LHCb 上的奇特强子态研究进展

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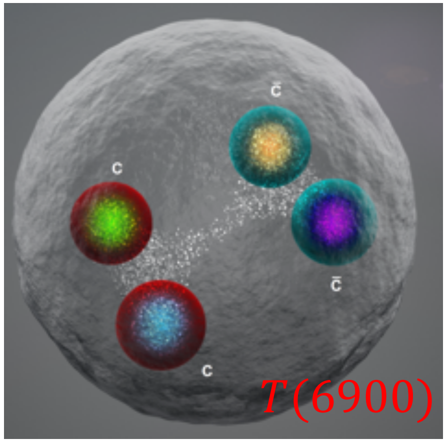
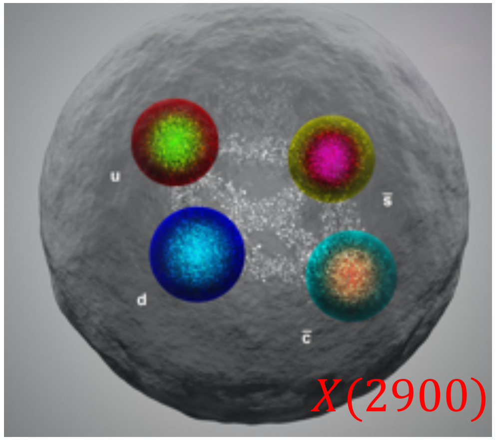
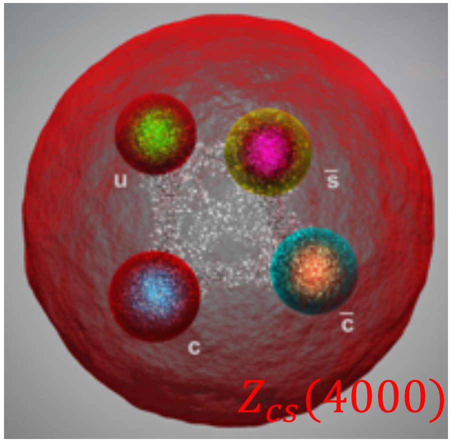






2021.05.15

第七届XYZ粒子研讨会 @ 青岛

Outline

- Evidence of a $J/\psi\Lambda$ resonance and observation of excited Ξ^{*-} states in the $\Xi_b \to J/\psi\Lambda K^-$ (See Jinlin's Talk)
  [arXiv:2012.10380, to appear in Science Bulletin]

- Study of the lineshape of the $\chi_{c1}(3872)$ [PRD 102 (2020) 092005]
- Study of the $\psi_2(3823)$ and $\chi_{c1}(3872)$ states in $B^+ \to (J/\psi\pi^+\pi^-)K^+$ decays
  [JHEP 08 (2020) 123]

- Observation of structure in the J/ψ-pair mass spectrum
  [Science Bulletin 65 (2020) 032]

- Study of $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays [JHEP 02 (2021) 024]

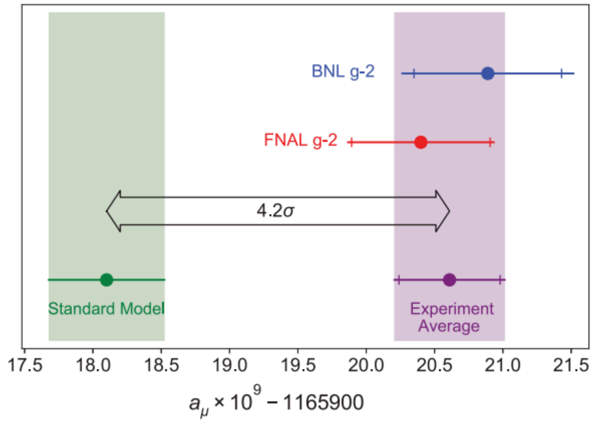
- Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$
  [arXiv:2103.01803]

- Amplitude analysis of $B^+ \to D^+D^-K^+$ decay
  (Details in Yi's Talk)
  [PRL 125 (2020) 242001, PRD 102 (2020) 112003]

Introduction

- New physics evidence in Muon g-2 experiment:
  - Precision measurement of α_μ
  - The error from experiment is smaller than the value from theory

$a_\mu(\mathrm{SM}) = a_\mu(\mathrm{QED}) + a_\mu(\mathrm{Weak}) + a_\mu(\mathrm{Hadronic})$



[PRL 126 (2021) 141801]

$$a_\mu(Exp) = 116592061(41) \times 10^{-11}$$

$$a_\mu(Theory) = 116591810(43) \times 10^{-11}$$

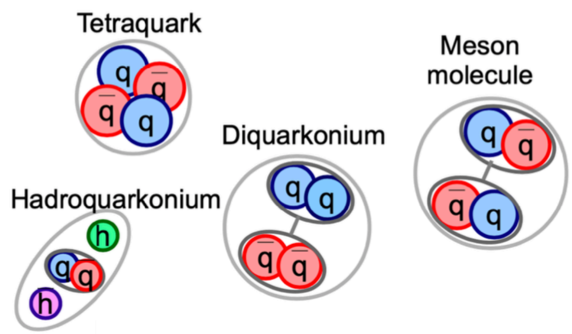
$$a_\mu(BMW) = 116591954(55) \times 10^{-11}$$

Latest LQCD result [NATURE (2021) 593]

- The largest uncertainty comes from strong interaction:
  - Exotic hadron study offers new approach to probe QCD

Questions in last XYZ workshop

Theory:

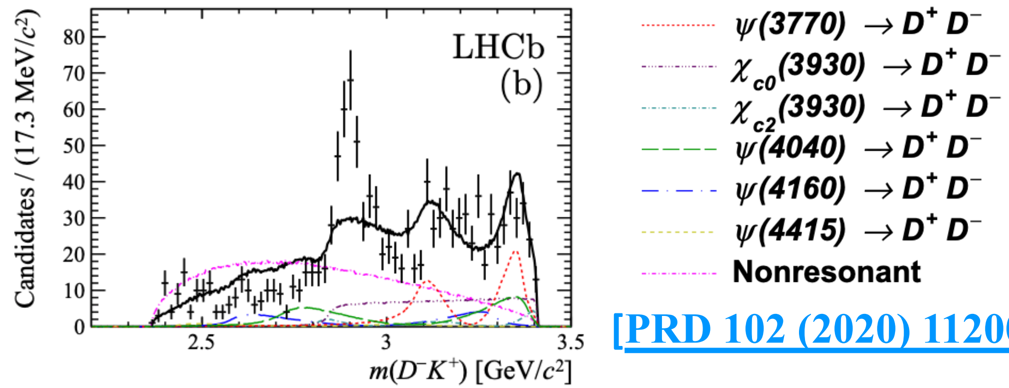


Experiment:

Not only to find new XYZ hadrons, but also determine properties: like production rates, quantum numbers, lineshapes etc.

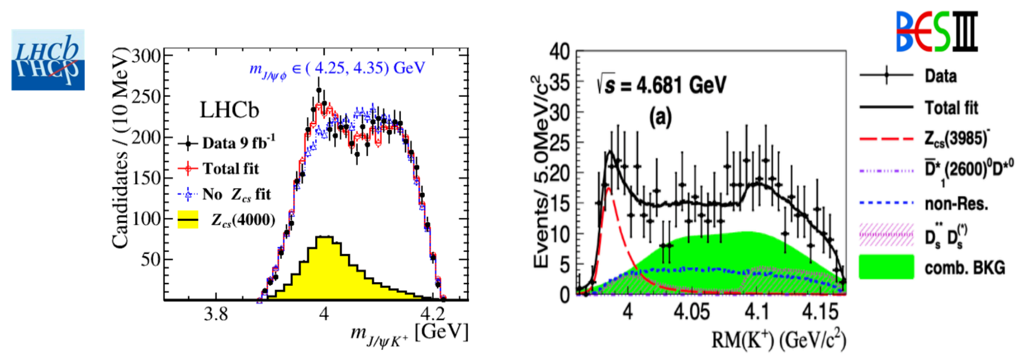
Raise two questions:

- If exist open charm exotic states?
- If exit exotic hidden-charm states with one strangeness?



[PRD 102 (2020) 112003]

✓ Yes. D^-K^+ structure observed in $B^+ \to D^+D^-K^+$ decay at LHCb.



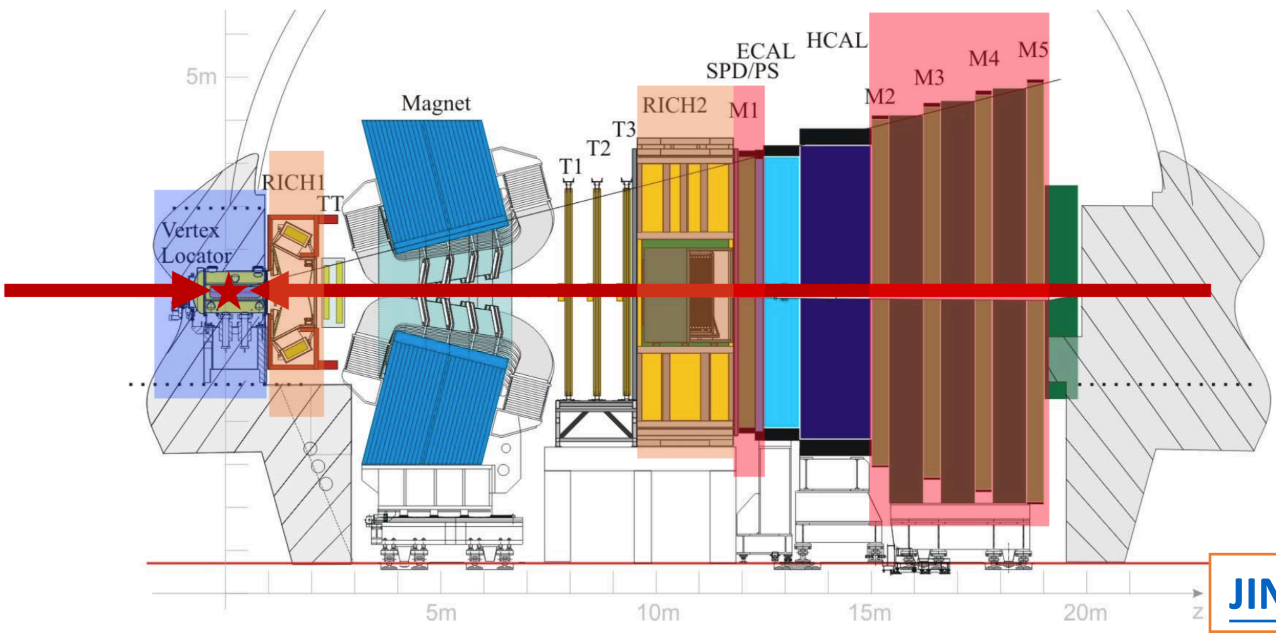
✓ Yes. $J/\psi K^+$ structure observed in $B^+ \to J/\psi\phi K^+$ decay at LHCb, D_sD^* structure observed in e^+e^- collision at BESIII.

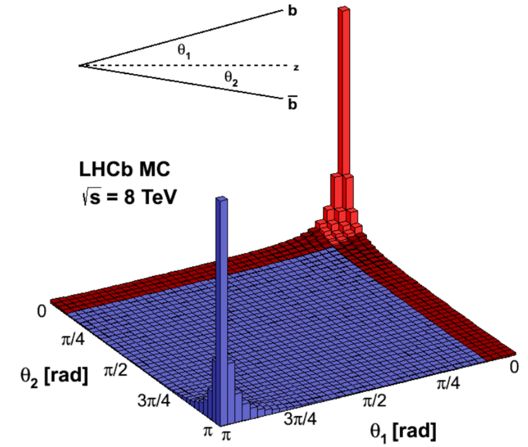
Screenshot from the talk at 6th XYZ workshop in 2020

LHCb detector

LHCb is a dedicated heavy flavor physics experiment at LHC

- $\sim 20{,}000/s\ b\bar{b}$ generated at LHCb point in Run2
- A single-arm forward region spectrometer covering $2 < \eta < 5$





JINST 3 (2008) S08005

Vertex:	$\sigma_{IP} = 20\ \mu m$
Time:	$\sigma_\tau\ = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%\ (5-100\ \text{GeV}/c)$
Mass :	$\sigma_m = 8\ \text{MeV}/c^2$ for $B \to J/\psi X$ (constrained $m_{J/\psi}$)
Hadron ID:	$\varepsilon(K \to K) \sim 95\%$ mis-ID $\varepsilon(\pi \to K) \sim 5\%$
Muon ID:	$\varepsilon(\mu \to \mu) \sim 97\%$ mis-ID $\varepsilon(\pi \to \mu) \sim 1-3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E\ (\text{GeV})}$

Many exotic states observed at LHCb

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

[Taken from CERNCOURIER]

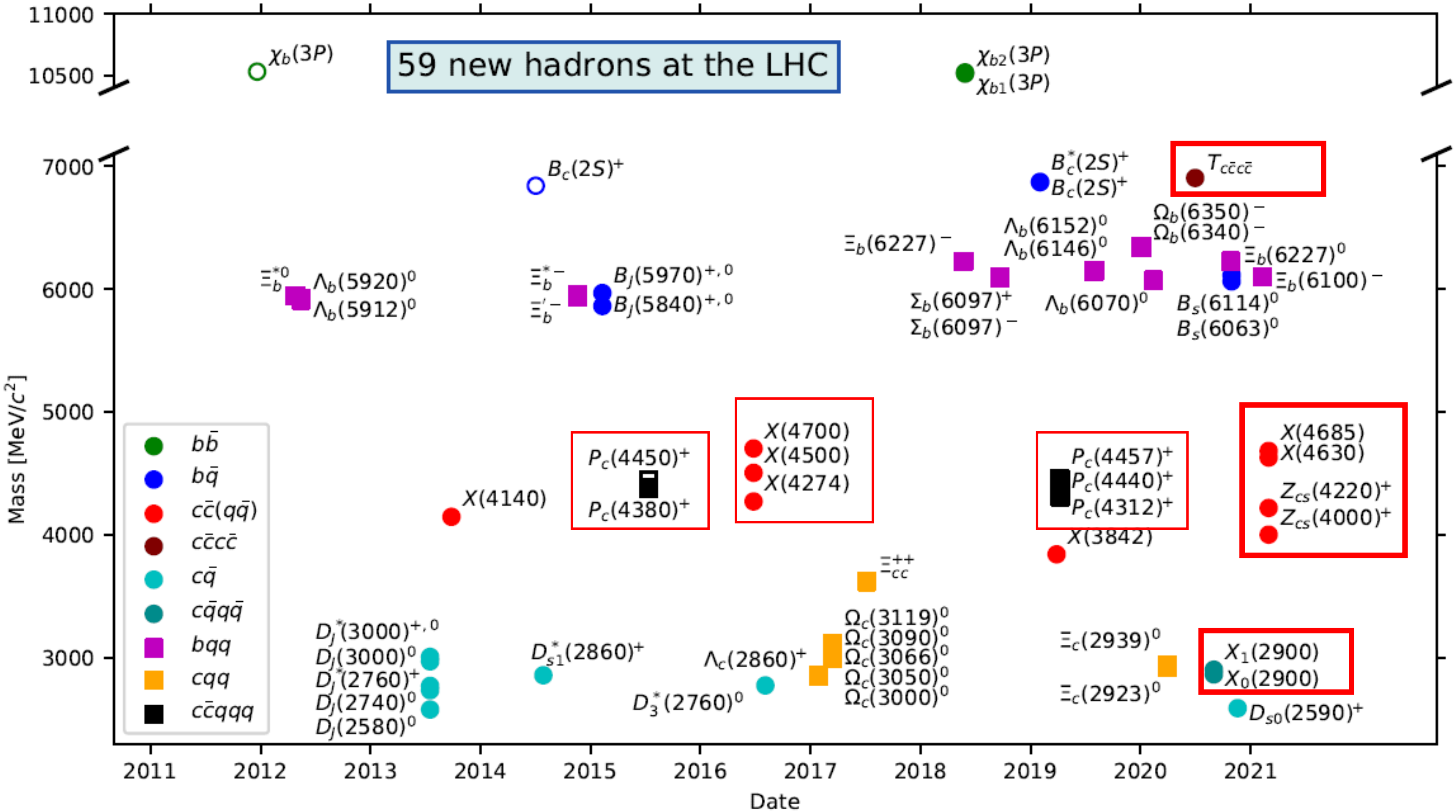


Diagram of discovery The ATLAS, CMS and LHCb collaborations have discovered 59 new hadronic states so far – the most recent being the four tetraquarks reported in this article. Credit: CERN

Recent $\chi_{c1}(3872)$ studies at LHCb

Motivation

- The nature of $\chi_{c1}(3872)$: conventional $\chi_{c1}(2^3P_1)$, $D^0\overline{D}^{*0}$ molecular state, tetraquark, hybrid, glueball or mixed ?

- Previous experimental studies:
  - $\sigma(\chi_{c1}(3872))/\sigma(\psi(2S))$ decrease with increasing multiplicity, prefer hadronic molecule explanation.

    [LHCb-CONF-2019-005]

  - The ratio of $\mathcal{B}(B_s^0 \to \chi_{c1}(3872)\phi)/\mathcal{B}(B^0 \to \chi_{c1}(3872)K^0)$ is consistent with one, while the $\mathcal{B}(B_s^0 \to \chi_{c1}(3872)\phi)/\mathcal{B}(B^+ \to \chi_{c1}(3872)K^+)$ is two times smaller, suggesting it is not a pure charmonium.

    [PRL 125 (2020) 152001]

  - The discovery of $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-\pi^0$ is consistent to the molecule prediction.

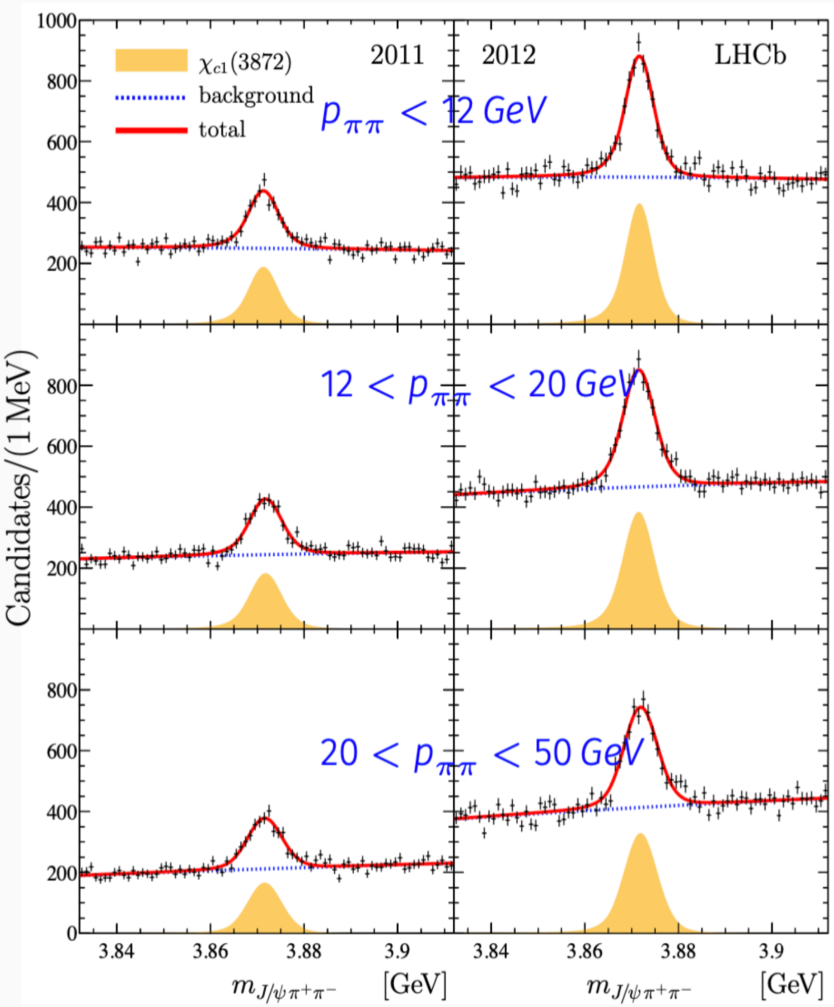
    [arXiv : 0410284]

  - ……

- Lineshape is the next experimental challenge!
  - Determination of $\delta E = M(D^0) + D(\overline{D}^{*0}) - M(\chi_{c1}(3872))$ is important

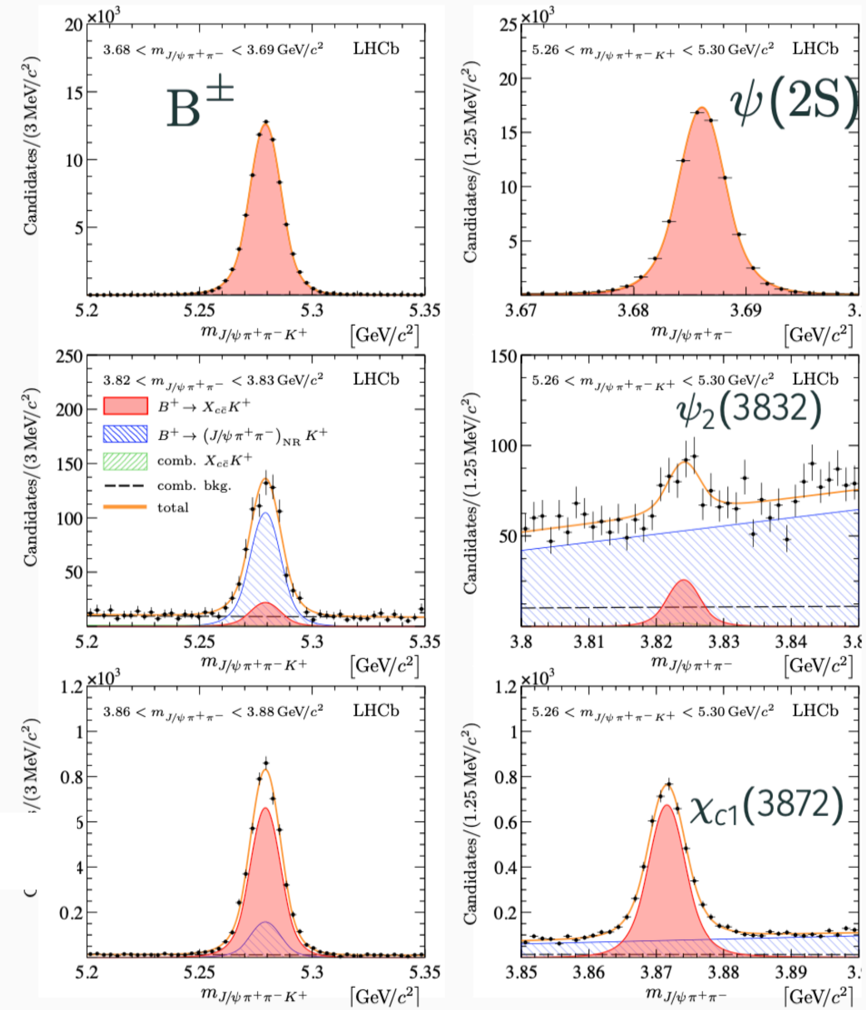
Prompt $\chi_{c1}(3872)$ and from B

[PRD 102 (2020) 092005]



Inclusive $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$

[JHEP 08 (2020) 123]

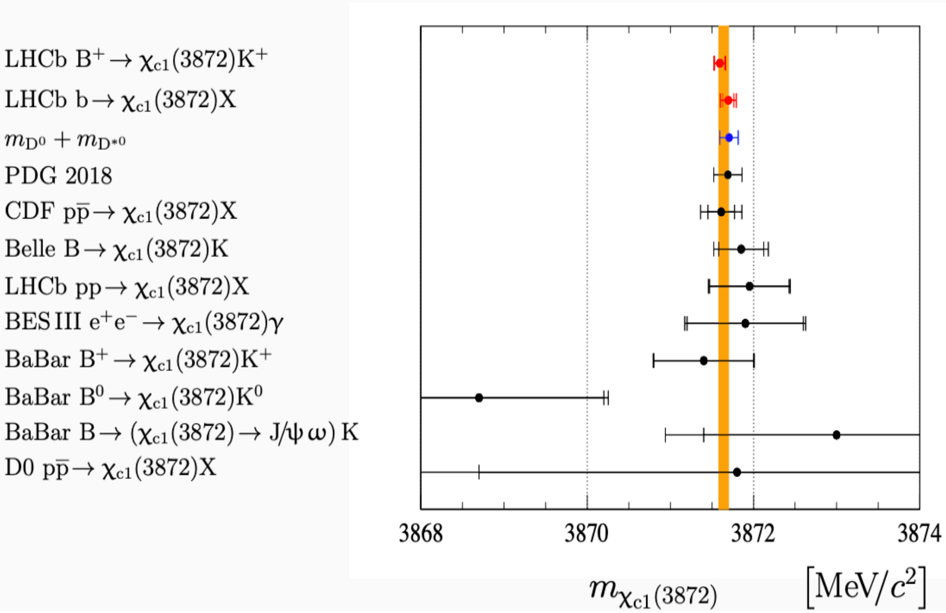


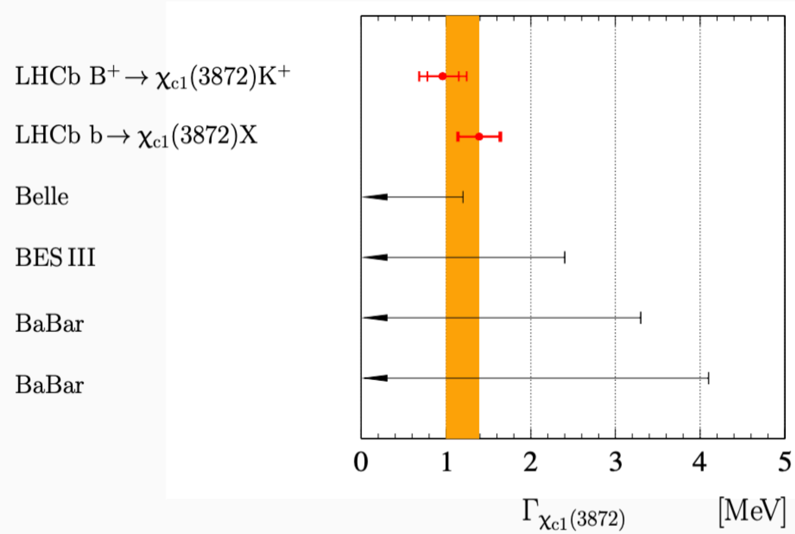
Exclusive $B^+ \to J/\psi\pi^+\pi^-K^+$

Precision mass and width

Comparison between inclusive and exclusive analysis and previous measurements

[JHEP 08 (2020) 123]
[PRD 102 (2020) 092005]





✓Significantly improved precisions on mass and width

✓LHCb average:

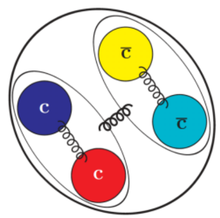
- $M_{\text{BW}} = 3871.64 \pm 0.06 \pm 0.01\ \text{MeV}/c^2$
- $\delta E = M(D^0) + M(\bar{D}^{*0}) - M\big(\chi_{c1}(3872)\big) = 0.07 \pm 0.12\ \text{MeV}/c^2$
- $\Gamma_{\text{BW}} = 1.19 \pm 0.19\ \text{MeV}/c^2$

First time a width was established for this state.

Observation of structure in the J/ψ-pair mass spectrum

Search for full charmed $cc\bar{c}\bar{c}$ tetraquark

- Motivation:
  - $T_{QQ\bar{Q}\bar{Q}}$ ($Q = c$ or b) states is isolated from both quarkonia and quarkonium-like exotic states
  - A $T_{cc\bar{c}\bar{c}}$ can decay into a pair of charmonia



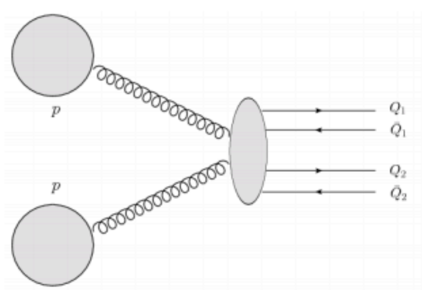
[arXiv: 1803.02522]

J^{PC}	S-wave	P-wave
0^{++}	$\eta_c(1S)\eta_c(1S)$, $J/\psi J/\psi$	$\eta_c(1S)\chi_{c1}(1P)$, $J/\psi h_c(1P)$
0^{-+}	$\eta_c(1S)\chi_{c0}(1P)$, $J/\psi h_c(1P)$	$J/\psi J/\psi$
0^{--}	$J/\psi\chi_{c1}(1P)$	$J/\psi\eta_c(1S)$
1^{++}	–	$J/\psi h_c(1P)$, $\eta_c(1S)\chi_{c1}(1P)$, $\eta_c(1S)\chi_{c0}(1P)$
1^{+-}	$J/\psi\eta_c(1S)$	$J/\psi\chi_{c0}(1P)$, $J/\psi\chi_{c1}(1P)$, $\eta_c(1S)h_c(1P)$
1^{-+}	$J/\psi h_c(1P)$, $\eta_c(1S)\chi_{c1}(1P)$	–
1^{--}	$J/\psi\chi_{c0}(1P)$, $J/\psi\chi_{c1}(1P)$, $\eta_c(1S)h_c(1P)$	$J/\psi\eta_c(1S)$

Decays in $2J/\psi$ directly or with feed-down

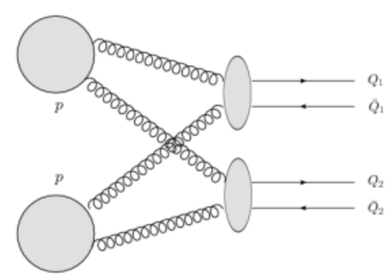
- Prompt J/ψ pair production:

Single parton scattering (SPS)



- $T_{cc\bar{c}\bar{c}}$ state is a special case of SPS

Double parton scatterings (DPS)



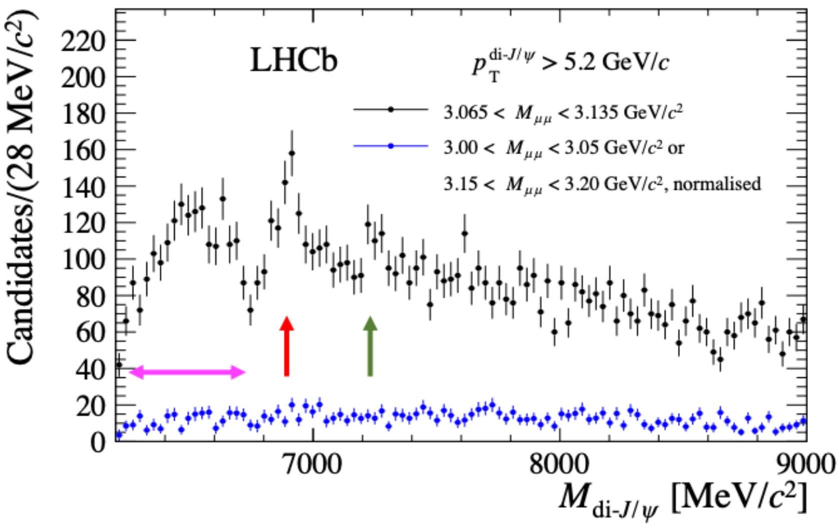
- Dominates high J/ψ pair mass region

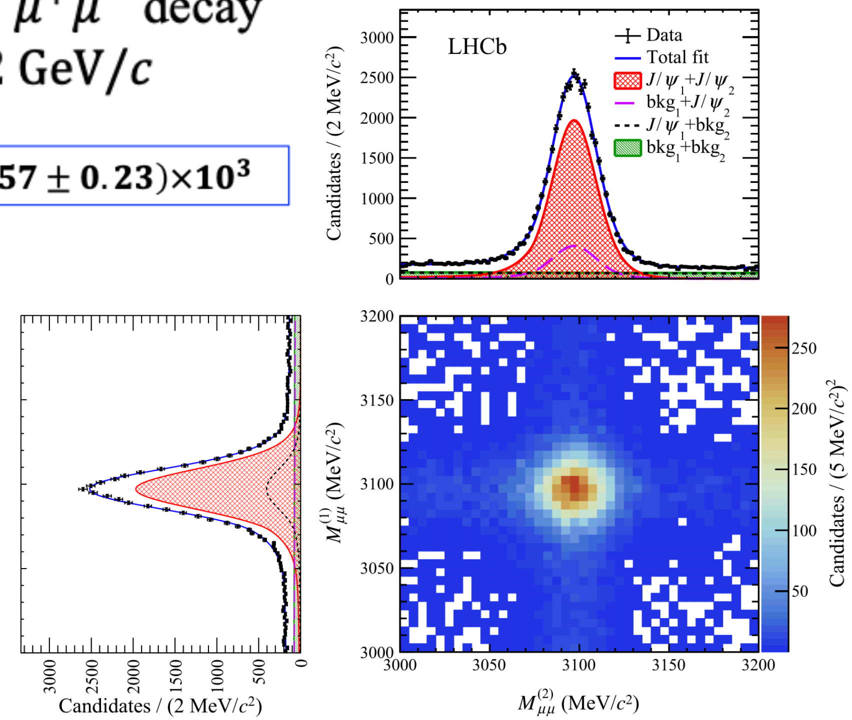
J/ψ pair mass spectrum

[Science Bulletin 65 (2020) 032]

- Full Run1+Run2 LHCb data corresponding to 9 fb^{-1}
- J/ψ candidates reconstructed using the $J/\psi \rightarrow \mu^+\mu^-$ decay
- SPS enhanced sample with J/ψ-pair $p_T > 5.2$ GeV/c

$N(J/\psi\ \text{pair}) = (33.57 \pm 0.23)\times 10^3$

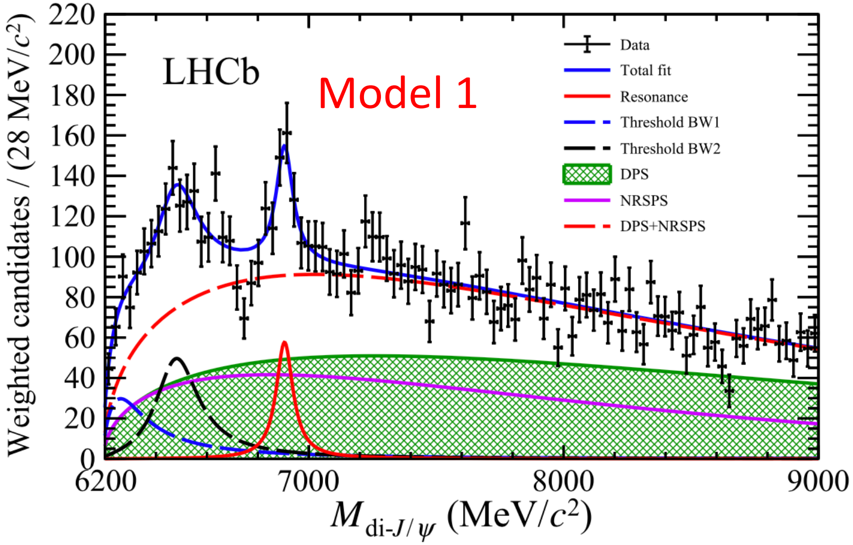


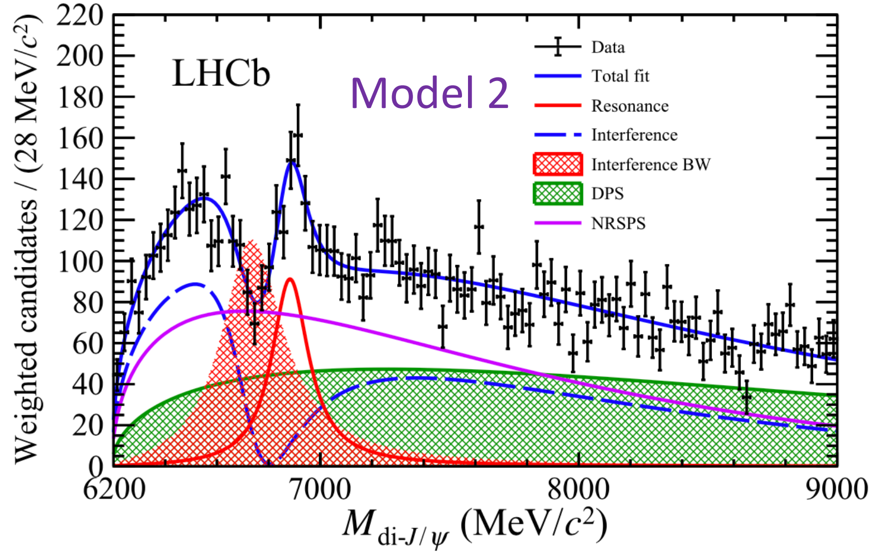


- J/ψ mass and pointing-to-PV constraints applied
- J/ψ-pair invariant mass spectrum shows
  - ✓A broad structure next to threshold ranging from 6.2 to 6.8 GeV/c^2
  - ✓A narrower structure at about 6.9 GeV/c^2
  - ✓Hint for another structure around 7.2 GeV/c^2
  - ✓No evidence for further structures above 7.2 GeV/c^2

$X(6900)$ observation

[Science Bulletin 65 (2020) 032]





- Model 1, no-interference fit:

$$M[\mathrm{X(6900)}] = 6905 \pm 11(\mathrm{stat}) \pm 7(\mathrm{syst})\ \mathrm{MeV}/c^2$$
$$\Gamma[\mathrm{X(6900)}] = 80 \pm 19(\mathrm{stat}) \pm 33(\mathrm{syst})\ \mathrm{MeV}/c^2$$

- Model 2, simple model with interference:

$$M[\mathrm{X(6900)}] = 6886 \pm 11(\mathrm{stat}) \pm 11(\mathrm{syst})\ \mathrm{MeV}/c^2$$
$$\Gamma[\mathrm{X(6900)}] = 168 \pm 33(\mathrm{stat}) \pm 69(\mathrm{syst})\ \mathrm{MeV}/c^2$$

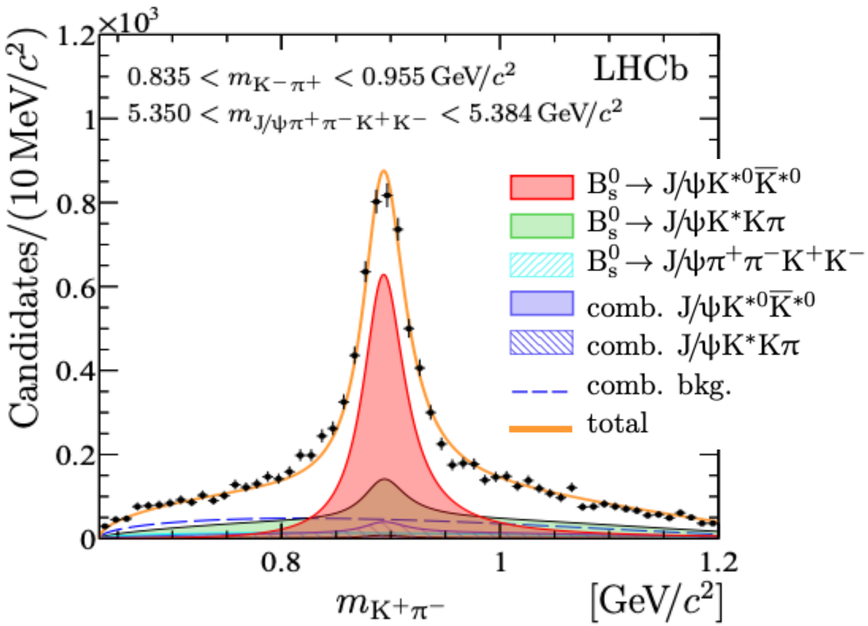
- The significance in two model both $> 5\sigma$, $X(6900)$ is observed.

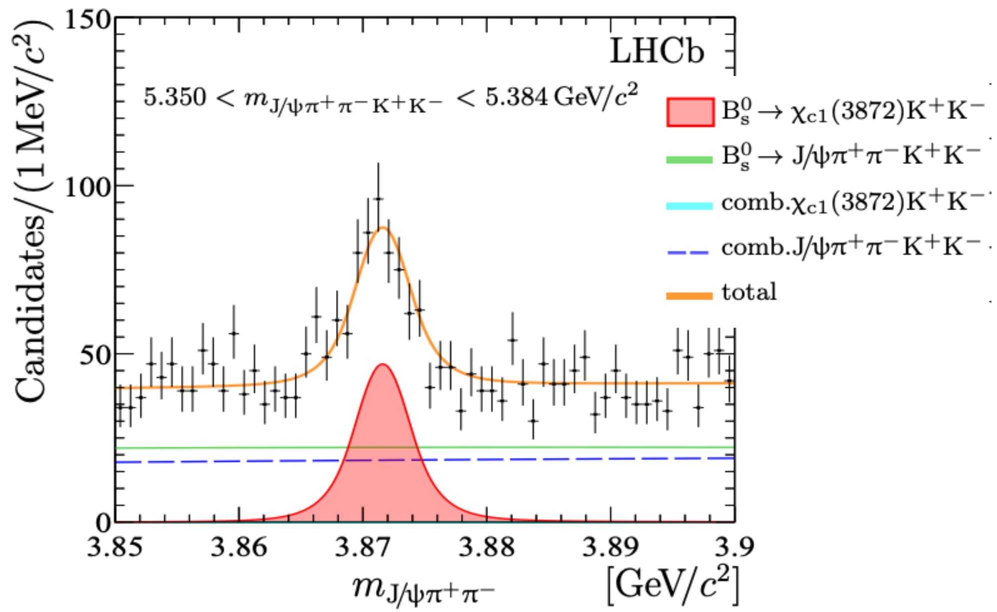
Study of $B_s^0 \to J/\psi \pi^+ \pi^- K^+ K^-$ decays

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





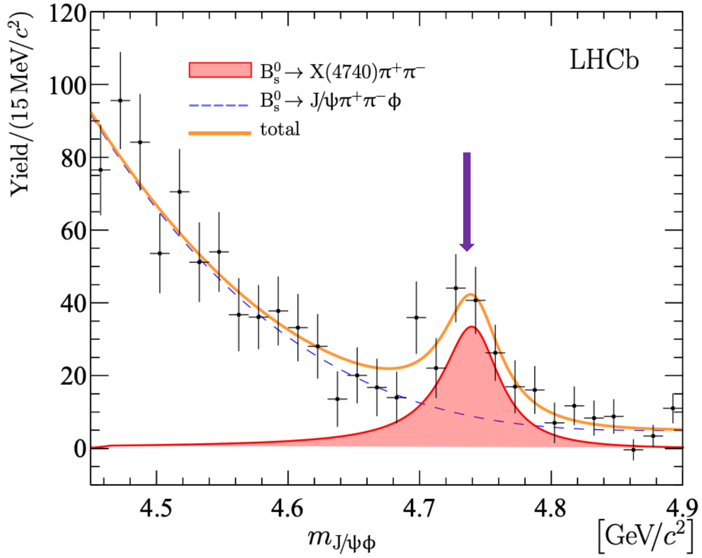
- Decays of $B_s^0 \to J/\psi K^{*0}\overline{K}^{*0}$ and $B_s^0 \to \chi_{c1}(3872)K^+K^-$ observed for the first time.
- Most precise single measurement of B_s^0 mass:

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

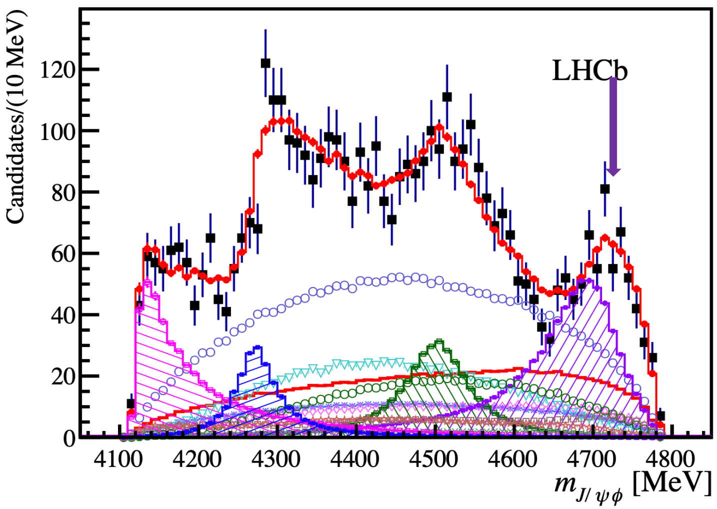
$X(4740)$ observed in this channel

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

[JHEP 02 (2021) 024]



[Phys. Rev. Lett. 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 same place

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

Motivation-1

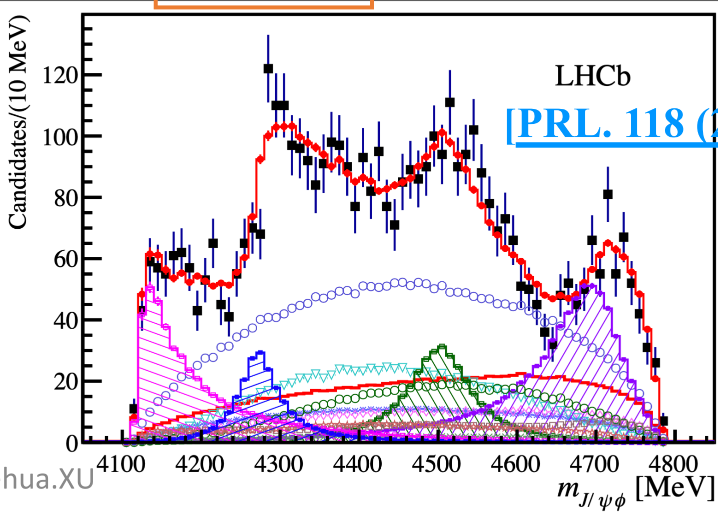
[arXiv:2103.01803]

- This 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.



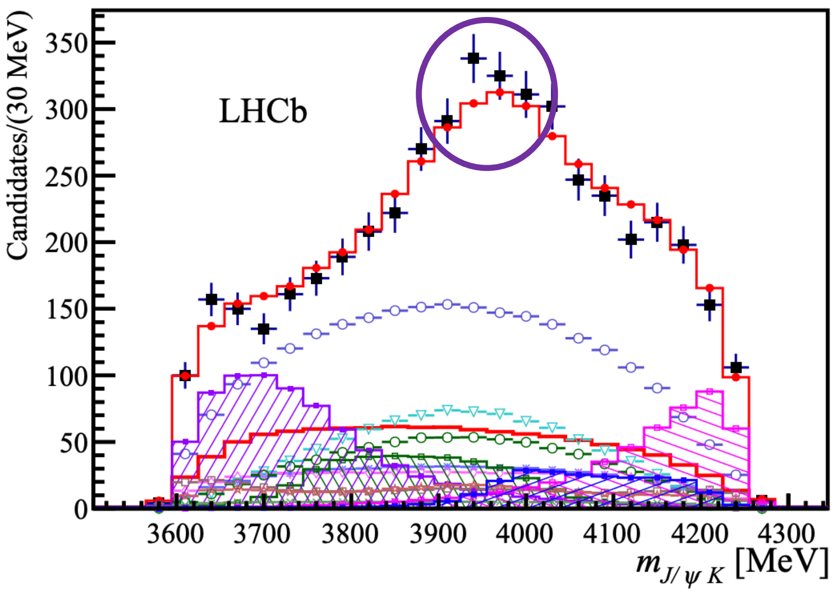
[PRL. 118 (2017) 022003]

Motivation-2

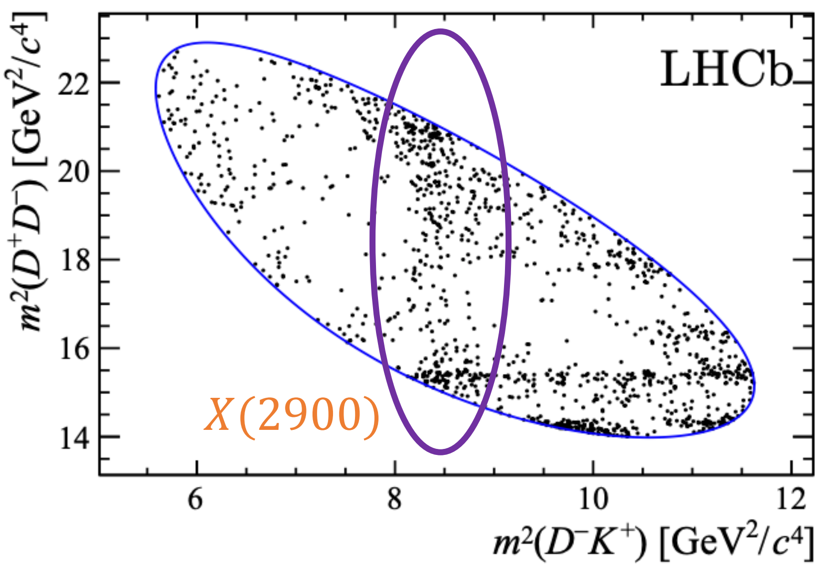
[arXiv:2103.01803]

- 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]



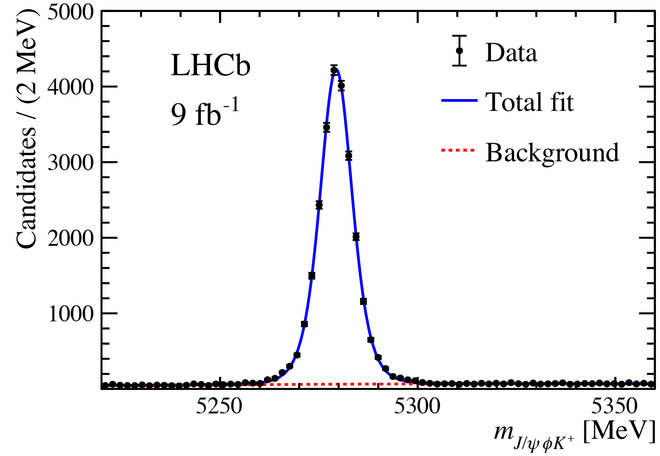
[PRL. 125 (2020) 242001]



Run 1 and Run 2 sample

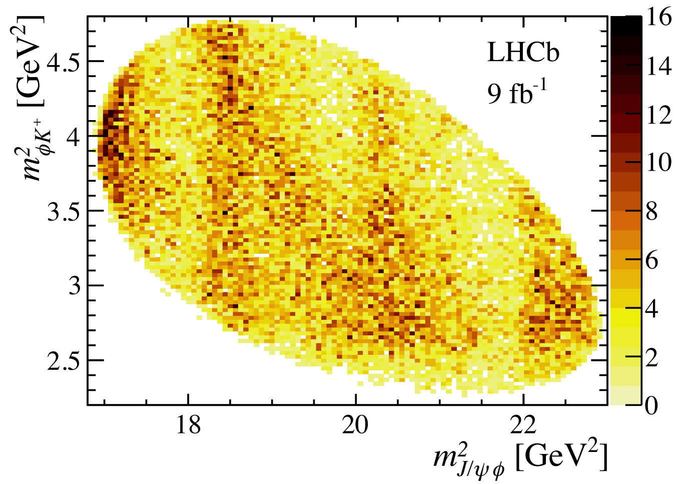
[arXiv:2103.01803]

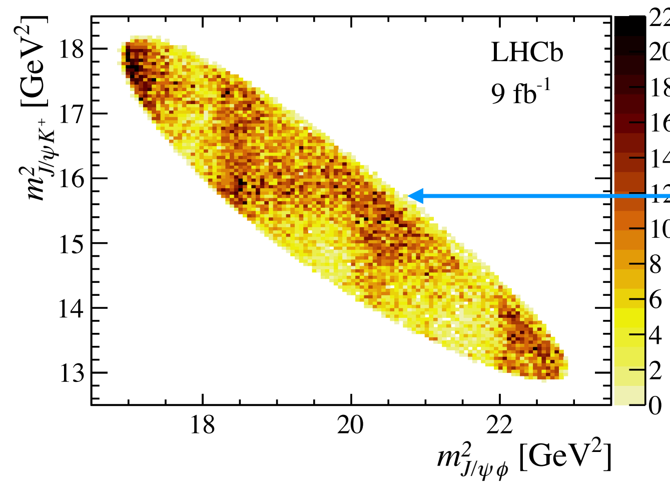
- Selection is optimized
  - ~ 24k signal (6 times larger than the previous publication)
  - overall background fraction ~ 4% (a factor of 6 smaller)



- Clear structures in Dalitz plot

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



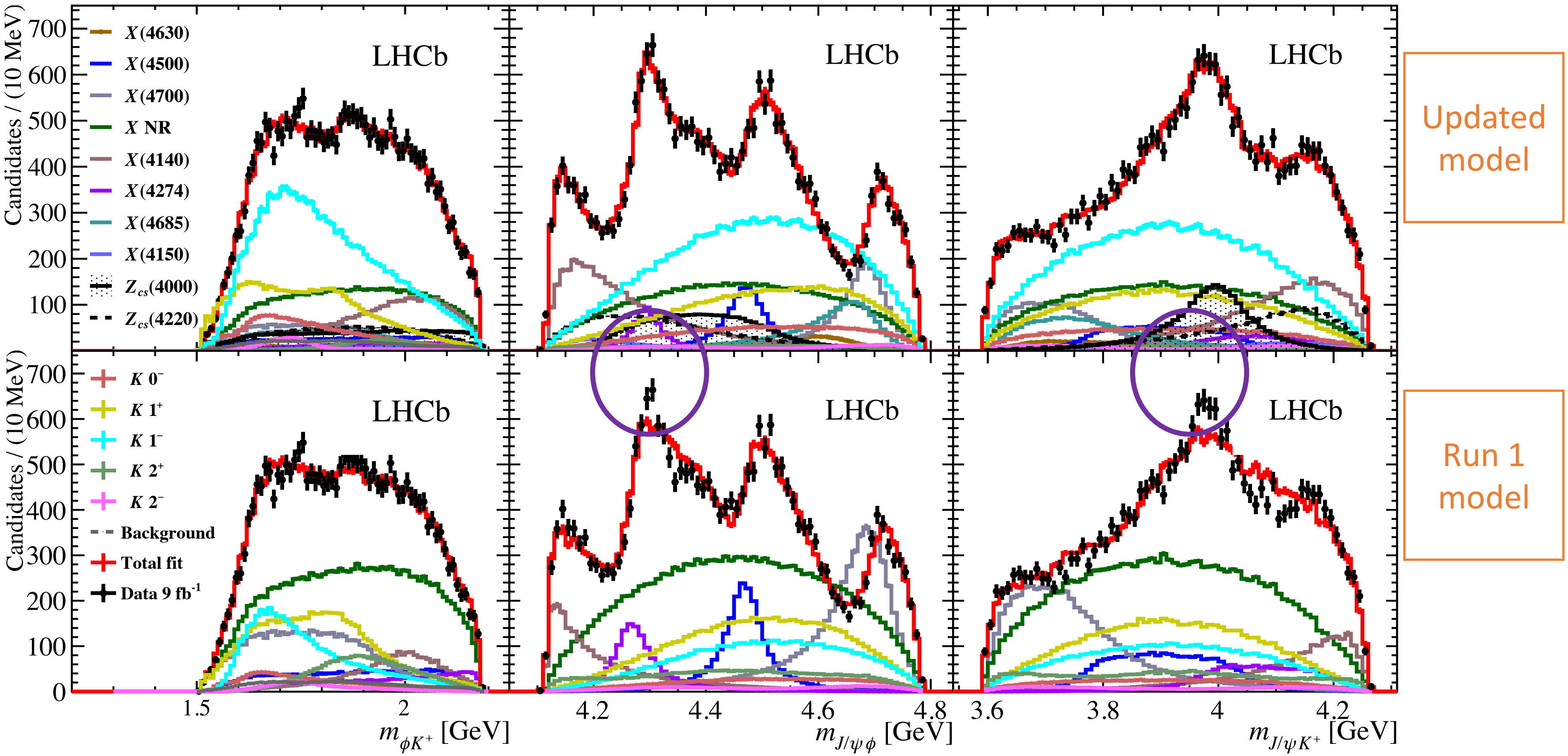


Z_{cs} state?

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]

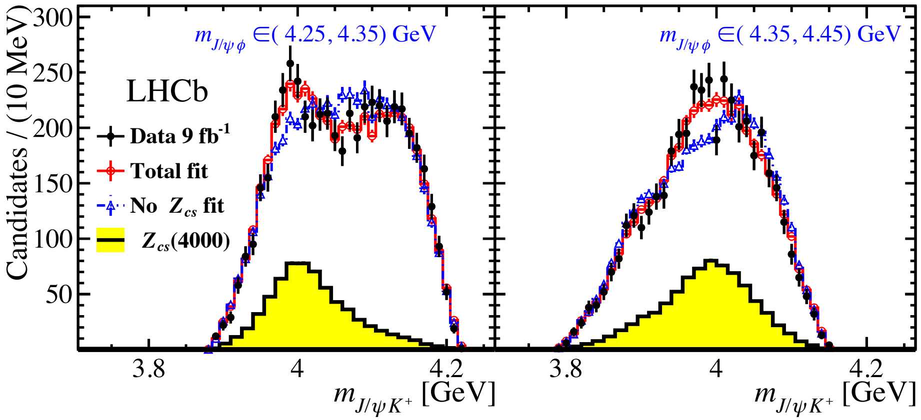
Contribution	Significance [$\times\sigma$]	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+\,59}_{-\,30}$	$2.0 \pm 0.5\,^{+\,0.8}_{-\,1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+\,18}_{-\,110}$	$174 \pm 27\,^{+\,134}_{-\,73}$	$2.6 \pm 0.5\,^{+\,2.9}_{-\,1.5}$
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)	$4694 \pm 4\,^{+\,16}_{-\,3}$	$87 \pm 8\,^{+\,16}_{-\,6}$	$8.9 \pm 1.2\,^{+\,4.9}_{-\,1.4}$
$NR_{J/\psi\phi}$	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)	$4216 \pm 24\,^{+\,43}_{-\,30}$	$233 \pm 52\,^{+\,97}_{-\,73}$	$10 \pm 4\,^{+\,10}_{-\,7}$

- 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

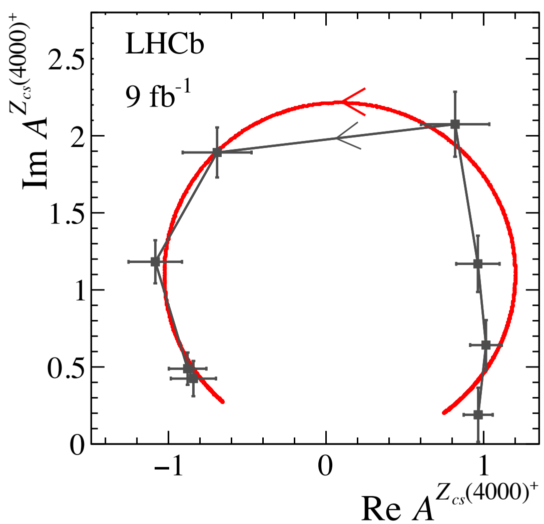
Z_{cs} results

[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 model independent fitting.



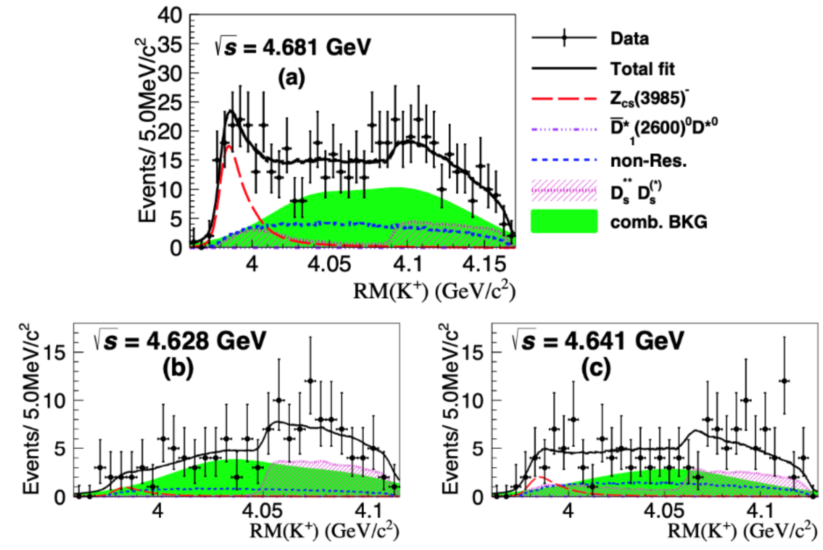
Comparison to BESIII

- 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.

BESIII [PRL 126 (2021) 102001]



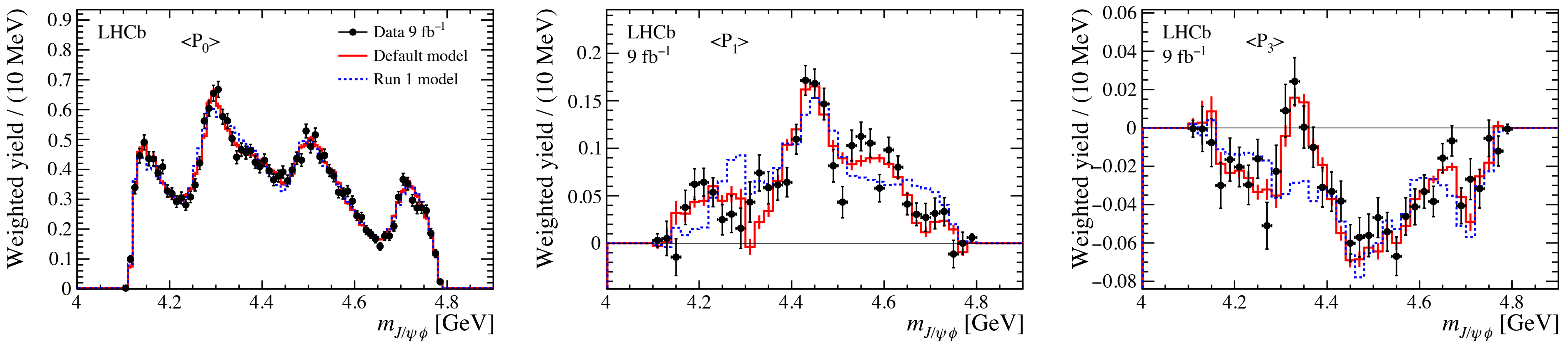
$$m_{\text{pole}}(Z_{cs}(3985)^-) = (3982.5^{+1.8}_{-2.6} \pm 2.1)\ \text{MeV}/c^2,$$
$$\Gamma_{\text{pole}}(Z_{cs}(3985)^-) = (12.8^{+5.3}_{-4.4} \pm 3.0)\ \text{MeV}.$$

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.

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

[arXiv:2103.01803]



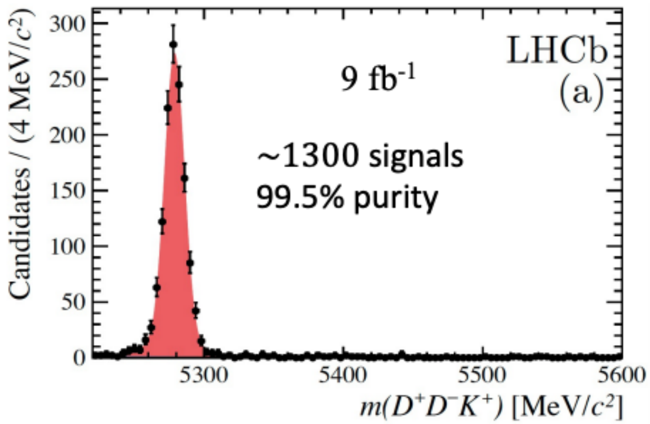
- The J^P of $X(4685)$ is 1^+, and the J^P $X(4630)$ is not determined.

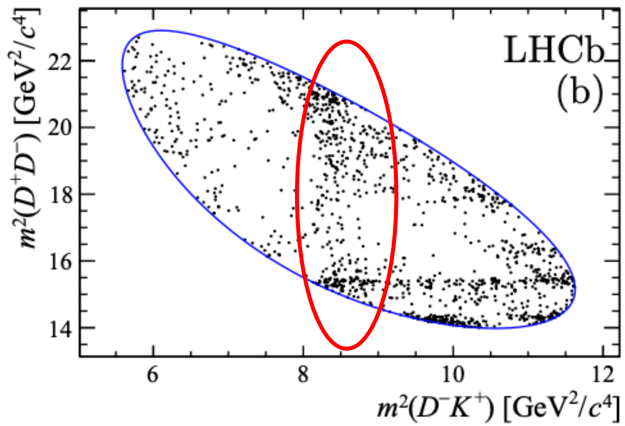
Observation of D^-K^+ structure in $B^+ \to D^+D^-K^+$

$X(2900)$ observation

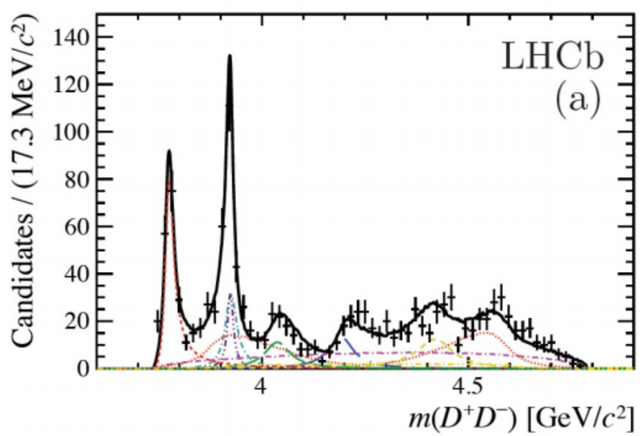
[PRL 125 (2020) 242001, PRD 102 (2020) 112003]

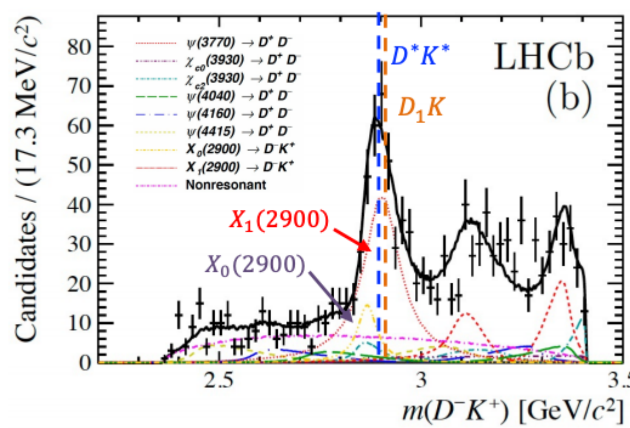
- $B^+ \to D^+D^-K^+$, an ideal channel to search for open-charm tetraquark.





- Amplitude analysis performed:





- More discussions about $B \to DDh$ in Yi Jiang's talk.

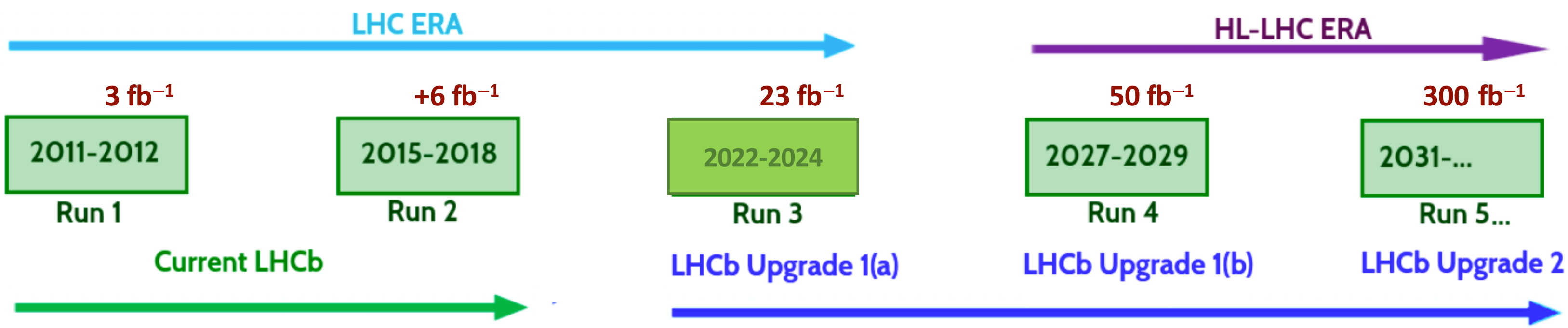
Summary

Presented only newest analyses performed by LHCb:

- Further understanding of $\chi_{c1}(3872)$
- Observation of first fully-charmed tetraquark $X(6900)(cc\bar{c}\bar{c})$
- $X(4740)$ ($c\bar{c}s\bar{s}$) is observed in $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays
- Four new $J/\psi K^+$ ($c\bar{c}u\bar{s}$) and $J/\psi\phi$ ($c\bar{c}s\bar{s}$) structures are observed in the decay of $B^+ \to J/\psi\phi K^+$
  1. The J^P of $Z_{cs}(4000)^+$ and $X(4685)$ state is also determined.
  2. An exotic zoo channel, $B^+ \to J/\psi\phi K^+$, two kinds of exotic states observed in one channel.
- First observation of open-charm tetraquark candidate

Prospects

- Prospects of more exotic states observed at LHCb



- 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 2023
  - Could have another 6x increase from Upgrade II

Thanks for listening

Backup

Outline

- Evidence of a $J/\psi\Lambda$ resonance and observation of excited Ξ^{*-} states in the $\Xi_b \to J/\psi\Lambda K^-$
  (Details in Jinlin's Talk)
  [arXiv:2012.10380, to appear in Science Bulletin]

- Study of the lineshape of the $\chi_{c1}(3872)$ [PRD 102 (2020) 092005]
- Study of the $\psi_2(3823)$ and $\chi_{c1}(3872)$ states in $B^+ \to (J/\psi\pi^+\pi^-)K^+$ decays
  [JHEP 08(2020)123]

- Observation of structure in the J/ψ-pair mass spectrum
  [Science Bulletin 65 (2020) 032]

- Study of $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays [JHEP 02 (2021) 024]

- Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$
  [arXiv:2103.01803]

- Amplitude analysis of $B^+ \to D^+D^-K^+$ decay
  (Details in Yi's Talk)
  [PRL 125 (2020) 242001, PRD 102 (2020) 112003]

Introduction

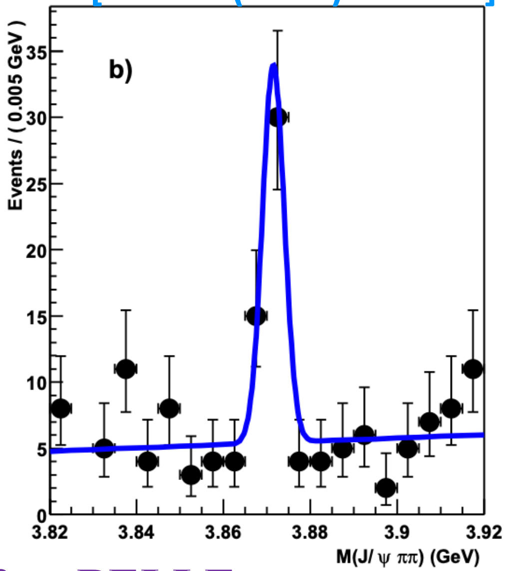
- Multiquark states are first predicted in 1964 in quark model, the original papers by M.Gell-Mann and G.Zweig.

The Nobel Prize in Physics 1969

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

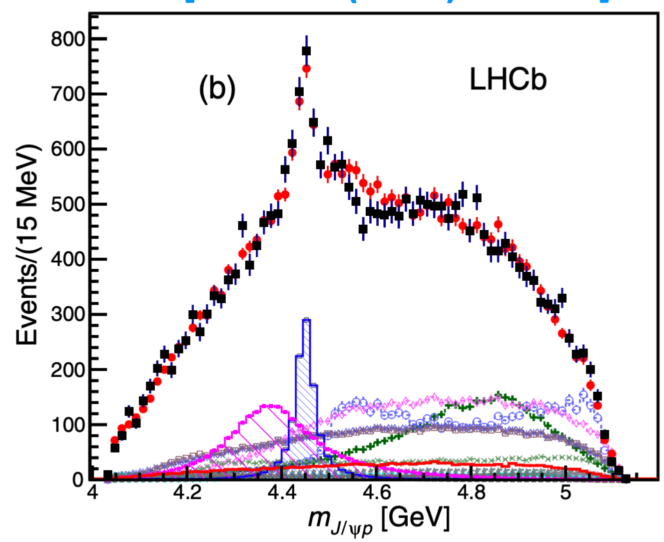
- First tetraquark candidate observed at BELLE in 2003, first pentaquark candidate at LHCb in 2015.

[PRL 91 (2003) 262001]



2003 at BELLE

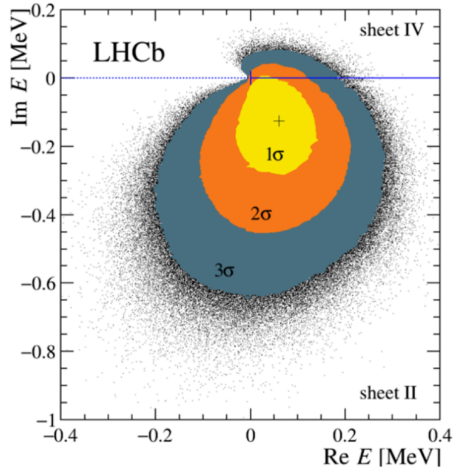
[PRL 115 (2015) 072001]



2015 at LHCb

Pole search

[PRD 102 (2020) 092005]



- The amplitude has two types of singularities
  - ✓Branch points: thresholds of coupled channels; lead to branch cuts of Riemann Surface
  - ✓Poles: hadronic states; real part of pole location is hadron mass; imaginary part of pole location is half width
- For $\chi_{c1}(3872)$, only Riemann sheets associated to $D^0\overline{D}^{*0}$ are important

$$\text{I:}\quad E - E_f - \frac{g}{2}\left(+\sqrt{-2\mu_1 E} + \sqrt{-2\mu_2(E-\delta)}\right) + \frac{i}{2}\Gamma(E) \text{ with } \mathrm{Im}\, E > 0\,,$$

$$\text{II:}\quad E - E_f - \frac{g}{2}\left(+\sqrt{-2\mu_1 E} + \sqrt{-2\mu_2(E-\delta)}\right) + \frac{i}{2}\Gamma(E) \text{ with } \mathrm{Im}\, E < 0\,,$$

} Physical sheet

$$\text{III:}\quad E - E_f - \frac{g}{2}\left(-\sqrt{-2\mu_1 E} + \sqrt{-2\mu_2(E-\delta)}\right) + \frac{i}{2}\Gamma(E) \text{ with } \mathrm{Im}\, E < 0\,,$$

$$\text{IV:}\quad E - E_f - \frac{g}{2}\left(-\sqrt{-2\mu_1 E} + \sqrt{-2\mu_2(E-\delta)}\right) + \frac{i}{2}\Gamma(E) \text{ with } \mathrm{Im}\, E > 0\,,$$

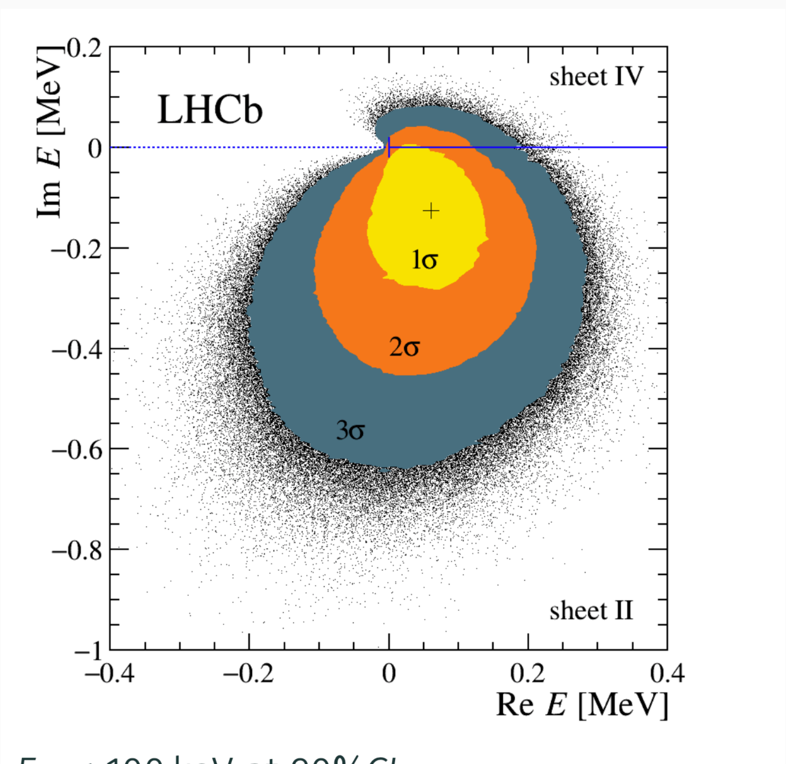
} Unphysical sheet

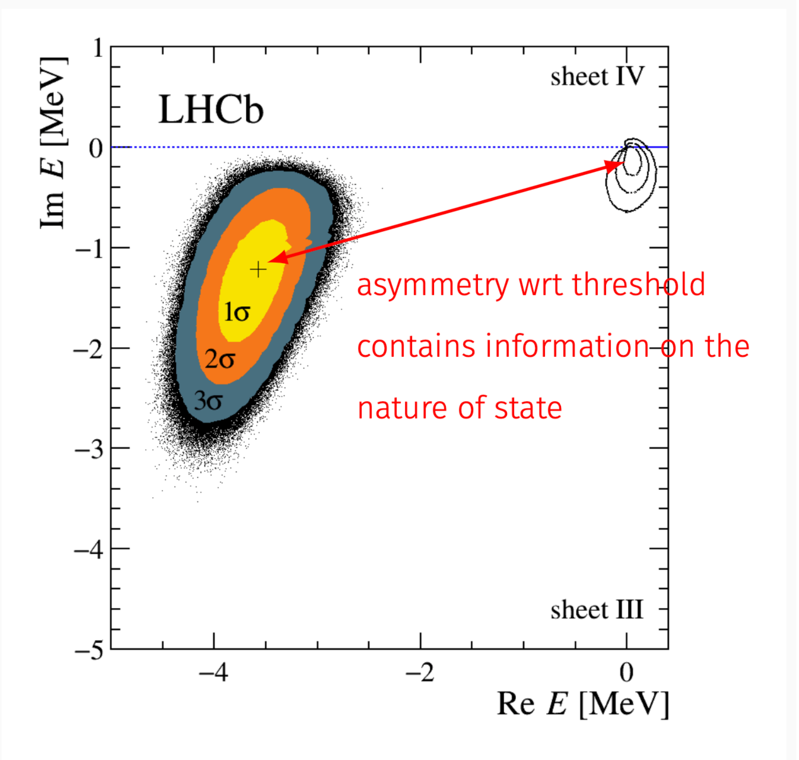
- Pole location on sheet II is preferred for all scenarios!

Flatté model

[PRD 102 (2020) 092005]

- Threshold is within the natural width ➔ Breit-Wigner is not the correct lineshape
- Flatté model is used, best fit gives two pole singularities:





$E_b < 100$ keV at 90%CL

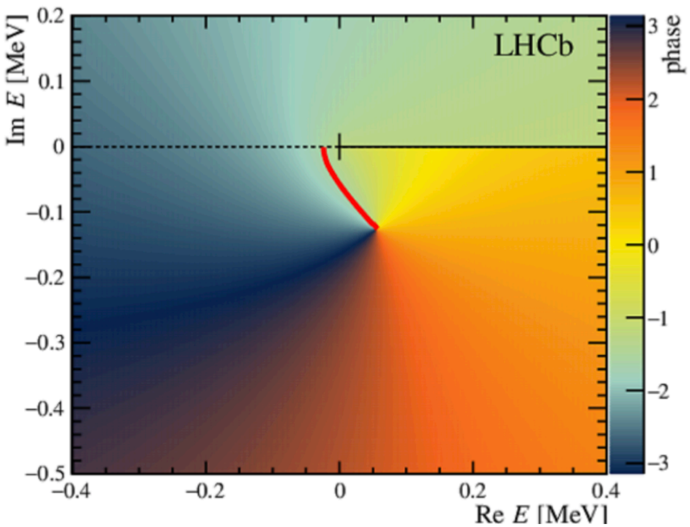
Best estimate: $E_{\mathrm{II}} = (0.06 - 0.13\,i)$ MeV

Best estimate: $E_{\mathrm{III}} = (-3.58 - 1.22\,i)$ MeV

✓ **Pole study compatible with a bound $D^0\overline{D}^{*0}$ state but a virtual state scenario is still allowed at 2σ level**

Mixture of molecule and compact state

- Pole locations of different kinds of hadronic states [PRD 102 (2020) 092005]
  - ✓Bound state: on physical sheet below threshold on real axis
  - ✓Virtual state: on unphysical sheet below threshold on real axis
  - ✓Resonance: on unphysical sheet in the complex plane
  - ✓Presence of inelastic channels shifts pole into complex plane and turns both a bound and virtual state into a resonance
- Setting the couplings to channels other than $D\bar{D}^*$ to zero gives $E_{\mathrm{II}} = -24$ keV, indicating a quasi-bound state with binding energy of $E_b = 24$ keV
- Quasi-bound state of $D^0\bar{D}^{*0}$ scenario preferred: $E_b < 100$ keV at 90% C.L.
- Quasi-virtual state assignment allowed at 2σ level

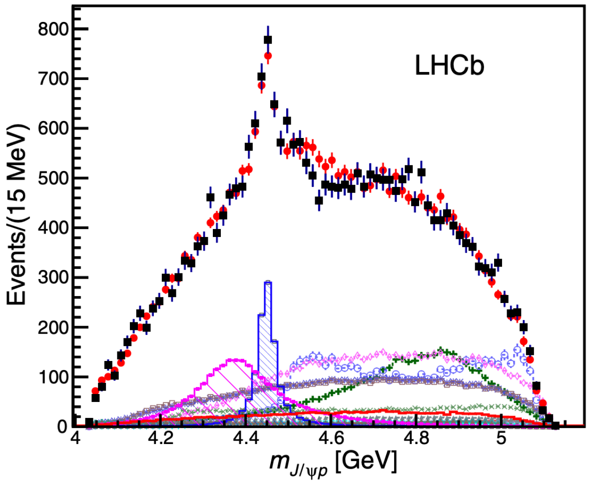


✓Pole study compatible with a bound $D^0\bar{D}^{*0}$ state but a virtual state scenario is still allowed at 2σ level

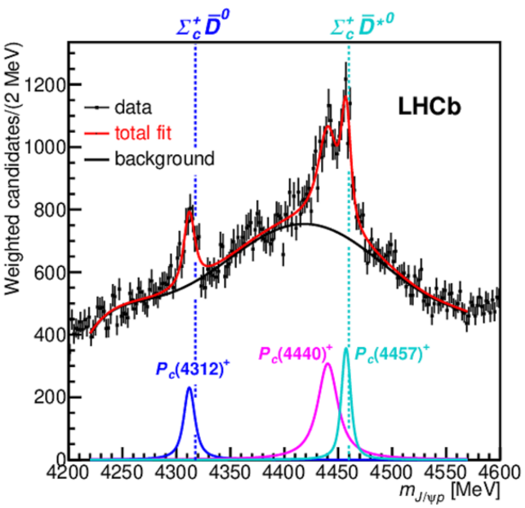
Motivation

- 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.

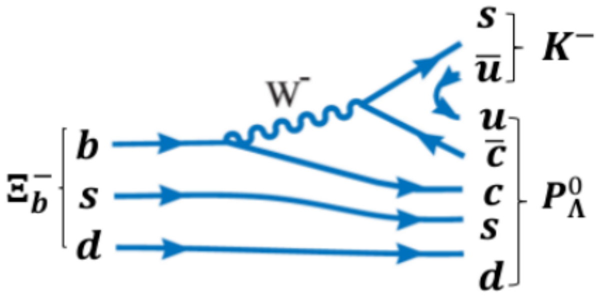
[PRL 115 (2015) 072001]

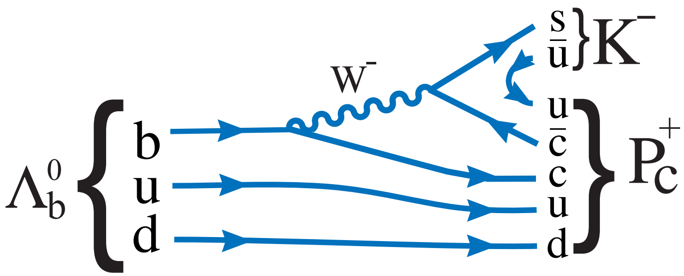


[PRL 122 (2019) 222001]



- 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.

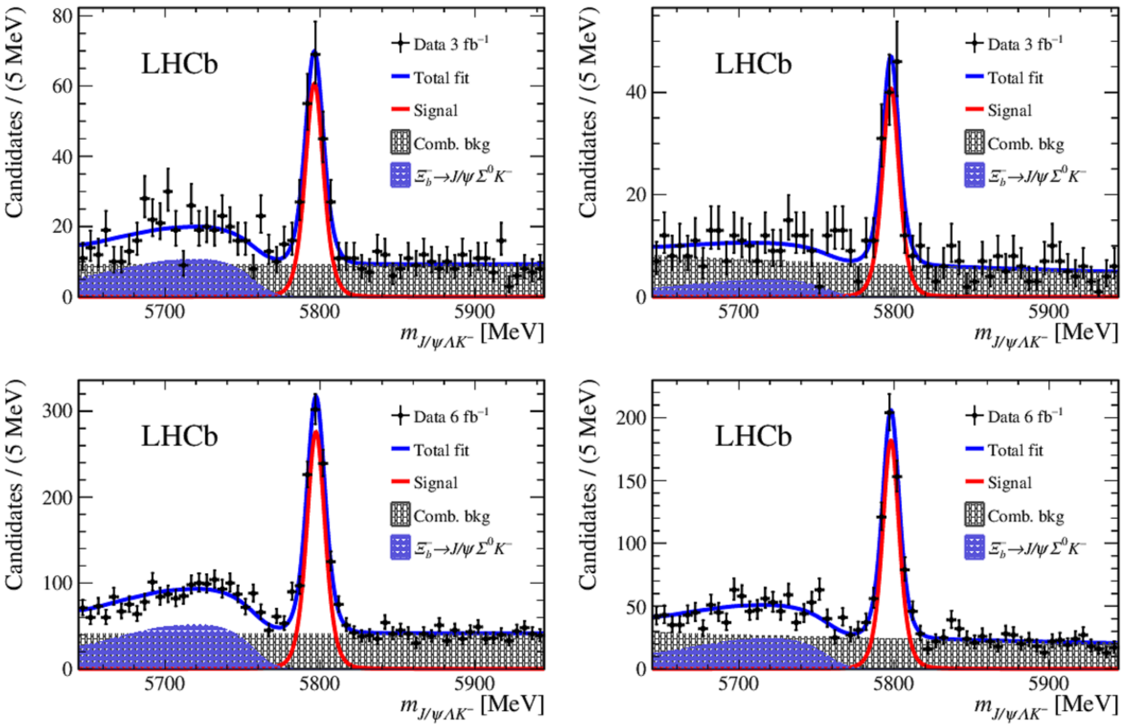




Run 1 + Run 2 data sample

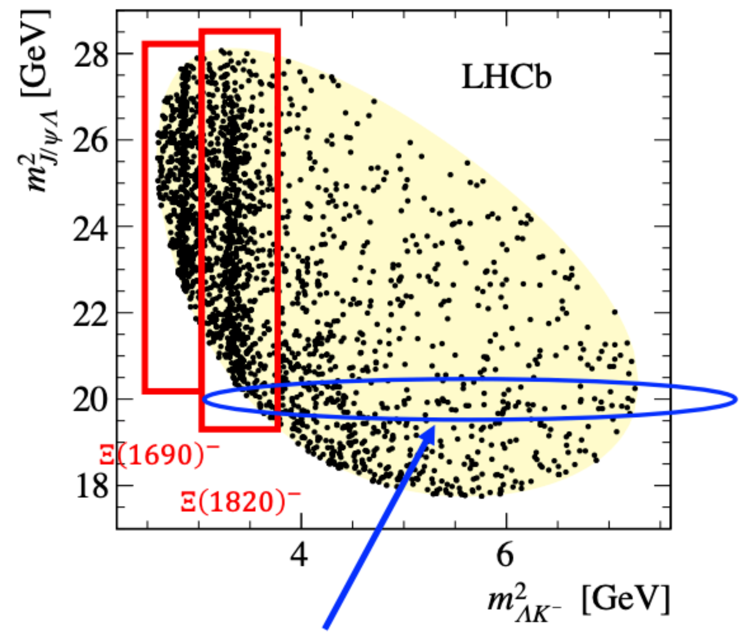
- ~1750 Ξ_b^- signals, purity ~ 80%

[arXiv:2012.10380]



Long tracks:
The tracks reconstructed from Vertex Detector and Track Stations.

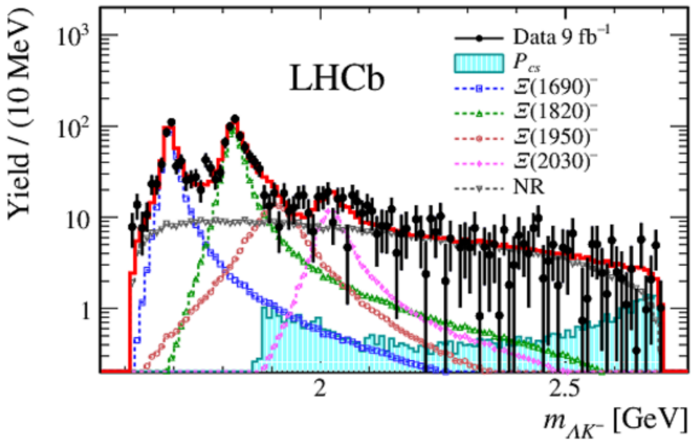
Downstream tracks:
The tracks reconstructed from Track Stations.

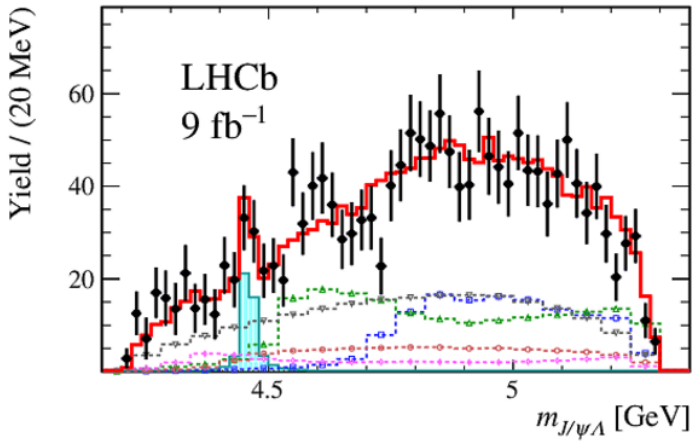


Potential P_{cs} contribution?
A full amplitude analysis is performed

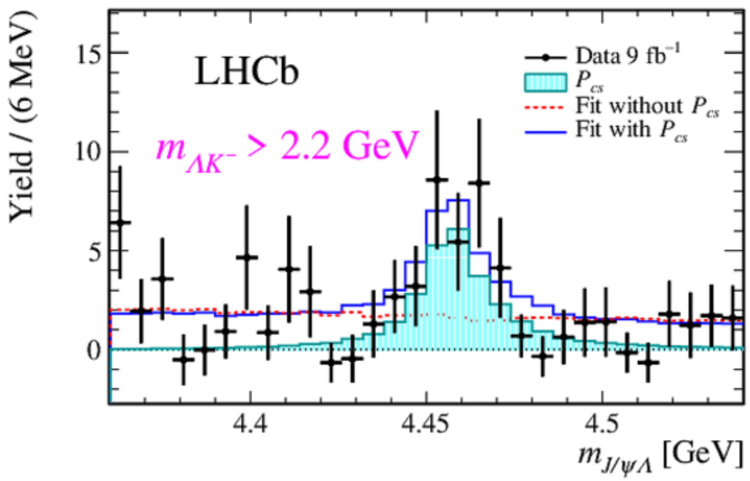
Significance of a P_{cs} in this channel [arXiv:2012.10380]

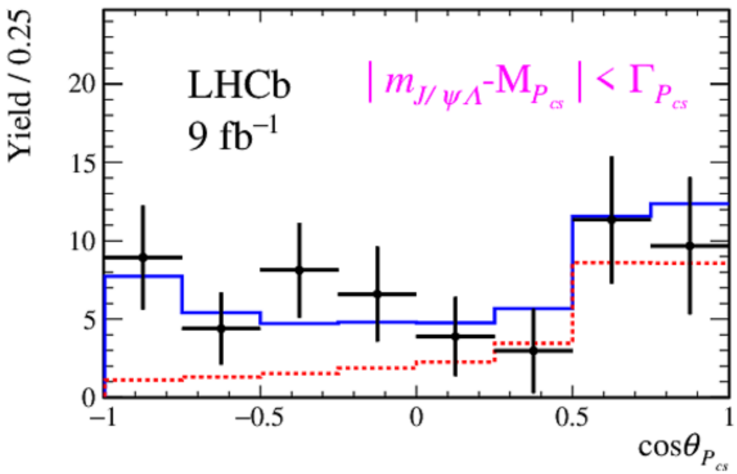
- ~3.1σ significance of P_{cs} (Syst. uncertainty and look-elsewhere effect considered)



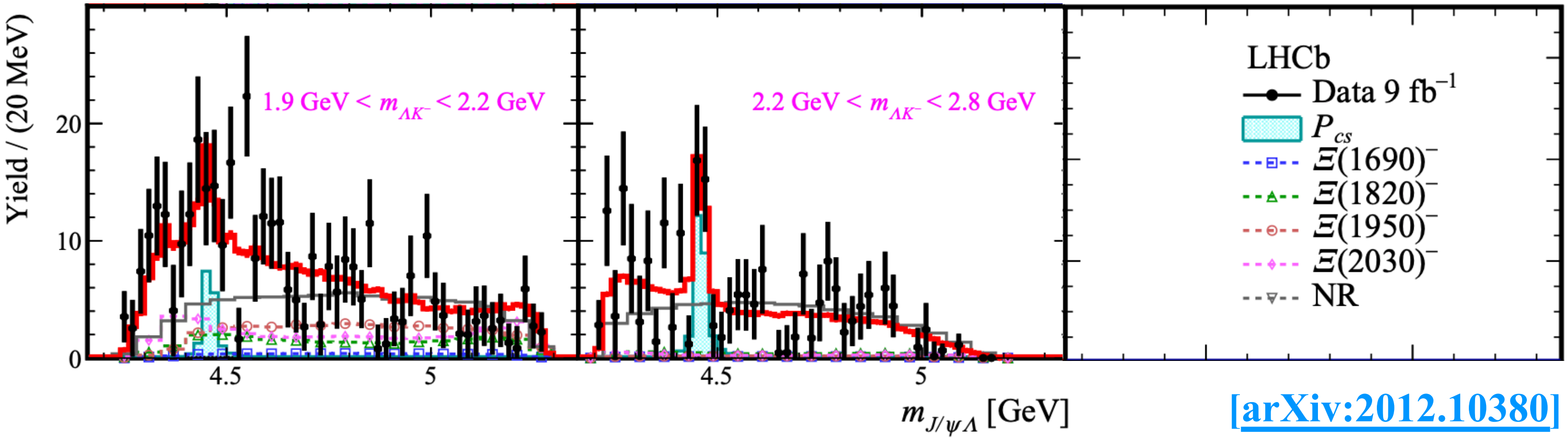


- A significant improvement is also found in the $\cos\theta_{P_{cs}}$ distributions when the P_{cs} included in fitting





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	–	–	$35.8\,^{+4.6}_{-6.4}\,^{+10.3}_{-11.2}$

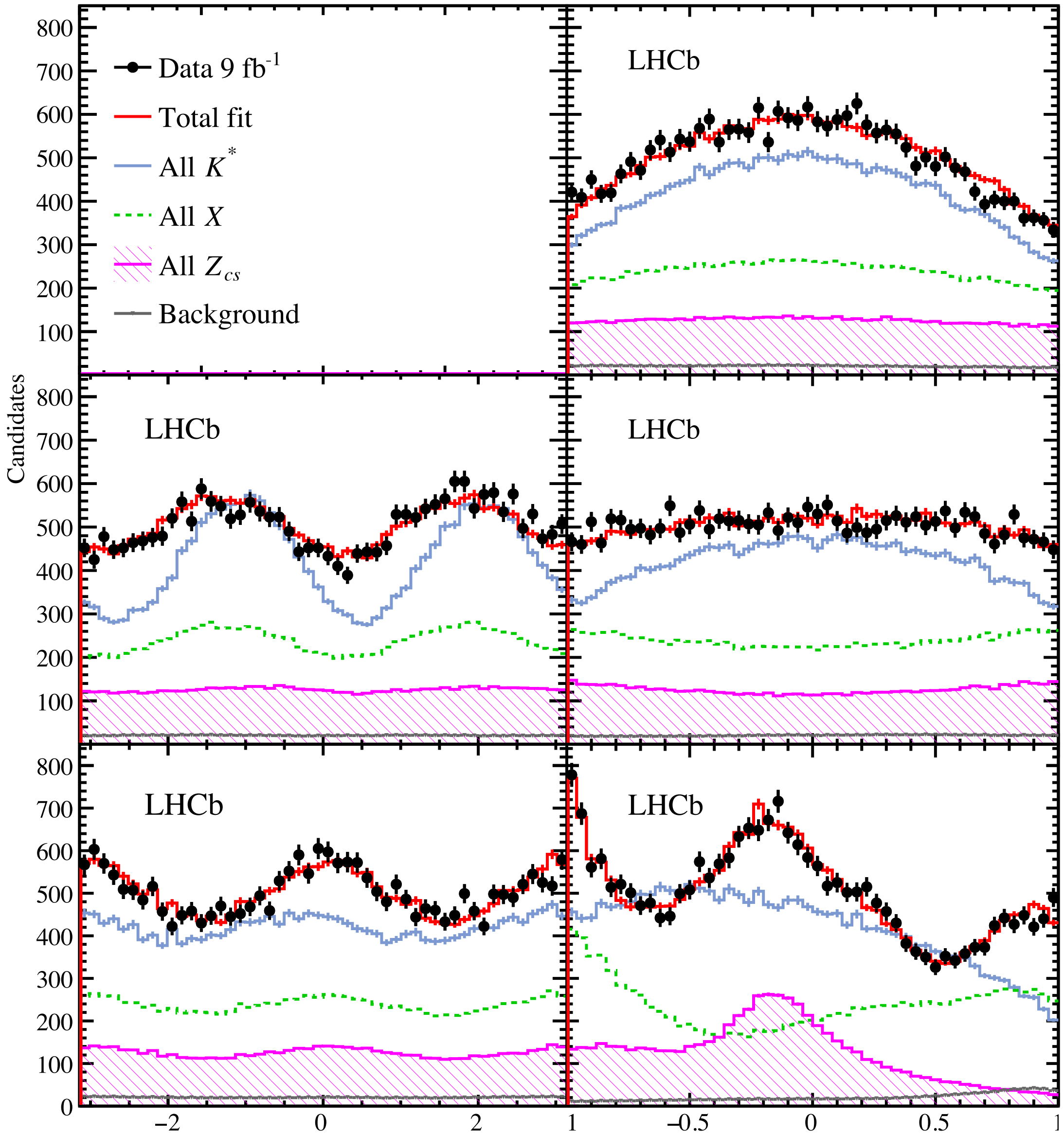
Fit fraction

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.

Angular distribution

[arXiv:2103.01803]



Legendre moments

[arXiv:2103.01803]

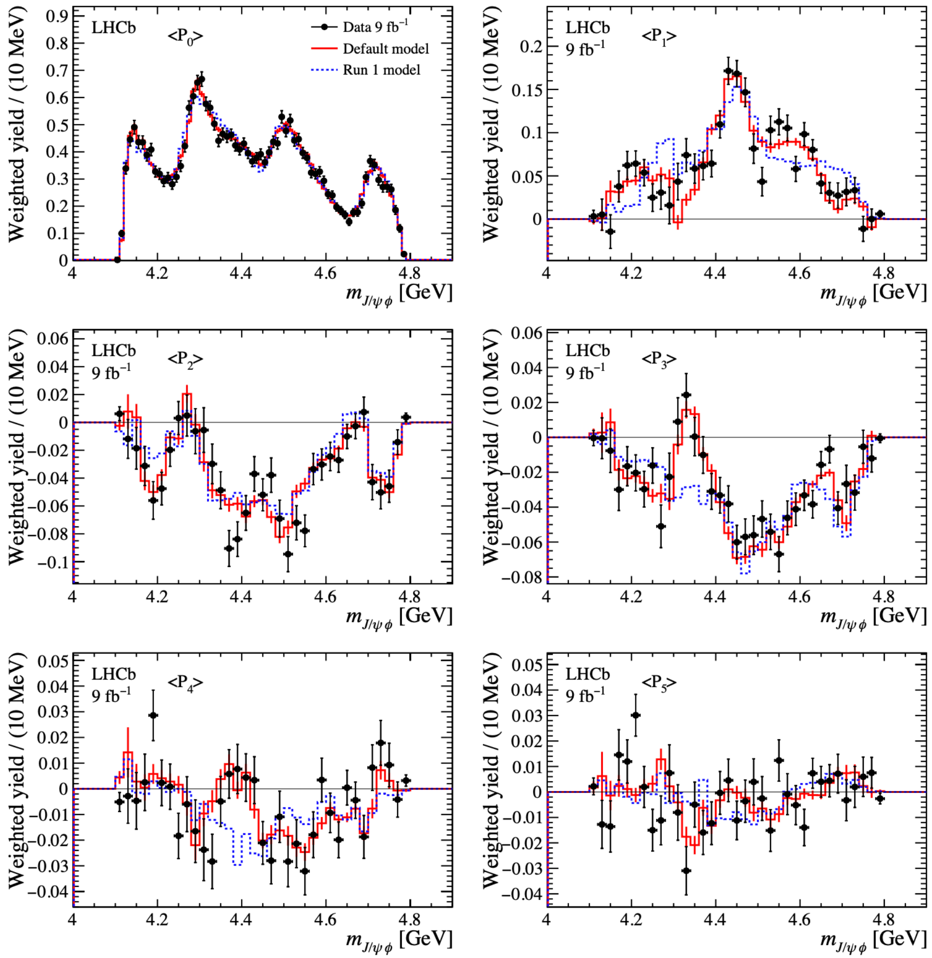
Angular moments of $J/\psi\phi$ helicity angle

- Unnormalized Legendre moments:

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

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

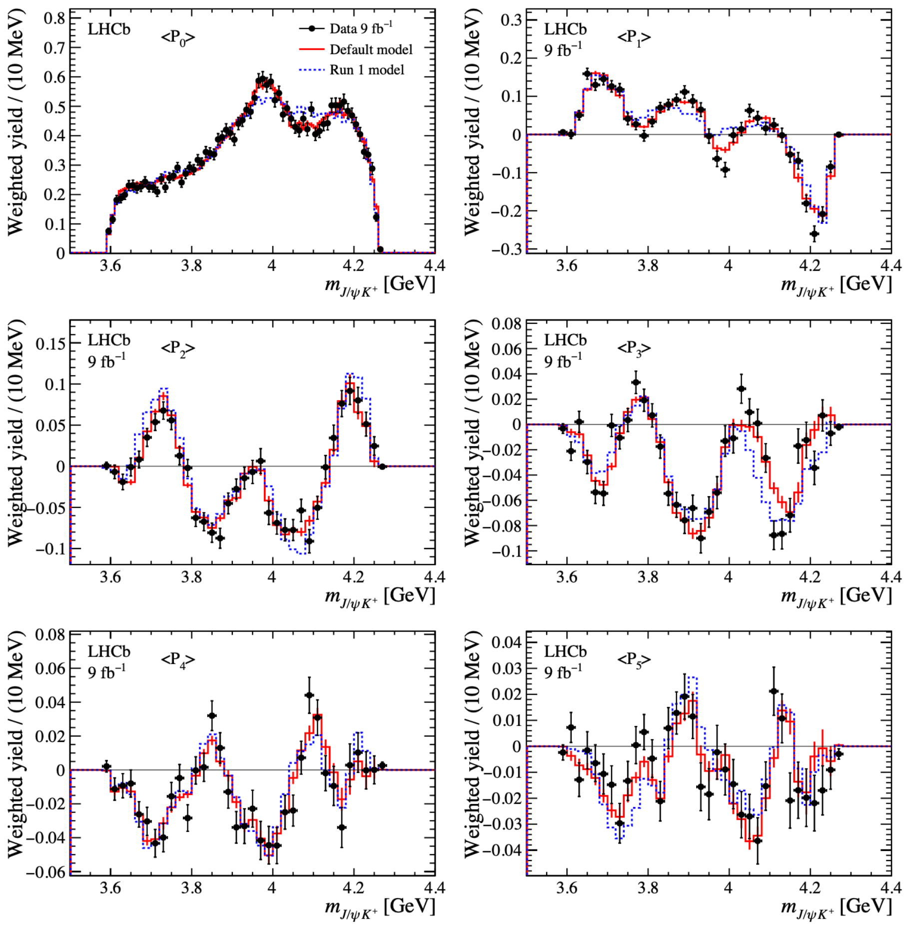
The moments distribution is obtained by a $\frac{1}{\epsilon_i} P_l(cos\theta)$.



Legendre moments

[arXiv:2103.01803]

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



Angular moments of ϕK^+ helicity angle