Bottom meson and baryon spectroscopy

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with results from the ATLAS and CMS collaborations

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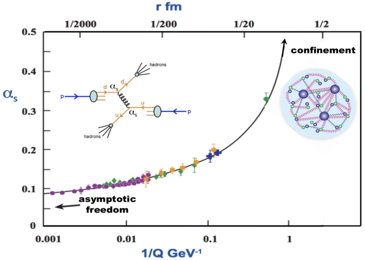
FPCP 2019,
6-10 May, Victoria BC Canada

Outline

- introduction on b-hadron spectroscopy
- b-hadrons at the LHC
- observation of two resonances in the $\Lambda_b^0\pi^\pm$ systems
- B_c^+ meson spectroscopy results
- conclusions and future perspectives

Introduction

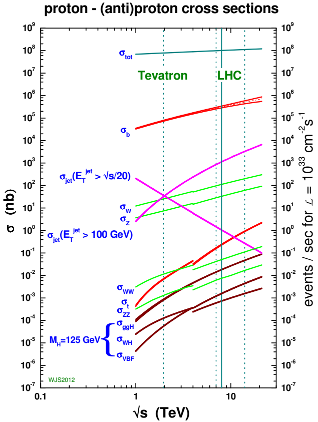
Quarks and gluons (theory) versus hadrons (experiment)



- the study of heavy hadrons plays an important role in the **understanding of the mechanism of confinement**
- the understanding of non-perturbative QCD is also crucial as the experimental sensitivity of new physics searches improve
- **many flavour physics observables are limited by hadron-related theoretical uncertainties**, either entering in measurements directly involving hadrons in the initial/final states or in hadronic contributions in loops
- the agreement between theory and experiments in the hadron spectroscopy sector is a measure of our knowledge of non-perturbative QCD

b-hadron production at the LHC

- all types of b-hadrons, and their excitations, can be produced at the LHC: $B^0 = |\bar{b}d\rangle$, $B^+ = |\bar{b}u\rangle$, $B_s^0 = |\bar{b}s\rangle$, $B_c^+ = |\bar{b}c\rangle$, $\Lambda_b^0 = |udb\rangle$, $\Xi_b^- = |dsb\rangle$ ...
- $\sigma(pp \to b\bar{b}X) = 72.0 \pm 0.3 \pm 6.8\,\mu\text{b}$ at 7 TeV in the forward region $\Rightarrow \sim 30,000\ b\bar{b}/s$ inside LHCb acceptance
- $\sigma(pp \to b\bar{b}X) = 154.3 \pm 1.5 \pm 14.3\,\mu\text{b}$ at 13 TeV in the forward region $\Rightarrow \sim 60,000\ b\bar{b}/s$ inside LHCb acceptance **[Phys. Rev. Lett. 118, 052002]**
- ATLAS and CMS ran at larger luminosity and have larger geometrical acceptance $\Rightarrow \sim 40x\ b\bar{b}/s$ inside acceptance

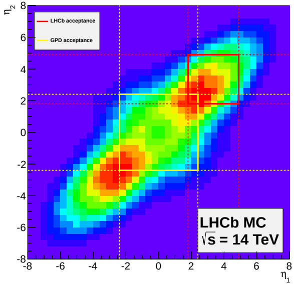


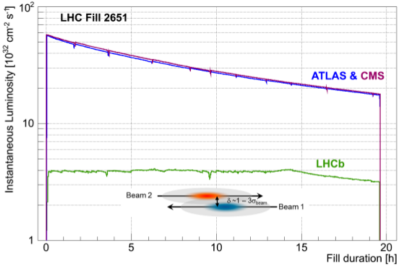
Unprecedented $b\bar{b}$ sample delivered by the LHC

The ATLAS, CMS and LHCb experiments

- complementary in b-hadron acceptance
- ATLAS and CMS cover high-p_T and $-2.4 < \eta < 2.4$ $\Rightarrow \sim$ 45% of $b\bar{b}$ pairs inside acceptance
- LHCb covers low-p_T and $1.8 < \eta < 4.9$ $\Rightarrow \sim$ 25% of $b\bar{b}$ pairs inside acceptance
- LHCb ran at $\mathcal{L} = 4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ levelled luminosity to optimise the triggering and reconstruction of b- and c-hadrons
- ATLAS and CMS ran at about one order of magnitude higher instantaneous luminosity

$\bar{b}b$ production angle plots





Observation of two resonances in the $\Lambda_b^0\pi^\pm$ systems

Observation of two resonances in the $\Lambda_b^0\pi^\pm$ systems: motivations

[Phys. Rev. Lett. 122 (2019) 012001]

- many QCD-inspired phenomenological models have been used to study the properties of the ground state heavy baryons
- there are also several Lattice QCD studies investigating the internal structure and the quark dynamics of the low lying bottom baryons
- less effort devoted to study the excited states and decay properties of singly heavy baryons
- **only a few excited baryons have been observed in the bottom sector**
- the search for and the measurement of their properties will shed light on the effective degrees of freedom necessary to describe the dynamics inside baryons
- the Λ_b^0 baryon is the lowest-lying singlet ground state $|udb\rangle$ with $J^P = \frac{1}{2}^+$
- $\Sigma_b^\pm$ ($|uub\rangle$ and $|ddb\rangle$) states can decay to the Λ_b^0 baryon via the emission of a charged pion: **no excited $\boldsymbol{\Sigma_b^\pm}$ states observed so far**

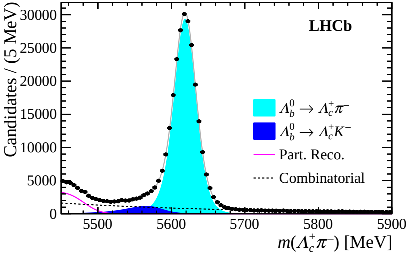
Observation of two resonances in the $\Lambda_b^0\pi^\pm$ systems: selection of the candidates

[Phys. Rev. Lett. 122 (2019) 012001]

- $3\,\mathrm{fb}^{-1}$ of pp collision data collected at $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$
- Λ_b^0 candidates from $\Lambda_c^+(\to pK^+\pi^-)\pi^+$ combinations
- particle identification (PID) and track quality requirements on the final state tracks

$\sim 235,000$ $\Lambda_b^0 \to \Lambda_c^+\pi^-$ events

- Λ_b^0 decay vertex required to be significantly displaced from the primary vertex (PV) to reduce combinatorial background
- Boosted Decision Tree (BDT) algorithm exploiting topological and kinematical variables to further reduce the background

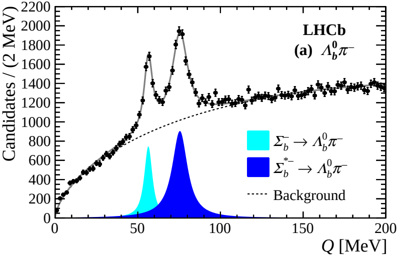


- Λ_b^0 candidates within $\pm 50\,\mathrm{MeV}$ around the peak combined with a prompt charged pion to form $\Lambda_b^0\pi^\pm$ combinations
- study of $\boldsymbol{Q \equiv m(\Lambda_b^0\pi^\pm) - m(\Lambda_b^0) - m(\pi^\pm)}$ where $m(\Lambda_b^0\pi^\pm)$ is recomputed constraining the Λ_b^0 and Λ_c^+ masses to their known values

Observation of two resonances in the $\Lambda_b^0\pi^\pm$ systems: $Q < 200\,\mathrm{MeV}$

[Phys. Rev. Lett. 122 (2019) 012001]

- apply the $Q < 200\,\mathrm{MeV}$ and $p_T(\pi^\pm) > 200\,\mathrm{MeV}$ requirements

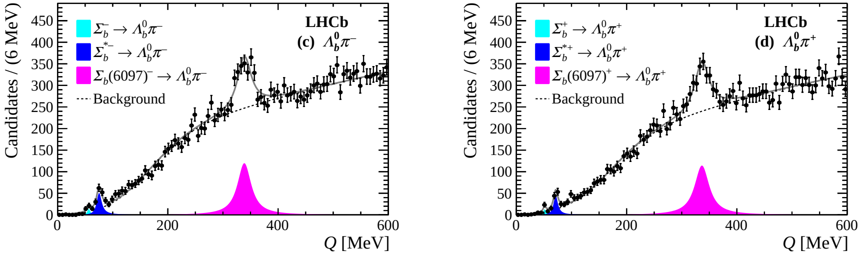


- $\Sigma_b^{(*)\pm}$ ($|uub\rangle$ and $|ddb\rangle$) $J^P = \frac{1}{2}^+$ $(\frac{3}{2}^+)$ ground states first observed by CDF **[Phys. Rev. Lett. 99 (2007) 202001]**
- signal shapes: relativistic Breit-Wigners convolved with the detector resolution function determined from simulation ($\sigma \sim 1\,\mathrm{MeV}$)
- background shape: smooth threshold function validated by using candidates from Λ_b^0 sidebands

Observation of two resonances in the $\Lambda_b^0\pi^\pm$ systems: $Q < 600\,\mathrm{MeV}$

[Phys. Rev. Lett. 122 (2019) 012001]

- study up to $Q = 600\,\mathrm{MeV}$
- larger Q-value $\Rightarrow$ larger prompt background $\Rightarrow$ $p_T(\pi^\pm) > 1000\,\mathrm{MeV}$ requirement



- **new $\Sigma_b(6097)^\pm$ resonances** (12.7σ and 12.6σ local statistical significance, respectively)
- signal shapes: relativistic Breit-Wigners convolved with the detector resolution function determined from simulation ($\sigma \sim 2.35\,\mathrm{MeV}$)
- background shape: sigmoid function validated by using candidates from Λ_b^0 sidebands

Observation of two resonances in the $\Lambda_b^0\pi^\pm$ systems: fit results and systematic uncertainties

[Phys. Rev. Lett. 122 (2019) 012001]

State	Q_0 [MeV]	Γ [MeV]	Yield
Σ_b^-	56.45 ± 0.14	5.33 ± 0.42	3270 ± 180
Σ_b^{*-}	75.54 ± 0.17	10.68 ± 0.60	7460 ± 300
Σ_b^+	51.36 ± 0.11	4.83 ± 0.31	3670 ± 160
Σ_b^{*+}	71.09 ± 0.14	9.34 ± 0.47	7350 ± 260
$\Sigma_b(6097)^-$	338.8 ± 1.7	28.9 ± 4.2	880 ± 100
$\Sigma_b(6097)^+$	336.6 ± 1.7	31.0 ± 5.5	900 ± 110

- fit results used to determine the parameters of the resonances, mass differences and isospin splittings
- dominant systematic uncertainty on the mass measurements comes from the 3×10^{-4} relative accuracy of the momentum scale (calibrated by using samples of $J/\psi \to \mu^+\mu^-$ and $B^+ \to J/\psi K^+$)
- this uncertainty largely cancels in the mass differences and splittings
- dominant systematic uncertainty on the width measurements comes from the parametrisation of the background

Observation of two resonances in the $\Lambda_b^0\pi^\pm$ systems: interpretation of the results

[Phys. Rev. Lett. 122 (2019) 012001]

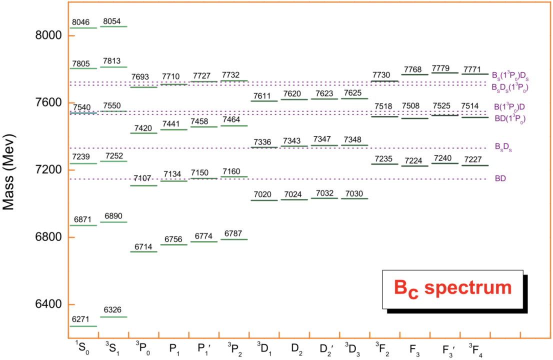
- masses and widths of the ground state baryons consistent with those measured by CDF, with a **precision improved by a factor 5**
- five $\Sigma_b(1P)$ states are expected in the heavy-quark limit: the predictions of their masses and widths depend on their J^P
- the widths may be too large to disentangle these states: the observed states may be superpositions of more than one state
- the **newly observed structures are consistent with being 1P excitations**, but the molecular interpretation may also be possible

Quantity	Value [MeV]
$m(\Sigma_b(6097)^-)$	$6098.0 \pm 1.7 \pm 0.5$
$m(\Sigma_b(6097)^+)$	$6095.8 \pm 1.7 \pm 0.4$
$\Gamma(\Sigma_b(6097)^-)$	$28.9 \pm 4.2 \pm 0.9$
$\Gamma(\Sigma_b(6097)^+)$	$31.0 \pm 5.5 \pm 0.7$
$m(\Sigma_b^-)$	$5815.64 \pm 0.14 \pm 0.24$
$m(\Sigma_b^{*-})$	$5834.73 \pm 0.17 \pm 0.25$
$m(\Sigma_b^+)$	$5810.55 \pm 0.11 \pm 0.23$
$m(\Sigma_b^{*+})$	$5830.28 \pm 0.14 \pm 0.24$
$\Gamma(\Sigma_b^-)$	$5.33 \pm 0.42 \pm 0.37$
$\Gamma(\Sigma_b^{*-})$	$10.68 \pm 0.60 \pm 0.33$
$\Gamma(\Sigma_b^+)$	$4.83 \pm 0.31 \pm 0.37$
$\Gamma(\Sigma_b^{*+})$	$9.34 \pm 0.47 \pm 0.26$
$m(\Sigma_b^{*-}) - m(\Sigma_b^-)$	$19.09 \pm 0.22 \pm 0.02$
$m(\Sigma_b^{*+}) - m(\Sigma_b^+)$	$19.73 \pm 0.18 \pm 0.01$
$\Delta(\Sigma_b(6097)^\pm)$	$-2.2 \pm 2.4 \pm 0.3$
$\Delta(\Sigma_b^\pm)$	$-5.09 \pm 0.18 \pm 0.01$
$\Delta(\Sigma_b^{*\pm})$	$-4.45 \pm 0.22 \pm 0.01$

B_c^+ meson spectroscopy

B_c^+ meson spectroscopy

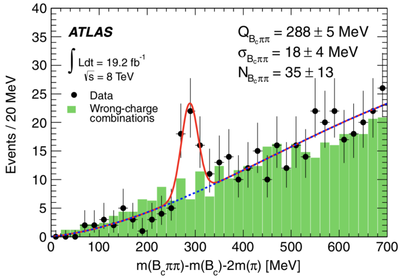
- the B_c^+ mesons are intermediate between charmonium and bottomonium states both in mass and size
- however, the **heavy-quark dynamics is richer** than $c\bar{c}$ and $b\bar{b}$ states and the examination of the B_c^+ spectrum may reveal where approximations used for quarkonium states break down
- both $c\bar{c}$ and $b\bar{b}$ pairs have to be produced in the same parton-parton interaction $\Rightarrow$ B_c^+ **production suppressed** by a factor $\alpha_s^2(Q^2)$



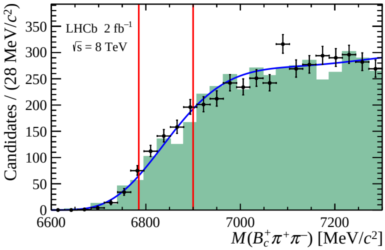
[arXiv:1903.11927 [hep-ph]]

Excited B_c^+ states

- the B_c^+ states cannot annihilate into gluons $\Rightarrow$ narrow excited B_c^+ mesons below the BD threshold with widths less than a few hundred keV
- excited B_c^+ mesons below the BD threshold decay via electromagnetic or hadronic transitions between two different B_c^+ states
- ATLAS observed a state consistent with both $B_c(2S)^+$ and $B_c^*(2S)^+$ states in the $B_c^+\pi^+\pi^-$ spectrum by using $L \sim 24\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$
- not seen by LHCb using a partial dataset corresponding to $L = 2\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$



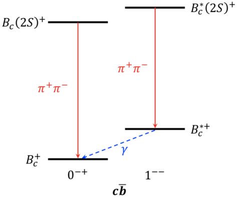
[Phys. Rev. Lett. 113, 212004]



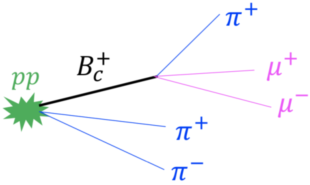
[JHEP 01 (2018) 138]

$B_c(2S)^+$ and/or $B_c^*(2S)^+$?

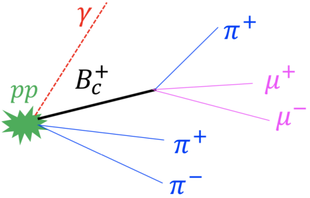
- ATLAS measurement could not distinguish between $B_c(2S)^+$ and $B_c^*(2S)^+$ because of the low yield and the Q-value resolution of $\sim 20\,\mathrm{MeV}$



$B_c(2S)^+ \to B_c^+\pi^+\pi^-$



$B_c^*(2S)^+ \to B_c^{*+}(\to B_c^+\gamma)\pi^+\pi^-$



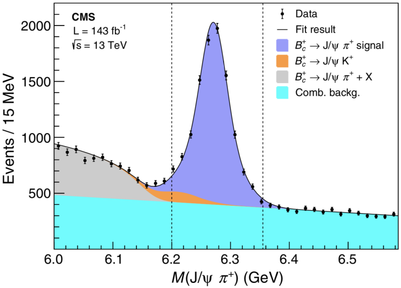
- the photon energy is predicted to be $\sim 50\,\mathrm{MeV} \Rightarrow$ too soft to be reconstructed at the LHC (huge combinatorial background)
- most predictions give $m(B_c(2S)^+) > m(B_c^*(2S)^+)_{\text{reco}}$

Observation of two excited B_c^+ states at CMS: selection of the candidates

[Phys. Rev. Lett. 122, 132001]

- full Run 2 143 fb^{-1} of pp collision data collected at $\sqrt{s} = 13\,\mathrm{TeV}$
- B_c^+ candidates from $J/\psi(\to \mu^+\mu^-)\pi^+$ combinations

$\sim$ 7500 $B_c^+ \to J/\psi\pi^+$ events



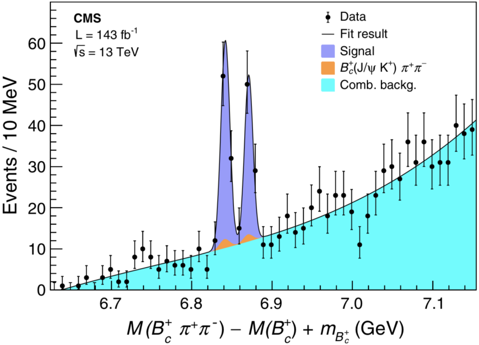
- selection criteria based on the event topology and on the quality of the final state tracks
- $\boldsymbol{p_T(B_c^+) > 15\,\mathrm{GeV}}$
- B_c^+ decay length greater than $100\,\mu\mathrm{m}$
- $B_c^+ \to J/\psi K^+$ yield constrained to the ratio of the $B_c^+ \to J/\psi\pi^+$ and $B_c^+ \to J/\psi K^+$ branching fractions

- B_c^+ candidates between 6.2 and 6.355 GeV combined with two opposite-sign high-purity tracks, one track $p_T > 800\,\mathrm{MeV}$ and the other track $p_T > 600\,\mathrm{MeV}$
- use $\boldsymbol{m(B_c^+\pi^+\pi^-) - m(B_c^+) + m(B_c^+)_{\mathrm{PDG}}}$ to improve the resolution

Observation of two excited B_c^+ states at CMS: resolved $B_c(2S)^+$ and $B_c^*(2S)^+$ peaks

[Phys. Rev. Lett. 122, 132001]

- signal peaks fitted with a superposition of two Gaussian distributions
- background parametrised with a third-order Chebyshev polynomial
- misidentified background: shape identical to the signal peaks, normalisation constrained by the ratio of the corresponding yields in the $J/\psi\pi^+$ spectrum
- $\boldsymbol{\sigma \sim 6\,\mathrm{MeV}}$, consistent with simulation studies (BCVEGPY Monte Carlo generator)



Observation of two excited B_c^+ states at CMS: results

[Phys. Rev. Lett. 122, 132001]

- 67 ± 10 and 51 ± 10 events for the lower-mass and higher-mass peak
- $\Delta M = 29.1 \pm 1.5\,\mathrm{MeV}$
- the low-energy photon in the $B_c^*(2S)^+ \to B_c^*(\to B_c^+\gamma)\pi^+\pi^-$ decay chain has a reconstruction efficiency of the order of 1% (from simulation studies) $\Rightarrow$ the **$B_c^*(2S)^+$ mass can not be measured**
- dominant systematic uncertainties: modelling of the peaks replacing Gaussians with Breit-Wigners convolved with Gaussian resolution functions (natural widths consistent with zero), and world-average B_c^+ mass
- **observation of two peaks rather than one established at 6.5σ** accounting for systematic uncertainties (dominant one is the background model)

$\Delta M = 29.1 \pm 1.5(\text{stat}) \pm 0.7(\text{syst})\,\mathrm{MeV}$
$m(B_c(2S)^+) = 6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst}) \pm 0.8(B_c^+)\,\mathrm{MeV}$
$m(B_c(2S)^+) - m(B_c^+) = 596.1 \pm 1.2(\text{stat}) \pm 0.8(\text{syst})\,\mathrm{MeV}$
$m(B_c^*(2S)^+) - m(B_c^{*+}) = 567.0 \pm 1.0(\text{stat}) \pm 0.0(\text{syst})\,\mathrm{MeV}$

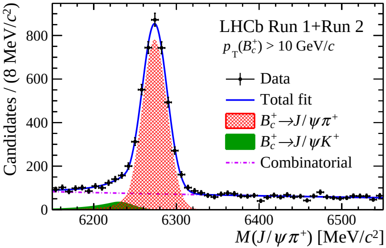
Observation of an excited B_c^+ state at LHCb: selection of the candidates

[arXiv:1904.00081 [hep-ex]]

- **full** $8.5\,\mathrm{fb}^{-1}$ of pp collision data collected at $\sqrt{s} = 7$, 8 and $13\,\mathrm{TeV}$
- B_c^+ candidates from $J/\psi(\rightarrow \mu^+\mu^-)\pi^+$ combinations
- PID and track quality requirements on final state tracks

- $p_T(\pi^+) > 1000\,\mathrm{MeV}$, $\tau(B_c^+) > 0.2\,\mathrm{ps}$, good quality decay vertex
- $\boldsymbol{p_T(B_c^+) > 10\,\mathrm{GeV}}$
- BDT classifier using topological and kinematical variables to further suppress combinatorial background (simulated samples for the signal, generated with BCVEGPY)

$\sim$ 3800 $B_c^+ \rightarrow J/\psi\pi^+$ events

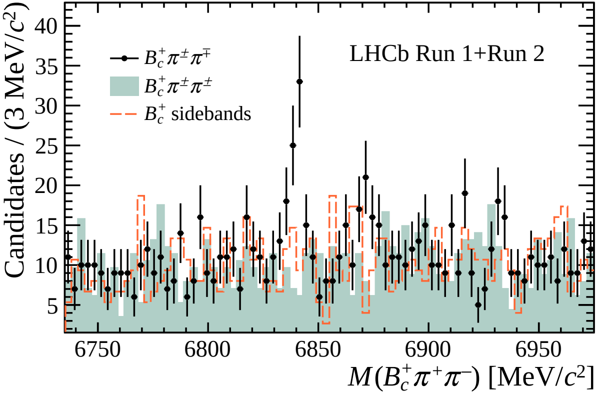


- B_c^+ candidates between 6200 and $6320\,\mathrm{MeV}$ combined with two opposite-sign tracks consistent with pions, $p_T(\pi^\pm) > 300\,\mathrm{MeV}$
- use $\boldsymbol{\Delta M \equiv m(B_c^+\pi^+\pi^-) - m(B_c^+)}$ with the J/ψ mass constrained to the PDG value to improve the resolution

Observation of an excited B_c^+ state at LHCb: $m(B_c\pi^+\pi^-)$ spectrum

[arXiv:1904.00081 [hep-ex]]

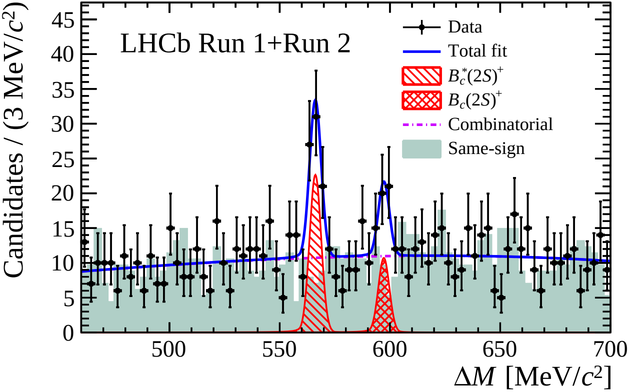
- $m(B_c^+\pi^+\pi^-) - m(B_c^+) - m(\pi^+\pi^-) < 200\,\mathrm{MeV}$ requirement
- same requirements applied to a same-sign sample, by using $m(B_c\pi^+\pi^+)$ or $m(B_c\pi^-\pi^-)$ combinations to ensure that the selection does not produce any artificial peaks
- selection efficiency found to change smoothly with $m(B_c^+\pi^+\pi^-)$
- **no peaks in the same-sign sample**



Observation of an excited B_c^+ state at LHCb: fit to the ΔM spectrum

[arXiv:1904.00081 [hep-ex]]

- each peak is modelled by a Gaussian function with asymmetric power-law tails
- combinatorial background described by a second-order polynomial
- $\sigma \sim 2.5\,\mathrm{MeV}$



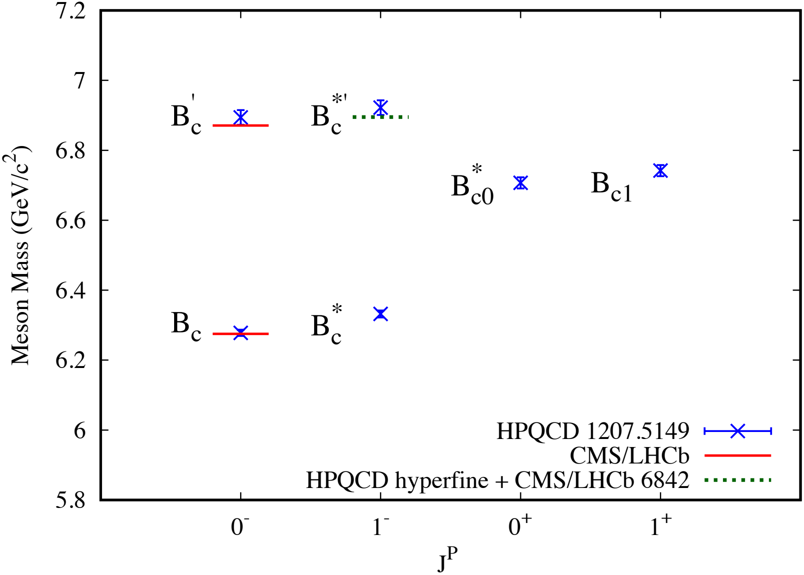
Observation of an excited B_c^+ state at LHCb: results

[arXiv:1904.00081 [hep-ex]]

- 51 ± 10 (6.8σ) and 24 ± 9 (3.2σ) events (local statistical significance)
- $\Delta M = 31.0 \pm 1.4\,\mathrm{MeV}$
- **global statistical significances: 6.3σ and 2.2σ**
- dominant systematic uncertainties: momentum scale and world-average B_c^+ mass
- assuming the hint for a second structure is due to the $B_c(2S)^+$ state

$\Delta M = 31.0 \pm 1.4(\text{stat}) \pm 0.0(\text{syst})\,\mathrm{MeV}$
$m(B_c(2S)^+) = 6872.1 \pm 1.3(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^+)\,\mathrm{MeV}$
$m(B_c^*(2S)^+)_{\text{reco}}) = 6841.2 \pm 0.6(\text{stat}) \pm 0.1(\text{syst}) \pm 0.8(B_c^+))\,\mathrm{MeV}$

CMS and LHCb results compared with Lattice QCD predictions



[Phys. Rev. D 86, 094510]

Conclusions

- crucial interplay between experiments, QCD-inspired phenomenological models and Lattice QCD to improve our understanding of the non-perturbative regime of QCD
- "indirect" impact on the measurement of flavour physics observables and SM self-consistency checks
- observations of new *b*-hadrons have been achieved by the LHC experiments
- new results, exploiting the huge integrated luminosity collected by ATLAS and CMS and the *b*-hadron reconstruction capabilities of LHCb, are expected in the near future

Thanks and stay tuned for new results!