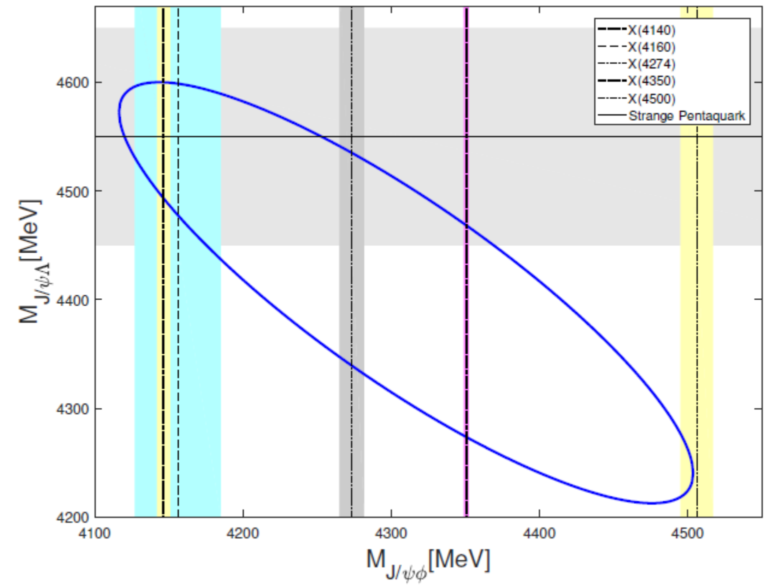
From $B^+ \to J/\psi\ \phi\ K^+$ decay

Resonances decaying into $J/\psi\ \phi$

1 or 2 states ?

$M_{J/\psi\phi}$			Observed at
$X(4140)$	4143.4 ± 1.9	15.5 ± 6.3	CMS
	$4146.5 \pm 4.5^{+4.5}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	LHCb
	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$	D0
	$4143 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$	Fermilab
$X(4160)$	4156 ± 29	139^{+113}_{-65}	Belle
	4169	132	[PRD80,2009]
$X(4274)$	4293 ± 20	35 ± 16	CMS, D0
	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56.2 \pm 10.9^{+8.4}_{-11.1}$	LHCb
$X(4350)$	4350.6 ± 0.7	13 ± 4	Belle
$X(4500)$	4506 ± 11	92 ± 21	LHCb

Theoretical model



The X(4160) as dynamically generated resonances from the vector-vector interaction

Molina, Oset, **Phys.Rev. D80 (2009) 114013**

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

D^*D^*	$D_s^*D_s^*$	K^*K^*	$\rho\rho$	$\omega\omega$
$1225 - i490$	$18927 - i5524$	$-82 + i30$	$70 + i20$	$3 - i2441$

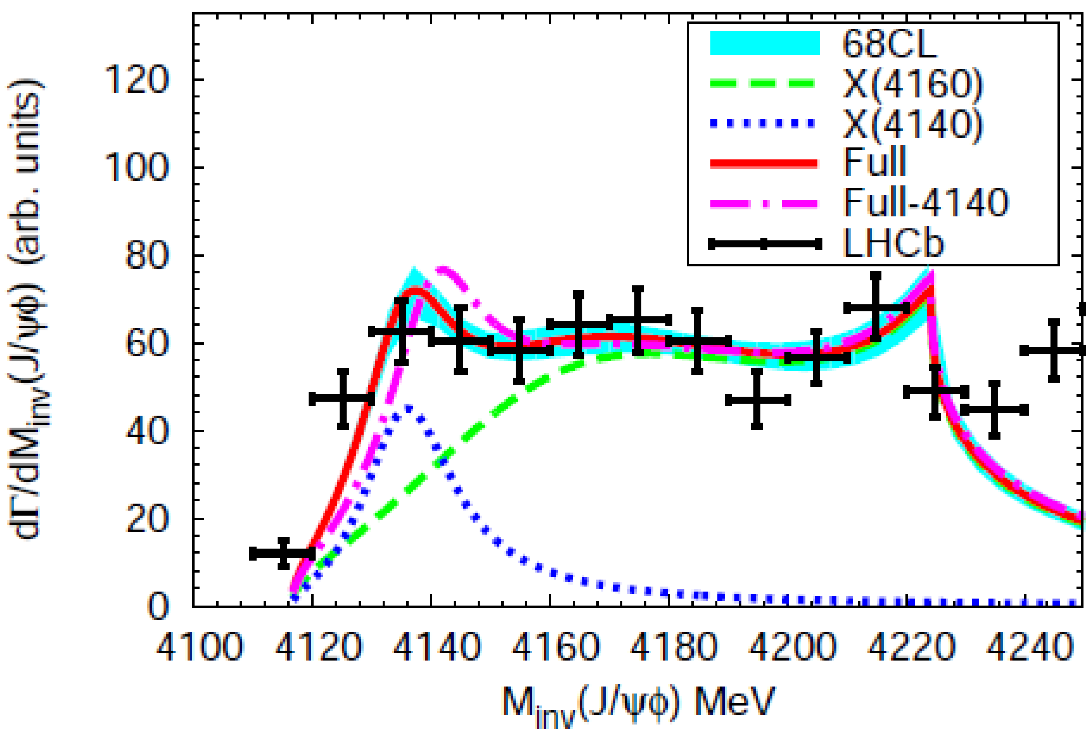
$\phi\phi$	$J/\psi J/\psi$	$\omega J/\psi$	$\phi J/\psi$	$\omega\phi$
$1257 + i2866$	$2681 + i940$	$-866 + i2752$	$-2617 - i5151$	$1012 + i1522$

Table 5: Couplings g_i in units of MeV for $I = 0$, $J = 2$ (second pole).

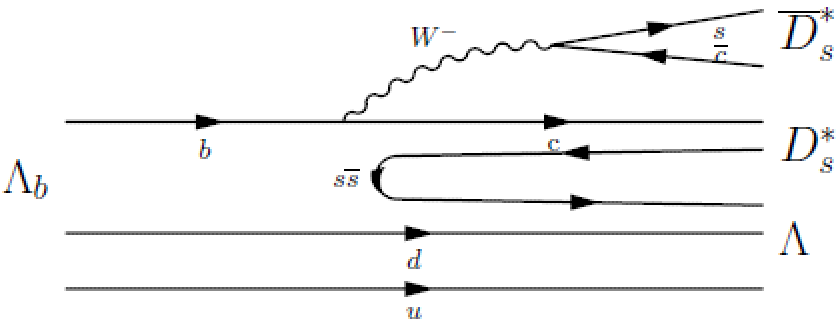
Resonances decaying into $J/\psi\ \phi$

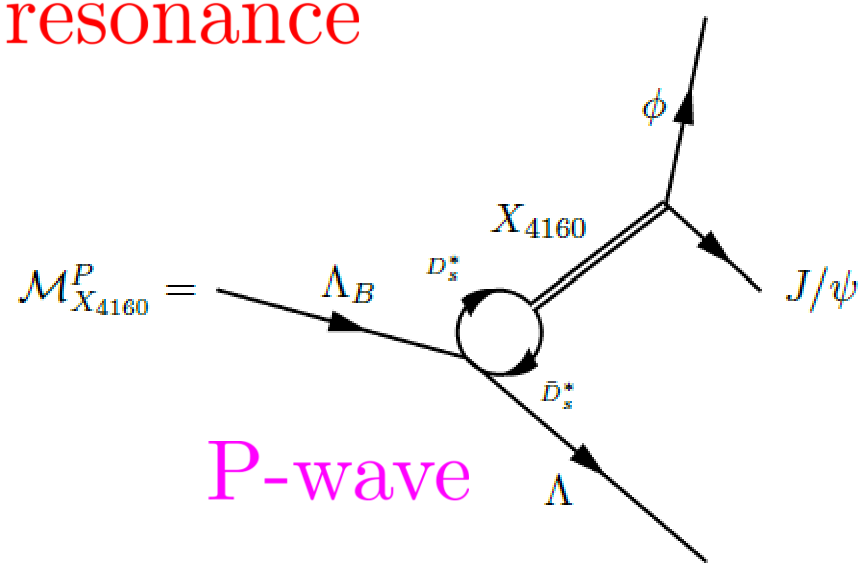
Wang, Xie, Geng, Oset, **Phys.Rev. D97 (2018) no. 1 014017**

We have studied the $J/\psi\phi$ mass distribution of the $B^+ \to J/\psi\phi K^+$ reaction from threshold to about 4250 MeV, and find that one needs the contribution of the $X(4140)$ with a narrow width, together with the $X(4160)$ which accounts for most of the strength of the distribution in that region. The existence of a clear cusp at the $D_s^*\bar{D}_s^*$ threshold indicates that the $X(4160)$ resonance is strongly tied to the $D_s^*\bar{D}_s^*$ channel, which finds a natural interpretation in the molecular picture of this resonance.



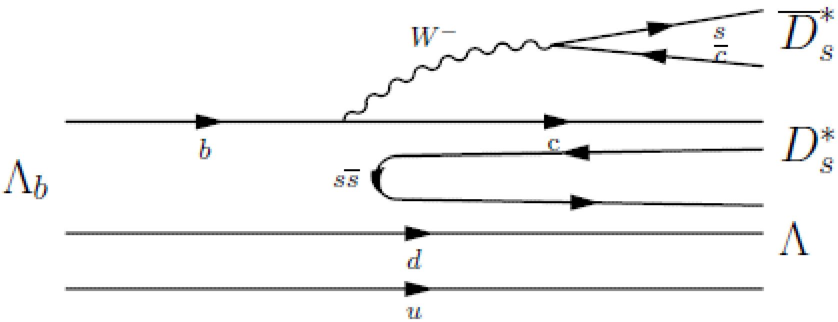
The $\Lambda_b \to J/\psi\ \phi\ \Lambda$ decay via X(4160) 2^{++} resonance



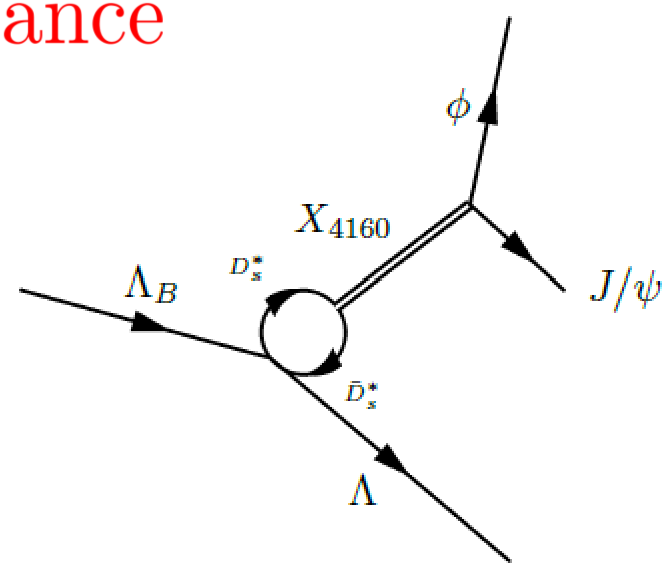


$$\mathcal{M}^P_{X_{4160}} = A(\vec{\epsilon}_{J/\psi} \times \vec{\epsilon}_{\phi}) \cdot \vec{P}_{\Lambda}\ G_{D_s^*\ \bar{D}_s^*}\ \frac{T_{D_s^*\bar{D}_s^*, J/\psi\phi}}{g_{D_s^*\bar{D}_s^*}\, g_{J/\psi\phi}}$$

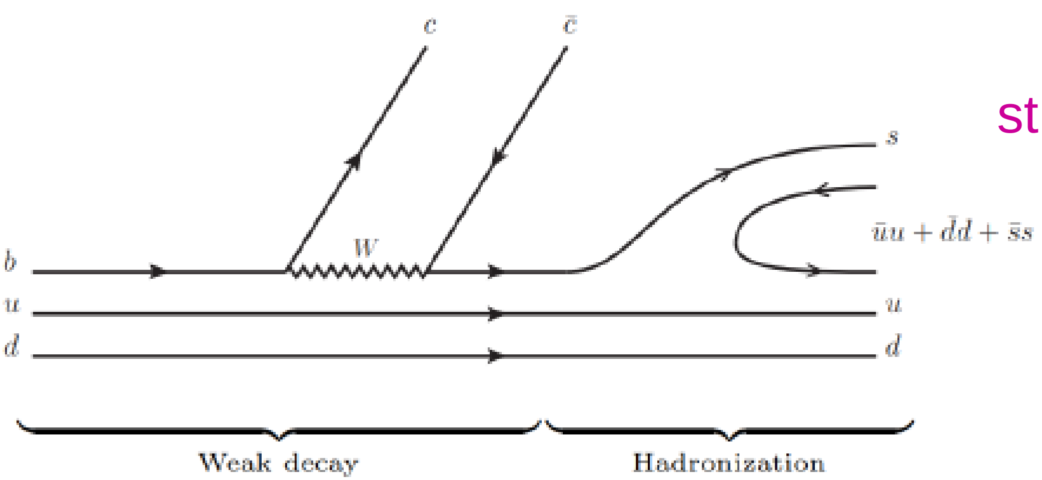
The $\Lambda_b \to J/\psi\ \phi\ \Lambda$ decay via X(4160) 2^{++} resonance



$\mathcal{M}^P_{X4160} =$



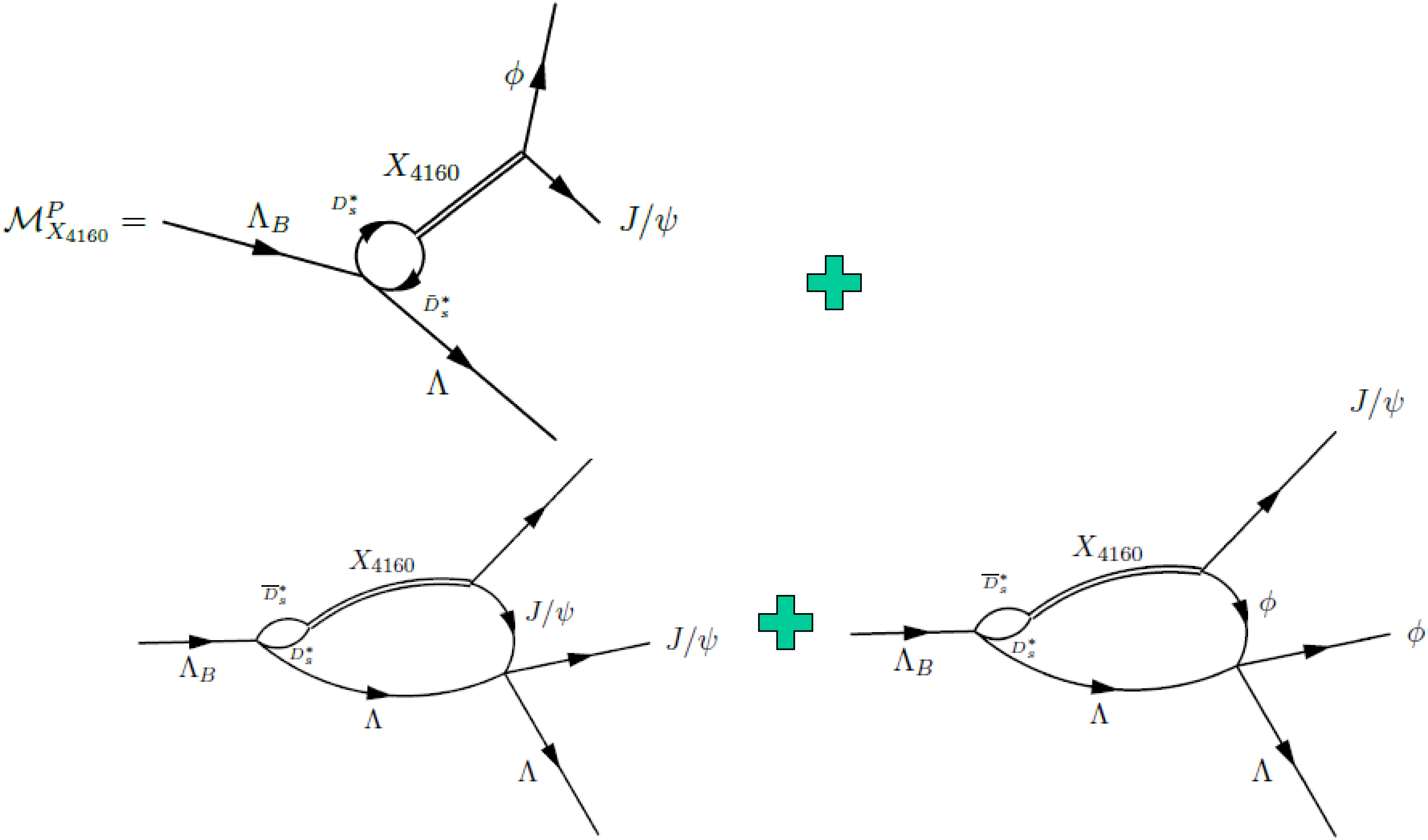
Direct production $\Lambda_b \to J/\psi\ \phi\ \Lambda$



Internal conversion process, strongly penalized by color factors

⇨ Neglected

The $\boldsymbol{\Lambda_b \to J/\psi\ \phi\ \Lambda}$ decay via X(4160) 2^{++} resonance

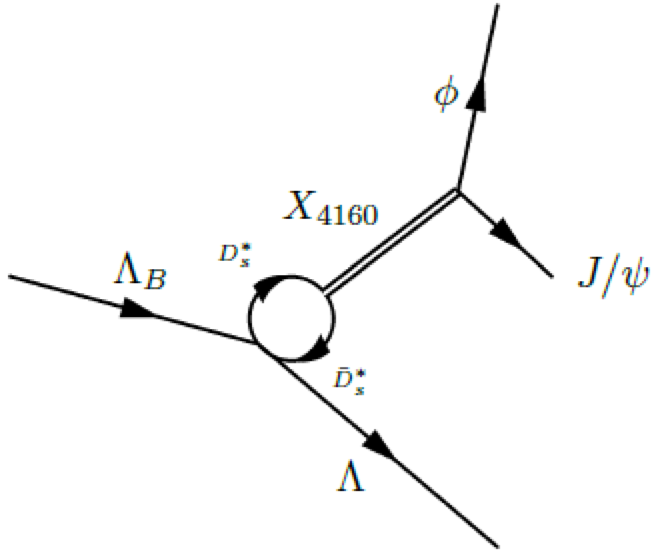


$$\mathcal{M}^{J/\psi\Lambda}_{X_{4160}} = A(\vec{\epsilon}_{J/\psi} \times \vec{\epsilon}_{\phi}) \cdot \left(\frac{\vec{P}_{\Lambda}-\vec{P}_{\phi}}{2}\right) \quad T_{J/\psi\Lambda,J/\psi\Lambda}\ I^{J/\psi\Lambda}_{X_{4160}}$$

$$\mathcal{M}^{\phi\Lambda}_{X_{4160}} = A(\vec{\epsilon}_{J/\psi} \times \vec{\epsilon}_{\phi}) \cdot \left(\frac{\vec{P}_{\Lambda}+\vec{P}_{\phi}}{2}\right) \quad T_{\phi\Lambda,\phi\Lambda}\ I^{\phi\Lambda}_{X_{4160}}$$

The $\Lambda_b \to J/\psi\ \phi\ \Lambda$ decay via X(4160) 2^{++} resonance

$\mathcal{M}^{P}_{X_{4160}} =$



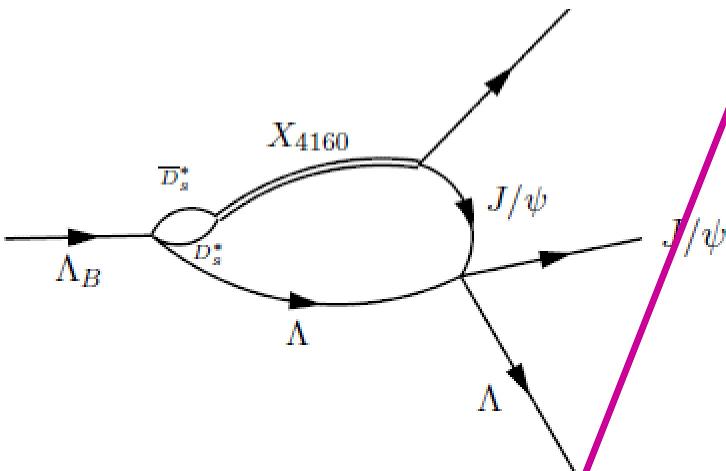
Strange Pentaquark

$$T_{J/\psi\Lambda,J/\psi\Lambda} = \frac{g^2_{J/\psi\Lambda}}{M_{J/\psi\Lambda} - M_R + i\frac{\Gamma_R}{2}}$$

$$M_R = 4550\ MeV\,, \quad \Gamma_R = 10\ MeV$$

$$g_{J/\psi\Lambda} = -0.61 - 0.06i$$

+



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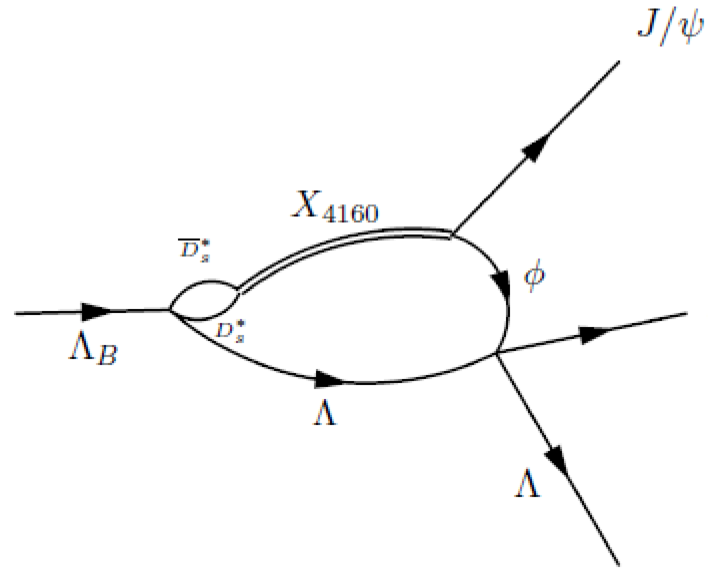
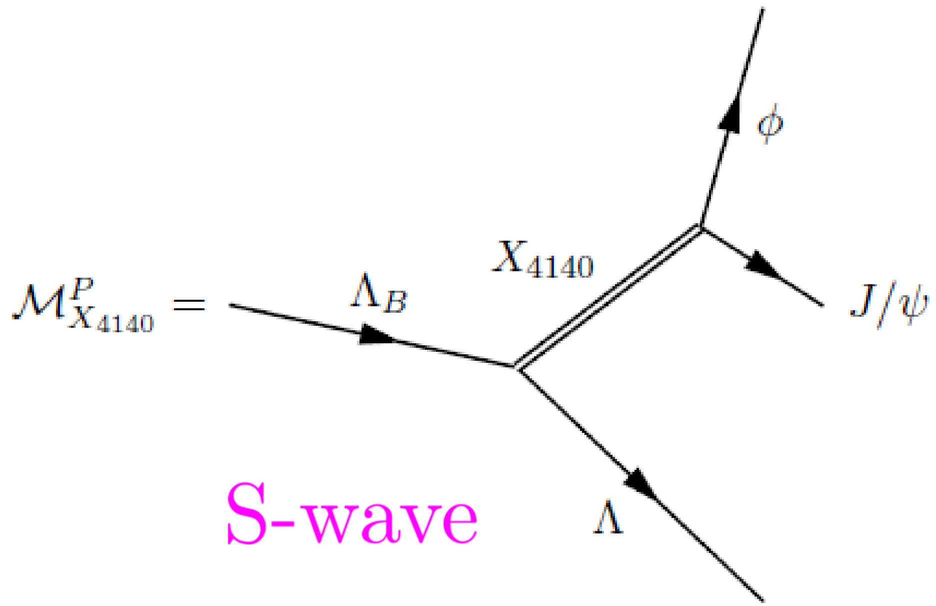


$$\mathcal{M}^{J/\psi\Lambda}_{X_{4160}} = A(\vec{\epsilon}_{J/\psi} \times \vec{\epsilon}_{\phi}) \cdot \left(\frac{\vec{P}_\Lambda - \vec{P}_\phi}{2}\right) \quad T_{J/\psi\Lambda,J/\psi\Lambda}\ I^{J/\psi\Lambda}_{X_{4160}}$$

$$\mathcal{M}^{\phi\Lambda}_{X_{4160}} = A(\vec{\epsilon}_{J/\psi} \times \vec{\epsilon}_{\phi}) \cdot \left(\frac{\vec{P}_\Lambda + \vec{P}_\phi}{2}\right) \quad T_{\phi\Lambda,\phi\Lambda} I^{\phi\Lambda}_{X_{4160}}$$

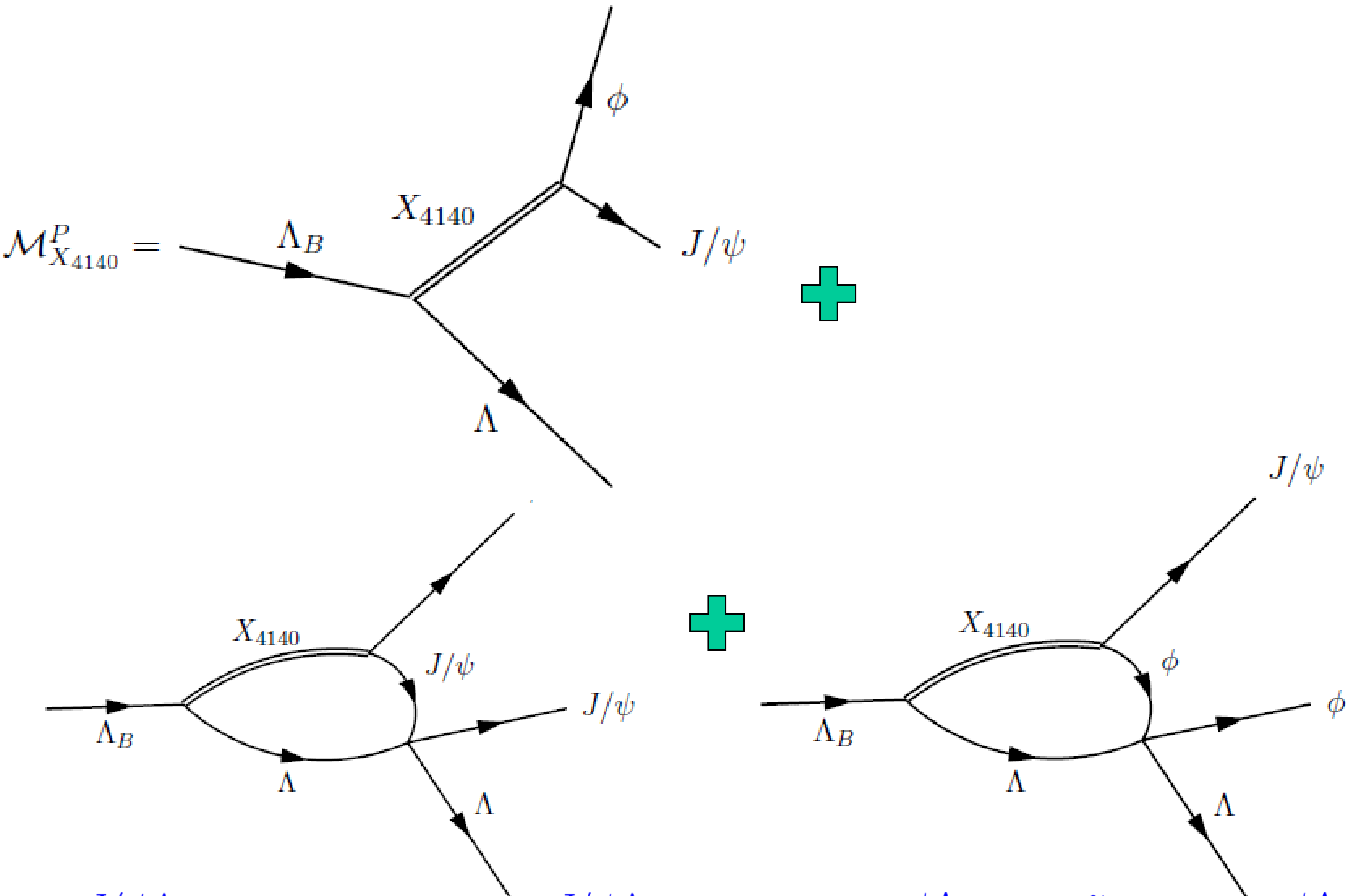
Model from **[Oset, Ramos, EPJ A44 (2010) 445]**

The $\mathbf{\Lambda_b \to J/\psi\ \phi\ \Lambda}$ decay via X(4140) 1^{++} resonance



$$\mathcal{M}^{P}_{X_{4140}} = \frac{\tilde{B}}{2M_{X(4140)}\left[M_{J/\psi\phi} - M_{X(4140)} + i\frac{\Gamma_{X(4140)}}{2}\right]}$$

The $\boldsymbol{\Lambda_b \to J/\psi\ \phi\ \Lambda}$ decay via X(4140) 1^{++} resonance



$$\mathcal{M}^{J/\psi\Lambda}_{X_{4140}} = \tilde{B}\ T_{J/\psi\Lambda, J/\psi\Lambda} I^{J/\psi\Lambda}_{X_{4140}}$$

$$\mathcal{M}^{\phi\Lambda}_{X_{4140}} = \tilde{B}\ T_{\phi\Lambda, \phi\Lambda} I^{\phi\Lambda}_{X_{4140}}$$

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

$$\mathcal{M}_{X_{4160}} = \mathcal{M}^{P}_{X_{4160}} + \mathcal{M}^{J/\psi\Lambda}_{X_{4160}} + \mathcal{M}^{\phi\Lambda}_{X_{4160}},$$

$$\mathcal{M}_{X_{4140}} = \mathcal{M}^{P}_{X_{4140}} + \mathcal{M}^{J/\psi\Lambda}_{X_{4140}} + \mathcal{M}^{\phi\Lambda}_{X_{4140}}.$$

Denoting the full amplitude as $\mathcal{M}$, we have

$$\overline{|\mathcal{M}|^2} = \overline{|\mathcal{M}_{X_{4160}}|^2} + \overline{|\mathcal{M}_{X_{4140}}|^2},$$

$$\overline{|\mathcal{M}|^2} = |A|^2\left(\overline{|\mathcal{M}_{X_{4160}}|^2} + \beta\ \overline{|\mathcal{M}_{X_{4140}}|^2}\right)$$

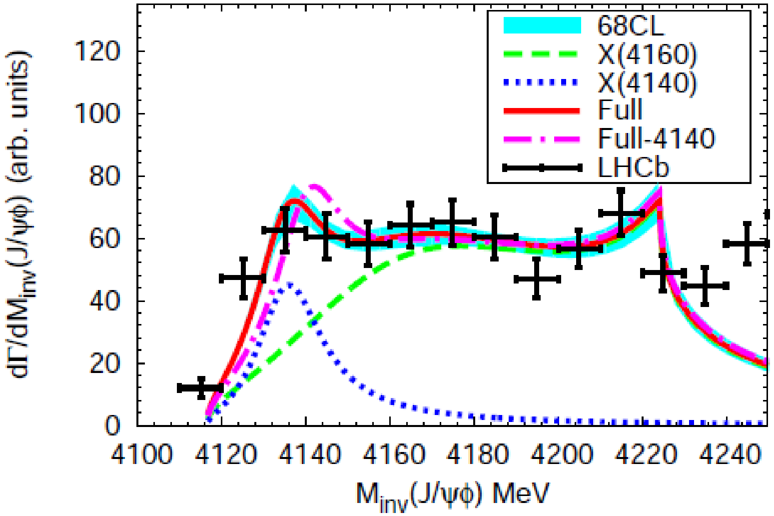
The $\Lambda_b \to J/\psi\ \phi\ \Lambda$ decay

$$\mathcal{M}_{X_{4160}} = \mathcal{M}^{P}_{X_{4160}} + \mathcal{M}^{J/\psi\Lambda}_{X_{4160}} + \mathcal{M}^{\phi\Lambda}_{X_{4160}},$$

$$\mathcal{M}_{X_{4140}} = \mathcal{M}^{P}_{X_{4140}} + \mathcal{M}^{J/\psi\Lambda}_{X_{4140}} + \mathcal{M}^{\phi\Lambda}_{X_{4140}}.$$

Denoting the full amplitude as $\mathcal{M}$, we have

$$\overline{|\mathcal{M}|^2} = \overline{|\mathcal{M}_{X_{4160}}|^2} + \overline{|\mathcal{M}_{X_{4140}}|^2},$$



$$\overline{|\mathcal{M}|^2} = |A|^2\left(\overline{|\mathcal{M}_{X_{4160}}|^2} + \beta\,\overline{|\mathcal{M}_{X_{4140}}|^2}\right)$$

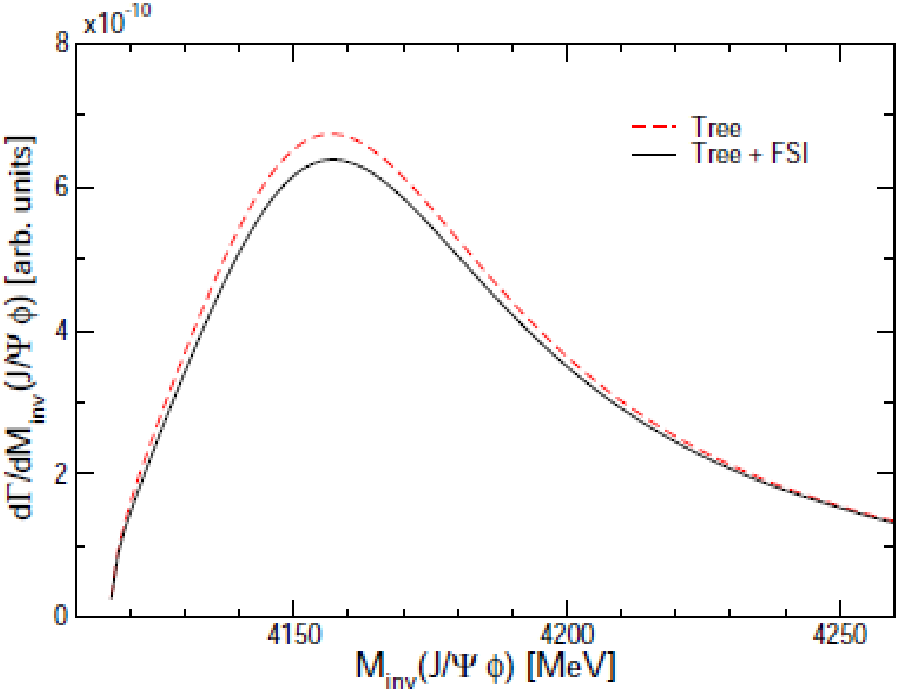
Unknown overall factor

⟹ Arbitrary units

Wang, Xie, Geng, Oset,

PRD97 (2018) no. 1 014017

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



Wide X(4140)

$M = 4146.5\ MeV\ ,\ \Gamma = 83\ MeV$

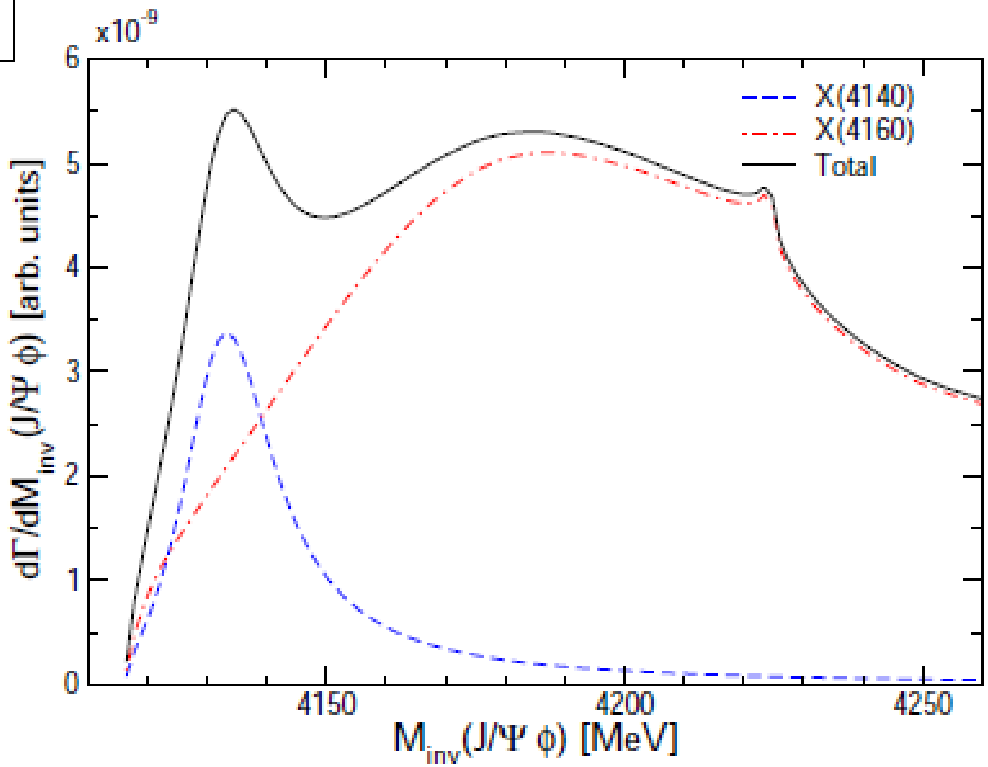
FSI has a little effect en este canal

Narrow X(4140)

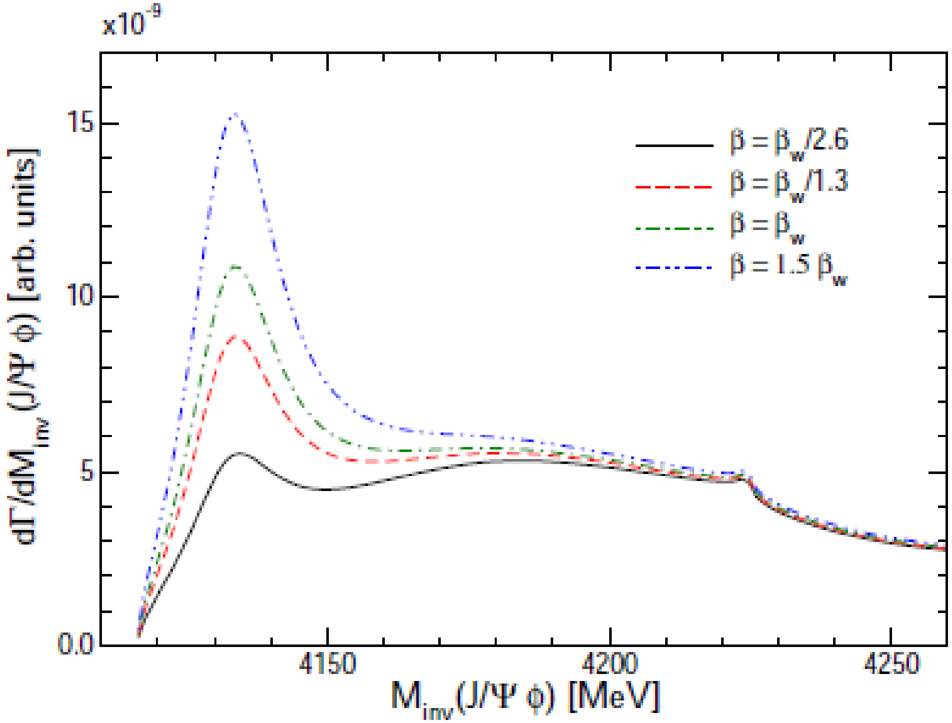
$M = 4132\ MeV\ ,\ \Gamma = 19\ MeV$

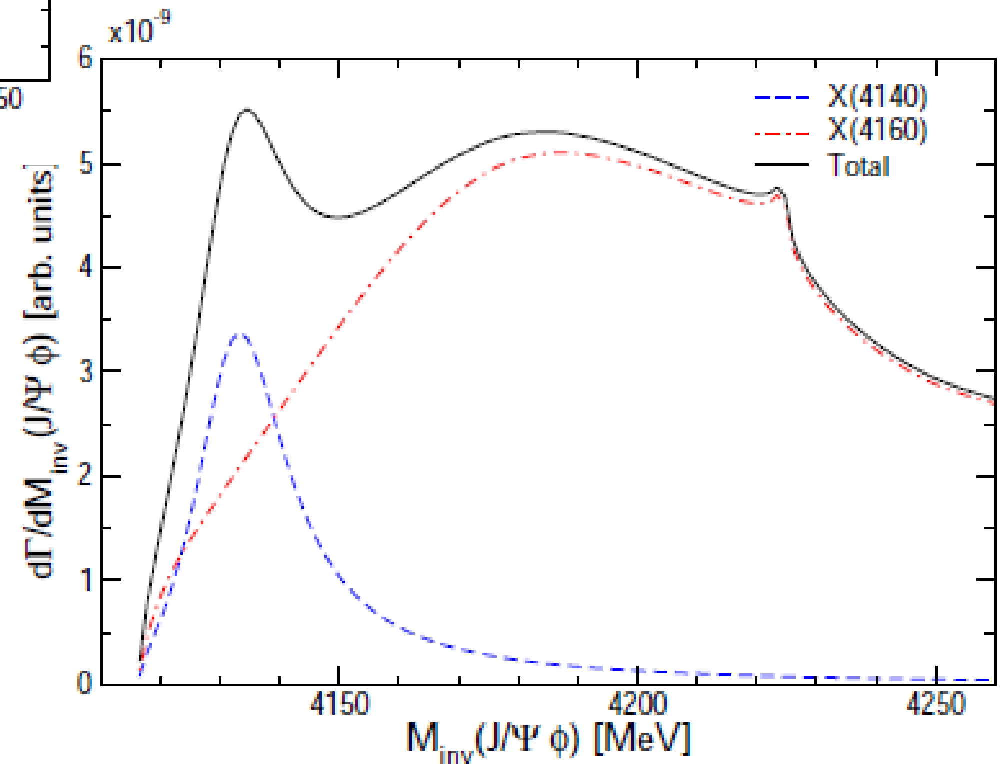
+

X(4160)

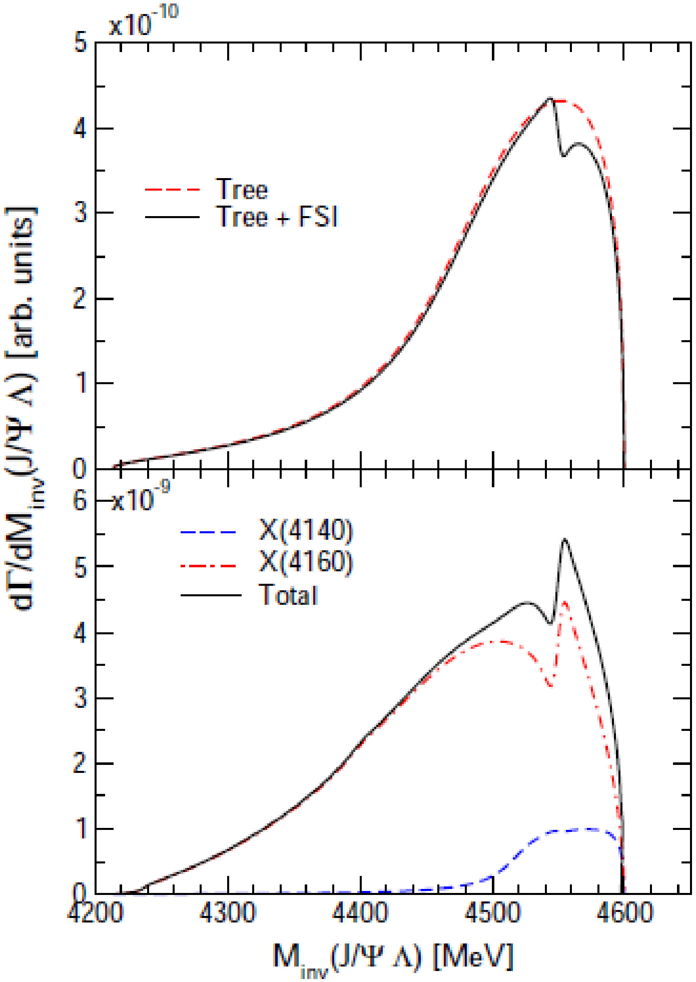


The $\Lambda_b \to J/\psi\ \phi\ \Lambda$ decay





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



Wide X(4140)

$M = 4146.5\ MeV\ ,\ \Gamma = 83\ MeV$

Pentaquark peak is qualitatively different in different scenarios

Narrow X(4140)

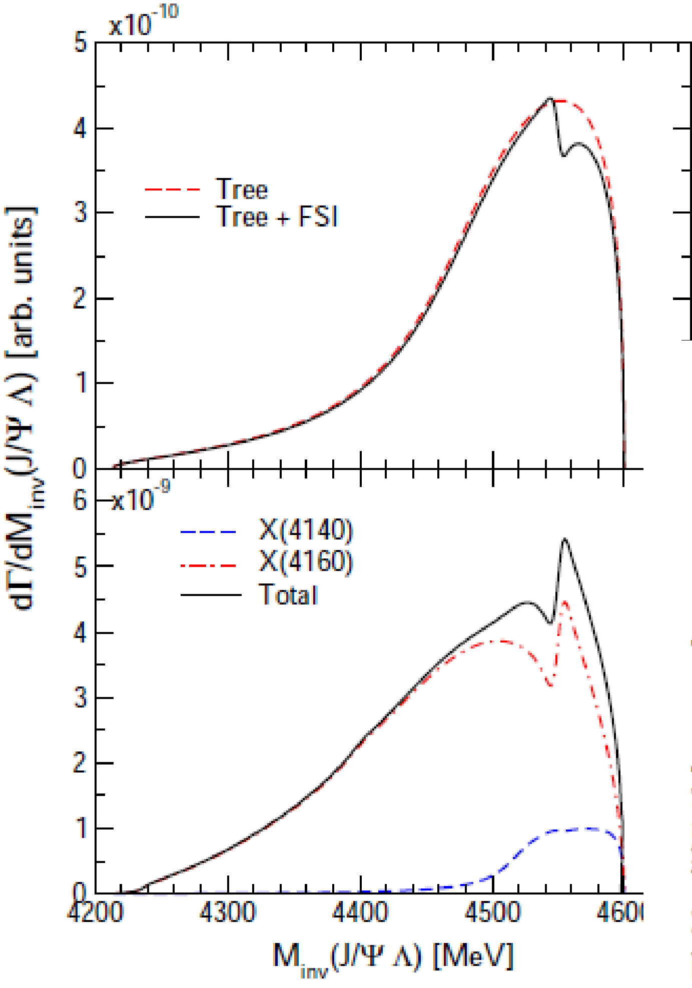
$M = 4132\ MeV\ ,\ \Gamma = 19\ MeV$

+

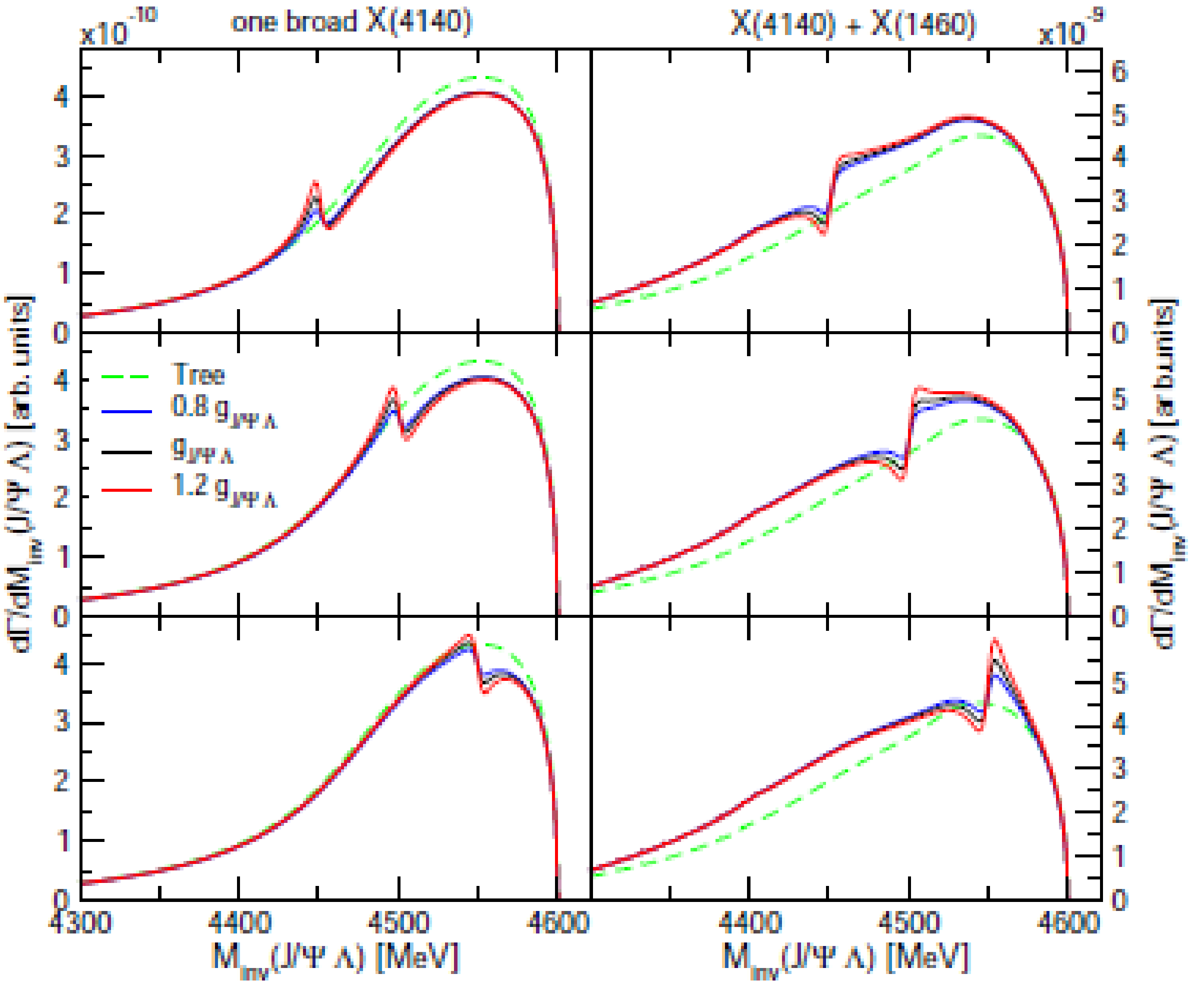
X(4160)

Pentaquark peak is observable

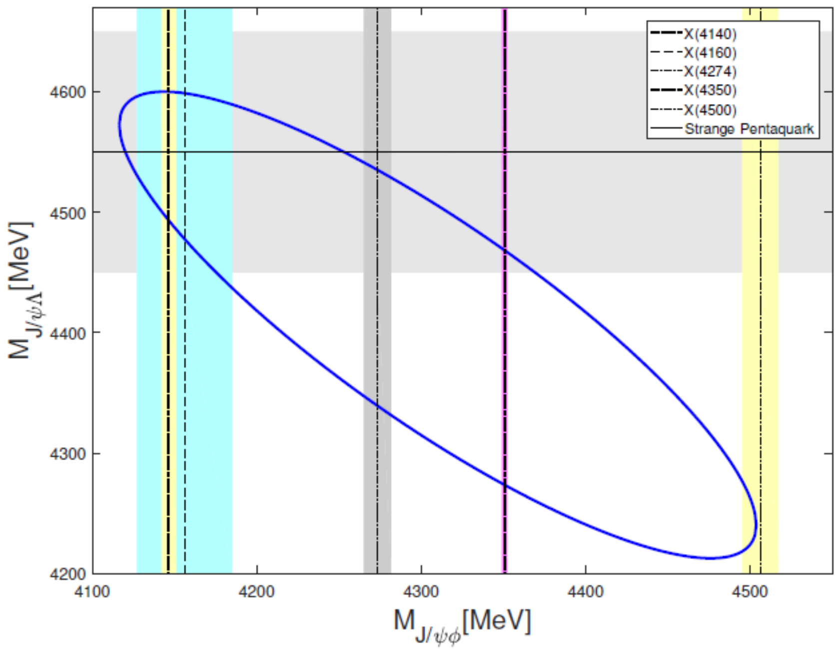
The $\Lambda_b \to J/\psi\ \phi\ \Lambda$ decay



$4450\ \text{MeV} \leq M_R \leq 4550\ \text{MeV}$

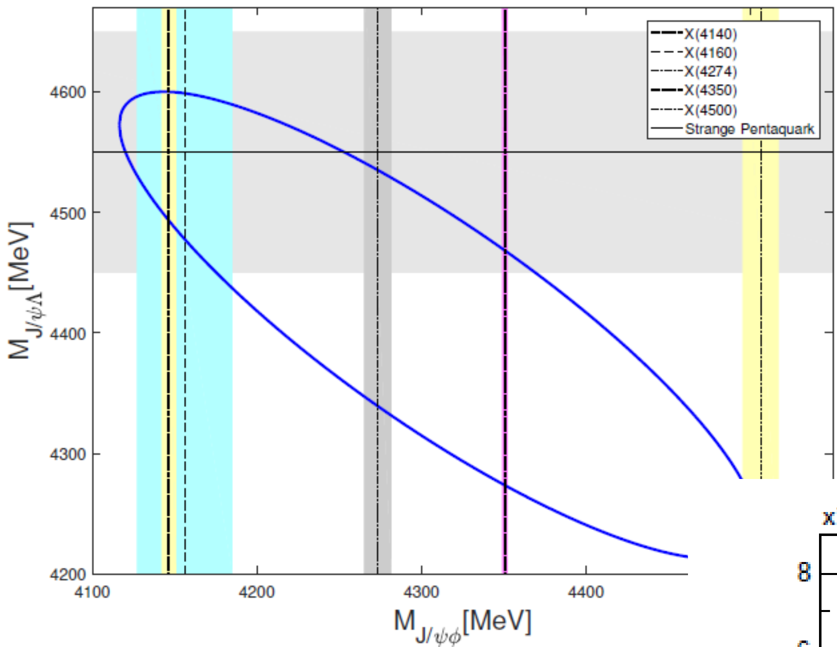


The $\Lambda_b \to J/\psi\ \phi\ \Lambda$ decay



Can we improve the observability implementing constraints in the spectra ?

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

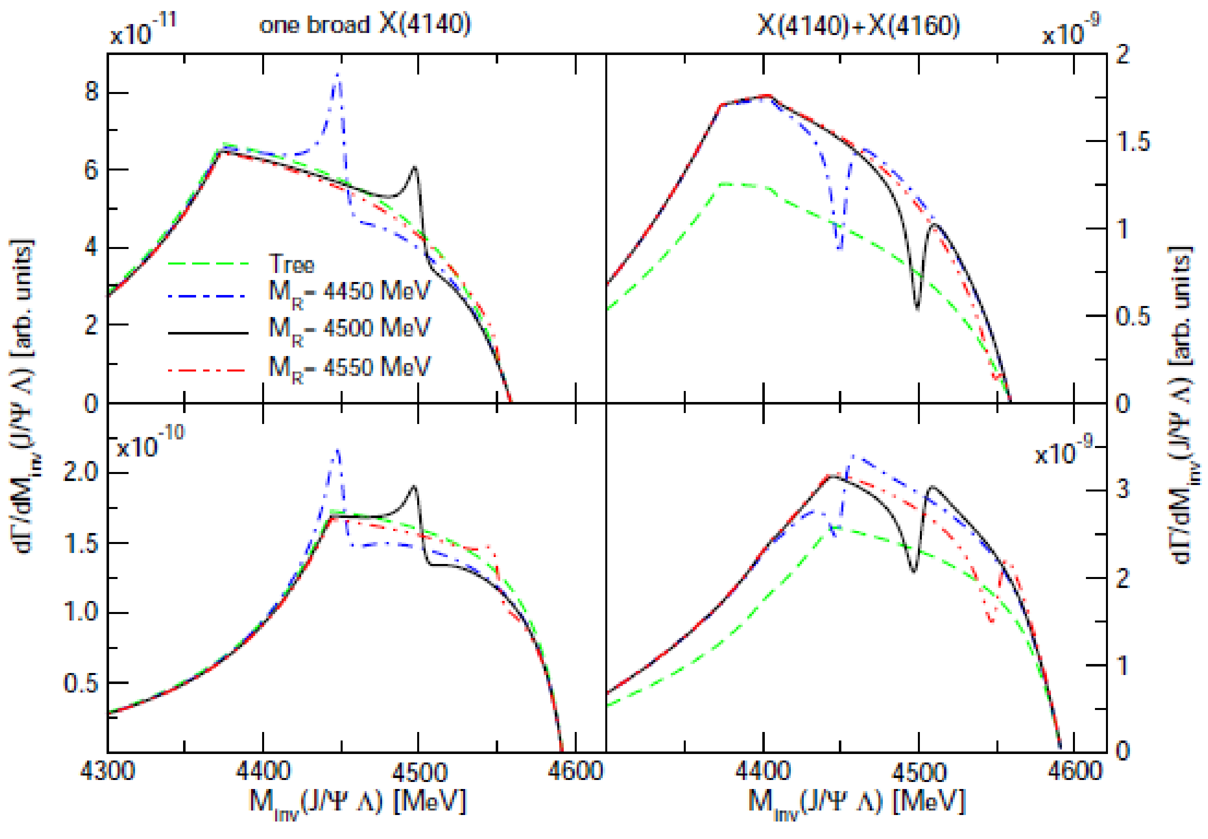


Strange Pentaquark can be clearly observed for masses ≤ 4500 MeV

Pentaquark peak is qualitatively different in different scenarios

$M_{J/\psi\phi} > 4240$ MeV

$M_{J/\psi\phi} > 4180$ MeV



Conclusions

The $\Lambda_b \to J/\psi\, \phi\Lambda$ decay allows to study various exotic states at the same time

Pentaquark P_{cs} peak is clearly observable for masses $M_{J/\psi\Lambda} \leq 4550$ MeV

The interlay between X(4140) and X(4160) resonances can be studied in this decay

$\Rightarrow$ The correlation of P_{cs} peak with background is qualitatively different in presence of X(4160)

The $M_{\Lambda\phi} = 2158\ MeV$ resonance is unlikely to be observed exp., with model parameters from [Oset, Ramos, EPJ A44 (2010) 445]