B→hh status

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on behalf of the LHCb collaboration
Motivation

Why do we want to study these decays?
Sensitive to New physics contributions
Loop level determination of weak phase $\gamma$
and mixing phases $\Phi_s, \Phi_d$.
Test U-spin symmetry.
Contribution to $A_{cp} K\pi$ -puzzle.

What channels can we use?
$B_d \rightarrow K\pi^*$, $B_d \rightarrow \pi\pi^*$, $B_d \rightarrow KK$, $B_d \rightarrow pK$.
$B_s \rightarrow \pi K^*$, $B_s \rightarrow \pi\pi$, $B_s \rightarrow KK^*$,
$B_s \rightarrow pK, \Lambda_b \rightarrow p\pi$, $\Lambda_b \rightarrow pK$ etc.

What information can we get?
Branching Ratios*
Time-integrated CP asymmetries ($A_{cp}$)*
Time-dependent CP asymmetries ($A(t)$)*
Effective lifetime
Triple decay asymmetries and polarization amplitudes

$$A_{cp} = \frac{\Gamma_{\bar{B} \rightarrow f} - \Gamma_{B \rightarrow f}}{\Gamma_{\bar{B} \rightarrow f} + \Gamma_{B \rightarrow f}}$$

$$A(t) = \frac{\Gamma_{\bar{B} \rightarrow f}(t) - \Gamma_{B \rightarrow f}(t)}{\Gamma_{\bar{B} \rightarrow f}(t) + \Gamma_{B \rightarrow f}(t)}$$

* In this talk
$\mathcal{L} = 1 \text{ fb}^{-1}$

$B_d \rightarrow K \pi$, $B_s \rightarrow \pi K$ Time-integrated $CP$ asymmetries

Raw Asymmetries

Event selection is cut-based and tuned to have better sensitivities for the CP violation variables. Exclusive event samples selected under $\pi \pi, K \pi, KK, pK, p \pi$ daughter mass hypothesis.

PID calibration is performed on data using $D^* \rightarrow D_0(K \pi) \pi$ and $\Lambda_b \rightarrow p \pi$ decays.

Maximum Likelihood fit is performed simultaneously to all the samples (additional samples are fixing the cross-feed backgrounds contributions under the signal peaks). The measured observable is

$$A_{\text{raw}}(B^0 \rightarrow K^+ \pi^-) = -0.091 \pm 0.006$$

$$A_{\text{raw}}(B_s^0 \rightarrow K^- \pi^+) = 0.28 \pm 0.04$$

The extracted asymmetries are, in fact, “raw” asymmetries (depend on the $B$ production asymmetries and detection asymmetries).
Corrections

We correct raw results using the following formula:

\[ A_{CP} = A^{\text{raw}} - A_{\Delta} \]

\[ A_{\Delta} = \zeta A_D - \kappa A_P \]

Detection asymmetry part: estimated from the tagged and untagged decays of \( D \to hh \), \( \zeta = +1 \) for \( B_d \) and \( \zeta = -1 \) for \( B_s \).

\[ A_D(B_d \to K\pi) = (-1.15 \pm 0.23)\% \]
\[ A_D(B_s \to K\pi) = (-1.22 \pm 0.21)\% \]

Production asymmetry part: determined from fits to untagged decay time spectra, \( \kappa \) takes mixing into account.

\[ A_{\Delta}(B_d) = (-1.12 \pm 0.23 \pm 0.30)\% \]
\[ A_{\Delta}(B_s) = (1.09 \pm 0.21 \pm 0.26)\% \]

\[ A_P(B^0) = (0.1 \pm 1.0)\% \]

\[ A_P(B_s) = (4 \pm 8)\% \]
Results

Most precise to date (10.5 $\sigma$ significance):

$$A_{CP}(B^0 \rightarrow K^+\pi^-) = -0.080 \pm 0.007 \text{ (stat)} \pm 0.003 \text{ (syst)}$$

First observation of CP violation in $B_s$ (6.5 $\sigma$ significance):

$$A_{CP}(B^0_s \rightarrow K^-\pi^+) = 0.27 \pm 0.04 \text{ (stat)} \pm 0.01 \text{ (syst)}.$$
$\mathcal{L} = 1 \text{ fb}^{-1} (2011)$
$2 \text{ fb}^{-1} (2012)$

$B \to K_s \gamma$ Time-integrated $CP$ asymmetries
Event selection is Boosted-Decision Tree based and tuned to have better sensitivities for the CP violation variables in each channel.

PID calibration is performed on data using $D^* \to D^0(K\pi)\pi$ decays.

Selection efficiencies from Monte Carlo

Correction of raw asymmetries:
Production and detection asymmetry: taken from $B^+ \to J/\psi K$ decays.

Ks related:
- CP violation in $K_S$
- $K_S$ regeneration from $K_L$ interaction with the detector

We obtain

$$A_{\text{raw}}(B^+ \to K_S\pi^+) = -0.032 \pm 0.025$$
$$A_{\text{raw}}(B^+ \to K_S K^+) = -0.23 \pm 0.14$$
Branching Fractions and results

Full results of the study are

\[
\frac{B(B^+ \to K_s^0 K^+)}{B(B^+ \to K_s^0 \pi^+)} = 0.064 \pm 0.009 \text{ (stat.)} \pm 0.004 \text{ (syst.)},
\]

\[
A^{CP}(B^+ \to K_s^0 \pi^+) = -0.022 \pm 0.025 \text{ (stat.)} \pm 0.010 \text{ (syst.)},
\]

\[
A^{CP}(B^+ \to K_s^0 K^+) = -0.21 \pm 0.14 \text{ (stat.)} \pm 0.01 \text{ (syst.)}.
\]

We also search for the $B_c \to K_s K$ decays (using 1 fb$^{-1}$) with retuned BDT selection. We find 2.8 signal events. Feldman-Cousin’s method has been used to estimate confidence intervals.

Weibull distribution

\[
f_c \cdot \frac{B(B_c^+ \to K_s^0 K^+)}{B(B^+ \to K_s^0 \pi^+)} < 5.8 \times 10^{-2}
\]

\[
\frac{f_c}{f_u} \cdot \frac{B(B_c^+ \to K_s^0 K^+)}{B(B^+ \to K_s^0 \pi^+)} < 5.8 \times 10^{-2}
\]

\[
\begin{array}{c|cc}
\text{BaBar, } 10^{-2} & \text{Belle, } 10^{-2} \\
\hline
A^{CP}(B^+ \to K_s \pi) & -2.9 \pm 3.9 \pm 1.0 & -1.1 \pm 2.1 \pm 0.6 \\
A^{CP}(B^+ \to K_s K) & 10 \pm 26 \pm 3 & 1.4 \pm 16.8 \pm 0.2 \\
\end{array}
\]

\[m_{B_c}^{PDG} = 6.274 \text{ GeV}/c^2\]

LHCb Preliminary

Candidates / (0.02 GeV/c$^2$) vs $K_s^0 K^+$ invariant mass [GeV$/c^2$]
$\mathcal{L} = 1 \text{ fb}^{-1}$

$B_d \rightarrow \pi \pi, B_s \rightarrow KK$ Time-dependent $CP$ asymmetries
CP asymmetry as a function of time for neutral $B$ mesons decaying to a CP eigenstate $f$ is given by

$$A(t) = \frac{\Gamma_{B(s)}^{0 \to f} \cdot t - \Gamma_{B(s)}^{0 \to f} \cdot t}{\Gamma_{B(s)}^{0 \to f} \cdot t + \Gamma_{B(s)}^{0 \to f} \cdot t} = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh \left( \frac{\Delta \Gamma_{d(s)} t}{2} \right) - A_f \Delta \Gamma \sinh \left( \frac{\Delta \Gamma_{d(s)} t}{2} \right)}$$

with $\Delta m_{d(s)} = m_{d(s), II} - m_{d(s), L}$ and $\Delta \Gamma_{d(s)} = \Gamma_{d(s), L} - \Gamma_{d(s), II}$

To obtain $C_f$ and $S_f$ we need to tag initial flavour of $B$ meson.
In this analysis, we exploit the decay products of the other $b$ hadron: lepton ($e$ or $\mu$); kaon; overall charge of secondary vertex (“opposite side” tags).

Tagging performance: mistag rate, $\omega_{\text{mistag}}$, tagging efficiency, $\varepsilon_{\text{tag}}$.
Neural Network determines $\omega_{\text{mistag}}$, which is than calibrated on the data sample.

Tagging and Decay time studies

Samples divided into categories of predicted mistag. Simultaneous invariant mass and decay fit with $B \rightarrow K \pi$ decays to calibrate the neural network performance.

Calibration of flavour tagging response: $\epsilon = (2.45 \pm 0.25)\%$

We also obtain production asymmetry $A_p(B^0) = (0.6 \pm 0.9)\%$ and $A_p(B_s^0) = (7 \pm 5)\%$

For $B_s \rightarrow K K$ study, the decay time resolution plays important role (as it is comparable to oscillation period). We estimate this quantity using $Y(nS), J/\Psi$, and $\psi(2S) \rightarrow \mu \mu$ data and Monte Carlo samples: $\sigma_t = 50 \pm 5 \text{ fs}$
We perform a 2D Maximum Likelihood fit to mass and time. Tagging parameters and production asymmetry are propagated from $K\pi$ fit using gaussian priors.

$$C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02,$$
$$S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02,$$
$$\rho(C_{\pi\pi}, S_{\pi\pi}) = 0.38$$

$$C_{KK} = 0.14 \pm 0.11 \pm 0.03,$$
$$S_{KK} = 0.30 \pm 0.12 \pm 0.04,$$
$$\rho(C_{KK}, S_{KK}) = 0.02$$
U-spin tests and previous results

Our results are in agreement with previous studies by BaBar and Belle in $B_d \rightarrow \pi\pi$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$C_{\pi\pi}$</th>
<th>$S_{\pi\pi}$</th>
<th>$\rho(C_{\pi\pi}, S_{\pi\pi})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>$-0.25 \pm 0.08 \pm 0.02$</td>
<td>$-0.68 \pm 0.10 \pm 0.03$</td>
<td>$-0.06$</td>
</tr>
<tr>
<td>Belle</td>
<td>$-0.33 \pm 0.06 \pm 0.03$</td>
<td>$-0.64 \pm 0.08 \pm 0.03$</td>
<td>$-0.10$</td>
</tr>
</tbody>
</table>

$B_s \rightarrow KK$ is the first time measurement.

Taking into account U-spin symmetry we are able to obtain CKM angle $\gamma$ using our experimental results (see talk by Paolo Gandini). Some other useful relations can be tested using also the time-integrated analysis.

In case of exact U-spin symmetry:

\[
\Delta = \frac{A_{\text{CP}}(B^0 \rightarrow K^+\pi^-)}{A_{\text{CP}}(B^0 \rightarrow K^-\pi^+)} + \frac{B(B_s^0 \rightarrow K^-\pi^+)}{B(B^0 \rightarrow K^+\pi^-)} \frac{\tau_d}{\tau_s} = 0
\]

Using LHCb results for branching ratios [JHEP 10 (2012) 037]:

\[
\Delta = -0.02 \pm 0.05 \pm 0.04
\]

Moreover, time-integrated and time-dependent results are related:

\[
C(B_d \rightarrow \pi\pi) = -0.38 \pm 0.15 \pm 0.02 \sim -A_{\text{CP}}(B_s \rightarrow \pi K) = -0.27 \pm 0.04 \pm 0.01
\]

\[
C(B_s \rightarrow KK) = 0.14 \pm 0.11 \pm 0.03 \sim -A_{\text{CP}}(B_d \rightarrow K\pi) = 0.080 \pm 0.007 \pm 0.003
\]
Evidence of baryonic decays $B \rightarrow pp$
The decay has never been observed before.

All theory predictions point to branching fraction $\sim 10^{-7}$.

We measure the ratio of decays of interest to $B \rightarrow K \pi$

$$B(B^0 \rightarrow p\bar{p}) = \frac{N(B^0 \rightarrow p\bar{p})}{N(B^0 \rightarrow K^{+}\pi^{-})} \cdot \frac{\epsilon_{B^0 \rightarrow K^{+}\pi^{-}}}{\epsilon_{B^0 \rightarrow p\bar{p}}} \cdot B(B^0 \rightarrow K^{+}\pi^{-})$$

Efficiency is taken from simulated events, other quantities are measured by LHCb.

Using Feldman-Cousins approach

\begin{align*}
B(B^0 \rightarrow p\bar{p}) &= (1.47^{+0.62}_{-0.51}^{+0.35}_{-0.14}) \times 10^{-8} \text{ at } 68.3\% \text{ CL} \\
B(B^0 \rightarrow p\bar{p}) &= (1.47^{+1.09}_{-0.81}^{+0.69}_{-0.18}) \times 10^{-8} \text{ at } 90\% \text{ CL} \\
B(B_s^0 \rightarrow p\bar{p}) &= (2.84^{+2.03}_{-1.68}^{+0.85}_{-0.18}) \times 10^{-8} \text{ at } 68.3\% \text{ CL} \\
B(B_s^0 \rightarrow p\bar{p}) &= (2.84^{+3.57}_{-2.12}^{+2.00}_{-0.21}) \times 10^{-8} \text{ at } 90\% \text{ CL}
\end{align*}
LHCb have provided several results in the field:

Time integrated $B \rightarrow K \pi$:
- $B_d \rightarrow K \pi$: world’s best (10$\sigma$) significance of the direct CP asymmetry.
- $B_s \rightarrow \pi K$: first observation of direct CP asymmetry (6$\sigma$).
- $B_u \rightarrow K_s h$: world leading measurement

Time dependent $B \rightarrow \pi \pi /KK$:
- $B_d \rightarrow \pi \pi$: measurement in agreement with B-factories results.
- $B_s \rightarrow KK$: first ever measurement in this channel

Rare decays:
- $B_d \rightarrow pp$ first evidence of the decay.
- $B_c \rightarrow K_s K$ first upper limit in sector.
$\mathcal{L} = 1.0 \text{ fb}^{-1}$

$B_s \rightarrow KK$ Effective Lifetime Measurement
Motivation and Selection

Comparison between CP even and CP odd lifetimes is useful to constrain the CP violation parameters

The untagged decay time distribution can be written as:

\[ \Gamma(t) \propto \left( 1 - A\Delta \Gamma_s \right) e^{-\Gamma_L t} + \left( 1 + A\Delta \Gamma_s \right) e^{-\Gamma_H t}. \]

In this case, fitting the decay time with a single exponential gives an effective lifetime defined as:

\[ \tau_{KK} = \tau_{B^0} \frac{1}{1 - y_s^2} \left[ \frac{1 + 2A\Delta \Gamma_s y_s + y_s^2}{1 + A\Delta \Gamma_s y_s} \right], \]

with \( y_s \equiv \frac{\Delta \Gamma_s}{2\Gamma_s} \).
Effective Lifetime Measurement

Analysis steps:
- two consecutive Neural Network NeuroBayes selections applied:
  1. based on the kinematic variables
  2. the kinematic information is combined with the PID
- only events with $\tau > 0.5$ ps are considered
- mass fit is used to extract sWeights for the signal decay time distribution

\[
\tau_{KK} = 1.455 \pm 0.046 \text{ (stat.)} \pm 0.006 \text{ (syst.) ps},
\]

Which can be compared to the SM predictions:

\[
\tau_{KK}^{\text{SM}} = 1.40 \pm 0.02 \text{ ps}
\]