Recent results on CP Violation in Charm sector by LHCb
I. LHCb detector and data
LHCb detector 2010-2018

- Single-arm forward spectrometer focused on heavy flavor ($b$, $c$) physics
- Effective as multi-purpose detector in forward region

**Vertex Locator (vertex reconstruction)**
- Impact parameter resolution: 20 µm
- Decay time resolution: 45 fs ($\tau_B \sim 1.5$ ps)

**Tracking system (particle reconstruction)**
- $\epsilon$(Tracking) $\sim$96%
- $\delta p/p \sim 0.5\%$-$1\%$ (5-200 GeV)
- $\sigma(m_{B\to hh}) \approx 22$ MeV

**RICH: particle ID**
- $\epsilon(K \to K) \sim 95\%$
- Mis-ID: $\epsilon(\pi \to K) \sim 5\%$

**Muon system**
- $\mu$ ID: $\epsilon(\mu \to \mu) \sim 97\%$
- Mis-ID: $\epsilon(\pi \to \mu) \sim 1\%-3\%$

**Magnet**
- Bending power: 4 Tm

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022
Data taking 2010-2018

- Run I (7-8 TeV, 2010-2012) and Run II (13 TeV, 2015-2018)
- Average efficiency of the data taking > 90%
- Various systems: pp, p-Pb, Pb-Pb, SMOG (fixed target)
Measurement of charm at LHCb

→ Large charm cross section at LHCb:

\[
\sigma(pp \rightarrow c\bar{c}) = [1419 \pm 12 \text{ (stat.)} \pm 116 \text{ (syst.)} \pm 65 \text{ (frag.)}] \mu b @ 7 \text{ TeV} \\
[2369 \pm 3 \text{ (stat.)} \pm 152 \text{ (syst.)} \pm 118 \text{ (frag.)}] \mu b @ 13 \text{ TeV}
\]

→ Significant statistics collected already during the Run I:
  - About \(5 \times 10^{12} \) \(D^0\) and \(2 \times 10^{12} \) \(D^{*+}\) collected

→ Run II: higher collision energy and improved trigger → more statistics than Run I
Experimental aspects at LHCb

→ Flavor tagging: prompt vs secondary → LHCb uses both methods

→ Production asymmetries (charge dependent):
  - Different cross-section for $D^{+}_{(s)}/D^{−}_{(s)}$, $Λ^{+}_{c}/Λ^{−}_{c}$, ...

→ Detection asymmetries (charge and momentum dependent):
  - Different interactions with the detector material (K$^{+}$ vs K$^{−}$, $π^{+}$ vs $π^{−}$)
II. Charge-Parity Violation
Mixing of $D^0 - \bar{D}^0$

- $D^0$ mesons are produced as a flavor eigenstates, but decays as mass eigenstates $D_1$ and $D_2$: $|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$, $|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$, $|q|^2 + |p|^2 = 1$

- Mixing occurs in the case: $\Delta M = M_1 - M_2 \neq 0$ or $\Delta \Gamma = \Gamma_1 - \Gamma_2 \neq 0$

- Associated mixing parameters: $x = \frac{\Delta M}{\Gamma}$, $y = \frac{\Delta \Gamma}{2\Gamma}$, where: $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$

- Influence of short and long distance effects

- For the small mixing parameters ($x, y < 10^{-2}$) the time-dependent asymmetry can be approximated as:

$$A_{CP}(t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} \approx A_{CP}^{dir,f} - A_{\Gamma} \frac{f}{t_D}$$

where $A_{\Gamma}$ is the asymmetry between effective decay widths of $D^0$ and $\bar{D}^0$:

$$A_{\Gamma} = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$
**CPV classification**

- CPV is present in the SM via Cabibbo-Kobayashi-Maskawa (CKM) mechanism, but is too weak to explain the Baryon asymmetry of the Universe.
- Two types of CPV: **Indirect** (CPV in mixing, CPV in interference) and **Direct**.

**CPV in mixing**
- Independent on final state
- Different mixing rates $D^0 \rightarrow \bar{D}^0$ and $\bar{D}^0 \rightarrow D^0$
  \[ |\frac{q}{p}| \neq 1 \]
- Accessible via the using flavor specifics decays
- **SM** prediction: $\mathcal{O}(10^{-4})$

**CPV in interference**
- Possibility of interference between mixing and decay amplitudes
  \[ \phi = \text{arg}(\frac{q\bar{A}_f}{pA_f}) \]
- Can be observed as a decay-time-dependent difference in decay rates and as a time-integrated difference
- **SM** prediction: $\mathcal{O}(10^{-4})$

**Direct CPV**
- Only possible CPV for charged hadrons
- Occurs in the case:
  \[ |\frac{\bar{A}_f}{A_f}| \neq 1 \]
- Typically (for SCS modes): $A_{CP} < 10^{-4} - 10^{-3}$
Charm sector and CPV

- Charm is unique, gives sensitivity to new physics coupling to up-type quark
- Charm is also difficult for theory calculations
- Complementary to direct searches for BSM particles
- BSM contributions could be hidden in loops
- Assuming generic BSM scenarios, much larger scale are accessible with respect to direct searches
- Flavour physics and CPV lead to breakthrough in particle physics many times

1956
Parity violation
T. D. Lee, C. N. Yang and C. S. Wu et al.

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
CP violation in $K$ meson decays
J. W. Cronin, V. L. Fitch et al.

1973
The CKM matrix
M. Kobayashi and T. Maskawa

2001
Beauty particles:
CP violation in $B^0$ meson decays
BaBar and Belle collaborations

2019
Charm particles:
CP violation in $D^0$ meson decays
LHCb collaboration
II. Recent LHCb results on $CP$ violation in Charm

1. Measurement of the mass difference between neutral charm-meson eigenstates
   (PHYS. REV. LETT. 122 (2019) 231802)

2. Search for time-dependent $CP$ violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays
   (LHCB-CONF-2019-001; INSPIRE: 1735332)

3. Observation of $CP$ violation in charm decays
   (PHYS. REV. LETT. 122 (2019) 211803)
1. Measurement of the mass difference between neutral charm-meson eigenstates
(PHYS. REV. LETT. 122 (2019) 231802)
D⁰ mass eigenstates $\Delta m$: introduction

→ CPV is an interference effect
→ How to enhance our sensitivity?
→ LHCb Run I full sample
→ Prompt and semileptonic production of $D^0 \to K_S^0 \pi^+ \pi^-$
→ Around $1.3 \times 10^6$ signal candidates for prompt production and around $1.0 \times 10^6$ for semileptonic decays
→ Channel with a rich resonance spectrum
→ Good sensitivity to mixing and time-dependent CPV parameters via varying strong phases
→ Experimentally complicated (decay dynamics and acceptance effects)
D^0 mass eigenstates $\Delta m$: method

- Bin flip method (Phys. Rev. D 99, 012007): a novel approach minimizing dependence on amplitude model and detector acceptance

- Data are binned in Dalitz plane ($R_{1-8}^{+/−}$) to keep strong phases approximately constant; input is taken from CLEO (Phys. Rev. D 82, 112006)

- Data are also binned in decay time (20 bins)

- Ratio of yields in opposition bins across the bisection is measured
  - Cancellation of acceptance effects, also a good sensitivity to $\chi$
D⁰ mass eigenstates Δm: fits

→ Simultaneous least-squares fit* to prompt and semileptonic data

→ Offset due to sample-specific efficiency variations across Dalitz plot

→ CP-averaged yield ratios as function of t/τ

→ Mixing measurement

→ Search for CP violation

→ Differences of D⁰ and anti-D⁰ yield ratios as function of t/τ

* details in backup slide 40
**D⁰ mass eigenstates Δm: results**

- The most precise measurement of x done by a single experiment, consistent with CP symmetry scenario

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>95.5% CL interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>x [10⁻²]</td>
<td>0.27 ± 0.17</td>
<td>[−0.05, 0.60]</td>
</tr>
<tr>
<td>y [10⁻²]</td>
<td>0.74 ± 0.37</td>
<td>[ 0.00, 1.50]</td>
</tr>
<tr>
<td>(</td>
<td>q/p</td>
<td>)</td>
</tr>
<tr>
<td>φ</td>
<td>−0.09 ± 0.11</td>
<td>[−0.73, 0.29]</td>
</tr>
</tbody>
</table>

- Combined with the world average, first evidence of x > 0 larger than 3σ
2. Search for time-dependent $CP$ violation in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays

(LHCB-CONF-2019-001; INSPIRE: 1735332)
CPV(t) in $D^0 \to h^+h^-$: introduction

$$A_\Gamma = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \approx y\left(\frac{q}{p} - 1\right) - x\phi_f - yA_{CP}^{decay}(f)$$

- LHCb 2015-2016 data, prompt $D^{*+}$ decays utilized for a tagging of $D^0$ decays
- Analysis done using two signal channels $D^0 \to K^+K^- / \pi^+\pi^-$ ($17 \times 10^6 / 5 \times 10^6$)
- $D^0 \to K^-\pi^+$ control channel ($146 \times 10^6$) used for a full analysis procedure validation

Asymmetry measured in 21 decay time bins

Current world average, $(-3.2 \pm 2.6) \times 10^{-4}$, dominated by LHCb Run I measurement (Phys. Rev. Lett. 118, 261803)

CPV in mixing
CPV in interference
Negligible with current exp. Precision ($3 \times 10^{-4}$ vs $1 \times 10^{-5}$)
CPV(t) in D⁰ → h⁺h⁻: detector asymm.

→ Time and momentum-dependent asymmetries arise from two main sources
  - Momentum-dependent detection asymmetry from tagging pion
  - Correlation between the measured decay time and the momentum of the D⁰ due to trigger requirements

→ Effect can be cancelled by weighting events between D⁰ and anti-D⁰ candidates
  - Separate weighting for different experimental conditions (magnet polarity, year)
  - 3D momentum weighting
CPV(t) in D⁰ → h⁺h⁻: systematic

- Contamination of D*⁺ by the secondary decays
  - Measured decay time of secondary decays biased to longer decay time
  - Fraction of secondary decays increases as a function of time

- Kinematic weighting depends on the exact binning
  - Bins has be to kept large enough to avoid large statistical fluctuations
  - Control channel used for bin size optimization

<table>
<thead>
<tr>
<th>Source</th>
<th>A_Γ(D⁰ → K^⁺K^-)</th>
<th>A_Γ(D⁰ → π^+π^-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary decays</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Δm background</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>m(h⁺h⁻) background</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Kinematic weighting</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Sum in quadrature</td>
<td>0.7</td>
<td>0.8</td>
</tr>
</tbody>
</table>
**CPV(t) in D⁰ → h⁺h⁻: results**

\[ A_Γ(K^+K^-) = (1.3 \pm 3.5 \pm 0.7) \times 10^{-4} \]

\[ A_Γ(\pi^+\pi^-) = (11.3 \pm 6.9 \pm 0.8) \times 10^{-4} \]

\[ A_Γ(K^+K^- + \pi^+\pi^-) = (3.4 \pm 3.1 \pm 0.6) \times 10^{-4} \]

\[ A_Γ(K^+K^- + \pi^+\pi^-, 2011 - 2016) = (0.9 \pm 2.1 \pm 0.7) \times 10^{-4} \]

→ Systematic uncertainty reduced by 30% with respect to previous LHCb analysis (Phys. Rev. Lett. 118, 261803)

→ Consistent with CP symmetry

→ Dominated by statistical uncertainty → full Run II analysis in progress
3. Observation of $CP$ violation in charm decays
(PHYS. REV. LETT. 122 (2019) 211803)
CPV in Charm: introduction

→ Full LHCb Run II data set

→ $D^0 \rightarrow K^+K^-/\pi^+\pi^-$ decays

→ Prompt ($44 \times 10^6/13 \times 10^6$) and semileptonic production ($9 \times 10^6/3 \times 10^6$)


→ Fit to invariant mass distribution to extract the raw asymmetries

→ However, raw asymmetries are influenced by the production and detection asymmetries
CPV in Charm: experimental issues

Detection and production asymmetries can be cancelled using suitable experimental procedure for prompt / semileptonic decays:

\[ A_{\text{raw}}(f) \approx A_{\text{CP}}(f) + A_{D}(D^0) + A_{D}(\pi/\mu) + A_{P}(D^{*+}/B) \]

\[ A_{\text{raw}}(f) = \frac{N(D^0 \rightarrow f) - N(\overline{D}^0 \rightarrow f)}{N(D^0 \rightarrow f) + N(\overline{D}^0 \rightarrow f)} \] - experimentally accessible asymmetry

- \( A_{\text{CP}}(f) \) - physical \( CP \) asymmetry of final state \( f \)
- \( A_{D}(D^0) \) - \( D^0 \) detection asymmetry, cancelled due to symmetric final states
- \( A_{D}(\pi/\mu) \) - detection asymmetry of tagging particle
- \( A_{P}(D^{*+}/B) \) - production asymmetry of mother particle

Under the assumption of small experimental asymmetries, \( CP \) can be obtained as

\[ \Delta A_{\text{CP}} \equiv A_{\text{CP}}(K^+K^-) - A_{\text{CP}}(\pi^+\pi^-) = A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-) \]
CPV in Charm: fiducial selection

→ Due to LHCb geometry, low momentum particle can be kicked out from the detector acceptance

→ Such a regions of phase space generate very large raw detector asymmetries

→ This part of phase space must be removed in order of kinematic equalization

→ Same procedure for prompt/semileptonic decays ($\pi/\mu$)

PHYS. REV. LETT. 122 (2019) 211803
CPV in Charm: kinematic weighting

- Detection and production asymmetries depend on the kinematic of the reconstructed particles
- Weighting procedure between modes to assure same kinematic
- Variables prompt/semileptonic: $p_T(D^*), p(D^*), \phi(D^*) / p_T(D^0), p(D^0), \phi(D^0)$
CPV in Charm: systematic

→ Prompt mode dominated by:
  - Fit model
    - Default model: Sum of three Gaussian and Johnson Su function (prompt) and two Gaussians convolved with a power-law function (sl)
    - Alternative: Fitting pseudoexperiments with alternative models
  - Misreconstructed background

→ Semileptonic mode dominated by mistagging of muon
  - Evaluated using control sample $B \rightarrow D^0(\rightarrow K^-\pi^+)\mu X$

<table>
<thead>
<tr>
<th>Source</th>
<th>$\pi$-tagged $[10^{-4}]$</th>
<th>$\mu$-tagged $[10^{-4}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit model</td>
<td>0.6</td>
<td>2</td>
</tr>
<tr>
<td>Mistag</td>
<td>–</td>
<td>4</td>
</tr>
<tr>
<td>Weighting</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>Secondary decays</td>
<td>0.3</td>
<td>–</td>
</tr>
<tr>
<td>$B^0$ fraction</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>$B$ reco. efficiency</td>
<td>–</td>
<td>2</td>
</tr>
<tr>
<td>Peaking background</td>
<td>0.5</td>
<td>–</td>
</tr>
<tr>
<td>Total</td>
<td>0.9</td>
<td>5</td>
</tr>
</tbody>
</table>
**CPV in Charm: results**

- **Run II results:**
  \[ \Delta A_{CP}^{\text{prompt}} = [-18.2 \pm 3.2\text{(stat)} \pm 0.9\text{(syst)}] \times 10^{-4} \]
  \[ \Delta A_{CP}^{\text{semileptonic}} = [-9 \pm 8\text{(stat)} \pm 5\text{(syst)}] \times 10^{-4} \]

- Compatible with the previous LHCb results and the world average values
- When combined with Run I LHCb results:
  \[ \Delta A_{CP}^{\text{RunI+RunII}} = [-15.4 \pm 2.9] \times 10^{-4} \]

- **CP violation at 5.3 \( \sigma \) level**
- \( \Delta A_{CP} \) is mostly sensitive to direct CPV
CPV in Charm: world average

- Updated HFLAV fit
  \[ \Delta a_{CP}^{dir} = (-16.4 \pm 2.8) \times 10^{-4} \]
  \[ \Delta a_{CP}^{ind} = (2.8 \pm 2.6) \times 10^{-4} \]

- Compatible with SM
  - Most predictions on \(10^{-4} - 10^{-3}\) level

- Progress in theory calculations needed

- Observation in other channels could provide a confirmation of this effect

- Thorough study needs to be done to decide if SM or BSM effect

- Indirect CPV still missing
**Conclusion and Outlook**

- Different mass between $CP$-even and $CP$-odd $D^0$ states
- Direct $CPV$ in Charm observed for the first time
- Inconclusive if SM or BSM effects
- Indirect $CPV$ still unobserved

**Future prospects**

- LHCb has access to the world largest Charm sample – analyses now have to exploit it
- Belle-II is now preparing for data taking
- Ongoing LHCb Upgrade – 5x higher luminosity and new software trigger
- 50/fb will be collected by 2030
- Expected statistical uncertainty: $\mathcal{O}(10^{-4})$
- Also a possibilities to utilize rare and multi-body decays
Thank you for your attention
BACKUP Slides
Planned LHCb upgrades
LHCb upgrade Phase I (Run III)

- New detectors
- New photodetectors
- Removed components
- Upgraded electronics and trigger
## LHCb upgrade Phase I (Run III)

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb 2018</th>
<th>Upgrade (50 fb(^{-1}))</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>B(_s^0) mixing</strong></td>
<td>(2\beta_s (B_s^0 \rightarrow J/\psi \phi))</td>
<td>0.10 [9]</td>
<td>0.025</td>
<td>0.008</td>
<td>(\sim 0.003)</td>
</tr>
<tr>
<td></td>
<td>(2\beta_s (B_s^0 \rightarrow J/\psi f_0(980)))</td>
<td>0.17 [10]</td>
<td>0.045</td>
<td>0.014</td>
<td>(\sim 0.01)</td>
</tr>
<tr>
<td></td>
<td>(A_f(B_s^0))</td>
<td>(6.4 \times 10^{-3}) [18]</td>
<td>(0.6 \times 10^{-3})</td>
<td>(0.2 \times 10^{-3})</td>
<td>(0.03 \times 10^{-3})</td>
</tr>
<tr>
<td><strong>Gluonic penguin</strong></td>
<td>(2\beta_{s}^{\text{eff}} (B_s^0 \rightarrow \phi\phi))</td>
<td>–</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>(2\beta_{s}^{\text{eff}} (B_s^0 \rightarrow K^{*0}\bar{K}^{*0}))</td>
<td>–</td>
<td>0.13</td>
<td>0.02</td>
<td>(&lt; 0.02)</td>
</tr>
<tr>
<td></td>
<td>(2\beta_{s}^{\text{eff}} (B_s^0 \rightarrow \phi K^0_S))</td>
<td>0.17 [18]</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Right-handed currents</strong></td>
<td>(2\beta_{s}^{\text{eff}} (B_s^0 \rightarrow \phi\gamma))</td>
<td>–</td>
<td>0.09</td>
<td>0.02</td>
<td>(&lt; 0.01)</td>
</tr>
<tr>
<td></td>
<td>(\tau^{\text{eff}} (B_s^0 \rightarrow \phi\gamma)/\tau_{B_s^0})</td>
<td>–</td>
<td>5%</td>
<td>1%</td>
<td>0.2%</td>
</tr>
<tr>
<td><strong>Electroweak penguin</strong></td>
<td>(S_3 (B^0 \rightarrow K^{*0}\mu^+\mu^- ; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4))</td>
<td>0.08 [14]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>(s_0 A_{FB}(B^0 \rightarrow K^{*0}\mu^+\mu^-))</td>
<td>25% [14]</td>
<td>6%</td>
<td>2%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>(A_1(K\mu^+\mu^- ; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4))</td>
<td>0.25 [15]</td>
<td>0.08</td>
<td>0.025</td>
<td>(\sim 0.02)</td>
</tr>
<tr>
<td></td>
<td>(B(B^+ \rightarrow \pi^+\mu^+\mu^-)/B(B^+ \rightarrow K^+\mu^+\mu^-))</td>
<td>25% [16]</td>
<td>8%</td>
<td>2.5%</td>
<td>(\sim 10%)</td>
</tr>
<tr>
<td><strong>Higgs penguin</strong></td>
<td>(B(B_s^0 \rightarrow \mu^+\mu^-))</td>
<td>(1.5 \times 10^{-9}) [2]</td>
<td>(0.5 \times 10^{-9})</td>
<td>(0.15 \times 10^{-9})</td>
<td>(0.3 \times 10^{-9})</td>
</tr>
<tr>
<td></td>
<td>(B(B^0 \rightarrow \mu^+\mu^-)/B(B_s^0 \rightarrow \mu^+\mu^-))</td>
<td>–</td>
<td>(\sim 100%)</td>
<td>(\sim 35%)</td>
<td>(\sim 5%)</td>
</tr>
<tr>
<td><strong>Unitarity triangle angles</strong></td>
<td>(\gamma (B \rightarrow D^{(<em>)}K^{(</em>)}))</td>
<td>(\sim 10–12^\circ) [19, 20]</td>
<td>4\°</td>
<td>0.9\°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>(\gamma (B_s^0 \rightarrow D_sK))</td>
<td>–</td>
<td>11\°</td>
<td>2.0\°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>(\beta (B^0 \rightarrow J/\psi K_S^0))</td>
<td>0.8\° [18]</td>
<td>0.6\°</td>
<td>0.2\°</td>
<td>negligible</td>
</tr>
<tr>
<td><strong>Charm</strong></td>
<td>(A_{\Gamma})</td>
<td>(2.3 \times 10^{-3}) [18]</td>
<td>0.40 \times 10^{-3}</td>
<td>0.07 \times 10^{-3}</td>
<td>–</td>
</tr>
<tr>
<td><strong>CP violation</strong></td>
<td>(\Delta A_{CP})</td>
<td>(2.1 \times 10^{-3}) [5]</td>
<td>0.65 \times 10^{-3}</td>
<td>0.12 \times 10^{-3}</td>
<td>–</td>
</tr>
</tbody>
</table>

CERN/LHCC 2012-007
LHCb upgrade Phase II (Run V)
**LHCb upgrade Phase II (Run V)**

<table>
<thead>
<tr>
<th>Topics and observables</th>
<th>Experimental reach</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EW Penguins</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global tests in many $b \to s \mu^+ \mu^-$ modes with full set of precision observables; lepton universality tests; $b \to d l^+ l^-$ studies</td>
<td>e.g. $440k \ B^0 \to K^* \mu^+ \mu^-$ &amp; $70k \ A_b^0 \to A \mu^+ \mu^-$; Phase-II $b \to d \mu^+ \mu^-$ $\approx$ Run-I $b \to s \mu^+ \mu^-$ sensitivity.</td>
<td>Phase-II ECAL required for lepton universality tests.</td>
</tr>
<tr>
<td><strong>Photon polarisation</strong></td>
<td>$A^\Delta$ in $B_s^0 \to \phi \gamma; B^0 \to K^* e^+ e^-$; baryonic modes</td>
<td>Uncertainty on $A^\Delta \approx 0.02$; $\sim 10k A_b^0 \to A \gamma; \Xi_b \to \Xi \gamma; \Omega_b^- \to \Omega \gamma$</td>
</tr>
<tr>
<td>$b \to c l^- \bar{\nu}_l$ lepton-universality tests</td>
<td>Polarisation studies with $B \to \bar{D}^{(*)} \tau^- \nu_\tau$; $\tau^-/\mu^-$ ratios with $B_s^0, A_b^0$ and $B_c^+$ modes</td>
<td>e.g. 8M $B \to D^{*} \tau^- \nu_\tau, \tau^- \to \mu^- \bar{\nu}<em>\mu \nu</em>\tau$ &amp; $\sim 100k \ \tau^- \to \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$</td>
</tr>
<tr>
<td>$B_s^0, B^0 \to \mu^+ \mu^-$</td>
<td>$R \equiv B(B_s^0 \to \mu^+ \mu^-)/B(B_s^0 \to \mu^+ \mu^-)$; $\tau_{B_s^0 \to \mu^+ \mu^-}$; CP asymmetry</td>
<td>Uncertainty on $R \approx 20%$ Uncertainty on $\tau_{B_s^0 \to \mu^+ \mu^-} \approx 0.03$ ps</td>
</tr>
<tr>
<td><strong>LFV $\tau$ decays</strong></td>
<td>$\tau^- \to \mu^+ \mu^- \mu^-$, $\tau^- \to h^+ h^- \mu^-$, $\tau^- \to \phi \mu^-$</td>
<td>Sensitive to $\tau^- \to \mu^+ \mu^- \mu^-$ at $10^{-9}$</td>
</tr>
<tr>
<td><strong>CKM tests</strong></td>
<td>$\gamma$ with $B^- \to DK^-, B_s^0 \to D_s^+ K^-$ etc.</td>
<td>Uncertainty on $\gamma \approx 0.4^\circ$</td>
</tr>
<tr>
<td>$\phi_s$ with $B_s^0 \to J/\psi K^+ K^-$, $J/\psi \pi^+ \pi^-$</td>
<td>Uncertainty on $\phi_s \approx 3$ mrad Uncertainty on $\phi_s^{\delta s} \approx 8$ mrad</td>
<td>Approach SM value.</td>
</tr>
<tr>
<td>$\Delta \Gamma_d/\Gamma_d$</td>
<td>Uncertainty on $\Delta \Gamma_d/\Gamma_d \sim 10^{-3}$</td>
<td>Approach SM value for $a_{s_4}^d$.</td>
</tr>
<tr>
<td>Semileptonic asymmetries $a_{d,s}^{s}$</td>
<td>Uncertainties on $a_{d,s}^{s} \sim 10^{-4}$</td>
<td>Significant gains achievable from thinning or removing RF-foil.</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>/</td>
</tr>
<tr>
<td><strong>Charm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CP-violation studies with $D^+ \to h^+ h^-$, $D^0 \to K_s^0 \pi^+ \pi^-$ and $D^0 \to K^+ \pi^+ \pi^+ \pi^-$</td>
<td>e.g. $4 \times 10^9 \ D^0 \to K^+ K^-; \ \text{Uncertainty on} \ A_\Gamma \sim 10^{-5}$</td>
<td>Access CP violation at SM values.</td>
</tr>
<tr>
<td><strong>Strange</strong></td>
<td>Rare decay searches</td>
<td>Sensitive to $K_s^0 \to \mu^+ \mu^-$ at $10^{-12}$</td>
</tr>
</tbody>
</table>
# LHC timeline

**LHC roadmap: according to MTP 2016-2020 V1**

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
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<tr>
<td>LS2</td>
<td>Run 2</td>
<td></td>
<td></td>
<td></td>
<td>LS 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS3</td>
<td>Run 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Run 4</td>
<td></td>
</tr>
</tbody>
</table>

**Phase 1**

- LS2 starting in 2019
- LHC: starting in 2024
- Injectors: in 2025

- => 24 months + 3 months BC
- => 30 months + 3 months BC
- => 13 months + 3 months BC

**Phase 2**

- LS 4
- Run 5
- LS 5

**Colors:**
- **Physics**: Green
- **Shutdown**: Red
- **Beam commissioning**: Yellow
- **Technical stop**: Blue
$D^0$ mass eigenstates $\Delta m$: fits

- Simultaneous least-squares fit* for prompt and semileptonic data
- Offset due to sample-specific efficiency variations across Dalitz plot

$$
\chi^2 = \sum_{Pr, SL, LL, DD} \sum_{b,j} \left[ \frac{(N^+_{-bj} - N^+_b R^+_b)^2}{(\sigma^+_{-bj})^2 + (\sigma^+_b R^+_b)^2} + \frac{(N^-_{-bj} - N^-_b R^-_b)^2}{(\sigma^-_{-bj})^2 + (\sigma^-_b R^-_b)^2} \right] + \chi^2_X,
$$

$$
\chi^2_X = \sum_{a,b} \left[ X_a^{CLEO} - X_a \right] (V_{CLEO}^{-1})_{ab} \left[ X_b^{CLEO} - X_b \right].
$$

- Simultaneously applied for prompt/semileptonic data, $D^0$/anti-$D^0$
- Two fits: $CP$ symmetry scenario and indirect $CPV$ allowed
VI. Future prospects for Run III and beyond
Prospect for indirect CPV searches

Results on the indirect CPV is already dominated by LHCb

<table>
<thead>
<tr>
<th></th>
<th>$\sigma(x) \ [10^{-3}]$</th>
<th>$\sigma(y) \ [10^{-3}]$</th>
<th>$\sigma(q/p) \ [10^{-3}]$</th>
<th>$\sigma(\phi) \ [mrad]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFAG 2016</td>
<td>1.4</td>
<td>0.7</td>
<td>80</td>
<td>173</td>
</tr>
<tr>
<td>Run II</td>
<td>0.8</td>
<td>0.6</td>
<td>47</td>
<td>83</td>
</tr>
<tr>
<td>Run III</td>
<td>0.3</td>
<td>0.2</td>
<td>17</td>
<td>32</td>
</tr>
<tr>
<td>Belle II (50 ab$^{-1}$)</td>
<td>0.8</td>
<td>0.5</td>
<td>60</td>
<td>70</td>
</tr>
</tbody>
</table>

1: BELLE2-TALK-CONF-2017-080
Prospects for direct CPV searches

→ Precision is already at $\mathcal{O}(10^{-3})$ level, one evidence for CPV in charm

→ With the the Run III data (50 fb$^{-1}$ in combination with Run I+II) the precision will be comparable with the SM prediction at $\mathcal{O}(10^{-4})$ level

→ Need for precise BR input by Belle II/HIEPA: $D^0 \rightarrow \pi^0\pi^0$, $D^0 \rightarrow K_S K_S$, $D^0 \rightarrow \pi^0\pi^+$

1) Multibody decays [slide: 42-43]

2) Rare decays (radiative, leptonic)  [slide: 45]

3) Double Cabibbo Suppressed (DCS) decays (e.g. $D^+ \rightarrow K^+\pi^+\pi^-/K^+K^-K^+$)

4) Exploring charm baryons [slide: 46-47]

→ Measured 1$^{\text{st}}$ evidence for CPV in baryons: $\Lambda_b \rightarrow p3\pi$  [Nature Phys. 13, 391-396 (2017)]
Prospect: CPV in N-body decays

- Strong phase vary in Phase Space → this leads to local CPV asymmetries
- Need for detailed study of Phase space
- Model dependent: amplitude analysis
- Model independent approach:
  
  Binned approach
  - \( S_{cp} \) approach
  - Significance of asymmetry in Dalitz plot
    [PLB 728 585 (2014)]

  Unbinned approach (Energy test)
  - Testing data consistency with no-CPV hypothesis
  - Significance of asymmetry for each event
    [PLB 740 158 (2015)]
Prospect: direct CPV 4-body decays

→ The more precise detector → more possibilities with the study of D multi-body decays

→ The 2+3-body decays: only P-even amplitude accessible → CPV via C-violation

→ The 4-body decays: also P-odd amplitudes → CPV via P-violation

→ We can write:

\[ A_{CP}^{P-\text{even}} \approx \sin \Delta \phi_{\text{weak}} \sin \Delta \phi_{\text{strong}} \]
\[ A_{CP}^{P-\text{odd}} \approx \sin \Delta \phi_{\text{weak}} \cos \Delta \phi_{\text{strong}} \]

→ First measurement: \( D^0 \rightarrow \pi^+\pi^-\pi^+\pi^- \), P-odd CPV with the 2.7 \( \sigma \) significance

[PLB 769 345-356 (2017)]

<table>
<thead>
<tr>
<th>Mode</th>
<th>( A_{CP}^{P-\text{odd}} ) ( [10^{-3}] )</th>
<th>Exp.</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D^+ \rightarrow K_S K^+ \pi^+ \pi^- )</td>
<td>(-12 \pm 10 \pm 5)</td>
<td>BaBar</td>
<td>PRD 84 031103</td>
</tr>
<tr>
<td>( D^0 \rightarrow K^+ K^- \pi^+ \pi^- )</td>
<td>(1.8 \pm 2.9 \pm 0.4)</td>
<td>LHCb</td>
<td>JHEP 10 005 (2014)</td>
</tr>
<tr>
<td>( D^0 \rightarrow K_S \pi^+ \pi^- \pi^0 )</td>
<td>(-0.3 \pm 1.4_{-0.8}^{+0.2})</td>
<td>Belle</td>
<td>PRD 95 091101</td>
</tr>
</tbody>
</table>
Prospect: CPV in rare decays

- Large contribution from penguin diagrams → larger values of CPV expected
- Two main categories: Leptonic and Radiative decays

Leptonic decays
- First observation of $D^0 \rightarrow K^+ K^- \mu^+ \mu^-$ and $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu$
- 5.4 σ signal
- CPV up to $\mathcal{O}(10^{-2})$

Radiative decays
- Large CPV within SM, up to 10 %
- With the upgrade, LHCb will be competitive in $D^0 \rightarrow \rho\gamma, \phi\gamma, K^*\gamma$
- Belle measurement$^1$: $A_{CP}(D^0 \rightarrow \rho^0\gamma) = (+5.6 \pm 15.1 \pm 0.6)\%$

1: PRL 118 051801
CPV in charmed baryons

→ Several theoretical works about CPV in charmed baryons
→ Multibody decays are preferred due to larger BR and access to CPV-odd observables

SCS
→ SM amplitudes are less suppressed, lower sensitivity to BSM amplitudes
→ Suggested channels: $\Lambda_c \to p\pi^+\pi^-/pK^+K^-$, $\Xi_c^+ \to pK^-\pi^+$

DCS
→ Significant suppression of SM amplitudes
→ No CP asymmetry from SM in such amplitudes
→ Suggested channel: $\Lambda_c^+ \to pK^+\pi^-$
**CPV in** $\Lambda_c^+ \rightarrow pK^-K^+ \text{ and } \Lambda_c^+ \rightarrow p\pi^+\pi^-$

→ First measurement of CPV parameters in three-body $\Lambda_c^+$ decays

→ Full Run I (3 fb$^{-1}$) data used

→ The $\Lambda_b^0 \rightarrow \Lambda_c^+\mu^-X$ decay channel used in order to reduce prompt background

→ Two SCS decays studied: $\Lambda_c^+ \rightarrow pK^-K^+$ (25 k) $\Lambda_c^+ \rightarrow p\pi^+\pi^+$ (160 k)

→ Measurement of difference $\Delta A_{CP} = A_{raw}(pK^-K^+) - A_{raw}(p\pi^+\pi^+)$ in order to cancel production and detection asymmetry

→ Final result: $\Delta A_{CP} = (0.30 \pm 0.91 \pm 0.61) \%$

*arXiv: 1712.07051*
$\textbf{CPV in } \Lambda_c^+ \rightarrow pK^-K^+ \textbf{ and } \Lambda_c^+ \rightarrow p\pi^+\pi^-$

→ Obtained results in the 4 bins: collision energy and magnet polarity

→ First result of search for direct CPV search in three-body $\Lambda_c^+$ decays:

$$\Delta A_{\text{CP}} = [0.30 \pm 0.91 \text{ (stat.)} \pm 0.61 \text{ (syst.)}] \%$$

→ Result shows no sign of direct CPV

→ More data required for more precise measurement