Spectroscopy at LHCb: experimental overview and prospects

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on behalf of the LHCb collaboration

Hadron Spectroscopy: The Next Big Steps
Mainz Institute for Theoretical Physics
(virtual)
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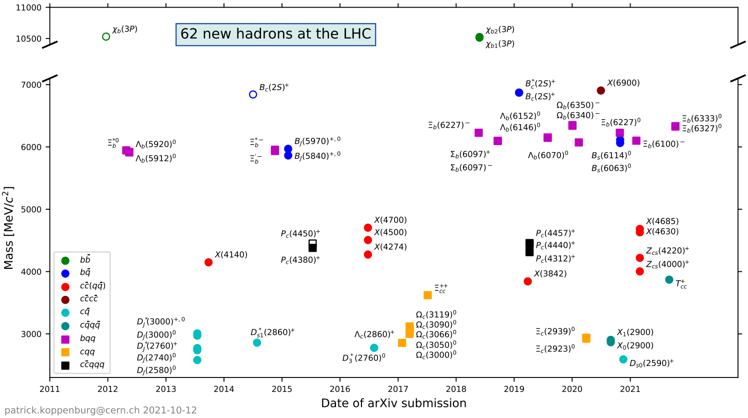
Spectroscopy at LHCb

High luminosity, high b/c production cross-section, a unique dedicated design
LHCb: major player in the field of heavy hadron spectroscopy



From [P. Koppenburg]

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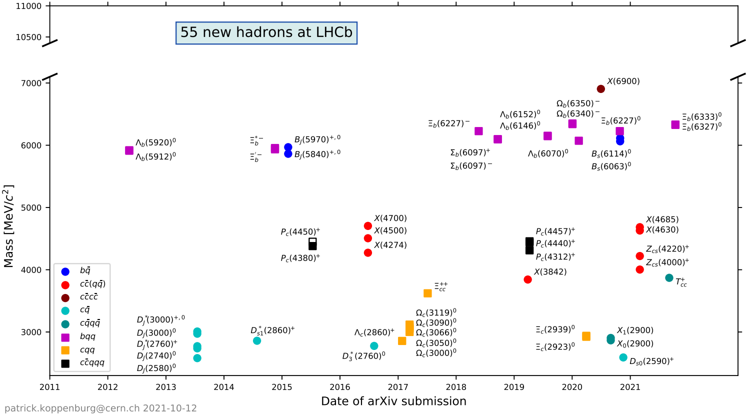

From [P. Koppenburg]

The spectroscopy programme

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Conventional heavy-hadron spectroscopy

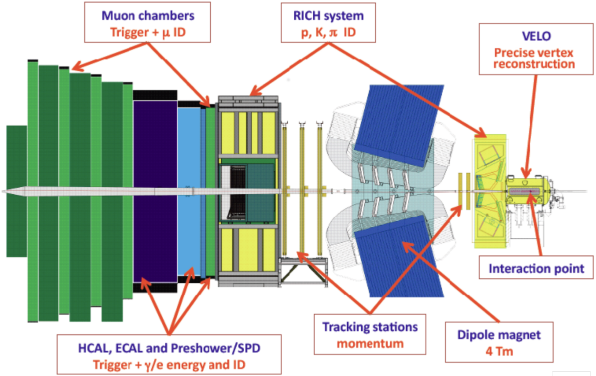
- Excited mesons: $B^{+,0}$, B_s^0, B_c^+, $D^{+,0}$, D_s^+...
- Excited conventional charmonia
- Excited baryons: Ξ_b^0, Λ_b^0, Σ_b^+, Ω_c^0, Ω_b^-...
- Discovery and searches of new particles and decay modes
- Precise mass, width, BR measurements and more

Exotic spectroscopy

- $\chi_{c1}(3872)$: production and decay, lineshape, mass, width
- Many other $c\bar{c}$ tetraquark candidates in various final states from b decays and primary vertex
- Exotic non-charmonia: charged states, cc, $cc\bar{c}\bar{c}$, open charm
- Pentaquark candidates
- Searches for unexpected contributions

The LHCb experiment at CERN

Single-arm spectrometer designed for high precision flavour physics measurements



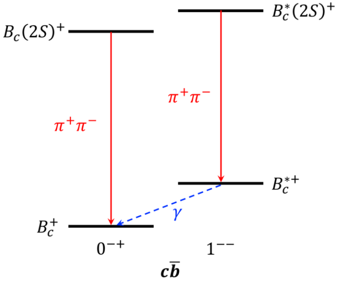
Total recorded luminosity:

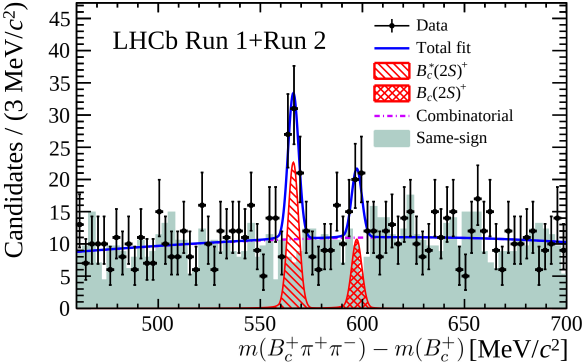
- Run 1: 1 fb^{-1} at $\sqrt{s} = 7$ TeV + 2 fb^{-1} at $\sqrt{s} = 8$ TeV
- Run 2: 6 fb^{-1} at $\sqrt{s} = 13$ TeV

[JINST 3 (2008) S08005]

CONVENTIONAL HEAVY HADRON SPECTROSCOPY

Observation of a new excited B_c^+ state





- Peak consistent with the $B_c^*(2S)^+$ state in the $B_c^+\pi^+\pi^-$ spectrum
- Significance 6.3σ global, 6.8σ local
- Hint for a second structure consistent with the $B_c(2S)^+$ state
- Significance 2.2σ global, 3.2σ local
- $\Delta m = 31.0 \pm 1.4 \pm 0.0$ MeV$/c^2$
- Consistent with, but more precise than the states observed by CMS

[PRL 122 (2019) 232001], [PRL 122 (2019) 132001]

Observation of new excited B_s^0 states

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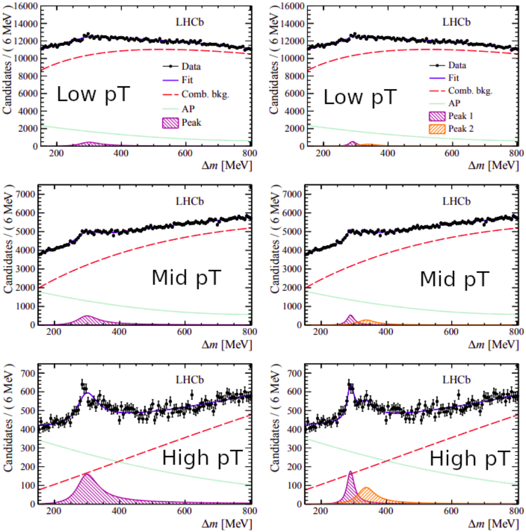
- Combine B^+ with a prompt K^-
- $B^+ \to J/\psi K^+$ or $B^+ \to \overline{D}^0\pi^+$
- $< 10\%$ background in B^+ peak
- $\Delta m = m(B^+K^-) - M_{B^+} - M_{K^-}$
- Structure at around 300 MeV$/c^2$
- Background: combinatorial and associated production (AP)
- Signal: one or two relativistic Breit-Wigners with resolution
- Two peaks hypothesis favoured with high significance
- Single resonance decaying through both B^+K^- and $B^{*+}K^-$ is disfavoured but cannot be excluded



[EPJC 81 7 (2021) 601]

Observation of new excited B_s^0 states

Under the two-peak hypothesis:

$$m_1 = 6063.5 \pm 1.2 \pm 0.8\ \text{MeV}/c^2,\ \Gamma_1 = 26 \pm 4 \pm 4\ \text{MeV},$$

$$m_2 = 6114 \pm 3 \pm 5\ \text{MeV}/c^2,\ \Gamma_2 = 66 \pm 18 \pm 21\ \text{MeV}.$$

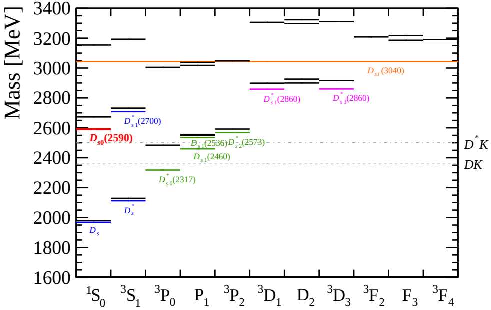
Including the photon the masses shift of about 45 MeV/c^2. Furthermore:

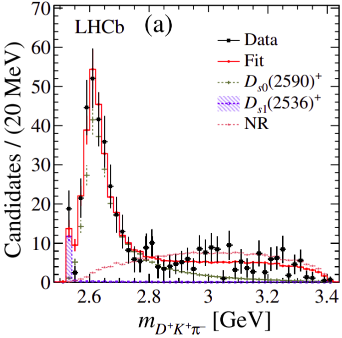
$$R = \frac{\sum \sigma(B_s^{**0}) \times \mathcal{B}(B_s^{**0} \to B^{(*)+}K^-)}{\sigma(B_{s2}^{*0}) \times \mathcal{B}(B_{s2}^{*0} \to B^+K^-)} = 0.87 \pm 0.15 \pm 0.19$$

[EPJC 81 7 (2021) 601]

Observation of a new excited D_s^+ state

$D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ masses are much smaller than predicted
Are they exotic candidates? Additional input is required.



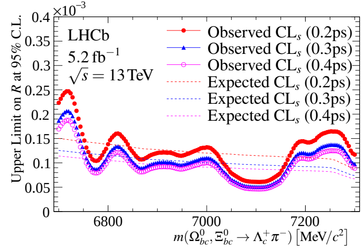


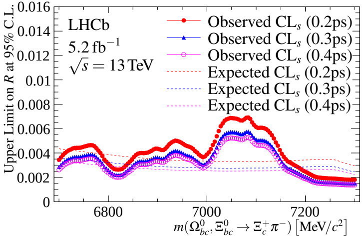
- Amplitude analysis of $B^0 \to D^+D^-K^+\pi^-$ with $m_{K^+\pi^-} < 750$ MeV$/c^2$
- Clear structure at $m_{D^+K^+\pi^-} \approx 2600$ MeV$/c^2$, $J^P = 0^-$ at 10σ
- $m_{D_{s0}(2590)^+} = 2591 \pm 6 \pm 7$ MeV$/c^2$, $\Gamma_{D_{s0}(2590)^+} = 89 \pm 16 \pm 12$ MeV$/c^2$
- Strong candidate for the $D_s(2^1S_0)^+$ state

[PRL 126 (2021) 122002]

Search for Ω_{bc}^0 and Ξ_{bc}^0

- Search for peaks in the $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$ final states
- Λ_c^+ and Ξ_c^+ reconstructed as $pK^-\pi^-$
- No evidence for either states is observed
- Upper limits at 95% CL are set
- R: production cross-section multiplied by BR and normalised with Λ_b^0 or Ξ_b^0 decays to $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$

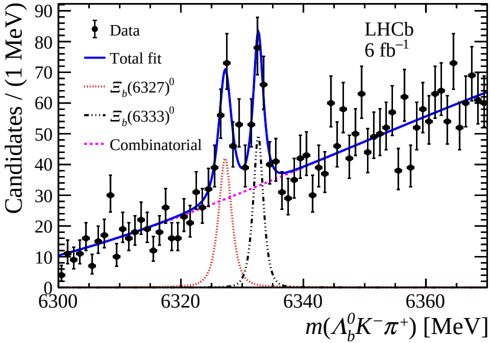




[Chin. Phys. C 45 093002]

New excited Ξ_b^0 states

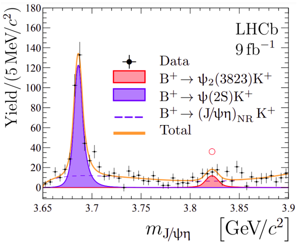
- Two narrow peaks observed in the $\Lambda_b^0 K^- \pi^+$ spectrum
- Large significance wrt one and no peak hypotheses
- $m(\Xi_b(6327)^0) = 6327.28^{+0.23}_{-0.21} \pm 0.08 \pm 0.24$ MeV, $\Gamma(\Xi_b(6327)^0) < 2.20$ MeV
- $m(\Xi_b(6333)^0) = 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22$ MeV, $\Gamma(\Xi_b(6333)^0) < 1.55$ MeV
- Consistent with the predicted 1D Ξ_b^0 doublet, $J^P = 3/2^+$ and $J^P = 5/2^+$

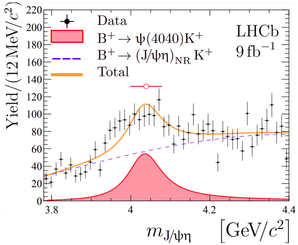


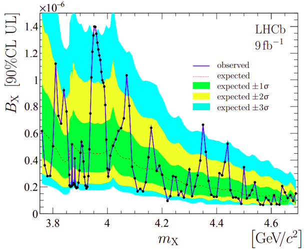
[arXiv:2110.04497], submitted to Phys. Rev. Lett.

Study of the $B^+ \to J/\psi \eta K^+$ decay

Search for charmonia and charmonia-like exotics decaying into $J/\psi\eta$







Only contribution found: $\psi_2(3823)$ and $\psi(4040)$
Limits at 90% CL set on $\mathcal{B}(X \to J/\psi\eta)$ scanning $m_X \in [3750, 4700]$ GeV$/c^2$

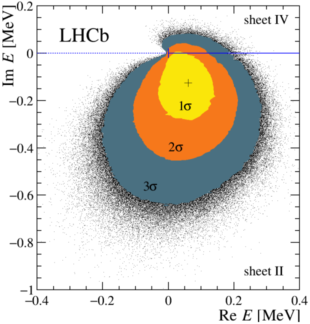
[arXiv:2202.04045], Submitted to JHEP

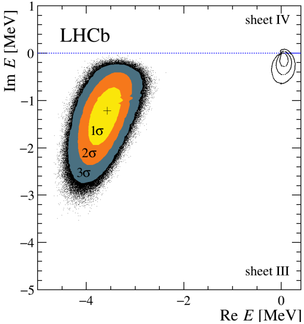
EXOTIC SPECTROSCOPY

Study of the $\chi_{c1}(3872)$ lineshape

Study of the analytic structure of the amplitude near $\overline{D}^0 D^{*0}$ threshold

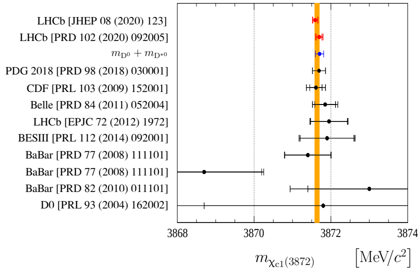
- Complex amplitude is a function of $\sqrt{E} \Longrightarrow$ two-sheeted Riemann surface
- Two poles are found using the Flatté amplitude for the $\overline{D}^0 D^{*0}$ channel
- One (left) on the physical sheet, the other (right) on the unphysical sheet
- Bound state preferred, virtual assignment cannot be ruled out
- Binding energy $E_b < 100$ keV, $Prob$(compact component) $< 33\%$

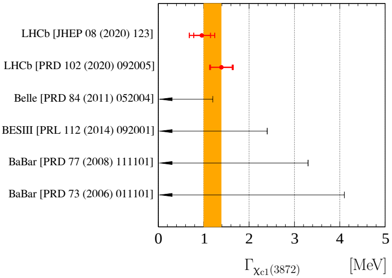




[PRD 102 (2020) 092005]

Mass and width of $\chi_{c1}(3872)$





Yellow vertical bands correspond to the new world averages:

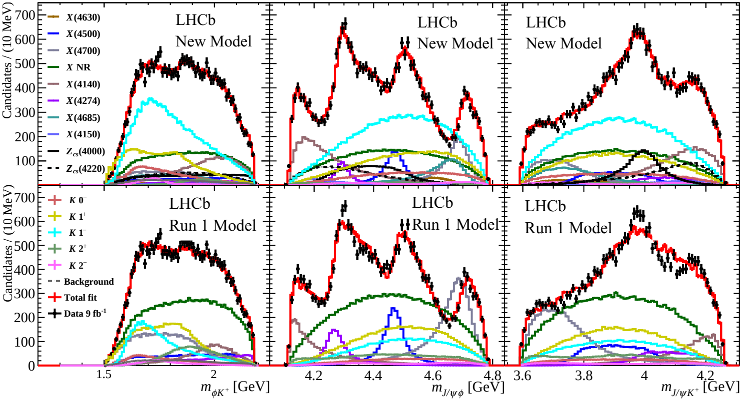
$$m^{BW}_{\chi_{c1}(3872)} = 3871.64 \pm 0.06 \text{ MeV}$$

$$\Gamma^{BW}_{\chi_{c1}(3872)} = 1.19 \pm 0.19 \text{ MeV}$$

More information on the dedicated $\chi_{c1}(3872)$ talk by Tomasz on Thursday

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

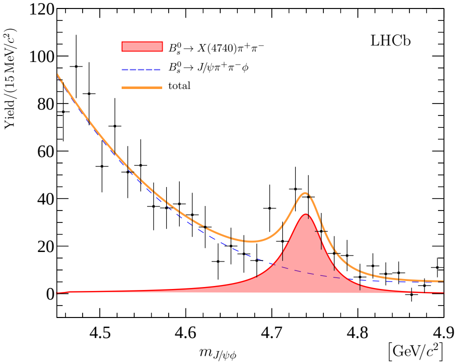
Exotics in $B^+ \to J/\psi\phi K$ decays



Confirmed states: $X(4150)$, $X(4500)$, $X(4700)$, $X(4140)$, $X(4274)$
New states: $X(4630)$, $X(4685)$, $Z_{cs}(4000)$, $Z_{cs}(4220)$
First observation of exotic states with $c\bar{c}u\bar{s}$ content in the $J/\psi K^+$ final state

[PRL 127 (2021) 082001]

Observation of $X(4740)$



Another exotic decaying into $J/\psi\phi$ from $B_s^0 \to J/\psi K^+K^-\pi^+\pi^-$

$$m_{X(4740)} = 4741 \pm 6 \pm 6 \text{ MeV}/c^2$$

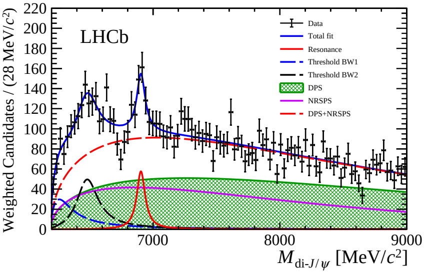
$$\Gamma_{X(4740)} = 53 \pm 15 \pm 11 \text{ MeV}/c^2$$

Still unclear whether this is the same state as $X(4700)$ from $B^+ \to J/\psi\phi K^+$

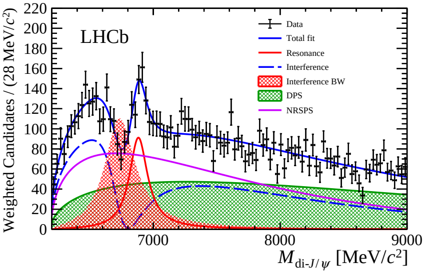
[JHEP 02 (2021) 024]

Structure in J/ψ-pair mass spectrum

No interference



SPS-BW interference



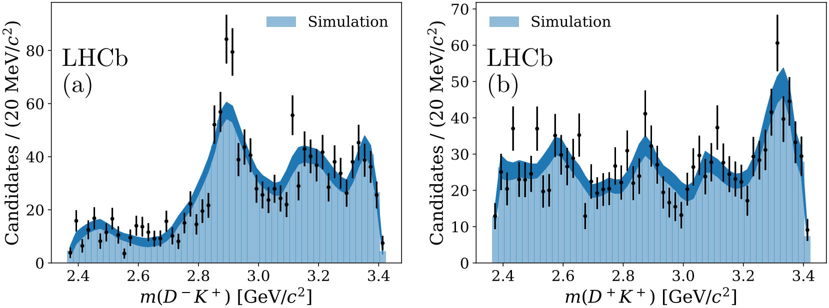
- Threshold enhancement described by two resonances
- S-wave BW $\times$ 2-body phase space
- $m_{X(6900)} = 6905 \pm 11 \pm 7$ MeV
- $\Gamma_{X(6900)} = 80 \pm 19 \pm 33$ MeV
- Significance $>5\sigma$

- Threshold enhancement described by interference
- One BW, interference with SPS
- $m_{X(6900)} = 6886 \pm 11 \pm 11$ MeV
- $\Gamma_{X(6900)} = 168 \pm 33 \pm 69$ MeV
- Significance $>5\sigma$

Further studies are required to investigate the nature of X(6900). If confirmed:
First observation of exotic hadron composed by heavy quarks of the same flavour

[Sci. Bull. 2020 65(23) 1983]

Model-independent study of $B^+ \to D^+ D^- K^+$

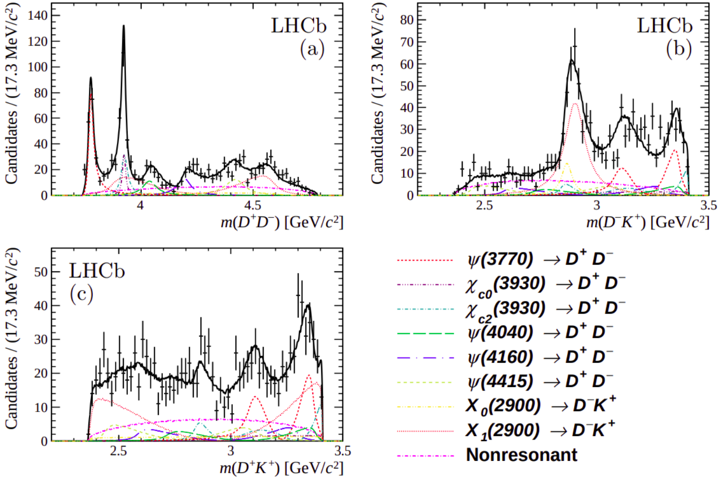


- Study of the resonant structure of $B^+ \to D^+ D^- K^+$, expanding the DD helicity angle in terms of Legendre polynomials
- Data not well described by Legendre moments from resonances up to $J = 2$
- Higher-spin resonances are suppressed
- The $D^+ K^+$ spectrum does not present any unexplained structure
- The hypothesis that only $D^+ D^-$ resonances up to spin 2 are present is rejected with a significance of 3.9σ

[PRL 125 (2020) 242001]

Amplitude analysis of $B^+ \to D^+ D^- K^+$

- Data not well described by considering only DD resonances
- Two $D^- K^+$ Breit-Wigners added to improve significantly the fit
- Spin-0 and spin-1, roughly the same mass



[PRD 102 (2020) 112003]

Amplitude analysis of $B^+ \to D^+ D^- K^+$

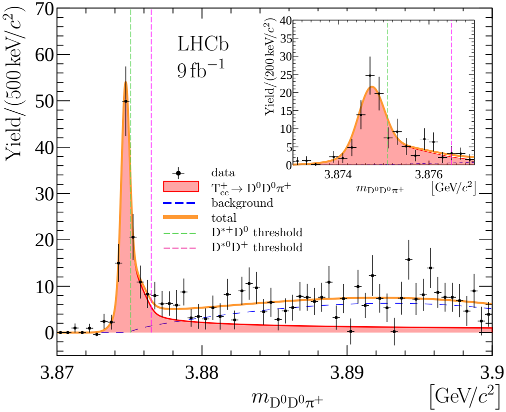
- No evidence for the $\chi_{c0}(3860) \to D^+ D^-$ state reported by Belle
- The $\chi_{c2}(3930)$ contribution is better described by two states
- Reasonable agreement with data when including 2 $D^- K^+$ Breit-Wigners

If interpreted as resonances $\Longrightarrow$ first clear observation of exotic hadrons with open flavour, and without a heavy quark-antiquark pair

Minimal quark content: $[cd\bar{s}\bar{u}]$

More information on the dedicated X(2900) talk by Ruiting Ma on Wednesday

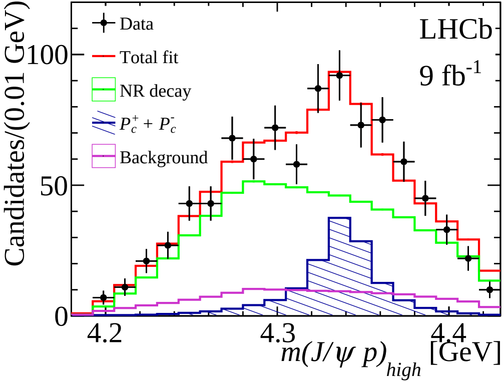
Observation of a doubly-charmed tetraquark



Narrow peak in the $D^0D^0\pi^+$ spectrum just below the $D^{*+}D^0$ threshold
Consistent with the ground isoscalar T_{cc}^+ tetraquark with quark content $cc\bar{u}\bar{d}$
More information on the dedicated T_{cc}^+ talk by Mikhail on Wednesday

[arXiv:2109.01038], [arXiv:2109.01056]

New pentaquarks: $P_c(4337)^+$



Evidence for a structure in $J/\psi p$ and $J/\psi\bar{p}$ from $B_s^0 \to J/\psi p\bar{p}$

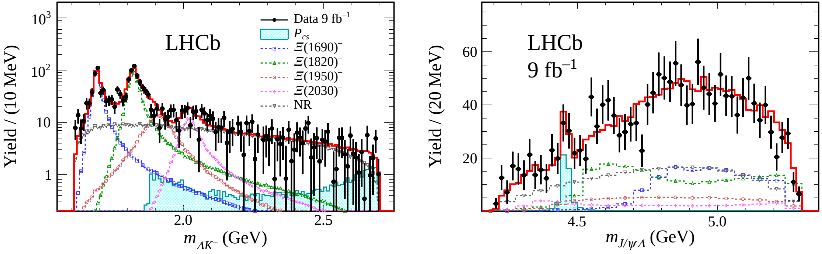
- $m_{P_c} = 4337^{+7+2}_{-4-2}$ MeV, $\Gamma_{P_c} = 29^{+26+14}_{-12-14}$ MeV
- No evidence for $P_c(4312)^+$ nor for $f_J(2220)$ (glueball)

More information on the dedicated Pentaquarks talk by Liming on Friday

Eur. Phys. C75 (2015) 101, [arXiv:2108.04720], submitted to PRL

New pentaquarks: $P_{cs}(4459)^0$

Amplitude analysis of $\Xi_b^0 \to J/\psi \Lambda K^-$ decays



- Two new Ξ^{*-} states observed: $\Xi(1690)^-$ and $\Xi(1820)^-$
- Evidence for a new pentaquark with strangeness
- Mass is 19 MeV below the $\Xi_c^0 \bar{D}^{*0}$, J^P not yet determined
- Limited yield, improvements foreseen in the next years

More information on the dedicated Pentaquarks talk by Liming on Friday

[Sci. Bull. 2021 66(13) 1278]

CONCLUSIONS AND PROSPECTS

Conclusions

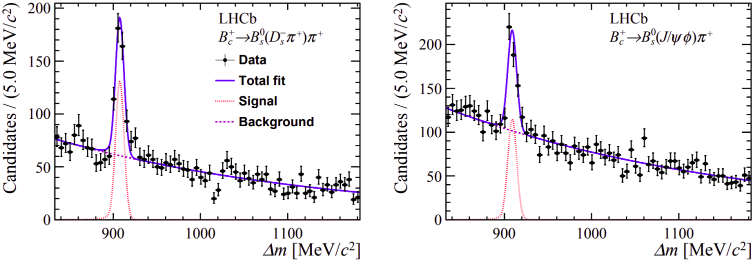
- Heavy meson spectroscopy is an extremely rich and productive field, both for conventional and exotic states
- New conventional (excited) and exotic hadrons are discovered every year
- LHCb has established itself to be a major player due to high luminosity, high b/c production cross-section and a unique, dedicated design
- Spectroscopy of heavy hadrons is crucial to understand QCD dynamics and binding rules
- Many excitation spectra are still mostly unexplored territory
- New "non-conventional" exotic states have been discovered recently

Prospects for Run 3

- Run 3 will start with an upgraded detector and a software-only trigger, with improvements on hadronic triggers
- LHC experiments will be the only explorers of the B_c^+ spectrum in the near future and LHCb will play a major role in it
- Heavy baryon spectroscopy already started in Run 2, focus on bc searches
- Run 3: access to bc tetraquarks and pentaquarks and $b\bar{b}$ spectroscopy
- Confirm P_c and P_{cs} and measure their properties
- For Runs 1-2 exotic hadron searches rely on J/ψ for reconstruction
- In Run 3, with the removal of the L0 trigger, fully-hadronic final states will be accessible allowing studies on open-flavour exotic states

BACKUP

B_c^+ - B_s^0 mass difference



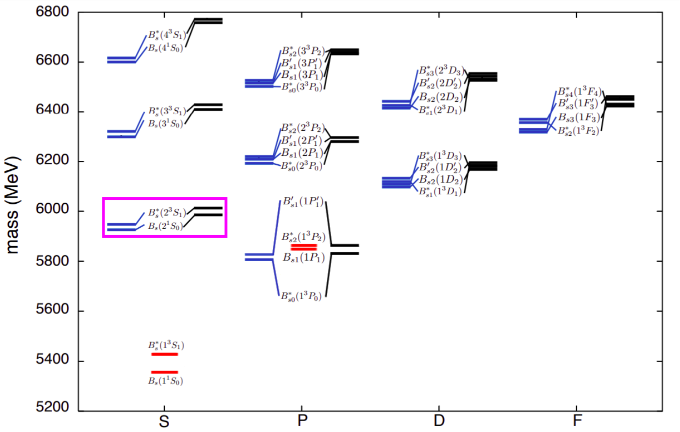
$$\Delta m = 907.75 \pm 0.37 \pm 0.27\ \mathrm{MeV}/c^2$$

[JHEP 07 (2020) 123]

Observation of new excited B_s^0 states

The B_s^0 excitation spectrum is mostly inexplored as well

- Only ground state + three excited states observed
- First radial excitation (B_s^{*0}) and first orbital excitations (B_{s1}^0, B_{s2}^{*0})
- This analysis: observation of two new states



Adapted from [PRD 94 (2016) 054025]

$B^+ \to J/\psi\phi K^+$ fit results

J^P		Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
1^+	$2^1\mathrm{P}_1$	$K(1^+)$	4.5 (4.5)	$1861 \pm 10\,^{+\,16}_{-\,46}$	$149 \pm 41\,^{+\,231}_{-\,23}$	
	$2^3\mathrm{P}_1$	$K'(1^+)$	4.5 (4.5)	$1911 \pm 37\,^{+\,124}_{-\,48}$	$276 \pm 50\,^{+\,319}_{-\,159}$	
	$1^3\mathrm{P}_1$	$K_1(1400)$	9.2 (11)	1403	174	$15 \pm 3\,^{+\,3}_{-\,11}$
2^-	$1^1\mathrm{D}_2$	$K_2(1770)$	7.9 (8.0)	1773	186	
	$1^3\mathrm{D}_2$	$K_2(1820)$	5.8 (5.8)	1816	276	
1^-	$1^3\mathrm{D}_1$	$K^*(1680)$	4.7 (13)	1717	322	$14 \pm 2\,^{+\,35}_{-\,8}$
	$2^3\mathrm{S}_1$	$K^*(1410)$	7.7 (15)	1414	232	$38 \pm 5\,^{+\,11}_{-\,17}$
2^-	$2^3\mathrm{P}_2$	$K_2^*(1980)$	1.6 (7.4)	$1988 \pm 22\,^{+\,194}_{-\,31}$	$318 \pm 82\,^{+481}_{-\,101}$	$2.3 \pm 0.5 \pm 0.7$
0^-	$2^1\mathrm{S}_0$	$K(1460)$	12 (13)	1483	336	$10.2 \pm 1.2\,^{+\,1.0}_{-\,3.8}$
2^-		$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+\,59}_{-\,30}$	$2.0 \pm 0.5\,^{+\,0.8}_{-\,1.0}$
1^-		$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+\,18}_{-\,110}$	$174 \pm 27\,^{+\,134}_{-\,73}$	$2.6 \pm 0.5\,^{+\,2.9}_{-\,1.5}$
0^+		$X(4500)$	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)			$28 \pm 8\,^{+\,19}_{-\,11}$
1^+		$X(4140)$	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)	$4684 \pm 7\,^{+\,13}_{-\,16}$	$126 \pm 15\,^{+\,37}_{-\,41}$	$7.2 \pm 1.0\,^{+\,4.0}_{-\,2.0}$
1^+		$Z_{cs}(4000)$	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)	$4216 \pm 24\,^{+\,43}_{-\,30}$	$233 \pm 52\,^{+\,97}_{-\,73}$	$10 \pm 4\,^{+\,10}_{-\,7}$