Exotic hadrons: recent LHCb discoveries

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On behalf of the LHCb collaboration

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Outline

- Study of $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays

  [JHEP 02 (2021) 024]

- Evidence of a $J/\psi\Lambda$ resonance and observation of excited Ξ^{*-} states in the $\Xi_b \to J/\psi\Lambda K^-$

  [arXiv:2012.10380, to appear in Science Bulletin]

- Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$

  First presentation

  [arXiv:2103.01803]

Introduction

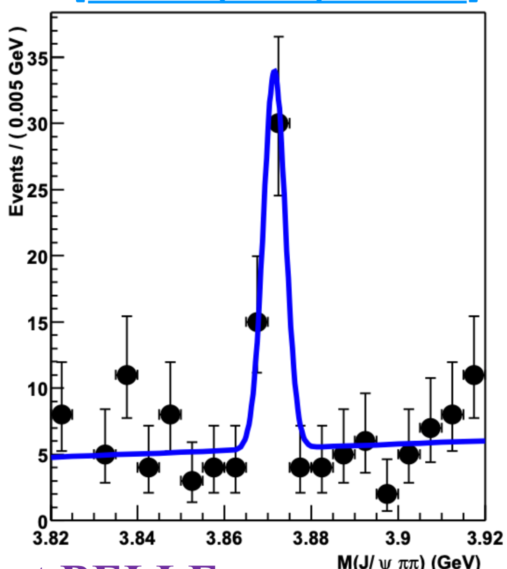
- Multiquark states are first predicted in 1964 in quark model, the original papers by M.Gell-Mann and G.Zweig.

The Nobel Prize in Physics 1969

- Mesons are 2-quark bounding states, baryons are 3-quark states, does multi-quark state exist?

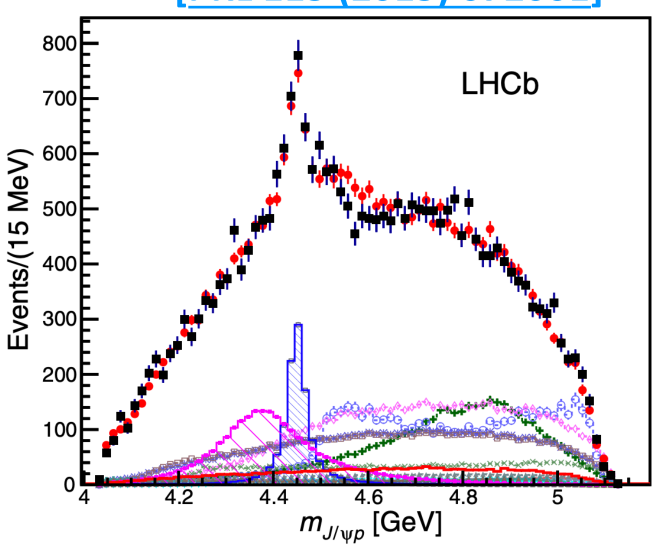
- First tetraquark candidate observed at BELLE in 2003, first pentaquark candidate at LHCb in 2015.

[PRL 91 (2003) 262001]



2003 at BELLE

[PRL 115 (2015) 072001]



2015 at LHCb

Many exotic states observed at LHCb

- 59 new hadron states (conventional & exotic) observed at LHC, most of them discovered at LHCb

[Taken from CERNCOURIER]

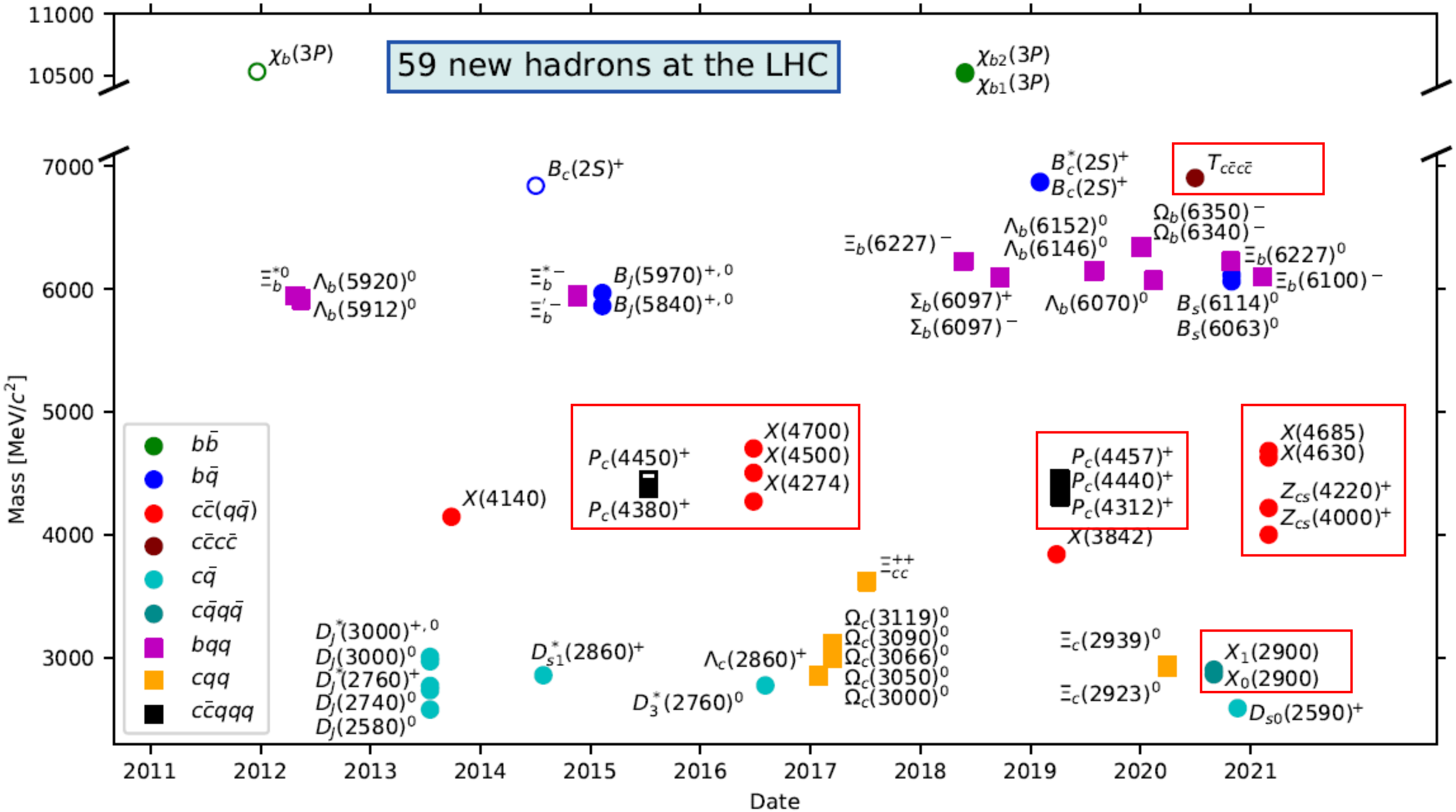


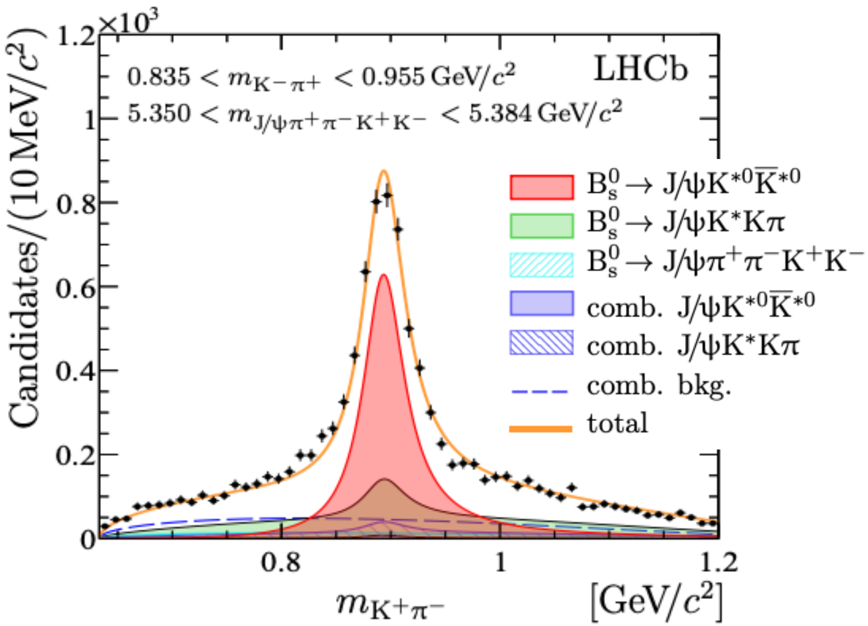
Diagram of discovery The ATLAS, CMS and LHCb collaborations have discovered 59 new hadronic states so far – the most recent being the four tetraquarks reported in this article. Credit: CERN

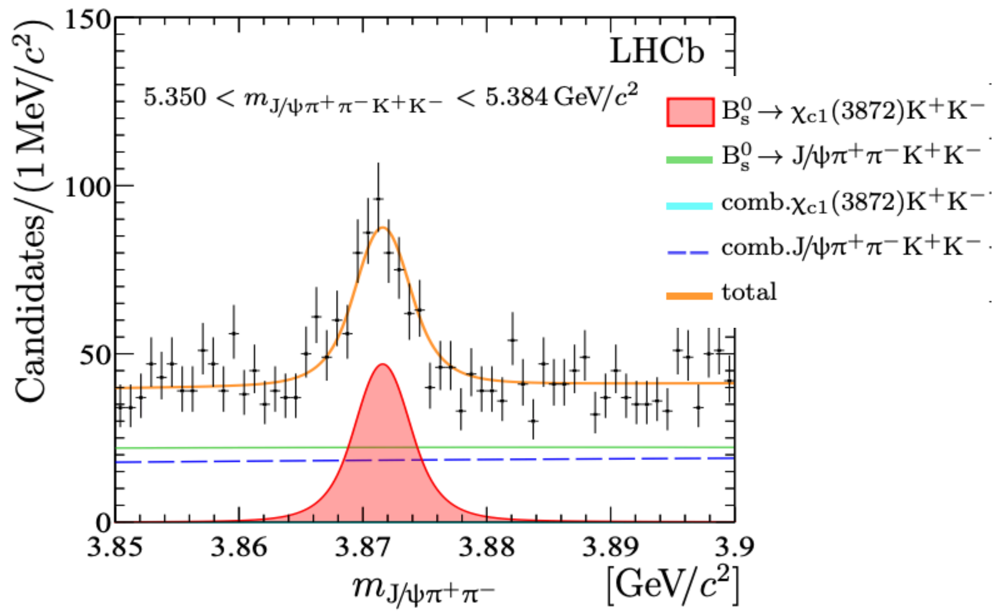
Study of $B_s^0 \to J/\psi\pi^+\pi^- K^+ K^-$ decays

Study of $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays

Motivation: [JHEP 02 (2021) 024]

- $\chi_{c1}(3872)$ and $J/\psi\phi$ structures can be studied in this decay
- Production rate measurements can shed light on the nature of exotic states





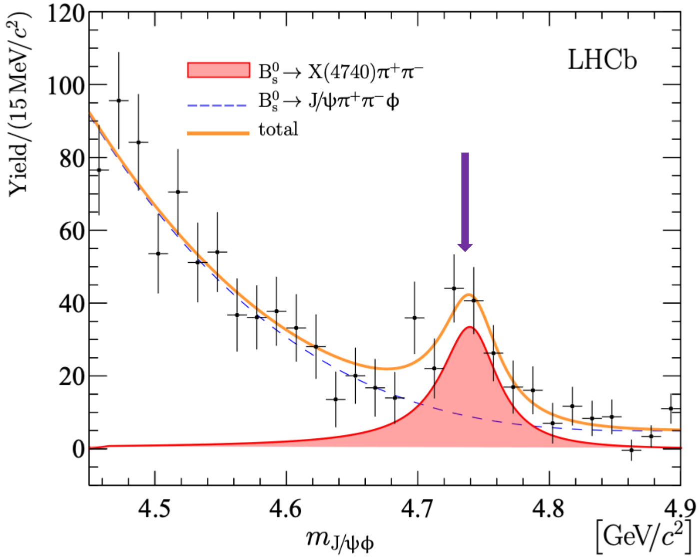
- Decays of $B_s^0 \to J/\psi K^{*0}\overline{K}^{*0}$ and $B_s^0 \to \chi_{c1}(3872)K^+K^-$ observed for the first time.
- Most precise single measurement of B_s^0 mass:

$$m_{B_s^0} = 5366.98 \pm 0.07 \pm 0.13\,\mathrm{MeV}/c^2\,.$$

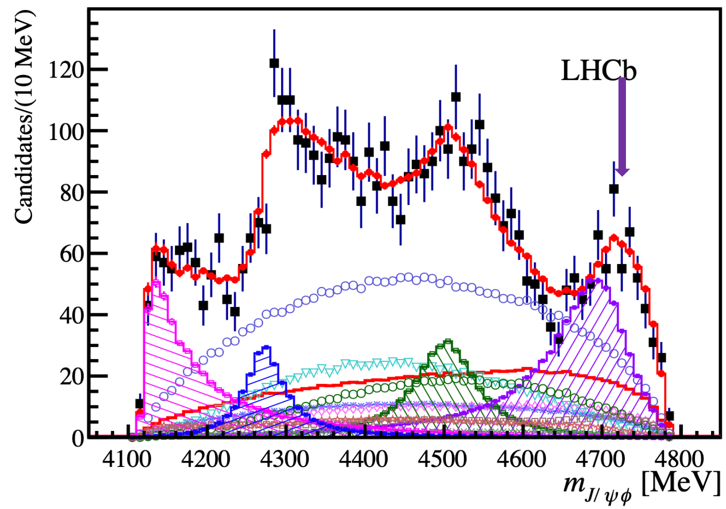
$X(4740)$ observed in this channel

➢ A peak around 4740 MeV in $J/\psi\phi$ mass spectrum

[JHEP 02 (2021) 024]



[PRL 118 (2017) 022003]



$X(4700)$ observed in $B^+ \to J/\psi\phi K^+$ at LHCb

➢ Fitting with the Breit-Wigner lineshape:

$$m_{X(4740)} = 4741 \pm 6 \pm 6 \ \text{MeV}/c^2,$$
$$\Gamma_{X(4740)} = 53 \pm 15 \pm 11 \ \text{MeV},$$

➢ Significance of $X(4740) > 5\sigma$

➢ Are $X(4700)$ and $X(4740)$ the same state? Further amplitude studies are required.

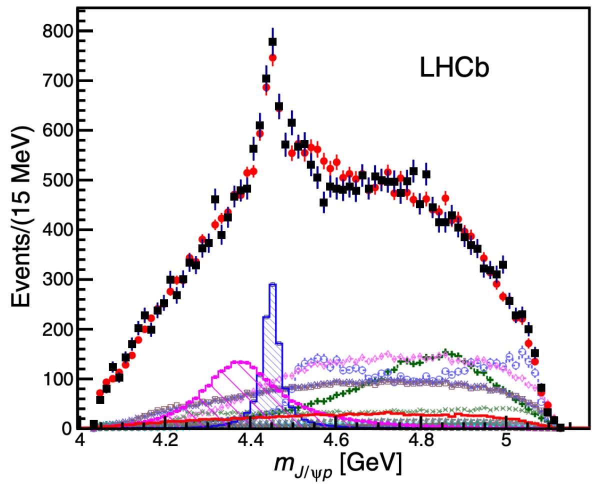
- Two channels peaks roughly at the same place

Evidence of a $J/\psi\Lambda$ resonance and observation of excited Ξ^{*-} states in the $\Xi_b \to J/\psi\Lambda K^-$

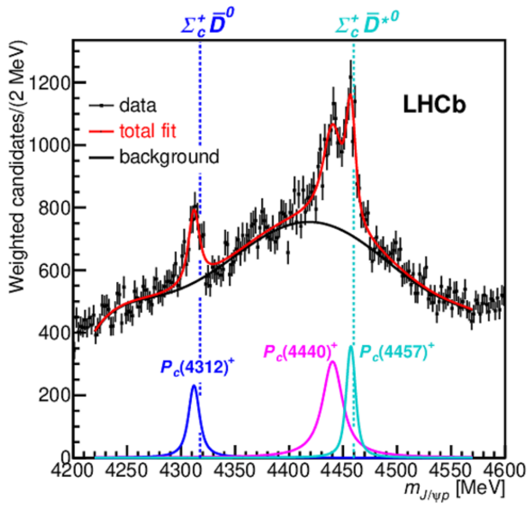
Motivation

- Two pentaquark states (P_c^+) observed in $\Lambda_b^0 \to J/\psi p K^-$ decay in 2015 at LHCb.
- New narrow $P_c(4312)^+$ observed in 2019 at LHCb, $P_c(4450)^+$ is resolved to two states. (with 10 times statistics)

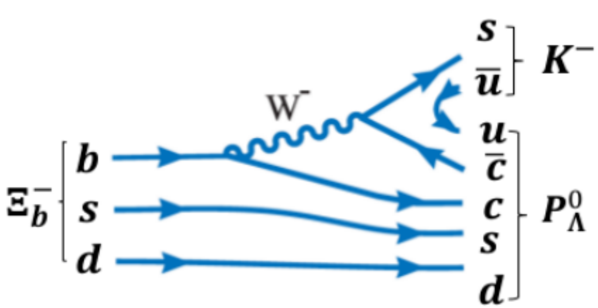
[PRL 115 (2015) 072001]

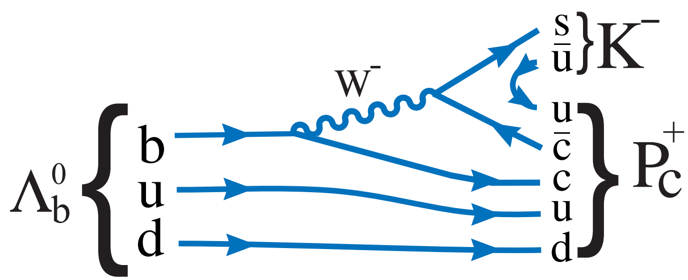


[PRL 122 (2019) 222001]



- With u quark changed to s quark, $\Xi_b^- \to J/\psi \Lambda K^-$ is an ideal channel to search for hidden-charm pentaquark (P_{cs}) state with strangeness.

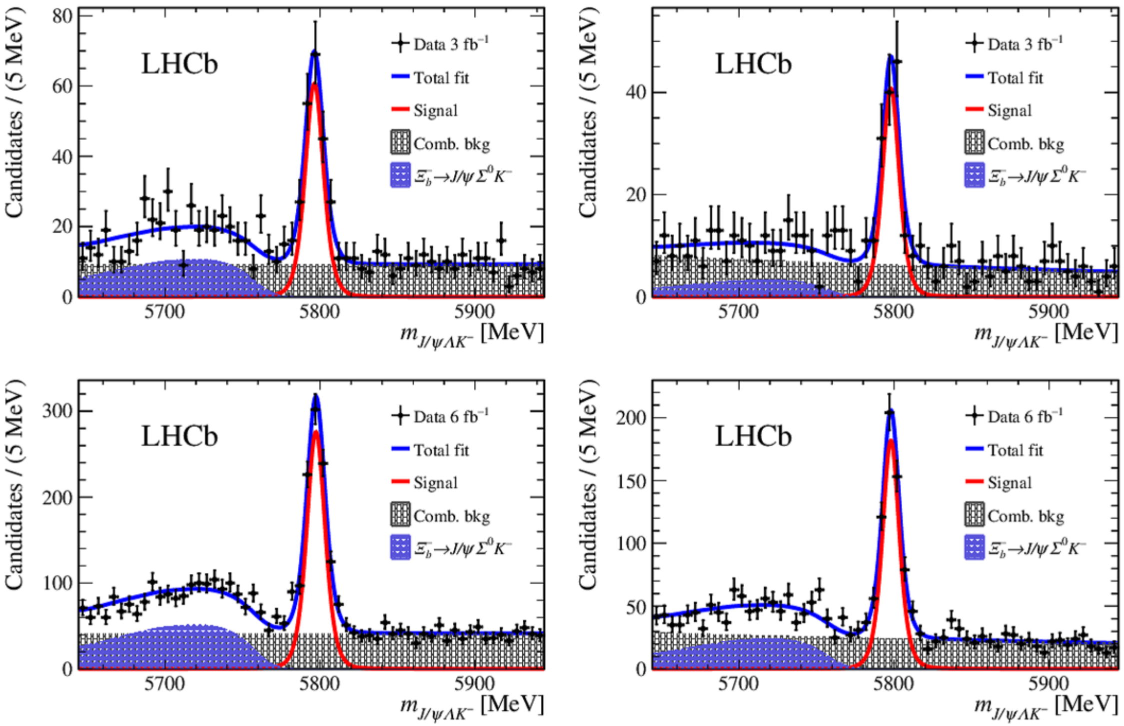




Run 1 + Run 2 data sample

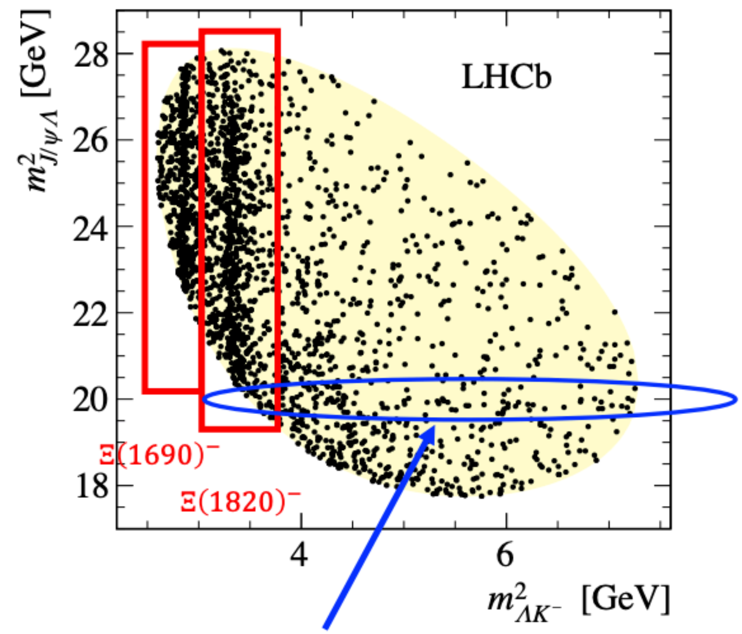
- $\sim$1750 Ξ_b^- signals, purity $\sim$ 80%

[arXiv:2012.10380]



Long Long:
Λ decay in VELO.

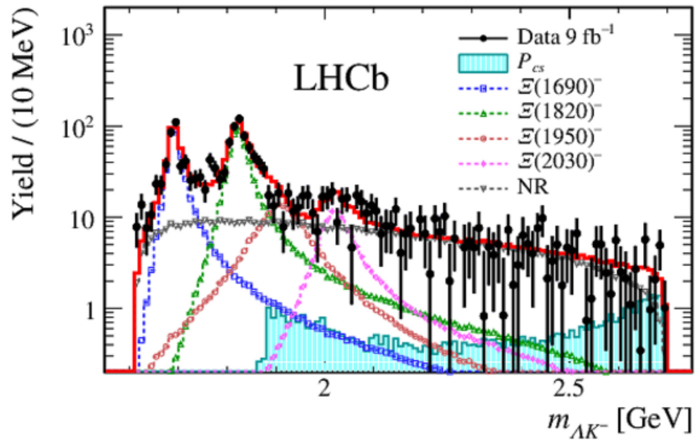
Downstream downstream:
Λ decay after VELO.

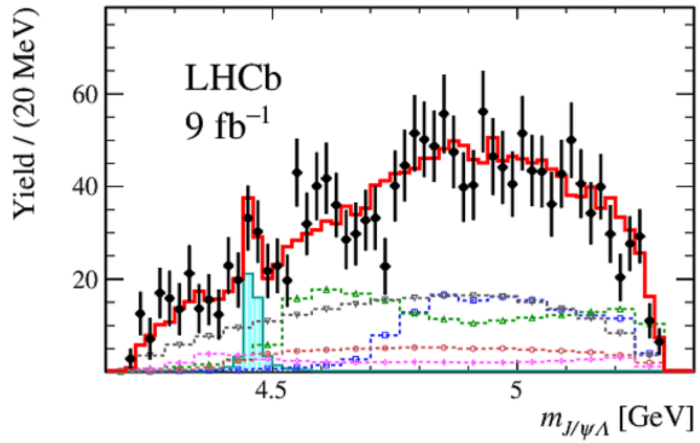


Potential P_{cs} contribution?
A full amplitude analysis is performed

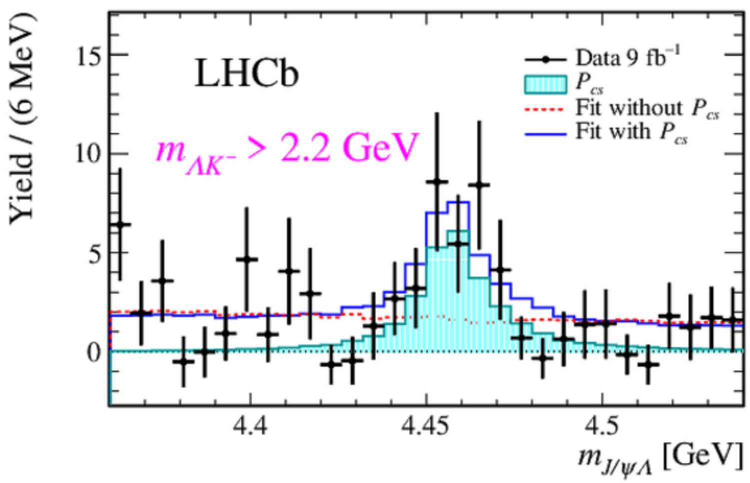
Significance of a P_{cs} in this channel [arXiv:2012.10380]

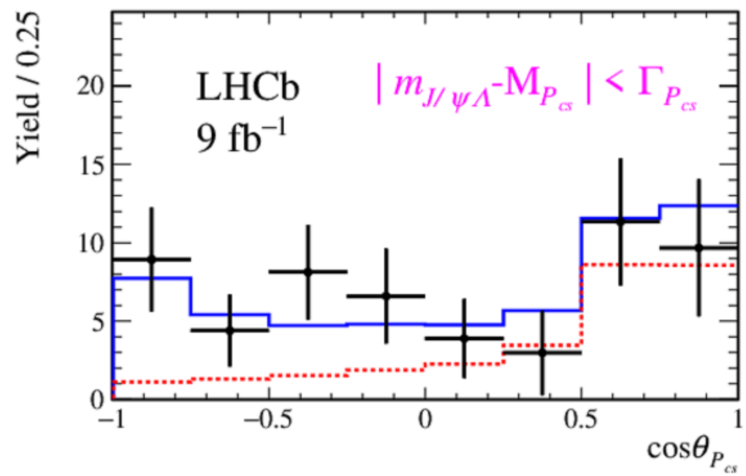
- ~3.1σ significance of P_{cs} (Syst. uncertainty and look-elsewhere effect considered)



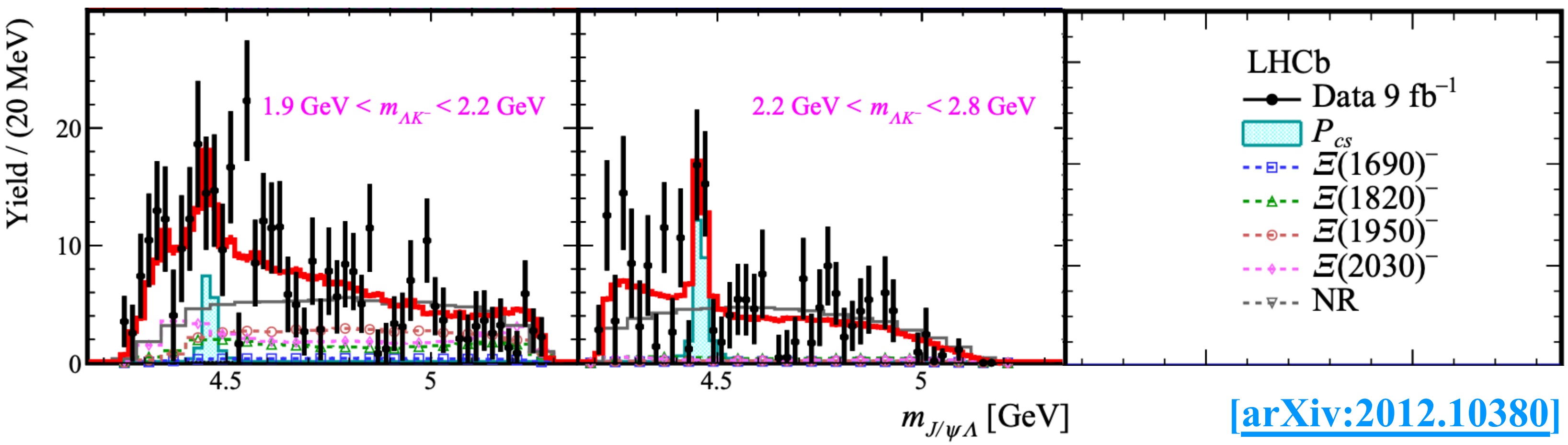


- A significant improvement is also found in the $\cos\theta_{P_{cs}}$ distributions when the P_{cs} included in fitting





Fitting results



[arXiv:2012.10380]

State	M_0 [MeV]	Γ_0 [MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9}_{-0.6}\,^{+0.7}_{-1.3}$
$\Xi(1690)^-$	$1692.0 \pm 1.3\,^{+1.2}_{-0.4}$	$25.9 \pm 9.5\,^{+14.0}_{-13.5}$	$22.1\,^{+6.2}_{-2.6}\,^{+6.7}_{-8.9}$
$\Xi(1820)^-$	$1822.7 \pm 1.5\,^{+1.0}_{-0.6}$	$36.0 \pm 4.4\,^{+7.8}_{-8.2}$	$32.9\,^{+3.2}_{-6.2}\,^{+6.9}_{-4.1}$
$\Xi(1950)^-$	1910.6 ± 18.4	105.7 ± 23.2	$11.5\,^{+5.8}_{-3.5}\,^{+49.9}_{-9.4}$
$\Xi(2030)^-$	2022.8 ± 4.7	68.2 ± 8.5	$7.3\,^{+1.8}_{-1.8}\,^{+3.8}_{-4.1}$
NR	—	—	$35.8\,^{+4.6}_{-6.4}\,^{+10.3}_{-11.2}$

Fit fraction

Consistent with PDG, with improved precision

- Two Ξ^{*-} states observed for the first time in Ξ_b^- decay
- Mass of $P_{cs}(4459)^0$ 19 MeV below the $\Xi_c^0 \overline{D}^{*0}$ threshold, similar to $P_c(4440)^+$ and $P_c(4457)^+$ pentaquark states.

Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$ in $B^+ \to J/\psi\phi K^+$

Motivation-1

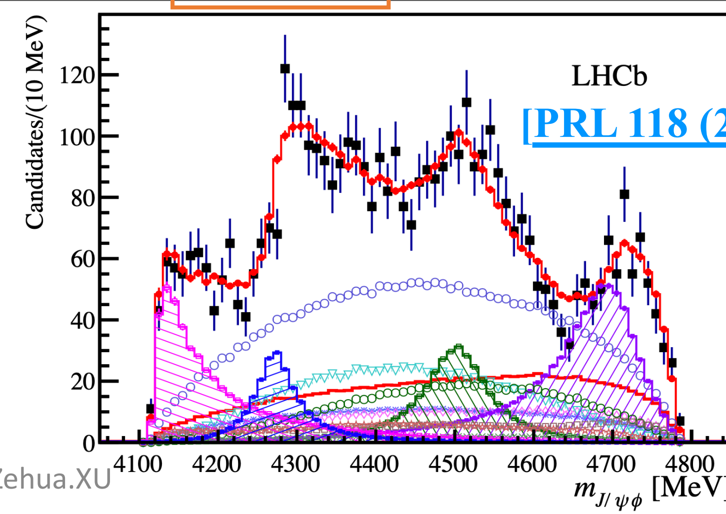
[arXiv:2103.01803]

- The channel $B^+ \to J/\psi\phi K^+$ was studied at LHCb using Run 1 sample.(First amplitude analysis for this channel)
- The width of $X(4140)$ is $83 \pm 21^{+21}_{-14}$ MeV, larger than the value measured from other experiments.

[PRD 95 (2017) 012002]

Year	Experiment luminosity	$B \to J/\psi\phi K$ yield	$X(4140)$ peak Mass [MeV]	Width [MeV]	Sign.	Fraction %
2008	CDF 2.7 fb^{-1} [1]	58 ± 10	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$	3.8σ	
2009	*Belle* [22]	*325 ± 21*	*4143.0 fixed*	*11.7 fixed*	*1.9σ*	
2011	*CDF 6.0 fb^{-1}* [29]	*115 ± 12*	*$4143.4^{+2.9}_{-3.0} \pm 0.6$*	*$15.3^{+10.4}_{-6.1} \pm 2.5$*	*5.0σ*	*$14.9 \pm 3.9 \pm 2.4$*
2011	LHCb 0.37 fb^{-1} [21]	346 ± 20	4143.4 fixed	15.3 fixed	1.4σ	< 7 @ 90%CL
2013	CMS 5.2 fb^{-1} [25]	2480 ± 160	$4148.0 \pm 2.4 \pm 6.3$	$28\ ^{+15}_{-11} \pm 19$	5.0σ	10 ± 3 (stat.)
2013	D0 10.4 fb^{-1} [26]	215 ± 37	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$	3.0σ	$21 \pm 8 \pm 4$
2014	BaBar [24]	189 ± 14	4143.4 fixed	15.3 fixed	1.6σ	< 13.3 @ 90%CL
2015	D0 10.4 fb^{-1} [27]	$p\bar{p} \to J/\psi\phi\ldots$	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$	4.7σ (5.7σ)	
Average			4147.1 ± 2.4	15.7 ± 6.3		

- Three other $J/\psi\phi$ structures, $X(4274)$, $X(4500)$ and $X(4700)$ were observed in Run-1 analysis.



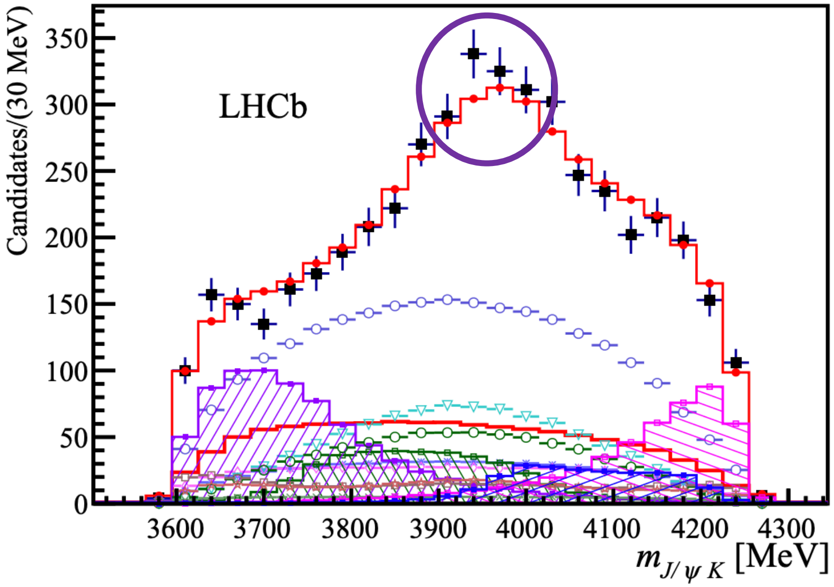
[PRL 118 (2017) 022003]

Motivation-2

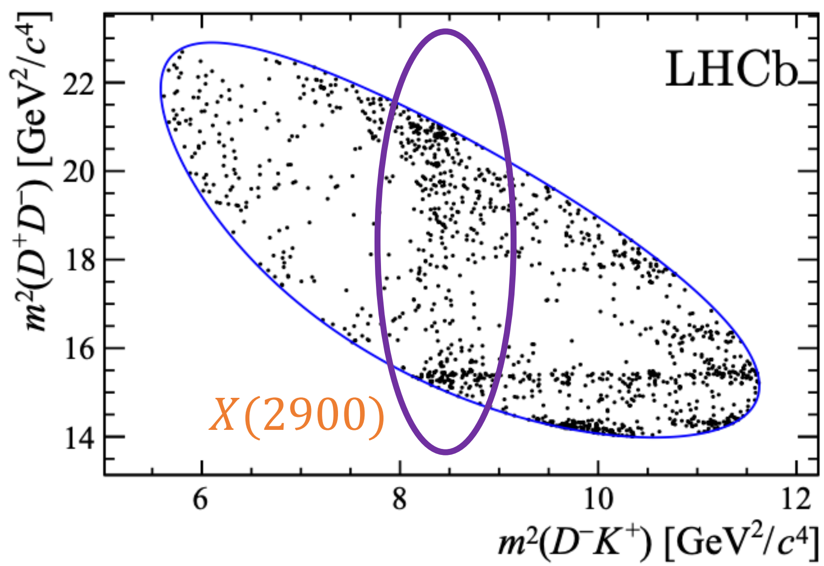
[arXiv:2103.01803]

- Hint of $J/\psi K^+$ structure in Run 1 analysis.
- Z_{cs}^+ in $B^+ \to J/\psi\phi K^+$ decay has similar topology as Z_c^+ in $B^+ \to J/\psi K^-\pi^+$ decay, and P_c^+ in $\Lambda_b^0 \to J/\psi p K^-$
- The observation of $X(2900)$ containing strange quark, and the evidence of P_{cs}^+ implies possible existence of Z_{cs}^+.

[PRL. 118 (2017) 022003]



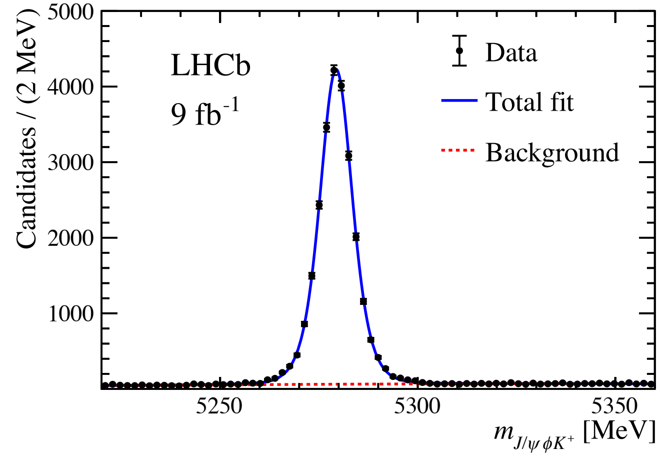
[PRL. 125 (2020) 242001]



Run 1 and Run 2 sample

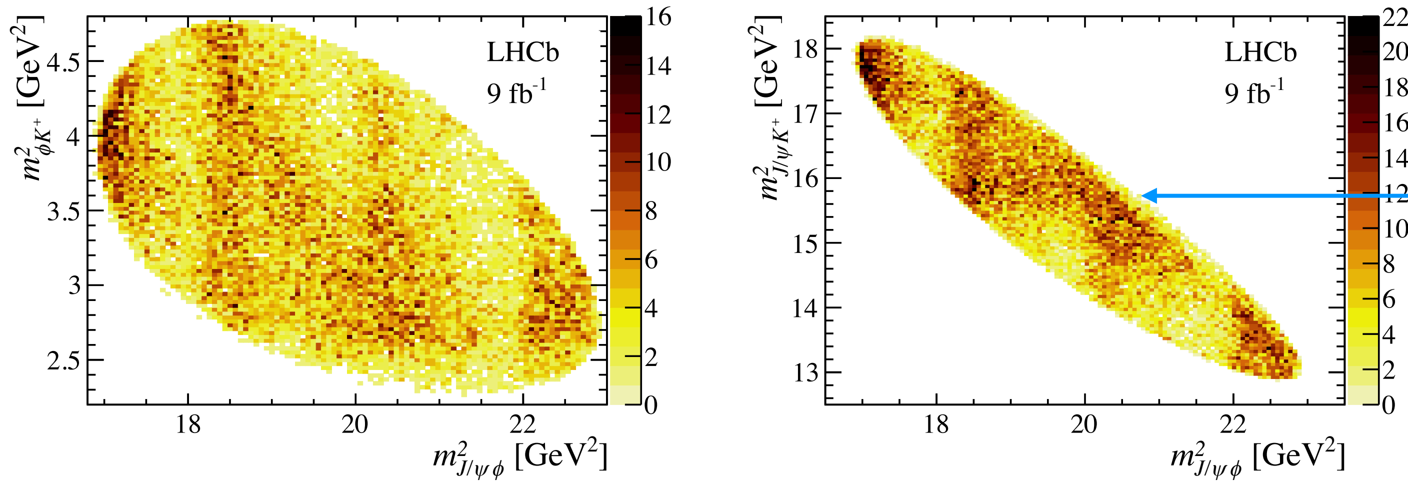
[arXiv:2103.01803]

- Selection is optimized
  - ~ 24k signal (6 times larger than the previous publication)
  - overall background fraction ~ 4% (a factor of 6 smaller)



- Clear structures in Dalitz plot

Several X states along $m_{J/\psi\phi}$.

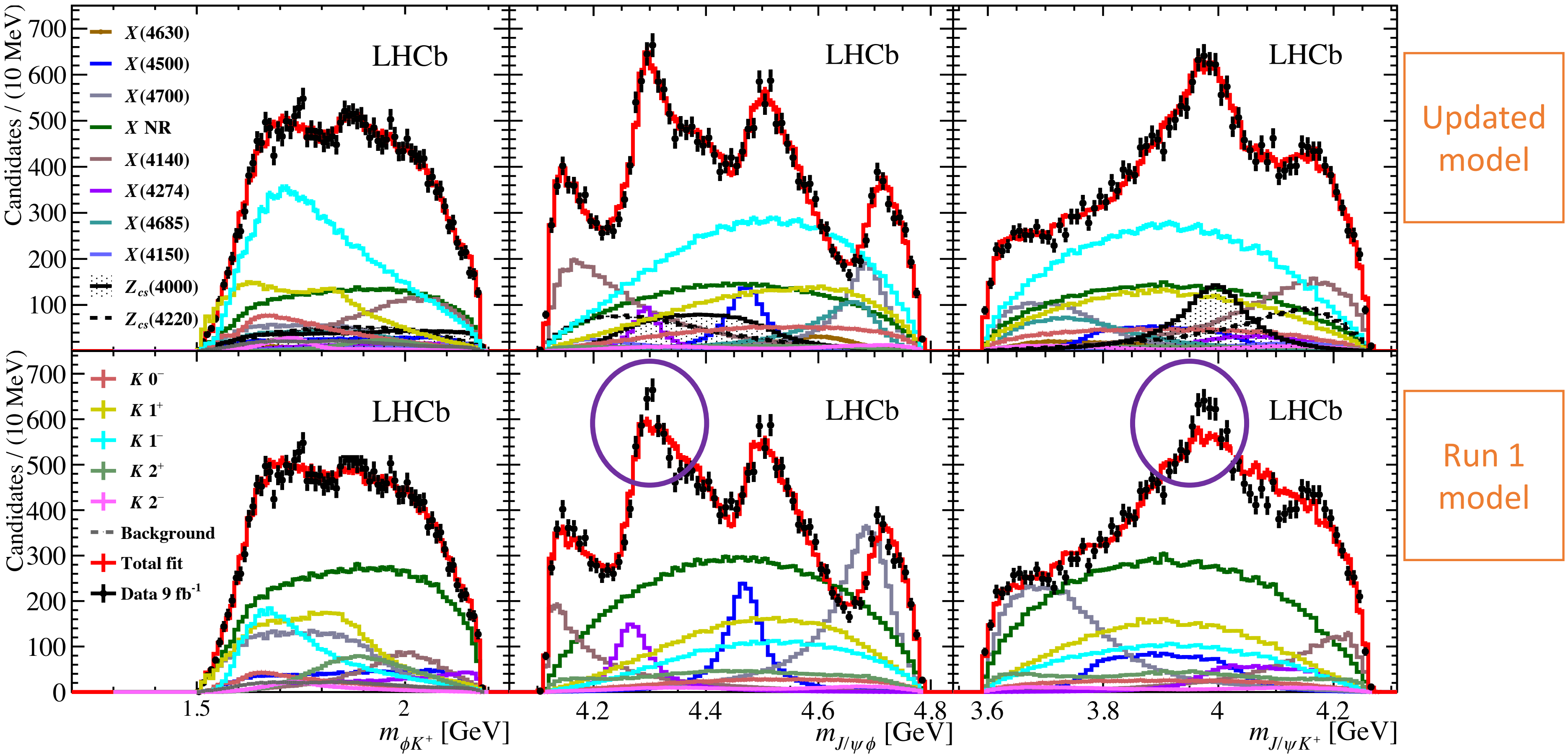


Z_{cs} state?

Clearly visible: 4 structures in $J/\psi\phi$ and an obvious structure in $J/\psi K$

6D amplitude fitting

- The fitting model was optimized based on previous analysis using Run 1 sample.
  More K^* states cannot improve the fitting
  By testing the contributions from other states [arXiv:2103.01803]



Fitting results

[arXiv:2103.01803]

Contribution	Significance [$\times\sigma$]	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28 ^{+59}_{-30}$	$2.0 \pm 0.5 ^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16 ^{+18}_{-110}$	$174 \pm 27 ^{+134}_{-73}$	$2.6 \pm 0.5 ^{+2.9}_{-1.5}$
All $X(0^+)$				$20 \pm 5 ^{+14}_{-7}$
$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6 ^{+10}_{-8}$	$5.6 \pm 0.7 ^{+2.4}_{-0.6}$
$X(4700)$	17 (18)	$4694 \pm 4 ^{+16}_{-3}$	$87 \pm 8 ^{+16}_{-6}$	$8.9 \pm 1.2 ^{+4.9}_{-1.4}$
$\mathrm{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8 ^{+19}_{-11}$
All $X(1^+)$				$26 \pm 3 ^{+8}_{-10}$
$X(4140)$	13 (16)	$4118 \pm 11 ^{+19}_{-36}$	$162 \pm 21 ^{+24}_{-49}$	$17 \pm 3 ^{+19}_{-6}$
$X(4274)$	18 (18)	$4294 \pm 4 ^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5 ^{+0.8}_{-0.4}$
$X(4685)$	15 (15)	$4684 \pm 7 ^{+13}_{-16}$	$126 \pm 15 ^{+37}_{-41}$	$7.2 \pm 1.0 ^{+4.0}_{-2.0}$
All $Z_{cs}(1^+)$				$25 \pm 5 ^{+11}_{-12}$
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6 ^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24 ^{+43}_{-30}$	$233 \pm 52 ^{+97}_{-73}$	$10 \pm 4 ^{+10}_{-7}$

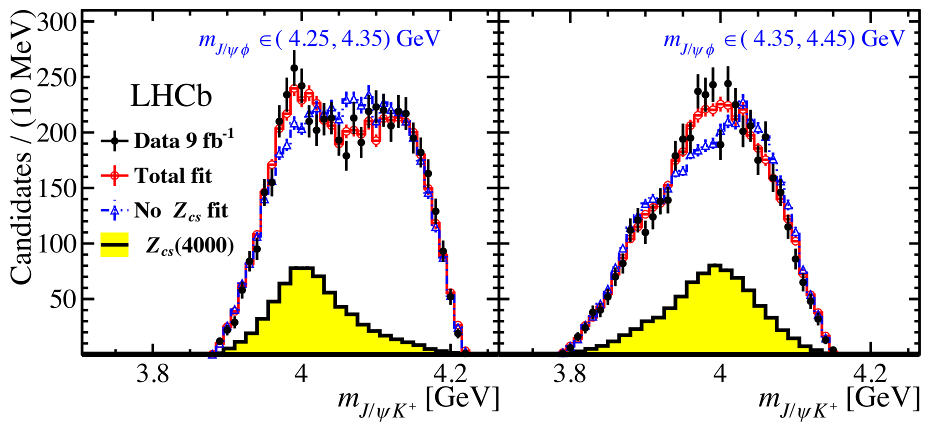
Fit fraction

- Two $Z_{cs}^+ \to J/\psi K^+$ states were observed, both significance $> 5\sigma$
- New $X(4630)$ and $X(4685)$ were observed, both significance $> 5\sigma$
- Previous results using Run 1 sample were confirmed with large significance

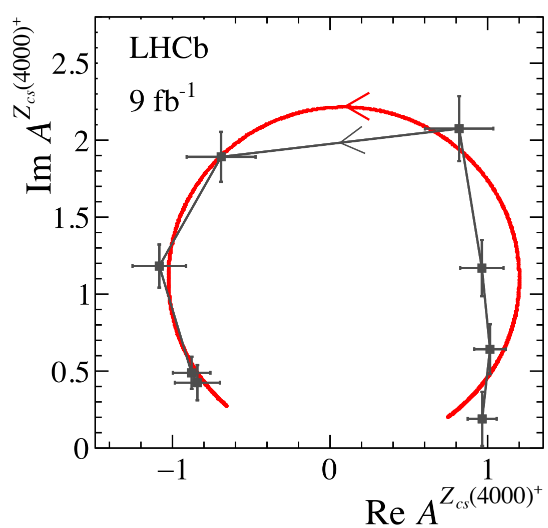
Z_{cs} results

[arXiv:2103.01803]

- The J^P of $Z_{cs}(4000)^+$ is determined as 1^+, the J^P of $Z_{cs}(4220)^+$ is 1^+ or 1^-
- The fit projection onto $J/\psi K^+$ in two slices of $J/\psi\phi$



- Resonance character of $Z_{cs}(4000)^+$ from Argand plot, obtained from lineshape independent fitting.



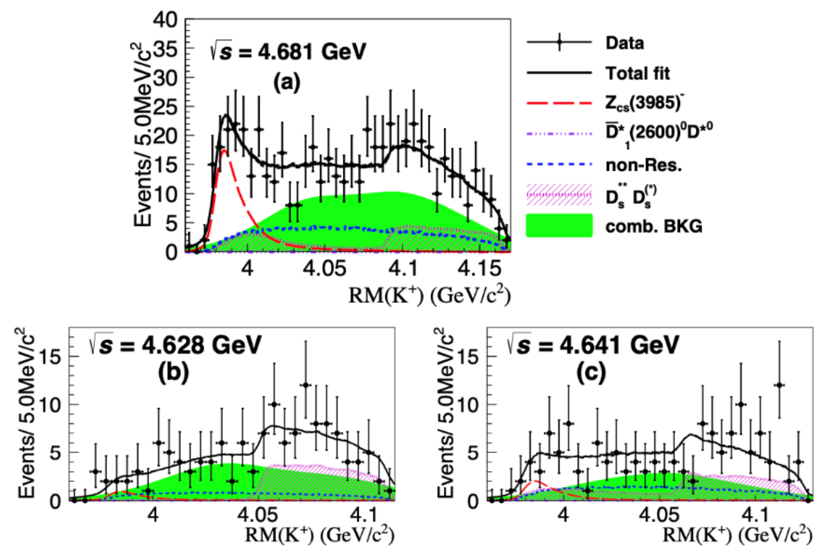
Comparison to BESIII

- BESIII experiment recently reported 5.3σ observation of a very narrow Z_{cs}^{-} in $D_sD^* + DD_s^*$ mass distributions, when our results were circulated in collaboration.

- Tests are applied:
  - Fixed $Z_{cs}(4000)^+$ to BESIII's result; twice the log-likelihood is worse by 160 units.
  - Adding on top of the default model almost doesn't improve the fit likelihood

- No evidence that $Z_{cs}(4000)^+$ state is the same as the $Z_{cs}(3985)^-$ seen by BESIII.

[arXiv:2011.07855]



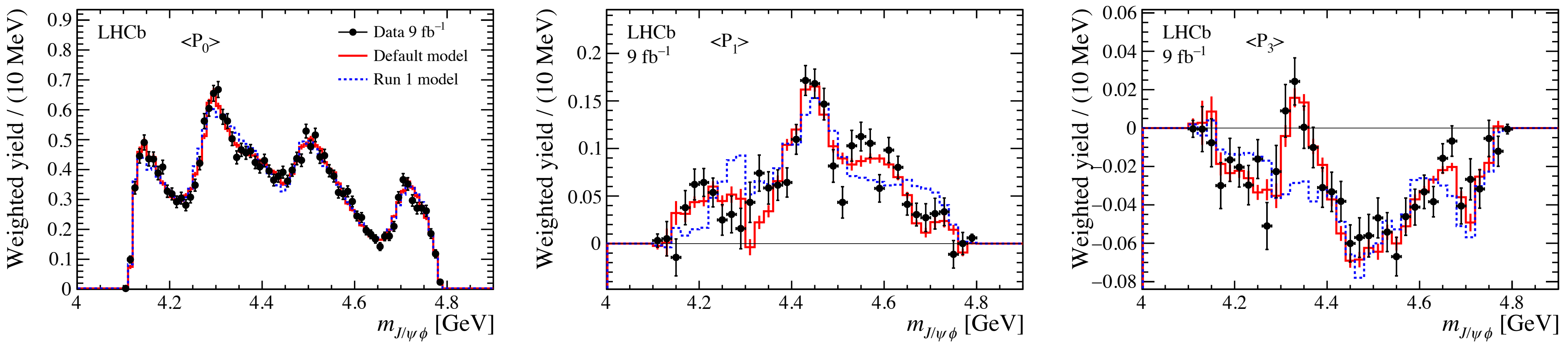
$$m_{\rm pole}(Z_{cs}(3985)^-) = (3982.5^{+1.8}_{-2.6} \pm 2.1)\,\mathrm{MeV}/c^2,$$
$$\Gamma_{\rm pole}(Z_{cs}(3985)^-) = (12.8^{+5.3}_{-4.4} \pm 3.0)\,\mathrm{MeV}.$$

X results

- The measured mass of $X(4140)$ is $4118 \pm 11^{+19}_{-36}$ MeV,   with width $162 \pm 21^{+24}_{-49}$ MeV, not very narrow; the mass is around the threshold of $J/\psi\phi$.
  No evidence of a narrow threshold resonance at $J/\psi\phi$ in our data
- Comparing the unnormalized Legendre moments of Run 1 model and updated model, new $X(4630)$ and $X(4685)$ are required.

$$< P_\ell^U >= \sum_{i=1}^{N_{\text{events}}} \frac{1}{\epsilon_i} P_\ell(\cos\theta)$$

[arXiv:2103.01803]



- The J^P of $X(4685)$ is 1^+, and the J^P $X(4630)$ is not determined.

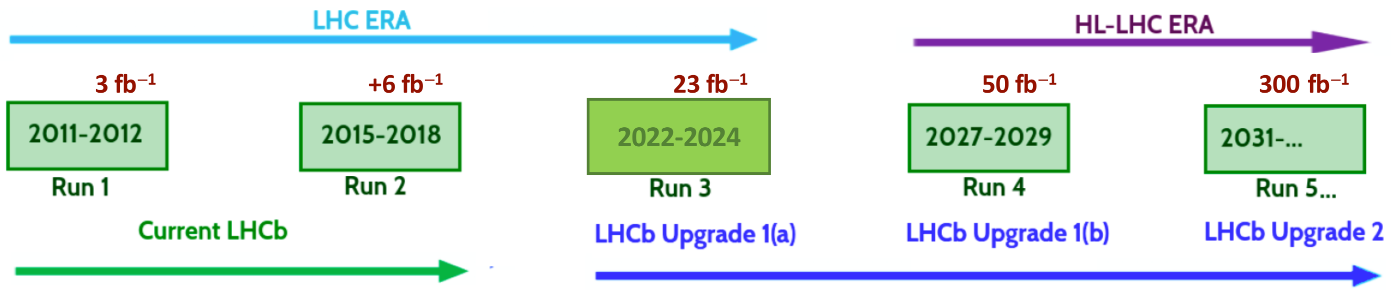
Summary

Presented only newest analyses performed by LHCb

- $X(4740)$ is observed in $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays
- Evidence of P_{cs}^+ state in $\Xi_b^- \to J/\psi\Lambda K^-$ is reported for first time
- Four new $J/\psi K^+$ and $J/\psi\phi$ structures are observed $B^+ \to J/\psi\phi K^+$
  1. 4 X states previous observed are confirmed, and J^P determined with higher significances.
  2. $Z_{cs}(4000)^+ \to J/\psi K^+$ state is observed for first time, the significance is around 15σ, and $J^P = 1^+$ is also determined; another broad $Z_{cs}(4220)^+$ is also observed
  3. A new 1+ $X(4685)$ is $> 15\sigma$, and new $X(4630) > 5\sigma$
  4. An exotic zoo channel, $B^+ \to J/\psi\phi K^+$

Prospects

- Prospects of more exotic states observed at LHCb:
  - To check the consistence between the $X(4740)$ in $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ and $X(4700)$ in $B^+ \to J/\psi\phi K^+$.
  - First P_{cs} evidence is reported, to confirm it with larger data sample.
  - Some new exotic observations in $B^+ \to J/\psi\phi K^+$ channel, accompanied by some intriguing questions; expect more data sample.



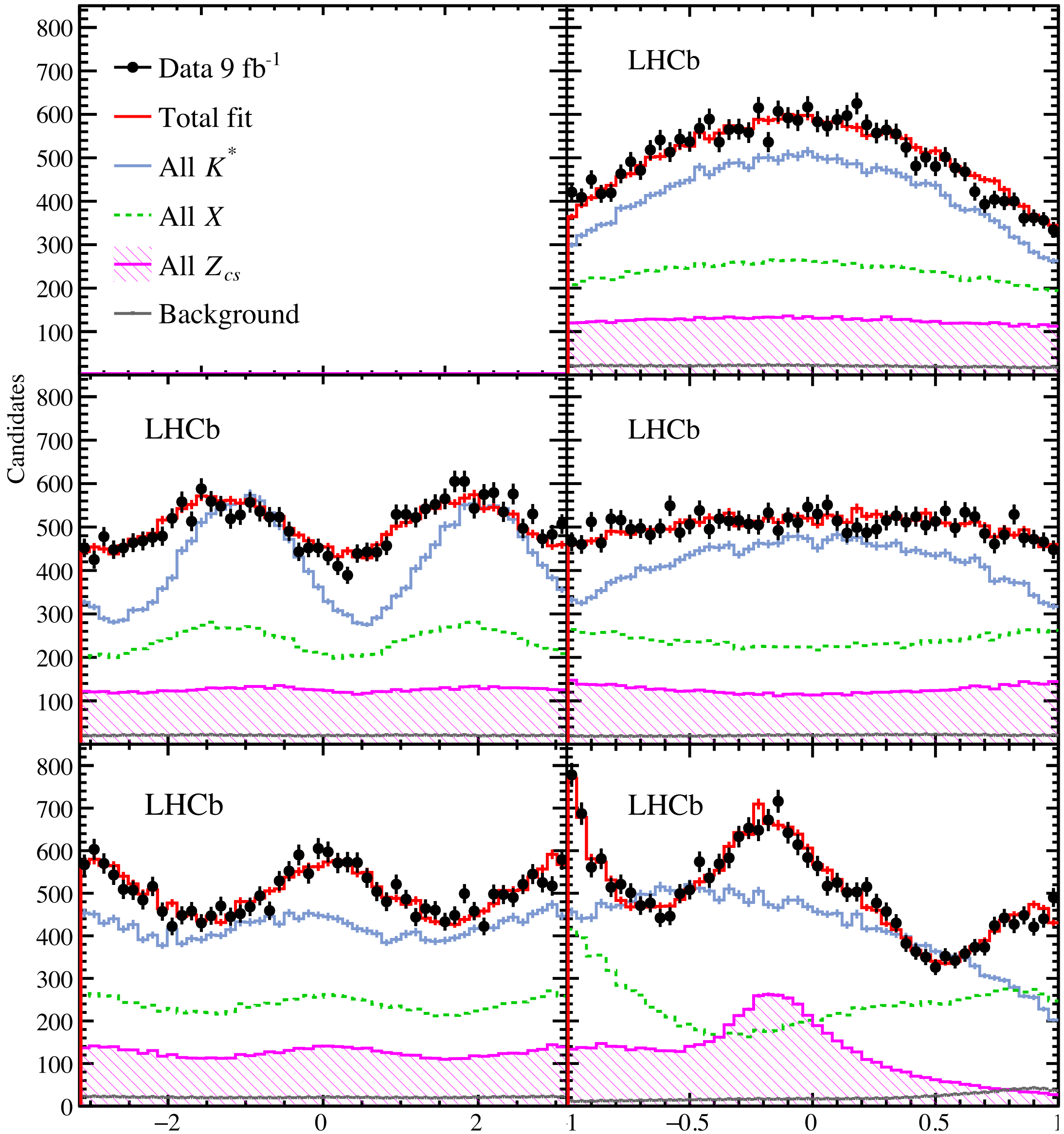
- LHCb is now boosting the data to a new level
  - Expect to 7x more data (14x hadronic events) by 2029 than current, half of these by 2024
  - Could have another 6x increase from Upgrade II

Thanks for listening

Backup

Angular distribution

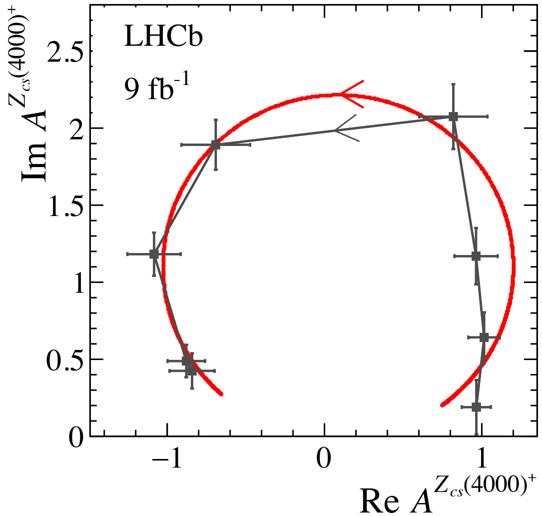
[arXiv:2103.01803]



Argand plot

[arXiv:2103.01803]

➢ Model independent fitting: the lineshape of $Z_{cs}(4000)^+$ is not presupposed.



Similar method to $Z_c(4430)^+$ study at LHCb: [Phys. Rev. Lett. 112, 222002]

8 $m(J/\psi K^+)$points:

$$m \pm 1/6\Gamma, m \pm 1/2\Gamma, m \pm 5/6\Gamma, m \pm 5/4\Gamma$$

Where m and Γ are the mass and width of $Z_{cs}(4000)^+$ obtained from nominal model.

$Z_{cs}(4000)^+$ amplitude as the combination of independent complex amplitudes at 8 points covering the $Z_{cs}(4000)^+$ peak.

Legendre moments

[arXiv:2103.01803]

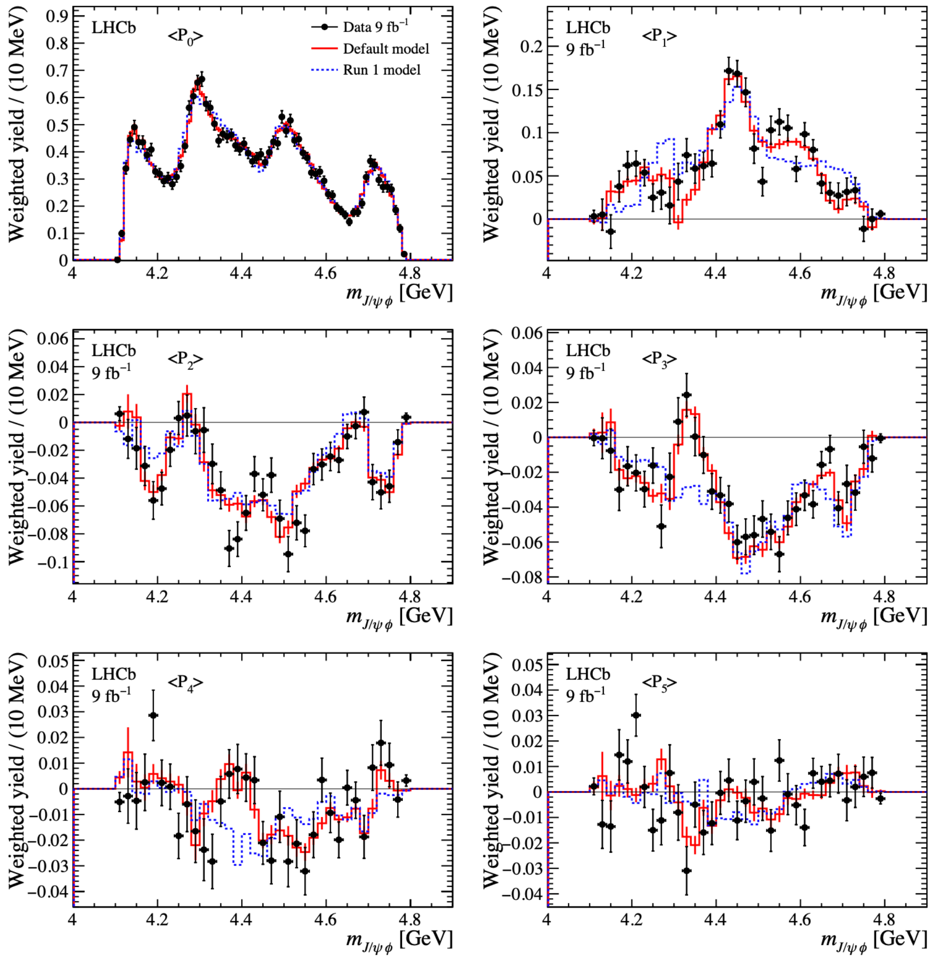
- Unnormalized Legendre moments:

$$< P_\ell^U >= \sum_{i=1}^{N_{\text{events}}} \frac{1}{\epsilon_i} P_\ell(\cos\theta)$$

Legendre polynomial of order l and efficiency for each event i.

The moments distribution is obtained by a $\frac{1}{\epsilon_i} P_l(cos\theta)$ weight.

Angular moments of $J/\psi\phi$ helicity angle

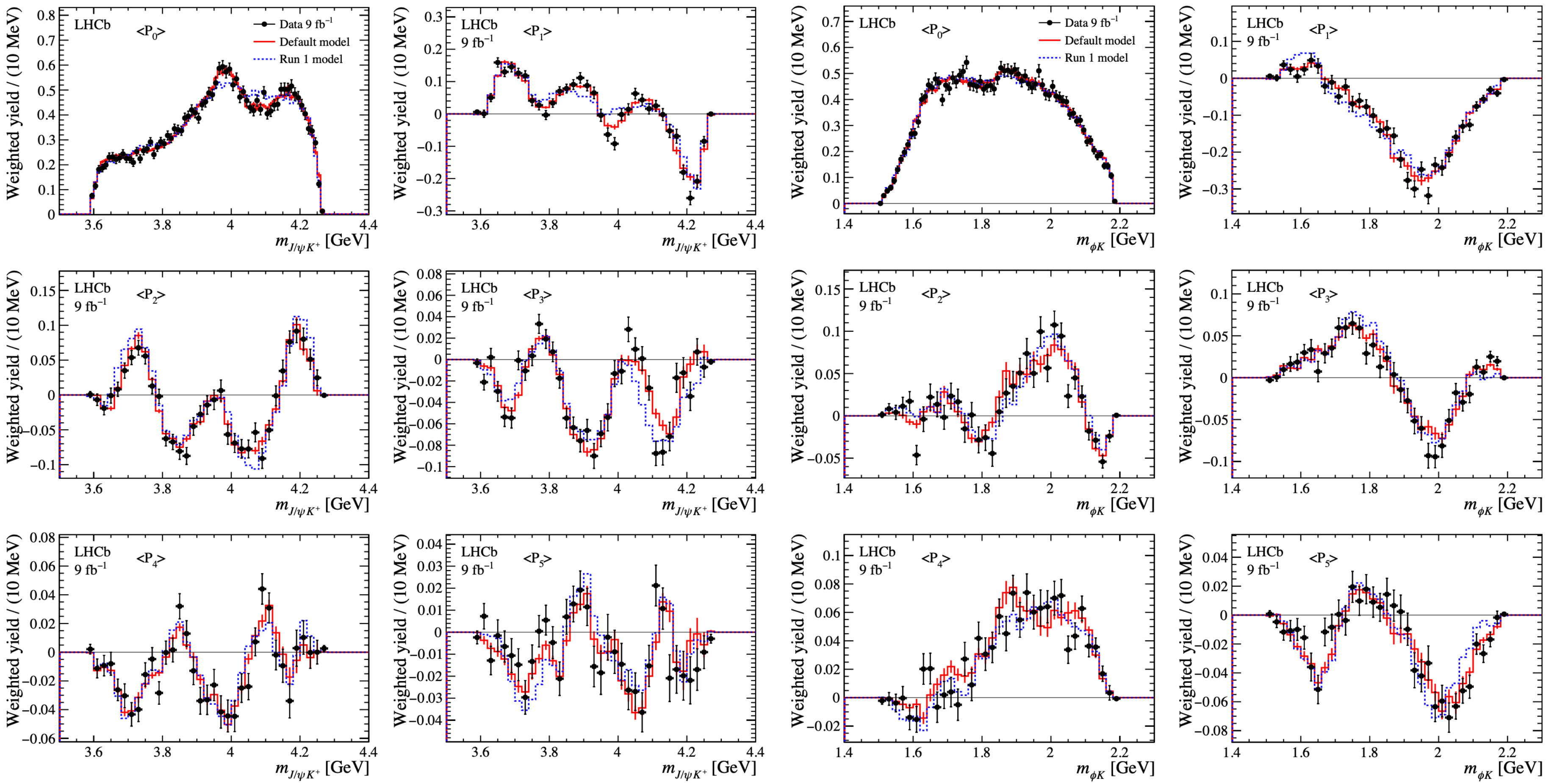


Legendre moments

[arXiv:2103.01803]

Angular moments of $J/\psi K^+$ helicity angle

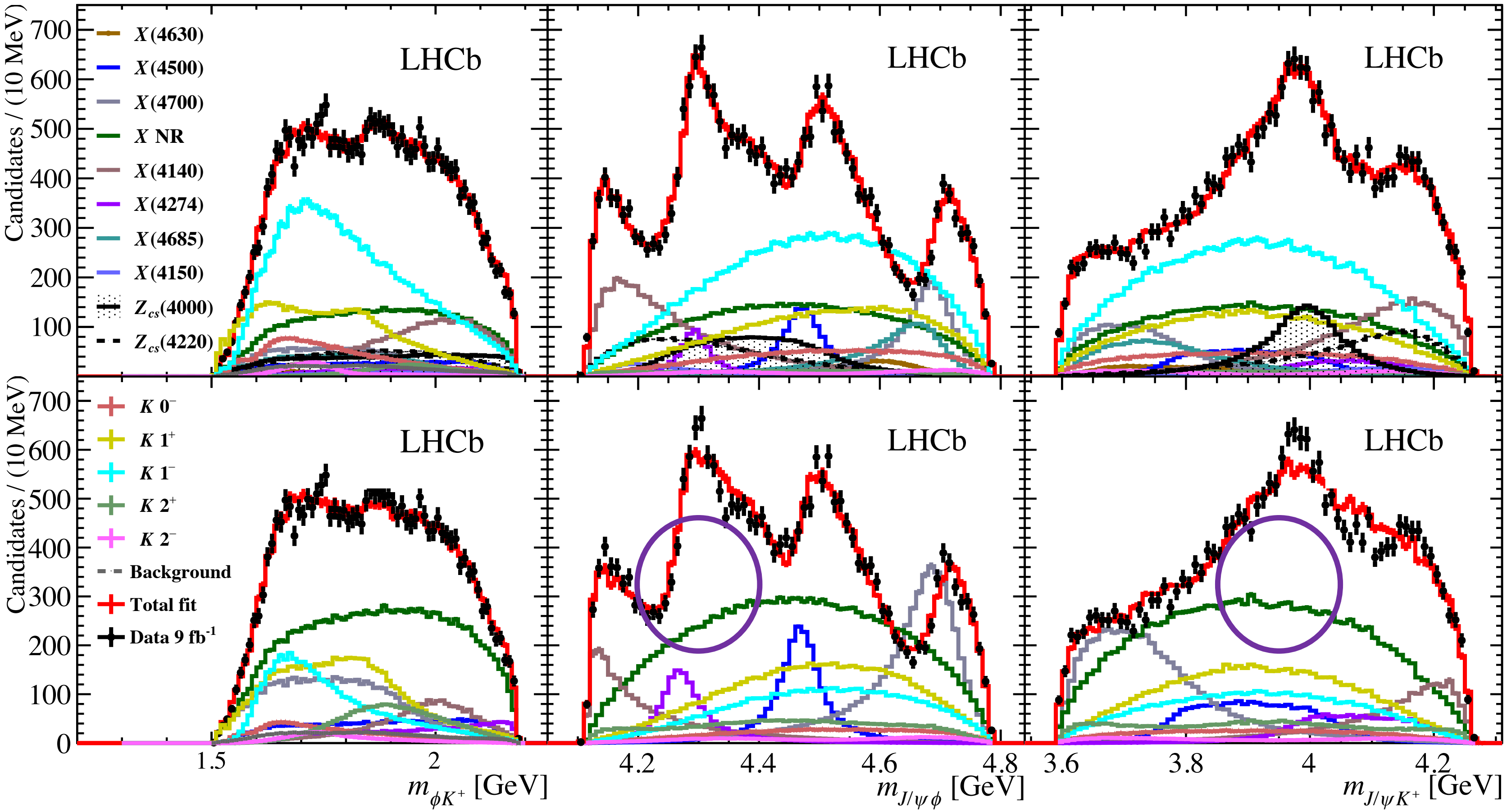
Angular moments of ϕK^+ helicity angle



K^* model improved

[arXiv:2103.01803]

More K^* states are included first, $K^*(1410)$, $K(1460)$ and $K_1(1400)$.
Help to describe the data better than previous one.



Updated model

Run 1 model