Recent LHCb spectroscopy results

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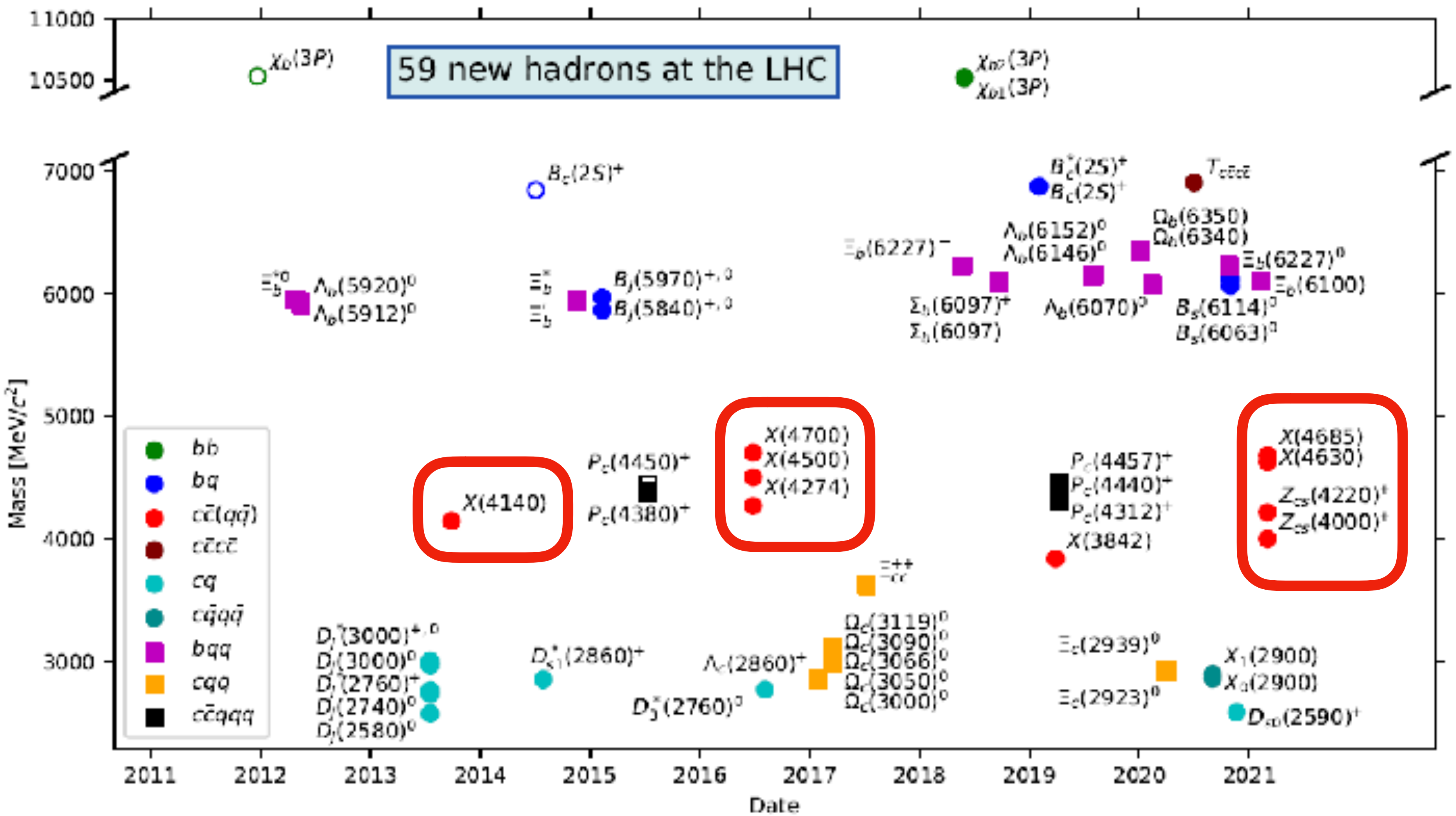
11.05.2021

Exotic charmonium-like states in beauty decays

- Plethora conventional and exotic charmonium states observed in b-decays
- Charmonium-like states, beyond the $q\bar{q}$ and qqq scheme
  - Multiquark states are predicted by Gell-Mann and Zweig in 1964
  - Theoretical explanation: molecules, hybrids, tetraquarks, etc
  - First observed state — X(3872) in 2003



$\chi_{c1}(3872)$ state

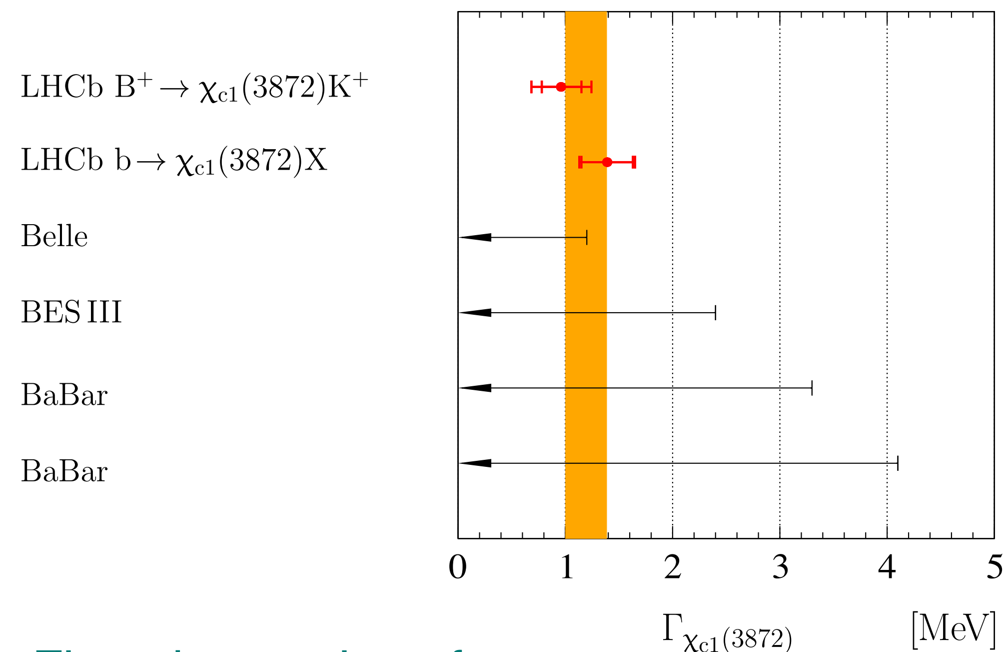
What've we already know:

- Narrow $\Gamma_{LHCb} \sim 1.13$ MeV (Breit - Wigner width)
- $m_{\chi_{c1}(3872)}$ close to $D^0\bar{D}^{*0}$ threshold ($3871.59 \pm 0.06 \pm 0.01$ MeV/c^2)
- $\delta E_{LHCb} = 0.07 \pm 0.12 MeV$
- $J^{PC} = 1^{++}$ (PDG 2019)

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

Signal: 4230 ± 70 events

JHEP 08 (2020) 123

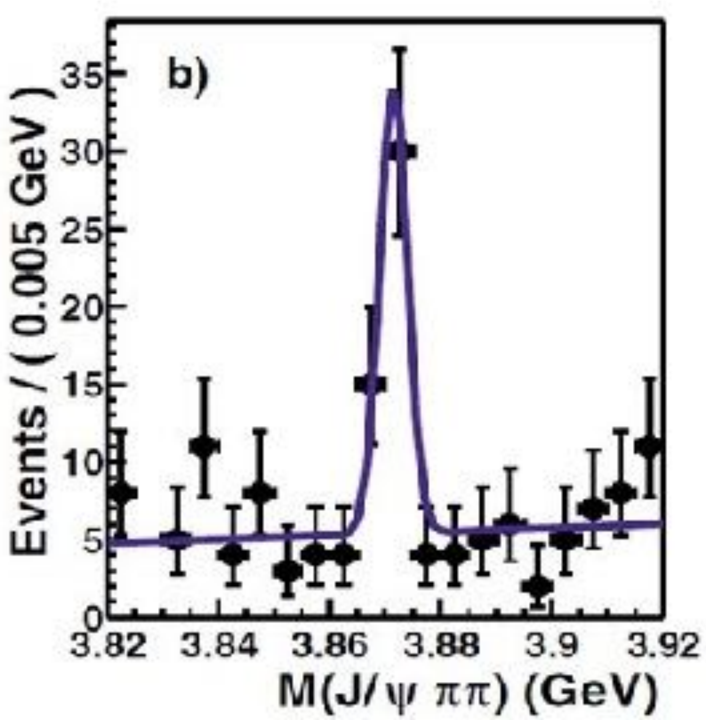


First observation by Belle in 2003

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

Signal: 35.7 ± 6.8 events

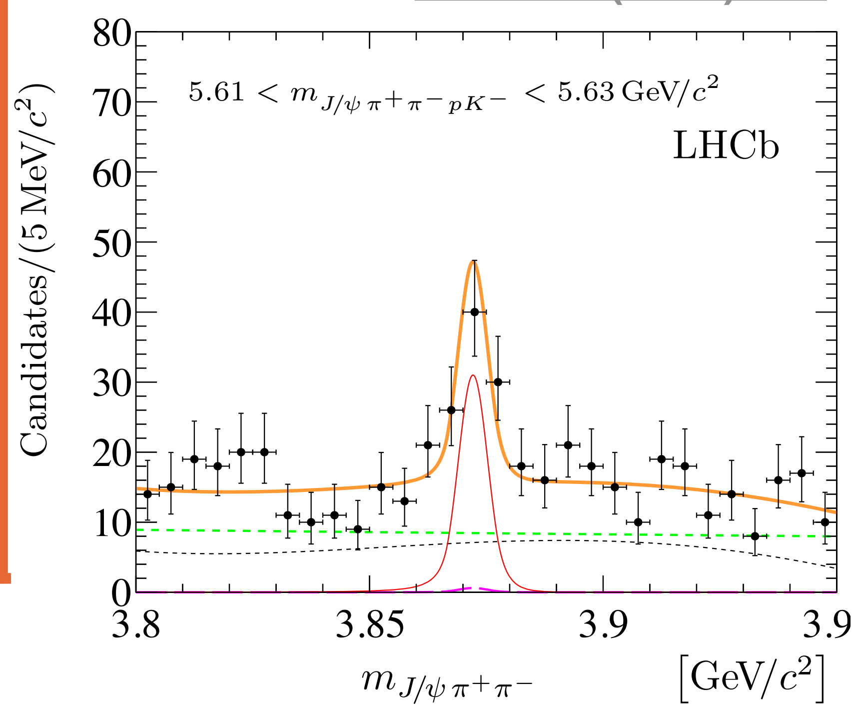
PRL 91 (2003) 262001



Latest results

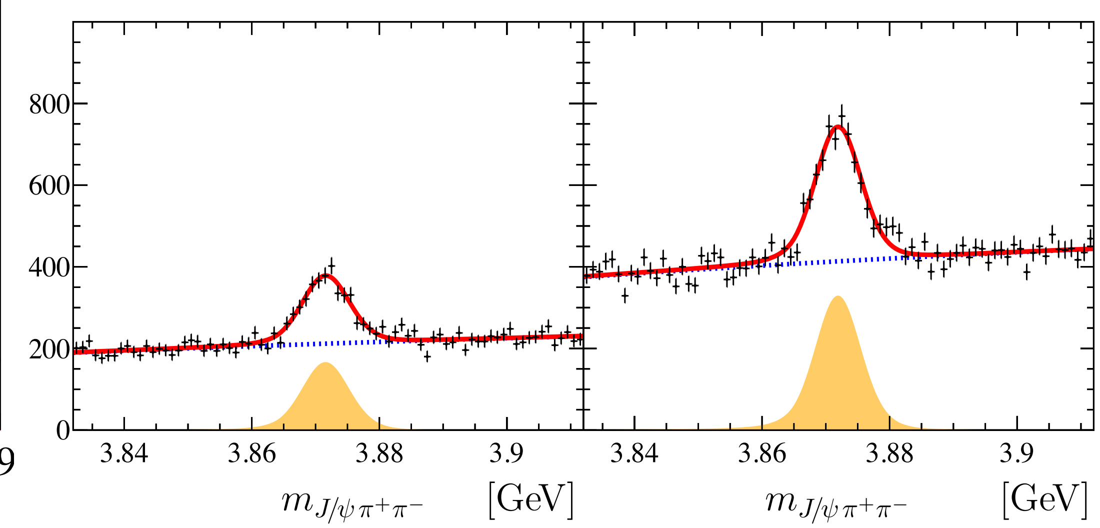
First observation in baryonic decay $-\Lambda_b^0 \to \chi_{c1}(3872)pK^-$

JHEP 09 (2019) 028



First observation of the non-zero width

PRD 102 (2020) 092005

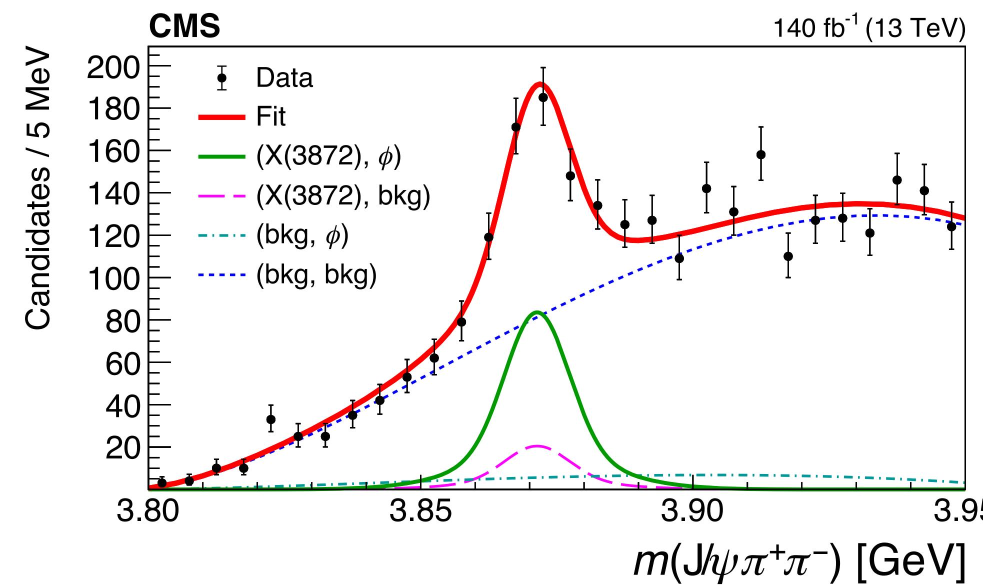


$\chi_{c1}(3872)$ state

Still unclear nature:

PRL 125 (2020) 152001

$$\frac{Br(B_s^0 \to \chi_{c1}(3872)\phi)}{Br(B^+ \to \chi_{c1}(3872)K^+)} \sim \frac{1}{2}\frac{Br(B_s^0 \to \psi(2S)\phi)}{Br(B^+ \to \psi(2S)K^+)}$$

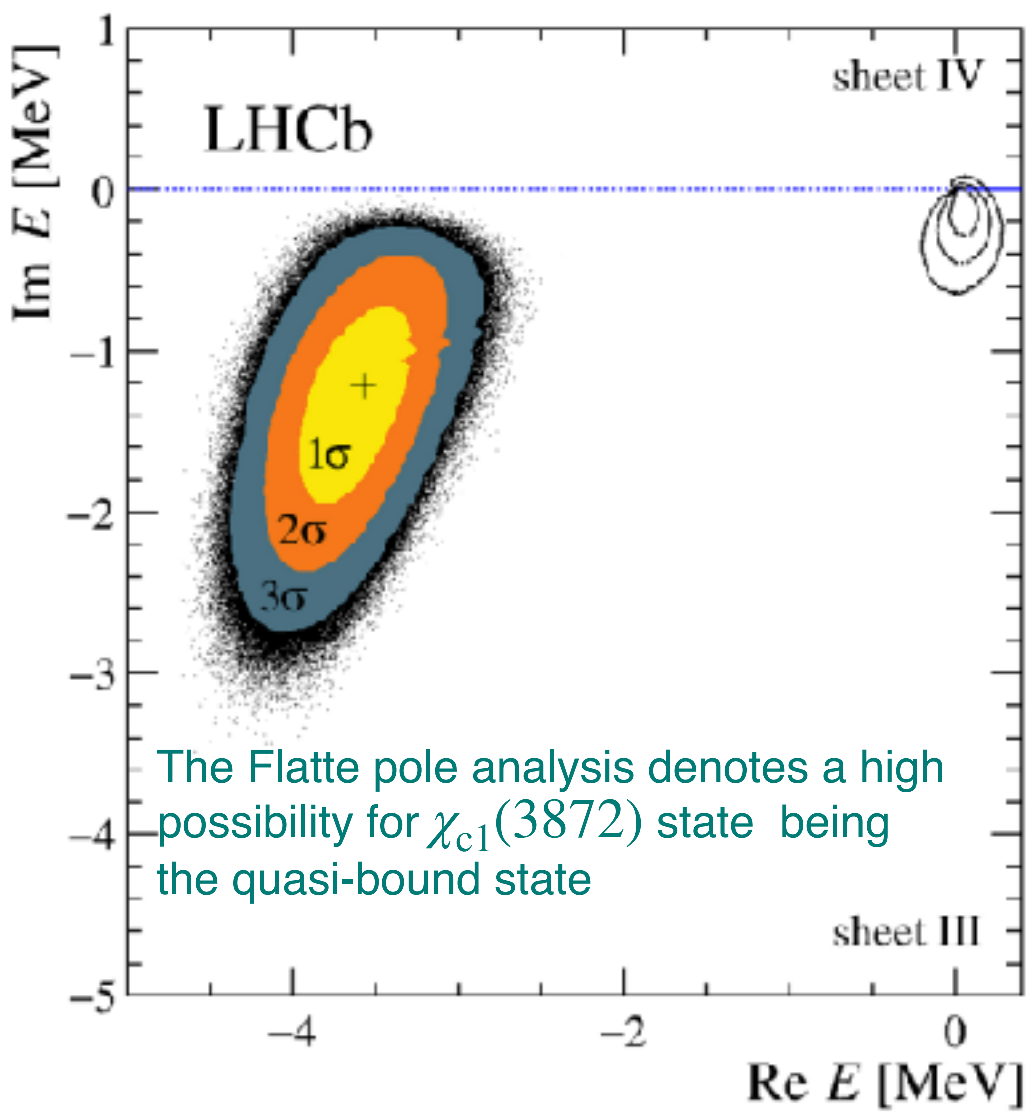


Could be a compact tetraquark?

The tetraquark (diquark-based) scenario Maiani et al:

PRD 129 (2020) 034017

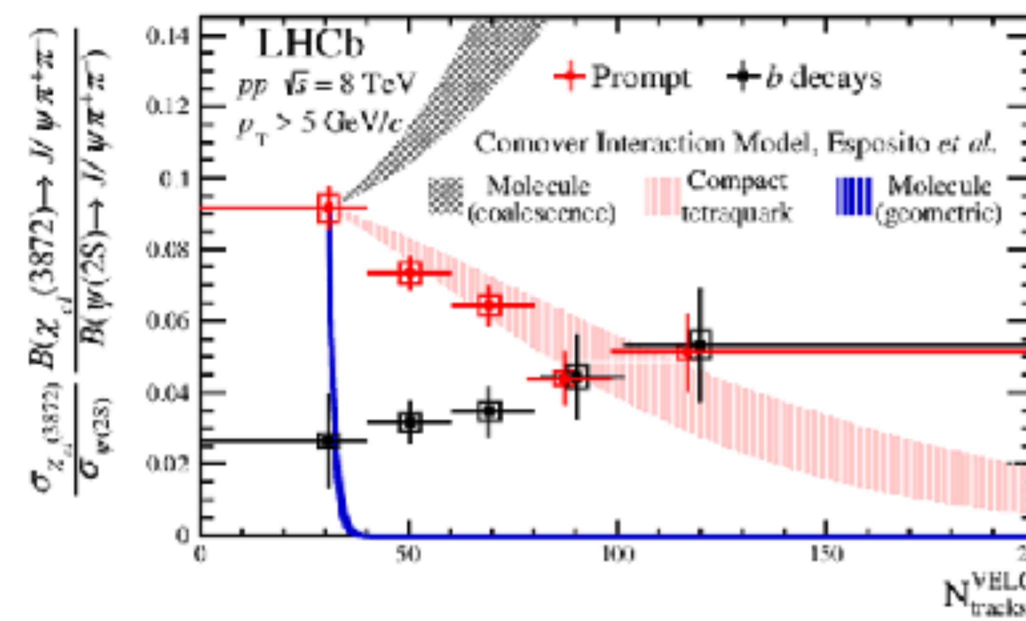
PRD 102 (2020) 092005



The Flatte pole analysis denotes a high possibility for $\chi_{c1}(3872)$ state being the quasi-bound state

Could be a molecule disintegrated at high multiplicity?
No rigorous theoretical treatment

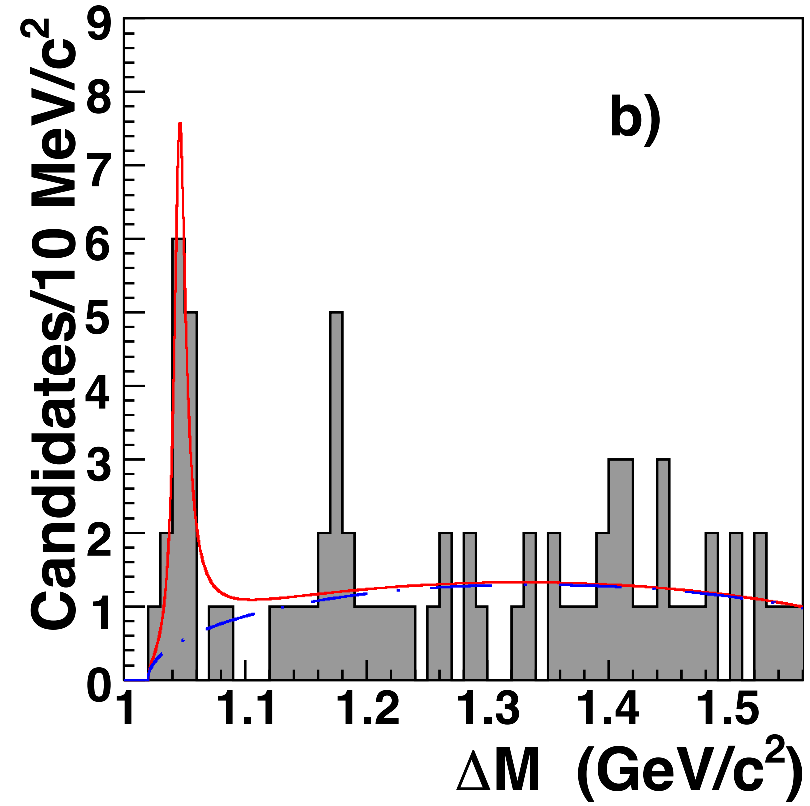
PRD 102 (2020) 092005



The BR comparison with conventional charmonium could help understood production mechanism

Exotic states in $J/\psi\phi$ spectrum

PRL 102 (2009) 242002

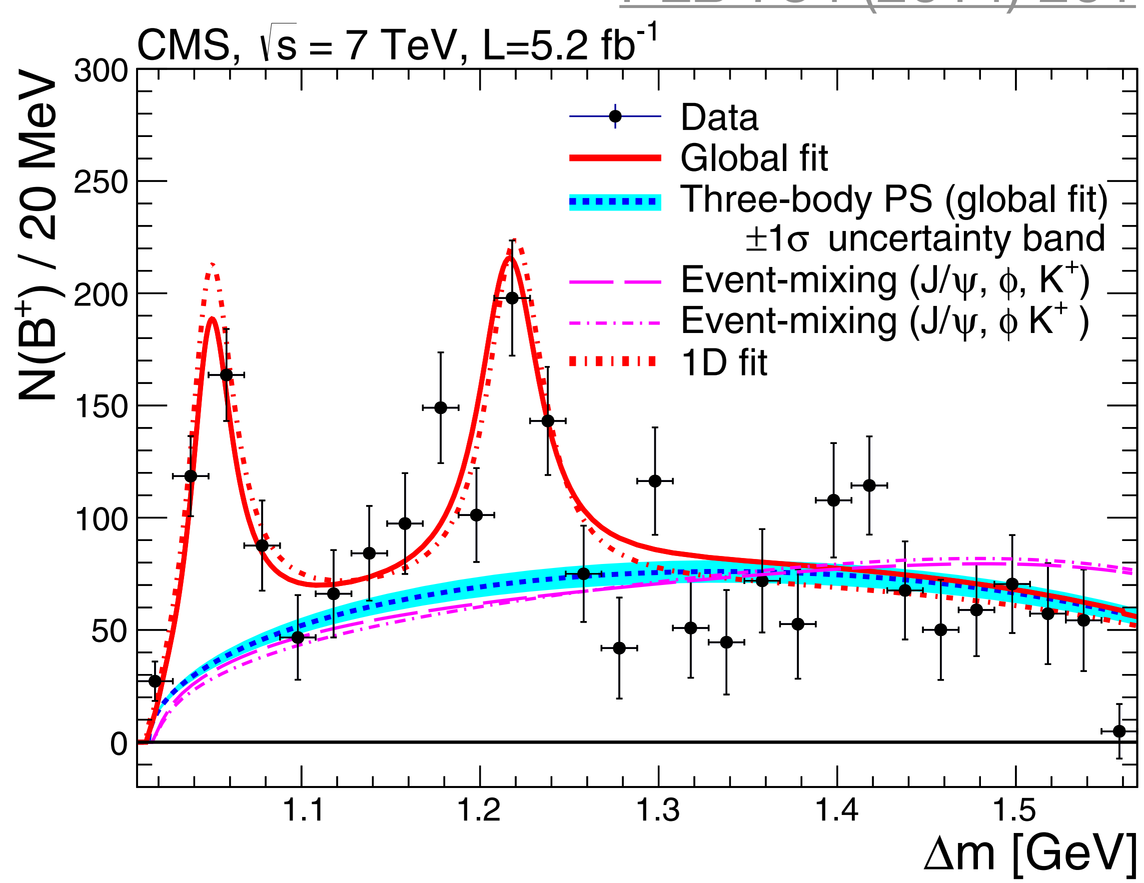


History of $X \to J/\psi\phi$ observations:

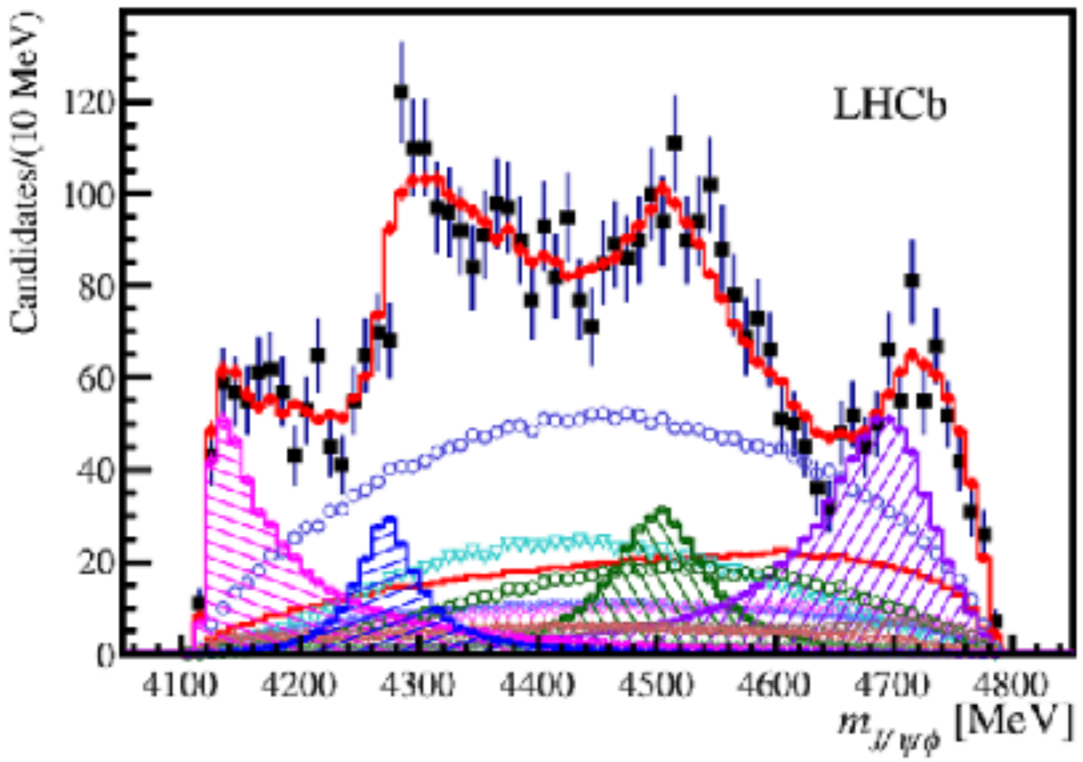
- First observation in $J/\psi\phi$ spectrum by CDF (2009):
  - Above $D_s^{*+}D_s^{*-}$ threshold
  - M $= 4143.4 \pm 3.0 \pm 0.6 \ \mathrm{MeV}/c^2$
  - $\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5 \ \mathrm{MeV}$
  - Hint of a second structure —X(4247)
    - Above $D_{s0}^{+}D_s^{-}$ threshold
  - Not confined by LHCb with $0.37 \mathrm{fb}^{-1}$
- X(4140) confirmed by CMS and D0 (2014):
  - CMS X(4140) ($>5\sigma$)
    - M $= 4148.4 \pm 2.4 \pm 6.3 \ \mathrm{MeV}/c^2$
    - $\Gamma = 28^{+15}_{-11} \pm 19 \ \mathrm{MeV}$
  - CMS X(4247-)X(4351) ($>3\sigma$)
    - M $= 4313.8 \pm 5.3 \pm 7.3 \ \mathrm{MeV}/c^2$
    - $\Gamma = 38^{+30}_{-15} \pm 16 \ \mathrm{MeV}$
- Also confirmed by CDF with large statistic:

MPLA 32-26 (2017) 1750139

PLB 734 (2014) 261



- Observation of four resonances at LHCb using Run 1 data PRD 95 (2017) 012002



Contri-bution	sign. or Ref.	M_0 [MeV]	Γ_0 [MeV]
All $X(1^+)$			
$X(4140)$	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$
ave.	Table 1	4147.1 ± 2.4	15.7 ± 6.3
$X(4274)$	6.0σ	$4273.3\pm8.3\,^{+17.2}_{-3.6}$	$56\pm11\,^{+8}_{-11}$
CDF	[29]	$4274.4\,^{+8.4}_{-6.7}\pm1.9$	$32\,^{+22}_{-15}\pm8$
CMS	[25]	$4313.8\pm5.3\pm7.3$	$38\,^{+30}_{-15}\pm16$
All $X(0^+)$			
$NR_{J/\psi\phi}$	6.4σ		
$X(4500)$	6.1σ	$4506\pm11\,^{+12}_{-15}$	$92\pm21\,^{+21}_{-20}$
$X(4700)$	5.6σ	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$

- The measured width of $X(4140)$ is larger that value obtained from other experiments

$\chi_{c1}(4140)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
22 $^{+8}_{-7}$ OUR AVERAGE		Error includes scale factor of 1.3. See the ideogram below.			
$83\pm21\,^{+21}_{-14}$	4289	[1] AAIJ	17C	LHCB	$B^+ \to J/\psi\phi K^+$
$15.3\,^{+10.4}_{-6.1}\pm2.5$	19	[2] AALTONEN	17	CDF	$B^+ \to J/\psi\phi K^+$
$16.3\pm5.6\pm11.4$	616	[3] ABAZOV	15M	D0	$p\overline{p} \to J/\psi\phi$ + anything
$20\pm13\,^{+3}_{-8}$	52	[4] ABAZOV	14A	D0	$B^+ \to J/\psi\phi K^+$
$28\,^{+15}_{-11}\pm19$	0.3k	[5] CHATRCHYAN	14M	CMS	$B^+ \to J/\psi\phi K^+$

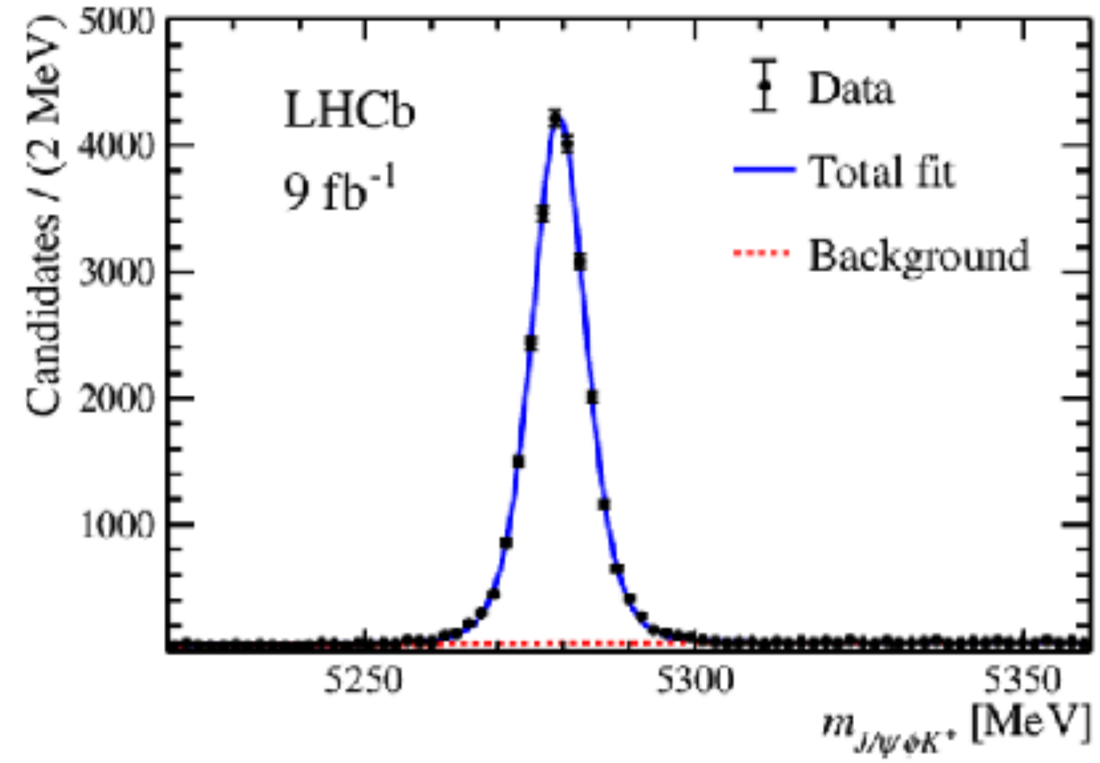
• • • We do not use the following data for averages, fits, limits, etc. • • •

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

The amplitude analysis of $B^+ \to J/\psi\phi K^+$

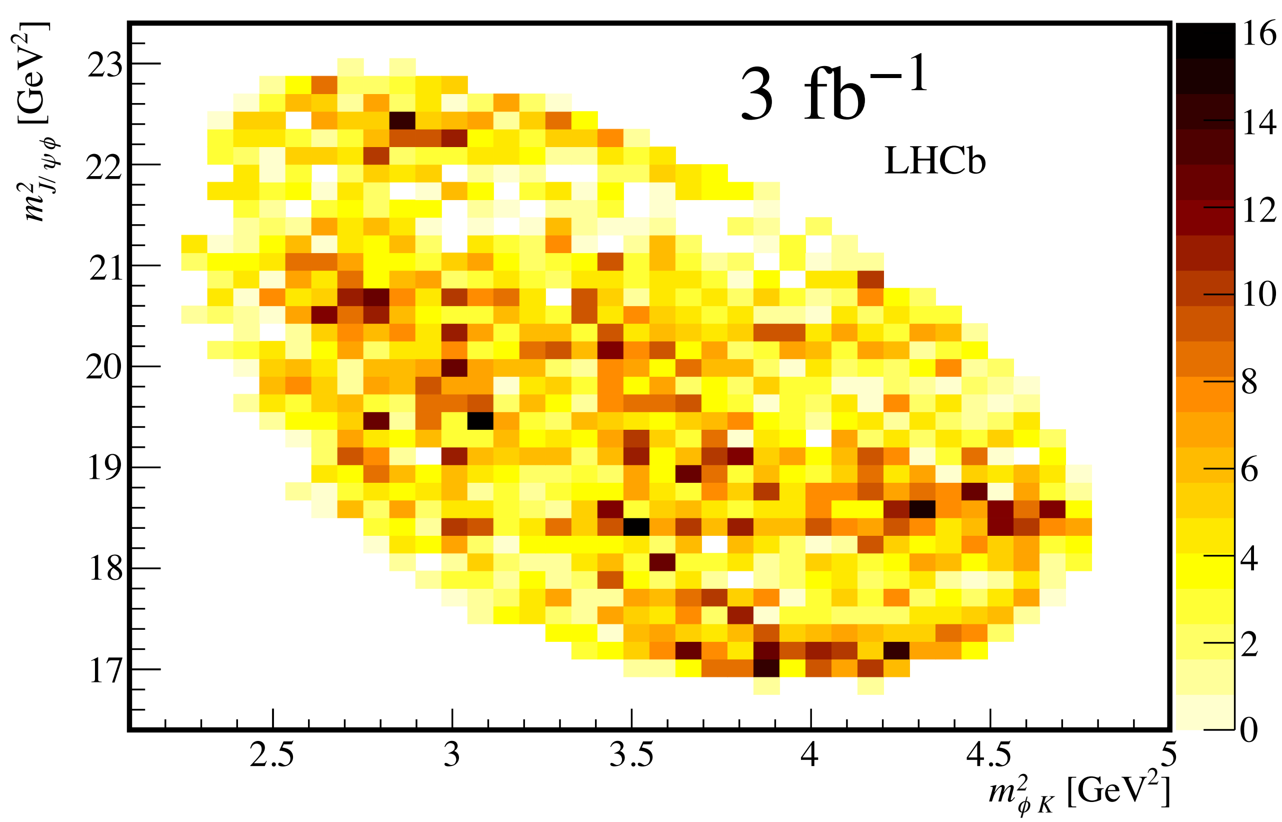
arXiv:2103.01803

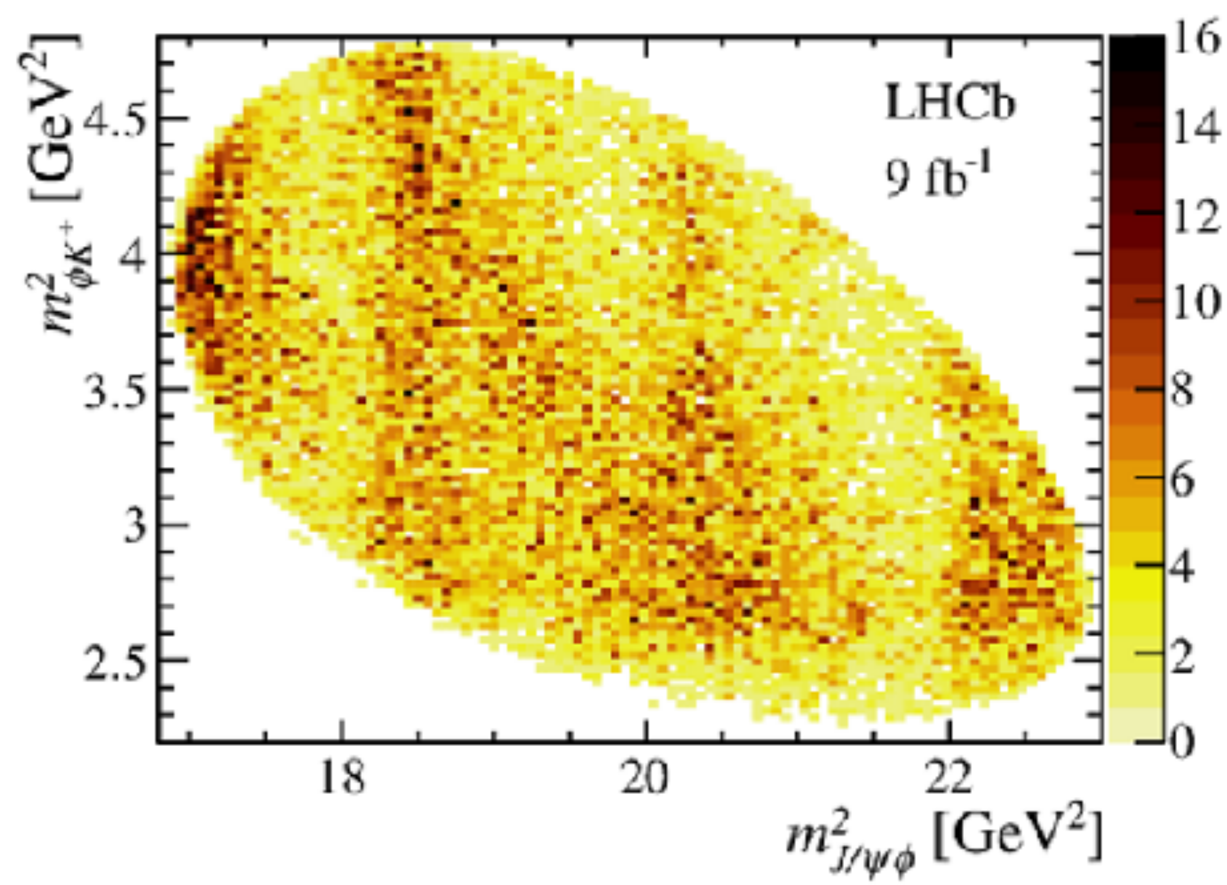
- Use full statistic of Run 1+2
  - $24200 \pm 170\ \ B^+$ candidates
  - Low background ~ 4% (a factor of 6 smaller)
  - Signal is in 6 times larger than in previous analysis



Possible contribution $B^+ \to J/\psi K^*$, $B^+ \to XK^+$

PRD 95 (2017) 012002



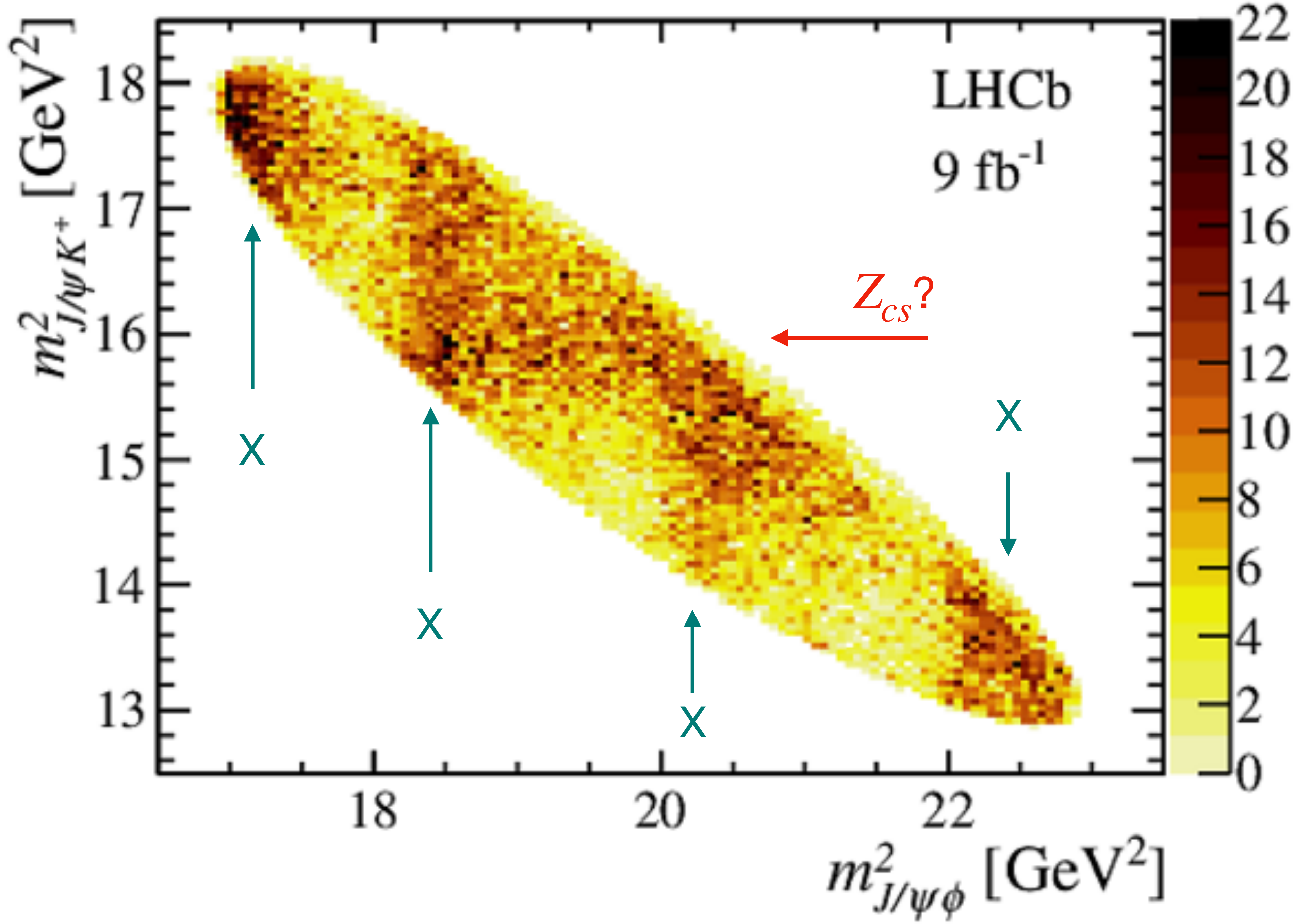


Clear structures In $J/\psi\phi$

The amplitude analysis of $B^+ \to J/\psi\phi K^+$

Hint to the presence of $B^+ \to Z_{cs}\phi$ contribution

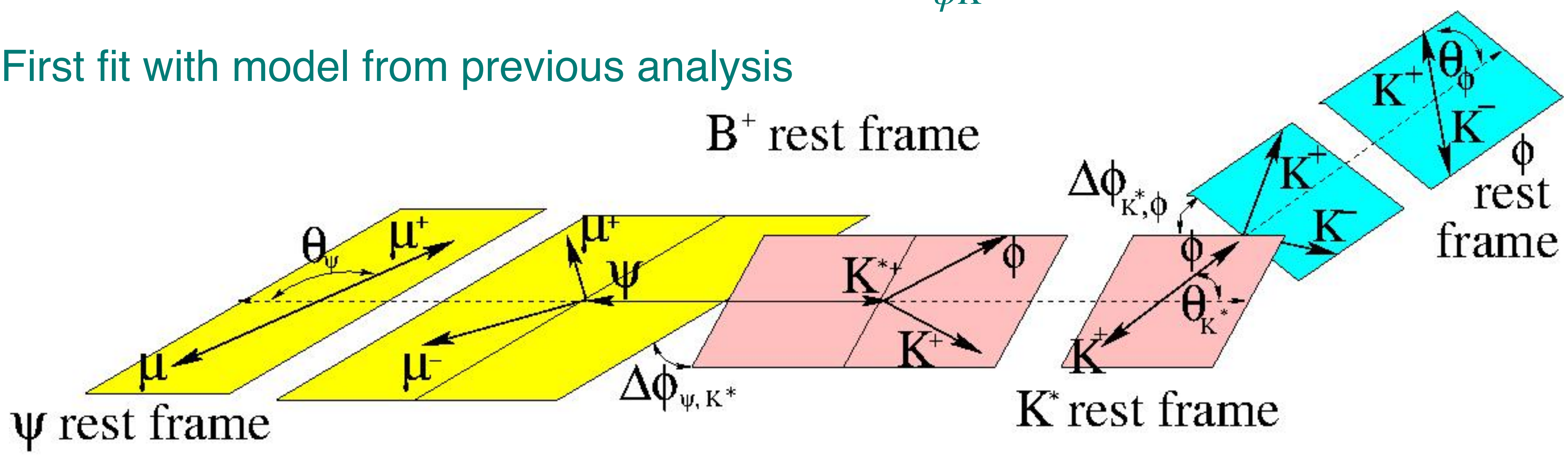
arXiv:2103.01803



Helicity amplitude fit

arXiv:2103.01803

- Components for each decays described by 6 parameters:
  - Mass $m_{\phi K}$, helicity angles θ, angles between two decay chains $\Delta\phi$
  - $\Omega = (\theta_{K*}, \theta_{J/\psi}, \theta_{\phi}, \Delta\phi_{K*,J/\psi}, \Delta\phi_{K*,\phi})$
  - Other invariant masses in the chain depend of $m_{\phi K}$ and Ω
  - First fit with model from previous analysis



$$-\ln L(\vec{\omega}) = -\sum_i \ln\left[(1-\beta)\,\mathcal{P}_{\rm sig}(m_{\phi K\ i}, \Omega_i|\vec{\omega}) + \beta\,\mathcal{P}_{\rm bkg}(m_{\phi K\ i}, \Omega_i)\right]$$

$$= -\sum_i \ln\left[(1-\beta)\,\frac{\left|\mathcal{M}(m_{\phi K\ i}, \Omega_i|\vec{\omega})\right|^2 \Phi(m_{\phi K\ i})\epsilon(m_{\phi K\ i}, \Omega_i)}{I(\vec{\omega})} + \beta\,\frac{\mathcal{P}^{u}_{\rm bkg}(m_{\phi K\ i}, \Omega_i)}{I_{\rm bkg}}\right]$$

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

determinated from MC

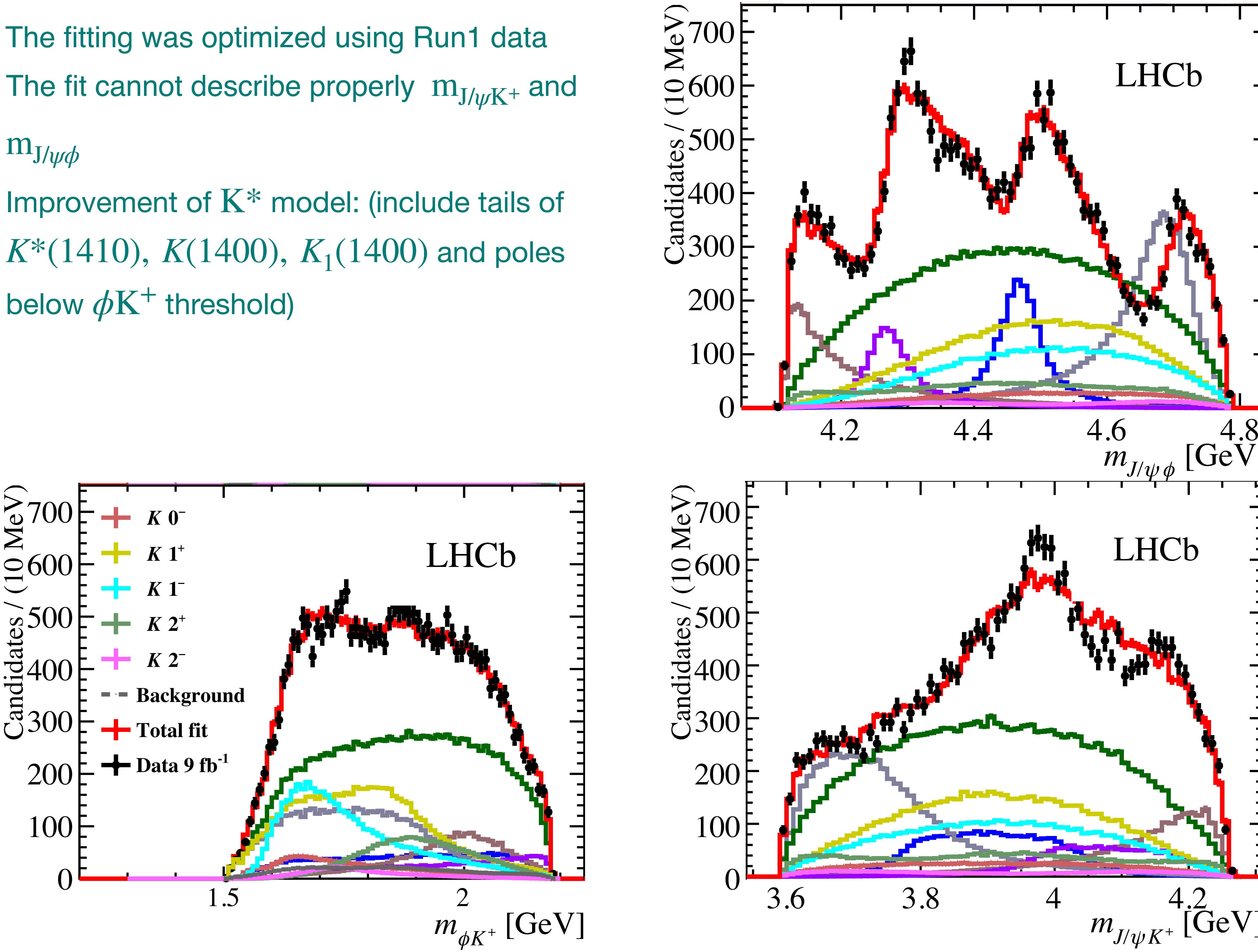
6D matrix element, resonance lineshapes - RBW with Blatt-Waiskopff barrier-factor

Fraction of comb. bkg., determinate from fit to $m_{J/\psi\phi K}$

Normalization integrals

phase space function

- The fitting was optimized using Run1 data
- The fit cannot describe properly $m_{J/\psi K^+}$ and $m_{J/\psi\phi}$
- Improvement of K^* model: (include tails of $K^*(1410)$, $K(1400)$, $K_1(1400)$ and poles below ϕK^+ threshold)

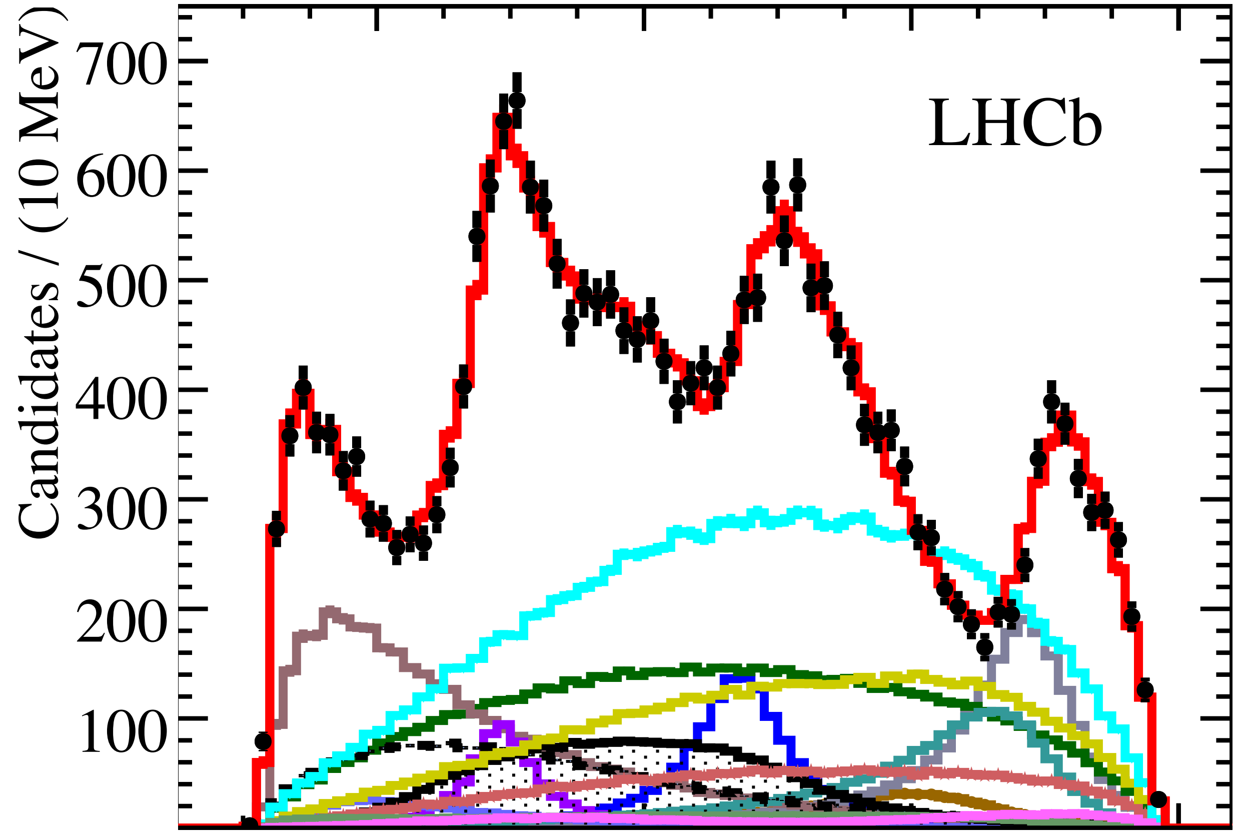


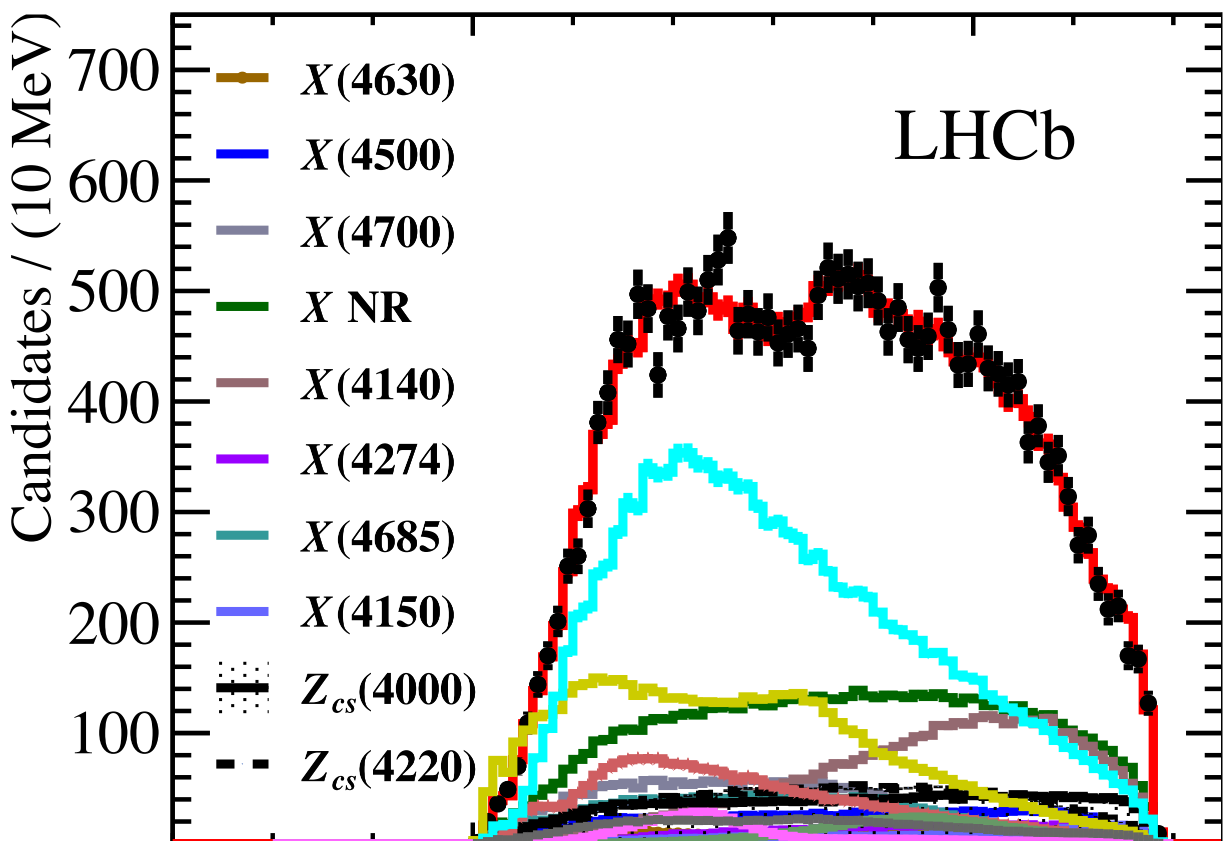
New resonances in $J/\psi K^+$ or $J/\psi\phi$?

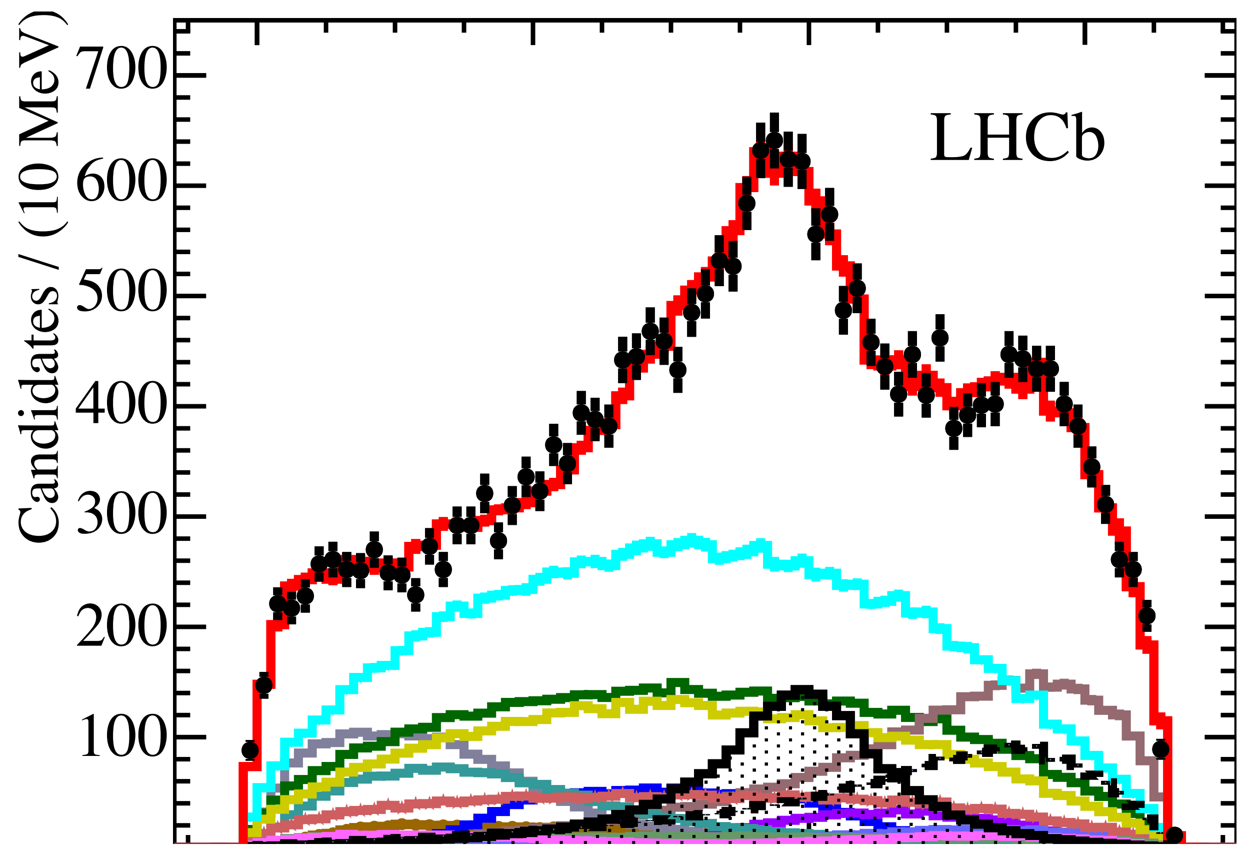
arXiv:2103.01803

- The expansion of K^* model by including new predicted resonance in ϕK^+ spectrum doesn't improve data description
- Test new exotic states (X and Z_{cs}) of different J^P
- Well described data
- The final nominal model contains

$9K^* + 7X + 1X(NR) + 2Z_{cs}$







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

- Two new $Z_{cs}^+ \to J/\psi K^+$ and several $X \to J/\psi\phi$ are observed with significance more 5 σ
- Results of Run 1 data are confirmed with large significance

J^P hypothesis and dominated systematics

- The different hypothesis for J^P of observed resonance are testes:
  - J^P confirmed for previous reported states with high significance
  - 1^+ favored for X(4685) and $Z_{cs}(4000)^+$
  - X(4150) and X(4630) are not very determined, 1^- and 2^- is preferred for X(4630) (3σ) and 2^- is preferred for X(4150) (4σ)
  - 1^- and 1^+ cannot be distinguished for $Z_{cs}(4220)^+$
- Various alternative models are investigated for systematics studies:
  - Simplified K-matrix for K^*, Flatte for X and Z states etc…
  - The difference between 1^- and 1^+ for $Z_{cs}(4220)^+$ state assigned as systematics and gives major contribution for the $Z_{cs}(4000)^+$ parameters

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

The difference between the preferred one and the alternative hypothesis

$(\sigma \sim \sqrt{\Delta(-2lnL)})$

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

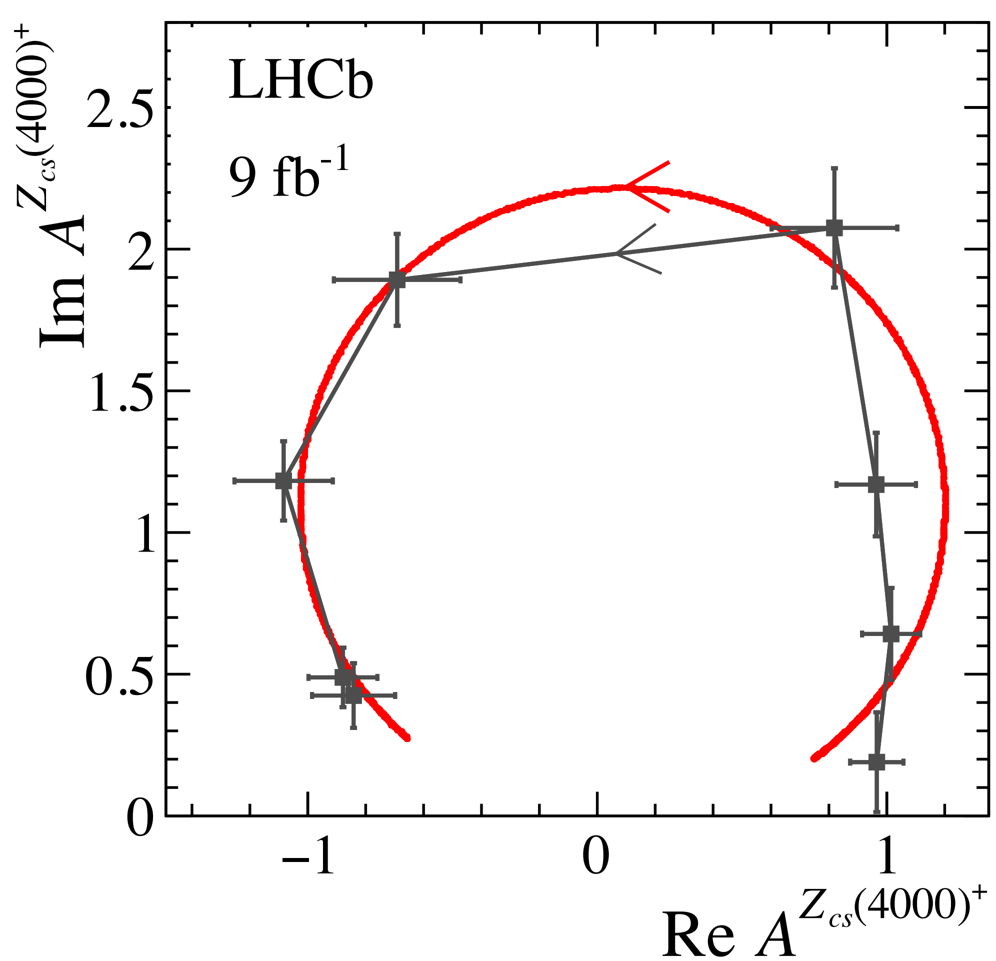
$Z_{cs}(4000)^+$ state

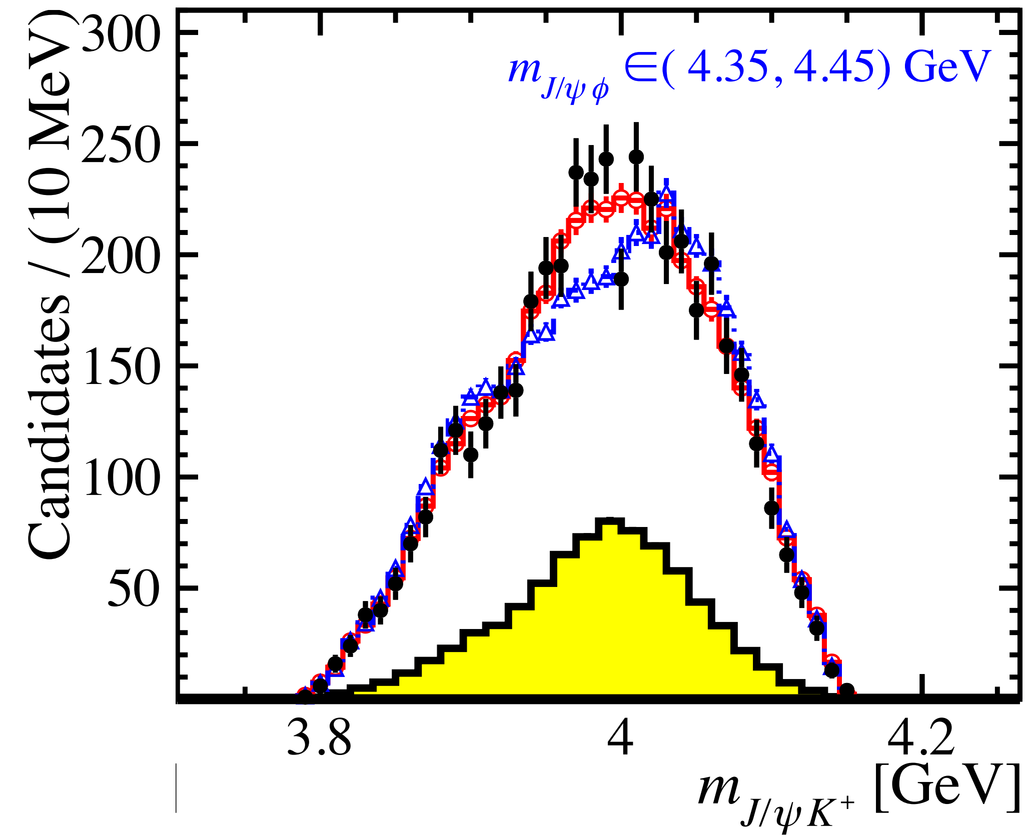
arXiv:2103.01803

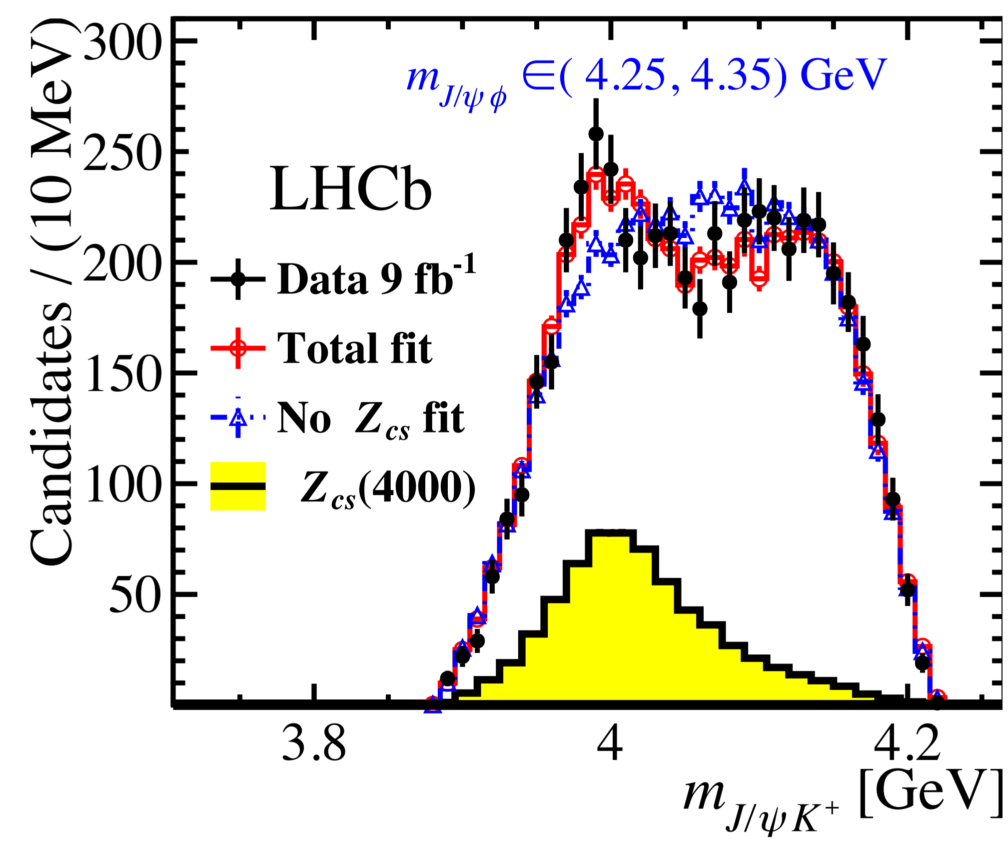
- Argand plot from independent fitting shows resonance character of $Z_{cs}(4000)^+$
- Including of this state significantly improves fit quality
- Fit with fixed to BESII's results of $Z_{cs}(3985)^-$ state for $Z_{cs}(4000)^+$ parameters shows worse log-likelihood w.r.t nominal model

arXiv:2011.07855

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



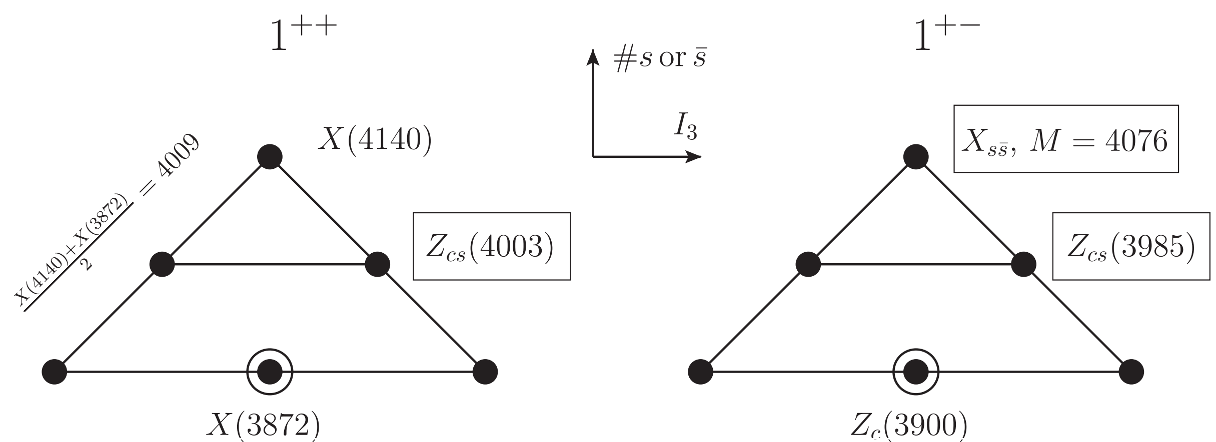




Z_{cs} states interpretation

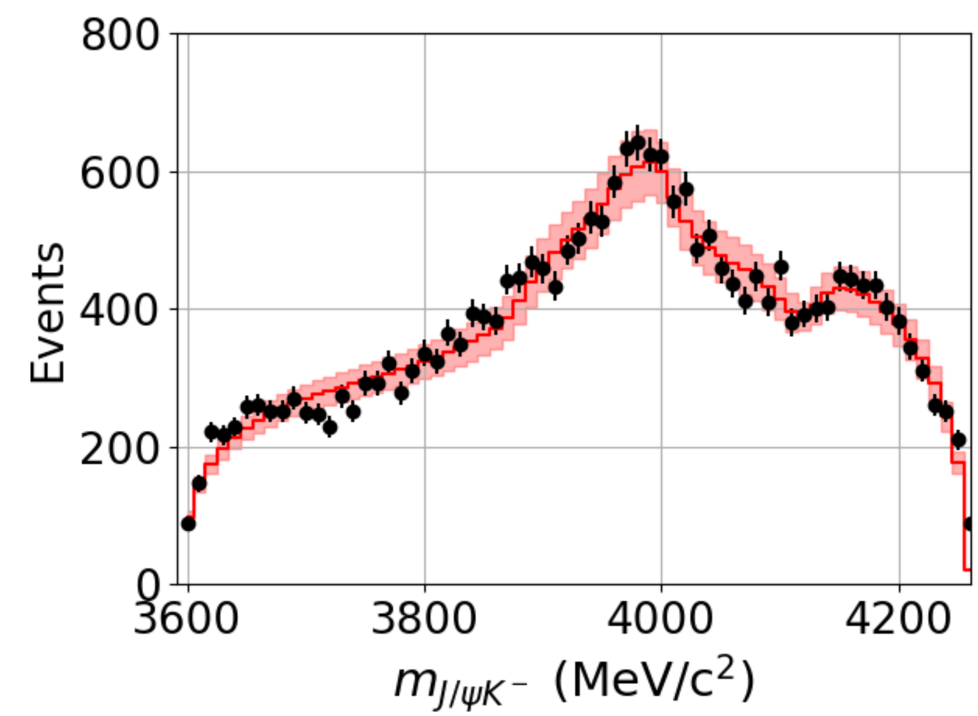
Several theoretical interpretation already appeared:

- Are $Z_{cs}(4000)^+$ and $Z_{cs}(3985)^+$ tetraquarks?



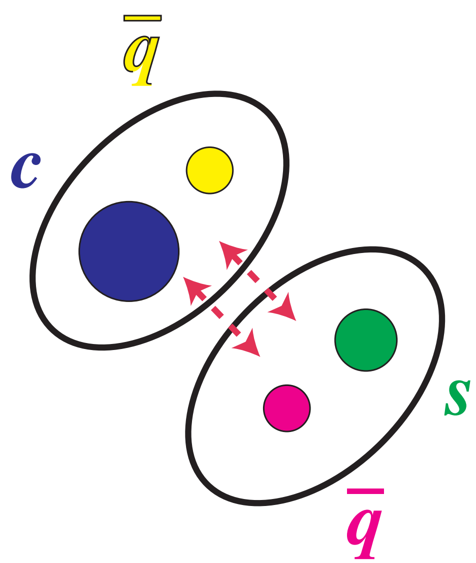
arXiv: 2103.08331

- Coupled channel model, are $Z_{cs}(4000)^+$ and $Z_{cs}(3985)^+$ states same?



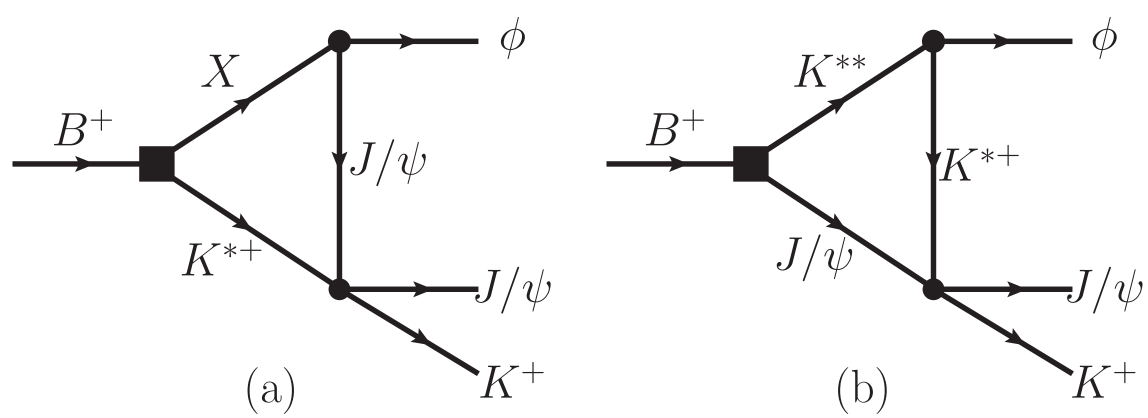
arXiv: 2103.07871

- $D\bar{D}_s^*$ molecules?



arXiv: 2103.08586

- Threshold cups?



arXiv: 2103.5282

- Etc.…

Prospect of observed states investigation

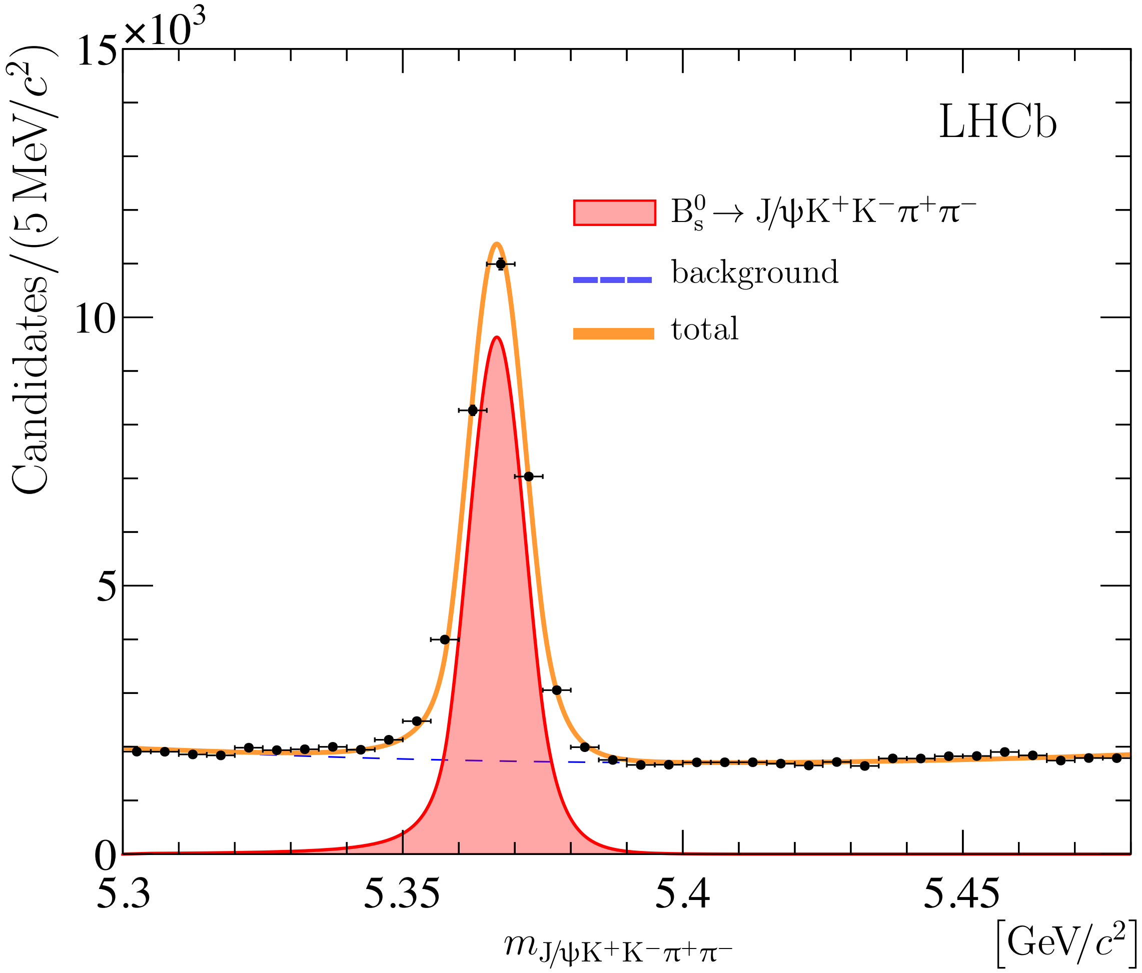
- Expect a significant increase in data after upgrade (7x in 2029) :
  - The $\mathrm{J^p}$ for $Z_{cs}^{+}(4220)$ could be determined with large data sample
  - As well as $\mathrm{J^p}$ for other new X states
  - Make a solid conclusion about the same nature of $Z_{cs}^{+}(4000)$ and $Z_{cs}^{-}(3985)$
- Search for same resonance decays in other channels:
  - In $\mathrm{B_s^0}$ decays the $J/\psi\phi$ spectrum could be probed up to approximately

    $300\ \mathrm{MeV/c^2}$

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

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

- Use full statistic of Run 1+2
  - 26500 ± 200 B_s^0 candidates
  - A lot of possible contributions due to 5 particles in final state
  - Clear visible signals after the background suppressions $\psi(2S), \chi_{c1}(3872), K^{*0}(892), \phi\ldots$
- The signal yields are obtained from the simultaneous fit to three dimensional distribution of $J/\psi\pi^+\pi^-K^+K^-$, K^+K^- и $J/\psi\pi^+\pi^-$ masses
  - Two regions around of $\psi(2S), \chi_{c1}(3872)$ states
  - Allow fixing resolution from the channel with high statistics



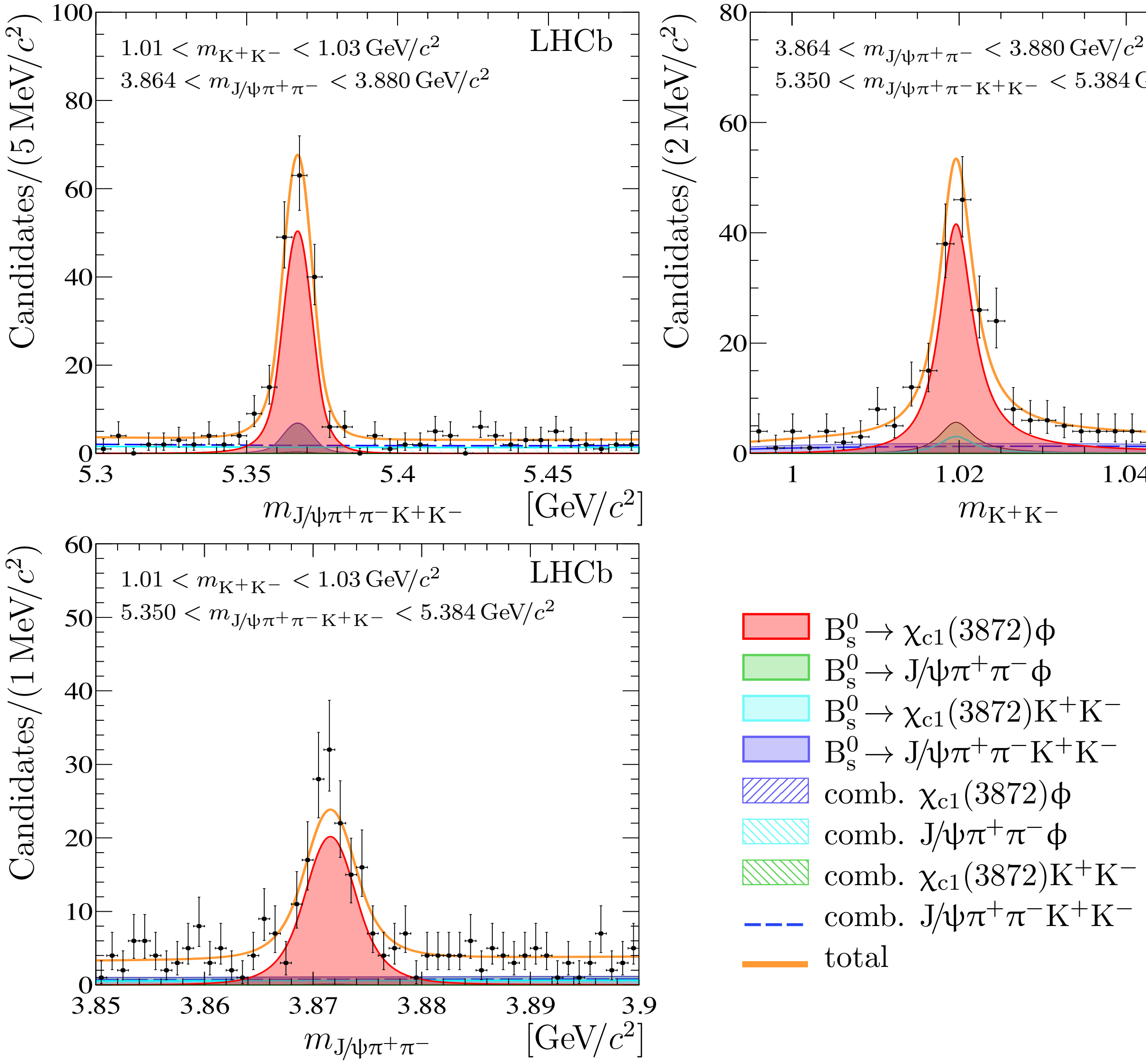
Measure a branching ratio:

Derived from the data

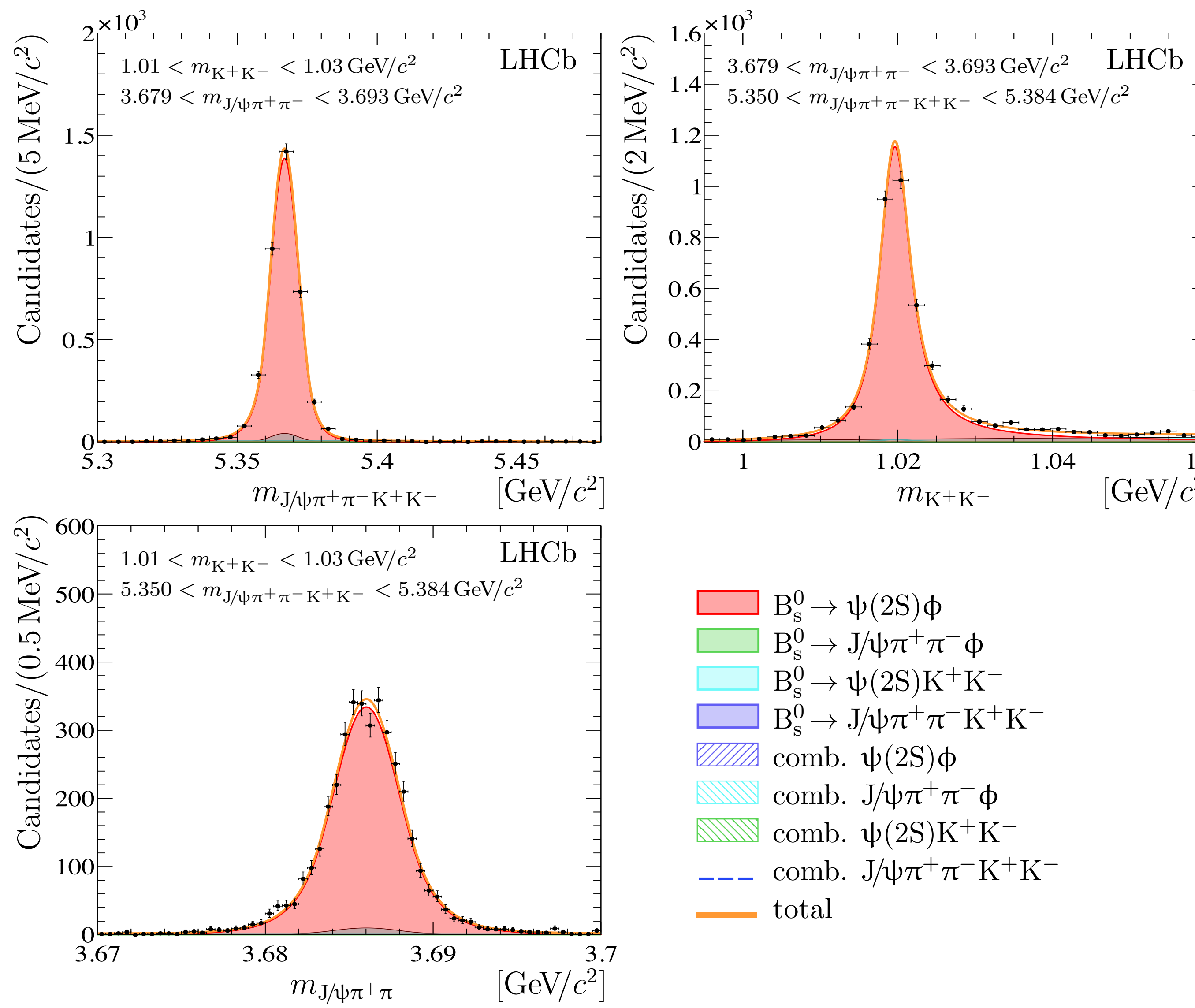
Derived from MC and calib samples

$$\frac{\mathcal{B}(B_s^0\to\chi_{c1}(3872)\phi)\times\mathcal{B}(\chi_{c1}(3872)\to J/\psi\,\pi^+\pi^-)}{\mathcal{B}(B_s^0\to\psi(2S)\phi)\times\mathcal{B}(\psi(2S)\to J/\psi\,\pi^+\pi^-)} = \frac{N_{\chi_{c1}(3872)\phi}}{N_{\psi(2S)\phi}} \times \frac{\varepsilon_{\psi(2S)\phi}}{\varepsilon_{\chi_{c1}(3872)\phi}}$$

Observation of the $B_s^0 \to \chi_{c1}(3872)\phi$ decays



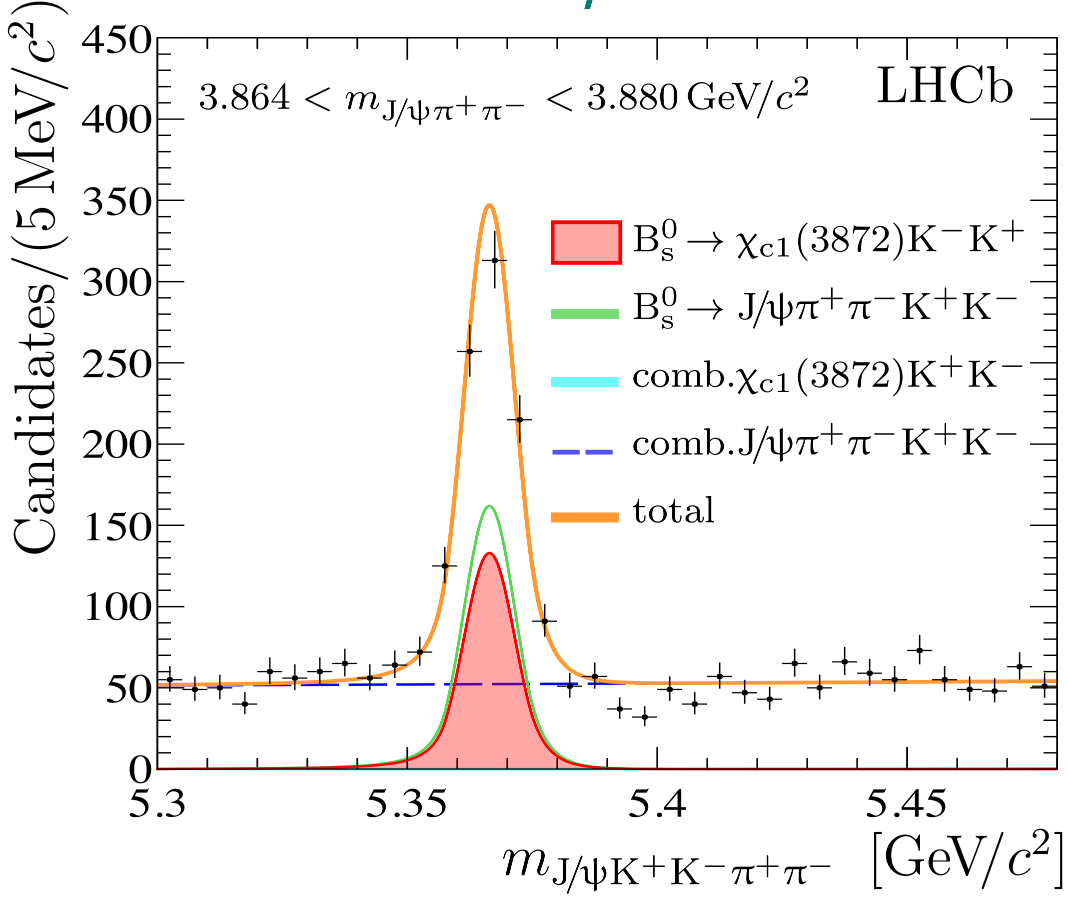
The $\chi_{c1}(3872)$ parameters in the fit are constrained with recent measurements (JHEP 08 (2020) 123)

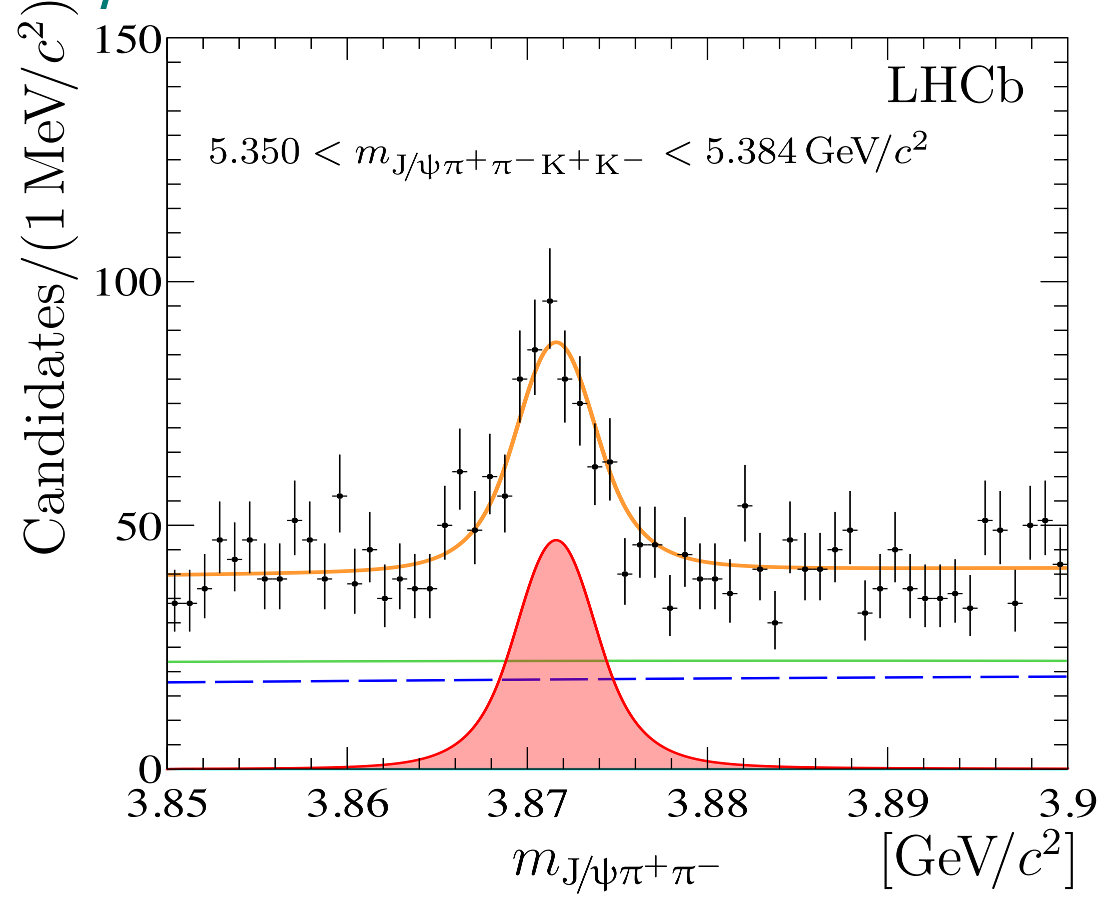


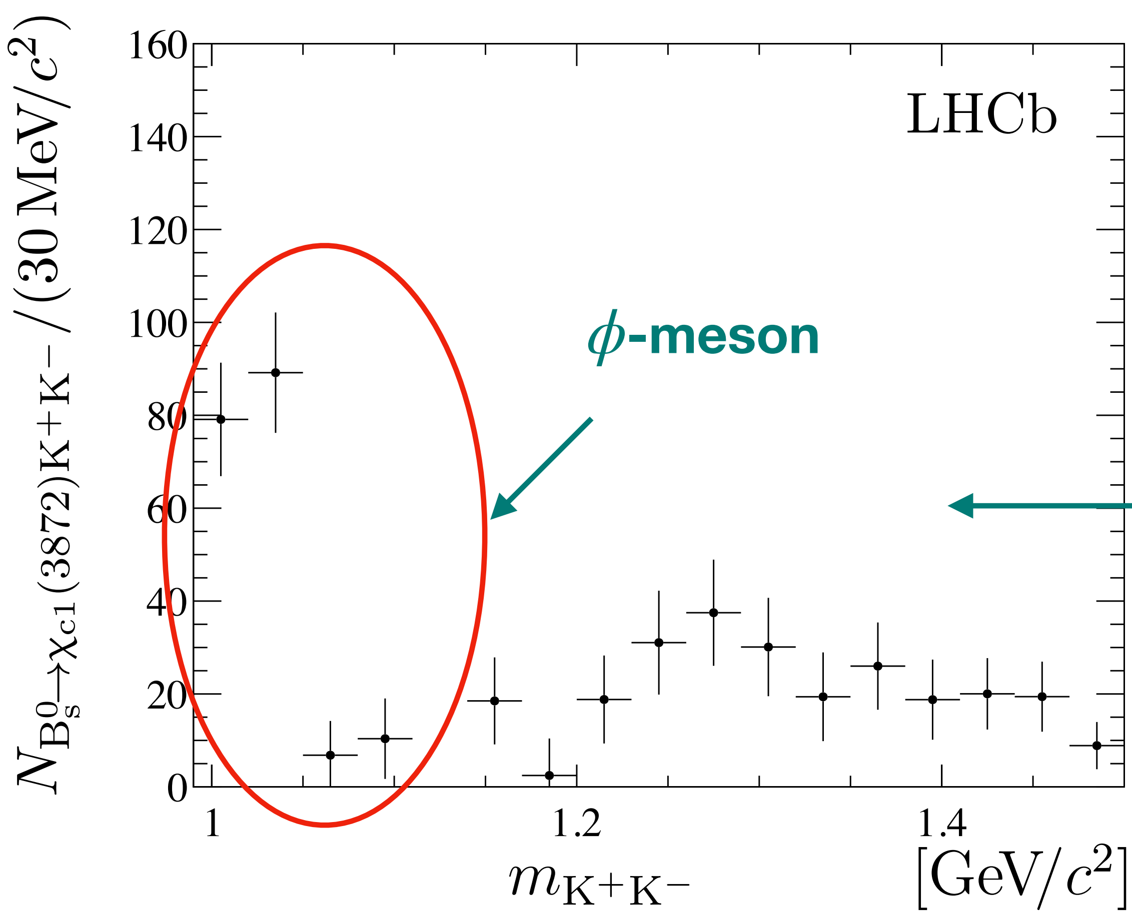
- Observation of the $B_s^0 \to \chi_{c1}(3872)\phi$ decays:
  - 154 ± 15 events
  - Significance more then ~ 12 σ
  - Seen the non-ϕ contribution
- Normalization channel: 4180 ± 66 events

Study of $B_s^0 \to \chi_{c1}(3872)(K^+K^-)_{non-\phi}$ decays

Fit to two-dimensional $J/\psi\pi^+\pi^-K^+K^-$ and $J/\psi\pi^+\pi^-$ distribution for whole K^+K^- region





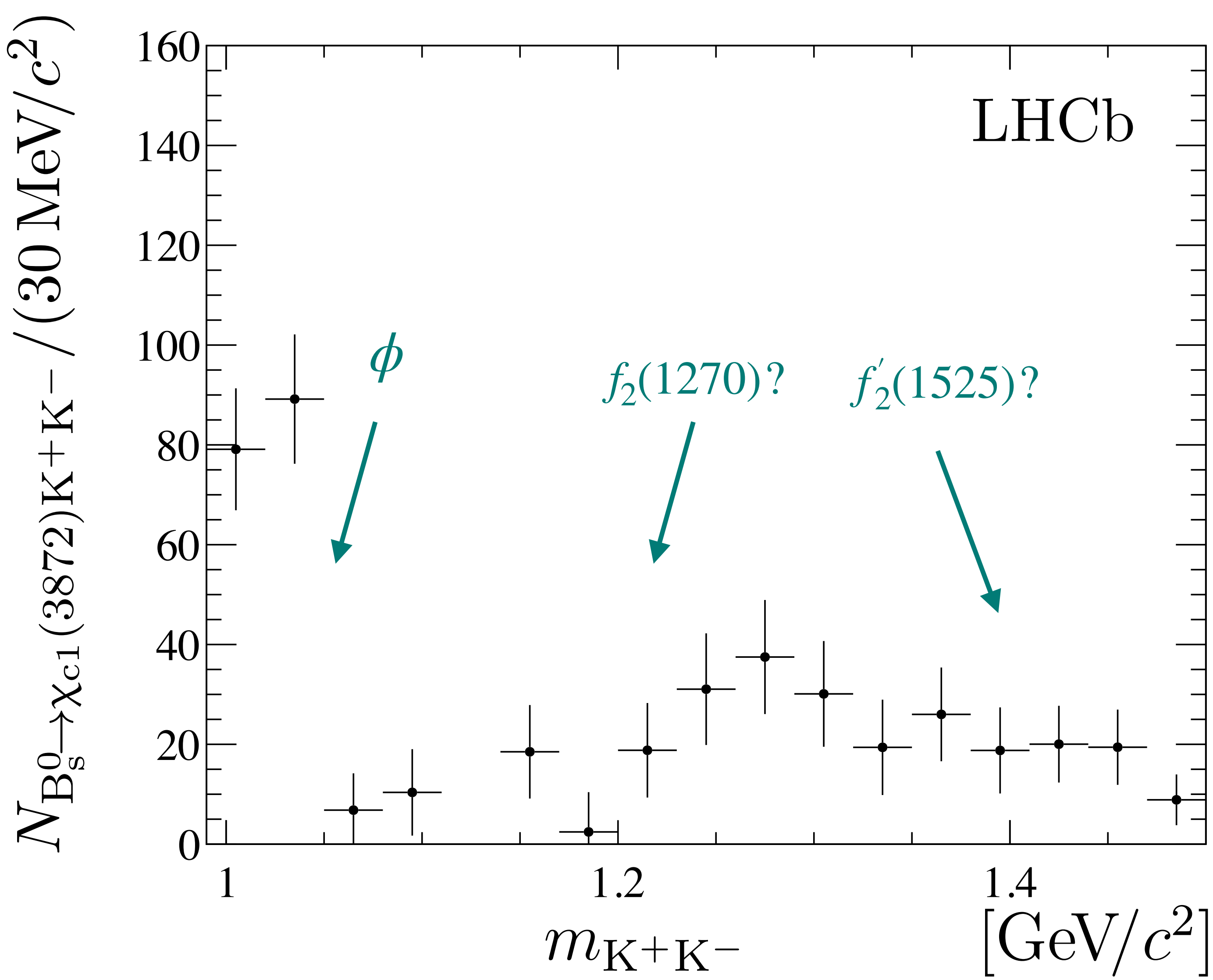


Significant contribution from the decays not associated with ϕ:

$$N_{B_s^0\to\chi_{c1}(3872)K^+K^-} = 378 \pm 33 \;>\; 154 \pm 15$$

Distribution after background subtraction

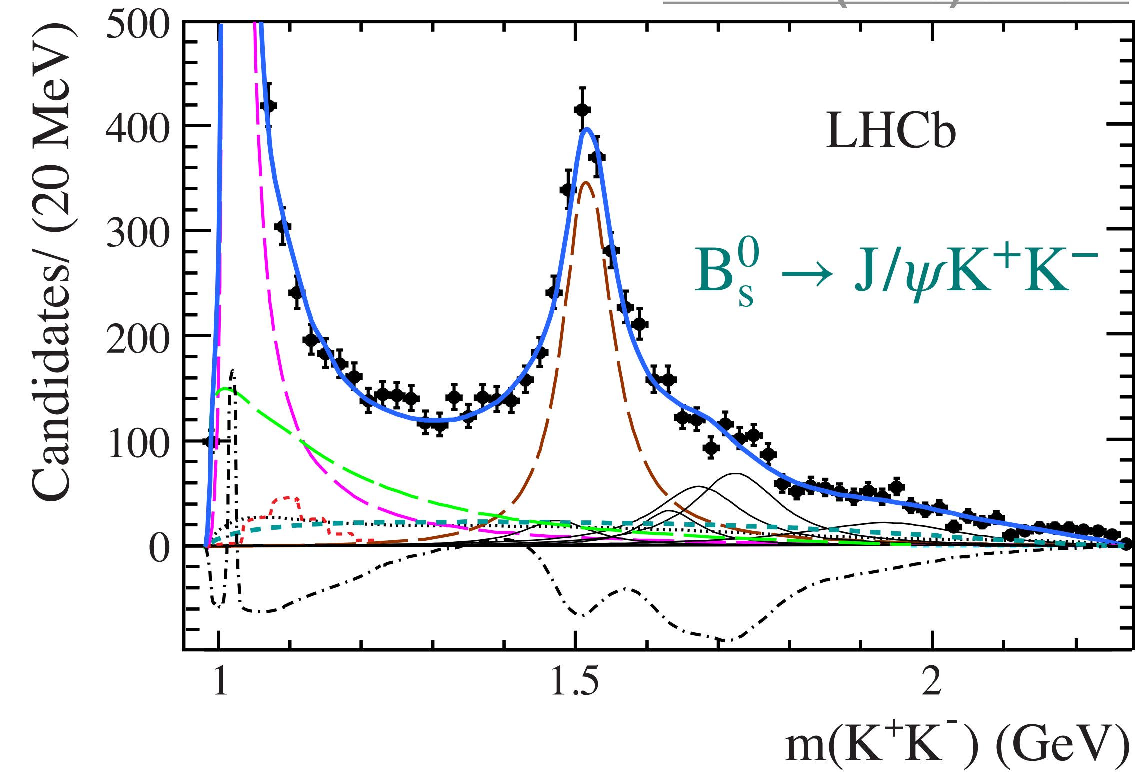
K^+K^- spectrum for $B_s^0 \to \chi_{c1}(3872)(K^+K^-)_{non-\phi}$ decays



Similar topology that for $B_s^0 \to J/\psi K^+K^-$

Dominated yields cased by $f_2^{'}(1525)$ and $f^0(980)$

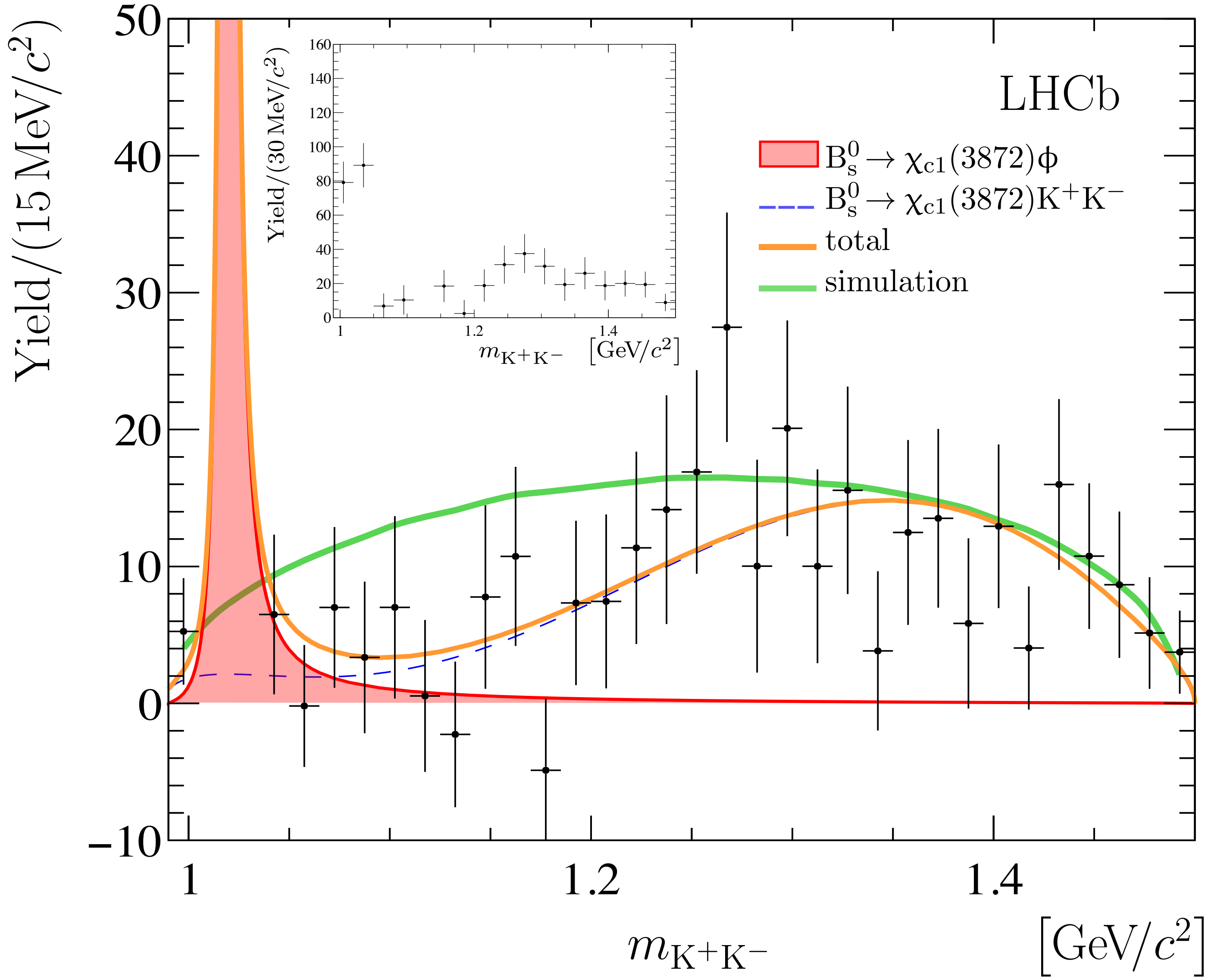
PRD 87 (2013) 072004



Component	LHCb	BES	BaBar
$\phi(1020)$, $\lambda = 0$	32.1 ± 0.5	32.1 ± 0.5	32.0 ± 0.5
$\phi(1020)$, $\lvert\lambda\rvert = 1$	34.6 ± 0.5	34.6 ± 0.5	34.5 ± 0.5
$f_0(980)$	12.0 ± 1.8	9.2 ± 1.4	4.8 ± 1.0
$f_0(1370)$	1.2 ± 0.3	1.2 ± 0.3	1.3 ± 0.3
$f_2'(1525)$, $\lambda = 0$	9.9 ± 0.7	9.8 ± 0.7	9.5 ± 0.7
$f_2'(1525)$, $\lvert\lambda\rvert = 1$	5.1 ± 0.9	5.1 ± 0.9	4.9 ± 0.9
$f_2(1640)$, $\lvert\lambda\rvert = 1$	1.5 ± 0.7	1.5 ± 0.7	1.5 ± 0.7
$\phi(1680)$, $\lvert\lambda\rvert = 1$	3.4 ± 0.3	3.4 ± 0.3	3.4 ± 0.3
$f_2(1750)$, $\lambda = 0$	2.6 ± 0.5	2.5 ± 0.5	2.2 ± 0.5
$f_2(1750)$, $\lvert\lambda\rvert = 1$	1.8 ± 1.0	1.8 ± 1.0	1.9 ± 1.0
$f_2(1950)$, $\lambda = 0$	0.4 ± 0.2	0.4 ± 0.2	0.4 ± 0.2
$f_2(1950)$, $\lvert\lambda\rvert = 1$	1.7 ± 0.5	1.8 ± 0.5	1.8 ± 0.5
Non-resonant S-wave	6.0 ± 1.4	4.7 ± 1.2	8.6 ± 1.7
Interference between S-waves	-5.5	-1.7	-1.1
Total S-wave	13.7	13.4	13.6
$-\ln\mathcal{L}$	29,275	29,275	29,281
χ^2/ndf	649/545	653/545	646/545

Non phase-space activity seen in region $K^+K^- > 1.1$ GeV

Possible contribution from the $f_2(1270)$ and $f_2^{'}(1525)$



Approximately 40% decays comes from ϕ meson:

$$f_\phi = (38.9 \pm 4.9)\,\%$$

First observation of the $BR_{B_s^0\to\chi_{c1}(3872)(K^+K^-)_{non-\phi}}$ channel

Non-extended fit to efficiency corrected background subtracted distribution

- $\phi-$signal multiplied to right part of phase space function
- Two-body phase space function from three body decay modified by polynomial (flexible to account for presence of broad resonances)

Branching fraction results

JHEP 04 (2021) 170

$$\frac{\mathcal{B}\left(B_s^0 \to \chi_{c1}(3872)\phi\right) \times \mathcal{B}\left(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-\right)}{\mathcal{B}\left(B_s^0 \to \psi(2S)\phi\right) \times \mathcal{B}\left(\psi(2S) \to J/\psi\pi^+\pi^-\right)} = (2.42 \pm 0.23 \pm 0.07) \times 10^{-2}$$

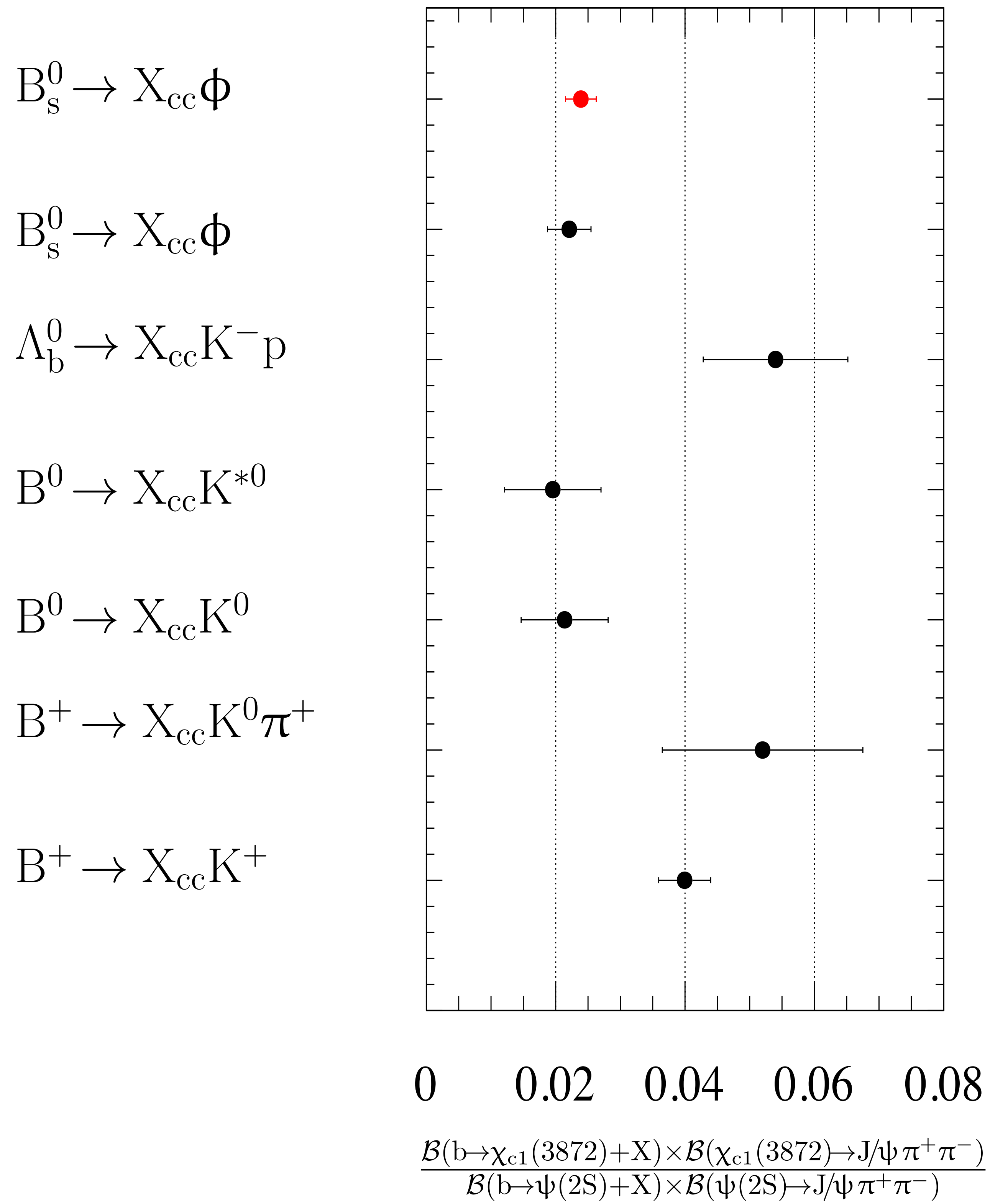
In agreement with CMS, but more precisely

CMS: $(2.21 \pm 0.29 \pm 0.17) \times 10^{-2}$

PRL 125 (2020) 152001

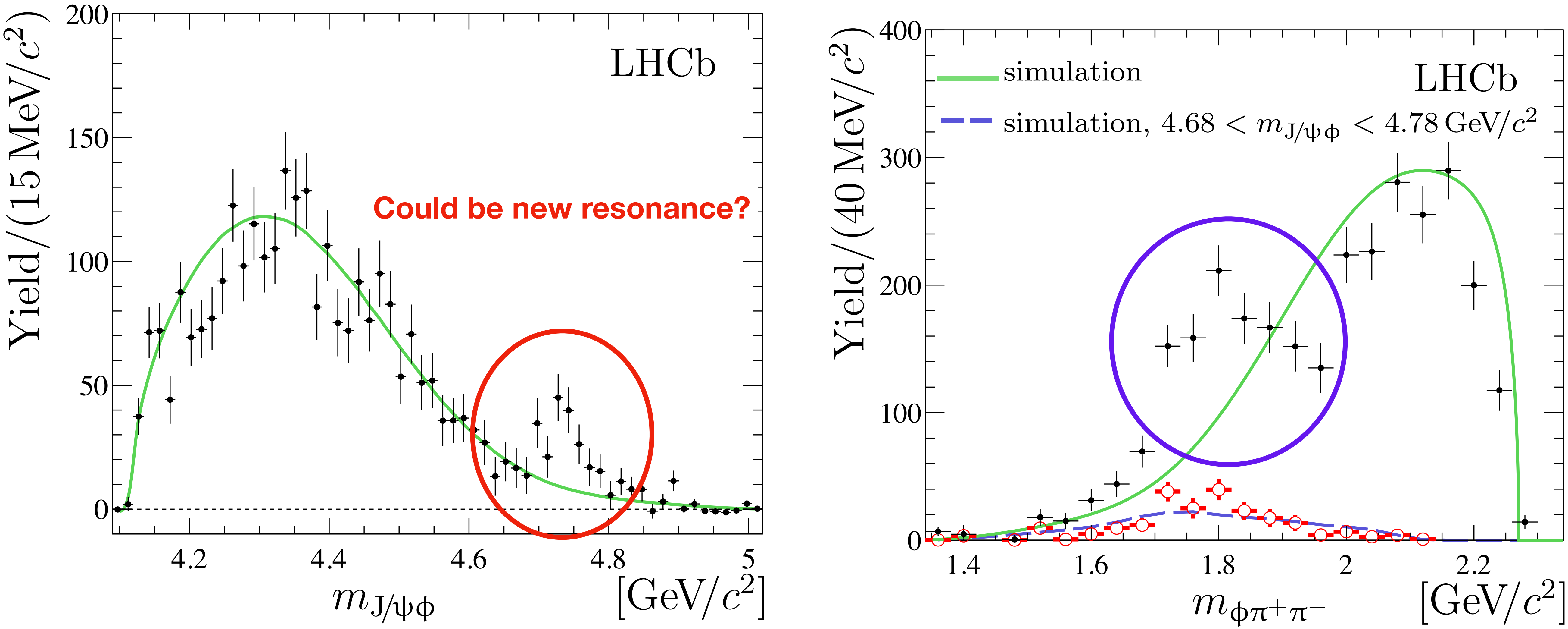
First measurement:

$$\frac{\mathcal{B}(B_s^0 \to \chi_{c1}(3872)\,(K^+K^-)_{\text{non-}\phi})}{\mathcal{B}\left(B_s^0 \to \chi_{c1}(3872)\phi\right) \times \mathcal{B}\left(\phi \to K^+K^-\right)} = 1.57 \pm 0.32 \pm 0.12$$



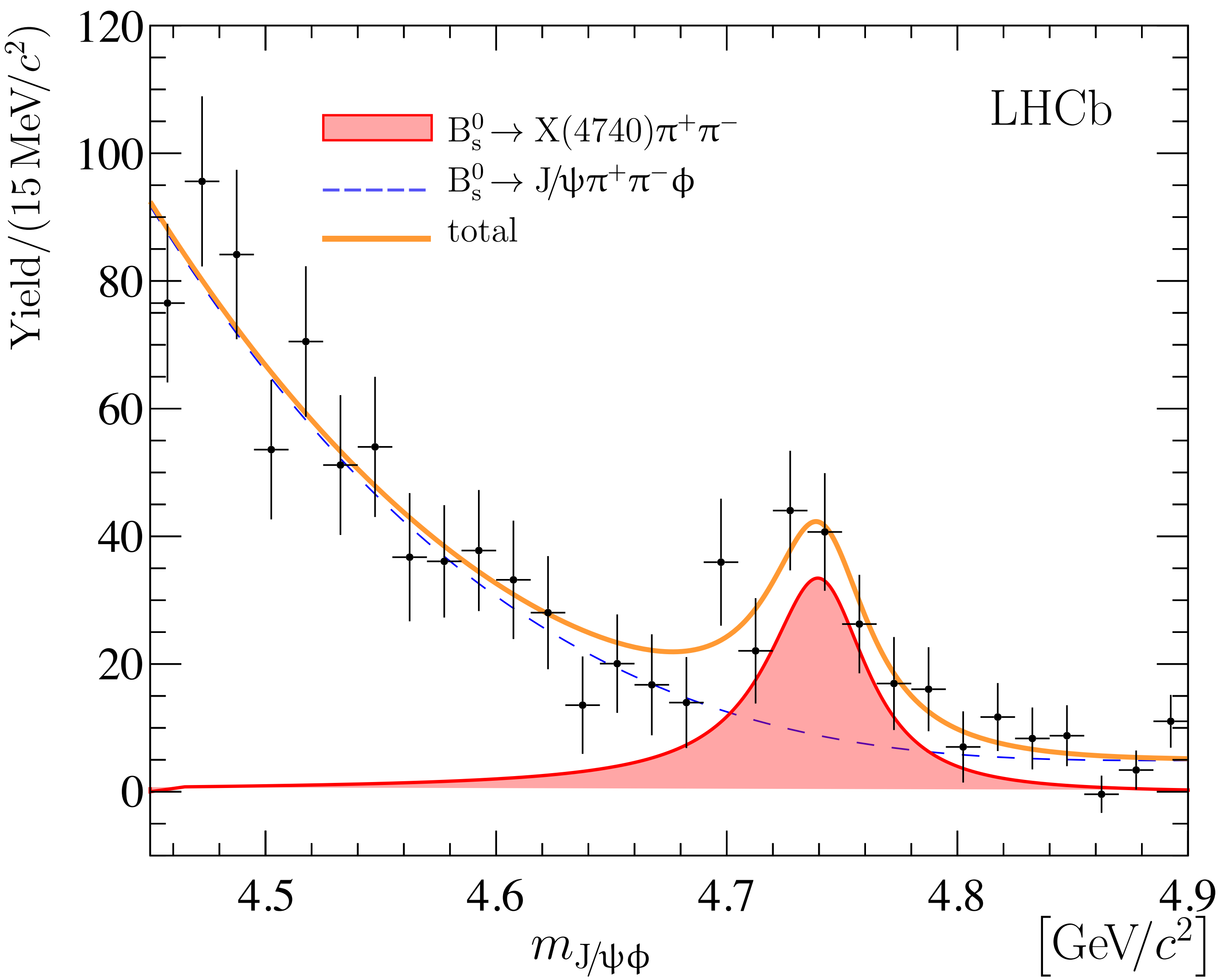
Study of $J/\psi\phi$ spectrum

- Fit to two-dimensional $J/\psi\pi^+\pi^-K^+K^-$ and K^+K^- distribution
- Look at background -subtracted distributions



- The $B_s^0 \to \psi(2S)\phi$ and $B_s^0 \to \chi_{c1}(3872)\phi$ contribution vetoed
- No structure in $\phi-$sideband
- $\phi^*(1850), \phi^*(1680)?, \phi^*(2170)?$
- Studied with MC, no peak in $J/\psi\phi$

X(4740) state?



Observation of $B_s^0 \to X(4740)\pi^+\pi^-$ decays:

- 175 ± 39
- Significance 5.3σ

Mass and width:

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

Fit to background-subtracted distribution

- S-wave RBW multiplied to phase space function
- Monotonic decreasing three-order polynomial function

X(4740) state?

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Mass and width:

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

Mass is close to the expected value for predicted $cs\bar{c}\bar{s}$ states ($J^{PC} = 2^{++}$)

$$m_{cs\bar{c}\bar{s}} = 4748 \ \text{MeV}/c^2$$

D. Ebert, R. N. Faustov, V. O. Galkin

EPJ C 58 (2008) 399

Mass and width are close to $\chi_{c1}(4700)$ and $\chi_{c1}(4684)$ states parameters:

$$m_{\chi_{c1}(4700)} = 4694 \pm 4^{+15}_{-3} \ \text{MeV}/c^2$$
$$\Gamma_{\chi_{c1}(4700)} = 87 \pm 8^{+16}_{-6} \ \text{MeV}$$
$$m_{\chi_{c1}(4685)} = 4684 \pm 7^{+13}_{-16} \ \text{MeV}/c^2$$
$$\Gamma_{\chi_{c1}(4685)} = 126 \pm 15^{+37}_{-41} \ \text{MeV}$$

arXiv:2103.01803

Systematics is quite large for $\chi_{c1}(4700)$ and $\chi_{c1}(4684)$ states

Needs to improve systematic

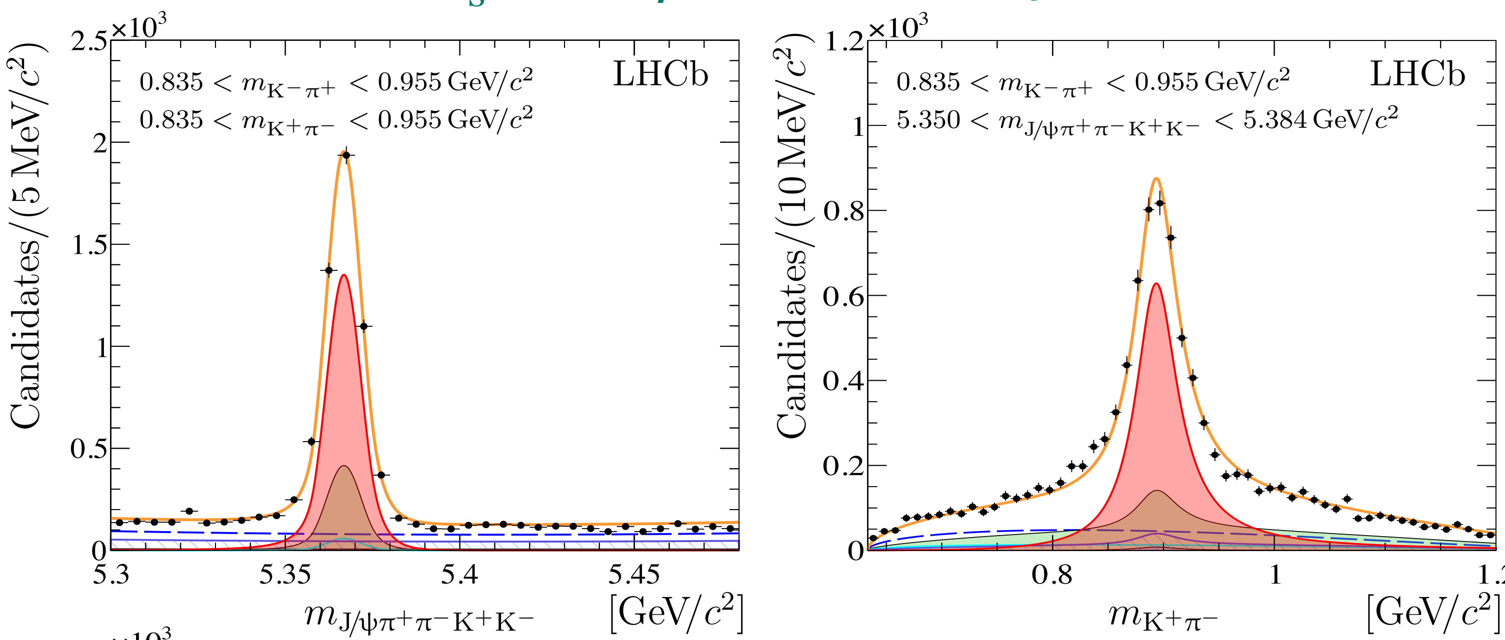
P-value:

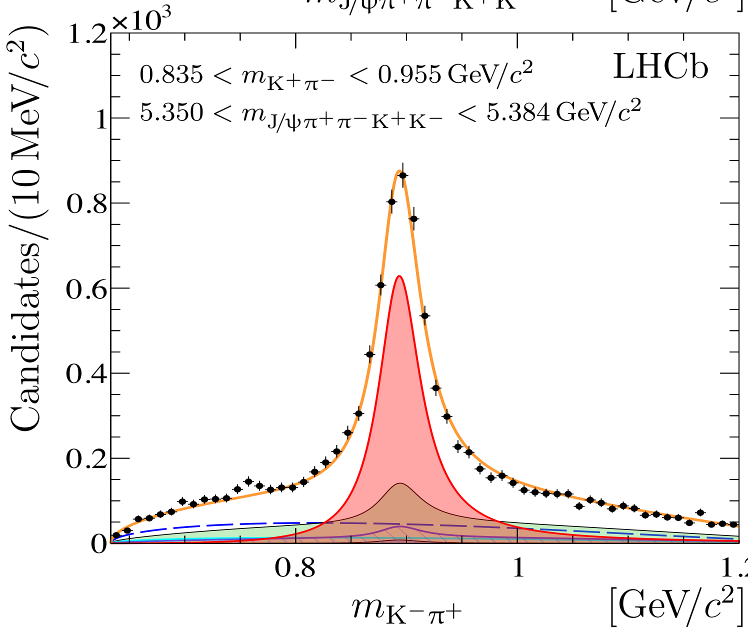
$$p^{syst} = 0.012 \ X(4700) - 2.3\sigma \qquad p^{w/o\ syst} = 8.07 \times 10^{-11} \ X(4700) - 6.3\sigma$$
$$p^{syst} = 0.0009 \ X(4684) - 3.1\sigma \qquad p^{w/o\ syst} = 1.34 \times 10^{-11} \ X(4684) - 6.6\sigma$$

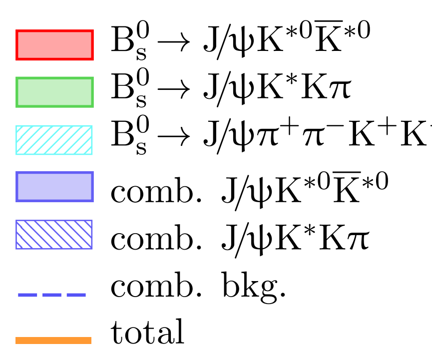
The full amplitude analysis is needed to account for interference effects

More results in $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays

Observation of the $B_s^0 \to J/\psi K^{*0}\bar{K}^{*0}$ decays







- Studied channel: $B_s^0 \to J/\psi K^{*0}\bar{K}^{*0}$
- Normalization channel: $B_s^0 \to \psi(2S)\phi$
- First observation of $B_s^0 \to J/\psi K^{*0}\bar{K}^{*0}$ decay: 5447 ± 125 events

First measurement:

$$\frac{\mathcal{B}\left(B_s^0 \to J/\psi K^{*0}\overline{K}^{*0}\right) \times \left(\mathcal{B}\left(K^{*0} \to K^+\pi^-\right)\right)^2}{\mathcal{B}\left(B_s^0 \to \psi(2S)\phi\right) \times \mathcal{B}\left(\psi(2S) \to J/\psi\pi^+\pi^-\right) \times \mathcal{B}\left(\phi \to K^+K^-\right)} = 1.22 \pm 0.03 \pm 0.04$$

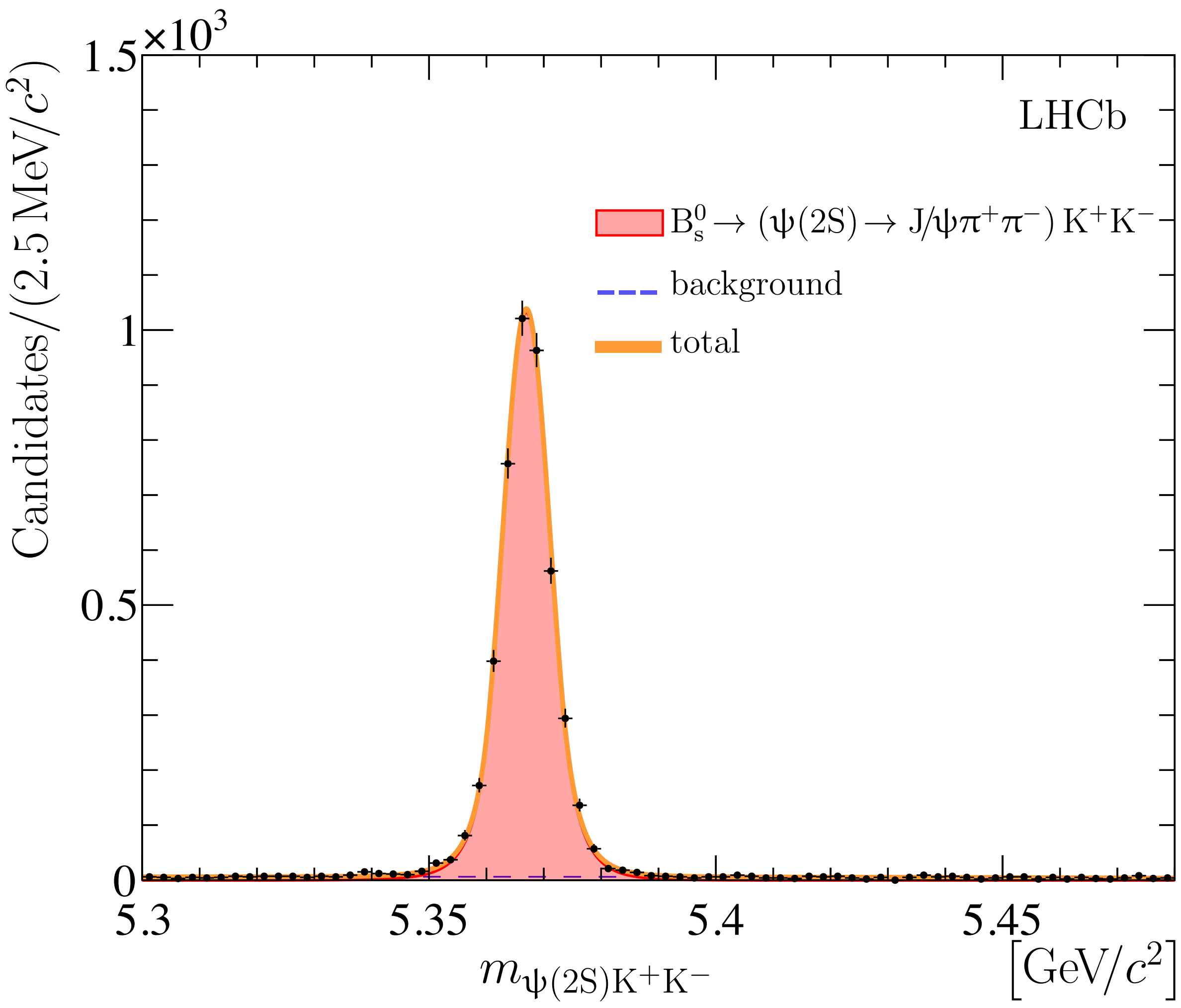
- Large branding fraction for the limited phase space
- Compare with BR for $B_s^0 \to J/\psi\eta'\phi$ and $B_s^0 \to J/\psi\eta'\eta'$ (not yet observed)

More results in $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays

- Fit in the narrow $\psi(2S)$ and ϕ mass region:

$$3.679 < m_{J/\psi\pi^+\pi^-} < 3.694\,\mathrm{GeV}/c^2$$

- Allow use $\psi(2S)$ mass constraint to B_s^0 mass
  - Improve resolution
  - Reduce systematic uncertainty
  - Systematic dominated by momentum scaling

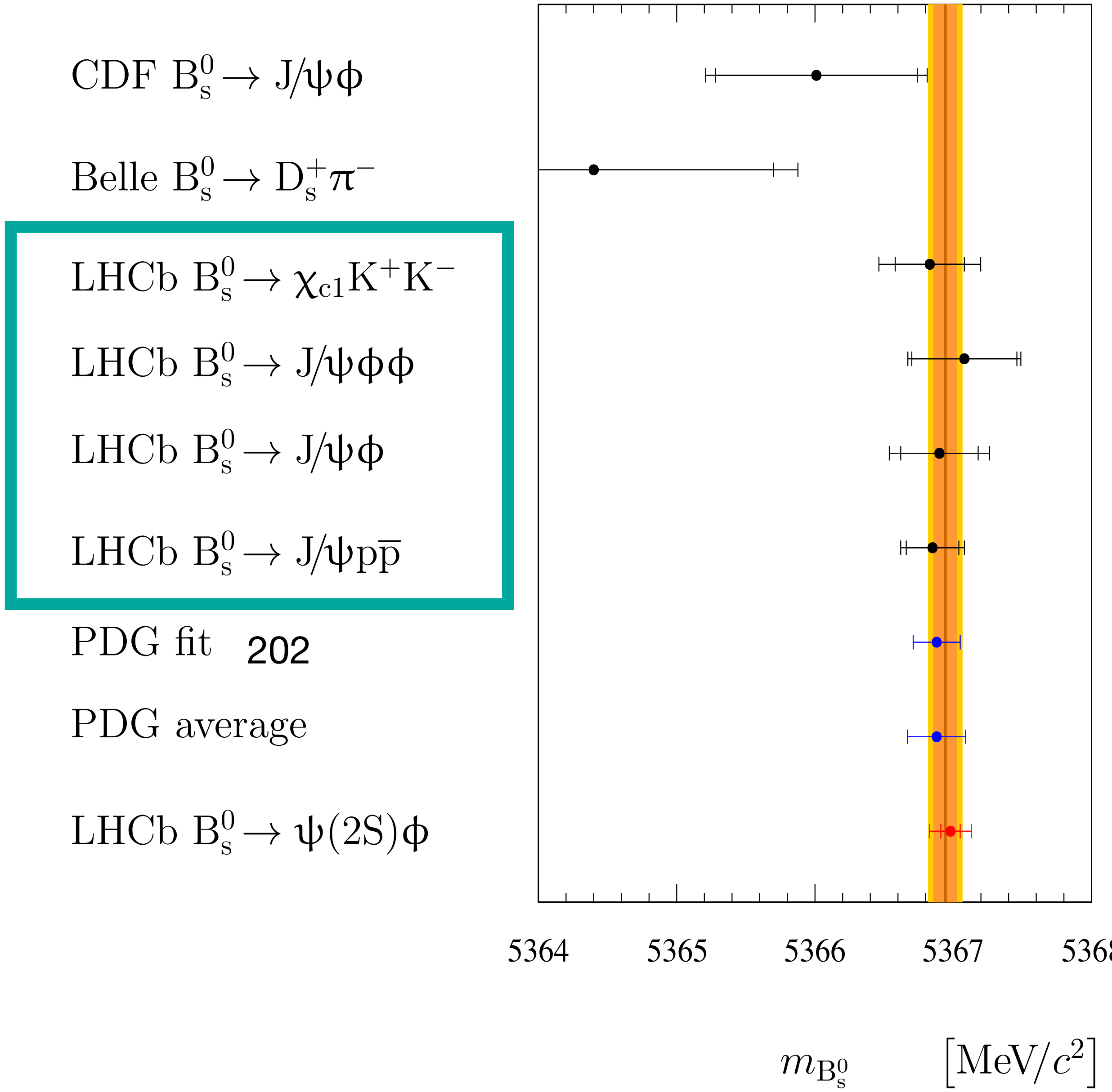


Most precise single measurements :

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

LHCb avarage:

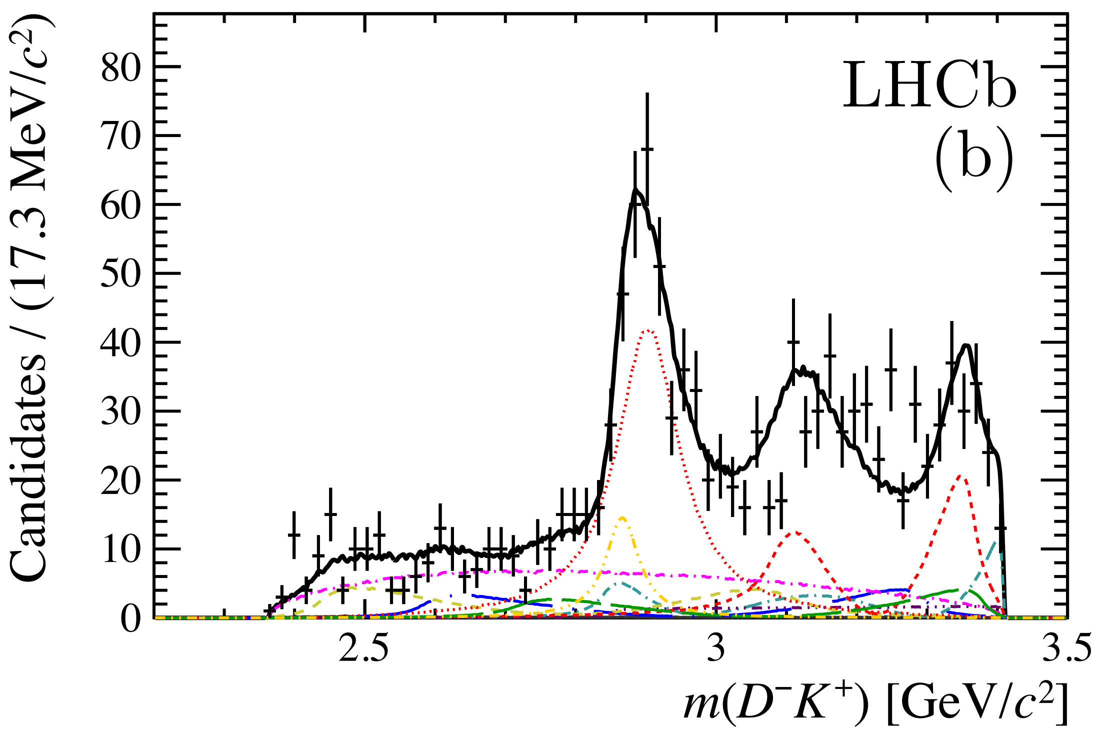
$$m_{B_s^0}^{\mathrm{LHCb}} = 5366.94 \pm 0.08 \pm 0.09\,\mathrm{MeV}/c^2$$



- The Run 1+2 amplitude analysis to $B^+ \to J/\psi\phi K^+$ channels are performed:
  - Previous result of Run 1 data are confirmed with high statistics
  - Four new state in $J/\psi K^+$ and $J/\psi\phi$ are observed
  - $Z_{cs}(4000)^+$ (1^+) is observed with high significance and broad $Z_{cs}(4220)$ state is observed
  - The X(4685)(1^+) and X(4630) states are also observed for the first time
- The study of the $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays is performed:
  - Several new channels are observed and their BR are measured
    - $B_s^0 \to \chi_{c1}(3872)\phi$, $B_s^0 \to \chi_{c1}(3872)(K^+K^-)_{\not\phi}$, $B_s^0 \to J/\psi K^{*0}\bar{K}^{*0}$
  - The new structure X(4740) in the $J/\psi\phi$ spectrum are observed with significance $> 5\sigma$
  - Precise B_s^0 mass measurement

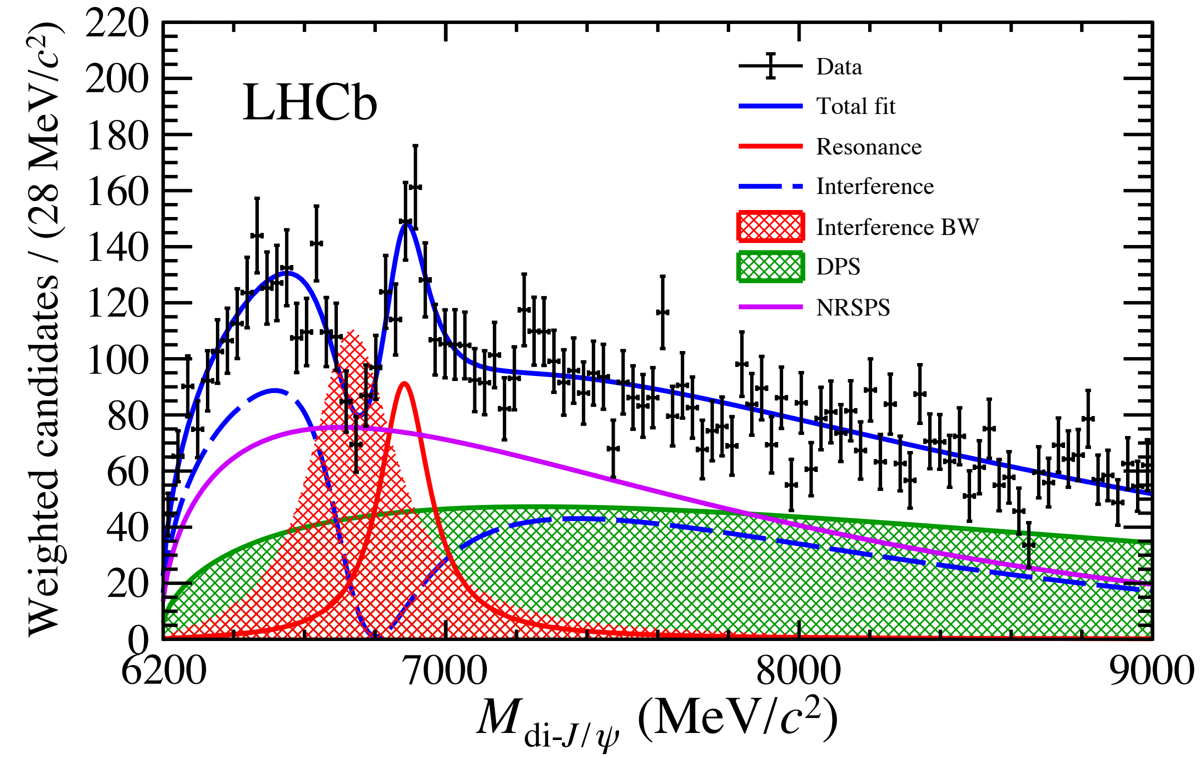
Strange tetraquark in D^-K^+ system

PRD 102 2020 112003



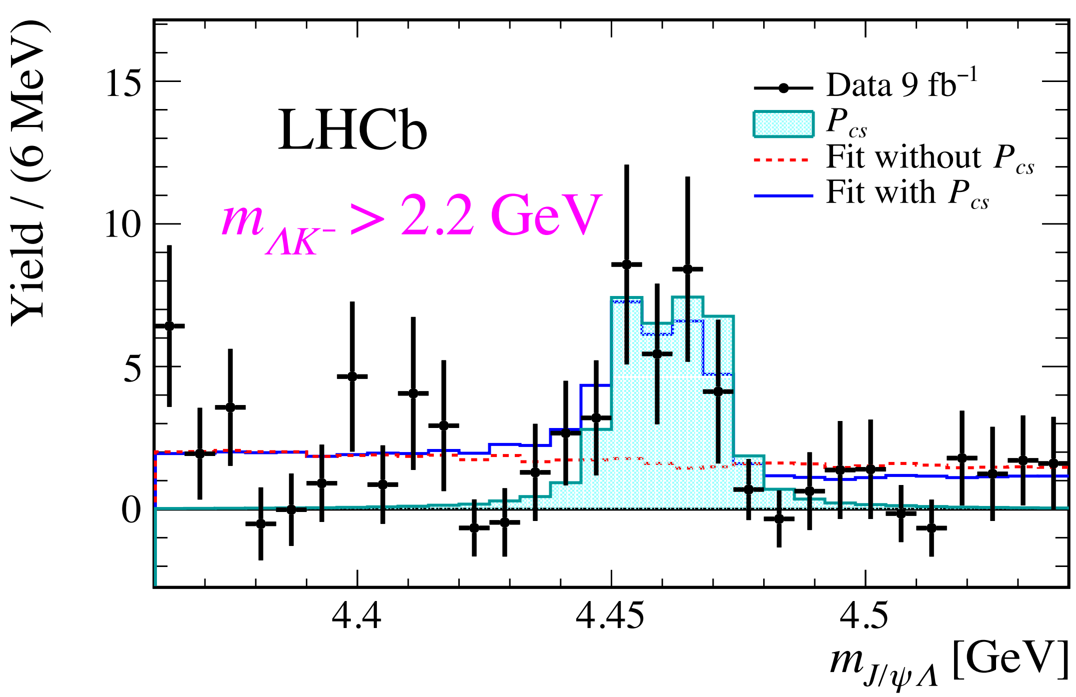
Four charm tetraquark in $J/\psi J/\psi$ system

SciB 65 (2020) 1983



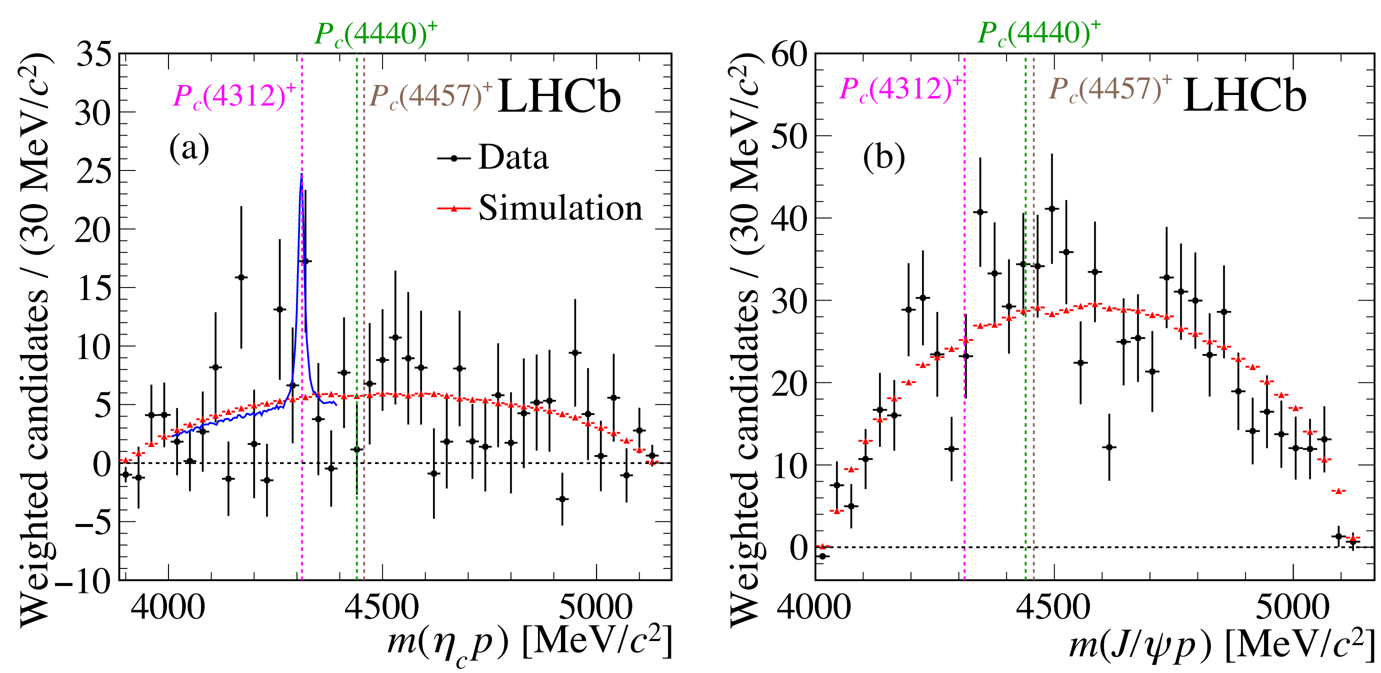
Evidence of structure in $J/\psi\Lambda$ spectrum

arXiv:2012.10380



Search for $P_c(4312)^+$ in $\Lambda_b^0 \to \eta_c(1S)pK^-$ decays

PRD 102 (2020) 112012



Thank you for attention!

A lot of analyses are ongoing with full LHCb data sample

Search for new exotic states are continuing

Stay tuned and look forward for new results at LHCb published papers web page!

Two most important link in this talk: 1,2