CP violation measurements in beauty and charm hadrons at LHCb

Angelo Di Canto on behalf of LHCb
CPV in the Standard Model (and beyond)

- The phase of the CKM matrix is the dominant source of CPV in the SM
- In extensions of the SM additional sources can arise from exchange of new particles (that may not be at directly accessible at the LHC)
- Decays of heavy-flavoured mesons are the best laboratory to test the CKM paradigm and look for new sources of CPV

\[ L = L_{\text{SM}} + \frac{1}{\Lambda^2} O_{\Delta F=2} \]

Reach of direct searches

\[ \text{FCC} \quad \text{LHC} \]
Experimental status
Experimental status

- **CP-conserving observables**
- **CP-violating observables**
CKM angle $\gamma$

- The least constrained angle of the CKM matrix and only CPV parameter that can be measured from trees

\[
\left| B \rightarrow V_{ub} e^{-i\gamma} K^- + B \rightarrow V_{cs} K^0 \overline{D}^0 \right|^2
\]

\[
\gamma = \arg \left( -\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right) \approx 76^\circ
\]

- Negligibly small theory uncertainties [JHEP 01 (2014) 051] → powerful test of the SM


\[
f_D = K^+ K^-, \pi^+ \pi^- \quad \text{GLW}
\]

\[
K^{\mp} \pi^\pm \quad \text{ADS}
\]

\[
K_S \pi^+ \pi^- \quad \text{GGSZ}
\]
LHCb combination

- Constraints from several decay modes (85 observables, 37 parameters) to find
  \[ \gamma = (76.8^{+5.1}_{-5.7})^\circ \]

- To be compared with world average of [HFLAV]
  \[ \gamma = (76.2^{+4.7}_{-5.0})^\circ \]

- Soon many more results from Run 2

- Expect \(\sim 1^\circ (0.4^\circ)\) precision after LHCb phase-1(2) upgrade [EPJC 73 (2013) 2373, CERN-LHCC-2017-003]

- Belle 2 with 50/ab will be competitive with LHCb phase-1 upgrade

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<th>GLW</th>
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\[ [\text{LHCb-CONF-2017-004}] \]
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$B^\pm \rightarrow DK^{*\pm}$ in Run 1+2 data

- Uses 2- and 4-body $D$ decays and $K^{*\pm} \rightarrow K_S\pi^{\pm}$ decays
- Constraints on $r_B$, $\delta_B$ and $\gamma$ from measurement of ratio of rates and CP asymmetries
  \[ R_{CP+} = 1 + r_B^2 + 2r_B \cos \delta_B \cos \gamma \]
  \[ A_{CP+} = r_B \sin \delta_B \sin \gamma / R_{CP+} \]
- Results in the 2-body modes consistent and more precise than BaBar [PRD 80 (2009) 092001]
  \[ R_{CP+} = 1.18 \pm 0.08 \pm 0.01 \]
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4.3\( \sigma \) evidence of suppressed ADS mode

[NEW]

[PRD 80 (2009) 092001]
$B^\pm \rightarrow DK^{*\pm}$ in Run 1+2 data

NEW

[LHCb-PAPER-2017-030]
CP violation in the $B^0$ system

- Interference between mixing and decay in $B^0 \to (c\bar{c})K_S$ is sensitive to the angle $\beta$
  \[
  \beta = \arg \left( -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right) \sim 22^\circ
  \]

- The B-factories still dominate the world average [HFLAV]
  \[
  \beta = (21.9 \pm 0.7)^\circ
  \]
  but LHCb with Run 1 data is already pretty close

- LHCb is expected to reach $0.6^\circ$ ($0.2^\circ$) precision with Run 2 (phase-1 upgrade) [EPJC 73 (2013) 2373]
\[ \sin(2\beta) \text{ from } B^0 \rightarrow (c\bar{c})K_S \text{ decays} \]

- Additional channels from Run 1 data

- About 20% improvement in precision wrt previous result [PRL 115 (2015) 031601]
CP violation in the $B_s$ system

\[ \beta_s = \arg \left( -\frac{V_{cs}V_{cb}^*}{V_{ts}V_{tb}^*} \right) \sim 1^\circ \]

- Golden channel is $B_s \rightarrow J/\psi \phi$, but additional sensitivity comes from other $b \rightarrow c\bar{c}s$ transitions
- Pioneering measurements from Tevatron have now been improved by more than a factor 10 by LHCb (+ Atlas and CMS)

**LHCb:**
- $J/\psi \phi$ [PRL114, 041801 (2015)]
- $D_s^+ D_s^-$ [PRL113, 211801 (2014)]

**CMS:**

**ATLAS:**
- $J/\psi \phi$ [JHEP 08 (2016) 147]
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**LHCb:**
- $J/\psi \phi$ [PRL114, 041801 (2015)]
- $D_s^+ D_s^-$ [PRL113, 211801 (2014)]

**CMS:**

**ATLAS:**
- $J/\psi \phi$ [JHEP 08 (2016) 147]
\[ \phi_s = -2\beta_s \] using \( B_s \to J/\psi KK \) decays

- Fully exploit Run 1 data by analysing the full \( m(KK) \) spectrum of \( B_s \to J/\psi KK \) decays

Flavor-tagged, time-dependent amplitude fit to separate the various CP-odd/even components

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
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<tr>
<td>( \Gamma_s ) [ps(^{-1})]</td>
<td>0.650 ( \pm 0.006 \pm 0.004 )</td>
</tr>
<tr>
<td>( \Delta \Gamma_s ) [ps(^{-1})]</td>
<td>0.066 ( \pm 0.018 \pm 0.010 )</td>
</tr>
<tr>
<td>( \phi_s ) [mrad]</td>
<td>119 ( \pm 107 \pm 34 )</td>
</tr>
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<td>(</td>
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New LHCb average (including \( J/\psi \phi \) and \( J/\psi \pi \pi \))

\[ \phi_s = (1 \pm 37) \text{ mrad} \]

Previous analyses focused on low-mass region where \( \phi(1020) \) dominates over a small KK S-wave
Experimental status for $\phi_s$

- Still far from the SM uncertainty ($\sim 1$ mrad) → plenty of room for new physics
- Sensitivity with LHCb phase-1(2) upgrade is expected to be $\sim 9(3)$ mrad [EPJC 73 (2013) 2373, CERN-LHCC-2017-003]

$\phi_s = (-21 \pm 31) \text{ mrad}$
What about the charm triangle?

\[ \beta_c = \arg \left( -\frac{V_{cd}V_{ud}^*}{V_{cs}V_{us}^*} \right) \sim 0.03^\circ \]

- CPV practically absent in the SM (charm transitions almost completely decoupled from the third generation)
- Ideal place to look for new physics (especially if couples preferentially to up-type quarks)
- Very challenging: requires huge samples and control of systematic uncertainties below the 0.1% level

NB: not in scale, the real angle is much smaller
CPV in $D^0 \to h^+ h^-$ decays

- Time-dependent asymmetry between $D^0$ and $\bar{D}^0$ to CP-even final states
  \[
  A(t) = \frac{\Gamma(D^0 \to h^+ h^-) - \Gamma(\bar{D}^0 \to h^+ h^-)}{\Gamma(D^0 \to h^+ h^-) + \Gamma(\bar{D}^0 \to h^+ h^-)} \approx A_{CP} - A_{\Gamma} \frac{t}{\tau_D}
  \]

- Linear term due to CPV in interference between mixing and decay: $A_{\Gamma} \approx -x \sin \phi_D$

- Identify flavour at production with $D^{*+} \to D^0 \pi^+$ decays

- Two different analysis methods return consistent results

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[LHCb](https://www.webcitation.org/6y5L8U62X) Run 1

$D^0 \to K^+ K^-$

$\sim 10M$

Candidates / (0.06 MeV/$c^2$)
Results

\[ A_{\Gamma}(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3} \]
\[ A_{\Gamma}(\pi^+\pi^-) = (+0.46 \pm 0.58 \pm 0.12) \times 10^{-3} \]
Results

Combining the two final states

\[ A_{\ell}(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3} \]
\[ A_{\ell}(\pi^+\pi^-) = (+0.46 \pm 0.58 \pm 0.12) \times 10^{-3} \]

• Combining the two final states

\[ A_{\ell} = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3} \]

• And with the result based on \( B \rightarrow D^0 \mu^-X \) decays [JHEP 04 (2015) 043]

\[ A_{\ell} = (-0.29 \pm 0.28) \times 10^{-3} \]

• Consistent with CP symmetry. World’s most precise measurement to date (Belle 2 would need to collect 50/ab to reach this precision)
Global fit to all charm mixing+CPV data

CFR in interference between mixing and decay

CPV in mixing $\rightarrow |q/p|_{D=1}$

|q/p| $D=1$

contours hold 68%, 95% CL (etc.)

HFLAV World Average Jan 2017

No CPV

[CERN-LHCC-2017-003]
Global fit to all charm mixing+CPV data

[Graph showing CPV in mixing and CPV in interference between mixing and decay.]

[CERN-LHCC-2017-003]

- Orange: HFLAV World Average Jan 2017
- Purple: LHCb with 300/fb

Contours hold 68%, 95% CL (etc.)

NO CPV

CPV in mixing → |q/p|D≠1

1.2

0.8

0.9

1

1.1

1.2

0

0.2

0.4

-0.2

-0.4

CPV in interference between mixing and decay

φD

φD≠0

φD=0

HFLAV World Average Jan 2017

add LHCb with 300/fb

contours hold 68%, 95% CL (etc.)
Conclusions

• Flavour/CP violation plays a key role in unravelling what lies beyond the SM, providing access to energy scales and couplings unaccessible at the energy frontier

• LHCb is the ideal place where to study flavour/CP violation

  • Many measurements (based on Run 1 data only) have already exceeded those from the B-factories and the Tevatron

  • Could not cover many other interesting results (e.g. evidence of CPV in beauty baryons [Nature Physics 13 (2017) 391], search for strong CPV [PLB 764 (2017) 233], …)

• All consistent with SM expectations and limited by statistics

• Need to exploit Run 2 data and be prepared for the upgrades
Backup
LHCb phase-1 upgrade

Trigger & DAQ:
- read-out full detector at 40 MHz
- replace FE and BE electronics
- replace all detectors with embedded electronics
- remove L0 bottleneck and have an all software trigger

Tracking system:
- Replace all detectors
  - VELO (Si pixels)
  - upstream tracker (Si strips)
  - downstream tracker (Sci-Fi)

Calorimeters:
- remove SPD & PS
- reduce HV & PMT gain
- replace FE electronics

RICH detectors:
- remove aerogel radiator and re-design optics for RICH1
- replace photo-detectors

Muons:
- remove M1
- replace FE electronics
LHCb phase-2 upgrade

Figure 4.1: Schematic side view of the Phase-II detector.

Within the LHCb acceptance from the initial interactions alone. These high multiplicities lead to challenging conditions for track and vertex reconstruction. Using the Phase-I Upgrade VELO detector design as a baseline, the performance of a number of potential modifications to the detector geometry and materials has been evaluated at the proposed Phase-II luminosity, and their effects on the final physics performance studied using full Monte Carlo simulations. Figure 4.2 summarises the tracking performance of the baseline (Phase-I) design under luminosities expected in the Phase-I and Phase-II Upgrade eras. The mean rate of reconstructing ghost tracks in the VELO alone from spurious hit combinations increases dramatically from 1.6% to 40% for the increased luminosity, even after tight track-quality requirements are imposed to limit the rate of these ghosts. There is a corresponding reduction in tracking efficiency, with the integrated value within the LHCb acceptance falling from $\sim 99\%$ to $\sim 96\%$. There is also a modest degradation in the impact parameter (IP) resolution, driven by the effect of the lowered tracking efficiency on the primary vertex (PV) resolution.

These losses in performance can be almost entirely recovered with a small number of design improvements. Most notably, by decreasing the pixel pitch from 55 $\mu$m to 27.5 $\mu$m and reducing the sensor silicon thickness from 200 $\mu$m to 100 $\mu$m, the ghost rate can be reduced back down to 2% while retaining a tracking efficiency of 96%, to choose one working point. Another potential design improvement would be the reduction of material. In the current and Phase-I Upgrade design...
CP observables in $B^\pm \to DK^\pm$

- Gronau-London-Wyler uses (quasi-)CP-even final states

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

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

- Atwood-Dunietz-Soni uses DCS mode

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

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