Excited $D_s$ and $B_s$ mesons spectroscopy at LHCb

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Deciphering strong-interaction phenomenology through precision hadron spectroscopy,
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Outline

• the LHCb detector

• production of $b$- and $c$-hadrons at LHCb

• LHCb contributions to excited $D_s$ mesons spectroscopy

• LHCb contributions to excited $B_s$ mesons spectroscopy

• future plans
By design: study CP-violating processes and rare $b$- and $c$-hadrons decays

Excellent tracking and PID performance $\Rightarrow$ extended Physics programme
$\Rightarrow$ not only CP violation and rare decays measurements, but also LFU tests, exotic and conventional spectroscopy, production and polarisation measurements, EW and QCD physics, dark photon searches ...
The LHCb data sample

- levelled instantaneous luminosity of $L = 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- Run 1: $\sim 3 \text{ fb}^{-1}$ of pp collisions at $\sqrt{s} = 7$-8 TeV
- Run 2: $\sim 6 \text{ fb}^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV
all types of $b$-hadrons, and their excitations, can be produced at the LHC:

\[ B^0 = |\bar{b}d\rangle, \quad B^+ = |\bar{b}u\rangle, \quad B_s^0 = |\bar{b}s\rangle, \]
\[ B_c^+ = |\bar{b}c\rangle, \quad \Lambda_b^0 = |u\bar{d}b\rangle, \quad \Xi_b^- = |d\bar{s}b\rangle \ldots \]

\[ \sigma(pp \rightarrow b\bar{b}X) = 72.0 \pm 0.3 \pm 6.8 \mu b \text{ at } 7 \text{ TeV in the forward region} \]
\[ \Rightarrow \sim 30k \ b\bar{b}/s \text{ inside LHCb acceptance} \]

\[ \sigma(pp \rightarrow b\bar{b}X) = 154.3 \pm 1.5 \pm 14.3 \mu b \text{ at } 13 \text{ TeV in the forward region} \]
\[ \Rightarrow \sim 60k \ b\bar{b}/s \text{ inside LHCb acceptance} \]
the production cross section of $c\bar{c}$ pairs is $\sim 20$ times larger than the $b\bar{b}$ one!

$\sigma(pp \rightarrow c\bar{c}X) = 1419 \pm 12 \pm 133 \, \mu b$ at 7 TeV in the forward region
$\Rightarrow \sim 600k \, c\bar{c}/s$ inside LHCb acceptance

$\sigma(pp \rightarrow c\bar{c}X) = 2369 \pm 3 \pm 198 \, \mu b$ at 13 TeV in the forward region
$\Rightarrow \sim 1M \, c\bar{c}/s$ inside LHCb acceptance

Unprecedented $b\bar{b}$ and $c\bar{c}$ samples delivered by the LHC
LHCb trigger and performance in a nutshell

LHCb 2012 Trigger Diagram

- **40 MHz bunch crossing rate**
- **L0 Hardware Trigger**: 1 MHz readout, high $E_T/P_T$ signatures
  - 450 kHz $h^\pm$
  - 400 kHz $\mu/\mu\mu$
  - 150 kHz $e/\gamma$

Software High Level Trigger
- Introduce tracking/PID information, find displaced tracks/vertices
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

- **5 kHz (0.3 GB/s) to storage**
  - 2 kHz Inclusive Topological
  - 2 kHz Inclusive/Exclusive Charm
  - 1 kHz Muon and DiMuon

- **trigger efficiency**: $\sim 90\%$ on muons, $\sim 30\%$ for multi-body hadronic final states
- **impact parameter resolution**: $15 + 29/p_T[GeV]\mu m$
- **decay time resolution**: 45 fs
- **momentum resolution**: $\Delta p/p = 0.5\%$ at low momentum to $1.0\%$ at 200 GeV
- **Kaon ID**: $\sim 95\%$ for $\sim 5\% \pi \rightarrow K$ misID probability
Examples of $b$-hadron samples

1.6M $B^+ \rightarrow J/\psi K^+$ (2015+2016)

120k $B_s^0 \rightarrow J/\psi K^+ K^-$ (2015+2016)

280k $\Lambda_b^0 \rightarrow J/\psi p K^-$ (Run1+Run2)

70k $B_s^0 \rightarrow D_s^0 \pi^-$ (2015+2016)

Examples of $c$-hadron samples

Excited $D_s$ and $B_s$ mesons spectroscopy at LHCb
Two complementary approaches can be used to study and discover new states at LHCb:

- **Inclusive (prompt) analysis**, e.g. \( pp \rightarrow D_s J \rightarrow D^* K_S^0 \)X
  - large cross sections
  - all resonances can be produced
  - signal purity may be poor
  - no spin analysis for two body decays

- **Exclusive (from \( B \)-decays) analysis**, e.g. \( B_s^0 \rightarrow D_{sJ}^* \rightarrow \bar{D}^0 K^- \)\( \pi^+ \)
  - quantum numbers assignment is possible through amplitude analysis
  - access to the amplitude and phase of the resonance
  - small background
  - limited statistics
  - model-dependence in amplitude analyses
Conventions and notations for excited heavy-light mesons

- $L$ is the orbital angular momentum
- $j_q = L \oplus s_q$
- $S = s_q \oplus s_Q$
- $J = j_q \oplus s_Q$

- In the heavy-quark limit, the properties of the heavy-light meson are determined by those of the light-quark
- The $S_Q$ and $j_q$ quantum numbers are separately conserved

- **Spectroscopy notation**: $n^{(2S+1)}L_J$
- States having $J^P = 0^+, 1^-, 2^+ ...$ are said to have *natural spin-parity*
- States having $J^P = 0^-, 1^+, 2^- ...$ are said to have *unnatural spin-parity*

- **PDG notation**: $D_{sJ}^{(*)}(m)^{0/\pm}$ or $B_{sJ}^{(*)}(m)^{0/\pm}$, where the * subscript is used if the state has natural spin-parity
LHCb contributions to the excited $D_s$ mesons spectroscopy
The excited $D_s$ mesons puzzle

- in the heavy-quark limit the two ($L = 1; j_q = 1/2$) states, named $D_{s0}^*$ ($J^P = 0^+$) and $D_{s1}^*$ ($J^P = 1^+$), were expected to decay through an S-wave transition to the $D^0 K^+$ final state and hence to be broad.

- the ($L = 1; j_q = 3/2$) states, named $D_{s1}$ ($J^P = 1^+$) and $D_{s2}^*$ ($J^P = 2^+$) were expected to decay through a D-wave transition, and indeed observed first.

- BaBar and CLEO discovered two narrow $D_s$ excitations in 2003, the $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ [Phys. Rev. Lett. 90, 242001], [Phys. Rev. D68 (2003) 032002].

- spin-parity consistent with $J^P = 0^+$ and $J^P = 1^+$ (they need confirmation).

- but their mass is much lower ($\sim 100 \text{ MeV}$) than expected.

Further studies of the full spectrum are required.
Study of $D_{sJ}^{+}$ decays to $D^{+}K_{S}^{0}$ and $D^{0}K^{+}$ final states

[JHEP 1210 (2012) 151]

- 1.0 fb$^{-1}$ of $pp$ collisions data collected in 2011
- $D^{+} \rightarrow K^{-}\pi^{+}\pi^{+}$, $D^{0} \rightarrow K^{-}\pi^{+}$, $K_{S}^{0} \rightarrow \pi^{+}\pi^{-}$
- two $K_{S}^{0}$ categories: LL (decaying inside the VELO ⇒ better resolution) and DD (decaying outside the VELO ⇒ factor 2 worst resolution)
Study of $D_{sJ}$ decays to $D^+ K_S^0$ and $D^0 K^+$ final states

[JHEP 1210 (2012) 151]

- charged tracks multiplicities in inelastic $pp$ events are above 100 tracks per event at $\sqrt{s} = 7$ TeV $\Rightarrow$ large combinatorial background when studying $D^+ K_S^0$ and $D^0 K^+$ combinations
- the combinatorial background is strongly reduced by using the angle $\theta$ between the momentum direction of the kaon in the DK rest frame and the momentum direction of the DK system in the laboratory frame
- symmetrical around zero for unpolarised resonant states , more than 90% of combinatorial background events are in the $\cos\theta < 0$ region
Study of $D_{sJ}$ decays to $D^+ K_S^0$ and $D^0 K^+$ final states

[JHEP 1210 (2012) 151]

- same structures in both final states, parametrised with relativistic Breit-Wigners
- structures identified with the $D_{s2}^*(2573)^+$, $D_{s1}^*(2700)^+$ and $D_{sJ}^*(2860)^+$, already observed by the $B$-factories
Study of $D_{sJ}$ decays to $D^+ K_S^0$ and $D^0 K^+$ final states

[JHEP 1210 (2012) 151]

\[
\begin{align*}
    m(D^*_s(2700)^+) &= 2709.2 \pm 1.9\,\text{(stat)} \pm 4.5\,\text{(syst)} \, \text{MeV}/c^2, \\
    \Gamma(D^*_s(2700)^+) &= 115.8 \pm 7.3\,\text{(stat)} \pm 12.1\,\text{(syst)} \, \text{MeV}/c^2, \\
    m(D^*_{sJ}(2860)^+) &= 2866.1 \pm 1.0\,\text{(stat)} \pm 6.3\,\text{(syst)} \, \text{MeV}/c^2, \\
    \Gamma(D^*_{sJ}(2860)^+) &= 69.9 \pm 3.2\,\text{(stat)} \pm 6.6\,\text{(syst)} \, \text{MeV}/c^2.
\end{align*}
\]

- consistent with previous results from $B$-factories
- the $D_s^*(2700)^+$ can also decay into the $D^* K$ final states
- depending on the $D_{sJ}^*(2860)^+$ spin-parity, also the latter state could be observed into the $D^* K$ final states
Dalitz plot analysis of $B_s^0 \rightarrow \bar{D}^0 K^- \pi^+$ decays

- 3.0 fb$^{-1}$ of $pp$ collisions data collected in 2011 and 2012
- \(~11000\) events used for a Dalitz plot analysis
Dalitz plot analysis of $B_s^0 \rightarrow \bar{D}^0 K^- \pi^+$ decays


- isobar model and Dalitz plot fit using the Laura++ package

- main contributions due to the $K^*(892)^0$ (28.6%), $D_{s2}^*(2573)^-$ (25.7%), $K^- \pi^+$ S-wave (21.4%) and $\bar{D}^0 K^-$ nonresonant component (12.4%)
Dalitz plot analysis of $B^0_s \rightarrow \bar{D}^0 K^- \pi^+$ decays


- significant improvement in the fit quality when including two overlapping spin-1 and spin-3 resonances in the $m(\bar{D}^0 K^-) \sim 2860$ MeV region
- improvements clearly visible when investigating the helicity angle distribution of the $\bar{D}^0 K^-$ system around $m(\bar{D}^0 K^-) \sim 2860$ MeV

- first observation of a heavy-flavoured spin-3 particle
Dalitz plot analysis of $B^0_s \rightarrow \bar{D}^0 K^- \pi^+$ decays


\[
egin{align*}
m(D_{s2}^* (2573)^-) &= 2568.39 \pm 0.29 \pm 0.19 \pm 0.18 \text{ MeV/c}^2, \\
\Gamma(D_{s2}^* (2573)^-) &= 16.9 \pm 0.5 \pm 0.4 \pm 0.4 \text{ MeV/c}^2, \\
m(D_{s1}^* (2860)^-) &= 2859 \pm 12 \pm 6 \pm 23 \text{ MeV/c}^2, \\
\Gamma(D_{s1}^* (2860)^-) &= 159 \pm 23 \pm 27 \pm 72 \text{ MeV/c}^2, \\
m(D_{s3}^* (2860)^-) &= 2860.5 \pm 2.6 \pm 2.5 \pm 6.0 \text{ MeV/c}^2, \\
\Gamma(D_{s3}^* (2860)^-) &= 53 \pm 7 \pm 4 \pm 6 \text{ MeV/c}^2.
\end{align*}
\]

- $D_{s2}^* (2573)^-$ resonance confirmed to be spin-2
- no significant $D_{s1}^* (2700)^-$ contribution
- $D_{s1}^* (2860)^-$ and $D_{s3}^* (2860)^-$ resonances have similar masses
- larger width of the spin-1 state support the interpretation of these states being the $J^P = 1^-$ and $3^-$ members of the $1D$ family
- the $1^-$ state may be partially mixed with the $2S$ family to give the physical $D_{s1}^* (2700)^-$ and $D_{s1}^* (2860)^-$
Study of $D_{sJ}^{(*)+}$ mesons decaying to $D^{*+}K_S^0$ and $D^{*0}K^+$ final states

[JHEP 1602 (2016) 133]

- 3.0 fb$^{-1}$ of $pp$ collisions data collected in 2011 and 2012
- $D^{*+}(\rightarrow D^0\pi^+)K_S^0$ used for studying $D_{sJ}^{(*)+}$ resonance structures and parameters
- $D^{*0}(\rightarrow D^0\pi^0)K^+$ used for cross-checks
- large $\pi^0$ and $\gamma$ combinatorial background reduced by requiring $E(\gamma) > 600$ MeV, $p_T(\pi^0) > 450$ MeV and $p_T(D^{*0}) > 6$ GeV

- same strategy of $D^+K_S^0$ and $D^0K^+$ to reduce combinatorial background in the $D^{*+}K_S^0$ and $D^{*0}K^+$ combinations
- $D^{*}(\rightarrow D\pi)K$ is a three-body decay $\Rightarrow$ discrimination between natural and unnatural parity assignments
Study of $D_{sJ}^{(*) \pm}$ mesons decaying to $D^{*+}K_S^0$ and $D^{*0}K^+$ final states [JHEP 1602 (2016) 133]

- $D_{s1}(2536)^+, D_{s2}^{*}(2573)^+, D_{s1}^{*}(2700)^+, D_{sJ}^{*}(2860)^+, D_{sJ}(3040)^+$ from 570k $D^{*+}K_S^0$ combinations
- $D_{sJ}(3040)^+$ parameters fixed to the ones obtained by BaBar [Phys. Rev. D80 (2009) 092003]

![Graph showing Candidates / (8 MeV) vs. m(D*K^0) [MeV]](image)

- inclusions of $D_{s1}^{*}(2860)^+$ results in a similar fit quality but with a large interference with the $D_{s1}^{*}(2700)^+ \Rightarrow$ data not sensitive to the $D_{s1}^{*}(2860)^+$
- $D_{s1}^{*}(2700)^+$ mass is $\sim 3\sigma$ higher than previous measurements, $D_{sJ}^{*}(2860)^+$ parameters consistent with the $D_{s3}^{*}(2860)^+$ resonance found in $B$-decays
Study of $D_{sJ}^{(*)+}$ mesons decaying to $D^{*+}K_S^0$ and $D^{*0}K^+$ final states

[JHEP 1602 (2016) 133]

- helicity angle $\theta_H$ defined as the angle between the $K_S^0$ and the $\pi^+$ from the $D^{*+}$ decay, in the rest frame of the $D^{*+}K_S^0$ system

$$|\cos \theta_H| < 0.5$$

Enhanced natural parity
(angular distributions $\propto \sin^2 \theta_H$)

Enhanced unnatural parity
(angular distributions $\propto 1 + h\cos^2 \theta_H$)
Study of $D_{sj}^{(*)+}$ mesons decaying to $D^{*+}K_S^0$ and $D^{*0}K^+$ final states

[JHEP 1602 (2016) 133]

- consistent with previous assignments
- poor quality for the $D_{s3}^*(2860)^+$ may suggest unnatural parity contributions
Study of $D_{sJ}^{(*)+}$ mesons decaying to $D^{*+}K_S^0$ and $D^{*0}K^+$ final states

$[\text{JHEP 1602 (2016) 133}]$

\[
m(D_{s1}^{*}(2700)^+) = 2732.3 \pm 4.3 \text{ (stat) } \pm 5.8 \text{ (syst) MeV},
\]
\[
\Gamma(D_{s1}^{*}(2700)^+) = 136 \pm 19 \text{ (stat) } \pm 24 \text{ (syst) MeV},
\]
\[
m(D_{sJ}^{*}(2860)^+) = 2867.1 \pm 4.3 \text{ (stat) } \pm 1.9 \text{ (syst) MeV},
\]
\[
\Gamma(D_{sJ}^{*}(2860)^+) = 50 \pm 11 \text{ (stat) } \pm 13 \text{ (syst) MeV}.
\]

- $D_{s1}^{*}(2700)^+$ can be identified with the $2^3S_1$ state

- the ratio of branching fractions of the $D_{s2}^{*}(2573)^+$ has also been measured

- the measurement makes use of the results of the fit to the $D_{s2}^{*}(2573)^+ \rightarrow D^+ K_S^0$ decay mode

\[
\frac{\mathcal{B}(D_{s2}^{*}(2573)^+ \rightarrow D^{*+}K_S^0)}{\mathcal{B}(D_{s2}^{*}(2573)^+ \rightarrow D^+K_S^0)} = 0.044 \pm 0.005 \text{ (stat) } \pm 0.011 \text{ (syst)}
\]

- value in agreement with the Quark Model expected value
Observation of the decay $B_s^0 \to \bar{D}^0 K^+ K^-$


- $3.0 \text{fb}^{-1}$ of $pp$ collisions data collected in 2011 and 2012
- most precise $\mathcal{B}(B^0 \to \bar{D}^0 K^+ K^-) = (6.1 \pm 0.4 \pm 0.3 \pm 0.3) \times 10^{-5}$
- $\mathcal{B}(B_{s}^{0} \to \bar{D}^{0} K^{+} K^{-}) = (5.7 \pm 0.5 \pm 0.4 \pm 0.5) \times 10^{-5}$
- first step towards the Dalitz plot analyses of the $B_{(s)}^{0} \to \bar{D}^{0} K^{+} K^{-}$ decay modes adding Run 2 data, enabling the study of the natural spin-parity members of the 1D and 1F families

![Graph showingCandidates over (8 MeV/c^2)]
Observation of the decay $B_s^0 \rightarrow \bar{D}^0 K^+ K^-$


$B^0 \rightarrow \bar{D}^0 K^+ K^-$ Dalitz plot ($\sim 2000$ events)

- $m^2(\bar{D}^0 K^-) < 6 \text{ GeV}^2$: partially reconstructed $D_{s1}(2536)^- \rightarrow \bar{D}^{*0} K^-$
- $m^2(\bar{D}^0 K^-) \sim 6.6 \text{ GeV}^2$: $D_{s2}^*(2573)^- \rightarrow \bar{D}^0 K^-$
- $m^2(\bar{D}^0 K^-) \sim 8.2 \text{ GeV}^2$: potential superposition of $D_{s1}^*(2860)^-$ and the $D_{s3}^*(2860)^-$ resonances
Observation of the decay $B_{s}^{0} \rightarrow \bar{D}^{0}K^{+}K^{-}$


$B_{s}^{0} \rightarrow \bar{D}^{0}K^{+}K^{-}$ Dalitz plot ($\sim 500$ events)

- the $D_{s2}^{*}(2573)^{-}$ resonance is identifiable
Near future prospects for excited $D_{sJ}$ mesons spectroscopy

- measurement of the $D_{s0}^{*}(2317)^-\pi^+$ spin-parity through $B_s^0 \rightarrow D_{s0}^{*}(2317)^-\pi^+$ decays
- search for radiative decays of the $D_{s0}^{*}(2317)^+$ meson
- measurement of $D_{s1}(2460)^+$ width through its decay to $D_s^+\mu^+\mu^-$ and $D_s^+\pi^+\pi^-$: very good mass resolution of $\sim 1\text{ MeV}$ given the low Q-value
- $D_s^+\mu^+\mu^-$ more promising given the lower combinatorial background with respect to $D_s^+\pi^+\pi^-$
- search for $D_s(2S)^+ (2^1S_0)$ from $B$-decays
- Dalitz plot analyses of $B_{(s)}^0 \rightarrow \bar{D}^0 K^+K^-$ decays including Run 2 data: expected $\sim 8000$ events and $\sim 2000$ events for the $B^0$ and $B_s$ modes, respectively
LHCb contributions to the excited $B_s$ mesons spectroscopy
First observation of the $B_{s2}^*(5840)^0 \rightarrow B^{*+}K^-$ and studies of excited $B_s^0$ mesons


- similar situation of excited $L = 1$ $D_s$ mesons, where the two $j_q = 1/2$ states, namely the $B_{s0}^*$ and the $B'_{s1}$, are expected to be broad $\mathcal{O}(100\text{ MeV})$
- two narrow peaks, identified with the $j_q = 3/2$ doublet states $B_{s1}^*(5830)^0$ and $B_{s2}^*(5840)^0$, observed by CDF [Phys. Rev. Lett. 100 (2008) 082001]
- 1.0 fb$^{-1}$ of $pp$ collisions data collected in 2011
- $B^+ \rightarrow J/\psi K^+$, $B^+ \rightarrow \bar{D}^0 \pi^+$, $B^+ \rightarrow \bar{D}^0 \pi^+ \pi^- \pi^+$
First observation of the $B_{s2}^*(5840)^0 \rightarrow B^{*+}K^-$ and studies of excited $B_s^0$ mesons


- $B_{s1} \rightarrow B^+K^-$ is forbidden $\Rightarrow$ first peak interpreted as $B_{s1} \rightarrow B^{*+}(\rightarrow B^{+}\gamma)K^-$ where the soft photon is not reconstructed
- both $B_{s2}^* \rightarrow B^{*+}K^-$ and $B_{s2}^* \rightarrow B^{+}K^-$ signals are observed
- $\Gamma(B_{s2}^*) = 1.56 \pm 0.13 \pm 0.47$ MeV

$$m(B^{*+}) = 5324.26 \pm 0.30 \pm 0.23 \pm 0.17 \text{ MeV}/c^2,$$
$$m(B_{s1}) = 5828.40 \pm 0.04 \pm 0.04 \pm 0.41 \text{ MeV}/c^2,$$
$$m(B_{s2}^*) = 5839.99 \pm 0.05 \pm 0.11 \pm 0.17 \text{ MeV}/c^2,$$
Near future prospects for excited $B_{sJ}$ mesons spectroscopy

• where are the $B_{s0}^*$ and $B_{s1}'$?

• search for them through radiative decays exploiting Run 2 data: $m(B_{s0}^0 \gamma)$ resolution around $20 \text{ MeV}$ for non-converted photons and $\sim 5 \text{ MeV}$ for converted photons, but statistics is much lower in the latter case because of the low probability for a photon to convert to $e^+e^-$

• updated studies of the $B^+K^-$ spectrum with full Run 1 and Run 2 samples: factor $\sim 10$ in the available statistics with respect to the previous paper

• studies of $B_c^+ \rightarrow B^{*+}K^-\pi^+$ decays start to become accessible when exploiting Run 2 data
Long term prospects for excited $D_{sJ}$ and $B_{sJ}$ mesons spectroscopy

- the LHCb detector is undergoing an upgrade to exploit a five-fold increase in luminosity
- removal of hardware level trigger ⇒ increase of a factor two/three in the trigger efficiency for hadronic modes
- great potential in $D_{sJ}$ and $B_{sJ}$ spectroscopy from $B$-decays
- in particular Dalitz plot analyses such as $B_c^+ \to B^+ K^- \pi^+$ will shed new light on excited $B_{sJ}$ states from the $B^+ K^-$ threshold to $\sim 6135$ MeV
Conclusions

- very large sample of $c$- and $b$-hadrons collected by LHCb
- several results already obtained using Run 1 data
- more results using Run 2 data will become public in the near future
- the upgraded LHCb experiment will collect an even larger sample of heavy-flavoured hadrons with a significant increase in efficiency for fully hadronic final states

Thanks and stay tuned for new results!