CP Violation
&
Matter anti-Matter Asymmetry

Lecture IV

SLAC Summer Institute 2022

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Outline of Lecture IV

- CP Violation beyond kaons:
  - Verification of CPV mechanism in the Standard Model
  - Observation of direct CPV in B decays
  - Observation of CPV in the charm system

- Future program

- Summary
The unitarity of the CKM matrix helps define some of the key “theoretically clean” experimental observables

\[ \sum_i V_{ij} V^*_{ik} = \delta_{jk} \quad \text{(Columns)} \]

\[ \sum_j V_{ij} V^*_{kj} = \delta_{ik} \quad \text{(Rows)} \]

6 diagonal and 6 off-diagonal (vanishing) unitarity relations
The six vanishing unitarity relations define triangles in the complex plane.

Some of the Key CPV observables: “CKM Unitarity angles” $\alpha, \beta, \gamma, (\beta_s)$ defined by:

- $B_d^0$ unitarity triangle
- $B_s^0$ unitarity triangle

All sides similar size

Nearly flat
CP Violation in the Standard Model

Testing the Unitarity of the CKM matrix

The six vanishing unitarity relations define triangles in the complex plane

Some of the Key CPV observables: “CKM Unitarity angles” \( \alpha, \beta, \gamma, (\beta_s) \) defined by:

- \( B^0_d \) unitarity triangle
- \( B^0_s \) unitarity triangle

Other notation (Belle)
- \( \phi_1 = \beta \)
- \( \phi_2 = \alpha \)
- \( \phi_3 = \gamma \)

Nearly flat

All sides similar size
CP Violation vs the Standard Model

Wolfenstein Parameterization of the CKM matrix

\[
\begin{pmatrix}
1 - \frac{1}{2} \lambda^2 & \lambda & A \lambda^3 (\rho - i \eta) \\
-\lambda & 1 - \frac{1}{2} \lambda^2 & A \lambda^2 \\
A \lambda^3 (1 - \rho - i \eta) & -A \lambda^2 & 1
\end{pmatrix}
\]

All CPV effects correlated & governed by a single parameter - \( \eta \)

Current status

A comprehensive test of the CKM picture involves both:

- CP violating observables \((\alpha, \beta, \gamma, \beta_s, \ldots), \epsilon_K\)
- CP conserving observables
  - mixing(\(\Delta m_d, \Delta m_s\)), CKM elements \(|V_{ub}|, |V_{cb}|, \ldots\)
Accessing the CKM phase via interference of decay & mixing

\[
A_{cp}(t) = \frac{\Gamma(\bar{B}^0(t)\to f_{cp}) - \Gamma(B^0(t)\to f_{cp})}{\Gamma(\bar{B}^0(t)\to f_{cp}) + \Gamma(B^0(t)\to f_{cp})} \propto \sin2(\phi_m - \phi_d)\sin\Delta m t
\]
Accessing the CKM phase via interference of decay & mixing

Bigi and Sanda

More generally:

$$A_{cp}(t) = S \sin \Delta mt - C \cos \Delta mt$$

$$S = \frac{2 \text{Im}(\lambda)}{1 + |\lambda|^2}$$

$$C = \frac{(1 - |\lambda|^2)}{(1 + |\lambda|^2)}$$

For the (rare) ideal case:

when one diagram dominates the decay

$$\lambda = \eta_{cp} e^{-i2(\phi_m - \phi_d)}$$

$$|\lambda| = 1$$, no direct CPV, $$C=0$$

$$S = \text{Im}(\lambda) = -\eta_{cp} \sin 2(\phi_m - \phi_d)$$
Measurement of the angle \( \beta = \text{arg}[\frac{\langle V_{cd}V_{cb}^* \rangle}{\langle V_{td}V_{tb}^* \rangle}] \) & \( \beta_s \)

With careful set up of the initial and final states, access the Unitarity Angles: e.g.

\[ \beta \sim \text{arg}(V_{td}^*) \sim 24^\circ \]

\[ \varphi_s = -2\beta_s \sim 2 \times \text{arg}(V_{ts}^*) \sim 1^\circ \]
By mid-1990’s all elements were in place for building the “CPV interferometer”

- **Long B lifetime** \([\text{MARK-II \& MAC at PEP (1983)}]\).
- **Large \(B^0\) mixing** \([\text{UA1, ARGUS (1987), CLEO (1988)}]\)
- \(|V_{cb}|\) and \(|V_{ub}|\) measured at CLEO and ARGUS. \(|V_{ub}|\) shown to be small but non-zero
- **Two \(e^+e^-\) Asymmetric Energy B Factory proposals at SLAC and KEK**
Experimental set up at the B Factories (SLAC, KEK)

- **Beam energy (GeV)**
  - PEP-II: 9.0 ($e^-$), 3.1 ($e^+$), 8.0 ($e^-$), 3.5 ($e^+$)
  - KEKB: 1.2 ($e^-$), 1.6 ($e^+$)

- **Beam current (A)**
  - PEP-II: 1.8 ($e^-$), 2.7 ($e^+$)
  - KEKB: 1.2 ($e^-$), 1.6 ($e^+$)

- **Design luminosity (cm$^{-2}$ s$^{-1}$)**
  - PEP-II: $1.2 \times 10^{34}$
  - KEKB: $2.1 \times 10^{34}$

Operating in the Upsilon energy region:

- $\Upsilon(1S)$
- $\Upsilon(2S)$
- $\Upsilon(3S)$
- $\Upsilon(4S)$

The initial goal of more than $10^7 B'$s/year quickly achieved at both labs.

**Y(1S) cross-section $\approx 1$ nb**

**$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$**

**B $\bar{B}$ production threshold**
Experimental set up at the B Factories (SLAC, KEK)

\[ e^+ + e^- \rightarrow \Upsilon(4S) \rightarrow B \bar{B} \]

\( \sim 50\% \) as \( B_d^0 \bar{B}_d^0 \) in \( J^{\text{cp}} = 1^- \)

The \( B_d^0 \bar{B}_d^0 \) system evolves coherently- until one \( B \) decays

\[
|\gamma\rangle = \frac{1}{\sqrt{2}} \left[ |B^0(t_1)\rangle|\bar{B}^0(t_2)\rangle - |\bar{B}^0(t_1)\rangle|B^0(t_2)\rangle \right]
\]

No \( (B^0 \bar{B}^0) \) or \( (\bar{B}^0 \bar{B}^0) \) states at the same time (violates Bose statistics)

The energy asymmetry of the colliders leads to boosted Center-of-Mass- \( \Upsilon(4S) \)- frame, thus boosted B mesons with displaced vertices.

The state of one \( B \) at \( t_1 \) (flavor tagged) determines the state of the other \( B \), which then evolves and decays at \( t_2 \)

Time evolution to be measured in \( \Delta t = t_2 - t_1 \)
Experiments at the B Factories *(BaBar, Belle)*

- Charge particle Tracking and vertex reconstruction: Drift chamber & silicon vertex tracker near IP, all in a solenoidal magnet
  - Particle identification & flavor tagging: DIRC (BaBar) and Aerogel and TOF (Belle), EM Calorimeters (CSI (TI)), Muon identification systems
  - \(\sim 250 \, \mu m\)
2001: Discovery of CP Violation in B decays

\( \sin 2\beta \) measurements \((\beta = \arg \left[ - \frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right] )\)

BaBar

\( \sin 2\beta = 0.59 \pm 0.14 \text{ (stat)} \pm 0.05 \)

Belle

\( \sin 2\phi_1 = 0.99 \pm 0.14 \text{ (stat)} \pm 0.06 \text{ (syst)} \)
Flavor Physics at Tevatron
CDF and D0 were major players

Some of the major contributions

- Observation of Bs mixing
- First measurement of $\beta_s$
- First hints of CPV in $B_d$
- DO mixing, (with BaBar, Belle)

CDF and D0 upgraded with Powerful vertex Silicon detectors
Flavor Physics at LHC (2010-)

All four experiments have flavor physics capabilities

Dedicated Flavor Physics experiment LHCb

Incoherent time evolution of B’s

$\sigma_{bb} \sim 500 \, \mu b$ at 13 TeV
Powerful Vertex Locator (VELO) & Tracking System
B decay length in few cm range-
[Decay time resolution ~40 fs]

Particle identification:
Muon system, EM Calorimeter & RICH (Hadron ID: 1-100 GeV)

Critical for flavor tagging and reconstruction of B and charm decays
Measuring the CKM Unitarity Angles
Measurement of the angle $\alpha = \text{arg} \left[ - \frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right]$ (recap)

Using hadronic $B \rightarrow \text{charmless decays}$ to access $\alpha$:

$B_d \rightarrow \pi^+\pi^-$

$B_d \rightarrow \rho^+\rho^-$

$\alpha = \text{arg} \left[ - \frac{(V_{td}V_{tb}^*)}{(V_{ud}V_{ub}^*)} \right]$
Measurement of the angle $\alpha = \arg \left[ - \frac{(V_{td}V_{tb}^*)}{(V_{ud}V_{ub}^*)} \right]$ 

- The $b \rightarrow u$ dominated decays, $[B \rightarrow \pi \pi: (\pi^+ \pi^-, \pi^+ \pi^0, \pi^0 \pi^0), \rho \pi, \rho \rho]$ serve as the “golden” modes for measuring the angle $\alpha$

\[ \lambda = \eta \frac{V_{tb}^* V_{td} V_{ub} V_{ud}^*}{V_{tb} V_{td}^* V_{ub}^* V_{ud}} = e^{i2\alpha} \]
\[ C = 0 \quad \text{&} \quad S = \sin(2\alpha) \]

But penguin (pollution) complicates the picture

\[ S = Im(\lambda) = \sin 2\alpha_{\text{eff}} \]
\[ \alpha_{\text{eff}} = (\alpha + \theta) \]

Use isopsin relation of the $((\pi^+ \pi^-, \pi^+ \pi^0, \pi^0 \pi^0)$ system, to disentangle tree and penguin (Gronau & London)
\( \alpha \) from \( B\to\pi\pi \) decays
Large penguin contribution, leads to large uncertainty and multiple solution from isospin analysis

\[ \alpha = (85.2^{+4.8}_{-4.3})^\circ \]

Combined result
\( B\to\pi\pi, \rho\pi, \rho\rho \)

\( \alpha \) from \( B\to\rho\rho \)
Much smaller penguin pollution (\( C\sim 0 \))

Currently dominated by \( B\to\rho\rho \)
Measurement of $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ (recap)

Interference of tree level $b\to cW$ & $b\to uW$ amplitudes

Direct CP violation & Branching ratios are sensitive to $\gamma$

Other parameters: $r_B = \left|\frac{A_u}{A_c}\right|$, $\delta_B = \delta_c - \delta_u$, $\{\delta_D = \delta_f - \delta_f, r_D = \left|\frac{A_f(D\to f)}{A_{\bar{f}}(D\to \bar{f})}\right|\}$
**Measurement of** \[ \gamma = \arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}) \]

**Classic methods:**

- Gronau, London, Wyler (GLW): \( D \to f_{cp}(K^+K^-, \pi^+\pi^-, K^0_s\pi^0...) \) \([\gamma, \delta_B, r_B]\)

- Atwood, Dunietz, Soni (ADS): \( D \to f \) [doubly Cabibbo suppressed] & \( \bar{D} \to f \) [Cabibbo favored] \([\gamma, \delta_B, r_B, \delta_D, r_D]\)

- Bondar, Giri, Grossman, Soffer, Zupan (BGGSZ): \( D \to 3\)-body \((K_s\pi^+\pi^-, K_sK^+K^-)\)

  **Combines** elements of [ADS, GLW] [the most powerful method]

  Study CPV across the Dalitz plot
Measurement of \( \gamma = \text{arg}(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}) \)

Includes contributions from \( B \to D^{(*)}K^{(*)} \) and from \( B_S^0 \) decays

Mixing and CPV in D decays assumed to be negligibly small

combined: \( \gamma = (66.2 \pm 3.4)^o \)

Dominated by LHCb measurements

LHCb: \( \gamma = (67 \pm 4)^o \)

2022 update \( \gamma = (65.4^{+3.8}_{-4.2})^o \)
Measurements of \( \phi_s = -2\arg\left(-\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*}\right) \)

- **From Time-dependent CPV in:**
  - \( B_s^0 \rightarrow J/\psi \ K^+K^- \ [\phi \rightarrow K+K-, \ s\text{-wave} (K+K-)] \)
  - \( B_s^0 \rightarrow J/\psi \ K^+K^- \ - \text{high-mass region} \)
  - \( B_s^0 \rightarrow J/\psi \ \pi^+ \pi^- \)
  - \( B_s^0 \rightarrow \psi(2s) \ K^+K^- \)

\[ \phi_s^{SM} = -36.8 \pm 1.0 \text{ mrad} \]

From CKM fit
Measurements of \( \phi_s = -2 \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \)

- From Time-dependent CPV in:
  - \( B_s^0 \rightarrow J/\psi K^+K^- \) \([\phi \rightarrow K+K-, s\text{-}wave (K+K-)]\)
  - \( B_s^0 \rightarrow J/\psi K^+K^- \) - high-mass region
  - \( B_s^0 \rightarrow J/\psi \pi^+\pi^- \)
  - \( B_s^0 \rightarrow \psi(2s) K^+K^- \)

- Mixture of CP odd & CP even states - Angular analysis is required to extract CPV info.

The decay is described in terms of four helicity amplitudes.

- Observables:
  - \( \phi_s \)
  - \( \Delta \Gamma = \Gamma_H - \Gamma_L \)
  - \( \Delta m = m_H - m_L \)

LHCb-paper-2019-013
Measurements of \( \phi_s = -2 \arg \left( -\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} \right) \)
Status of CKM (2022)

Consistent with the CKM picture

<table>
<thead>
<tr>
<th>Direct (deg)</th>
<th>CKM fit</th>
</tr>
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<tbody>
<tr>
<td>( \alpha = 86.4^{+4.5}_{-4.3} )</td>
<td>( 91.9^{+3.0}_{-1.2} )</td>
</tr>
<tr>
<td>( \beta = 22.2 \pm 0.7 )</td>
<td>( 23.90^{+1.2}_{-1.2} )</td>
</tr>
<tr>
<td>( \gamma = 66.2^{+3.4}_{-3.6} )</td>
<td>( 65.81^{+0.99}_{-1.66} )</td>
</tr>
</tbody>
</table>

\[ \bar{\rho} = 0.1566^{+0.0085}_{-0.0048} \]

\[ \eta = 0.3475^{+0.0118}_{-0.0054} \]
Is there room for New Physics?
Search for CPV sources beyond SM- *via mixing*

Through new loop diagrams in mixing
tree level processes: $V_{ub}$ & $\gamma$
Free of New Physics effects

Any Inconsistency between the two sets of measurements may be due to the influence of New Physics effects.

Observables involving loop diagrams ($K^0$ and $B^0$ oscillations) are sensitive to New Physics.
**Key test:**
Tree-level quantities \((V_{ub}, \gamma)\) and loop-affected quantities \((\text{mixing}, \beta, \alpha, \epsilon_K)\) are consistent.
New Physics Through Mixing

Fit the data allowing departure from SM in $B^0$ mixing amplitude

From the $\text{UT}_{\text{fit}}$

$$C_{Bq} e^{2i\phi_{Bq}} = \frac{\langle B^0_q | H^{\text{full}}_{\text{eff}} | \bar{B}^0_q \rangle}{\langle B^0_q | H^{\text{SM}}_{\text{eff}} | \bar{B}^0_q \rangle},$$

Consistent With SM

$$C_{Bd} = 1.05 \pm 0.11$$

$$\phi_{Bd} = -2.0 \pm 1.8$$

$$C_{Bs} = 1.110 \pm 0.090$$

$$\phi_{Bs} = 0.42 \pm 0.89$$
Is there room for New Physics?
Search for CPV sources beyond SM - via Penguins

Through new loop diagrams in decay:

New Physics loops can lead to deviation of CPV from $\sin 2\beta$
Penguin dominated $B^0$ decays:

Measurements of $\sin 2\beta$, $\phi_s$

New addition from $B_s^0$ to this program

$\phi_s$ from $B_s^0 \rightarrow \phi\phi$ (penguin dominated process) - Analog of $B_d^0 \rightarrow \phi K_s$

$\phi_s = -73 \pm 115 \pm 27$ (mrad)

$\lambda = 0.99 \pm 0.05 \pm 0.01$

Consistent with SM:

$\phi_s^{SM} = -36.8 \pm 1.0$ mrad

Naïve average of $\sin 2\beta$ penguins:

$0.654 \pm 0.037$

From $(b \rightarrow ccs)$: $0.70 \pm 0.02$

Current results are consistent with SM.
Direct CP Violation

\[ |A(M \to f)| \neq |A(\bar{M} \to \bar{f})| \implies A_{CP} = \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})} \]

Direct CPV occurs in decays that involve contributions from two or more processes with different weak and strong phases.

**Example:** $B \to K\pi$

\[ A(B^0 \to K^+\pi^-) = |P|e^{i\delta} + |T|e^{i\gamma}, \]
\[ A(\bar{B}^0 \to K^-\pi^+) = |P|e^{i\delta} + |T|e^{-i\gamma} \]

Both strong & weak phases must be different

\[ A_{CP}(K^+\pi^-) \equiv \frac{\Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\bar{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)} = -\frac{2\left|T/P\right|\sin\delta\sin\gamma}{1 + \left|T/P\right|^2 + 2\left|T/P\right|\cos\delta\cos\gamma}, \quad (2) \]
Observation of Direct CPV in B decays

First observation of direct CP violation in B decays

\[ B \to K^-\pi^+ \]

CPV asymmetries for all members of the B→Kπ system are now measured

\[
\begin{array}{llll}
\text{Mode} & \text{BF} \times 10^{-6} & \text{Direct } A_{CP} & \sin(2\beta^{\text{eff}}) \\
B^0 \to K^0\pi^0 & 9.9 \pm 0.5 & 0.01 \pm 0.10 & 0.57 \pm 0.17 \\
B^+ \to K^0\pi^+ & 23.8 \pm 0.8 & -0.017 \pm 0.016 & \\
B^0 \to K^+\pi^- & 19.6 \pm 0.5 & -0.084 \pm 0.004 & \\
B^+ \to K^+\pi^0 & 12.9 \pm 0.5 & 0.040 \pm 0.021 & \\
\end{array}
\]

A small puzzle:
Naïve expectation based on isospin symmetry
(Simply changing the spectator quark: d to u)

\[ A_{CP}(B^0 \to K^+\pi^-) = A_{CP}(B^+ \to K^+\pi^0) \]

Measurements differ by more than 5\sigma
The \( B \to k\pi \) puzzle continues with the LHCb Measurements

\[
A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015 \text{(stat.)} \pm 0.006 \text{(syst.)} \pm 0.003 \text{(ext.)}
\]

A more accurate test based on isospin: (Buras, Rosner and Gronau, Fleischer)

\[
A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+) \frac{B(K^0\pi^+)}{B(K^+\pi^-)} \frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0) \frac{2B(K^+\pi^0)}{B(K^+\pi^-)} \frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0) \frac{2B(K^0\pi^0)}{B(K^+\pi^-)}
\]

**Predicts:** \( A_{cp}(B \to K^0\pi^0) = -0.138 \pm 0.025 \) (5.5 \( \sigma \) from zero)

Current measurements: BaBar & Belle: \( 0.01 \pm 0.10 \)  Key to solving the puzzle

A major goal of the Belle-II experiment (& possibly LHCb)
More puzzles in Direct CPV measurements
Large Direct CPV seen in charmless decays

$B_S^0 \rightarrow K^-\pi^+ = 0.213 \pm 0.017$

$B^{\pm} \rightarrow \pi^{\pm}\pi^+\pi^-$

Intriguing interference effects at work
CP Violation in charm decays
Within the SM: CPV in charm decays is very small

- CPV requires contribution from all three generations:
  - CPV in $D^0$ mixing:
    Dominant contributions are from the 1st two generations $\rightarrow$ negligible CPV in $D^0$ mixing

- Direct CPV from interference of Tree and penguin diagrams - also dominated by the 1st two generations; $\rightarrow$ negligible direct CPV

Loops with some $b$-quark contributions can induce small CPV $\sim O(|V_{ub}V_{cb}^*/V_{ud}V_{cd}^*|) \sim \lambda^4 \ll 10^{-3}$
CP Violation in $D^0$ mixing

Mixing is firmly established but no evidence for CPV in mixing

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$X = \frac{\Delta m}{\Gamma} \quad y = \frac{\Delta \Gamma}{\Gamma}$$

CPV if:

- $|q/p| \neq 1$
- $\arg(q/p) \neq 0$

![Graph showing CPV allowed regions](image)
Direct CPV in the charm system

\[ A_{\text{cp}} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} \]

Searches performed in a large number of channels: No evidence for CPV
Precision in some channels at \( \sim O(10^{-3}) \) level already:

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<td>-0.20 ± 0.17</td>
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<td>( D^0 \to K^+K^- )</td>
<td>-0.16 ± 0.12</td>
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<td>-0.41 ± 0.09</td>
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\( >3\sigma \) Expect \( A_{\text{cp}} \sim -0.33\% \)
induced by indirect CPV in \( K^0 \)
Direct CPV in the charm system

\[
A_{\text{cp}} = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})}
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\(>3\sigma\) Expect \(A_{\text{cp}} \sim -0.33\%\) induced by indirect CPV in \(K^0\)

The LHCb data (Runs I & II) enables yet another major leap in precision \(\rightarrow O(10^{-4})\)
Observation of Direct CP violation in charm decays at LHCb

\[ \Delta A_{cp} = A_{raw}(K^+K^-) - A_{raw}(\pi^+\pi^-) = A_{cp}(K^+K^-) - A_{CP}(\pi^+\pi^-) \]

The idea is that: \[ A_{raw}(D \rightarrow h+h-) = A_{cp}(h+h-) + A(\text{det}) + A(\text{prod}) \]

Common to both channels

Flavor of D^0 is tagged via: \( D^{*+} \rightarrow D^0\pi^+ \) or from \( B \rightarrow D \mu^+ \nu X \)

Measured CP violation asymmetry: sigma

\[ \Delta A_{CP} \approx (1 + \frac{\langle t \rangle}{\tau_{D^0}}) y_{CP} \frac{\Delta \langle t \rangle}{\tau_{D^0}} a_{CP}^{ind} \]

\[ \Delta a_{CP}^{dir} = (-15.6 \pm 2.9) \times 10^{-4} \]

5.3 \( \sigma \) from zero

LHCb-paper-2019-006
Observation of Direct CP violation in charm decays at LHCb

With measurement of \( A_{CP}(D^0 \rightarrow K^+K^-) \)

\[
\begin{align*}
    a_{K^-K^+}^d &= (7.7 \pm 5.7) \times 10^{-4} \\
    a_{\pi^+\pi^-}^d &= (23.2 \pm 6.1) \times 10^{-4}
\end{align*}
\]

Non-zero CPV at 3.8 \( \sigma \)

Not too far from SM (~10\(^{-3}\)). Specific mechanism yet to be determined. It’s soon to invoke BSM observation.
The quark sector remains the sole source of observed CP violation effects. Current measurements are consistent with the CKM mechanism.

- CPV measured in Weak decays of Neutral Kaons, B mesons, and charm mesons.
- No evidence for CPV in charged kaons and baryons
- No evidence for EDM

Major plans underway to measure CPV in the lepton sector.

Time-Reversal (T) violation observed in the B system

- In balance with observed CPV in B, consistent with CPT invariance.
Huge progress made since the 25th Anniversary but: Do we really understand CP violation?
Future
Experimental Evolution of the CKM picture & the search for New Physics in flavor decays

Last century

2001

Today

Towards O(1%) test of CKM

Constraint on NP/SM amplitude (arXiv: 1309.2293)

\[ M_{12} = M_{12}^{SM} \times (1 + h e^{2i\sigma}) \]
Experimental Landscape

LHCb phase-1 Upgrade

HL LHC

Run 2
Run 3
LS2
LS3
Run 4
LS4
Run 5 & beyond

2023
2026
2029
2033-2035
2042

LHCb
~9 fb-1
LHCb Upgrade I & Belle-II
50 fb-1
50 ab-1
LHCb-Upgrade II
→300 fb-1
Recent results from the Belle II experiment

SuperKEKB and Belle II

- Operation with full detector started in 2019.
- Luminosity $4.1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ achieved (May 17, 2022).
  - World record ($\sim \times 2$ of KEKB)
  - Aiming one order higher.
- $\sim 380$ fb$^{-1}$ of data accumulated so far.
  - Belle: 1 ab$^{-1}$ ($= 1000$ fb$^{-1}$) in 11 years’ operation.
  - Belle II target: 50 ab$^{-1}$.

1 ab$^{-1} \sim 10^9$ BB

- Long shutdown (LS) 1 starts from summer 2022 for 15 months to fully install VXD.
- A SuperKEKB international taskforce is discussing additional improvements.
- LS2 for machine improvements could happen on the time frame of 2026-27
The LHCb upgrade - I

The upgrade is designed to run at peak luminosity of $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$; Aiming for 50 fb$^{-1}$

- New approach to the LHCb trigger scheme to overcome L0 (1MHz) limitation.

- New Novel Trigger Approach:
  - Remove L0 (hardware) trigger
  - Readout the detector at the 40 MHz LHC clock rate
  - Move to a fully flexible software trigger

=> Major upgrade of LHCb detector to cope with increase occupancy, data rate, radiation dose & to preserve efficiency and low ghost rate:

- Replaced all readout electronics, entire tracking system (Vertex locator, upstream & downstream tracking detectors) & upgrade Particle ID system

Installation mostly completed & being commissioned

Physics Data taking in 2023
LHCb Upgrade-II for HL-LHC operation

Aimed at operating at peak Luminosity of $1.5 \times 10^{34} / \text{cm}^2 / \text{s}$ (pile up of 40)
Integrated Luminosity of $\sim 300 \text{ fb}^{-1}$ ($+50 \text{ fb}^{-1}$ Runs 1-4)

Will need precision timing, $O(20 \text{ ps})$, and rad hard technology in nearly every detector element to overcome the high pile up and the HL-LHC radiation level

Timeline
Framework TDR approved by LHCC, March 2022
Physics reach of LHCb Upgrade-II

Table 2.1: Anticipated uncertainties at future upgrades of LHCb for some key flavour observables, modified and updated from Ref. [3]. Upgrade I projections are given both with the data sample available after Run 3 (23 fb\(^{-1}\)) and with that after Run 4 (50 fb\(^{-1}\)). Uncertainties are extrapolated assuming that systematic uncertainties will not becoming limiting (see Ref. [3] for further discussion).

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current LHCb (up to 9 fb(^{-1}))</th>
<th>Upgrade I (23 fb(^{-1}))</th>
<th>Upgrade II (50 fb(^{-1}))</th>
<th>Upgrade II (300 fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CKM tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\gamma(B \to DK, \text{ etc.}))</td>
<td>4° [9, 10]</td>
<td>1.5°</td>
<td>1°</td>
<td>0.35°</td>
</tr>
<tr>
<td>(\phi_s(B_s^0 \to J/\psi\phi))</td>
<td>32 mrad [8]</td>
<td>14 mrad</td>
<td>10 mrad</td>
<td>4 mrad</td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
<td>(A^0_s \to p\mu^-\bar{\nu}_\mu, \text{ etc.}))</td>
</tr>
<tr>
<td>(a^d_{sl}(B^0 \to D^-\mu^+\nu_\mu))</td>
<td>(36 \times 10^{-4}) [34]</td>
<td>(8 \times 10^{-4})</td>
<td>(5 \times 10^{-4})</td>
<td>(2 \times 10^{-4})</td>
</tr>
<tr>
<td>(a^s_{sl}(B^0_s \to D^-<em>s\mu^+\nu</em>\mu))</td>
<td>(33 \times 10^{-4}) [35]</td>
<td>(10 \times 10^{-4})</td>
<td>(7 \times 10^{-4})</td>
<td>(3 \times 10^{-4})</td>
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<tr>
<td><strong>Charm</strong></td>
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</tr>
<tr>
<td>(\Delta A_{CP}(D^0 \to K^+K^-\pi^+\pi^-))</td>
<td>(29 \times 10^{-5}) [5]</td>
<td>(13 \times 10^{-5})</td>
<td>(8 \times 10^{-5})</td>
<td>(3.3 \times 10^{-5})</td>
</tr>
<tr>
<td>(A_{\Gamma}(D^0 \to K^+K^-\pi^+\pi^-))</td>
<td>(11 \times 10^{-5}) [38]</td>
<td>(5 \times 10^{-5})</td>
<td>(3.2 \times 10^{-5})</td>
<td>(1.2 \times 10^{-5})</td>
</tr>
<tr>
<td>(\Delta x(D^0 \to K^0\pi^+\pi^-))</td>
<td>(18 \times 10^{-5}) [37]</td>
<td>(6.3 \times 10^{-5})</td>
<td>(4.1 \times 10^{-5})</td>
<td>(1.6 \times 10^{-5})</td>
</tr>
<tr>
<td><strong>Rare Decays</strong></td>
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<tr>
<td>(B(B^{0\to}\mu^+\mu^-)/B(B^{0}_{s}\to\mu^+\mu^-))</td>
<td>69% [40, 41]</td>
<td>41%</td>
<td>27%</td>
<td>11%</td>
</tr>
<tr>
<td>(S_{\mu\mu}(B^{0}_{s}\to\mu^+\mu^-))</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.2</td>
</tr>
<tr>
<td>(A^{(2)}_{\Gamma}(B^{0}\to K^{*0}e^+e^-))</td>
<td>0.10 [52]</td>
<td>0.060</td>
<td>0.043</td>
<td>0.016</td>
</tr>
<tr>
<td>(A^{lm}_{\Gamma}(B^{0}\to K^{*0}e^+e^-))</td>
<td>0.10 [52]</td>
<td>0.060</td>
<td>0.043</td>
<td>0.016</td>
</tr>
<tr>
<td>(A_{\phi\gamma}(B^0_s \to \phi\gamma))</td>
<td>(+0.41) (-0.44)</td>
<td>0.124</td>
<td>0.083</td>
<td>0.033</td>
</tr>
<tr>
<td>(S_{\phi\gamma}(B^0_s \to \phi\gamma))</td>
<td>0.32 [51]</td>
<td>0.093</td>
<td>0.062</td>
<td>0.025</td>
</tr>
<tr>
<td>(\alpha_{\gamma}(A^0_b \to A\gamma))</td>
<td>(+0.17) (-0.29)</td>
<td>0.148</td>
<td>0.097</td>
<td>0.038</td>
</tr>
<tr>
<td><strong>Lepton Universality Tests</strong></td>
<td></td>
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<tr>
<td>(R_K(B^+ \to K^+\ell^+\ell^-))</td>
<td>0.044 [12]</td>
<td>0.025</td>
<td>0.017</td>
<td>0.007</td>
</tr>
<tr>
<td>(R_{K^*}(B^{0}\to K^{*0}\ell^+\ell^-))</td>
<td>0.12 [61]</td>
<td>0.034</td>
<td>0.022</td>
<td>0.009</td>
</tr>
<tr>
<td>(R(D^<em>)(B^{0}\to D^{</em>-}\ell^+\nu_\ell))</td>
<td>0.026 [62, 64]</td>
<td>0.007</td>
<td>0.005</td>
<td>0.002</td>
</tr>
</tbody>
</table>
Summary:

- The puzzle of CP violation is only partially solved: all observed CP violation effects in the quark sector are consistent with the CKM picture. The puzzle of missing antimatter is yet to be resolved. New source(s) of CPV needed.

- Future: The only certain statement that can be made is that the planned experimental program for the next two decades will lead to yet another major leap in the precision of key observables plus access to new observables. There is hope for solving the CP and the antimatter puzzle.
Backup slides
BaBar measurement of T-violation

Entangled $B^0_d \bar{B}^0_d$ system allows to compare rates for T-conjugated transitions

Table 1 Time-ordered event classes $(f_1, f_2)$ and their corresponding transitions between $B$ meson states

<table>
<thead>
<tr>
<th>Reference Event class</th>
<th>Transition $B^0 \to B_+$</th>
<th>Time reversed Event class</th>
<th>Transition $B_+ \to \bar{B}^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\ell^+ X, J/\psi K^0_S)$</td>
<td>$B^0 \to B_+$</td>
<td>$(J/\psi K^0_S, \ell^+ X)$</td>
<td>$B_+ \to \bar{B}^0$</td>
</tr>
<tr>
<td>$(J/\psi K^0_S, \ell^+ X)$</td>
<td>$B_+ \to B^0$</td>
<td>$(\ell^- X, J/\psi K^0_S)$</td>
<td>$B^0 \to B_+$</td>
</tr>
<tr>
<td>$(\ell^+ X, J/\psi K^0_S)$</td>
<td>$B^0 \to B_-$</td>
<td>$(J/\psi K^0_S, \ell^- X)$</td>
<td>$B_- \to \bar{B}^0$</td>
</tr>
<tr>
<td>$(J/\psi K^0_S, \ell^+ X)$</td>
<td>$B_- \to B^0$</td>
<td>$(\ell^- X, J/\psi K^0_S)$</td>
<td>$B^0 \to B_-$</td>
</tr>
</tbody>
</table>
The data rules out T-invariance at 14 sigma.

Measure $\sin2\beta=0.686 \pm 0.029$ consistent with that from CP asymmetries. That implies, the observed T-violation is in balance with the CP violation in B decays, as expected from CPT invariance.

FIG. 2 (color online). The four independent T-violating asymmetries for transition (a) $B^0 \rightarrow B^- (\ell^+ X, c\bar{c}K_S^0)$, (b) $B^+ \rightarrow B^0 (c\bar{c}K_S^0, \ell^+ X)$, (c) $\bar{B}^0 \rightarrow B^+ (\ell^+ X, J/\psi K_L^0)$, (d) $B^- \rightarrow B^0 (J/\psi K_L^0, \ell^+ X)$, for combined flavor categories with low misID (leptons and kaons), in the signal region ($5.27 < m_{ES} < 5.29$ GeV/$c^2$ for $c\bar{c}K_S^0$ modes and $|\Delta E| < 10$ MeV for $J/\psi K_L^0$). The points with error bars represent the data, the red solid and dashed blue curves represent the projections of the best fit results with and without T violation, respectively.