LHCb多夸克态实验进展

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

张黎明 (清华大学)

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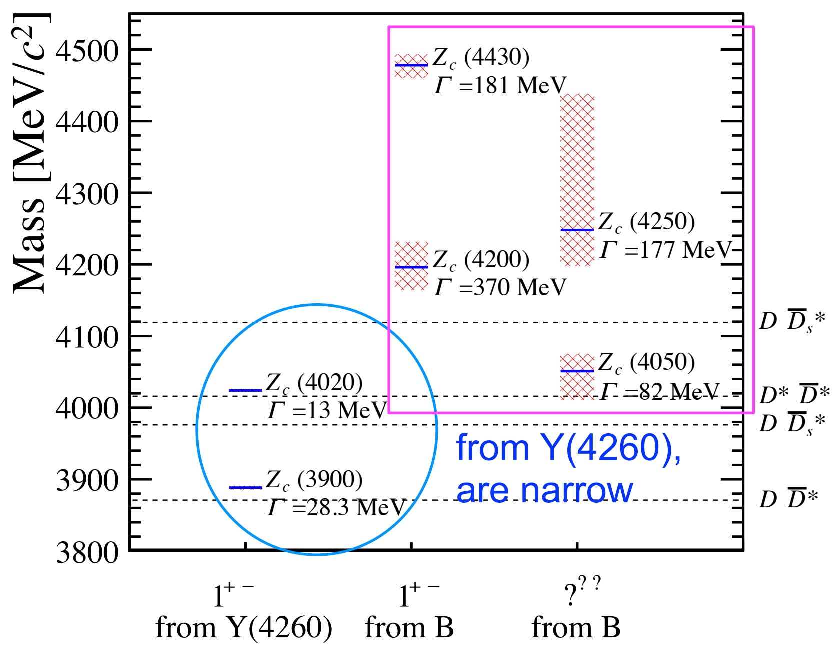
兰州大学

Z_c^- and earlier predictions of Z_{cs}

- Several Z_c^- states were observed from Y(4260) or B decays, at least have $c\bar{c}d\bar{u}$ four quarks
- Would be nice to look for Z_{cs}, the SU(3) partners of $X(3872)/Z_c(3900)$
- Useful to distinguish different models
  - Less exchange particles expected in the Z_{cs} molecule picture
- Several papers have predicted the existence of Z_{cs} state in early time

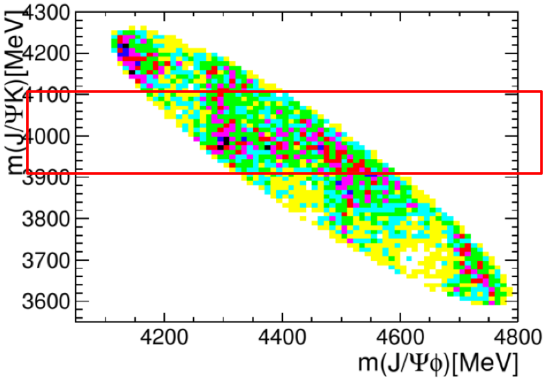
Others from B decays are broad



[Phys. Soc. 55(2009)424, PRL 110(2013)232001, PRD 88(2013)096014, PLB 798(2019)135022, JHEP 04(2020)119]

Which channel?

- We first looked at $B^+ \to J/\psi\phi K^+$ in winter of 2019, as a control channel to study Cabibbo-suppressed $B^+ \to J/\psi\overline{K}^{*0}K^+$ motived by Z_{cs} search.
- Instead, the control channel showed a possible $J/\psi K^+$ structure in Dalitz plot
- But at that time:
  - No exotic state with strangeness observed
  - The structure is not super narrow, amplitude analysis required
- We then prepared simulation sample, read the Run-1 amplitude analysis note, searched theoretical predictions about exotic states containing strange quark, tried to find other channels to confirm it …



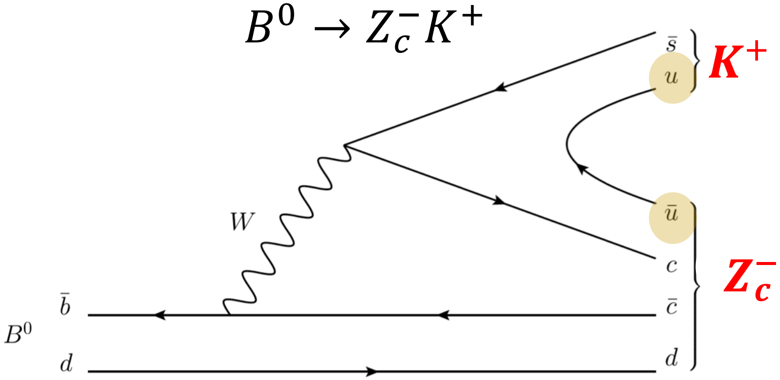
Which channel?

- Known topology to generate exotics in B-hadron decays
  - Spectator quark in in b-hardon contributes to the exotic valence quarks.

Known exotics	Observation channel
$\boldsymbol{Z_c^- \to J/\psi\pi^-}$	$B^0 \to J/\psi K^+\pi^-$
$P_c^+ \to J/\psi p$	$\Lambda_b^0 \to J/\psi p K^-$
$X_{0,1}(2900) \to D^- K^+$	$B^+ \to D^+ D^- K^+$

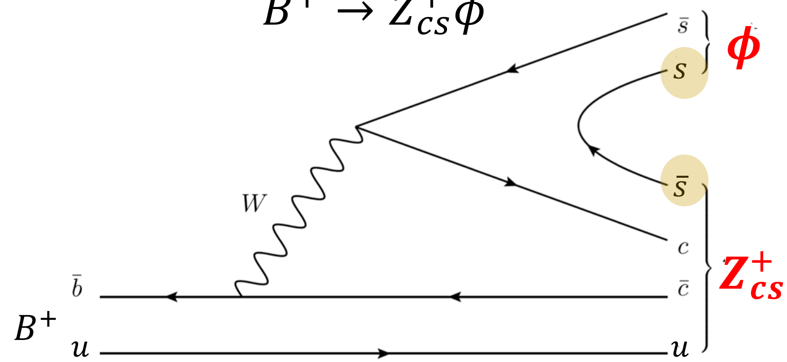
Similar Topology for Z_{cs}^+ in

$B^0 \to Z_c^- K^+$



[PLB 798 (2019) 135022]

$B^+ \to Z_{cs}^+ \phi$



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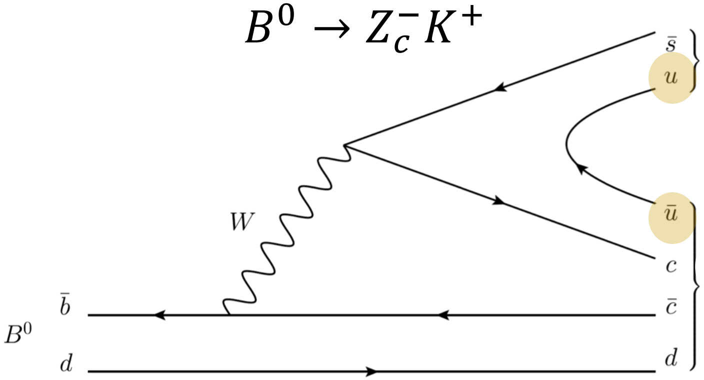
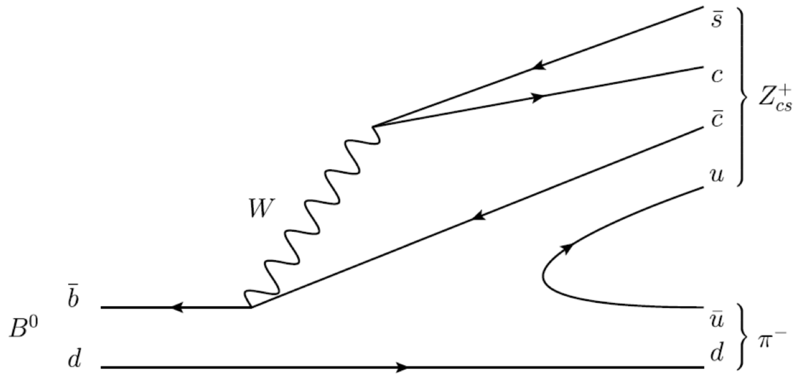
$X_{0,1}(2900) \to D^-K^+$	$B^+ \to D^+D^-K^+$

$B^0 \to Z_c^- K^+$



[PLB 798 (2019) 135022]

No evidence found in this topology

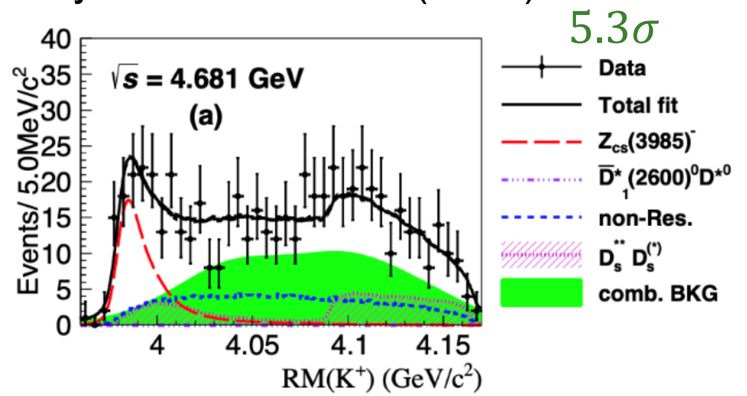


BESIII observation

- BESIII recently observed a **narrow** $Z_{cs}(3985)^-$ in $D_s^- D^* + D D_s^{*-}$ mass

Phys. Rev. Lett. 126 (2021) 102001

5.3σ



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

- Theory interpretations
  - Molecular partner of $Z_c(3900)^-$ from $D_s^- D^{*0} + D_s^{*-} D^0 +$ others exchanging $\eta/\sigma/f_0$, $2K$, $c\bar{c}$
  - Diquark-antidiquark compact type
  - Kinematic reflection
- Some theorists points out 1^{++} and 1^{+-} may both exist in both Molecular and compact pictures [2011.10495,2011.10959,2012.11869]

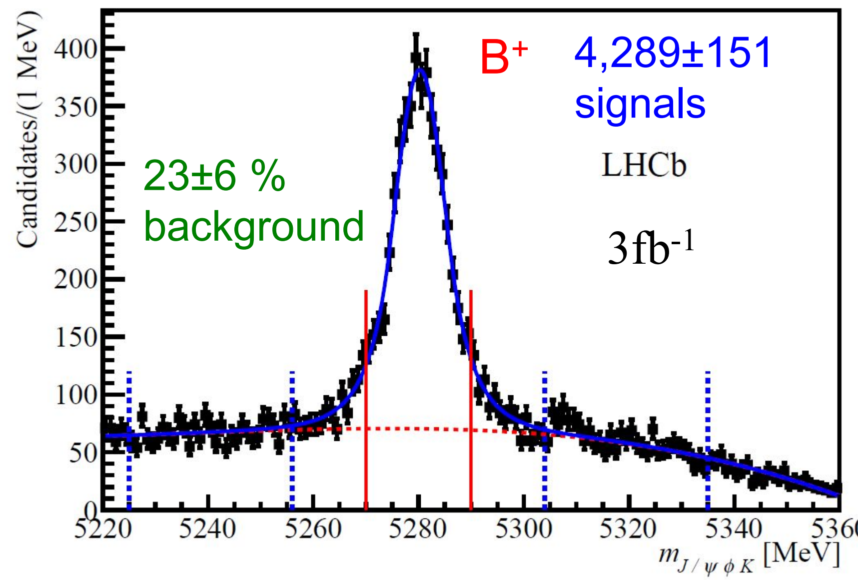
System	Current	J^P	m_H(GeV)
$\bar{D}_s D$	J_1	0^+	3.74 ± 0.13
$\bar{D}_s^* D^*$	J_2	0^+	4.11 ± 0.14
$\bar{D}_s^* D$	$J_{1\mu}$	1^+	3.99 ± 0.12
$\bar{D}_s D^*$	$J_{2\mu}$	1^+	3.97 ± 0.11
$\bar{D}_s^* D^*$	$J_{3\mu}$	1^+	4.22 ± 0.14
$\bar{D}_s^* D^*$	$J_{4\mu}$	1^+	4.22 ± 0.14
$\bar{D}_s^* D^*$	$J_{\mu\nu}$	2^+	4.34 ± 0.13
$\mathbf{0}_{[sc]} \oplus \mathbf{0}_{[\bar{q}\bar{c}]}$ (spin-spin)	η_1	0^+	3.84 ± 0.15
$\mathbf{1}_{[sc]} \oplus \mathbf{1}_{[\bar{q}\bar{c}]}$	η_2	0^+	4.13 ± 0.17
$\mathbf{1}_{[sc]} \oplus \mathbf{0}_{[\bar{q}\bar{c}]}$	$\eta_{1\mu}$	1^+	3.98 ± 0.16
$\mathbf{0}_{[sc]} \oplus \mathbf{1}_{[\bar{q}\bar{c}]}$	$\eta_{2\mu}$	1^+	3.97 ± 0.15
$\mathbf{1}_{[sc]} \oplus \mathbf{1}_{[\bar{q}\bar{c}]}$	$\eta_{3\mu}$	1^+	4.28 ± 0.14
$\mathbf{1}_{[sc]} \oplus \mathbf{1}_{[\bar{q}\bar{c}]}$	$\eta_{4\mu}$	1^+	4.28 ± 0.14
$\mathbf{1}_{[sc]} \oplus \mathbf{1}_{[\bar{q}\bar{c}]}$	$\eta_{\mu\nu}$	2^+	4.33 ± 0.13

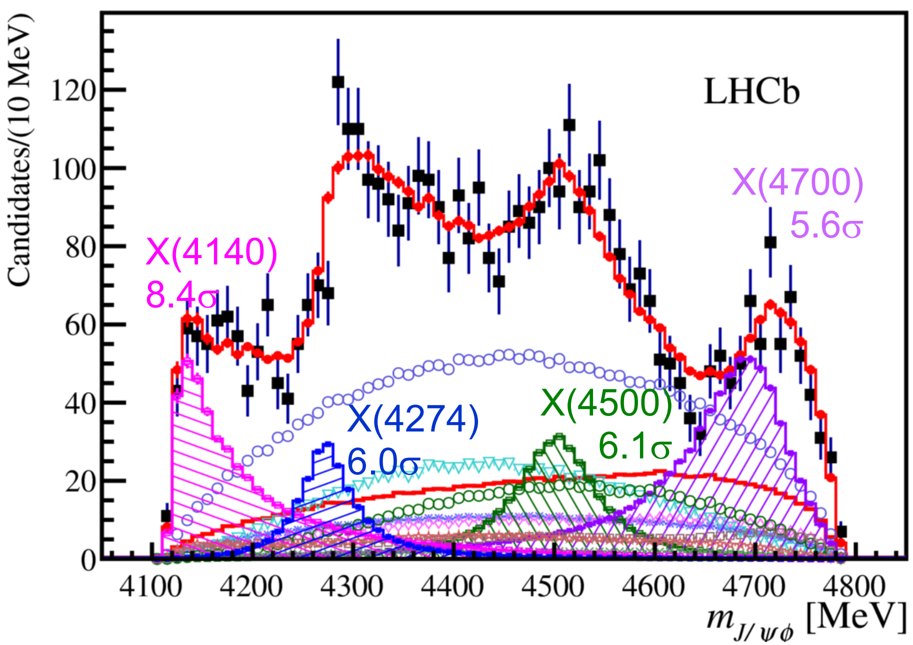
[2011.10495]

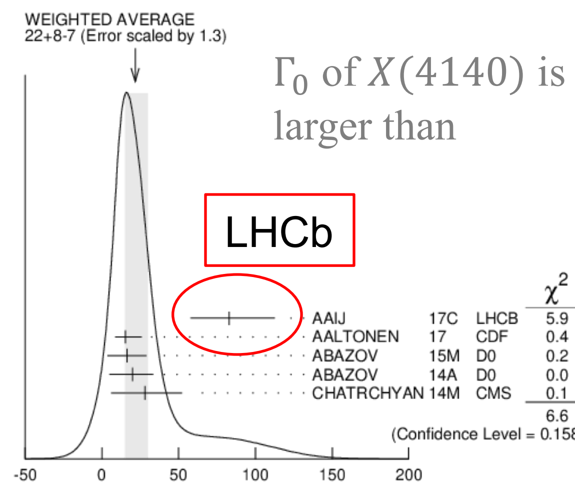
Observation of four X

- With Run-1 $B^+ \to J/\psi\phi K^+$ data, LHCb performed 1st amplitude fit with 4300 signals
- Observed $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$

[PRL118(2017)022003]

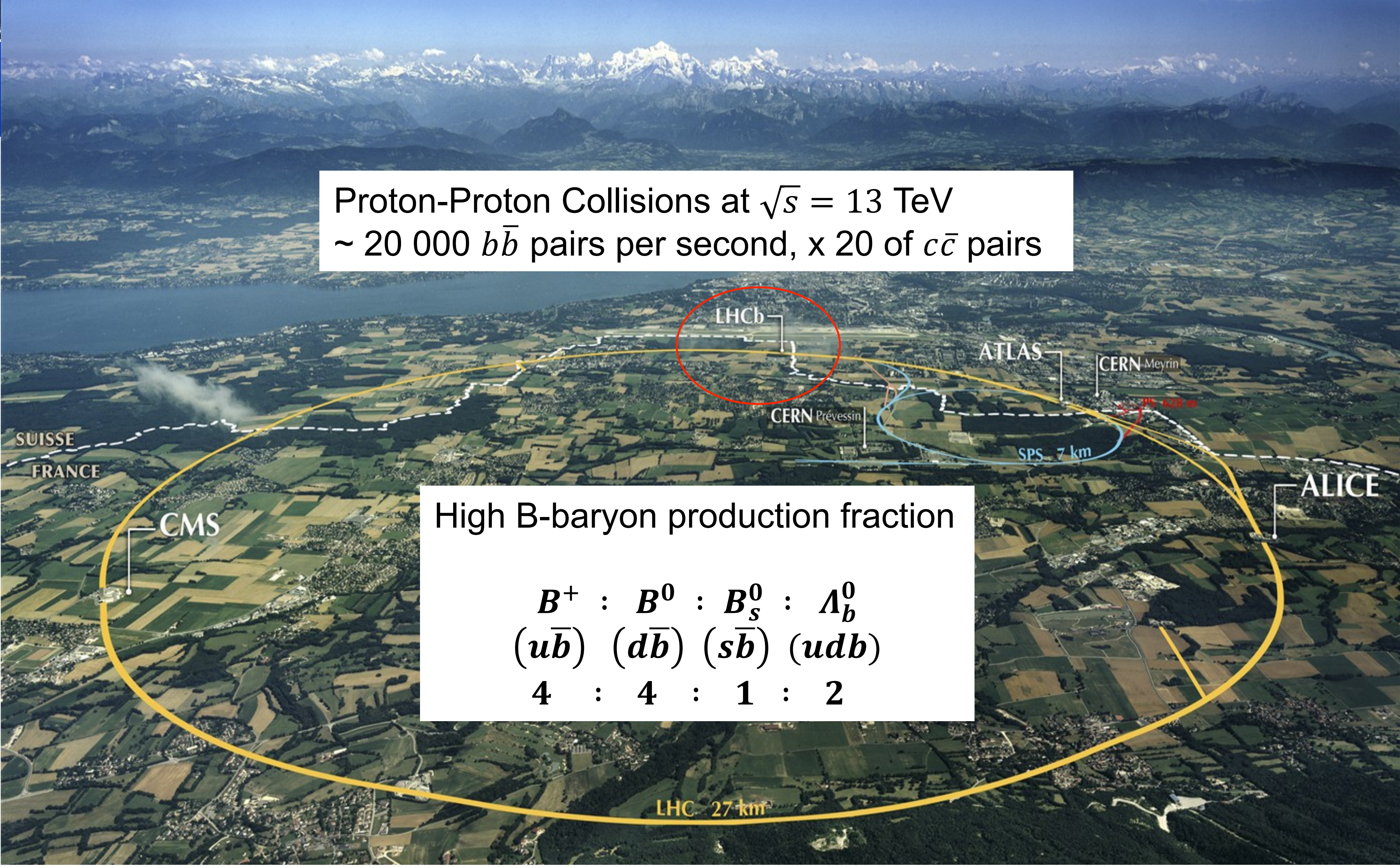






Γ_0 of $X(4140)$ is substantially larger than

The LHC as a Beauty and Charm factory



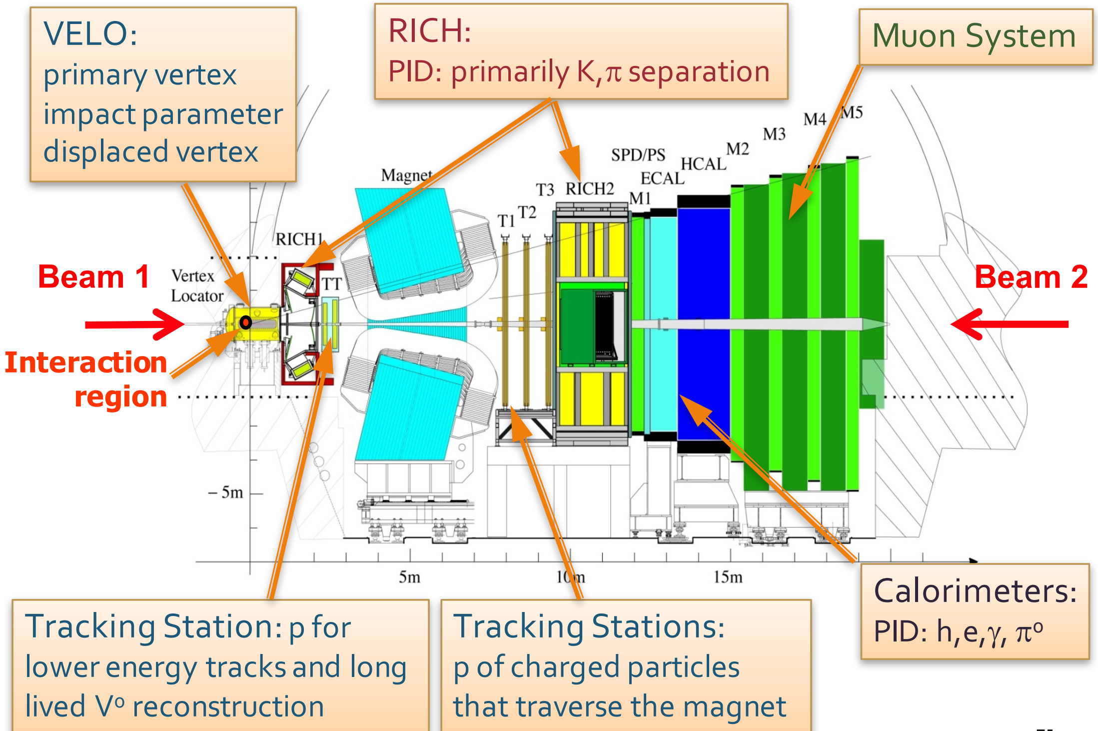
Proton-Proton Collisions at $\sqrt{s} = 13$ TeV
~ 20 000 $b\bar{b}$ pairs per second, x 20 of $c\bar{c}$ pairs

High B-baryon production fraction

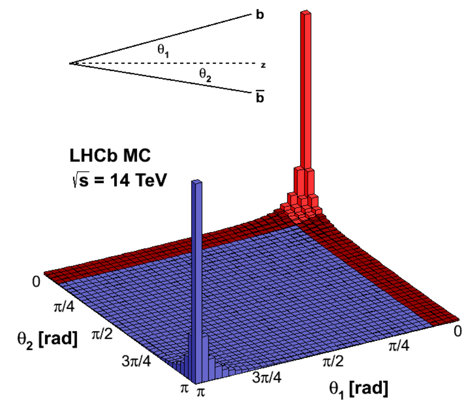
$$\begin{array}{ccccccc} B^+ & : & B^0 & : & B_s^0 & : & \Lambda_b^0 \\ (u\bar{b}) & & (d\bar{b}) & & (s\bar{b}) & & (udb) \\ 4 & : & 4 & : & 1 & : & 2 \end{array}$$

LHCb detector and performance

JINST 3 (2008) S08005



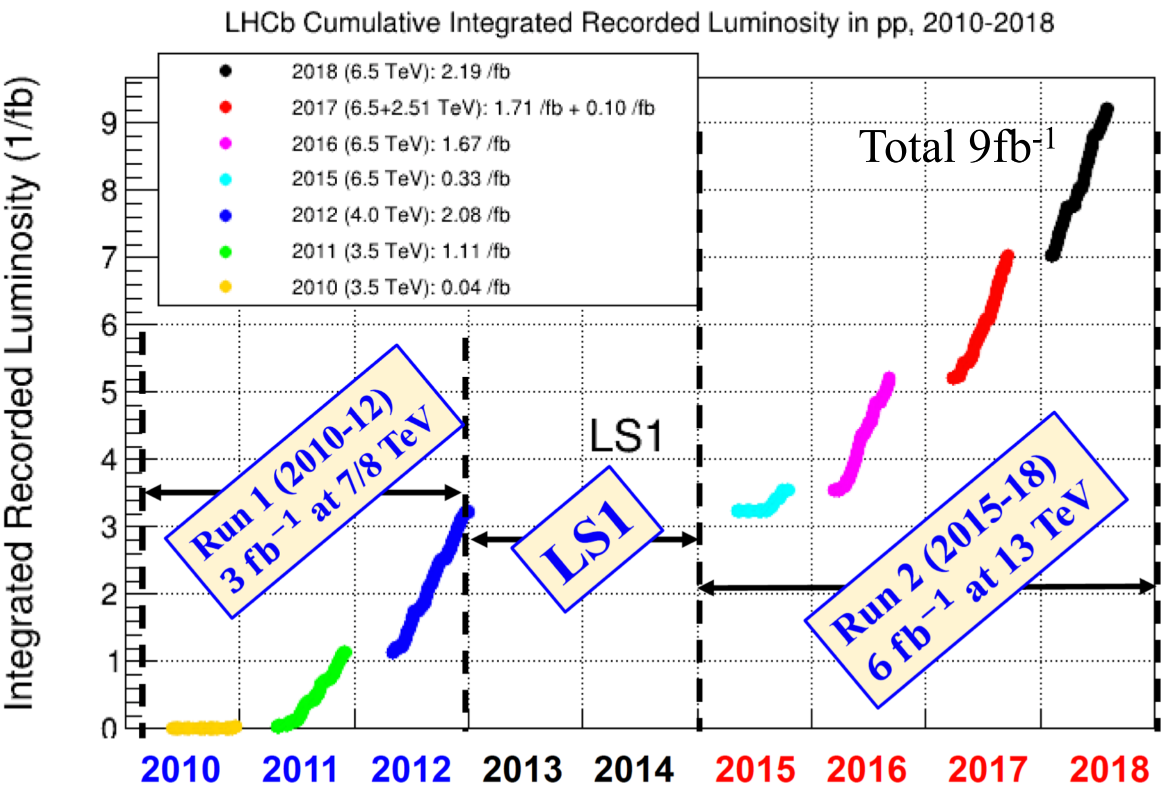
- $2 < \eta < 5$ range: $\sim 25\%$ of $b\bar{b}$ pairs inside LHCb acceptance



[Int. J. Mod. Phys. A 30 (2015) 1530022]

Impact parameter:	$\sigma_{IP} = 20\ \mu\text{m}$
Proper 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 $m_{J/\psi}$)
RICH $K - \pi$ separation:	$\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$
Muon ID:	$\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1 - 3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})}$

LHCb collected luminosity



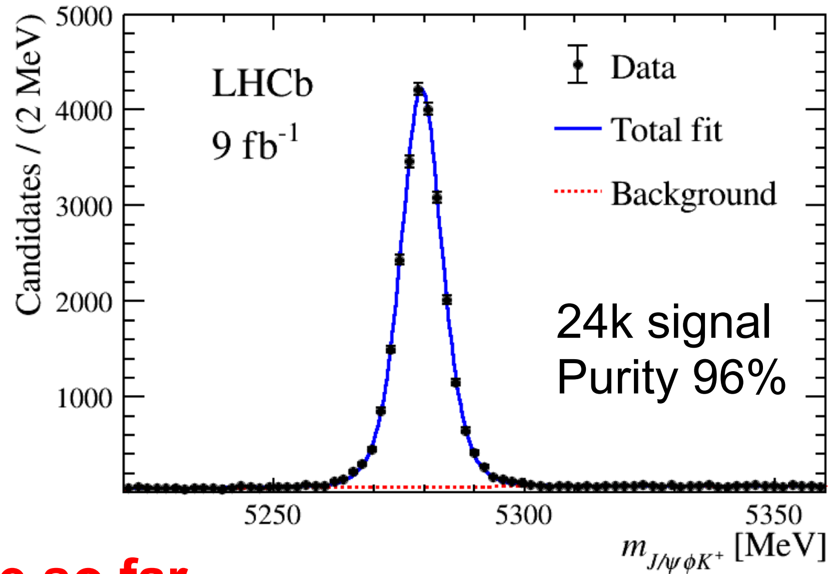
Signal: Run2 = 4× Run1

We add Run2 data and improved selection for this analysis

B mass fit and background

[arXiv:2103.01803]

- We have improved selection w.r.t. old publication
  - **PID used in MVA**
  - **Efficiency increases by 15%, background reduces by factor 6**
  - **Signal yield 6×**

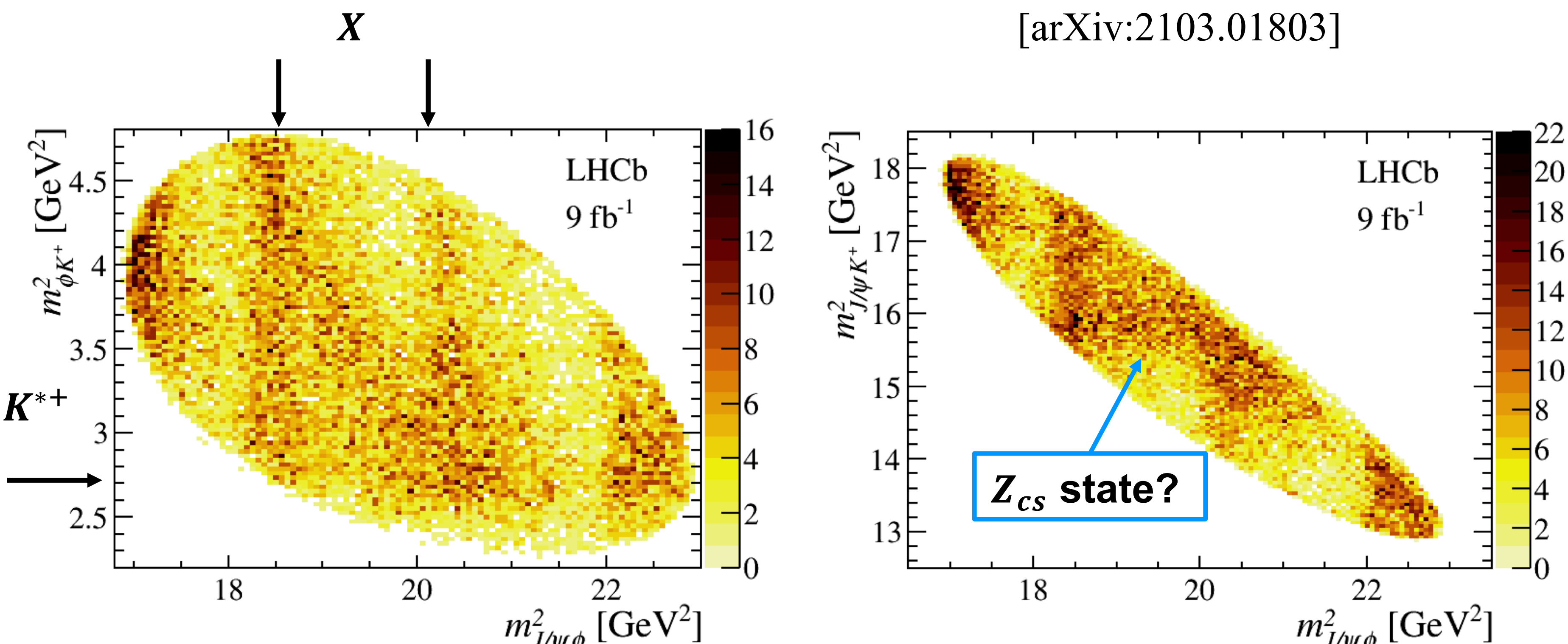


The largest $B^+ \to J/\psi\phi K^+$ sample so far

- In the $B^\pm$ signal, about 2% are non-ϕ $B^\pm \to J/\psi K^+K^-K^\pm$
  - They are neglected in the amplitude model but considered in the evaluation of the systematic uncertainties.

Dalitz plots of $B^+ \to J/\psi \phi K^+$

- In ± 15 MeV signal mass window
- Clearly visible: 4 structures in $J/\psi\phi$ mass and an obvious $J/\psi K^+$ band
- No clear $K^{*+} \to K^+\phi$ peaks because K^{*+} resonances are broad?



6D amplitude fit

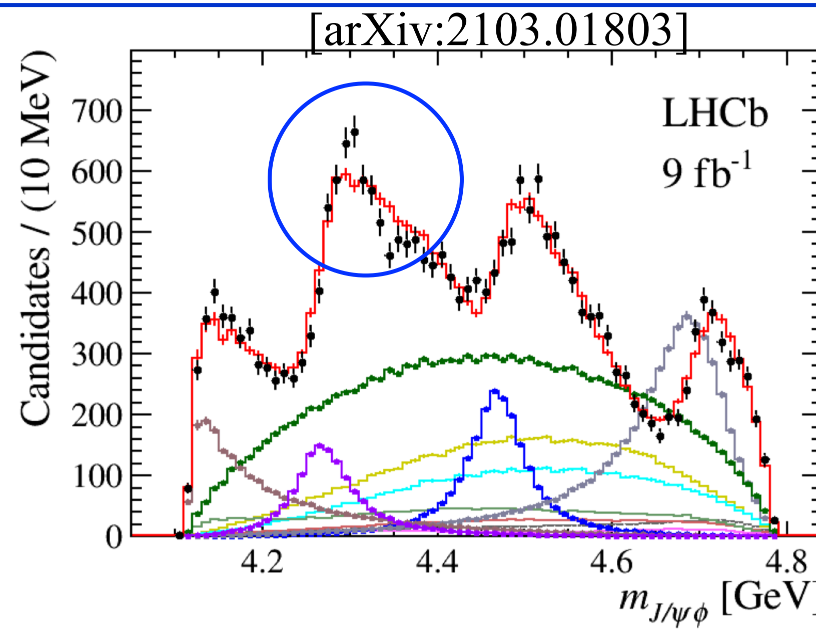
[PRD95(2017)012002]

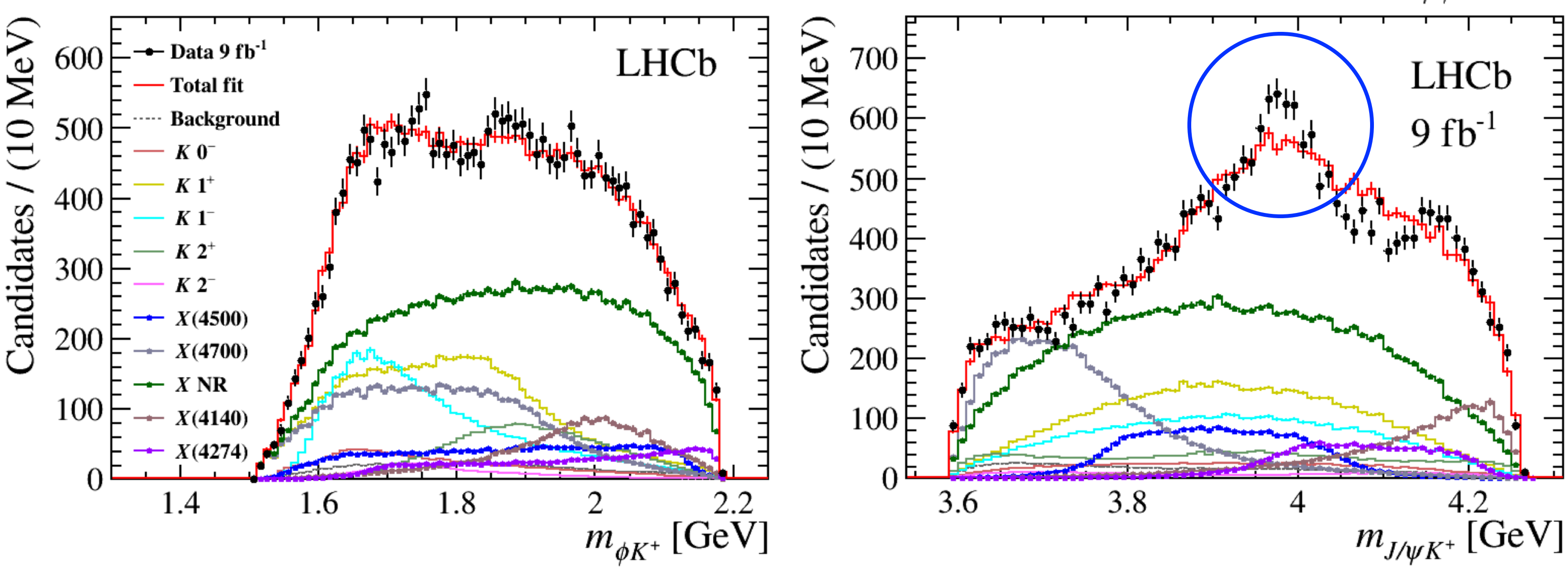
- Candidates in the signal region are used in the fit
- Helicity formalism for full amplitude construction
- Three decay chains, K^{*+}, X and Z_{cs}^{+}
- Each decay chain is described by 6 observables
  - Resonant mass, and 5 angles to better determine J^P
- Resonant lineshape: Breit-Wigner; simplified K-matrix or Flatté function for systematic studies
- PDF includes signal and background components

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

Start from run 1 model

- Run 1 model cannot fit well the data, due to increase of statistics
- Selection of resonance model is required





$K^{*+} \to \phi K^+$ model

9 $K(n^{2S+1}L_J)$ excitations

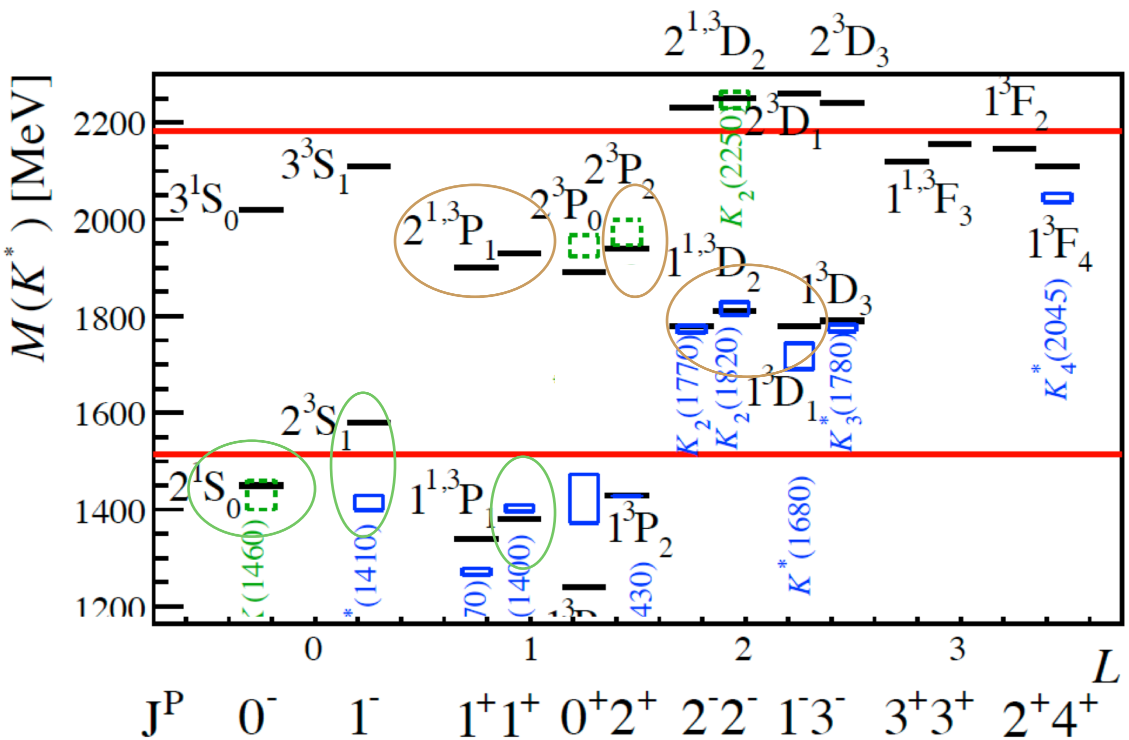
	All $K(1^+)$
2^1P_1	$K(1^+)$
2^3P_1	$K'(1^+)$
1^3P_1	$K_1(1400)$
	All $K(2^-)$
1^1D_2	$K_2(1770)$
1^3D_2	$K_2(1820)$
	All $K(1^-)$
1^3D_1	$K^*(1680)$
2^3S_1	$K^*(1410)$
	$K(2^+)$
2^3P_2	$K_2^*(1980)$
	$K(0^-)$
2^1S_0	$K(1460)$

Replace NR (for $K_1(1400)$)

Replace 3^3S_1 (for $K^*(1410)$)

0^+ cannot decay to ϕK^+

- Based on Godfrey-Isgur model
- Compared to run-1 model
  - Add three below threshold resonances to replace two components
  - Other high mass states are not significant, used as systematic study (Extended model)



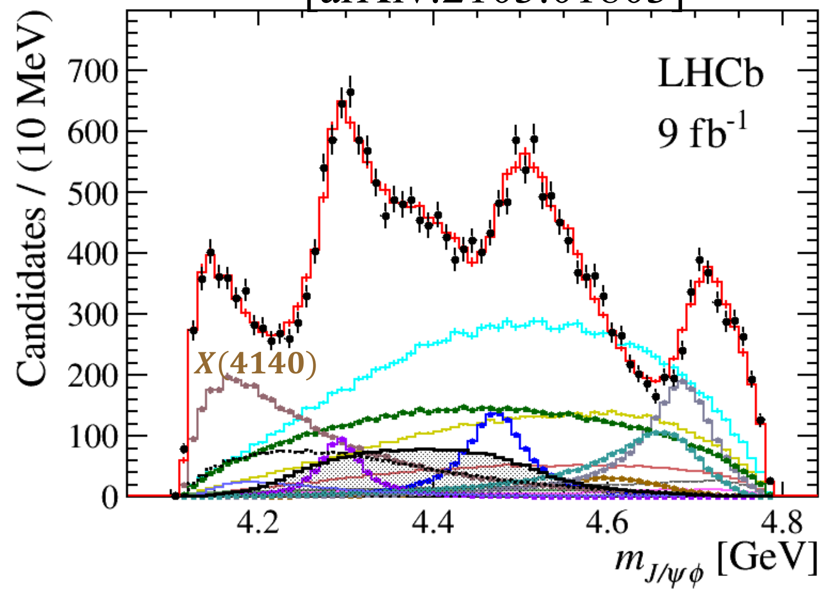
Test new exotics

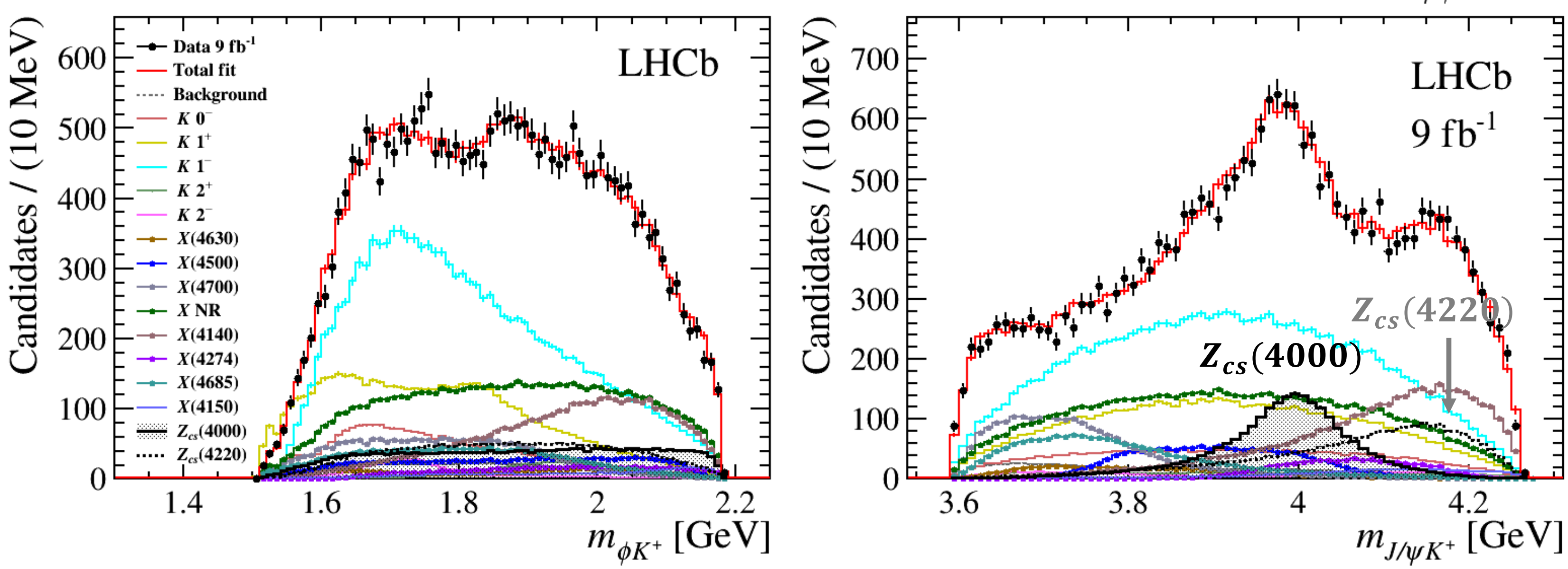
- The K* model still cannot well describe the data
- Test new exotic states (X and Z_{cs}^{+}) of different J^P
  - 1^+ Z_{cs} and 1^+ X, giving the largest improvements, were first included.
  - In 2nd iteration, several states giving large fit improvements were included in the default model: a second Z_{cs} (either 1^+or 1^-), 1^- and 2^- X states.
- The default model includes $9\,K^* + 7\,X + 1\,X(NR) + 2\,Z_{cs}$

Default model fit

- Data is well described by the model

[arXiv:2103.01803]





Fit results

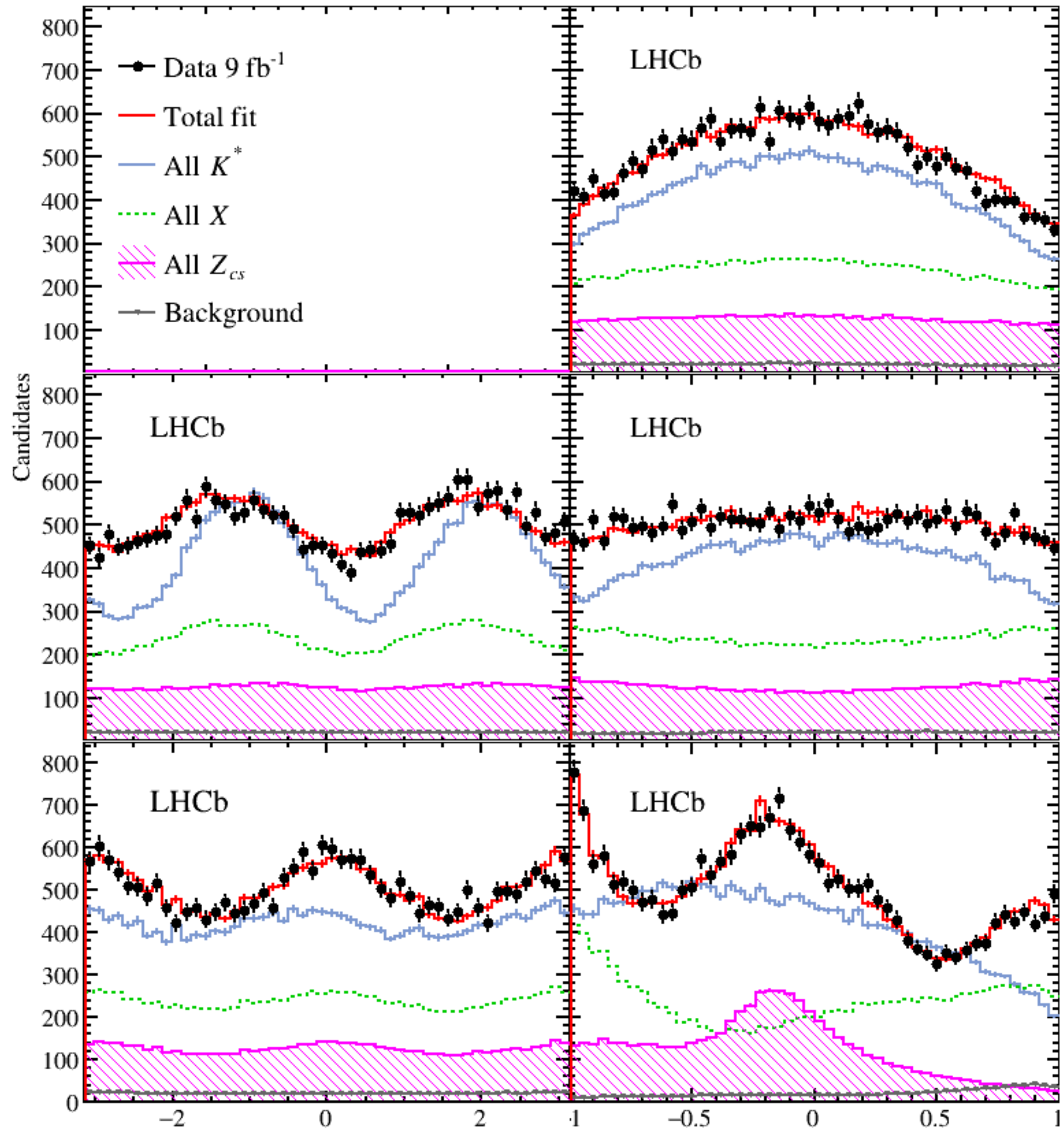
- New states: $Z_{cs}(4000)$, $X(4685)$ > 15σ [arXiv:2103.01803]
  $Z_{cs}(4220)$, $X(4630)$ > 5σ
  $X(4150)$ < 5σ

Fit fraction

Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$	Syst. included(Stat.)			
$X(4150)$	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)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-7}$

Angular projections

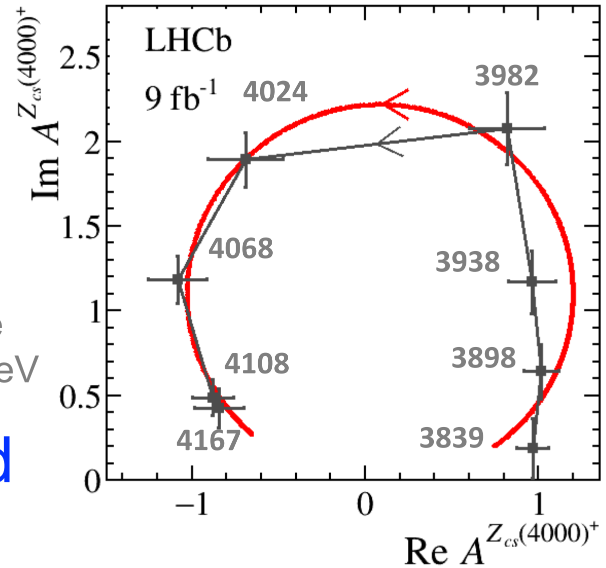
Angles in $K^* \to \phi K$ decay chain are described well by the fit



$Z_{cs}(4000)^+$

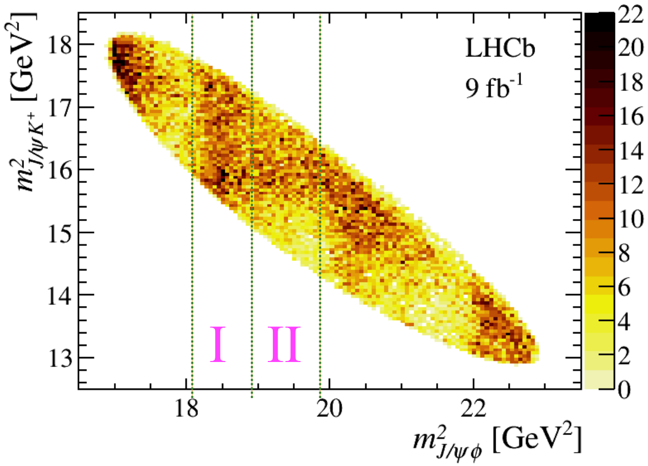
[arXiv:2103.01803]

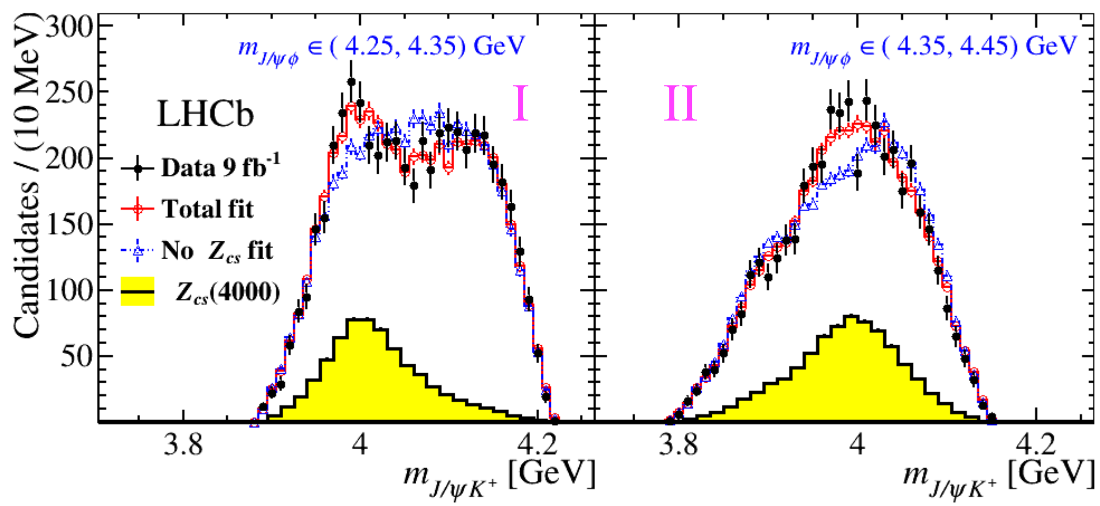
- Argand diagram gives further evidence of resonant character
  - Magnitude and phase evolved in the counter-clockwise direction



numbers are $m_{J/\psi K^+}$ in MeV

- $Z_{cs}(4000)^+$ can be clearly viewed in the two slices of $m_{J/\psi\phi}$

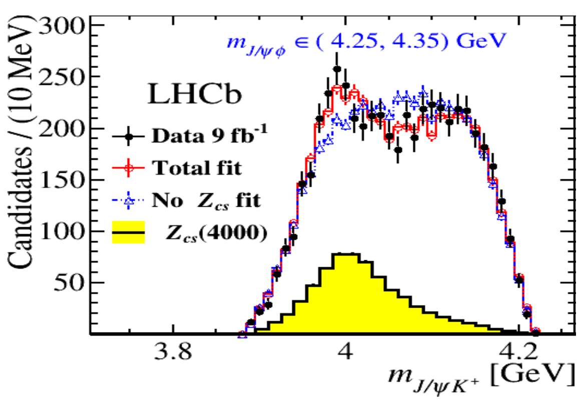


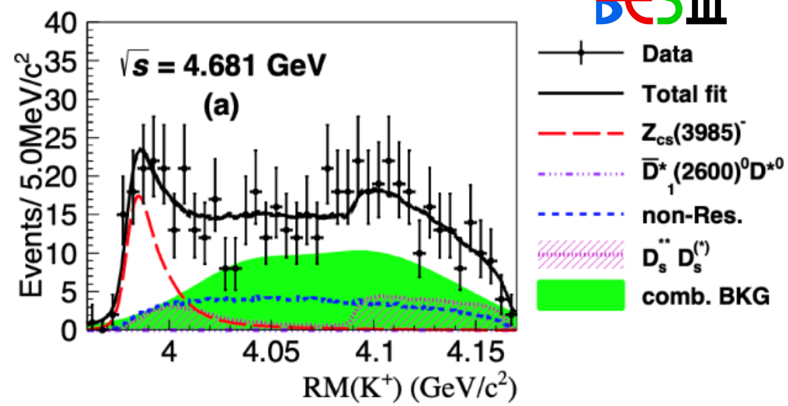


Comparison with BESIII

Phys. Rev. Lett. 126 (2021) 102001

- BESIII experiment recently reported 5.3σ observation of a very narrow Z_{cs}^{-} in $D_s^{-}D^{*} + DD_s^{*-}$ mass distributions
- Their masses are close, but $Z_{cs}(4000)^{+}$ is $\sim 10\times$ broader
- No evidence $Z_{cs}(4000)^{+}$ is the same as $Z_{cs}(3985)^{-}$ seen by BESIII
  - Fix $Z_{cs}(4000)^{+}$ 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





$m(Z_{cs}(4000)^{+}) = (4003 \pm 6^{+\ 4}_{-14})$ MeV
$\Gamma(Z_{cs}(4000)^{+}) = (131 \pm 15 \pm 26)$ MeV

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

J^P analysis

- Rejection significance: $\sigma \sim \sqrt{\Delta(-2\ln L)}$, using $2\ln L$ difference between preferred and alternative hypothesis.
  - Previous observed four X J^P are confirmed
  - $Z_{cs}(4000)$ and $X(4685)$ are 1^+ >15σ
  - $X(4630)$ prefers 1^{-+} [exotic quantum number] over 2^{-+} by 3σ
  - $Z_{cs}(4220)$ can be 1^+ or 1^-

Systematic uncertainty included

J^P	0^+	0^-	1^+	1^-	2^+	2^-
$\boldsymbol{X(4630)}$	6.7σ	5.3σ	5.8σ	prefer	5.9σ	**3.0σ**
$X(4500)$	prefer	18σ	18σ	18σ	18σ	18σ
$X(4700)$	prefer	18σ	18σ	18σ	14σ	17σ
$X(4140)$	14σ	15σ	prefer	14σ	13σ	14σ
$X(4274)$	18σ	18σ	prefer	18σ	18σ	18σ
$\boldsymbol{X(4685)}$	16σ	16σ	prefer	15σ	16σ	15σ
$\boldsymbol{Z_{cs}(4000)}$	-	17σ	prefer	17σ	15σ	16σ
$\boldsymbol{Z_{cs}(4220)}$	-	8.6σ	prefer	**2.4σ**	4.9σ	5.7σ

J^{PC} of X states

- For $X \to J/\psi\phi$, S-wave decays: $J^{PC} = (0,1,2)^{++}$, P-wave decays $J^{PC} = (0,1,2,3)^{-+}$
- We expect S-wave dominates and this is the case.
- We are confident that our J^{PC} determination is right
  - We have randomly assigned J^{P} for X states, and found the default results give the best fit
  - We can easily distinguish e.g. 0^{++} vs 1^{++} using the correlation between two decay angles of $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$

0++ only has the following two terms, 1++ contains more terms

$\lvert H_0\rvert^2$	$\sin^2\theta_\ell \cos^2\theta_h$
$\lvert H_+\rvert^2 + \lvert H_-\rvert^2$	$\frac{1}{4}(1+\cos^2\theta_\ell)\sin^2\theta_h$

Systematic sources

- Many sources (see backup) are considered

- Here only discuss several important ones for modelling
  - Extended model including 5 more K*
  - 1^+ vs 1^- $Z_{cs}(4220)$
  - Additional X states with different J^P in the extended model, **no further *X* contribution >5σ**
  - NR shape, and additional 1^+ or 2^+ NR *X* contributions
  - Flatté function to parameterize $X(4140)$ or $Z_{cs}(4000)$ to replace BW function
  - Neglected no-ϕ contribution: 1) Change the ϕ mass window from $\pm$ 15MeV to $\pm$7MeV, 2) sFit to subtract no-ϕ contribution is performed as alternative to cFit
  - Several K-Matrix models for K*

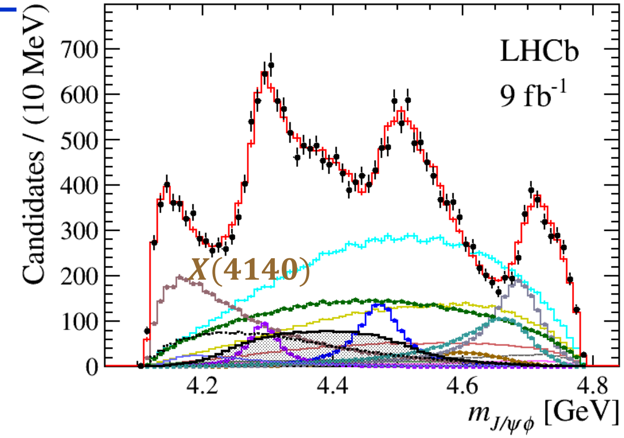
$X(4140)$

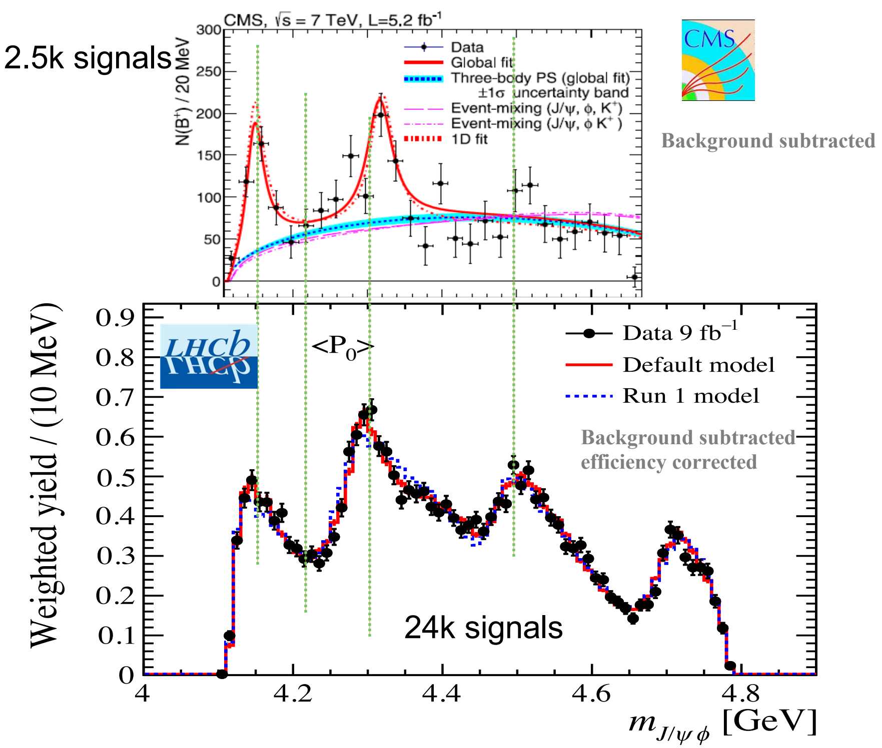
- $X(4140)$ $M = 4118 \pm 11^{+19}_{-36}$ **MeV**, $\Gamma = 162 \pm 21^{+24}_{-49}$ **MeV**
  No evidence of a narrow threshold resonance at $J/\psi\phi$ in our data

- CMS [PLB 734 (2014) 261]
  M=4148.0±2.4±6.3 MeV
  $\Gamma = 28^{+15}_{-11} \pm 19$ MeV

- LHCb's $X(4140)$ peak height is lower than CMS (efficiency enhanced at threshold?)

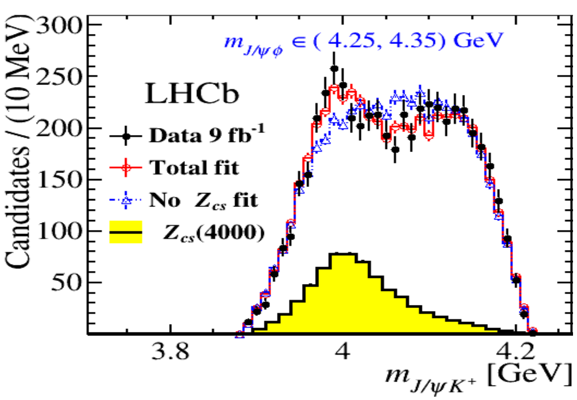
- Let's wait for CMS update their results with a (much) larger data sample, and more sophisticated analysis technique, than previously.

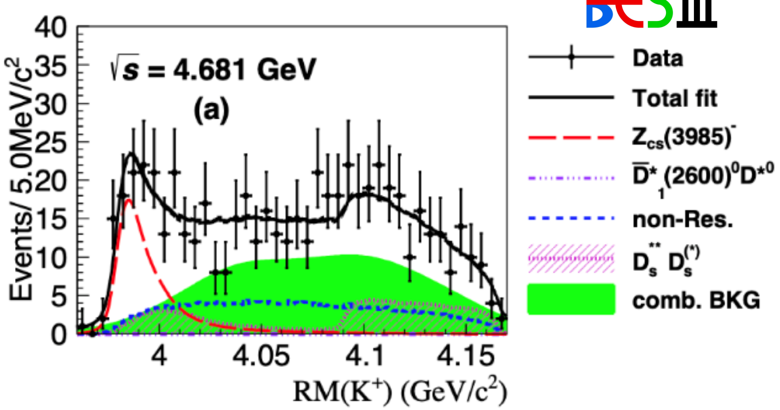




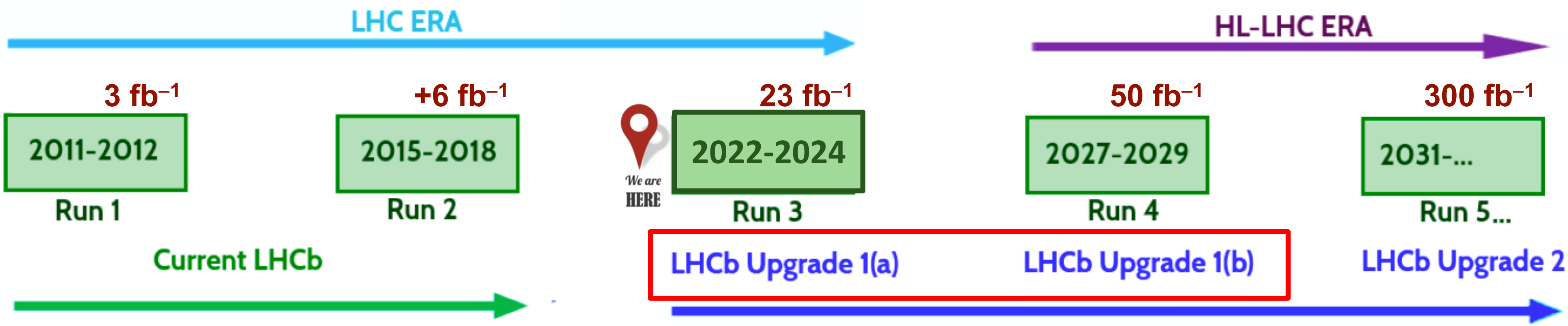
Summary

- 4 new $J/\psi K^+$ and $J/\psi\phi$ structures observed in $B^+ \to J/\psi\phi K^+$ decays with 6 times data and much clean environment
  - **Two $Z_{cs}^+ \to J/\psi K^+$ with new quark contents $c\bar{c}u\bar{s}$ are observed 1^+ $Z_{cs}(4000)^+$, significance $> 15\sigma$ and a broad $Z_{cs}(4220)^+ > 5\sigma$**
  - **A new 1^+ $X(4685)$ is $> 15\sigma$, and new $X(4630) > 5\sigma$**
  - **4 X states previously observed are confirmed, and J^{PC} determined with higher significances**
- Understanding of $Z_{cs}(4000)^+$ and $Z_{cs}(3985)^-$ may shed lights on molecular and compact tetraquarks





LHCb Upgrade I



CERN-LHCC-2011-001

Upgrade I: installation ongoing

- Almost a new detector for factor 5 luminosity increase
- Remove the hardware trigger ➞ all detector read out at 40 MHz
- Expect to have data of **23 fb^{-1}** by 2024 and of **50 fb^{-1}** by 2029

3x **7x** **Run1+2**

- Efficiency of pure hadronic final states will be **doubled**, good for studies of $(\eta_c, \chi_{c0})(K, \phi)$ and $D_{(s)}^{(*)}\bar{D}_{(s)}^{(*)}$ to search for various J^P exotics

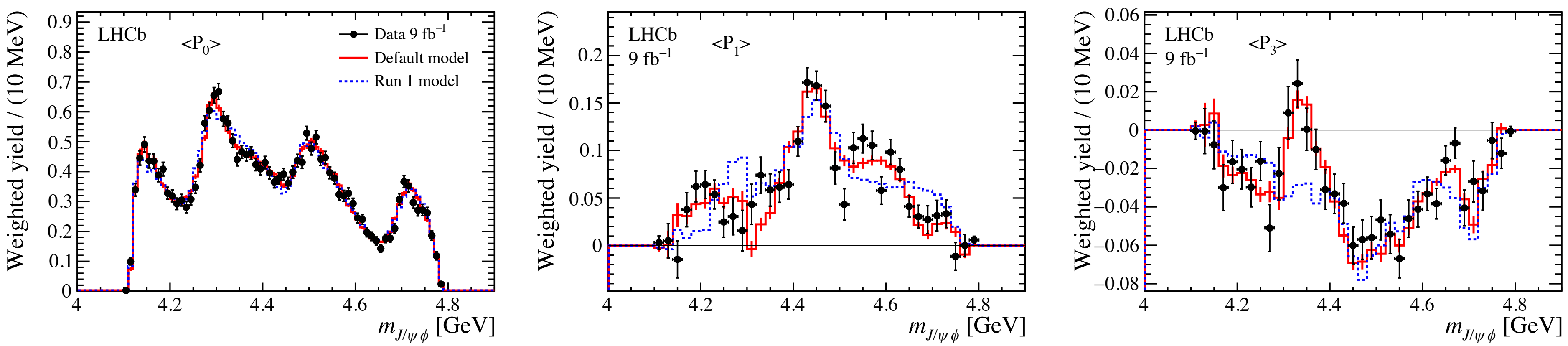
Thank you!

New X states are necessary

- Can improve angular distributions
- Comparing the Legendre angular moments of Run 1 model and updated model, new $X(4630)$ and $X(4685)$ are required

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

https://cds.cern.ch/record/2751229

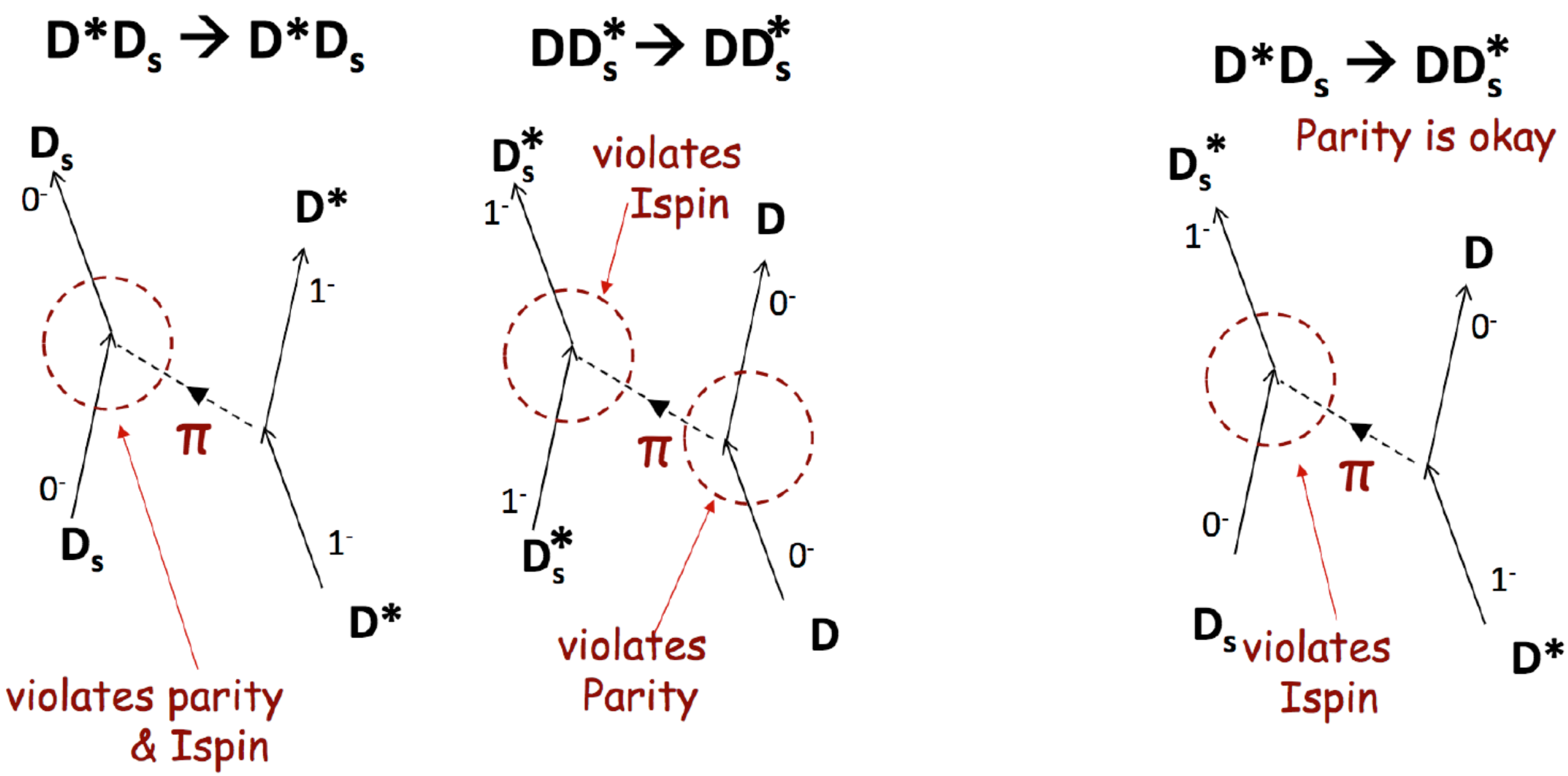


Background subtracted and efficiency corrected distribution

from Steve Olsen

If it's a molecule, what holds it together

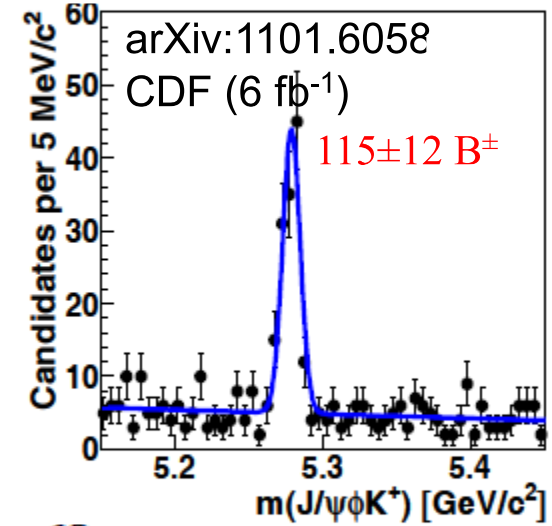
Yukawa force dominated by π-exchange ← not allowed for D_sD^*/D_s^*D

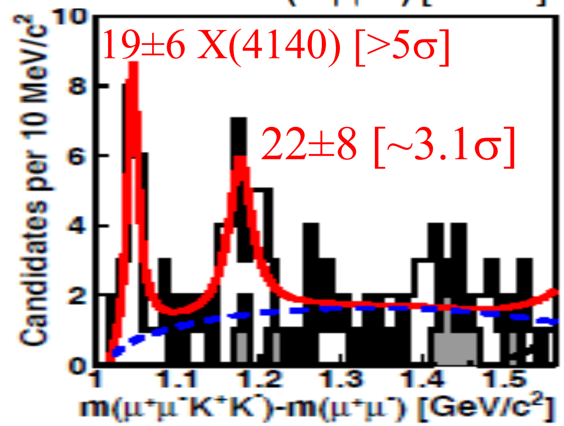


$X(4140)$ and $X(4274)$

- $B^+ \to J/\psi\phi K^+$ decays provide rich exotic spectra, initially used for study of $J/\psi\phi$ structures

- CDF observed a narrow $J/\psi\phi$ structure in [Initial publication on 2.7 fb^{-1} PRL102 (2009) 242002]
  - M=4143.4±3.0±0.6 MeV
  - Γ=$15.3^{+10.4}_{-6.1} \pm 2.5$ MeV
  - Necessarily exotic since it is narrow and above the DsDs threshold
  - $[cs\bar{c}\bar{s}]$ tetraquark ?
  - Hint of a second structure: $X(4274)$

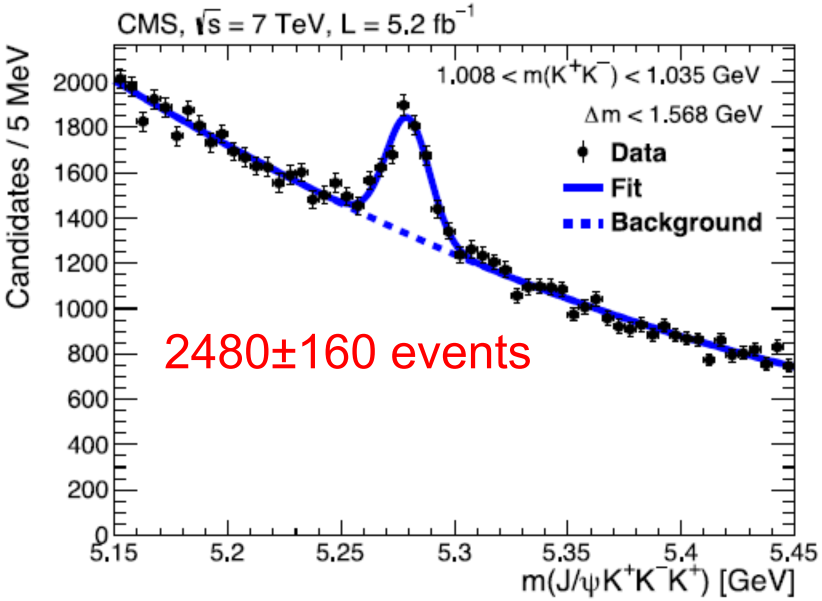


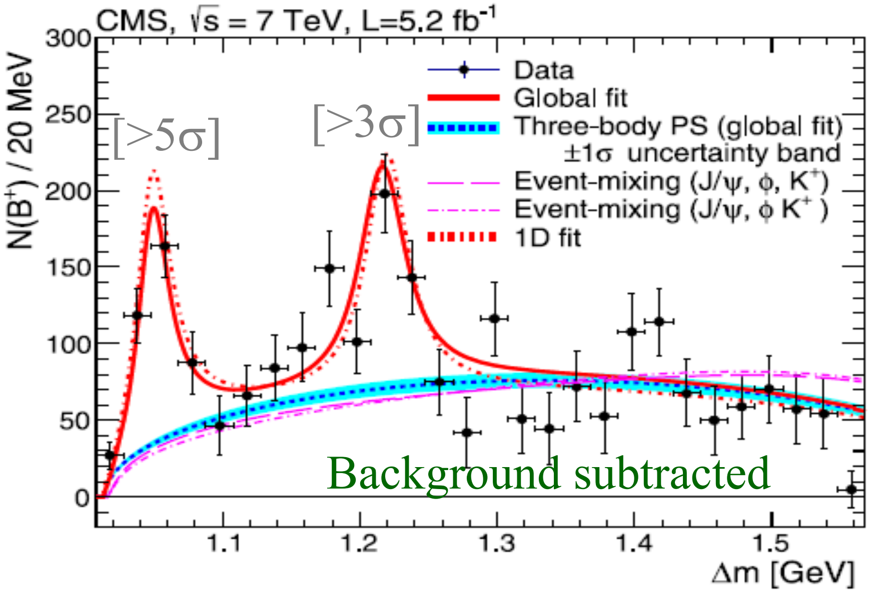


$X(4140)$ and $X(4274)$

- Confirmed by CMS with large statistics
- But the background is also large

[PLB 734 (2014) 261]





4148.0±2.4±6.3
$28^{+15}_{-11} \pm 19$

Expected yields in future

- We are now boosting our data to a new level
  - Expect to **7x** more data (**14x** more hadronic events) by 2029 than current data
  - Could have another factor of **6** increase from Upgrade II

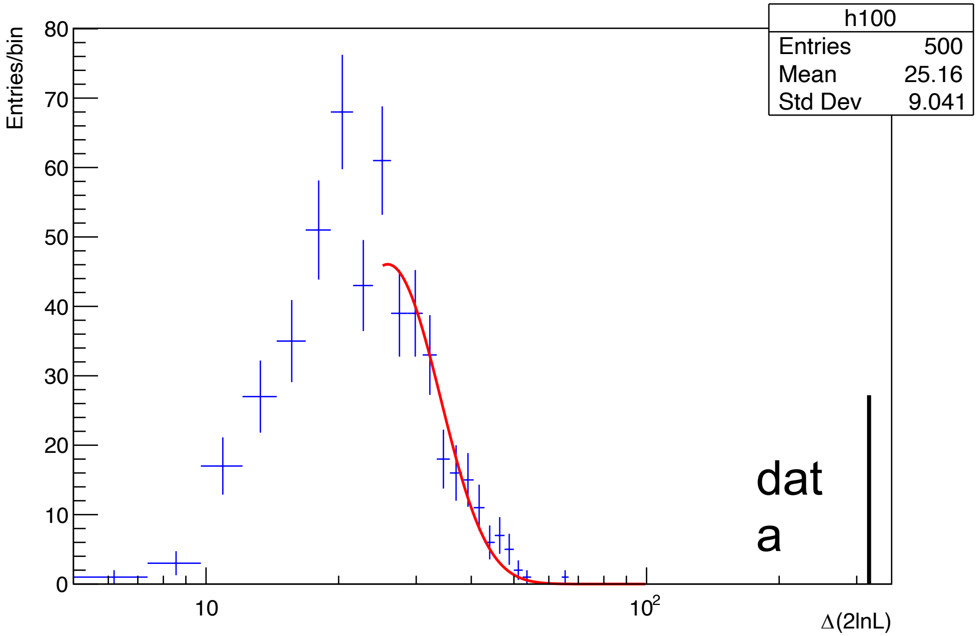
Decay mode	LHCb		
	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
$B^+ \to X(3872)(\to J/\psi\,\pi^+\pi^-)K^+$	14k	30k	180k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100
$\Lambda_b^0 \to J/\psi\, pK^-$ [*]	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

[*] updated according to the latest result

CERN-LHCC-2018-027
arXiv:1808.08865

Significance

- Use ndf = 2 x N of parameters for new resonance
- Verified by pseudo-experiments



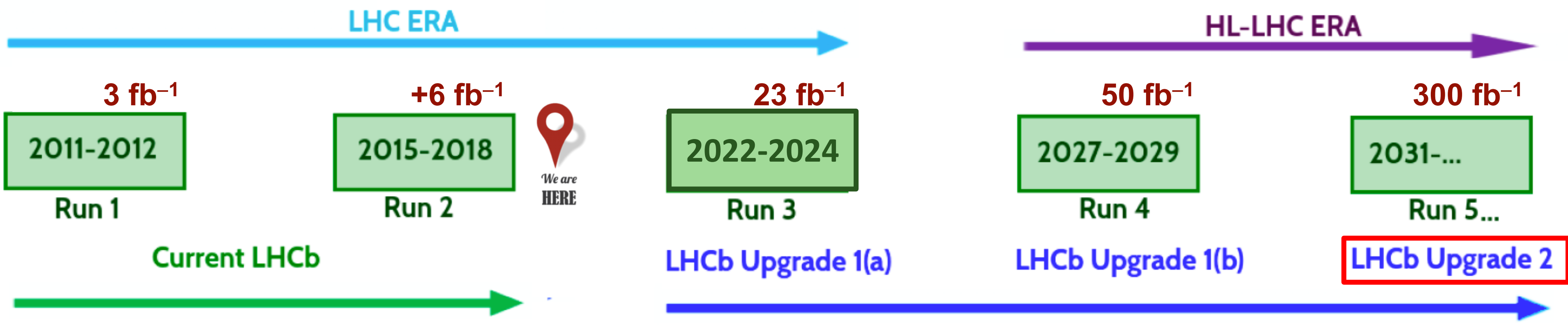
500 toy samples without $Z_{cs}(4000)$ are generated.
The significance obtained from the tail extrapolation to the data is 15.2σ, which is consistent with 15.7σ obtained from the empirical method using the χ^2 PDF with ndf equal to twice the number of additional free parameters

$$n_\sigma = \sqrt{2}\texttt{TMath::ErfcInverse}\left(f \cdot \frac{\texttt{TMath::Prob}(\Delta^{\rm data}_{2\ln\mathcal{L}}, \rm NDF)}{\texttt{TMath::Prob}(\Delta^{0}_{2\ln\mathcal{L}}, \rm NDF)}\right)$$

Run-1 results

	Contribution	Significance	M_0 [MeV]	Γ_0 [MeV]	FF%
	All K(1^+)	8.0σ			$42 \pm 8^{+5}_{-9}$
	$\mathrm{NR}_{\phi K}$				$16 \pm 13^{+35}_{-6}$
$2^1\mathrm{P}_1$	K(1^+)	7.6σ	$1793 \pm 59^{+153}_{-101}$	$365 \pm 157^{+138}_{-215}$	$12 \pm 10^{+17}_{-6}$
$2^3\mathrm{P}_1$	$K'(1^+)$	1.9σ	$1968 \pm 65^{+70}_{-172}$	$396 \pm 170^{+174}_{-178}$	$23 \pm 20^{+31}_{-29}$
	All K(2^-)	5.6σ			$11 \pm 3^{+2}_{-5}$
$1^1\mathrm{D}_2$	$K_2(1770)$	5.0σ	$1777 \pm 35^{+122}_{-77}$	$217 \pm 116^{+221}_{-154}$	
$1^3\mathrm{D}_2$	$K_2(1820)$	3.0σ	$1853 \pm 27^{+18}_{-35}$	$167 \pm 58^{+83}_{-72}$	
	$K(1^-)$				
$1^3\mathrm{D}_1$	$K^*(1680)$	8.5σ	$1722 \pm 20^{+33}_{-109}$	$354 \pm 75^{+140}_{-181}$	$6.7 \pm 1.9^{+3.2}_{-3.9}$
	$K(2^+)$				
$2^3\mathrm{P}_2$	$K_2^*(1980)$	5.4σ	$2073 \pm 94^{+245}_{-240}$	$678 \pm 311^{+1153}_{-559}$	$2.9 \pm 0.8^{+1.7}_{-0.7}$
	$K(0^-)$				
$3^1\mathrm{S}_0$	$K(1830)$	3.5σ	$1874 \pm 43^{+59}_{-115}$	$168 \pm 90^{+280}_{-104}$	$2.6 \pm 1.1^{+2.3}_{-1.8}$
	All $X(1^+)$				$16 \pm 3^{+6}_{-2}$
	$X(4140)$	8.4σ	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	$13.0 \pm 3.2^{+4.8}_{-2.0}$
	$X(4274)$	6.0σ	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	$7.1 \pm 2.5^{+3.5}_{-2.4}$
	All $X(0^+)$				$28 \pm 5 \pm 7$
	$\mathrm{NR}_{J/\psi\phi}$	6.4σ			$46 \pm 11^{11}_{-21}$
	$X(4500)$	6.1σ	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	$6.6 \pm 2.4^{+3.5}_{-2.3}$
	$X(4700)$	5.6σ	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	$12 \pm 5^{+9}_{-5}$

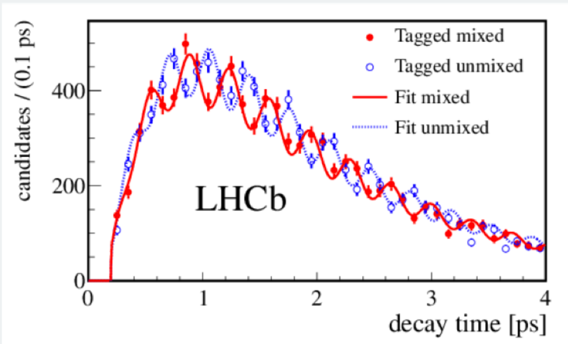
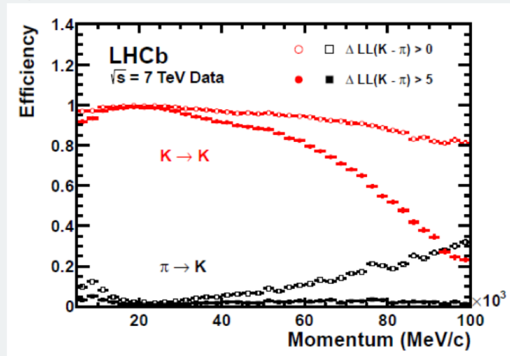
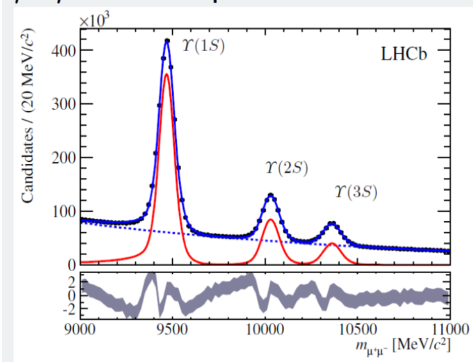
LHCb Upgrade II



Upgrade II: started to investigate

- Aim to collect > **300 fb^{-1}**
- Instantaneous $\mathcal{L}$ = 2 x10^{34} , x10 with respect to Upgrade I
- Expression of Interest issued in 2017 [CERN-LHCC-2017-003]
- Physics case document released [CERN-LHCC-2018-027]
- Green light from LHCC to proceed to TDRs (expected ~late 2020)

Detector performance

Vertexing	PID	Tracking
B_s^0 oscillations with $B_s^0 \to D_s \pi$	K/π ID efficiency and misID rate	$\mu^+\mu^-$ mass spectrum
		
[New J. Phys. 15 (2013) 053021]	[EPJ C73 (2013) 2431]	[PRL 111 (2013) 101805]

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

Systematic uncertainty

- To evaluate uncertainties due to the fixed masses and widths of known K^* resonances: free the masses and widths but impose Gaussian constraints to the PDG values.
- χ^2_{IP} of B^+ is not well modeled, smeared to match the data.
- To explore uncertainty in the background model, vary the B^+ sideband window.
- The uncertainty in the background fraction β: change background shape to exponential function.
- Vary the Blatt-Weisskopf barrier factor d (hadron-size parameter).
- Vary the smallest allowed orbital momentum in the resonance description function, associate the L dependent term with each LS coupling.

Orbital momentum

$$R_{K_n^*}(m_{K\phi}) = B'_{L_B^{K_n^*}}(p, p_0, d)\left(\frac{p}{M_B}\right)^{L_B^{K_n^*}} \mathrm{BW}(m_{K\phi}|M_0^{K_n^*}, \Gamma_0^{K_n^*})\, B'_{L_{K_n^*}}(q, q_0, d)\left(\frac{q}{M_0^{K_n^*}}\right)^{L_{K_n^*}}$$

Angular momentum barrier factor

Relative Breit-Wigner function

Systematic uncertainty

- Uncertainty due to the choice of NR component, change the constant parameterization to exponential function.
- 1^+ or 2^+ NR X contributions are optionally introduced.

- The difference between nominal model and extended model.
- Flatté function to parameterize $X(4140)$ or $Z_{cs}(4000)$ to replace BW function.

$$\mathrm{Flatte}_X(m|M_0\,,g_{J/\psi\phi}\,,g_{D_s^*D_s}) = \frac{1}{M_0^2 - m^2 - iM_0(g_{J/\psi\phi}\rho_{J/\psi\phi} + g_{D_s^*D_s}\rho_{D_s^*D_s})},$$

- Additional X states with different J^P in the extended model.
- Neglected no-ϕ contribution: 1)Change the ϕ mass window from $\pm$15MeV to $\pm$ 7MeV, 2) sFit to subtract no-ϕ contribution is performed as alternative to cFit

- Modification of K^* width: as the partial width to ϕK is unknown, try a fit with mass dependence of the width driven by the lowest allowed decay channel, which is $K\pi$ for the natural spin-parity and $K\omega$ for others.

Systematic uncertainty

- As an alternative to the 2D factorization of 6D background PDF, decompose the background density into multidimensional moments in the K^* decay chain variables (this uncertainty is small)
- K-Matrix model :

  1. Some K^* with the same J^P are overlapping, we use a simple K-Matrix formula to describe them as alternative

$$RKM_n(m|M_{0n},\Gamma_{0n}) = \frac{\frac{1}{M_{0n}^2-m^2}}{1-i(\sum_j \frac{M_{0j}\Gamma_{0j}(m)}{M_{0j}^2-m^2} + f_{sc}\cdot\rho(m))},$$

  denominator sums over the same J^P K^* resonances, f_{sc} accounts for possible non-resonance contribution. This fit didn't change the conclusion.

  2. Alternative K-Matrix model with two coupling channels are tested, used to describe the 2^1 P_1 and 2^3 P_1 K^* resonances

$$\mathcal{K}_{ba}(s) = \sum_R \frac{g_b^R g_a^R}{M_R^2 - s} + \sum_{i=0}^{N_{\mathrm{b.g.}}} b_{ba}^{(i)} s^i$$

  more floating parameters are included, the nominal model is stable.

Table 2: Summary of the systematic errors on the parameters of the $Z_{cs}(4000)^+$ and $X(4685)$ states. All numbers for masses and widths are in MeV and fit fractions in %.

Source	$Z(4000)$			$X(4685)$		
	M_0	Γ_0	FF	M_0	Γ_0	FF
Fixed M_0&Γ_0	−0.22	−3.60	−0.83	−0.14	2.72	0.25
$\chi^2_{\rm IP}$ smearing	0.21	1.01	0.09	−0.53	1.11	0.12
Right sideband	0.01	0.58	0.11	−0.13	1.07	−0.13
Left sideband	−0.30	−1.16	−0.24	−0.09	−2.21	0.09
$\beta = 0.043$	−0.06	−0.00	0.01	0.01	−0.70	−0.09
$\beta = 0.037$	−0.02	0.26	0.02	−0.33	0.21	0.03
L0 Trigger	0.45	0.58	0.19	−0.58	1.12	0.11
PID efficiency	−1.06	−1.82	−0.69	−0.82	−4.42	−0.26
MC size	2.39	9.93	1.54	3.02	7.00	0.65
ϕ window	−4.71	−23.91	−2.75	8.60	−26.60	−1.17
Non ϕ subtraction	−2.87	−18.39	−1.79	12.40	−39.80	−1.80
Poly NR	−4.24	−16.36	−2.56	4.26	−22.07	−1.28
X NR(1^+)	1.49	−21.25	−2.53	−15.72	35.54	3.84
X NR(2^+)	2.16	3.09	1.26	1.88	−6.87	−0.03
BW d=1.5	−0.29	−5.27	−0.58	0.29	1.55	2.14
BW d=4.5	0.08	1.81	0.04	0.06	−3.53	−1.06
L	2.75	−3.19	−1.18	2.45	−24.33	−1.48
$X(4140)$ Flatté	0.52	−2.80	−0.45	−3.77	15.14	1.37
Extended model	−2.35	−6.66	−1.16	−3.61	−6.53	−0.94
Additional X	−0.68	2.07	0.30	0.74	−3.11	−0.18
1^- Z	−14.00	−21.09	−3.46	−9.41	−5.60	−1.52
K^* BW	0.08	−0.66	−0.32	−0.06	−8.09	−0.82
K-Matrix	−3.75	−20.80	−2.85	4.10	−11.95	−0.06
$Z_{cs}(4000)$ Flatté	0.18		2.83	−0.85	2.79	0.18
Background model	0.10	−0.32	−0.12	−1.04	−1.72	−0.15
Total	(−14.26 , +3.85)	(−26.26, +26.26)	(−3.43, +3.41)	(−16.05, +12.82)	(−40.85, +36.72)	(−1.96, +3.92)

Thresholds vs LHCb run1 data

arXiv:2101.01021