Review of CP-violation and spectroscopy measurements at LHCb

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On behalf of the LHCb Collaboration

Corfu Summer Institute
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Outline

- General introduction
- A review of CP-violation measurements
  - The unitarity triangle parameters
  - Angle $\beta_s$ in the $B_s$ system
  - CP violation in charm
- New measurements on spectroscopy
- The upgraded LHCb detector and outlook
- Summary
The CKM matrix

- The CKM matrix is unitary, and reduces to three rotation angles and one phase.
- The Wolfenstein parameterisation is commonly used to expand in orders of $\lambda$, the sine of the Cabibbo angle: $\lambda \sim 0.22$
- The imaginary term (phase) gives rise to CP violation in the SM.

\[
\begin{bmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{bmatrix} = \begin{bmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{bmatrix} + O(\lambda^4)
\]

- Measured magnitudes:

The Unitarity Triangle

- 6 unitarity conditions of the CKM matrix
- Gives 6 triangles in the complex plane
- 2 of these triangles do not have a side which is much shorter than the other two:

\[(V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td}) = 0\]
\[(V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb}) = 0\]
Beauty and Charm triangles

- **Beauty system**
  - **B Triangle**
  - $V_{ud} V_{ub} \sim \lambda^3$, $V_{td} V_{tb} \sim \lambda^3$
  - $V_{cd} V_{cb} \sim \lambda^3$
  - $\alpha$, $\beta$, $\gamma \sim 1$
  - $B$ system: angles $\alpha$, $\beta$, $\gamma \sim 1$

- **B<sub>s</sub> Triangle**
  - $V_{us} V_{ub} \sim \lambda^4$
  - $V_{ts} V_{tb} \sim \lambda^2$
  - $V_{cs} V_{cb} \sim \lambda^2$
  - $\lambda \approx 0.2$

- **Charm system**
  - **D Triangle**
  - $V_{ud} V_{cd} \sim \lambda$
  - $V_{ub} V_{cb} \sim \lambda^5$
  - $V_{us} V_{cs} \sim \lambda$
  - $\beta_c \sim \lambda^4$

Charm system: angle $\beta_c \sim \lambda^4$

Diagrams from Jolanta Brodzicka
Unitarity Triangle measurements

Amazing progress in the last 25 years; the SM remains intact, but still a whole lot still to learn.

1995

2004

2019 (dominated by LHCb)

LHCb CP-violation and Unitarity Triangle measurements
Measurement of the angle $\beta$

**Interference** between $B^0$ decay to $J/\psi K^0_S$ directly and via $B^0$ oscillation gives rise to a CP violating phase

$$\phi = \phi_{\text{Mixing}} - 2 \phi_{\text{Decay}} = 2\beta$$
LHCb measurement of $\sin(2\beta)$

$\sin(2\beta)$ from $B^0 \rightarrow J/\psi K^0_S$ and $B^0 \rightarrow \psi(2S)K^0_S$

$$A_{[c\bar{c}]K^0_S}(t) \equiv \frac{\Gamma(B^0(t) \rightarrow [c\bar{c}]K^0_S) - \Gamma(B^0(t) \rightarrow [c\bar{c}]K^0_S)}{\Gamma(B^0(t) \rightarrow [c\bar{c}]K^0_S) + \Gamma(B^0(t) \rightarrow [c\bar{c}]K^0_S)} \approx S \sin(\Delta m t) - C \cos(\Delta m t)$$

where $S = \sin(2\beta)$ assuming $C_{J/\psi K^0_S}$ (≡ penguin contribution) =

JHEP 11 (2017) 170

3 fb$^{-1}$ @ 7 & 8TeV

Competitive with Babar & Belle. HFLAV world average from all modes:

$\sin(2\beta) = 0.695 \pm 0.019$
The angle $\gamma$ (a key measurement)

- Loop processes are very sensitive to the presence of New Physics
- Constraints on the triangle apex largely come from loop decay measurements
- Large uncertainty on $\gamma$, the only angle accessible at tree level: forms a SM benchmark*
- $\gamma$ measurement theoretically

* assuming no significant New Physics in tree decays


$$\gamma \equiv \text{arg} \left[ -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right]$$

Combination of all direct measurements from tree decays

$$\gamma = (72.1^{+5.4}_{-5.7})$$

Determinations from CKM fit excluding all direct measurements of $\gamma$

$$\gamma = (65.8^{+1.0}_{-1.7})$$

Reachng degree level precision from direct measurements is crucial

Several methods to measure $\gamma$

- From $B^\pm$ (and $B^0$) decays: the “time-integrated”,
  direct CP-violation modes $B^\pm \rightarrow D^0 K^\pm$

  - GLW
    - Gronau & London, PLB 253 (1991) 483,
    - Gronau & Wyler PLB 265 (1991) 172
  - ADS
    - Atwood, Dunietz & Soni  PRL 78 (1997) 3257,
    - Atwood, Dunietz & Soni  PRD 63 (2001) 036005
  - GGSZ
    - Dunietz & Sachs Phys. Rev. D37(1988) 3186,

- $B_s^0 \rightarrow D_s^0 K$ time-dependent (TD) analysis
The time-integrated mode: $B^- \to D^0 K^-$

\[ \gamma \equiv \arg \left[ -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right] \]

(and charge conjugate mode $B^+ \to D^0 K^+$)

- Interference possible if $D^0$ and $\bar{D}^0$ decay to same final state
- Two possible decay paths to $K^+\pi^-$ final state via $D^0$ and $\bar{D}^0$

Branching fraction for favoured $B$ decay only $\sim 10^{-4}$

- Measurements require high statistics
GLW: $B \to D^{(*)}(\pi \pi \text{ or KK}) h \ (h = K, \pi)$

Method where $D^0$ and $\bar{D}^0$ decay to CP eigenstates

$3.0 \text{ fb}^{-1}$ Run 1 $+ 2.0 \text{ fb}^{-1}$ Run 2

\[ A_{K}^{\pi\pi} = +0.115 \pm 0.025 \ (\text{stat}) \pm 0.007 \ (\text{syst}) \]

\[ A_{\bar{K}K}^{\pi\pi} = +0.126 \pm 0.014 \ (\text{stat}) \pm 0.002 \ (\text{syst}) \]

At the level of $>5\sigma$

Phys Lett B 760 (2016) 117
**ADS :** $B \rightarrow D^{(*)}(K \pi)h \ (h = K, \pi)$

Method where $D^0$ and $D^0$ decay into flavour-specific final states

**Cabibbo favoured :** $3.0 \text{ fb}^{-1}$ Run 1 + $2.0 \text{ fb}^{-1}$ Run 2

**Phys Lett B 777 (2018) 16**

![Graphs showing $B^{-}[K^{-}\pi^{+}]_{D}K^{-}$ and $B^{+}[K^{+}\pi^{-}]_{D}K^{+}$ distributions with significance of 3.8σ.]

$A_{K}^{K\pi} = -0.019 \pm 0.005 \text{ (stat)} \pm 0.002 \text{ (syst)}$

**Cabibbo suppressed :** $3.0 \text{ fb}^{-1}$ Run 1

**Phys Lett B 760 (2016) 117**

![Graphs showing $B^{-}[\pi^{-}K^{+}]_{D}K^{-}$ and $B^{+}[\pi^{+}K^{-}]_{D}K^{+}$ distributions with significance of 7σ.]

$A_{\pi K}^{\text{ADS}(K)} = -0.403 \pm 0.056 \pm 0.011$
Dalitz analysis: CP observables measured in $B^\pm \rightarrow DK^\pm$ decays with $D \rightarrow K_S \pi^+ \pi^-$ and $D \rightarrow K^+K^-$.

- Divide up Dalitz space into $2N$ symmetric bins, chosen to optimise sensitivity to $\gamma$. 

**Figure:**
- A scatter plot showing the distribution of events in the Dalitz plot for $m^2(K_S^0 \pi^-)$ vs. $m^2(K_S^0 \pi^+)$, with a blue line indicating the Dalitz plot boundary. 
- The plot is color-coded with different shades indicating different bins, with a legend providing a color scale. 

**Note:** The plots are sourced from LHCb-PAPER-2018-017.
Model-independent GGSZ analysis

- Dalitz analysis: CP observables measured in $B^\pm \rightarrow DK^\pm$ decays with $D \rightarrow K_S\pi^+\pi^-$ and $D \rightarrow \pi^+\pi^-$ binning

- Divide up Dalitz space into $2N$ symmetric bins, chosen to optimise sensitivity to $\gamma$
Combination from different modes

The most recent combination includes the following:

<table>
<thead>
<tr>
<th>B decay</th>
<th>D decay</th>
<th>Method</th>
<th>Ref.</th>
<th>Dataset</th>
<th>Status since last combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW</td>
<td>[14]</td>
<td>Run 1 &amp; 2</td>
<td>Minor update</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>ADS</td>
<td>[15]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+\pi^-\pi^+\pi^-$</td>
<td>GLW/ADS</td>
<td>[15]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+h^-\pi^0$</td>
<td>GLW/ADS</td>
<td>[16]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow K^0_hh^-$</td>
<td>GGSZ</td>
<td>[17]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow K^0\pi^+\pi^-$</td>
<td>GLS</td>
<td>[19]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW</td>
<td>[14]</td>
<td>Run 1 &amp; 2</td>
<td>Minor update</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW/ADS</td>
<td>[20]</td>
<td>Run 1 &amp; 2</td>
<td>Updated results</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$D \rightarrow h^+\pi^-\pi^+\pi^-$</td>
<td>GLW/ADS</td>
<td>[20]</td>
<td>Run 1 &amp; 2</td>
<td>Most recent</td>
</tr>
<tr>
<td>$B^0 \rightarrow DK^0$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW/ADS</td>
<td>[21]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^0 \rightarrow DK^0$</td>
<td>$D \rightarrow K^+$</td>
<td>ADS</td>
<td>[22]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^0 \rightarrow DK^0$</td>
<td>$D \rightarrow h^+h^-$</td>
<td>GLW-Dalitz</td>
<td>[23]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^0 \rightarrow DK^0$</td>
<td>$D \rightarrow K^0\pi^+\pi^-$</td>
<td>GGSZ</td>
<td>[24]</td>
<td>Run 1</td>
<td>As before</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^0\pi^+$</td>
<td>$D^+_s \rightarrow h^+h^-\pi^+$</td>
<td>TD</td>
<td>[25]</td>
<td>Run 1</td>
<td>Updated results</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^+\pi^+$</td>
<td>$D^+ \rightarrow K^+\pi^-\pi^+$</td>
<td>TD</td>
<td>[26]</td>
<td>Run 1</td>
<td>Most recent</td>
</tr>
</tbody>
</table>

\* Run 1 corresponds to an integrated luminosity of 3 fb\(^{-1}\) taken at centre-of-mass energies of 7 and 8 TeV. Run 2 corresponds to an integrated luminosity of 2 fb\(^{-1}\) taken at a centre-of-mass energy of 13 TeV.

LHCb-CONF-2018-002

LHCb average:

\[ \gamma = (74.0^{+5.0}_{-5.8})^\circ \]

Dominates HFLAV average:

\[ \gamma = (73.5^{+4.2}_{-5.1})^\circ \]

Reminder of indirect constraint:

\[ \gamma = (65.8^{+1.0}_{-1.7})^\circ \]

BaBar:

\[ \gamma = (69^{+17}_{-16})^\circ \]

Belle:

\[ \gamma = (63^{+15}_{-14})^\circ \]

PRD 87 (2013) 052015

arXiv:1301.2033
LHCb combination from different modes

LHCb average

\[ \gamma = (74.0^{+5.0}_{-5.8})^\circ \]

- Comparison between \( B_s^0 \) and \( B^\pm \) initial states \( \sim 2 \) sigma.
- More \( B_s \) channels to be added (\( B_s \rightarrow D_{s(*)}K^{(*)}, B_s \rightarrow D\phi \)).
**B_s weak mixing phase φ_s in B_s → J/ψ φ**

- "Golden mode" for this study is $B_s \rightarrow J/\psi \phi$ ($\rightarrow K^+K^-$)
- Analogue of $2\beta$ (phase of $B^0$ mixing) but in the $B_s$ system
- *Interference* between $B^0$ decay to $J/\psi \phi$ directly and via $B^0 - \bar{B}^0$ oscillation gives rise to a CP violating phase in the SM
  $$\phi_s = \phi_{\text{Mixing}} - 2 \phi_{\text{Decay}} = -2\beta_s$$
- $\phi_s$ is expected to be very small in the SM and precisely predicted:
  $$\phi_{\text{SM}} = -0.036 \pm 0.002$$  
  (see eg Charles et al PRD84 (2011) 033005)
Status of $\phi_s$ before Spring 2019

- World average dominated by LHCb
- Results consistent with SM-based global fits to data, but still room for NP

$\phi_s^{\text{exp}} = -0.020 \pm 0.031 \text{ rad}$

$\phi_{\text{SM}} = -0.036 \pm 0.002 \text{ rad}$

LHCb : 3 fb$^{-1}$  PLB 736 (2014)  186
NEW: Add Run-II LHCb measurements with 2015 (0.3 fb$^{-1}$) and 2016 (1.6 fb$^{-1}$) datasets

- $B_s \rightarrow J/\psi K^+K^-$


![Graph showing $B_s \rightarrow J/\psi K^+K^-$]

$N_{\text{sig}} \sim 117k$

[arXiv:1906.08356]

- $B_s \rightarrow J/\psi \pi^+\pi^-$


![Graph showing $B_s \rightarrow J/\psi \pi^+\pi^-$]

$N_{\text{sig}} \sim 34k$
- $\phi$ is a vector meson (spin 1)
- Vector-vector final state: mixture of CP-odd and CP-even components

Need to perform $B_s \rightarrow J/\Psi \phi$ angular analysis

- Good tagging performance of $B_{s\bar{s}}$ & $B_s$ is important

<table>
<thead>
<tr>
<th>Category</th>
<th>$\varepsilon_{\text{tag}}$ (%)</th>
<th>$D^2$</th>
<th>$\varepsilon_{\text{tag}} D^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS only</td>
<td>11.4</td>
<td>0.078</td>
<td>0.88 ± 0.04</td>
</tr>
<tr>
<td>SSK only</td>
<td>42.6</td>
<td>0.032</td>
<td>1.38 ± 0.30</td>
</tr>
<tr>
<td>OS &amp; SSK</td>
<td>23.8</td>
<td>0.104</td>
<td>2.47 ± 0.15</td>
</tr>
<tr>
<td>Total</td>
<td>77.8</td>
<td>0.061</td>
<td>4.73 ± 0.34</td>
</tr>
</tbody>
</table>
$B_s \rightarrow J/\psi \phi$: fit projections

Results and new LHCb combination

- $\phi_s$ fitted value correlated with $\Delta \Gamma_s = \text{width diff. of the } B_s \text{ mass eigenstates} \rightarrow \text{plot as contours in } (\phi_s \text{ vs } \Delta \Gamma_s) \text{ plane}$

$$\Delta \Gamma_s = 0.0816 \pm 0.0048 \text{ ps}^{-1}$$

CP-violating phase: $\phi_s = -0.041 \pm 0.025 \text{ rad}$
HFLAV combination

\[\Delta \Gamma_S = 0.0764 \pm 0.0024 \text{ ps}^{-1}\]

CP-violating phase: \(\phi_S = -0.055 \pm 0.021 \text{ rad}\)
**CP violation in charm**

- Direct CP violation

\[
\begin{align*}
\left| \begin{array}{c}
D^0 \\
\end{array} \right|^2 & \neq \left| \begin{array}{c}
\bar{D}^0 \\
\end{array} \right|^2
\end{align*}
\]

Measure asymmetry

\[
A(D \rightarrow f) = \frac{N(D \rightarrow f) - N(\bar{D} \rightarrow \bar{f})}{N(D \rightarrow f) + N(\bar{D} \rightarrow \bar{f})}
\]

- Most promising channels are *Cabibbo-suppressed* (CS) decays where CPV may arise from the *interference* between the *tree* and the *penguin* amplitudes

- SM prediction is very small \(O(10^{-4}) \rightarrow O(10^{-3})\)
Tag $D^0$ and $\bar{D}^0$ via “prompt” and “semileptonic” decays:

- Prompt: coming from primary vertex, \( i.e. \ D^{*\pm} \rightarrow D^0 \pi^{\pm} \)

- Semileptonic: coming from B-decays, \( i.e. \ B^{\pm} \rightarrow D^0 \mu^{\pm}X \)

The raw asymmetry \( \Delta A_{CP} \) in Cabibbo-suppressed \( D^0 \rightarrow h^+ h^- \) decays (\( h = K \) or \( \pi \)) defined as

\[
A(D \rightarrow f) = \frac{N(D \rightarrow f) - N(\bar{D} \rightarrow \bar{f})}{N(D \rightarrow f) + N(\bar{D} \rightarrow \bar{f})}
\]

includes physics and detector effects:

\[
A = A_{CP} + A_D + A_P
\]

To eliminate these contributions and cancel the systematics measure:
\[ \Delta A_{\text{CP}} \text{ measurement: fits and yields} \]

- Measurement performed with almost full Run-2 data-set (5.9/\text{fb})
- Get the raw asymmetries from fits to the \( m(D^0 \pi^+_\text{soft}) \) or \( m(D^0) \) distributions

[Phys. Rev. Lett. 122, 211803]
Observation of CPV in charm decays

- Run-2 results alone:

  \[ \Delta A_{CP}^{\pi\text{-tagged}} = \left[ -18.2 \pm 3.2 \text{ (stat.)} \pm 0.9 \text{ (syst.)} \right] \times 10^{-4} \]

  \[ \Delta A_{CP}^{\mu\text{-tagged}} = \left[ -9 \pm 8 \text{ (stat.)} \pm 5 \text{ (syst.)} \right] \times 10^{-4} \]

- Add in the Run-1 result gives:

  \[ \Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4} \]

- A 5.3\sigma measurement of CPV in the charm system!

- This opens a completely new window for the study of CP violation.
LHCb new spectroscopy measurements
Corfu Workshop as of last year ...

- Reported an unexpected narrow resonance in the mass spectrum of $(J/\psi p)$ in $\Lambda_b \rightarrow (J/\psi p) K^-$ decays.
- First observed in 2015 → LHC Run 1 data: $3 \text{ fb}^{-1}$
- Consistent with pentaquarks: allowed by QCD, but not observed in 50 years of searching.

Diagram from Liming Zhang
Pentaquarks – 2015 reminder

P_{c}^{+}(4380): M = 4380\pm8\pm29 \text{ MeV} \quad \Gamma = 205\pm18\pm86 \text{ MeV}

P_{c}^{+}(4450): M = 4449.8\pm1.7\pm2.5 \text{ MeV} \quad \Gamma = 39\pm5\pm19 \text{ MeV}

9\sigma

12\sigma
New Run I and II analysis

- 9.5x more data than used in Run-I
- Improvements in the data selection (2x), integrated luminosity (3x) and cross section (13 TeV vs 7-8 TeV)

\[ \Lambda_b \rightarrow (J/\psi \ pK) \]
Fits to data

- Confirms the peaking structure at ~4450 MeV
The previously observed $P_c^+(4450)$ is now superseded by the $P_c^+(4440)$ and $P_c^+(4457)$.

New state $P_c^+(4312)$.

The broad $P_c^+(4380)$ state is neither excluded nor confirmed by current analysis.

Updated amplitude analysis required to identify the states.

<table>
<thead>
<tr>
<th>State</th>
<th>$M$ [MeV]</th>
<th>$\Gamma$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4312)^+$</td>
<td>$4311.9 \pm 0.7^{+6.8}_{-0.6}$</td>
<td>$9.8 \pm 2.7^{+3.7}_{-4.5}$</td>
</tr>
<tr>
<td>$P_c(4440)^+$</td>
<td>$4440.3 \pm 1.3^{+4.1}_{-4.7}$</td>
<td>$20.6 \pm 4.9^{+8.7}_{-10.1}$</td>
</tr>
<tr>
<td>$P_c(4457)^+$</td>
<td>$4457.3 \pm 0.6^{+4.1}_{-1.7}$</td>
<td>$6.4 \pm 2.0^{+5.7}_{-1.9}$</td>
</tr>
</tbody>
</table>
Nature of pentaquarks?

Possible models describing the observed pentaquark states:

- Tightly bounded states
- Re-scattering models
- Molecular-state model favoured: bound mesons and baryons are expected to form narrow resonances just below mass thresholds
- More work needed
New: $\Sigma_b$ and $\Sigma_b^*$ spectroscopy

- Study the $\Lambda_b\pi^\pm$ spectrum where $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$ and $\Lambda_c^+ \rightarrow p K \pi$
- Find $(234,270 \pm 900) \Lambda_b$ candidates in 3 fb$^{-1}$ (Run I)

$\Lambda_c^+ \pi^-$ mass

$\Lambda_b \pi^+$ mass

$\Sigma_b$ and $\Sigma_b^*$ resonances
Study excitations by adding $\pi^+\pi^-$ to the $\Lambda_b$

$\Lambda_b$ reconstructed in $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$, and also add in $\Lambda_b \rightarrow J/\psi \ p \ K^-$

Structure seen around 6.15 GeV/c$^2$
**Λ_b excitations in (Λ_b π^+ π^-)**

- Study excitations by adding π^+ π^- to the Λ_b
- Λ_b reconstructed in Λ_b → Λ_c^+ π^-, and also add in Λ_b → J/ψ p K^-
- Structure seen around 6.15 GeV/c^2
- Investigate substructure of the decays where Χ → Σ_b^0 π → Λ_b π^+ π^-
Observation of two new $\Lambda_b$ excitations

Very rich spectroscopy in the $\Lambda_b$ & $\Sigma_b^{(*)}$ systems!

arXiv:1907.13598

Corfu Summer Institute                     3 September 2019                            N. Harnew
Observation of new state in DD spectrum

- Use full Run1+Run2 dataset
  → new narrow state observed in the invariant mass spectra of $D^0D^0$ and $D^+D^-$

![Graph showing invariant mass spectra with peaks at 3.84 GeV/c² for $X(3842)$ and 3.93 GeV/c² for $X_c(3930)$.

$$M_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12 \text{ MeV/c}^2$$
$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35 \text{ MeV}$$
The upgraded LHCb detector and outlook
LHCb Upgrade planning

WE ARE HERE

Run 2 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029
Run 3 LS2 2030 2031 2032 2033 2034 2035 2036 2037
Run 4 LS4
Up to 50 fb\(^{-1}\) collected

Luminosity \(4 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}\)
~1.1 visible interactions/crossing
~9 fb\(^{-1}\) collected

Luminosity \(2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}\)
~5.5 visible interactions/crossing
Up to 50 fb\(^{-1}\) collected

Luminosity \(2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\)
~55 visible interactions/crossing
300 fb\(^{-1}\) collected
**LHCb Upgrade I**

- New scintillating fibre tracker (SciFi)
- New silicon upstream tracker (UT)
- New PIXEL vertex detector (VELO)
- New RICH1 and photodetectors
- New RICH2 photodetectors
- New RICH1 and photodetectors
- New electronics for muon and calorimeter systems
- Plus new trigger
\( \gamma \) prospects: Run 1 & II \( \rightarrow \) Upgrade

- Run 1 target of 8° surpassed: (analyses now essentially complete)
- Run II data well into analysis:
  target <4° (\( \sim 9 \text{ fb}^{-1} \))
- LHCb Upgrade:
  target 0.9° (\( \sim 50 \text{ fb}^{-1} \))

\[
\gamma = (74.0^{+5.0}_{-5.8})^\circ
\]

EPJC (2013) 73:2373
... and beyond 2026: Upgrade II
Evolution of the Unitarity Triangle

LHCb : 2019 Run 2

LHCb Upgrade I 2025 (23 fb$^{-1}$)

LHCb Upgrade II 2035 (300 fb$^{-1}$)
Summary and Outlook

- The LHCb experiment has performed spectacularly well:
  - $\sim 9 \text{ fb}^{-1}$ of recorded data up to $\sqrt{s} = 13 \text{ TeV}$
- So far all Unitarity Triangle measurements are consistent with the Standard Model:
  - New Physics is becoming constrained
- LHCb is a fantastic platform for spectroscopy measurements: many measurements were never foreseen in LHCb’s original physics portfolio.
- Still much room for New Physics, but higher precision required
  - preparing for LHCb Upgrades beyond 2020 and the decade afterwards!
Spare Slides
**LHCb forward spectrometer**

- Forward-peaked production → LHCb is a forward spectrometer (operating in LHC collider mode)
- $b\bar{b}$ cross-section = $72.0 \pm 0.3 \pm 6.8 \text{ mb}$ at $\sqrt{s} = 7 \text{ TeV}$ in the LHCb acceptance $2<\eta<5$
- At $\sqrt{s} = 13 \text{ TeV} : 154.3 \pm 1.5 \pm 14.3 \text{ mb}$
- $\Rightarrow \sim 100,000 \, b\bar{b}$ pairs produced/second ($10^4 \times$ B factories)

and all species of B hadron

---

PRL 118, 052002 (2017)

LHCb data taking

- Design luminosity = \(2 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}\) (50 times less than ATLAS/CMS). Typical running luminosity \(\sim 4 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}\)
After LHCb’s hardware trigger, events are buffered.

- LHCb’s automated real-time alignment and calibration runs:
  - Full detector alignment and calibration in minutes.

- Full event reconstruction in software trigger:
  - Exclusive decay modes and calibration modes fully reconstructed,
  - Results stored and used as basis for analysis.

- See LHCb-PROC-2015-011
- Mixing loop dominated by the top
- Length of side from ratio of $B_d$ and $B_s$:
x-mixing frequencies extracted with input from lattice QCD (systematics cancel)
B(s) mixing at LHCb

\[
\frac{N(B^0 \to B^0) - N(B^0 \to \bar{B}^0)}{N(B^0 \to B^0) + N(B^0 \to \bar{B}^0)}
\]

\[
LHCb
\]

\[
B^0 \to D^- \mu^+ \nu_{\mu} X
\]

\[
\Delta m_d = (505.0 \pm 2.1 \pm 1.0) \text{ ns}^{-1}
\]

\[
|V_{td}/V_{ts}| = 0.210 \pm 0.001 \pm 0.008.
\]

Mixing measurements dominated by LHCb (L-QCD systematics to be improved)


Corfu Summer Institute 3 September 2019

N. Harnew
\[ |V_{ub}| \] measurement for side opposite to $\beta$

- Closure test of UT mainly limited by $|V_{ub}|$

- Side opposite to $\beta$ proportional to $|V_{ub}| / |V_{cb}|$

- $V_{ud}$ and $V_{cd}$ very well known. $|V_{cb}|$ known to better than 3%

- $|V_{ub}|^2$ is directly proportional to the decay rate $B \to X_u \ell \nu$ and is then calculated using HQET
|V_{ub}| / |V_{cb}| difficult at hadron colliders due to presence of neutrino

LHCb measures $\Lambda_b \rightarrow p \mu^- \nu$

(the $B^0 \rightarrow \pi^- \mu^+ \nu$ channel is extremely difficult)

The measurement relies on $\Lambda_b \rightarrow p$ form factors from the lattice)

$|V_{ub}| = (3.27 \pm 0.15(\text{exp}) \pm 0.17(\text{theory}) \pm 0.06 (|V_{cb}|)) \times 10^{-3}$

Nature Physics 10 (2015) 1038
Tension between B-factory inclusive and exclusive $|V_{ub}|$ measurements limit the precision on UT side. World average

\[
|V_{ub}| = (4.49 \pm 0.15 \pm 0.16 \pm 0.17) \times 10^{-3} \quad \text{(inclusive)}
\]

\[
|V_{ub}| = (3.70 \pm 0.10 \pm 0.12) \times 10^{-3} \quad \text{(exclusive)}
\]

\[
|V_{ub}| = (3.94 \pm 0.36) \times 10^{-3} \quad \text{(average)}.
\]

Measurement of $\alpha$

- Constraints on $\alpha$ from $B \to \pi \pi$, $\rho \pi$ and $\rho \rho$ (Babar and Belle)
  - $\alpha = (87.6^{+3.5}_{-3.3})^\circ$ world average measurement

- Compared to the prediction from the global CKM fit (not including the $\alpha$-related measurements)
  - $\alpha = (90.6^{+3.9}_{-1.1})^\circ$

- As yet there has been no LHCb 'standalone' measurement of $\alpha$

- LHCb can provide useful input to B-factories measurements to constrain alpha.
Yields of $B^+ \rightarrow \pi^+K^+K^-$ and $B^- \rightarrow \pi^-K^-K^+$ show a striking asymmetry in the region of phase space dominated by re-scattering effects.

CP asymmetry between $B^+ \rightarrow \pi^+\pi^+\pi^-$ and $B^- \rightarrow \pi^-\pi^-\pi^+$ decays in a region of phase space including the $\rho(770)^0$ and $f_2(1270)$, divided according to whether the cosine of the helicity angle is positive (blue) or negative (red). The bands indicate the spreads of the isobar, $K$-matrix and quasi-model-independent models.
"GLW" method

- Method where $D^0$ and $\bar{D}^0$ decay to CP eigenstates
- Eigenstates are equally accessible to $D^0$ and $\bar{D}^0$
- Only 2 hadronic parameters $r_B$, $\delta_B$ to be determined alongside $\gamma$ ($r_B \sim 0.1$)

"Counting experiment": observe the rate of $B^-$ vs. $B^+$ decays

Weak phase changes sign for equiv $B^+$ diagram, thickness of arrows indicate relative strengths

\[
\frac{N(B^-) - N(B^+)}{N(B^-) + N(B^+)} = A_{CP^+} = \frac{1}{R_{CP^+}} 2r_B(2F_+ - 1) \sin(\delta_B) \sin(\gamma)
\]

\[
\frac{N(B \to [KK]_D K) \times \Gamma(D \to K\pi)}{N(B \to [K\pi]_D K) \times \Gamma(D \to KK)} = R_{CP^+} = 1 + r_B^2 + 2r_B(2F_+ - 1) \cos(\delta_B) \cos(\gamma)
\]

For CP+ eigenstates e.g. KK, $\pi \pi$, $F_+ = 1$
“ADS” method

- Decay into flavour-specific final states
- Larger interference effects than for GLW as both amplitudes of similar sizes.
- $r_B, \delta_B$ hadronic parameters again to be determined alongside $\gamma$ ($r_B \sim 0.1$)
- Additional two parameters $r_D, \delta_D$.

Weak phase changes sign for equivalent $B^+$ diagram

\[
\frac{N(B^-) - N(B^+)}{N(B^-) + N(B^+)} = A_{ADS} = \frac{1}{R_{ADS}} 2r_B r_D \sin(\delta_B + \delta_D) \sin(\gamma)
\]

\[
\frac{N(B^\pm \to [\pi^\pm K^\mp]_D K^\pm)}{N(B^\pm \to [K^\pm \pi^\mp]_D K^\pm)} = R_{ADS} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos(\gamma)
\]

Again, a counting experiment: observing the rate of $B^-$ vs. $B^+$ decays
“GGSZ” method

- 3-body final D states e.g. $D \rightarrow K^0_S \pi \pi$

- Dalitz plot analysis: a counting experiment in bins of phase space

GGSZ observables (rate as function of Dalitz position)

$$d\Gamma_{B^\pm}(x) = A^2_{(\pm,\mp)} + r_B^2 A^2_{(\mp,\pm)} + 2A_{(\pm,\mp)} A_{(\mp,\pm)} \left[ r_B \cos(\delta_B \pm \gamma) \cos(\delta_D(\pm,\mp)) + r_B \sin(\delta_B \pm \gamma) \sin(\delta_D(\pm,\mp)) \right]$$

$c_i$ and $s_i$ measured from Q-C D decays at CLEO

arXiv:1010.2817
New model-independent GGSZ analysis

LHCb GGSZ only

The most precise determination of $\gamma$ from a single analysis

\[ \gamma = 80^\circ \pm 10^\circ \left( +19^\circ \right), \]

\[ r_B = 0.080 \pm 0.011 \left( +0.022 \right), \]

\[ \delta_B = 110^\circ \pm 10^\circ \left( +19^\circ \right). \]
Evolution of $\gamma$ precision

- It is necessary to pursue different B decays to provide crosschecks
- Current measurements still dominated by statistical uncertainties
It is necessary to pursue different B decays to provide crosschecks.

Current measurements still dominated by statistical uncertainties.
Two methods for accessing D decay information

Two ways to deal with the varying $r_D$, $\delta_D$

**Model dependent**
- $r_D$ and $\delta_D$ determined from flavour tagged decays (e.g. Babar/Belle) via amplitude model
- Systematic uncertainties due to model hard to quantify

**Model independent**
- Use CLEO data to measure average values of $r_D$ and $\delta_D$ in pre-defined bins
- Direct phase information, uncertainties on which can be propagated

PRD 82 (2010) 112006
Interference between $B^0$ decay to $D_s^+K^-$ directly and via $B^0$ $B^0$ oscillation gives a CP violating phase

$$\phi = \phi_{\text{Decay}} - \phi_{\text{Mixing}} = (\gamma - 2\beta_S)$$

$\beta_S$ is (small) mixing phase, $\phi_s = -2\beta_S = 0.01 \pm 0.07 \pm 0.01$ (syst)

$$\frac{d\Gamma_{B^0 \to f(t)}}{dt} = \frac{1}{2} |A_f|^2 (1 + |\lambda_f|^2)e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_{s,t}}{2} \right) + A_f^\Delta \Gamma \sinh \left( \frac{\Delta \Gamma_{s,t}}{2} \right) \right]$$

$$\frac{d\Gamma_{\bar{B}^0 \to f(t)}}{dt} = \frac{1}{2} |A_f|^2 \left| \frac{p}{q} \right|^2 (1 + |\lambda_f|^2)e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_{s,t}}{2} \right) + A_f^\Delta \Gamma \sinh \left( \frac{\Delta \Gamma_{s,t}}{2} \right) \right] - C_f \cos (\Delta m_s t) - S_f \sin (\Delta m_s t) \right] ,$$
B⁰→Dˢ⁺K⁻ continued

- Only 1 fb⁻¹ of data published so far. The full Run-I 3 fb⁻¹ measurement is expected towards the end of this year.

\[
A_{f}^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}, \quad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}, \quad C_f = \frac{1 - r_{D_sK}^2}{1 + r_{D_sK}^2}
\]

- Measure folded asymmetry distributions:

\[
S_f = \frac{2r_{D_sK}\sin(\delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}, \quad S_{\bar{f}} = \frac{-2r_{D_sK}\sin(\delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}
\]

\[
\gamma = (115^{+28}_{-43})^\circ
\]
“Visualizing” the effect of $\phi_s$ in $B_s \rightarrow J/\psi \phi$

- Amplitude of asymmetry $\propto \sin \phi_s$
- Frequency is the same as in $B_s$ mixing

Ampl. $\propto \sin \phi_s$

$MC : \phi_s = 0.04$

$MC : \phi_s = 0.4$

$BS^0 \rightarrow DS^-\pi^+$ decays

Data

Measurement of CP violation in $B_s \to \phi \phi$

- Enhanced sensitivity to NP since decay is dominated by penguin loop
- SM prediction of CP violating phase is small
- Perform time-dependent angular analysis, Run1data + 2 fb$^{-1}$ Run 2

$|\phi| = 78 \pm 115 \pm 27$

arXiv:0810.0249

LHCb-PAPER-2019-019
Possible assignment of excited $\Omega_c$ states

Matching between observed peaks and predictions requires spin-parity information

M. Karliner, J.L. Rosner, PR D95, 114012 (2017)
Comparisons with SELEX

- SELEX (Fermilab E781) collides high energy hyperon beams ($\Sigma^-, p$) with nuclear targets, dedicated to study charm baryons
- Observed $\Xi_{cc}^+(ccd)$ in $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^+ \rightarrow pD^+ K^-$ decays
- Large mass difference: $m(\Xi_{cc}^{++})_{\text{LHCb}} - m(\Xi_{cc}^+)_{\text{SELEX}} = 103 \pm 2$ MeV
Previous pentaquark $J^P$ assignments

- Preferred $J^P$ assignments of opposite parity, with $P_c^+(4380)$ having $3/2^-$ and the $P_c^+(4450)$ having $5/2^+$.

- Good evidence for the resonant character of $P_c^+(4450)$: Too large errors for $P_c^+(4380)$: hard to make a definitive conclusion.

PRL 115 (2015) 072001
Pentaquarks in $\Lambda_b \rightarrow (J/\psi \ p) \pi^-$

- Search for additional Pentaquark candidates in other production channels
- $\Lambda_b \rightarrow (J/\psi \ p) \pi^-$ (Cabbibo suppressed $\approx 15$ times smaller statistics)
- Contributions from:
  - $N^* \rightarrow p \pi^-$
  - $P_c(4380)^+ \rightarrow J/\psi \ p$
  - $P_c(4450)^+ \rightarrow J/\psi \ p$
  - $Z_c(4200)^- \rightarrow J/\psi \pi^-$
- Fit with 2 pentaquarks + $Z_c(4200)$ tetraquark : favoured by $3\sigma$ compared to no exotic contributions

![Graph showing yields vs $m_{J/\psi p}$]
Another possible pentaquark mode

- Can look for ud\overline{d}cc pentaquark in $\Xi_b^-(bds)\rightarrow J/\psi K^-$

- Observation of $\Xi_b^-$ in Run I data (~300 candidates)

$M(\Xi_b^-) - M(\Lambda_b^0) = 177.08 \pm 0.47 \text{ (stat)} \pm 0.16 \text{ (syst)}$ MeV/c$^2$

- Amplitude analysis with Run II data to follow
The quark model predicts three weakly decaying $C = 2\ J^P = 1/2^+$ states: $\Xi^{+}(ccd)$, $\Xi^{+}(ccu)$, and $\Omega^{+}(ccs)$.

$J^P = 1/2^+$ states decay weakly with a $c$ quark decaying to lighter quarks.

$J^P = 3/2^+$ states expected to decay to $1/2^+$ states via strong or EM interaction.
Search in decay mode: \( \Xi_{cc}^{++} \rightarrow \Lambda_c^- K^+ \pi^+ \pi^+ \)

Branching fraction can be significant (10%) (Yu et al., arXiv:1703.09086)

Run 2 data sample: \( \sqrt{s}=13\) TeV, \( \sim 1.7\) fb\(^{-1} \)
**Observation of $\Xi^{++}_{cc}$**

- $\Xi^{++}$ is mass-corrected for $\Lambda_c$:
  \[ m_{\text{cand}}(\Xi^{++}_{cc}) = m(\Lambda^+_c K^- \pi^+) - m(\Lambda^+_c) + m_{\text{PDG}}(\Lambda^+_c) \]

- Signal yield: $313 \pm 33$ events
- Width $6.6 \pm 0.8$ MeV, consistent with resolution
- Local significance $> 22\sigma$

$m(\Xi^{++}_{cc}) = 3621.40 \pm 0.72\,\text{(stat)} \pm 0.27\,\text{(syst)} \pm 0.14(\Lambda^+_c)\,\text{MeV}$

$m(\Xi^{++}_{cc}) - m(\Lambda^+_c) = 1134.94 \pm 0.72\,\text{(stat)} \pm 0.27\,\text{(syst)}\,\text{MeV}$
**$\Xi^{++}_{cc}$ lifetime measurement**

- Analysis of 1.7 fb$^{-1}$ sample of Run 2 data, using $\Lambda^0_b \to \Lambda^+_c K^- \pi^+\pi^+$ control mode to measure the $\Xi^{++}_{cc}$ lifetime with respect to that of $\Lambda^0_b$.

- **Lifetime result**: $	au(\Xi^+_{cc}) = (256_{-22}^{+24} \pm 14)$ fs

- Confirms that $\Xi^{++}_{cc}$ is a weakly decaying baryon.

The puzzle of the $\Omega_c^\pm$ lifetime

- Via the decay $\Omega_b^\pm \rightarrow \Omega_c^0 \mu^\pm \nu_\mu X$ then $\Omega_c^0 \rightarrow pK^-\pi^+$ [ $\Omega_c^0$ is (css)]
- Measured relative to that of $D^+$ meson decays (reduce systematics)
- Lifetime $\sim$4 times greater than previous experiments, which have $\sim$10 times less statistics

$\tau(\Omega_c^0) = 268\pm24\pm10\pm2$ fs

arXiv:1807.02024
Observation of a new $\Xi_b^{**-}\bar{\nu}$ resonance

- Seen both in $\Xi_b^{**-}\rightarrow \Lambda_b^0 K^-$ & $\Xi_b^{**-}\rightarrow \Xi_b^0 \pi^-$ decays
- $J^P$ not yet measured

$M(\Xi_b^{**-}) - M(\Lambda_b^0) = 607.3 \pm 2.0 \text{ (stat)} \pm 0.3 \text{ (syst)} \text{ MeV}/c^2,$
$\Gamma = 18.1 \pm 5.4 \text{ (stat)} \pm 1.8 \text{ (syst)} \text{ MeV}/c^2,$
$M(\Xi_b^{**-}) = 6226.9 \pm 2.0 \text{ (stat)} \pm 0.3 \text{ (syst)} \pm 0.2(\Lambda_b^0) \text{ MeV}/c^2.$

arXiv:1805.09418
Observation of $\Omega_c$ excited states

- Single charmed baryons predicted to form SU(3) $3 \otimes 3 = 3 \oplus 6$ baryon multiplets (Jaffe, Phys. Rep. 409 (2005) 1)

- All ground states have been observed, as have excited states $\Lambda_c$, $\Sigma_c$, and $\Xi_c$.
Observation of five new narrow $\Omega_c^0$ excited states

- Decay: $\Omega_c^{0*}(css) \rightarrow \Xi_c^+(csu) K^-$; $\Xi_c^+(csu) \rightarrow pK^-\pi^+$

- Decay well separated from primary vertex $\tau(\Xi_c) \approx 45$ ps

Mass of $\Xi_c$
### Masses and widths

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_c(3000)^0$</td>
<td>$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$</td>
<td>$4.5 \pm 0.6 \pm 0.3$</td>
</tr>
<tr>
<td>$\Omega_c(3050)^0$</td>
<td>$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$</td>
<td>$0.8 \pm 0.2 \pm 0.1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$&lt; 1.2\text{ MeV, 95% CL}$</td>
</tr>
<tr>
<td>$\Omega_c(3066)^0$</td>
<td>$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$</td>
<td>$3.5 \pm 0.4 \pm 0.2$</td>
</tr>
<tr>
<td>$\Omega_c(3090)^0$</td>
<td>$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$</td>
<td>$8.7 \pm 1.0 \pm 0.8$</td>
</tr>
<tr>
<td>$\Omega_c(3119)^0$</td>
<td>$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$</td>
<td>$1.1 \pm 0.8 \pm 0.4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$&lt; 2.6\text{ MeV, 95% CL}$</td>
</tr>
<tr>
<td>$\Omega_c(3188)^0$</td>
<td>$3188 \pm 5 \pm 13$</td>
<td>$60 \pm 15 \pm 11$</td>
</tr>
</tbody>
</table>

- 5 narrow states & evidence for 6th broader state at high mass
- Assignment of $J^P$ states in the quark model (see backup slides)  
  (M. Karliner, J.L. Rosner, PR D95, 114012 (2017))
- Suggestion the 2 narrowest states might be pentaquarks?
- Confirmation of states awaits spin-parity assignments
LHCb Upgrade I trigger system

30 MHz collision rate

- Trigger-less readout and full software trigger
  - Process data at machine clock (40 MHz crossings and 30 MHz of visible interactions)
  - No L0 (hardware) bottleneck
- No further offline processing
  - Run II was already a critical test-bed for this technology (turbo mode)

HLT

- HLT1: full event reconstruction, inclusive and exclusive kinematic/ geometric selections
- Buffer events to disk, online calibration/alignment
- HLT2: offline precision PID and track quality. Output full event information for inclusive triggers, trigger candidates, and related PVs for exclusive triggers

100 kHz (2-5 GB/s) to storage