Heavy flavour physics at LHCb

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on behalf of the LHCb collaboration

Aspen Winter Conference

22 March 2017
LHCb status

- LHC experiment focussed on heavy flavour physics.

- We do plenty more than this though - remember Mike’s talk [here].

- Collected \( \sim 2.0 \text{fb}^{-1} \) so far in the LHC run II (2015-2016).

- In run II, calibration/alignment performed online to allow trigger objects to be used directly in analysis.

- Hope to collect another \( 1.5 \text{fb}^{-1} \) in 2017 - looking forward to the restart!
Quark flavour physics

- Quark flavour physics is the study of how different flavours of quarks interact.

Two main avenues in this field:

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<th>Indirectly search for New Physics</th>
<th>Study QCD</th>
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<td>- Make auxiliary measurements to verify QCD effective theories (HQET).</td>
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<td>- Study nature of bound states (spectroscopy).</td>
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- Test CKM matrix unitarity.
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Observation of 5 narrow $\Omega_c^0$ states.


- And maybe find something exotic!
$B^0_{(s)} \rightarrow \mu^+ \mu^-$
The decay $B_{(s)}^{0} \rightarrow \mu^{+}\mu^{-}$

- One in every billion $B_{s}^{0}$ mesons decays into two muons

- For example, like this:

- Or this:

- The two things that make this decay special are:

  - Doubly suppressed (Helicity and GIM)

  - Good theoretical uncertainty (Lattice QCD needed for B meson decay constant).
Main challenge is to deal with huge background from random combinations of muons from different B decays.

- $\mathcal{B}(B \rightarrow \mu X) \sim 10\%$, $\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) \sim 10^{-9}$.

- Train multivariate selection to remove this.
- Dangerous peaking backgrounds from $B \rightarrow hh$ and $B \rightarrow \mu h$.
- Normalise signal yield to $B^+ \rightarrow J/\psi K^+$ and $B^0 \rightarrow K^+ \pi^-$ with the ratio of $B_s/B^+$ production fractions.

- Fit dimuon mass in bins of the multivariate response.
New $B^0_{(s)} \rightarrow \mu^+ \mu^-$ measurement

- Update run 1 result (used in LHCb-CMS combination) to include 2015+2016 data.

- Significantly improve isolation algorithm (important input to MVA).

- Improve treatment of peaking backgrounds (look in data for mis-identified muons).
Dimuon mass fit

- Fit dimuon mass to determine signal yield, accounting for all different backgrounds.

- Yields of peaking backgrounds checked by looking at data without muon ID - consistent results.

- Much less background this time, mainly due to isolation improvements.

Signal not S/B weighted
New $B^0_{(s)} \rightarrow \mu^+ \mu^-$ results

- Using ratio of signal and normalisation yields and their efficiencies from simulation, determine branching fractions.

- In general results consistent with the SM.
- Also measure effective lifetime: $\tau(B^0_s \rightarrow \mu^+ \mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$, not yet enough data to be sensitive to NP.
Measurement of the $B_{s}^{0}$ and $D_{s}^{+}$ lifetimes
The importance of the $B_s^0$ lifetime

- When calculating SM observables of heavy flavour decays - common approximation: set the heavy quark masses to infinity (HQET).

- Another assumption: quark-hadron duality - if average over large number of states, you can use a quark-level calculation to approximate the hadronic.

- Testing these frameworks of utmost importance - lifetimes of $b$-hadrons are excellent place to do this.

HQET predicts that the $B_s$ and $B_0$ lifetimes should be the same, previous results (e.g. [1]) have indicated otherwise.

Recent measurement at LHCb

- Use flavour specific ‘semi-leptonic’ decays $B^0_s \rightarrow D_s^{(*)} + \mu \nu$.

- Normalise to the well known $B^0$ lifetime using $B^0 \rightarrow D^{(*)} + \mu \nu$ decays.

- Use the same charm final state of $K^+ K^- \pi^+$ for both $D^+$ and $D_{s^+}$.

- Correct for missing neutrino using the k-factor technique.

- Determine time acceptance using simulation.

- Fit corrected mass in bins of decay time to determine lifetime ratio.
Corrected mass fit

- Corrected mass defined as:
\[ m_{\text{corr}} = \sqrt{m_{\text{vis}}^2 + p^2_\perp + p_\perp} \]

  Mass of visible decay products

- Momentum perpendicular to B direction.

- Only ground and first excited states of charm meson considered as signal.

- \( B^0 \) sample much more separated than \( B_s^0 \) due to soft \( D_s^{*+} \) decay mode.

Figure 2: (Color online) Distributions of corrected mass for (top panel) reference sample and (bottom panel) signal sample. The shapes of all components are modeled empirically from simulation, except for the variations of the relative proportions are evaluated among the systematic uncertainties. A fit similar to that of the charm-meson decay time: in each of 20 decay-time bins, the combined yields of corrections are needed since the final state is fully reconstructed. We determine the composition fit is validated on the reference and mirror those of the simpler composition fit used for the combinatorial component, which is modeled using same-sign data. Contributions expected to the composition fit are evaluated among the systematic uncertainties. A fit includes two signal components (\( B^0 \) and \( B_s^0 \)) and two physics backgrounds, low-mass (\( B^0 \rightarrow D_s^{(*)-} \mu^+ \nu \)) and high-mass (\( B^0 \rightarrow D_s^{(*)-} \mu^+ \nu \)). The composition fit is used for the determination of candidates satisfying the selection. Results of the global composition fit are overlaid. In the signal sample, the fit deviations, with fit observed discrepancy in individual fractional contributions is 1.3 (2.9) statistical standard deviation.
Decay time fit

- Correct for acceptance in simulation (almost flat after re-weighting due to $D^+/D^+_s$ lifetime difference).

- Cross-check using more abundant $D^+ \rightarrow K^- \pi^+ \pi^+$ decay mode and find consistent results.

- No significance difference in decay widths found:
  \[ \Delta \Gamma(B) = -0.0115 \pm 0.0053 \text{ (stat)} \pm 0.0041 \text{ (syst)} \text{ ps}^{-1} \]

- Also measure the difference in $D^+/D^+_s$ lifetimes:
  \[ \Delta \Gamma(D) = 1.0131 \pm 0.0117 \text{ (stat)} \pm 0.0065 \text{ (syst)} \text{ ps}^{-1} \]

- Systematics dominated by:
  - Composition of signal (e.g. knowledge of form factors)
  - Decay time acceptance (production kinematics)
Results

• $B_s^0$ and $D_s^+$ lifetimes are found to be:

  $1.547 \pm 0.013$ (stat) $\pm 0.010$ (syst) $\pm 0.004$ ($\tau_B$) ps,

  $0.5064 \pm 0.0030$ (stat) $\pm 0.0017$ (syst) $\pm 0.0017$ ($\tau_D$) ps

• These are the world’s most precise.

• The $B_s^0$ lifetime is in agreement with HQET theory and LHCb’s previous measurement with fully reconstructed decays [1], but is in tension from results from D0 [2]

Observation of five narrow $\Omega_c^0$ states
The $\Omega_c^0$ spectrum

- Spectroscopy another important way to improve our understanding of QCD and test HQET.

- The $\Omega_c^0$ baryon has quark content $c\bar{s}s$ and their spectrum is almost completely unknown - only two have been found previously.

- Predictions of the masses in boxes here are from Refs[1-7].

- In the LHCb analysis, look for the decay mode $\Omega_c^0 \to \Xi_c^+ K^-$ using 2011,2012 and 2015 data.

\[ \Omega_c^0 \text{ spectrum} \]

Selection of $\Xi_c^+$ candidates

• First select $\Xi_c^+$ candidates.

• Selection uses a likelihood ratio approach.

• Useful variables include vertex quality, flight significance and particle ID of proton.

• Fit to looser selection criteria used to determine kinematic/geometric properties of the signal (production not so well known).

• After full selection see 1M signal at around 83% purity.
Add a kaon to look for $\Omega_c^0$

- Combine a kaon which has a good PID response and vertex quality.
- Also require $pT > 4.5$ GeV for $\Omega_c^0$ candidate.
- Opposite sign spectrum looks very peaky!
- No such structure seen in same-sign data.
- Checked pion hypothesis - no narrow structures seen.

Where $m(\Xi_c^+ K^-) = m([pK^-\pi^+]\Xi_c^+ K^-) - m([pK^-\pi^+]\Xi_c^+) + m_{\Xi_c^+}$
Fit spectrum

- Fit data to determine significance and mass/widths of the new states.
- Parameterise signal peaks with relativistic Breit-Wigner functions.
- Feed-down from other $\Omega_c^0$ decay modes shown in grey.
- Background parameterisation inspired by same-sign data.

- **Five** states observed with over 10 significance! (record for a single analysis?).
- Also see a broad structure around 3200 - single or multiple states??

$F_{\Xi^+ K^-}$

LHCb
Mass results

- Systematics include:
  - Alternate background model
  - Vary Blatt-Weisskopf factors.
  - Mass scale/resolution.
  - Possibility of interference.
  - Description of broad structure.

- Masses seem broadly consistent with predictions.

- For the widths, see the paper: arXiv:1703.04639.

- Dramatic increase in experimental knowledge in this area.
Summary

• LHCb very pleased with the run II dataset so far.
  • We are now publishing heavy flavour results with it.
  • I just gave a very small and biased taste of what’s come out recently.
    • $B_{(s)}^0 \rightarrow \mu\mu$ update [arXiv:1703.05747]
    • $B_s^0$ and $D_{s^+}$ lifetimes [LHCb-PAPER-2017-004]
    • Observation of five narrow $\Omega_c^0$ states [arXiv:1703.05747].
Summary

- I did not talk about the latest CP violation studies, a central theme of heavy flavour physics.

- For example, new result on $\phi_s$ with $B_s^0\rightarrow J/\psi K^+K^-$ with $m_{KK} > m_\phi$.

I also did not discuss our anomalies in SL decays - discussed by Zoltan.

\[ \phi_s = 0.12 \pm 0.11 \pm 0.03 \]


- If you are interested in more, take a look at our public results pages [here]
k-factor technique

- To determine the decay time, need to know flight distance and B momentum: \( \tau = \frac{m_B L}{p_B} \).

- At each point of visible mass \( m_{D\mu} \), use simulation to relate visible B momentum to total B momentum (k-factor).

- The k-factor response depends on exactly which semileptonic decay you are looking at.

- Therefore, need to determine relative amounts of \( B \rightarrow D \) vs \( B \rightarrow D^* \) in data.