LHCb physics prospects for CP violation measurements with 0.2 and 1 fb$^{-1}$

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15-20 July 2010

On behalf of the LHCb collaboration
CP violation in the Standard Model

**CKM matrix (Wolfenstein parametrization):**

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

**Unitarity:** \(V_{ij}^* V_{jk} = \delta_{ik}\)

**b – d triangle (i = b, k = d)**

\[
V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0
\]

\[
\begin{align*}
V_{ud} V_{ub}^* & \sim \lambda^2 \\
V_{cd} V_{cb}^* & \sim \lambda^2 \\
\alpha(\phi_2) & \quad V_{ts} V_{tb}^* \sim \lambda^2 \\
\gamma(\phi_3) & \quad \beta(\phi_1)
\end{align*}
\]

**b – s triangle (i = b, k = s)**

\[
V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} = 0
\]

\[
\begin{align*}
V_{ts} V_{tb}^* & \sim \lambda^2 \\
V_{cs} V_{cb}^* & \sim \lambda^2 \\
\beta_s & = 21.7^\circ \pm 0.9^\circ \\
\alpha & = 89^\circ \pm 4^\circ \\
\gamma & = 70^\circ +14^\circ \\
\beta_s & = 0.01811 \pm 0.00085 \text{ rad}
\end{align*}
\]
CP violation in heavy flavors

The way to search for New Physics, complementary to direct high-energy searches.

- CP violation in $B$ system ($B^+, B^0$)
  - Search for NP by comparing CPV parameters in loop- and tree-dominated decays.
- CP violation in $B_s$ system
  - CPV phase $\phi_s$: small in SM, large NP contribution possible.
- CP violation in charm
  - Mixing observed (in the combination, but no observation in the single experiment so far), no CPV visible (neither direct nor in mixing).
Flavor physics at the LHC

\( \bar{b}b \) cross-section: 0.5 mb (14 TeV)
Flavor ratio: \( B^+ : B^0 : B_s : \Lambda_b : B_c = 40% : 40% : 10% : 10% : 0.1\% \).

**Altas, CMS**

- Central detectors, \( |\eta| < 2.5 \)
- High \( p_t \) trigger threshold

**LHCb**

- Optimized \( B \) meson acceptance
- Forward spectrometer, \( 2 < \eta < 5 \) (15 – 300 mrad)
- Softer low \( p_t \) triggers
- Efficient for hadronic \( B \) decays
- Design luminosity \( 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \), 2 fb\(^{-1}\) per nominal year.
Flavor physics at the LHC: LHCb experiment

\(b\bar{b}\) cross-section: 0.5 mb (14 TeV)
Flavor ratio: \(B^+ : B^0 : B_s : \Lambda_b : B_c = 40\% : 40\% : 10\% : 10\% : 0.1\%\).

- \(\sqrt{s} = 7\) TeV, \(b\bar{b}\) cross-section reduced by \(\sim 50\%\) compared to 14 TeV. Can partially compensate by lower background, lower thresholds.
- Integrated luminosity milestones:
  - 0.2 fb\(^{-1}\) by the end of 2010
  - 1 fb\(^{-1}\) in 2011.
- \(> 200\) nb\(^{-1}\) collected, \(\sim 10\) nb\(^{-1}\) analysed (first results next week at ICHEP!).
LHCb detector: features

Needed for efficient B physics:

Good PID ($\pi/K/p/\mu$ separation):
- B decay products separation
- Flavor tagging ($p < 100$ GeV)

Good vertexing ($\sigma_t \sim 40$ fs):
- Decay time measurement, esp. for fast $B_s$ oscillations
- Background suppression (vertex separation)

![Diagram showing B decays and tagging](image)
Interference between decays $B_s \to J/\psi(\mu\mu)\phi(KK)$ with and without mixing. $\phi_s(SM) = -2\beta_s = -0.036 \pm 0.002$.

Measured from the time-dependent asymmetry

$$A_{CP}(t) = -\frac{\eta_f \sin \phi_s \sin \Delta m_s t}{\cosh \Delta \Gamma_s t/2 - \eta_f \cos \phi_s \sinh \Delta \Gamma_s t/2}$$

$P \to VV$ decay. Angular analysis to separate CP-odd and CP-even states.

Flavor tagging needed for time-dependent asymmetry.

First 13 nb$^{-1}$: do not expect signal, observe components: $J/\psi \to \mu\mu$, $\phi \to KK$. 
CP violation in mixing of $B_s$: $\phi_s$ phase

Expect $\sim 30000 \, B_s \rightarrow J/\psi \phi$ decays with 1 fb$^{-1}$.

$B/S \sim 2$ (mostly prompt component, easy to separate by proper time).

- CDF 5.2 fb$^{-1}$: now consistent with SM (0.8σ).
- Expect sensitivity competitive to Tevatron with 0.2 fb$^{-1}$
- $\sigma(\phi_s) \sim 0.07$ with 1 fb$^{-1}$
- If NP $\sim$ CDF measurement, 5σ discovery with 1 fb$^{-1}$.
Flavor-specific $CP$-asymmetry

Charge asymmetry in semileptonic $b$ decays: \[ a_{sl}^q = \frac{\Gamma(B_q^0 \to \mu^+X) - \Gamma(B_q^0 \to \mu^-X)}{\Gamma(B_q^0 \to \mu^+X) + \Gamma(B_q^0 \to \mu^-X)} \]

D0 [arXiv:1005.2757]: Using like-sign dimuon asymmetry and inclusive charge asymmetry, \[ A_{sl}^b = a_{sl}^b + a_{sl}^s = (-0.96 \pm 0.25 \pm 0.15)\% \]

\[ A_{sl}^b(SM) = -2.3^{+0.5}_{-0.6} \times 10^{-4}. \]

Need good control of systematic factors:

- Background asymmetry
- Detector asymmetry $\delta_c$ (flip $B$-field)
- Production asymmetry $\delta_p$
  (difficult at $pp$-machine!)

Time-dependent charged asymmetry:

\[ A_{sl}^q(t) = \frac{a_{sl}^q}{2} - \frac{\delta_q^c}{2} - \left( \frac{a_{sl}^q}{2} + \frac{\delta_q^p}{2} \right) \frac{\cos \Delta m_q t}{\cosh \Delta \Gamma_q t/2}. \]

Take time-independent component:

\[ \rightarrow \text{get rid of } \delta_p \]

Measure difference $\Delta A_{sl}^{s,d} = A_{sl}^s - A_{sl}^d$:

\[ \rightarrow \text{cancel } \delta_c \]

Using $B_{s,d}^0 \to D_{s,d}(KK\pi)\mu\nu$

\[ \sigma(\Delta A_{fs}) \approx 10^{-3} \text{ with } 1 \text{ fb}^{-1} \]
CP violation in $B$ decays with trees

Provides SM reference for loop-induced decays.
Angle $\gamma$ appears in the interference of amplitudes with $V_{ub}$ and another CKM element.

- Interference between decays with $D^0$ and $\bar{D}^0$ ($B^\pm$, $B^0$ self-tagged). Need $D^0$ and $\bar{D}^0$ to decay into the same final state:

$$D^0 \rightarrow KK, K\pi, K_S\pi\pi, \ldots$$

- Interference between decays with and without mixing (for $B^0$, $B_s$ time-dependent). Can use charged $D$.

Many decay modes involved with comparable sensitivity.
$B^\pm \rightarrow DK^\pm$ time-integrated measurements

CPV magnitude determined by $r_B = \frac{|A(B^+\rightarrow D^0K^+)|}{|A(B^+\rightarrow D^0K^+)|}$, strong phase difference $\delta_B$

**$D \rightarrow \pi\pi, KK, K\pi$**

Observables - charge asymmetries and allowed-suppressed ratios:

$A_{ADS} \equiv \frac{B(B^-\rightarrow D(K^+\pi^-)K^-) - B(B^+\rightarrow D(K^-\pi^+)K^+)}{B(B^-\rightarrow D(K^+\pi^-)K^-) + B(B^+\rightarrow D(K^-\pi^+)K^+)}$

$R_{ADS} = \frac{Br(B^\pm\rightarrow [K^\mp\pi^\pm]DK^\pm)}{Br(B^\pm\rightarrow [K^\mp\pi^\pm]DK^\pm)}$

**$D \rightarrow K_S\pi\pi, K_SKK$**

Observable - $D$ decay Dalitz plot density (different for $B^+$ and $B^-$):

$|A_\pm|^2 = \left| \begin{array}{c} \phantom{+} \end{array} \right|^2 + \text{re}^{i\delta_B \pm i\gamma}$

Input from charm studies ($D$ amplitude ratios, strong phase differences — CLEO).
Practically no theoretical uncertainty.
Measured parameters: $r_B$, $\delta_B$, $\gamma$.
$\gamma$ sensitivity depends on $r_B$, $\delta_B$ values.
Today (13 nb$^{-1}$): $B \to D\pi$

signal is seen.

2010 (0.2 fb$^{-1}$): Precision comparable to B factories ($\sigma_\gamma \sim 12 - 15^\circ$)

2011 (1 fb$^{-1}$):

- $B \to D(hh)K$: $N_{signal} \sim 3000$ events
- $B \to D_{sup}(K\pi)K$: $N_{signal} \sim 400$ events
- $D \to D(K_s\pi\pi)K$: $N_{signal} \sim 1500$ events.
- Combined $\sigma_\gamma \sim 6 - 8^\circ$
CP violation in charmless $B$ decays

- Charmless two-body decays can probe $\gamma$.
- Observables: time-dependent asymmetries

$$A_f^{CP}(t) = \frac{A_f^{dir} \cos \Delta mt + A_f^{mix} \sin \Delta mt}{\cosh \Delta \Gamma t/2 - A_f^{\Delta} \sinh \Delta \Gamma t/2}$$

Need flavor tagging and $B$ decay time measurements.

- Measurable $A_f^{mix}$ and $A_f^{dir}$ contain information about $\gamma$. Can be extracted by measurements with $B^0$ and $B_s$ decays to $f = \pi\pi, KK, K\pi$, using U-spin symmetry ($d - s$ SU(3) subgroup).
Measurements with $B^0$ performed by B factories. 1.9$\sigma$ disagreement between Belle and BaBar measurements.

LHCb competitive with B factories for $A_{\pi\pi}$ measurement with 1 fb$^{-1}$, can measure $A_{KK}$ from $B_s$.

<table>
<thead>
<tr>
<th></th>
<th>Current value</th>
<th>0.2 fb$^{-1}$</th>
<th>1 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\pi\pi}^{dir}$</td>
<td>0.38 ± 0.06</td>
<td>0.13</td>
<td>0.06</td>
</tr>
<tr>
<td>$A_{\pi\pi}^{mix}$</td>
<td>−0.65 ± 0.07</td>
<td>0.13</td>
<td>0.06</td>
</tr>
<tr>
<td>$A_{KK}^{dir}$</td>
<td>-</td>
<td>0.15</td>
<td>0.07</td>
</tr>
<tr>
<td>$A_{KK}^{mix}$</td>
<td>-</td>
<td>0.11</td>
<td>0.05</td>
</tr>
</tbody>
</table>
CPV in charm

$D$ mixing: $D_{1,2} = pD^0 \pm q\bar{D}^0$

- $x = (M_2 - M_1)/\Gamma$,  
- $y = (\Gamma_2 - \Gamma_1)/2\Gamma$.
- $q/p \neq 1 \Rightarrow$ CPV in mixing.

Example of a first-year measurement for LHCb: CPV in $D \to hh$.

Observables:

- $y_{CP} = \tau(K\pi)/\tau(KK) - 1$,
- $A_{\Gamma} = \frac{\tau(D^0 \to KK) - \tau(\bar{D}^0 \to KK)}{\tau(D^0 \to KK) + \tau(\bar{D}^0 \to KK)}$

Flavor-tagged signals $D^*\pm \to D^0\pi^\pm$, $D^0 \to KK$, $K\pi$ already seen:

Can reach $\sigma(y_{CP}), \sigma(A_{\Gamma}) \sim 0.1\%$ ($\times 3$ better than current limit) with only $0.1$ fb$^{-1}$.
Many possibilities to search for CPV at LHCb with first data:

- $B_s \rightarrow J/\psi \phi$ — competitive with CDF/D0 with 0.2 fb$^{-1}$.
- Flavor-specific charge asymmetry: measurement complementary to D0: $\sigma(\Delta A_{fs}) \sim 10^{-3}$ with 1 fb$^{-1}$.
- $\gamma$ measurements with $B \rightarrow DK$ (different $D$ decay modes), time-dependent $B_s \rightarrow D_s K$ (not covered here) — precision comparable to $B$ factories with 0.2 fb$^{-1}$ ($\sigma_\gamma \sim 15^\circ$), $\sigma_\gamma \sim 6 - 8^\circ$ with 1 fb$^{-1}$.
- CPV in charmless decays: $B \rightarrow \pi \pi, K \pi, KK$ — comparable to $B$ factories with 1 fb$^{-1}$ for $B^0$ (solve Belle-BaBar disagreement), best constraint for $B_s$.
- CPV in charm mixing (e.g. $y_{CP}$ from $D \rightarrow hh$) — $\sim$ 3 times improvement possible with 0.1 fb$^{-1}$.

Excellent detector performance confirmed, analyses using first $O(10 \text{ nb}^{-1})$ to be reported at ICHEP.