Recent results with exotic charmonia hadrons at LHCb

Mengzhen Wang

Center of High Energy Physics, Tsinghua University

(On behalf of the LHCb collaboration)

Conference on Flavor Physics and CP Violation

07 June – 11 June 2021

Outline

- Overview of recent LHCb publications for exotic charmonia hadrons

- Selected topics

  arXiv: 2012.10380

  - Evidence of P_{cs} candidate in $\Xi_b^- \to J/\psi\Lambda K^-$

  arXiv: 2012.10380

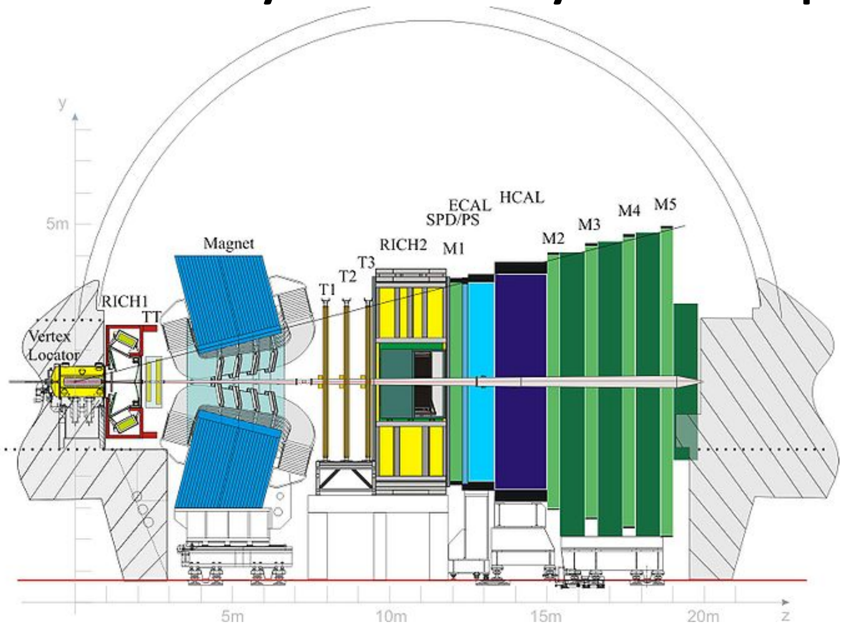
  - Observation of new resonances decaying into $J/\psi\phi$ and $J/\psi K$

- Summary and prospects

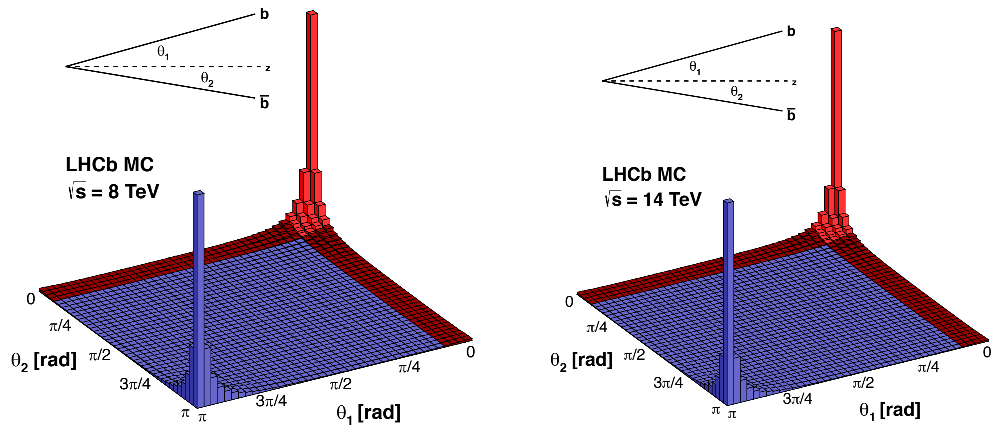
The LHCb detector

Int. J. Mod. Phys. A 30, 1530022 (2015)   JINST 3 (2008) S08005

- Single-arm forward spectrometer, designed for the study of heavy flavor physics



$2 < \eta < 5$ range: $\sim 25\%$ $b\bar{b}$ pairs in LHCb acceptance



Excellent vertex, IP and decay-time resolution:

- $\sigma(\mathrm{IP}) \approx 20\ \mu\mathrm{m}$ for high-p_{T} tracks
- $\sigma(\tau) \approx 45$ fs for $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^- \pi^+$ decays

Very good momentum resolution

- $\delta p/p \approx 0.5\% - 1\%$ for $p \in (0{,}200)\mathrm{GeV}$
- $\sigma(m_B) \approx 24$ MeV for two-body decays

Hadron and Muon identification

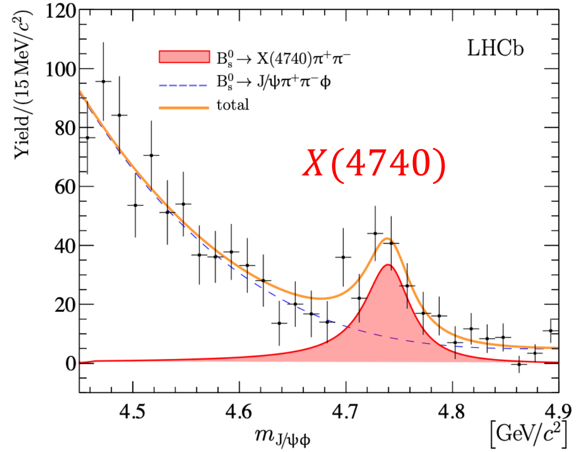
- $\epsilon_{K\to K} \approx 95\%$ for $\epsilon_{\pi\to K} \approx 5\%$ up to 100 GeV
- $\epsilon_{\mu\to\mu} \approx 97\%$ for $\epsilon_{\pi\to\mu} \approx 1-3\%$

Overview of recent LHCb publications for exotic hadrons

JHEP 2102 (2021) 024

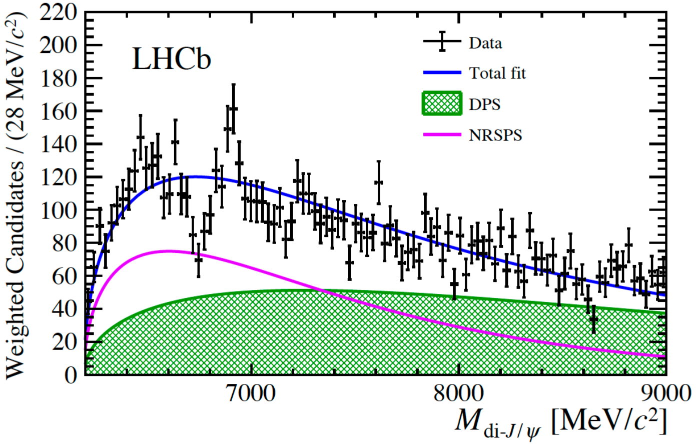
- A $J/\psi\phi$ structure in $B_s^0 \to J/\psi\phi\pi^+\pi^-$ decays
  - Based on 1-D mass-spectrum analysis
  - Significance $\sim 5.3\sigma$

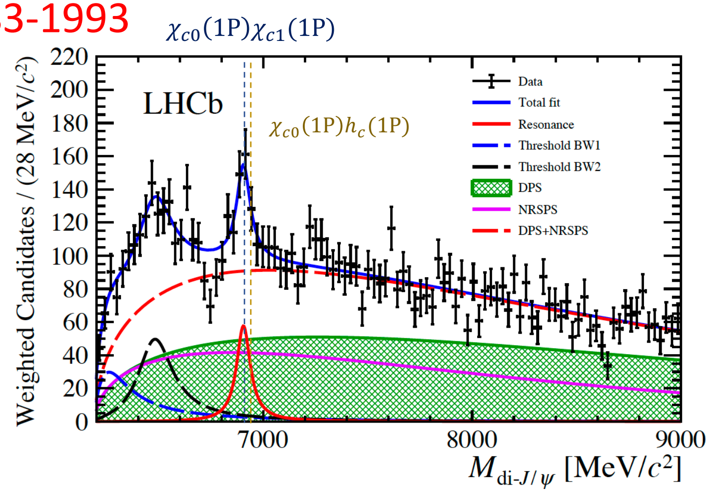
$$m_{X(4740)} = 4741 \pm 6 \pm 6 \ \mathrm{MeV}/c^2 ,$$
$$\Gamma_{X(4740)} = 53 \pm 15 \pm 11 \,\mathrm{MeV} .$$



- $X(6900)$ in di-J/ψ system

Sci.Bull.65(2020)23 1983-1993





- $\chi_{c1}(3872)$
  - Mass measurement (JHEP 08 (2020) 123)
  - Line shape study (PRD 102 (2020) 092005)
  - Multiplicity-dependent production (PRL 126 (2021) 092001)

$$m_{\chi_{c1}(3872)} - m_{\psi(2S)} = 185.49 \pm 0.06 \pm 0.03 \,\mathrm{MeV}/c^2$$

$$\Gamma_{BW} = 1.39 \pm 0.24 \pm 0.10 \,\mathrm{MeV}$$

arXiv: 2012.10380
To be published at Science Bulletin

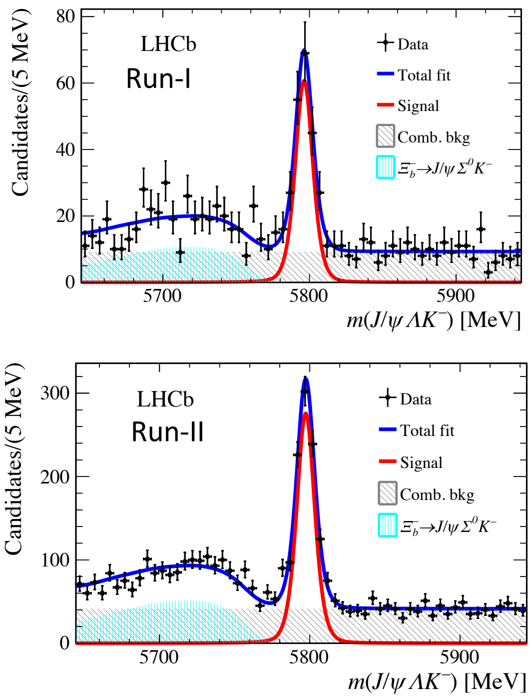
Evidence of a $J/\psi\Lambda$ resonance in $\Xi_b^- \to J/\psi\Lambda K^-$ decay

arXiv: 2012.10380

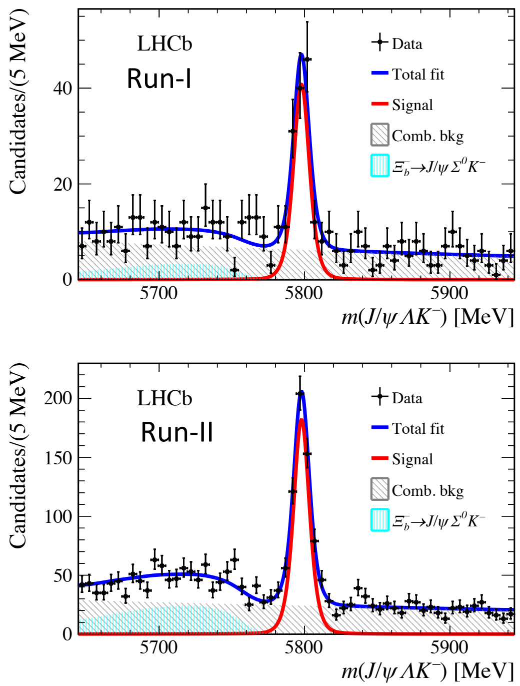
The $\Xi_b^- \to J/\psi \Lambda K^-$ data sample

PRC93 (2016) 065203

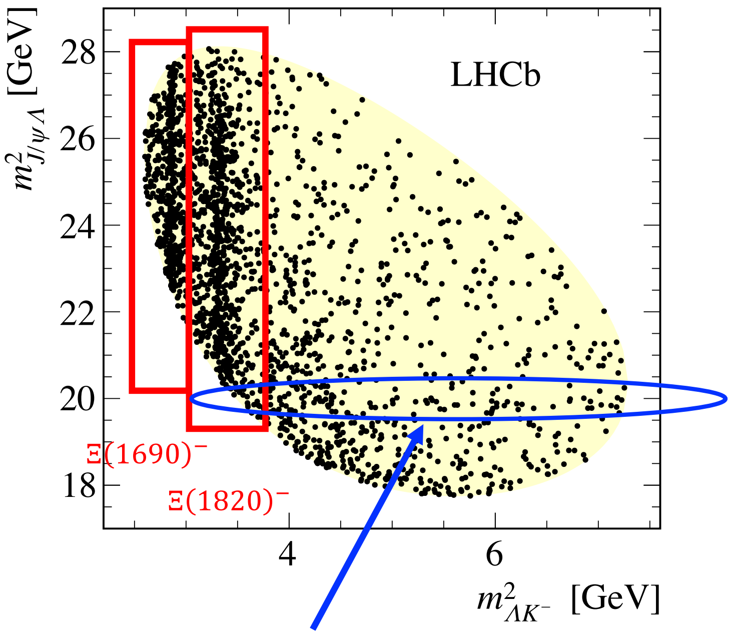
- Used to search for predicted $[udsc\bar{c}]$ pentaquark P_{cs}
- Run-I + Run-II data: $\sim$1750 signals, purity $\sim$80%
  - $J/\psi \to \mu^+\mu^-, \Lambda \to p\pi^-$



Λ decay in vertex detector



Λ decay outside the vertex detector



Potential P_{cs} contribution?
Amplitude analysis required.
(next slide)

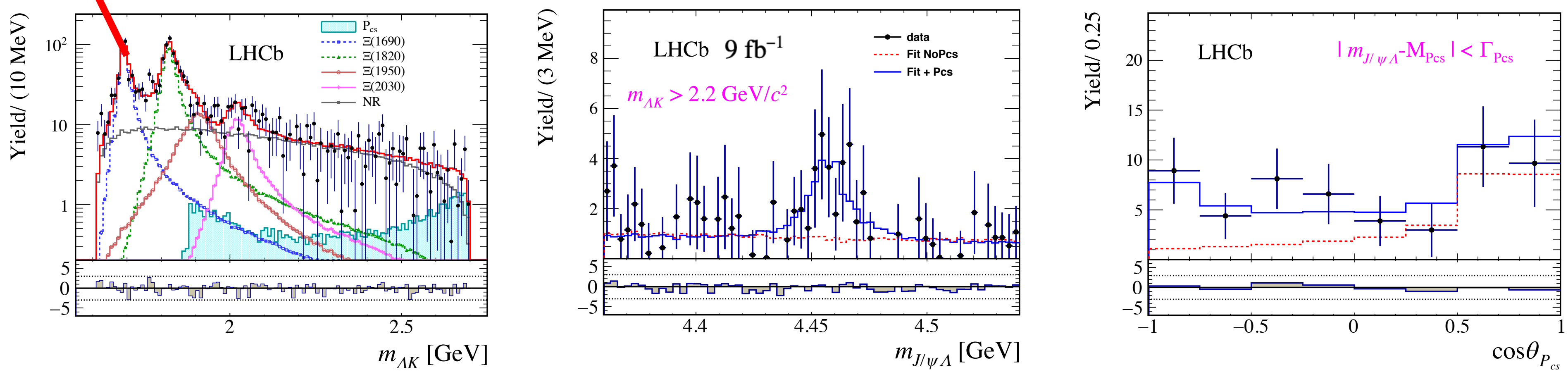
arXiv: 2012.10380

Full 6D amplitude analysis

- Adding a P_{cs} improves $2\ln L$ by 43 units, $\sim 4.3\sigma$ significance
  - **3.1σ significance** when syst. uncertainty considered

Two Ξ^{*-} states

Zooms in to P_{cs} signal region for better visibility



P_{cs} mass 19MeV below the $\Xi_c^0\overline{D}^{*0}$ threshold. Statistic not enough for J^P determination.

State	M_0 [MeV]	Γ[MeV]
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$
$\Xi(1690)^-$	$1692.0 \pm 1.3\,^{+1.2}_{-0.4}$	$25.9 \pm 9.5\,^{+14.0}_{-13.5}$
$\Xi(1820)^-$	$1822.7 \pm 1.5\,^{+1.0}_{-0.6}$	$36.0 \pm 4.4\,^{+7.8}_{-8.2}$

Consistent with PDG, with improved precision

arXiv: 2103.01803

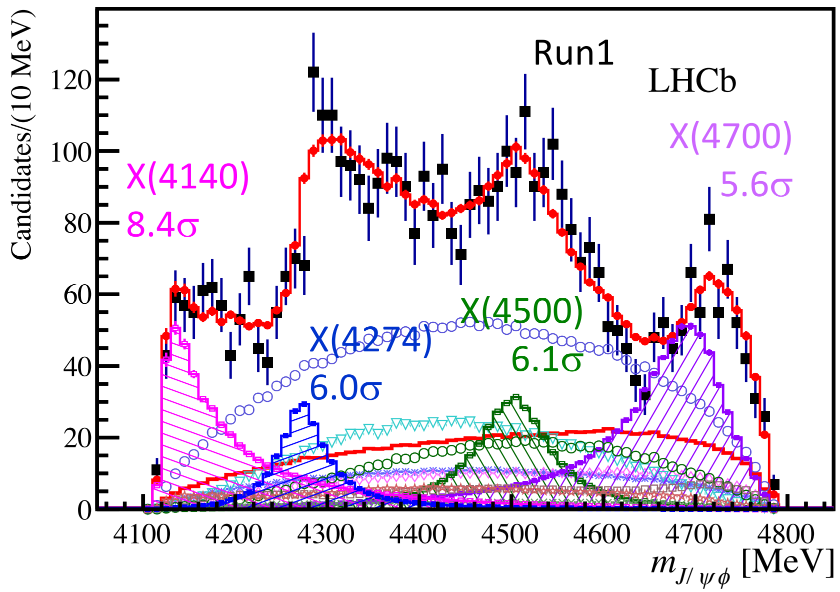
New $X \to J/\psi\phi$ and $Z_{cs}^{+} \to J/\psi K^{+}$ states in $B^{+} \to J/\psi\phi K^{+}$ decays

arXiv: 2103.01803

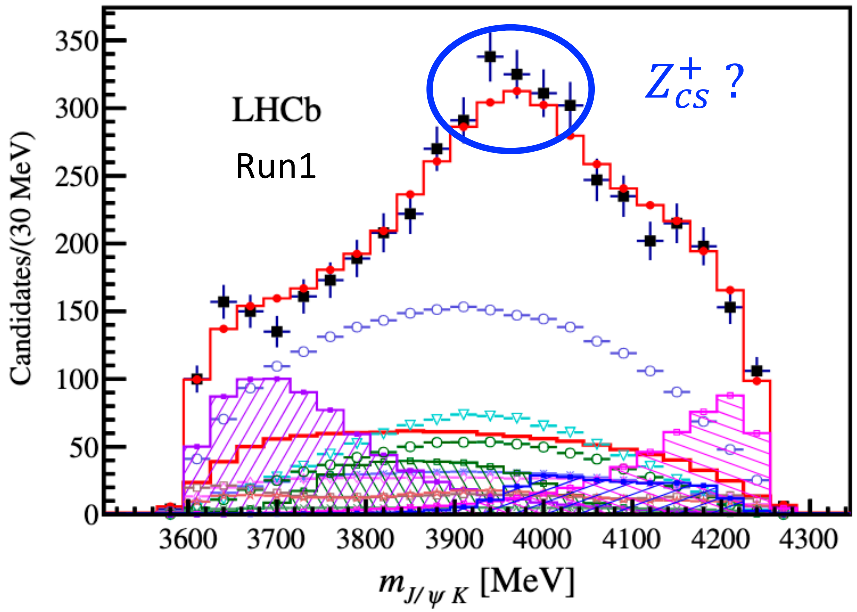
Previous $B^+ \to J/\psi\phi K^+$ analysis

- $B^+ \to J/\psi\phi K^+$ amplitude analysis was performed using LHCb Run1 data PRL 118 (2017) 022003, PRD 95 (2017) 012002

Four exotic $J/\psi\ \phi$ structures were observed



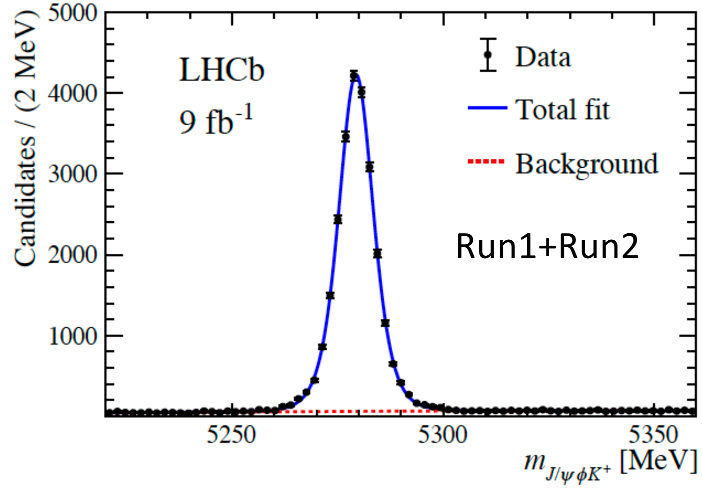
Hint to a $J/\psi K$ structure

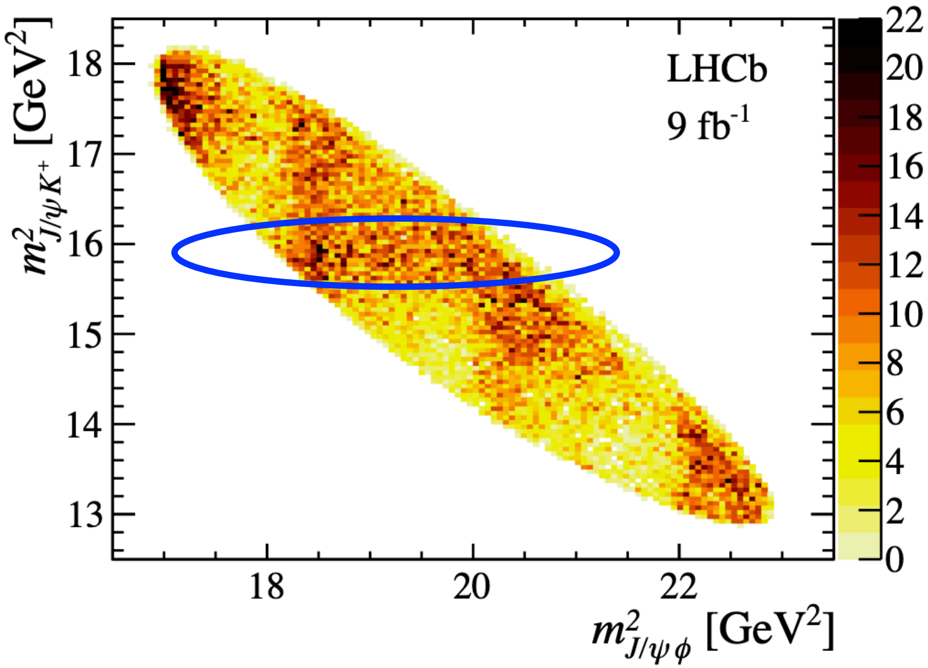


- Investigate potential Z_{cs} contribution with larger data sample

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

- Run1+Run2 data & improved event selections
  - $6\times$ more B^+ signal yields (~ 24 k)
  - Much smaller BKG fraction ($\sim 4\%$)



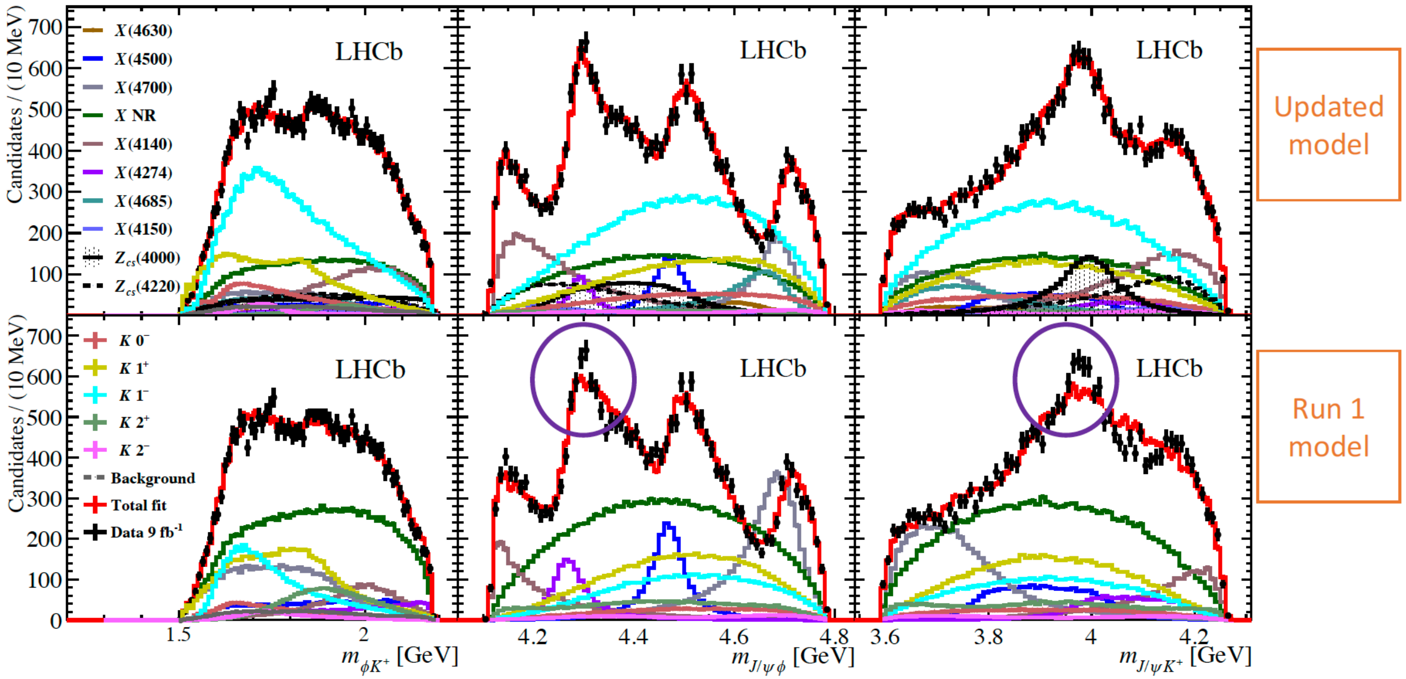


- Clear structures in Dalitz-plot
  - Four clear $J/\psi\phi$ bands observed in Run1
  - Clear $J/\psi K^+$ bands: Z_{cs}^+ candidate
  - Confirmed using full amplitude analysis

arXiv: 2103.01803

6D amplitude analysis

- Run1 model + extended K^* components cannot well fit the data. Need new exotics
  - $1^+ \ Z_{cs}, 1^+ \ X$ gives the largest improvement
  - Additional $1^{\pm} \ Z_{cs}, 1^{-}X, \ 2^{-}X$ also significantly improves fit quality
  - Above states considered in updated model



arXiv: 2103.01803

Amplitude fit result

BW mass, width

Fit fraction

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)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-7}$

$J^P = 1^+$ confirmed

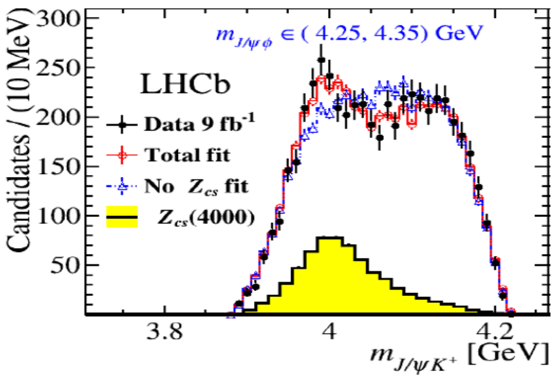
$J^P = 1^\pm$ preferred

- Two $Z_{cs}^+ \to J/\psi K^+$ states observed. Both significance $> 5\sigma$
- $X(4630), X(4685)$ states observed. Both significance $> 5\sigma$
- X states observed in Run1 analysis are confirmed

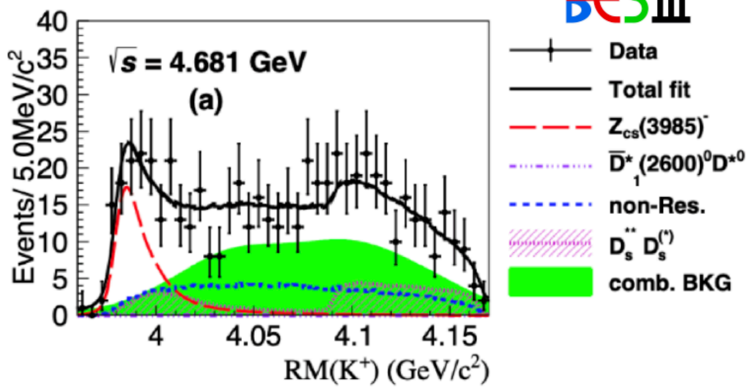
Compare to Z_{cs} in BESIII

- BESIII experiment recently reported 5.3σ observation of a very narrow $Z_{cs}^{\pm}$ in $D_s^- D^* + D D_s^{*-}$ mass distributions
- Their masses are close, but $Z_{cs}(4000)^{\pm}$ is $\sim 10\times$ broader
- No evidence $Z_{cs}(4000)^{\pm}$ is the same as $Z_{cs}(3985)^{\pm}$ seen by BESIII
  - Fix $Z_{cs}(4000)^{\pm}$ to BESIII's result; $2\ln L$ is worse by 160
  - Adding on top of the default model almost doesn't improve the fit likelihood

[arXiv:2103.01803]



[Phys. Rev. Lett. 126 (2021) 102001]

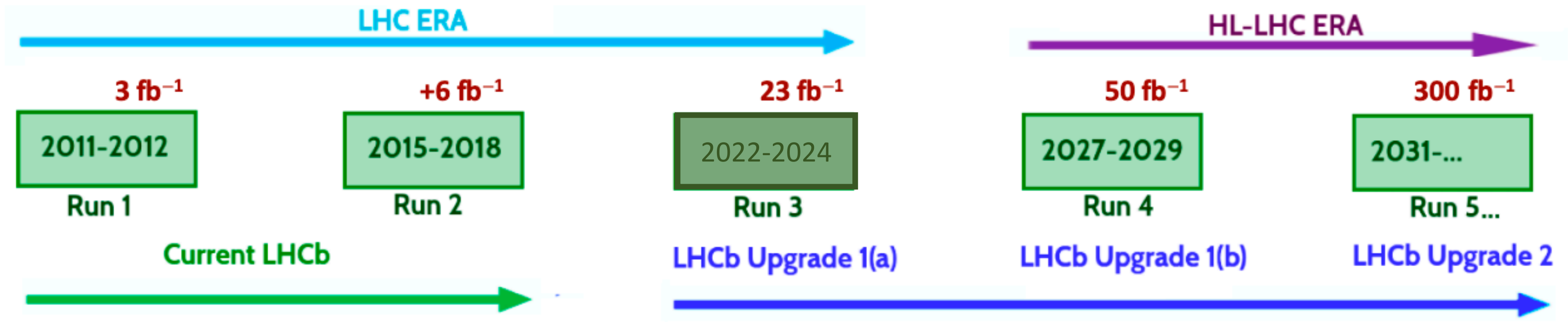


$m(Z_{cs}(4000)^+) = (4003 \pm 6^{+4}_{-14})$ MeV $\Gamma(Z_{cs}(4000)^+) = (131 \pm 15 \pm 26)$ MeV	$m(Z_{cs}(3985)^{\pm}) = (3985.2^{+2.1}_{-2.0} \pm 1.7)$ MeV $\Gamma(Z_{cs}(3985)^{\pm}) = (13.8^{+8.1}_{-5.2} \pm 4.9)$ MeV

Conclusions

- Many nice results about exotic charmonia hadrons obtained by LHCb
  - Evidence of $P_{cs}(4459)^0$ in $\Xi_b^- \to J/\psi \Lambda K^-$
    - Mass peak at $19\ \mathrm{MeV}$ below the $\Xi_c^0 \overline{D}^{*0}$ threshold
    - Sensitivity limited by statistics. Stay tuned with Run3 data. (J^P measurement, potential two-peak structure…)
  - New exotic structures observed in $B^+ \to J/\psi \phi K^+$ decays
    - Two Z_{cs} states with a minimal quark content of $c\bar{c}u\bar{s}$
      - $Z_{cs}(4000)^+$ with significance $> 15\sigma,\ J^P = 1^+$
      - Broader $Z_{cs}(4220)^+$ with significance $> 5\sigma$
    - Two new X states observed
    - 4 X states observed in $B^+ \to J/\psi \phi K^+$ Run1 analysis confirmed, with improved precision of mass, width and J^P determinations

Prospects



- LHCb is boosting the data collection to a new level
  - 7x data by 2029 than current (14x for hadronic decays)
  - Half of these by 2024
  - Another 6x increase from Upgrade II

Decay mode	LHCb $23\,\text{fb}^{-1}$	LHCb $50\,\text{fb}^{-1}$	LHCb $300\,\text{fb}^{-1}$
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100
$\Lambda_b^0 \to J/\psi pK^-$	680k	1.4M	8M
$\Xi_b^- \to J/\psi \Lambda K^-$	4k	10k	55k
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k
$\Xi_{bc}^+ \to J/\psi\, \Xi_c^+$	50	100	600

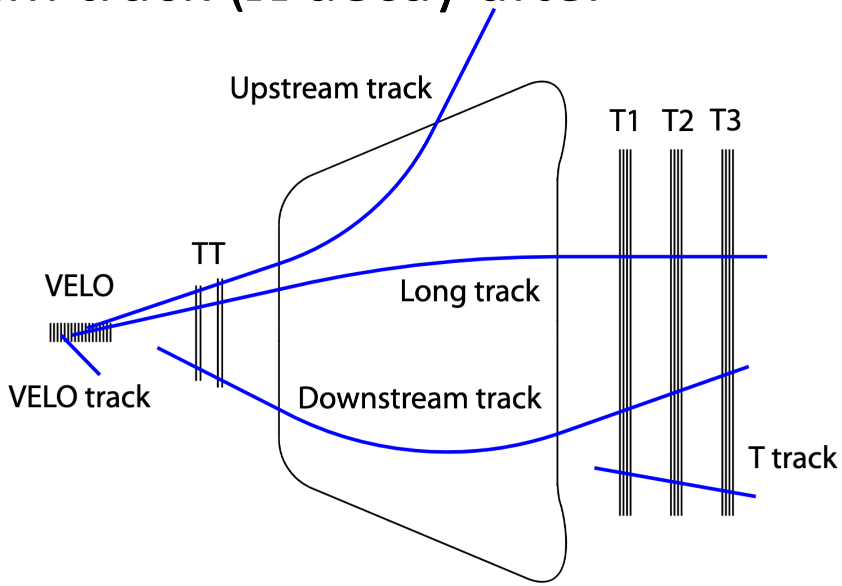
Thank you for your attention !

Any questions or comments ?

Back up

Λ reconstruction in LHCb

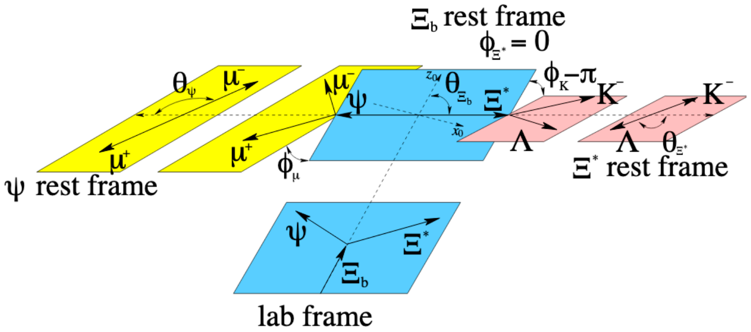
- The decay time of Λ is relatively large
- Large fraction of Λ particles decay after VELO
- Two methods for $\Lambda \rightarrow p\pi$ reconstruction
  - Long track + Long track (Λ decay in Velo)
  - Downstream track + Downstream track (Λ decay after VELO)



Full 6D amplitude analysis

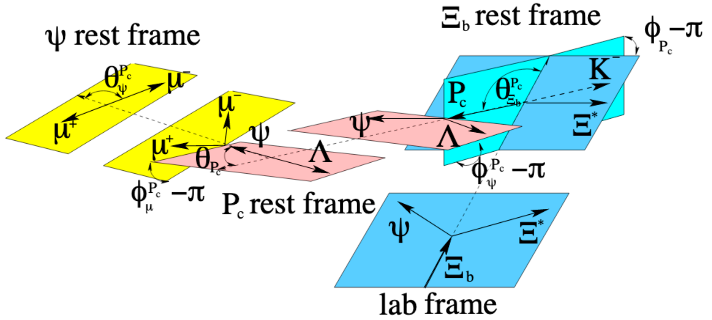
- Two decay chains considered

$\Xi_b^- \to \Xi^{*-}(\to K^-\Lambda)\, J/\psi(\to \mu^+\mu^-)$



(a) Ξ^{*-} chain

$\Xi_b^- \to P_{cs}(\to J/\psi(\to \mu^+\mu^-)\Lambda)K^-$



(b) P_{cs}^0 chain

- Fit the 6D kinematic distribution (1 mass + 5 angles), with sFit for background subtraction
  - Angular term: helicity formalism
  - Mass dependency: BW amplitude
  - A novel technique for final-state alignment between different chains

arXiv: 2012.03699, to be published at Chinese Physics C

6D amplitude analysis

- All B^+ candidates in signal regions used as input
- Three decay chains with K^*, X or Z_{cs} resonances
- 6 individual kinematic variables: 1 mass & 5 angles
  - Helicity formalism for angular-dependent amplitude
  - Several line shapes tested for mass term: Relativistic BW, single-channel K-Matrix, Flatté function
- Incoherent background considered in the fit model (cFit)

$$
\begin{aligned}
-\ln L(\vec{\omega}) &= -\sum_i \ln\left[(1-\beta)\,\mathcal{P}_{\rm sig}(m_{\phi K\ i},\Omega_i|\vec{\omega}) + \beta\,\mathcal{P}_{\rm bkg}(m_{\phi K\ i},\Omega_i)\right] \\
&= -\sum_i \ln\left[(1-\beta)\,\frac{\left|\mathcal{M}(m_{\phi K\ i},\Omega_i|\vec{\omega})\right|^2 \Phi(m_{\phi K\ i})\epsilon(m_{\phi K\ i},\Omega_i)}{I(\vec{\omega})} + \beta\,\frac{\mathcal{P}^u_{\rm bkg}(m_{\phi K\ i},\Omega_i)}{I_{\rm bkg}}\right] \\
&= -\sum_i \ln\left[\left|\mathcal{M}(m_{\phi K\ i},\Omega_i|\vec{\omega})\right|^2 + \frac{\beta\, I(\vec{\omega})}{(1-\beta) I_{\rm bkg}}\,\frac{\mathcal{P}^u_{\rm bkg}(m_{\phi K\ i},\Omega_i)}{\Phi(m_{\phi K\ i})\epsilon(m_{\phi K\ i},\Omega_i)}\right] + N \ln I(\vec{\omega})\,.
\end{aligned}
$$

More discussions about $Z_{cs}(4000)^+$

- Argand diagram gives further evidence of resonant character
  - The magnitude & phase obtained from line-shape independent fit (Black dots) is consistent with a BRW behavior (Red curve)
- $Z_{cs}(4000)^+$ contribution visible in different $m(J/\psi\phi)$ slices