Spectroscopy of conventional mesons at LHCb

Lorenzo Capriotti

on behalf of the LHCb collaboration

HADRON, Mexico City
(virtual)
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lorenzo.capriotti@bo.infn.it

Summary of the talk

Precision mass measurements

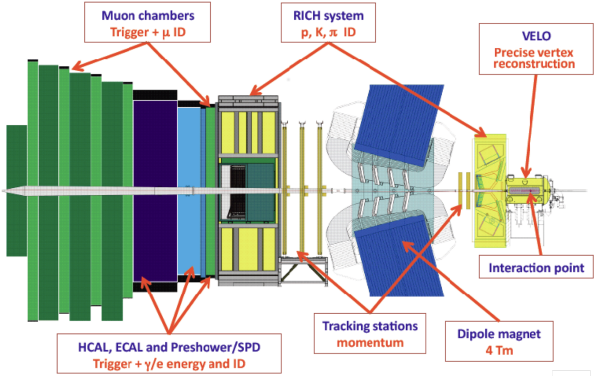
- Update of the $\psi_2(3823)$ mass
- Precision measurement of the B_c^+ mass

New excited mesons

- Excited charmonium in near-threshold $D\overline{D}$ spectroscopy
- Observation of an excited B_c^+ state
- Observation of new excited B_s^0 states
- Excited D_s^+ meson in $B^0 \to D^- D^+ K^+ \pi^-$ decays

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]

PRECISION MASS MEASUREMENTS

$\psi_2(3823)$ in $B^+ \to J/\psi\pi^+\pi^-K^+$

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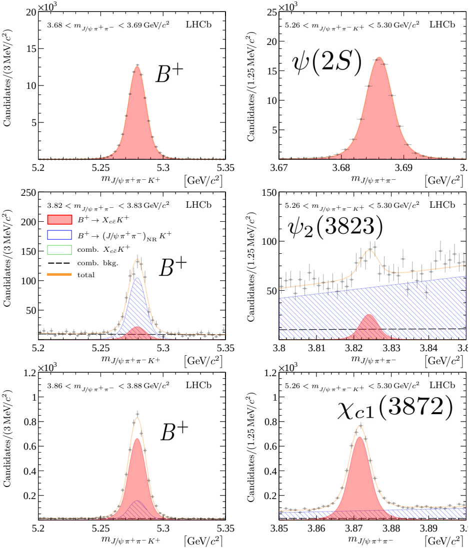
- $X(3823)$ interpreted as the $\psi_2(1^3D_2)$ state, $J^{PC} = 2^{--}$
- $\psi_2(3823) \to \chi_{c1}\gamma$ only final state observed with more than 5σ (BESIII)
- Full Run 1 + Run 2 dataset
- Using both $\psi(2S) \to J/\psi\pi\pi$ and $\chi_{c1}(3872) \to J/\psi\pi\pi$ as normalisation channels
- This allows to measure $\chi_{c1}(3872)$ properties as well
- 2D fit to m_{B^+} and $m_{J/\psi\pi^+\pi^-}$
- $\psi_2(3823)$ significance: 5.1σ
- $\chi_{c1}(3872)$ is described by a Breit-Wigner convoluted with a resolution function



[PRL 115, 011803 (2015)], [JHEP 08 (2020) 123]

$\psi_2(3823)$ in $B^+ \to J/\psi\pi^+\pi^- K^+$

Calculation of branching fractions ratios, where $\mathcal{R}_Y^X = \frac{\mathcal{B}(B^+ \to XK^+) \times \mathcal{B}(X \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B^+ \to YK^+) \times \mathcal{B}(Y \to J/\psi\pi^+\pi^-)}$:

- $\mathcal{R}_{\chi_{c1}(3872)}^{\psi_2(3823)} = (3.56 \pm 0.67 \pm 0.11) \times 10^{-2}$ **First measurement**
- $\mathcal{R}_{\psi(2S)}^{\psi_2(3823)} = (1.31 \pm 0.25 \pm 0.04) \times 10^{-3}$ **First measurement**
- $\mathcal{R}_{\psi(2S)}^{\chi_{c1}(3872)} = (3.69 \pm 0.07 \pm 0.06) \times 10^{-3}$ **Most precise**

Mass, binding energy and width of $\chi_{c1}(3872)$:

- $m_{\chi_{c1}(3872)} = 3871.59 \pm 0.06 \pm 0.03 \pm 0.01(m_{\psi(2S)})$ MeV **Most precise**
- $\Delta m_{\chi_{c1}(3872)} = m_{\overline{D}^0} + m_{D^{*0}} - m_{\chi_{c1}(3872)} = 0.12 \pm 0.13$ MeV
- $\Gamma_{\chi_{c1}(3872)} = 0.96^{+0.19}_{-0.18} \pm 0.21$ MeV **Non-zero width**

Mass and width of the $\psi_2(3823)$ state:

- $m_{\psi_2(3823)} = 3824.08 \pm 0.53 \pm 0.14 \pm 0.01(m_{\psi(2S)})$ MeV **Most precise**
- $\Gamma_{\psi_2(3823)} < 5.2$ MeV at 90% CL **World best limit**

[JHEP 08 (2020) 123]

Precision B_c^+ mass measurement

Using the full Run 1 and Run 2 dataset, eight different final states:

- $B_c^+ \to J/\psi\pi^+$
- $B_c^+ \to J/\psi\pi^+\pi^+\pi^-$
- $B_c^+ \to J/\psi p\bar{p}\pi^+$
- $B_c^+ \to J/\psi(D_s^+ \to K^+K^-\pi^+)$
- $B_c^+ \to J/\psi(D_s^+ \to \pi^+\pi^-\pi^+)$
- $B_c^+ \to J/\psi(D^0 \to K^-\pi^+)K^+$
- $B_c^+ \to (B_s^0 \to D_s^-\pi^+)\pi^+$
- $B_c^+ \to (B_s^0 \to J/\psi\phi)\pi^+$

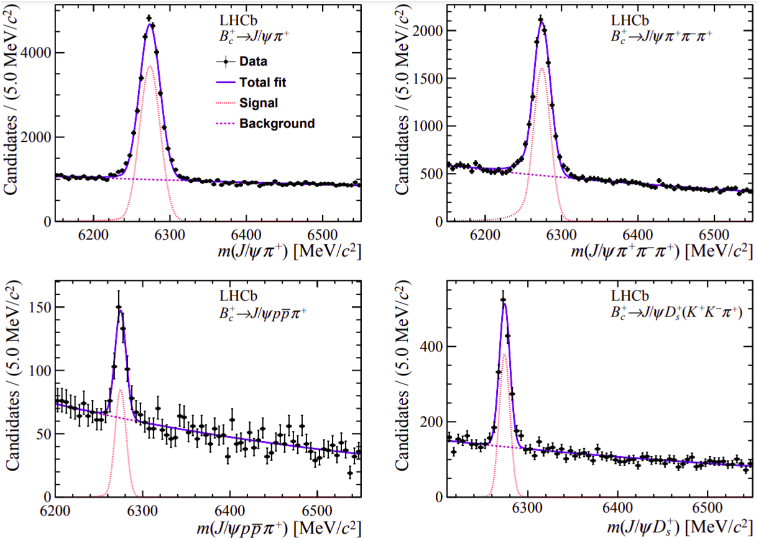
First two channels: large signal yield
Other channels: smaller phase space, lower momentum tracks, better mass resolution

Fit model: double-sided Crystal Ball + exponential background

Also: measure $\Delta m = m(B_c^+) - m(B_s^0)$ so that future $m(B_s^0)$ measurements can be used as inputs to update $m(B_c^+)$

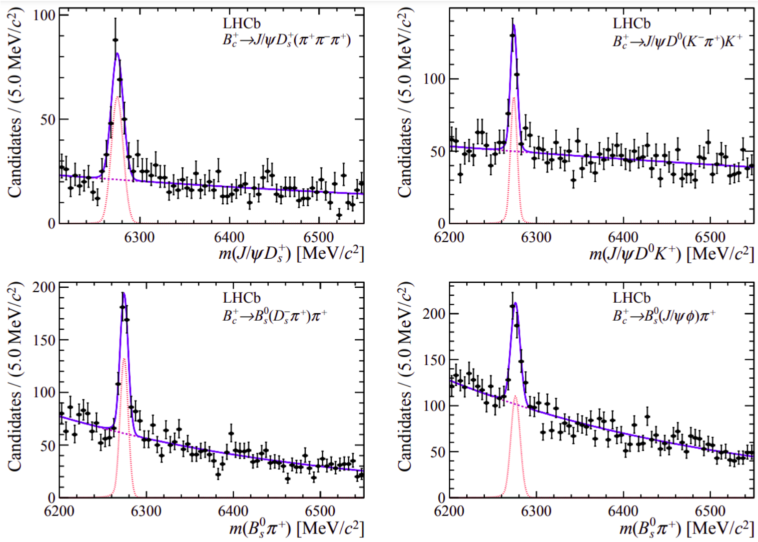
[JHEP 07 (2020) 123]

B_c^+ mass fits



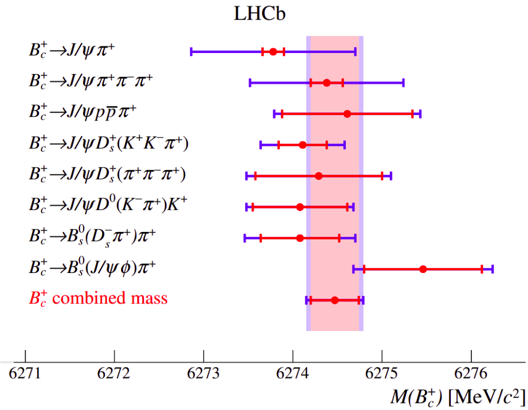
[JHEP 07 (2020) 123]

B_c^+ mass fits



[JHEP 07 (2020) 123]

B_c^+ mass measurement



Combined measured mass: $m(B_c^+) = 6274.47 \pm 0.27 \pm 0.17$ MeV$/c^2$

Mass difference: $\Delta m = m(B_c^+) - m(B_s^0) = 907.75 \pm 0.37 \pm 0.27$ MeV$/c^2$

Mass from Δm: $m(B_c^+) = \Delta m + m_{B_s^0}^{PDG} = 6274.6 \pm 3.2$ MeV$/c^2$

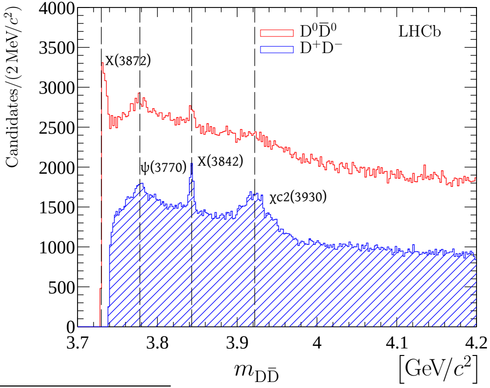
[JHEP 07 (2020) 123], [PDG 2020]

OBSERVATION OF NEW EXCITED MESONS

Near-threshold $D\overline{D}$ spectroscopy

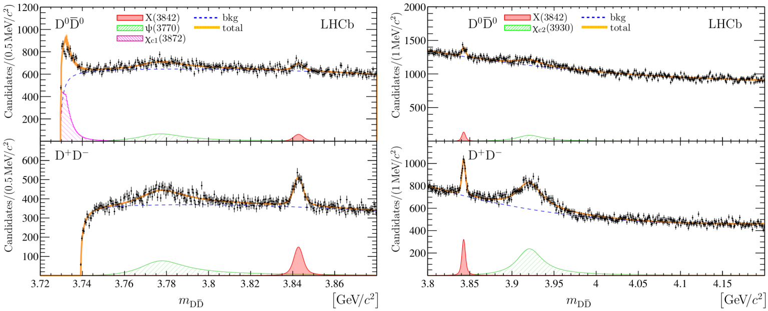
Search for prompt resonances decaying into $D^0\overline{D}^0$ and D^+D^-

- Run 1 and Run 2 data
- $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, pointing to primary vertex
- At threshold $\chi_{c1}(3872) \to D^{*0}\overline{D}^0$
- New resonance at $m_{D\overline{D}} = 3842$ MeV



[JHEP 07 (2019) 035]

Near-threshold $D\overline{D}$ spectroscopy



- Separate, overlapping fits for better background parametrisation
- X(3842) interpreted as $\psi_3(1^3D_3)$, $J^{PC} = 3^{--}$
- Relativistic Breit-Wigner with Blatt-Weisskopf form factors
- $\chi_{c2}(3930)$: D-wave Breit-Wigner, $\psi(3770)$: P-wave Breit-Wigner
- $\chi_{c1}(3872)$: shape from simulation
- $m(\psi_3) = 3842.71 \pm 0.16 \pm 0.12$ MeV, $\Gamma(\psi_3) = 2.79 \pm 0.51 \pm 0.73$ MeV

[JHEP 07 (2019) 035]

Production mechanisms of ψ_3

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Selecting detached $D\overline{D}$ candidates does not remove completely contributions from b-hadrons decays

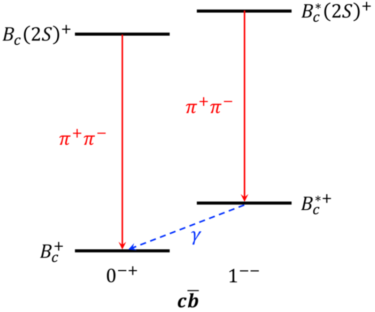
- Checked using the pseudo decay time $t_z = \frac{z_{DD} - z_{PV}}{p_z} m_{DD}$
- No significant b-hadrons decay contribution is observed

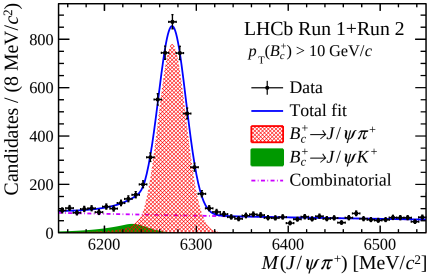
Barnes, Godfrey and Swanson [PRD 72 (2005) 054026] suggest $\chi_{c2}(3930) \rightarrow \psi_3\gamma$ as possible production mechanism

- Given the measured masses and widths of the two states and using $\Gamma(\chi_{c2}(3930) \rightarrow \psi_3\gamma) = 100$ keV, this accounts at most for 5% of observed decays
- If the J^{PC} assumption is correct, then either $\Gamma(\chi_{c2}(3930) \rightarrow \psi_3\gamma)$ is significantly larger or there are other mechanisms for ψ_3 production

Observation of a new excited B_c^+ state

Searching for structures in $B_c^+\pi^+\pi^-$ using Run 1 and Run 2 data

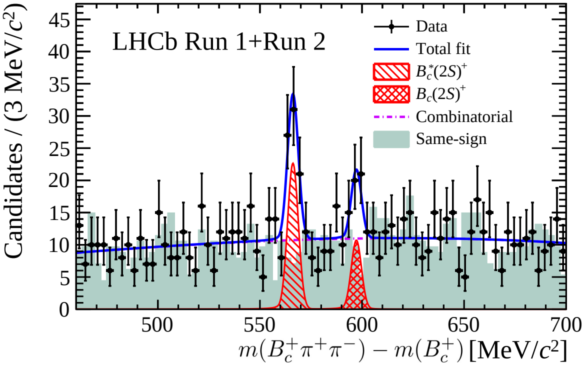




- The low-energy photon is ignored: not sensitive to B_c^{*+}
- Various predictions for the mass difference of the excited states
- $\Delta m_{theory} = [m(B_c(2S)^+) - m(B_c^*(2S)^+)_{reco}] \in [11, 53]$ MeV$/c^2$
- Dominant systematic: momentum scale calibration ($\simeq 0.02\%$)

[PRL 122 (2019) 232001]

Observation of a new excited B_c^+ state



- A peaking structure consistent with the $B_c^*(2S)^+$ state is observed
- Significance 6.3σ global, 6.8σ local
- Hint for a second structure consistent with the $B_c(2S)^+$ state is observed
- 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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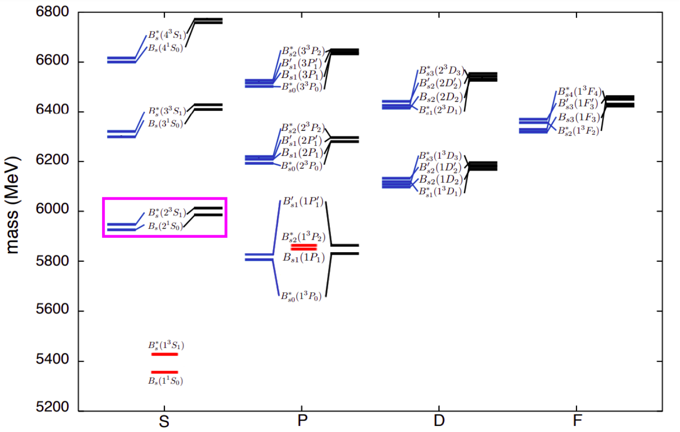
The B_s^0 excitation spectrum is mostly inexplored as well

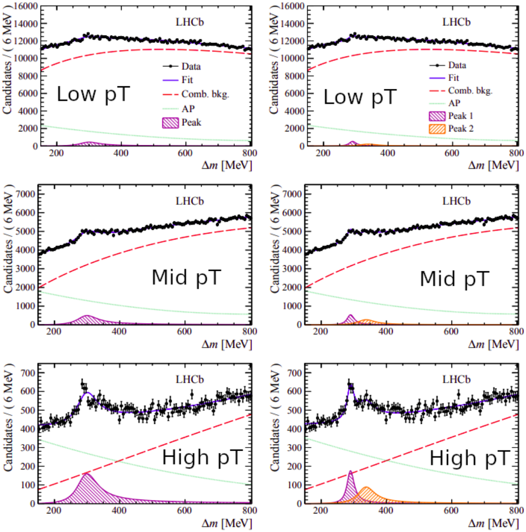
- Only ground state + three excited states observed
- First radial excitation (B_s^{*0}) and first orbital excitations (B_{s1}^0, B_{s2}^{*0})
- This analysis: observation of two new states



Adapted from [PRD 94 (2016) 054025]

Observation of new excited B_s^0 states

- Using full Run 1&2 dataset
- 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
- 20σ significance for one peak vs null, 7σ significance for two peaks vs one peak



[EPJC 81 7 (2021) 601]

Observation of new excited B_s^0 states

- The excess observed at about 300 MeV/c^2 above the B^+K^- threshold is not well described by a single resonance
- Two-peak structure hypothesis favoured with large significance
- Single resonance decaying through both B^+K^- and $B^{*+}K^-$ is disfavoured but cannot be excluded

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

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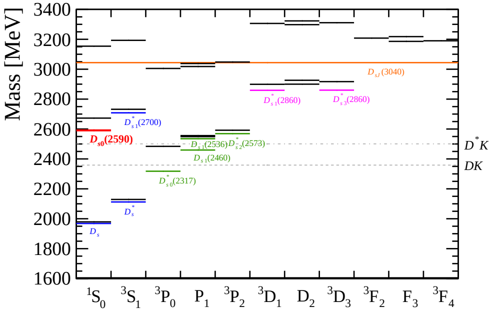
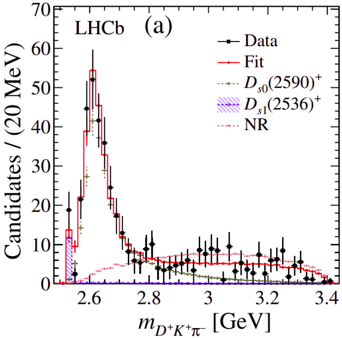
$D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ masses are much smaller than predicted
Are they exotic candidates? Additional input is required.





- 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
- See [Alberto's talk] on Tuesday for more details

[PRL 126 (2021) 122002]

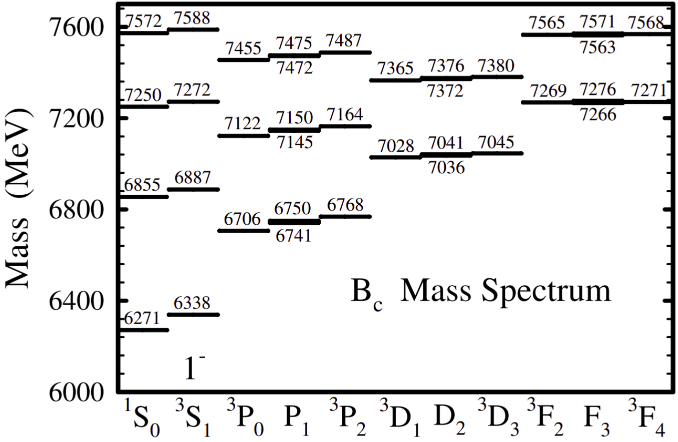
CONCLUSIONS

Conclusions

- Heavy meson spectroscopy is an extremely rich and productive field, both for conventional and exotic states
- $\psi_2(3823)$ and B_c^+ properties studied with high precision
- Five new excited $c\bar{c}$, $b\bar{c}$, $b\bar{s}$ and $c\bar{s}$ mesons
- 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
- The B_c^+ and B_s^0 excitation spectra are still mostly unexplored territory

Conclusions

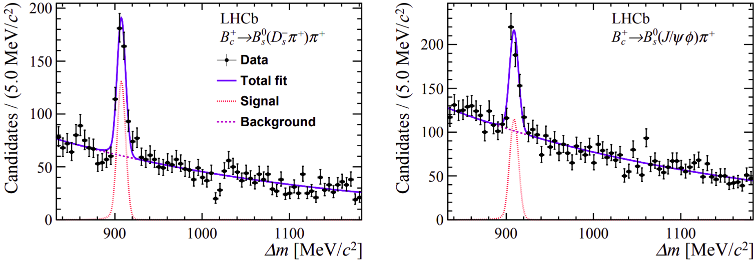
- Run 3 will start with an upgraded detector and a software-only trigger, with improvements on hadronic triggers
- LHC experiments will be the only explorers of the B_c^+ spectrum in the near future and LHCb will play a major role in it



[PRD 70 (2004) 054017]

BACKUP

B_c^+ - B_s^0 mass difference



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

[JHEP 07 (2020) 123]