CP Violation at LHCb

Olaf Steinkamp
on behalf of the LHCb collaboration

Physik-Institut der Universität Zürich
Winterthurerstrasse 190 CH-8057 Zürich
olafs@physik.uzh.ch
Sources of CP violation (I)

**CP violation in mixing** ("indirect" CP violation)

- neutral meson systems ($K^0\bar{K}^0$, $D^0\bar{D}^0$, $B^0\bar{B}^0$, $B^0_s\bar{B}^0_s$): particle-antiparticle mixing due to box diagrams

- time evolution described by Schrödinger equation:

\[
\frac{i}{\hbar} \frac{d}{dt} \begin{pmatrix} B^0_s \\ \bar{B}^0_s \end{pmatrix} = \begin{pmatrix}
M_{11}^s - i \frac{\Gamma_{11}^s}{2} & M_{12}^s - i \frac{\Gamma_{12}^s}{2} \\
M_{12}^{s*} - i \frac{\Gamma_{12}^{s*}}{2} & M_{22}^s - i \frac{\Gamma_{22}^s}{2}
\end{pmatrix} \cdot \begin{pmatrix} B^0_s \\ \bar{B}^0_s \end{pmatrix}
\]

- solution yields mass eigenstates (= particles that propagate in vacuum):

\[
| B_{s,L} \rangle = p | B^0_s \rangle + q | \bar{B}^0_s \rangle \quad | B_{s,H} \rangle = p | B^0_s \rangle - q | \bar{B}^0_s \rangle
\]

- CP violation due to interference of $\Gamma_{12}$ and $M_{12}$ if $\phi_M^s = \arg\left(-\frac{M_{12}^s}{\Gamma_{12}^s}\right) \neq 0$

- results in $|q/p| \neq 1$: mass eigenstates are not CP eigenstates

- different transition rates for $B^0_s \rightarrow \bar{B}^0_s$ and $\bar{B}^0_s \rightarrow B^0_s$

- New Physics can enter through heavy new particles in box and affect $\phi_M^s$
Sources of CP violation (II)

**CP violation in decay** ("direct" CP violation)

- due to interference of decay diagrams with different weak and strong phases
- causes different decay amplitudes for a process and its CP conjugate: $|\frac{A_f}{A_{\bar{f}}}| \neq 1$
- measure time-integrated decay rate asymmetry

$$A_{\pm} = \frac{\Gamma(B^- \rightarrow f) - \Gamma(B^+ \rightarrow \bar{f})}{\Gamma(B^- \rightarrow f) + \Gamma(B^+ \rightarrow \bar{f})} \neq 0$$

- interfering amplitudes usually involve Penguin diagrams
- New Physics can then enter through new heavy particles in Penguin loops
- challenge: disentangle weak phase from strong phase
Sources of CP violation (III)

CP violation due to the interference of mixing and decay

- if final state $f$ accessible to both $B^0_s$ and $\bar{B}^0_s$:

  CP violated due to interference between direct decay and decay after mixing if

  \[
  \text{Im} \left( \frac{A_f}{A_f} \cdot \frac{q}{p} \right) \neq 0
  \]

- measure time-dependent decay rate asymmetry:

  \[
  A_{CP}(t) = \frac{\Gamma(B^0_s(t=0) \to f(t)) - \Gamma(\bar{B}^0_s(t=0) \to f(t))}{\Gamma(B^0_s(t=0) \to f(t)) + \Gamma(\bar{B}^0_s(t=0) \to f(t))} = S \sin(\Delta m_s t) + C \cos(\Delta m_s t)
  \]

- most prominent example pre-LHCb:

  measurement of CKM angle $2\beta$ in $B^0 \to J/\psi K^0_s$ by Babar and Belle

- NP can change phase of mixing (box diagram) and decay (if penguin)

- n.b. CP can be violated in this case even if $|q/p| = 1$ and $|\bar{A}_f/A_f| = 1$
CP Why?olation

- New Physics models usually predict new heavy particles
  - these can enter in internal loops (Box diagrams and Penguins), lead to sizeable modification of CP phases
- the comparison of precise measurements of CP phases with precise predictions from Standard Model can therefore reveal the presence of New Physics
- these indirect searches for New Physics make use of the appearance of virtual particles in loop diagrams
- are therefore sensitive to higher mass scales than direct searches for new particles

  classic example: CP violation in $K^0\bar{K}^0$ (1964)

→ prediction of 3rd quark family (top direct discovery 1995)

- moreover, the pattern of observed deviations can hint at the structure of the New Physics at work
LHCb Apparatus

VERtex LOcator

RICH detectors

muon system

tracking system

calorimeters

interaction point

Eugen's talk on Tuesday

[The LHCb Detector at the LHC, JINST 3 (2008) S08005]

06.12.2012

Kruger2012 - CPV @ LHCb (6/50)

O. Steinkamp
Key Features

- impact parameter resolution
- identify secondary vertices
- proper time resolution
- resolve fast $B^0_s - \bar{B}^0_s$ oscillations
- momentum, invariant mass resolution
- against combinatorial backgrounds
- magnetic field reversed regularly to cancel detector asymmetries

- $K/\pi$ separation
  - against peaking backgrounds
  - flavour tagging
- selective and efficient trigger, also for hadronic final states

---

"B mesons are the elephants of the particle zoo - they are heavy and they live long."

(T. Schietinger)
Key Features

- Impact parameter resolution
- Identify secondary vertices
- Proper time resolution
- Resolve fast $B_s^0$-$\bar{B}_s^0$ oscillations
- Momentum, invariant mass resolution
- Against combinatorial backgrounds
- Magnetic field reversed regularly to cancel detector asymmetries

- $K/\pi$ separation
  - Against peaking backgrounds
  - Flavour tagging
  - Selective and efficient trigger, also for hadronic final states
Overview

• Short introduction

• CP violation in $B^0_s \bar{B}^0_s$ mixing from semileptonic decays

• CP phase $\phi_s$ from $B^0_s \rightarrow J/\psi \phi$ and $B^0_s \rightarrow J/\psi \pi^+ \pi^-$

• CKM phase $\gamma$ from $B^\pm \rightarrow D K^\pm$ and $B^\pm \rightarrow D \pi^\pm$ Tree decays

• CP violation in charmless B decays ("$\gamma$ from loops")

• Summary and outlook: LHCb upgrade
CP violation in $B^0_s - \bar{B}^0_s$ mixing
Semileptonic Asymmetry

- remember, CP violated in $B^0_s - \bar{B}^0_s$ mixing if
  \[ \phi_M = \arg \left( -\frac{M_{12}^s}{\Gamma_{12}^s} \right) \neq 0 \]
  
- can be measured in semileptonic decay asymmetry
  \[ a_{s_{\text{sl}}} = \frac{\Gamma(B^0_s \to D^-_s \mu^+ X) - \Gamma(\bar{B}^0_s \to D^+_s \mu^- X)}{\Gamma(B^0_s \to D^-_s \mu^+ X) + \Gamma(\bar{B}^0_s \to D^+_s \mu^- X)} = \frac{\Delta \Gamma_s}{\Delta m_s} \tan \phi_M \]

($\Delta \Gamma_s$, $\Delta m_s$: lifetime and mass difference between the two mass eigenstates)

- predicted to be very small in Standard Model
  \[ a_{s_{\text{sl}}} = (1.9 \pm 0.3) \times 10^{-5} \quad [\text{A. Lenz, arXiv:1205.1444}] \]

- very sensitive to possible New Physics contributions in box diagram

- LHCb analysis of 1.0 fb$^{-1}$
  - 193k signal events
  - very low backgrounds

  [LHCb-CONF-2012-022]
Semileptonic Asymmetry

• LHC collides protons on protons
  • $B^0_s \bar{B}^0_s$ production asymmetry, $a_p \sim 1\%$
  • but: $a_p$ strongly diluted by the very rapid $B^0_s - \bar{B}^0_s$ oscillation

\[ A_{\text{raw}} = \frac{N(D_s^- \mu^+) - N(D_s^+ \mu^-)}{N(D_s^- \mu^+) + N(D_s^+ \mu^-)} = \frac{a_s^s}{2} + \frac{a_{sI}}{2} \times \frac{\int e^{-\Gamma s t} \cos(\Delta m_s t) \varepsilon(t) dt}{\int e^{-\Gamma s t} \cosh(\Delta \Gamma_s t/2) \varepsilon(t) dt} \]

• detection asymmetries: measured from data using various control channels
• also: look at data separately for the two magnet polarities

so $B^0_s$ mesons are NOT like elephants - they forget!

\[=2 \times 10^{-3} \text{ for LHCb acceptance} \varepsilon(t)\]
Semileptonic Asymmetry

- LHCb result

\[ a_{sl}^s = (-0.24 \pm 0.54 \text{(stat)} \pm 0.33 \text{(syst)}) \% \]

- most precise measurement to date
- consistent with Standard Model
- remember: D0 reports 2.9 \( \sigma \) deviation from Standard Model in measurement of like-sign dimuon asymmetry

\[ A_{\mu\mu} = \frac{N(\mu^+\mu^+)-N(\mu^-\mu^-)}{N(\mu^+\mu^+)+N(\mu^-\mu^-)} \approx 0.6 a_{sl}^s + 0.4 a_{sl}^d \]

for D0

[D0 collaboration, arXiv:1208.5813]

- LHCb and D0 results compatible with each other at < 2 \( \sigma \) level

06.12.2012
\( \phi_s \) from \( B^0_s \rightarrow J/\psi \phi \)

and \( B^0_s \rightarrow J/\psi \pi^+\pi^- \)
CP violation in $B^0_s \rightarrow J/\psi \phi$

- example for CP violation in interference between mixing and decay
- CP violating phase

$$\phi_s = \phi_M - 2\phi_D$$

- $\phi_s$ predicted to be very small in Standard Model
- $B^0_s - \bar{B}^0_s$ mixing phase $\phi_M$ expected to be very small
- decay dominated by Tree diagram with $\phi_D \sim 0$, only small contamination from Penguin

$$\phi_s = 0.036 \pm 0.002 \text{ rad}$$


- highly sensitive to New Physics contributions in $B^0_s - \bar{B}^0_s$ mixing

$\phi_D^{SM} = \arg(V_{cb}V_{cs}^*) \approx 0$

NP ?
**CP violation in $B^0_s \rightarrow J/\psi \phi$**

- time-dependent CP asymmetry for CP eigenstate $f$ with eigenvalue $\eta_f = \pm 1$

  $$A_{CP}(t) = \frac{\Gamma(B^0_s(t=0) \rightarrow f) - \Gamma(B^0_s(t=0) \rightarrow f)}{\Gamma(B^0_s(t=0) \rightarrow f) + \Gamma(B^0_s(t=0) \rightarrow f)} = \eta_f \sin\phi_s \sin(\Delta m_s t)$$

- need to determine flavour of $B_s$ meson at $t=0$ $\rightarrow$ mis-tag fraction $\omega_{\text{tag}}$
- need to resolve $B^0_s - \bar{B}^0_s$ oscillations $\rightarrow$ finite proper time resolution $\sigma_t$

  $$A_{CP}(t) \approx (1 - 2\omega_{\text{tag}}) e^{-\frac{1}{2} \Delta m_s^2 \sigma_t^2} \eta_f \sin\phi_s \sin(\Delta m_s t)$$

- final state in $B^0_s \rightarrow J/\psi \phi$ is a mix of CP even and odd ($L_{J/\psi \phi} = 0, 1, 2$)
  - three polarisation amplitudes, plus contribution from S-wave $K^+K^-$
  - time-dependent angular analysis to disentangle these and determine $\phi_s$
- finite lifetime difference $\Delta \Gamma_s$ between CP eigenstates in $B^0_s \bar{B}^0_s$ system
  - not well measured yet, needs to be determined simultaneously with $\phi_s$
CP violation in $B^0_s \to J/\psi \phi$

- opposite-side flavour tagging: imply $B^0_s$ flavour at production from decay properties of the associated $b$ hadron produced
  - neural net algorithm using charge of lepton, kaon, inclusive vertex
  - calibrated on flavour-specific decays such as $B^\pm \to J/\psi K^\pm$
- effective tagging power:

  $$\varepsilon_{\text{tag}} \times (1 - 2 \bar{\omega}_{\text{tag}})^2 = (2.35 \pm 0.06 (\text{stat})) \%$$

- same-side tagging (charge of $K^\pm$ from hadronisation chain) not yet used

06.12.2012

Kruger2012 - CPV @ LHCb (17/50)

O. Steinkamp
**CP violation in $B^0_s \to J/\psi \phi$**

- **time-dependent angular fit using transversity angles**
  \[ \Omega = (\theta = \theta_\mu, \phi = \phi_\mu, \psi = \theta_K) \]

- **full fit function:**
  \[
  \frac{d^4 \Gamma(B^0_s \to J/\psi \phi)}{dt \, d\Omega} \propto \sum_{k=1}^{10} h_k(t) \, f_k(\Omega)
  \]
  \[
  h_k(t) = N_k e^{-Gt} \left[ a_k \cosh \left( \frac{1}{2} \Delta \Gamma_s t \right) + b_k \sinh \left( \frac{1}{2} \Delta \Gamma_s t \right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t) \right]
  \]

<table>
<thead>
<tr>
<th>$k$</th>
<th>$f_k(\theta_\mu, \theta_K, \phi_K)$</th>
<th>$N_k$</th>
<th>$a_k$</th>
<th>$b_k$</th>
<th>$c_k$</th>
<th>$d_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$2 \cos^2 \theta_K \sin^2 \theta_\mu$</td>
<td>$</td>
<td>A_0(0)</td>
<td>^2$</td>
<td>1</td>
<td>$D$</td>
</tr>
<tr>
<td>2</td>
<td>$\sin^2 \theta_K (1 - \sin^2 \theta_\mu \cos^2 \phi_K)$</td>
<td>$</td>
<td>A_1(0)</td>
<td>^2$</td>
<td>1</td>
<td>$D$</td>
</tr>
<tr>
<td>3</td>
<td>$\sin^2 \theta_K (1 - \sin^2 \theta_\mu \sin^2 \phi_K)$</td>
<td>$</td>
<td>A_{1\perp}(0)</td>
<td>^2$</td>
<td>1</td>
<td>$-D$</td>
</tr>
<tr>
<td>4</td>
<td>$\sin^2 \theta_K \sin^2 \theta_\mu \sin 2\phi_K$</td>
<td>$</td>
<td>A_{1\parallel}(0)</td>
<td>^2$</td>
<td>$C \sin(\delta_{\parallel} - \delta_{\perp})$</td>
<td>$S \cos(\delta_{\parallel} - \delta_{\perp})$</td>
</tr>
<tr>
<td>5</td>
<td>$\frac{1}{2} \sqrt{2} \sin 2 \theta_K \sin 2 \theta_\mu \cos^2 \phi_K$</td>
<td>$</td>
<td>A_{1\perp}(0)</td>
<td>^2$</td>
<td>$\cos(\delta_{\parallel} - \delta_{\perp})$</td>
<td>$D \cos(\delta_{\parallel} - \delta_{\perp})$</td>
</tr>
<tr>
<td>6</td>
<td>$-\frac{1}{2} \sqrt{2} \sin 2 \theta_K \sin 2 \theta_\mu \sin \phi_K$</td>
<td>$</td>
<td>A_{1\parallel}(0)</td>
<td>^2$</td>
<td>$C \sin(\delta_{\parallel} - \delta_{\perp})$</td>
<td>$S \cos(\delta_{\parallel} - \delta_{\perp})$</td>
</tr>
<tr>
<td>7</td>
<td>$\frac{1}{2} \sqrt{3} \sin^2 \theta_\mu$</td>
<td>$</td>
<td>A_{1\perp}(0)</td>
<td>^2$</td>
<td>$1$</td>
<td>$-D$</td>
</tr>
<tr>
<td>8</td>
<td>$\frac{1}{2} \sqrt{6} \sin \theta_K \sin 2 \theta_\mu \cos \phi_K$</td>
<td>$</td>
<td>A_{1\parallel}(0)</td>
<td>^2$</td>
<td>$C \cos(\delta_{\parallel} - \delta_{\perp})$</td>
<td>$S \sin(\delta_{\parallel} - \delta_{\perp})$</td>
</tr>
<tr>
<td>9</td>
<td>$-\frac{1}{2} \sqrt{6} \sin \theta_K \sin 2 \theta_\mu \sin \phi_K$</td>
<td>$</td>
<td>A_{1\parallel}(0)</td>
<td>^2$</td>
<td>$\sin(\delta_{\parallel} - \delta_{\perp})$</td>
<td>$-D \sin(\delta_{\parallel} - \delta_{\perp})$</td>
</tr>
<tr>
<td>10</td>
<td>$\frac{3}{2} \sqrt{3} \cos \theta_K \sin^2 \theta_\mu$</td>
<td>$</td>
<td>A_{1\perp}(0)</td>
<td>^2$</td>
<td>$C \cos(\delta_{\parallel} - \delta_{\perp})$</td>
<td>$S \sin(\delta_{\parallel} - \delta_{\perp})$</td>
</tr>
</tbody>
</table>

- **physics parameters:**
  \[
  S \approx -\sin \phi_s; \quad D \approx -\cos \phi_s; \quad \Delta m_s; \quad \Delta \Gamma_s; \quad |A_{\parallel}|; \quad |A_{\perp}|; \quad |A_0|; \quad \delta_{\parallel}; \quad \delta_{\perp}; \quad \delta_0
  \]

- **two-fold ambiguity in solution:** fit function invariant under transformation
  \[
  (\phi_s, \Delta \Gamma_s, \delta_{\parallel}, \delta_{\perp}) \leftrightarrow (\pi - \phi_s, -\Delta \Gamma_s, 2\pi - \delta_{\parallel}, -\delta_{\perp})
  \]

06.12.2012

Kruger2012 - CPV @ LHCb (18/50)

O. Steinkamp
CP violation in $B_0^s \rightarrow J/\psi \phi$

- LHCb analysis based on 1.0 fb$^{-1}$
- 21k signal events
- World's largest sample
- Only few % background
- Angular fit cleanly separates CP even/odd components
- Different lifetimes clearly visible in fit projection

[06.12.2012] Kruger2012 - CPV @ LHCb (19/50) O. Steinkamp
CP violation in $B^0_s \rightarrow J/\psi \phi$

- Result consistent with Standard Model prediction

$$\phi_s = -0.001 \pm 0.101 \text{(stat)} \pm 0.027 \text{(syst)} \text{ rad}$$

- First observation (> 5 $\sigma$ significance) of $\Delta \Gamma_s \neq 0$

$$\Delta \Gamma_s = 0.116 \pm 0.018 \text{(stat)} \pm 0.006 \text{(syst)} \text{ ps}^{-1}$$

- Both results dominated by statistical uncertainties
Sign of $\Delta \Gamma_s$

- resolve two-fold ambiguity

$$(\phi_s, \Delta \Gamma_s, \delta_{\parallel}, \delta_{\perp}) \leftrightarrow (\pi - \phi_s, -\Delta \Gamma_s, 2\pi - \delta_{\parallel}, -\delta_{\perp})$$

("solution I")

looking at strong phase difference $\delta_{s\perp} = \delta_s - \delta_{\perp}$

between $K^+K^-$ P-wave and S-wave amplitudes as a function of $m(K^+K^-)$ around the $\phi(1020)$

- P-wave: going through $\phi(1020)$ resonance
  $\rightarrow$ expect rapid positive phase shift

- S-wave: non-resonant + tail from $f_0(980)$
  $\rightarrow$ expect no significant variation of phase

- LHCb analysis based on 0.37 fb$^{-1}$

- determine $\delta_{s\perp}$ in four $K^+K^-$ mass bins

solution corresponding to $\Delta \Gamma_s > 0$

selected with 4.7 $\sigma$ significance
\( \phi_s \) from \( B^0_s \rightarrow J/\psi \, \pi^+\pi^- \)

- dominated by \( f_0(980) \rightarrow \pi^+\pi^- \)
- from modified Dalitz-plot analysis:
  \[ \text{in } 775 < m(\pi^+\pi^-) < 1550 \text{ MeV}/c^2 \]

\( \phi_s \) measurement in \( B^0_s \rightarrow J/\psi \, \pi^+\pi^- \)
- based on \( \sim 7400 \) candidates from \( 1.0 \text{ fb}^{-1} \)
- lower BF than \( B^0_s \rightarrow J/\psi \phi \)
- but no angular analysis required

\[ \phi_s = -0.019^{+0.173}_{-0.174} \text{ (stat)} + 0.004_{-0.003} \text{ (syst)} \text{ rad} \]
\( \phi_s \) Combination and Comparison

- simultaneous fit of \( B_{s}^{0} \rightarrow J/\psi \phi \) and \( B_{s}^{0} \rightarrow J/\psi \pi^{+}\pi^{-} \)

\[
\phi_s = -0.002 \pm 0.083 \text{(stat)} \pm 0.027 \text{(syst)} \text{ rad}
\]

- most precise measurement to date

- excellent agreement with Standard Model prediction

- but still space for possible contribution from New Physics

- precision completely dominated by statistical uncertainty

- expect significant improvement with more data
Some tension between $\phi_s$ measurements and dimuon asymmetry from D0
CKM angle $\gamma$
from Tree Decays
CKM angle $\gamma$ from Tree Decays

- CKM fits so far a huge success story for the Standard Model
- need more precise measurements to test for subtle effects from New Physics
- least well constrained CKM parameter by direct measurement:
  \[\gamma = \arg \left(\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}\right)\]

  $\gamma = (66 \pm 12)^\circ$ \[\text{[CKMfitter]}\]
  $\gamma = (72 \pm 9)^\circ$ \[\text{[UTfit]}\]

- Tree-level B decays: theoretically “clean” measurement of $\gamma$
  - no loops $\rightarrow$ largely unaffected by possible effects from New Physics
  - but experimentally very challenging
    - purely hadronic final states ($\rightarrow$ trigger, $K/\pi$ separation)
    - small branching fractions ($\rightarrow$ need large number of B's)

06.12.2012
Kruger2012 - CPV @ LHCb (26/50)

O. Steinkamp
CKM angle $\gamma$ from Tree Decays

- **time-integrated methods:** exploit interference of
  \[ B^\pm \rightarrow D^0 K^\pm \rightarrow [f]_D K^\pm \quad \text{and} \quad B^\pm \rightarrow \bar{D}^0 K^\pm \rightarrow [f]_D K^\pm, \]
  where final state $[f]_D$ is accessible to $D^0$ and $\bar{D}^0$

- **GLW:** CP eigenstates $D^0 \rightarrow K^+K^-$, $D^0 \rightarrow \pi^+\pi^-$

- **ADS:** favoured $D^0 \rightarrow K^+\pi^- / suppressed D^0 \rightarrow K^-\pi^+$

- **GGSZ:** Dalitz-plot analysis of 3-body $D^0 \rightarrow K^0_s \pi^+\pi^-$

$r_B \sim 0.1$

$r_B \sim 1$ for GLW, $\sim 0.05$ for ADS

combined analysis of all modes to extract $\gamma$ and hadronic parameters $r_B$, $\delta_B$, $r_D$, $\delta_D$
\( \gamma \) from Trees: GLW modes

- form ratios and asymmetries of decay rates \( \rightarrow \) cancellation of systematics

\[
R_{CP^+} = \frac{\Gamma(B^- \to [h^+h^-]_bK^-) + \Gamma(B^+ \to [h^+h^-]_bK^+)}{1/2 \cdot \left[ \Gamma(B^- \to [K^+\pi^-]_bK^-) + \Gamma(B^+ \to [K^-\pi^+]_bK^+) \right]} = 1 + r_B^2 + 2r_B \cos \delta_B \cdot \cos \gamma
\]

\[
A_{CP^+} = \frac{\Gamma(B^- \to [h^+h^-]_bK^-) - \Gamma(B^+ \to [h^+h^-]_bK^+)}{\Gamma(B^- \to [h^+h^-]_bK^-) + \Gamma(B^+ \to [h^+h^-]_bK^+)} = + \frac{2 \cdot r_B \cos \delta_B \cdot \cos \gamma}{R_{CP^+}}
\]

- LHCb analysis of 1.0 fb\(^{-1}\)
- clear asymmetry in \( B^\pm \to DK^\pm \) and (as expected) no asymmetry in \( B^\pm \to D\pi^\pm \)

\[
A_{CP^+}(KK) = (-14.8 \pm 3.7 \pm 1.0) \%
\]

\[
A_{CP^+}(\pi\pi) = (-13.5 \pm 6.6 \pm 1.0) \%
\]
γ from Trees: ADS modes

- ratios and asymmetries of decay rates to flavour-specific final states

$$R_{\text{ADS}} = \frac{\Gamma(B^- \to [K^+\pi^-]_d K^-) + \Gamma(B^+ \to [K^-\pi^+]_d K^+)}{\Gamma(B^- \to [K^-\pi^+]_d K^-) + \Gamma(B^+ \to [K^+\pi^-]_d K^+)} = r_B^2 + r_D^2 + 2 \cdot r_B r_D \cos(\delta_B + \delta_D) \cos \gamma$$

$$A_{\text{ADS}} = \frac{\Gamma(B^- \to [K^+\pi^-]_d K^-) - \Gamma(B^+ \to [K^-\pi^+]_d K^+)}{\Gamma(B^- \to [K^-\pi^+]_d K^-) + \Gamma(B^+ \to [K^+\pi^-]_d K^+)} = 2 \cdot \frac{r_B r_D \sin(\delta_B + \delta_D) \cdot \sin \gamma}{R_{\text{ADS}}}$$

- LHCb analysis of 1.0 fb⁻¹
- first observation of the rare ADS decay (10 σ significance)
- evidence for asymmetry in $B^\pm \to DK^\pm$ (4 σ significance)

$$A_{\text{ADS}}(DK) = (-52 \pm 15 \pm 2) \%$$

- hint for asymmetry also in $B^\pm \to D\pi^\pm$ (2.4 σ significance)

$$A_{\text{ADS}}(D\pi) = (-14.3 \pm 6.2 \pm 1.1) \%$$
γ from Trees: $D \rightarrow \pi K\pi\pi$

- similar to 2-body ADS, but different values of $r_D$ and $\delta_D$

- add statistics but also new information

- LHCb analysis of 1.0 fb$^{-1}$:
- first observation of rare ADS decays (10 $\sigma$ in $B^\pm \rightarrow D\pi^\pm$, 5.1 $\sigma$ in $B^\pm \rightarrow D\pi^\pm$)

$$R_{ADS}(DK) = (1.24 \pm 0.27)\%$$

$$A_{ADS}(DK) = (4.2 \pm 2.2)\%$$

$$R_{ADS}(D\pi) = (0.369 \pm 0.036)\%$$

$$A_{ADS}(D\pi) = (13 \pm 10)\%$$

- systematics small, dominated by
  - particle identification (R)
  - production, interaction, detection asymmetries (A)

06.12.2012

Kruger2012 - CPV @ LHCb (30/50)

O. Steinkamp

[LHCb-CONF-2012-030]
preliminary

for all “γ from Trees” analyses
γ from Trees: LHCb Impact

\[ R_{CP} \text{ Averages} \]

- **BaBar**: 1.18 ± 0.09 ± 0.05
- **Belle**: 1.03 ± 0.07 ± 0.03
- **CDF**: 1.30 ± 0.24 ± 0.12
- **LHCb**: 1.01 ± 0.04 ± 0.01
- **Average**: 1.03 ± 0.03

\[ R_{ADS} \text{ Averages} \]

- **BaBar**: 0.011 ± 0.006 ± 0.002
- **Belle**: 0.015 ± 0.004 ± 0.001
- **CDF**: 0.022 ± 0.005 ± 0.003
- **LHCb**: 0.015 ± 0.002 ± 0.000
- **Average**: 0.015 ± 0.002

\[ A_{CP} \text{ Averages} \]

- **BaBar**: 0.25 ± 0.06 ± 0.02
- **Belle**: 0.29 ± 0.06 ± 0.02
- **CDF**: 0.39 ± 0.17 ± 0.04
- **LHCb**: 0.14 ± 0.03 ± 0.01
- **Average**: 0.19 ± 0.03

\[ A_{ADS} \text{ Averages} \]

- **BaBar**: -0.86 ± 0.47 ± 0.12
- **Belle**: -0.39 ± 0.25 ± 0.04
- **CDF**: -0.82 ± 0.44 ± 0.09
- **LHCb**: -0.52 ± 0.15 ± 0.02
- **Average**: -0.54 ± 0.12
\( \gamma \) from Trees: GGSZ

- exploit interference patterns in \( D^0 \to K^0_s h^+ h^- \) Dalitz plot (\( h=\pi, K \))
- powerful method, dominates precision on \( \gamma \) from B factories
- complication: strong phase difference \( \delta_D \) varies across Dalitz plot
- rich resonance structure, difficult to model correctly
- model-independent approach chosen to minimize systematics:
  - divide Dalitz plot into regions of \( \sim \) constant \( \delta_D \) using input from CLEO measurements

\[ N_i(B^\pm) = K^\pm,i + (x^2 + y^2) K^\pm,i + 2 \sqrt{K^+_i K^-_i} \left\{ x^\pm \cos \delta_{D,i} + y^\pm \sin \delta_{D,i} \right\} \]

- asymmetries measured in flavour-specific D decays
  \[ x^\pm = r^B \cdot \cos (\delta^B \pm \gamma) \]
  \[ y^\pm = r^B \cdot \sin (\delta^B \pm \gamma) \]
  measured by CLEO

\[ \text{[PRD82 (2010) 112006]} \]
γ from Trees: GGSZ

- LHCb analysis of 1.0 fb$^{-1}$
  - $\sim 650$ B$^\pm \rightarrow [K^0_s\pi^+\pi^-]_D K^\pm$ candidates
  - $\sim 100$ B$^\pm \rightarrow [K^0_sK^+K^-]_D K^\pm$ candidates
- precision on $x^\pm$, $y^\pm$ similar to B factories
- systematic uncertainty dominated by assumption of no CPV in $B \rightarrow D\pi$ (used to determine efficiencies)

\[
x^- = (0.0 \pm 4.3 \pm 1.5 \pm 0.6) \%
\]
\[
y^- = (2.7 \pm 5.2 \pm 0.8 \pm 2.3) \%
\]
\[
x^+ = (-10.3 \pm 4.4 \pm 1.8 \pm 1.4) \%
\]
\[
y^+ = (-0.9 \pm 3.7 \pm 0.8 \pm 3.0) \%
\]
\[ \langle \gamma \rangle = \left( 71^{+16}_{-15} \right) ^\circ \]

- LHCb \( \gamma \) average from combination of \( B^\pm \rightarrow D K^\pm \)
- using frequentist approach to combine the shown results from
  - GLW/ADS \( B^\pm \rightarrow [h^+h^-]_d K^\pm \) [PLB 713 (2012) 351]
  - ADS 4-body \( B^\pm \rightarrow [\pi K \pi \pi]_d K^\pm \) [LHCb-CONF-2012-030]
  - GGSZ \( B^\pm \rightarrow [K^0_s h^+h^-]_d K^\pm \) [PLB 718 (2012) 43]

- precision already comparable with \( \gamma \) averages from B factories
  - Babar: \( \gamma = \left( 69^{+17}_{-16} \right) ^\circ \)
  - Belle: \( \gamma = \left( 68^{+15}_{-14} \right) ^\circ \)

\[ [43.9^\circ - 98.8^\circ] @ 95\% C.L. \]
Charmless $B$ decays: towards $\gamma$ from Loops
\( \gamma \) from Loops

- 2-body charmless B decays: \( \gamma \) from interference of \( b \to u \) Tree diagrams and \( b \to s(d) \) Penguin diagrams
- sensitive to possible New Physics contribution in Penguin loops
- hadronic uncertainties can be controlled using U-Spin symmetry between \( B^0 \) and \( B^0_s \) decays

\[ \text{[Fleischer, EPJC 52 (2007) 267]} \]

- two approaches:
  - time-dependent CP asymmetry in \( B^0 \to \pi^+\pi^- \) and \( B^0_s \to K^+K^- \)
  - time-integrated CP asymmetry in \( B^0 \to K^+\pi^- \) and \( B^0_s \to \pi^+K^- \)
  - also: time-integrated CP asymmetry in 3-body charmless \( B^{\pm} \) decays
**Time-dependent CPV in $B^0_{(s)} \to h^+h^-$**

- measure time-dependent asymmetry of decay rates

$$A_{CP}(t) = \frac{\Gamma(B^0_{(s)}(t=0) \to f) - \Gamma(B^0_{(s)}(t=0) \to f)}{\Gamma(B^0_{(s)}(t=0) \to f) + \Gamma(B^0_{(s)}(t=0) \to f)} = \frac{A_{f}^{dir} \cos(\Delta m_{(s)} t) + A_{f}^{mix} \cos(\Delta m_{(s)} t)}{\cosh(\Delta \Gamma_{(s)} t/2) - A_{f}^{\Delta \Gamma} \sinh(\Delta \Gamma_{(s)} t/2)}$$

- use flavour tagging algorithms to determine flavour of $B^0_{(s)}$ at production

- LHCb analysis of 0.69 fb$^{-1}$

- fix values of $\Delta m_d$ and $\Delta m_s$ and sign of $\Delta \Gamma_s$ to previous LHCb measurements

- use $B^0 \to K^+\pi^-$ to calibrate tagging and determine mis-tag probability

---

**First $B^0 \to \pi^+\pi^-$ asymmetry at a hadron collider**

**First $B^0_s \to K^+K^-$ asymmetry ever**

06.12.2012  Kruger2012 - CPV @ LHCb (37/50)  O. Steinkamp
Time-dependent CPV in $B^0_{(s)} \rightarrow h^+h^-$

$A^\text{dir}_{\pi\pi} = 0.11 \pm 0.21 \pm 0.03$

$A^\text{mix}_{\pi\pi} = -0.56 \pm 0.17 \pm 0.03$

$LHCb$ preliminary

- $A^\text{dir}_{\pi\pi}$ result favours Babar $[\text{arXiv:0807.4226}]$ over Belle $[\text{PRL 98 (2007) 211801}]$

$B^0 \rightarrow \pi^+\pi^-$

$B^0_{(s)} \rightarrow K^+K^-$

$A^\text{dir}_{KK} = 0.02 \pm 0.18 \pm 0.04$

$A^\text{mix}_{KK} = 0.17 \pm 0.18 \pm 0.05$

$LHCb$ preliminary

06.12.2012

Kruger2012 - CPV @ LHCb (38/50)

O. Steinkamp
Direct CP Violation in $B^0_{(s)} \rightarrow K\pi$

- time-integrated asymmetry of decay rates to flavour-specific final states

$$A_{CP} = \frac{\Gamma(B^0_{(s)} \rightarrow f) - \Gamma(\overline{B}^0_{(s)} \rightarrow \bar{f})}{\Gamma(B^0_{(s)} \rightarrow f) + \Gamma(\overline{B}^0_{(s)} \rightarrow \bar{f})}$$

- LHCb analysis of 0.35 fb$^{-1}$
- $B^0 \rightarrow K^+\pi^- / \overline{B}^0 \rightarrow K^-\pi^+$
  $$A_{CP} = (-0.088 \pm 0.011 \pm 0.008)$$
  $> 6 \sigma$: first observation of CP violation at a hadron collider

- $B^0_s \rightarrow K^-\pi^+ / \overline{B}^0_s \rightarrow K^+\pi^-$
  $$A_{CP} = (0.27 \pm 0.08 \pm 0.02)$$
  $3.2 \sigma$: first evidence for CP violation in the $B^0_s$ system

- production/detection asymmetries small, corrected using control channels
- dominating systematic: different $K^+/K^-$ interaction cross-sections

06.12.2012  Kruger2012 - CPV @ LHCb (39/50)  O. Steinkamp
CP Violation in 3-body $B^\pm$ decays

• again, interference of $b \to u$ Tree transitions and $b \to s(d)$ Penguins

$$ A_{CP} = \frac{\Gamma(B^- \to f^-) - \Gamma(B^+ \to f^+)}{\Gamma(B^- \to f^-) + \Gamma(B^+ \to f^+)} \left\{ \begin{array}{l} K^\pm \pi^+ \pi^-, K^\pm K^+ K^- \\ \pi^\pm \pi^+ \pi^-, K^+ K^- \pi^\pm \end{array} \right. $$

• LHCb analyses using 1.0 fb$^{-1}$
• measure production and detection asymmetries from $B^\pm \to J/\psi K^\pm$

$A_{CP}(K^\pm \pi^+ \pi^-) = 0.034 \pm 0.009 \pm 0.004 \pm 0.007$

$A_{CP}(K^\pm K^+ K^-) = 0.046 \pm 0.009 \pm 0.005 \pm 0.007$

$A_{CP}(\pi^+ \pi^- \pi^\pm) = 0.120 \pm 0.020 \pm 0.019 \pm 0.007$

$A_{CP}(K^+ K^- \pi^\pm) = -0.153 \pm 0.046 \pm 0.019 \pm 0.007$

06.12.2012

Kruger2012 - CPV @ LHCb (40/50)

O. Steinkamp

[LHCb-CONF-2012-018]
[LHCb-CONF-2012-028]
CP Violation in 3-body $B^\pm$ decays

- analyses also performed as a function of phase space
- subdivide Dalitz plots into bins of ~ equal population
- determine asymmetry in each bin
- observe large local asymmetries in all four channels
- interpretation pending (not related to intermediate resonances)

$LHCb$ Preliminary

$B^\pm \rightarrow K^\pm K^- \pi^\pm$

$B^-$

$B^+$

$\Delta\text{CP}$

$06.12.2012$  
Kruger2012 - CPV @ LHCb (41/50)  
O. Steinkamp
Conclusion and Outlook
Conclusion

- LHC and LHCb are a spectacular success
- so is the Standard Model
  … up to now
- but current precision of measurements still leaves lots of room for sub-dominant contributions from New Physics
Outlook: LHCb Upgrade

- LHC and LHCb are a spectacular success
- so is the Standard Model
  ... still
- current precision of measurements still leaves lots of room for sub-dominant contributions from New Physics
- almost all LHCb results are completely dominated by statistical uncertainties
- leading systematic uncertainties will also decrease with increasing statistics

Need more statistics
⇒ THE LHCb UPGRADE!

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>0.037 fb$^{-1}$ @ 7 TeV</td>
</tr>
<tr>
<td>2011</td>
<td>1 fb$^{-1}$ @ 7 TeV</td>
</tr>
<tr>
<td>2012</td>
<td>2 fb$^{-1}$ @ 8 TeV</td>
</tr>
<tr>
<td>2013</td>
<td>LHC LS1</td>
</tr>
<tr>
<td>2014</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>5 fb$^{-1}$ @ 13 TeV</td>
</tr>
<tr>
<td>2017</td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>LHC LS2, LHCb upgrade</td>
</tr>
<tr>
<td>2019</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td></td>
</tr>
<tr>
<td>2021</td>
<td>5 fb$^{-1}$ per year</td>
</tr>
<tr>
<td>2022</td>
<td></td>
</tr>
</tbody>
</table>
**LHCb Upgrade**

- **goal:** reach measurement precision that matches theory uncertainties

<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>$B_s^0$ mixing</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>$A_{fs}(B_s^0)$</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>Gluonic penguin</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>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi K_s^0)$</td>
<td>0.17 [18]</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</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>Electroweak penguin</td>
<td>$S_3 (B^0 \rightarrow K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</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>$A_1 (K \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.25 [15]</td>
<td>0.08</td>
<td>0.025</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-)/\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)$</td>
<td>25% [16]</td>
<td>8%</td>
<td>2.5%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$</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>$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$</td>
<td>–</td>
<td>$\sim 100%$</td>
<td>$\sim 35%$</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>$\gamma (B \rightarrow D^{(<em>)} K^{(</em>)})$</td>
<td>$\sim 10–12%$ [19, 20]</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma (B_s^0 \rightarrow D_s K)$</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>Charm $CP$ violation</td>
<td>$A_T$</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></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>

**06.12.2012**

*Kruger2012 – CPV @ LHCb (45/50)*

O. Steinkamp
Upgrade

- two lines of attack
  - increase trigger efficiencies for hadronic final states
    - read out the full detector at the LHC bunch-crossing frequency
  - operate the detector at up to $\times 5$ higher luminosity
    - new main tracker to cope with increase in particle densities

expected increase in rate (compared to 2011):
- $\times 10$ for channels involving final-state muons
- $\times 20$ for channels to fully hadronic final states

- details are described in
  - Letter of Intent [CERN-LHCC-2011-001]
  - Framework TDR [CERN-LHCC-2012-007]
  - endorsed by the LHCC
Reminder: Current LHCb Trigger

**Hardware level (L0):**
- maximum output rate 1 MHz
- typical thresholds 2012:
  - $E_T(e/\gamma) > 2.7 \text{ GeV}$
  - $E_T(h) > 3.6 \text{ GeV}$
  - $p_T(\mu) > 1.4 \text{ GeV}$

**Software level (HLT):**
- ~ 30000 tasks in parallel on ~ 1500 nodes

**Combined efficiency (L0+HLT):**
- ~ 90% for di-muon channels
- ~ 30% for multi-body hadronic final states

**Offline processing:**
- ~ $10^{10}$ events, 700 TB recorded per year
Upgrade

- 2012/2013: R&D, technology choices, preparation of sub-system TDRs
- 2014: funding, procurements
- 2015-2019: construction and installation
The engine is running,
the safari has
only just begun
fetch your binoculars
and join the party
Not Mentioned ...

- $B^0_s \rightarrow K K$ effective lifetime
- $B^0_s \rightarrow J/\psi f_0$ effective lifetime
  - both sensitive to new physics in $B^0_s - \bar{B}^0_s$ mixing
- BF ($B^0_s \rightarrow J/\psi \eta'$)
  - another channel to measure $\phi_s$
- BF ($B^0_s \rightarrow J/\psi K^{0*}$)
  - to estimate penguin contamination in $J/\psi$ phi
- GLW-type analysis of $B^0 \rightarrow D K^{*0}$
- Time-dependent CP violation in $B^0_s \rightarrow D_s K^\pm$
  - other channels to measure gamma from Trees
- BF ($B^0_s \rightarrow D_s D_s$)
- CP violation in $B_0 \rightarrow K^{*0} \mu^+ \mu^-$
- CP violation in $B_0 \rightarrow K^{*0} \gamma$
- $\Delta A_{CP}$ (CP violation in $D \rightarrow h^+ h^-$)

Eugeni's talk on Tuesday

[PLB 716 (2012) 393]
[PRD 86 (2012) 071102]
[LHCb-CONF-2012-024]
[LHCb-CONF-2012-029]
[LHCb-CONF-2012-009]
[LHCb-CONF-2012-024]
[arXiv:1210.2631]
[arXiv:1210.4492]
[arXiv:1210.2631]
[Nucl Phys B 867 (2013) 1]
[PRL 108 (2012) 111602]