Experimental prospects in rare hadronic b-hadron decays

Thomas Latham

14th July 2016
Questions

• The list of questions I was sent by the organisers:
  – How well will we be able to test SU(3) with $B \to hh$ decays?
  – How precisely can/should we measure CP violation and triple products in $B \to VV$ decays?
  – What do the large CP violation effects in $B^+ \to h^+h^+h^-$ tell us?
  – What will we be able to do in hadronic b-baryon and $B_c^+$ decays?

• I do not claim that I shall answer these myself in the next 30 minutes but hopefully can stimulate the discussion!
Introduction
Why charmless decays?

• Contributions from both loop (penguin) and tree decay diagrams
• Have comparable magnitude and a relative weak phase (= \(\gamma\) in SM)
• Interference can therefore give rise to CP violation in decay
• In neutral \(B\) decays can also perform time-dependent measurements, giving sensitivity to mixing-induced CP asymmetries
• Comparison with measurements from "golden modes", e.g. \(B^0 \rightarrow J/\psi K^0_S\) or \(B_S^0 \rightarrow J/\psi\phi\) to search for signs of new physics
Why charmless decays?

- Contributions from both loop (penguin) and tree decay diagrams
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$B \rightarrow hh'$ decays

- Family of $B$ decays to two light mesons ($h/h' = $ kaons or pions)
- Large number of measurements from $B$-factories and now LHCb
- Will concentrate on more recent CPV results, then give some prospects for near and far future
$B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow K^-\pi^+$

Fits to samples that use different selection criteria
CP violation in decay

• First observation (6.5σ) of CP violation in $B_s^0$ system:

$A_{CP} (B_s \rightarrow K^- \pi^+) = \frac{\Gamma(\bar{B}_s \rightarrow K^+ \pi^-) - \Gamma(B_s \rightarrow K^- \pi^+)}{\Gamma(\bar{B}_s \rightarrow K^+ \pi^-) + \Gamma(B_s \rightarrow K^- \pi^+)} = 0.27 \pm 0.04 \text{(stat.)} \pm 0.01 \text{(syst.)}$

• Also world’s best single measurement of:

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

• Results consistent with world averages and previous LHCb measurements

• Also appear consistent with prediction of U-spin symmetry that $\Delta = 0$ [Phys. Lett. B492 (2000) 297]

$\Delta = \frac{A_{CP} (B^0 \rightarrow K^+ \pi^-)}{A_{CP} (B_s^0 \rightarrow K^- \pi^+)} + \frac{BF (B_s^0 \rightarrow K^- \pi^+)}{BF (B^0 \rightarrow K^+ \pi^-)} \cdot \frac{\tau_d}{\tau_s} = -0.02 \pm 0.05 \pm 0.04$
$B_S^0 \rightarrow K^+ K^- \text{ and } B^0 \rightarrow \pi^+ \pi^-$

$m_B$

$K^+ K^-$

Decay time

$\pi^+ \pi^-$

Decay time asymmetry

14/07/2016

Heavy Flavour 2016 - Quo Vadis?

2011 data, 1.0 fb$^{-1}$
Time-dependent CP violation

<table>
<thead>
<tr>
<th>Quantity</th>
<th>BaBar</th>
<th>Belle</th>
<th>CDF</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{π^+π^-}$</td>
<td>$-0.25 ± 0.08 ± 0.02$</td>
<td>$-0.33 ± 0.06 ± 0.03$</td>
<td>–</td>
<td>$-0.38 ± 0.15 ± 0.02$</td>
</tr>
<tr>
<td>$S_{π^+π^-}$</td>
<td>$-0.68 ± 0.10 ± 0.03$</td>
<td>$-0.64 ± 0.08 ± 0.03$</td>
<td>–</td>
<td>$-0.71 ± 0.13 ± 0.02$</td>
</tr>
<tr>
<td>$ρ(C_{π^+π^-}, S_{π^+π^-})$</td>
<td>$-0.06$</td>
<td>$-0.10$</td>
<td>–</td>
<td>0.38</td>
</tr>
<tr>
<td>$B_{π^+π^-}\times 10^6$</td>
<td>$5.5 ± 0.4 ± 0.3$</td>
<td>$5.04 ± 0.21 ± 0.18$</td>
<td>$5.02 ± 0.33 ± 0.35$</td>
<td></td>
</tr>
<tr>
<td>$C_{K^+K^-}$</td>
<td>$-0.03 ± 0.08 ± 0.01$</td>
<td>–</td>
<td>–</td>
<td>$0.14 ± 0.11 ± 0.03$</td>
</tr>
<tr>
<td>$S_{K^+K^-}$</td>
<td>$5.02 ± 0.46 ± 0.29$</td>
<td>$5.86 ± 0.26 ± 0.38$</td>
<td>–</td>
<td>$0.30 ± 0.12 ± 0.04$</td>
</tr>
<tr>
<td>$ρ(C_{K^+K^-}, S_{K^+K^-})$</td>
<td>–</td>
<td>$38^{+10}_{-9} ± 7$</td>
<td>$25.8 ± 2.2 ± 1.7$</td>
<td></td>
</tr>
<tr>
<td>$B_{K^+K^-}\times 10^6$</td>
<td>–</td>
<td>–</td>
<td>$23.0 ± 0.7 ± 2.3$</td>
<td></td>
</tr>
<tr>
<td>$A_{π^+π^0}$</td>
<td>$5.02 ± 0.46 ± 0.29$</td>
<td>$5.86 ± 0.26 ± 0.38$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$B_{π^+π^0}\times 10^6$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$C_{π^0π^0}$</td>
<td>$-0.43 ± 0.26 ± 0.05$</td>
<td>$-0.44^{+0.53}_{-0.52} ± 0.17$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$B_{π^0π^0}\times 10^6$</td>
<td>$1.83 ± 0.21 ± 0.13$</td>
<td>$2.3^{+0.4+0.2}_{-0.5-0.3}$</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

NB Belle has since produced a preliminary update of $B_{π^0π^0}$ with a much smaller central value

- This information can be combined using relations based on U-spin and isospin symmetries to make constraints on CKM parameters $γ$ and $β_S$
Constraints on CKM parameters

- Some dependence of extracted values of $\gamma$ and $-2\beta_s$ on the allowed amount of non-factorisable U-spin breaking
- Allowing up to 50% ($\kappa = 0.5$), the values and uncertainties found are:
  \[
  \gamma = (63.5^{+7.2}_{-6.7})^\circ \\
  -2\beta_s = -0.12^{+0.14}_{-0.16} \text{ rad.}
  \]
- Very little effect of U-spin breaking on extraction of $-2\beta_s$
- But further improvements in extraction of $\gamma$ using this method are potentially limited by understanding of U-spin breaking
Future prospects

• Updates of all these analyses (and lifetime measurements) to the 3 fb\(^{-1}\) Run 1 dataset are in progress:
  – Can expect results from time-dependent CPV analysis by end of this year
  – Results of updated search for \(B^0 \rightarrow K^+ K^-\) to appear imminently

• Can the method for extracting CKM parameters benefit from inclusion of information on the rare annihilation modes \((B^0 \rightarrow K^+ K^- \text{ and } B^0_S \rightarrow \pi^+ \pi^-)\)?
  – Naïve extrapolation of yields to LHCb phase-2 upgrade scenario (300 fb\(^{-1}\) @ 14 TeV) indicates yields of 5-10M for the favoured CP-eigenstate modes and 30-100k for these rare modes
  – So time-dependent measurements of these could be very interesting

• Although LHCb has demonstrated ability to reconstruct decays such as \(B^+ \rightarrow K^+ \pi^0\), it will be tough to improve significantly on existing precision before Belle II comes online
  – Possibility to improve LHCb ECAL during LS3 being investigated
  – But until then will have to rely on Belle II to drive precision on \(B^+ \rightarrow \pi^+ \pi^0\) (and of course \(B^0 \rightarrow \pi^0 \pi^0\))

LHCb-CONF-2015-001
$B \rightarrow VV$ decays

- Will concentrate here on $B_s^0 \rightarrow K^{*0} \overline{K}^{*0}$ and $B_s^0 \rightarrow \phi \phi$ and the measurement of $\phi_S$
- Other very important measurements in this sector include the determination of $\alpha$ from $B \rightarrow \rho \rho$
\[ B_s^0 \rightarrow VV \] decays

- \( B_s^0 \rightarrow K^{*0} \bar{K}^{*0} \) and \( B_s^0 \rightarrow \phi\phi \) are both pure penguin decays in SM
- Intriguingly small \( f_L \) values
- Final states are a mixture of CP eigenstates – need amplitude analysis to disentangle polarisation states
- Sensitive to CP violation in interference between mixing and decay
- For \( B_s^0 \rightarrow K^{*0} \bar{K}^{*0} \), the U-spin partner \( B^0 \) decay results in the same final state – can be used to control SM uncertainties
- Good future prospects for testing SM in both decays
$B_s^0 \rightarrow K^{*0} \overline{K}^{*0}$ analysis

- Untagged, time-integrated amplitude analysis, uses 1 fb$^{-1}$ of data from 2011
- Reconstruct $B_s^0 \rightarrow (K^+\pi^-)J_1 (K^-\pi^+)J_2$ candidates
- Each $K\pi$ pair in $\pm 150$ MeV $m_{K\pi}$ window around $K^*(892)^0$
- Consider combinations of contributions where either $K\pi$ pair can be in:
  - P-wave ($J=1$): $K^*(892)^0$
  - S-wave ($J=0$): $K_0^*(1430)^0 + \text{NR}$
- Assume D-wave ($J=2$) or higher is negligible in selected region

$A_{0,\parallel,\perp}$
$\eta_0, \parallel = +1$, $\eta_\perp = -1$

$A_s^+, A_s^-$
$\eta_s^+ = -1$, $\eta_s^- = +1$

$A_{ss}$
$\eta_{ss} = +1$

$B \rightarrow VV$

$B \rightarrow SV$

$B \rightarrow SS$
CP violation

\[ N(B_s^0 \rightarrow K^+\pi^-K^-\pi^+) = 697 \pm 31 \pm 11 \]

- Untagged analysis due to relatively small signal yield
- Still have sensitivity to CP violation through interferences between CP-odd and CP-even amplitudes:
  - T-odd triple products
  - S-wave induced direct CP asymmetries

\[ \mathcal{A}_T^i \propto Im(A_f A_\perp - \bar{A}_f \bar{A}_\perp) \]
\[ \mathcal{A}_D^i \propto Re(A_f A^+_s - \bar{A}_f \bar{A}^+_s) \]

- Expected to be small in SM
- All consistent with zero but some intriguing \( \sim 2\sigma \) “hints”
- Motivates update with more data

<table>
<thead>
<tr>
<th>Asymmetry</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_T^1 )</td>
<td>0.003 ± 0.041 ± 0.009</td>
</tr>
<tr>
<td>( A_T^2 )</td>
<td>0.009 ± 0.041 ± 0.009</td>
</tr>
<tr>
<td>( A_T^3 )</td>
<td>0.019 ± 0.041 ± 0.008</td>
</tr>
<tr>
<td>( A_T^4 )</td>
<td>-0.040 ± 0.041 ± 0.008</td>
</tr>
<tr>
<td>( A_D^1 )</td>
<td>-0.061 ± 0.041 ± 0.012</td>
</tr>
<tr>
<td>( A_D^2 )</td>
<td>0.081 ± 0.041 ± 0.008</td>
</tr>
<tr>
<td>( A_D^3 )</td>
<td>-0.079 ± 0.041 ± 0.023</td>
</tr>
<tr>
<td>( A_D^4 )</td>
<td>-0.081 ± 0.041 ± 0.010</td>
</tr>
</tbody>
</table>

\( CP\)-even: \( f = 0, \parallel, s^-, ss \)
\( CP\)-odd: \( \perp, s^+ \)
Amplitude analysis

- 5D fit to the two $m_{K\pi}$ and 3 angles
- Full expression contains 21 terms
- Assuming no CPV eliminates 11 of these
- Systematic uncertainties dominated by the angular acceptance and $m_{K\pi}$ lineshapes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_L$</td>
<td>$0.201 \pm 0.057 \pm 0.040$</td>
</tr>
<tr>
<td>$f_\parallel$</td>
<td>$0.215 \pm 0.046 \pm 0.015$</td>
</tr>
<tr>
<td>$</td>
<td>A_s^+</td>
</tr>
<tr>
<td>$</td>
<td>A_s^-</td>
</tr>
<tr>
<td>$</td>
<td>A_{ss}</td>
</tr>
<tr>
<td>$\delta_\parallel$</td>
<td>$5.31 \pm 0.24 \pm 0.14$</td>
</tr>
<tr>
<td>$\delta_- - \delta_s^+$</td>
<td>$1.95 \pm 0.21 \pm 0.04$</td>
</tr>
<tr>
<td>$\delta_s$</td>
<td>$1.79 \pm 0.19 \pm 0.19$</td>
</tr>
<tr>
<td>$\delta_{ss}$</td>
<td>$1.06 \pm 0.27 \pm 0.23$</td>
</tr>
</tbody>
</table>

- Small value of $f_L$ is confirmed
- Large S-wave contribution

$P \rightarrow VV$
$P \rightarrow SV, VS, SS$
$Re(A_0^* A_s^+)$
\[ B_{s}^{0} \rightarrow \phi \phi \]

- Tagged, time-dependent amplitude analysis of 3fb\(^{-1}\) Run 1 dataset
- Using approximately 4000 signal events measured the CP-violating phase:

\[ \phi_{s} = -0.17 \pm 0.15 \text{(stat)} \pm 0.03 \text{(stat)} \text{ rad} \]

- Consistent with the SM
- Also measured the polarisation amplitudes, S-wave fraction and triple-product asymmetries
Future prospects

• $B_S^0 \to K^*0 \bar{K}^*0$ analysis being updated to 3fb$^{-1}$ Run 1 dataset
  – A flavour-tagged, time-dependent analysis to measure $\phi_s^{d\bar{d}s}$
  – Uses wider $m_{K\pi}$ window – includes D-wave contributions
  – Should be made public by end of year
• $B_S^0 \to \phi\phi$ analysis will soon be updated to include Run 2 data (2015 + some or all of 2016)
  – Plan to determine $\phi_s$ independently for each polarisation state
• Long term prospects:
  – Naïve extrapolation of $B_S^0 \to \phi\phi$ analysis to LHCb phase-2 upgrade scenario indicates potential to improve statistical precision on $\phi_s$ to < 0.01 rad.
  – Sensitivity of $B_S^0 \to K^*0 \bar{K}^*0$ expected to be not far behind but requires dedicated studies once current analysis is completed
$B \rightarrow hhh$ decays

- Large $A_{CP}$ in $B^+$ decays
- Time-dependent CPV
- Very rare decays
Large $A_{CP}$ in charmless $B^+$ decays

- Both BaBar and Belle performed Dalitz-plot analyses of some of these modes
- One of most interesting results was evidence for large CPV in $B^+ \rightarrow \rho(770)^0 K^+$ from both experiments:

**BaBar:** $A_{CP} = (44 \pm 10 \pm 4^{+5}_{-13})\%$


**Belle:** $A_{CP} = (30 \pm 11 \pm 2^{+11}_{-4})\%$

Recent LHCb Results

• LHCb analysis of $B^+ \rightarrow h^+ h^- h'^+$ decays using full LHC Run 1 data sample
• Much larger samples (20-40x) than $B$-factories
• CP asymmetries measured in full phase space:

\[
A_{CP}(B^{\pm} \rightarrow K^\pm \pi^+ \pi^-) = +0.025 \pm 0.004 \pm 0.004 \pm 0.007, \\
A_{CP}(B^{\pm} \rightarrow K^\pm K^+ K^-) = -0.036 \pm 0.004 \pm 0.002 \pm 0.007, \\
A_{CP}(B^{\pm} \rightarrow \pi^\pm \pi^+ \pi^-) = +0.058 \pm 0.008 \pm 0.009 \pm 0.007, \\
A_{CP}(B^{\pm} \rightarrow \pi^\pm K^+ K^-) = -0.123 \pm 0.017 \pm 0.012 \pm 0.007,
\]

• Asymmetries in some regions of the phase space are even more pronounced
Large $A_{CP}$ in charmless $B^+$ decays

Large positive asymmetries at low $m_{\pi\pi}^2$
Large negative asymmetries at low $m_{KK}^2$
Large $A_{CP}$ in charmless $B^+$ decays

- Larger data samples allow more detail to be extracted than previous analyses:
  - Want to understand the origin of the strong-phase difference
  - Examine dependence of asymmetry as function of invariant mass and helicity angle in regions around resonances, e.g. for $B^+ \rightarrow \pi^+\pi^+\pi^-$

- Asymmetries as large as 60% in some regions!!
- Flips of sign indicate interference between S- and P-wave is important
- Rescattering may also play a role in region between 1.0 and 1.5 GeV

\[
\cos \theta < 0 \quad \text{and} \quad \cos \theta > 0
\]
Large $A_{CP}$ in charmless $B^+$ decays

• Need amplitude analyses to understand the origin of the strong phase differences
• Such analyses are ongoing at LHCb
• Building models for these decays is challenging:
  – Very large yields, e.g. ~180k events in $B^+ \rightarrow K^+\pi^+\pi^-$
  – Enormous phase space – important to model the nonresonant contributions, in particular since these appear to have large asymmetries in some modes
  – Dialogue with theory colleagues essential
• It is also essential to accurately (and precisely) describe the variation of the efficiency and the background contributions over the Dalitz plot
BaBar DP analysis of $B^+ \rightarrow K_S^0 \pi^+ \pi^0$

- Extremely challenging mode
- $\sim$1000 signal, very large backgrounds
- Model contains $K^*(892)$, $K\pi$ S-wave and $\rho(770)^+$ contributions
- Both charged and neutral $K^*$'s included
- $K\pi$ S-wave modelled using LASS parameterisation (coherent sum of $K_0^*(1430)$ resonance and effective range nonresonant terms) [Nucl. Phys. B296, 493 (1988)]
CP violation in decay

- First evidence of CP violation in the decay $B^+ \rightarrow K^{*+}\pi^0$
- $3.4\sigma$ significance estimated including statistical, systematic and model uncertainties
- $A_{CP}$ for $B^+ \rightarrow K^{*0}\pi^+$ consistent with zero (as expected)

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>$A_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0\pi^+\pi^0$</td>
<td>$0.07 \pm 0.05 \pm 0.03^{+0.02}_{-0.03}$</td>
</tr>
<tr>
<td>$K^*(892)^0\pi^+$</td>
<td>$-0.12 \pm 0.21 \pm 0.08^{+0.0}_{-0.11}$</td>
</tr>
<tr>
<td>$K^*(892)^+\pi^0$</td>
<td>$-0.52 \pm 0.14 \pm 0.04^{+0.04}_{-0.02}$</td>
</tr>
<tr>
<td>$K^*_0(1430)^0\pi^+$</td>
<td>$0.14 \pm 0.10 \pm 0.04^{+0.13}_{-0.05}$</td>
</tr>
<tr>
<td>$K^*_0(1430)^+\pi^0$</td>
<td>$0.26 \pm 0.12 \pm 0.08^{+0.12}_{-0.0}$</td>
</tr>
<tr>
<td>$\rho(770)^+K^0$</td>
<td>$0.21 \pm 0.19 \pm 0.07^{+0.23}_{-0.19}$</td>
</tr>
</tbody>
</table>

BaBar Preliminary
Large $A_{CP}$ in charmless $B^+$ decays

• The very large local CP asymmetries seen by LHCb in the $h^+ h^+ h^-$ channels also appear in the BaBar analysis of $K_S^0 \pi^+ \pi^0$

• The B-factories have also seen quite sizable asymmetries (around 20%) in $B^0 \rightarrow K^{*+} \pi^-$, although not as huge as the >50% asymmetries seen in the $B^+$ decays

• Some of the regions of high asymmetry in the $h^+ h^+ h^-$ channels are in the centre of the Dalitz plot, far from the narrow resonances

• Is this New Physics staring us in the face? Or is this just what happens when you have various interfering resonances that each receive different levels of tree and penguin contributions?
  – Can we tell these apart with our amplitude analyses?
Time-dependent CPV

• Several previous results from B factories
• Time-dependent DP analyses of $B^0 \rightarrow \pi^+\pi^-\pi^0$ that have provided constraints on CKM angle $\alpha$
• Time-dependent DP analyses of $B^0 \rightarrow K_S^0\pi^+\pi^-$ and $B^0 \rightarrow K_S^0 K^+ K^-$ that have yielded information on CKM angle $\beta$
• Information from various $K^*\pi$ and $\rho K$ decays can also be combined to give $\gamma$-like constraint on $(\rho, \eta)$ plane
LHCb results: $B_{(s)}^0 \rightarrow K_S^0 h^+ h'^-\,$ decays

- Also have results on quasi-two-body BF measurements of $B_s^0 \rightarrow K^{*\pm} h^\mp$ and $B_s^0 \rightarrow K^{*0} K_S^0$: [New J. Phys. 16 (2014) 123001] and [JHEP 01 (2016) 012]
- Long-term prospects for time-dependent amplitude analyses: measure CKM phases
- In shorter term can perform time-integrated analyses to explore the resonant structure in these decays
  - Also have sensitivity to CP asymmetries in flavour-specific contributions such as $B^0 \rightarrow K^{*+} \pi^-$
  - Results expected from these analyses in next few months
Complementarity of LHCb and Belle II

• The modes with neutral pions are challenging
  – Almost all of the existing DP analyses have come from BaBar
    • The one exception being $B^0 \rightarrow \pi^+\pi^-\pi^0$, both BaBar and Belle have results
    • Would love to see results from Belle in $B^0 \rightarrow K^+\pi^-\pi^0$, $B^+ \rightarrow K_S^0\pi^+\pi^0$, etc.
  – For LHCb these modes will be particularly difficult
  – However, LHCb has a great advantage in that it can perform time-dependent analyses of $B_S^0$ decays, which Belle II can not do
    – Potential upgrade of LHCb ECAL in LS3 would also help a lot
• The tree-dominated $B_S^0 \rightarrow K^*\pi$, $K^*K$ and $\rho K$ decays are potentially an excellent prospect for extracting $(\rho, \eta)$ constraints with smaller uncertainties from EW penguins than the corresponding $B^0$ decays
• To get the most out of these decays will require inputs from both experiments – e.g. DP models may be more precisely extracted at Belle II, which can then be fed into time-dependent analyses at LHCb, etc.
• Adoption of common conventions for the amplitude analyses would be highly beneficial for this effort
Null tests of SM

• The decays $B^+ \to K^-\pi^+\pi^+$ and $B^+ \to \pi^-K^+K^+$ are highly suppressed in the SM
  – Respective BF predictions are $10^{-14}$ and $10^{-11}$ [JHEP 02 (2010) 028]

• But some NP models can enhance these by several orders of magnitude

• Preliminary results from latest search by LHCb show no evidence of signal and sets upper limits:
  \[
  B(B^+ \to K^-\pi^+\pi^+) < 4.6 \times 10^{-8} \\
  B(B^+ \to \pi^-K^+K^+) < 1.1 \times 10^{-8}
  \]

• These constitute factor 14-20 improvements on the previous best limits (from BaBar [Phys. Rev. D78 (2008) 091102])

• Naïve extrapolation to LHCb phase-2 upgrade scenario indicates potential for similar factor improvement, so down to $10^{-9}$ or slightly below
  – This is the region where many NP models predict the BF to be
$B^+_c$ and $b$-baryon decays
$B_{c}^{+}$ mesons

- Only meson composed of heavy quarks with different flavours
- Knowledge rapidly expanding
  - Recent results have much improved precision on lifetime, mass, etc.
- But still largely unexplored territory
  - Production fraction in pp collisions unknown
  - Still rather few decay modes observed
- Charmless final states are reached via annihilation diagrams
- Will show a couple of recent results in this rapidly developing field

\[ B_{c}^{+} \bar{b} \rightarrow W^{+} \bar{s} K^{+} \bigg( \bar{s} \rightarrow K^{0}, \bar{d} \rightarrow K^{-} \pi^{+} \bigg) \]

\[ B_{c}^{+} \bar{b} \rightarrow W^{+} \bar{s} K^{+} \bigg( \bar{s} \rightarrow K^{+} \pi^{-}, \bar{u} \rightarrow K^{+} \pi^{-} \bigg) \]
$B_c^+ \rightarrow p\bar{p}\pi^+$

- Search performed in mass region $m_{pp\bar{p}} < 2.85$ GeV
- Fit $m_{pp\bar{p}\pi}$ in 3 bins of BDT of topological variables:

- No signal observed, upper limit determined:

$$\frac{f_c}{f_u} \times B(B_c^+ \rightarrow p\bar{p}\pi^+) < 3.6 \times 10^{-8}$$
$B_c^+ \rightarrow K^+ K^- \pi^+$

- Very similar analysis strategy
- Many possible contributions in this enormous phase space
- Preliminary results show a $2.4\sigma$ hint of signal in the region $m_{K^-\pi^+} < 1.834$ GeV, a region likely populated by annihilation decays
- Evidence ($4.0\sigma$) for the decay $B_c^+ \rightarrow \chi_{c0} \pi^+$
  - BF measurement:
  \[
  \frac{\sigma(B_c^+)}{\sigma(B^+)} \times B(B_c^+ \rightarrow \chi_{c0} \pi^+) = (9.8^{+3.4}_{-3.0} \pm 0.8) \times 10^{-6}
  \]
Future prospects for $B_c^+$ decays

• Have learned much from these two analyses
  – New selections implemented that will increase efficiencies for Run 2

• Assuming that the hint of signal seen in the annihilation region of $B_c^+ \rightarrow K^+K^-\pi^+$ holds out, we should be able to observe it with Run 2 data

• Looking much further forward to the LHCb Phase-2 upgrade scenario, can expect $O(1k-10k)$ events in these channels
  – This will allow to really start exploring the physics in detail with amplitude analyses etc.
$b$-baryon decays

- Also largely unexplored territory up to now but LHC collisions produce copious $b$-baryons, so much can be done
- First BF and $A_{CP}$ measurements of charmless decays starting to emerge, e.g.
  - $\Lambda_b^0/\Xi_b^0 \to K_S^0 p h^-$  
    [JHEP 04 (2014) 087]
  - $\Lambda_b^0/\Xi_b^0 \to \Lambda h^+ h^-$  
    [JHEP 05 (2016) 081]
  - $\Lambda_b^0 \to \Lambda \phi$  
CP asymmetries

• All CP asymmetries measured so far are consistent with zero, although a few intriguingly large central values:

\[ A_{CP} \left( \Lambda_b^0 \rightarrow K_S^0 p\pi^- \right) = 0.22 \pm 0.13 \pm 0.03 \]
\[ A_{CP} \left( \Lambda_b^0 \rightarrow \Lambda K^+\pi^- \right) = -0.53 \pm 0.23 \pm 0.11 \]
\[ A_{CP} \left( \Lambda_b^0 \rightarrow \Lambda K^+ K^- \right) = -0.28 \pm 0.10 \pm 0.07 \]

• Strongly motivates updates with more data
  – In particular, \( \Lambda_b^0 \rightarrow K_S^0 p\pi^- \) result is based on 1fb\(^{-1} \) sample

• Measurements of triple-product asymmetries in \( \Lambda_b^0 \rightarrow \Lambda\phi \) also consistent with zero [Phys. Lett. B 759 (2016) 282]
$b$-baryon decays

- Other modes under study include:
  - $\Lambda_b^0/\Xi_b^0 \rightarrow ph^-$
  - $\Lambda_b^0/\Xi_b^0 \rightarrow ph^+ h^- h^-$
  - $\Xi_b^-/\Omega_b^- \rightarrow ph^- h'^-$

- All CP violation measurements consistent with CP symmetry so far – hope for first observation from one of the above modes
- Particularly interesting to see if the multi-body modes exhibit large local CP violation like the $B^+ \rightarrow 3h$ decays
- Amplitude analyses are more complex than for the mesons but much ground work is being done to prepare for larger datasets
- Predictions of BFVs and CP asymmetries rather lacking for these modes, would be really great to have more input here
- Is there any hope for interpretation of CPV results in these decays in terms of CKM parameters?
Conclusion
Summary

• Enormous wealth of physics to be found in charmless hadronic decays of b-hadrons
• Some very intriguing results obtained recently
• Look out for further progress in these areas very soon
• To extract the maximum potential from this rich seam requires the larger datasets that the LHCb upgrade(s) and Belle II will provide
• Will also require close coordination between the two experiments and between theory and experiment
• Look forward to continued dialogue and exciting physics results in the future
Backup Slides
LHCb $\sigma(pp \rightarrow H_b \, X) = (75 \pm 5 \pm 13) \, \mu b$


Approximate acceptance:
$2 < \eta < 5$

$\sim$4% of solid angle
$\sim$40% of heavy quarks
2011 + 2012 data set (3 fb\(^{-1}\)) used in analyses discussed today

- L0 Hardware Trigger: 1 MHz readout, high E\(_T\)/P\(_T\) signatures
  - 450 kHz h\(^\gamma\)
  - 400 kHz \(\mu/\mu\)
  - 150 kHz e/\(\gamma\)

- Software High Level Trigger
  - 29000 Logical CPU cores
  - Offline reconstruction tuned to trigger time constraints
  - Mixture of exclusive and inclusive selection algorithms

- Trigger Efficiencies:
  - \(\sim30\%\) efficient for multi-body hadronic
  - \(\sim90\%\) efficient for dimuons
Kaon/pion separation

- Most particle identification information comes from the Ring Imaging Cherenkov detectors.
- Three different radiators provide separation over a wide momentum range.

\[
\cos \theta = \frac{1}{\beta n}
\]
Trigger categories

**Trigger On Signal**
- Particle from the signal decay fires a trigger line.
- Triggered by HCAL deposits.

**Trigger Independent of Signal**
- Particle from the rest of the event fires a trigger line.
- Triggered mostly by HCAL deposits or muons.
$K_S^0$ reconstruction

- $K_S^0$ decays to $\pi^+\pi^-$ divided into two categories:
  - **Long**: pion tracks have hits in the vertex detector (VELO)
  - **Downstream**: pion tracks have no VELO hits
Current status

- CKM mechanism agrees well with experiment
- But still room for new physics
- Vital to measure $CP$ violating observables in as many different decay processes as possible
- Look for disagreements
Why amplitude analyses?

- Source of strong phase differences in 2-body decays not well understood
- Interferences between intermediate states in 3- and 4-body decays allow the measurement of relative phases as well as magnitudes
- Provide additional information to better constrain theoretical models
- Give greater sensitivity for (and can also help to resolve trigonometric ambiguities in) weak phase measurements
Extra information from 3-body decays

• Three-body decays generally proceed through several intermediate states
• These different paths from initial to final state interfere
• Analogous with the famous double-slit experiment
Interference pattern

Toy simulation of $D_s^+ \rightarrow K^+K^-\pi^+$
The Dalitz plot

A graphical representation of the 3-body phase space: $M \rightarrow a \ b \ c$

Kinematics for decay $B^0 \rightarrow \bar{D}^0 \pi^+\pi^-$
Measuring relative phases

- Interference between intermediate states allows measurement of relative phases
- Provides greater sensitivity to CP violating effects
- Can also help to resolve ambiguities in weak phase measurements
- Also excellent tool for hadron spectroscopy
The Dalitz plot

\[ B_s^0 \rightarrow \overline{D}^0 K^- \pi^+ \]
The Dalitz plot

\[ B_s^0 \rightarrow \bar{D}^0 K^- \pi^+ \]
The Dalitz plot

- See structures in the invariant masses of pairs of daughters
- Structures correspond to resonances in that pair of daughters or reflections from other resonances
Dalitz plot analysis formalism

• Resonance parameterisation (e.g. isobar model):

\[
\lambda = \sum \lambda_i = \sum c_i F_i(DP)
\]

• Directly extracted parameters:
  – \(\text{Re}(c_i)\) & \(\text{Im}(c_i)\)
  or
  – \(|c_i|\) & \(\text{arg}(c_i)\)

• Other quantities (BF, \(A_{\text{CP}}\)) are derived from these
Time dependent analysis

- Vertex measurements by LHCb VELO allow decay times of particles to be precisely determined.
- Can therefore measure decay rates as a function of the decay time.
- Allows more CP violation observables to be probed.
Time-dependent decay rates

- For an initially pure state, the time evolution proceeds as:

\[
\frac{d\Gamma[B_s^0(t) \rightarrow f]}{dt} \propto e^{-\Gamma t} \left[ \left(|A_f|^2 + |\bar{A}_f|^2\right) \cosh\left(\frac{\Delta r_s}{2} t\right) + \left(|A_f|^2 - |\bar{A}_f|^2\right) \cos(\Delta m_s t) 
+ 2 \text{Re}\left(\frac{q}{p} A_f^* \bar{A}_f\right) \sinh\left(\frac{\Delta r_s}{2} t\right) - 2 \text{Im}\left(\frac{q}{p} A_f^* \bar{A}_f\right) \sin(\Delta m_s t) \right]
\]

\[
\frac{d\Gamma[B_s^0(t) \rightarrow f]}{dt} \propto e^{-\Gamma t} \left[ \left(|A_f|^2 + |\bar{A}_f|^2\right) \cosh\left(\frac{\Delta r_s}{2} t\right) - \left(|A_f|^2 - |\bar{A}_f|^2\right) \cos(\Delta m_s t) 
+ 2 \text{Re}\left(\frac{q}{p} A_f^* \bar{A}_f\right) \sinh\left(\frac{\Delta r_s}{2} t\right) + 2 \text{Im}\left(\frac{q}{p} A_f^* \bar{A}_f\right) \sin(\Delta m_s t) \right]
\]

- There is sensitivity to the mixing phase through the \text{sin} and \text{sinh} terms
Angular distributions

Angular distribution of resonance bands related to Legendre Polynomials
(for decay of spin-0 particle into 3 spin-0 daughters)
The square Dalitz plot

- For greater convenience for binned quantities (such as efficiency), we transform such that the Dalitz plot is mapped to a square
- Plots show toy experiments including $\bar{K}^*(892)^0$, $\bar{K}_{0,2}^*(1430)^0$ and $D_{s2}^*(2573)^-$,
- $m'$ is effectively $m_{D^0K^-}$ in reverse and $\theta'$ is the $D^0K^-$ helicity angle
The square Dalitz plot

- Plots show LHCb data from the full Run 1 sample
- Events in the signal region (so includes some background as well as signal – purity \(~87\%)
$B^0 \rightarrow \rho^0 \rho^0$

- $B^0 \rightarrow \rho \rho$ decays currently give greatest sensitivity to CKM angle $\alpha$
- B-factories both reported evidence for $B^0 \rightarrow \rho^0 \rho^0$ but found (2$\sigma$) different $f_L$ values:
  - BaBar: $0.75 \pm 0.14$ [PRD 78, 071104 (2008)]
  - Belle: $0.21 \pm 0.24$ [PRD 89, 072008 (2014)]

- LHCb analysis uses 3fb$^{-1}$ of data from 2011+2012
- Select $B^0 \rightarrow (\pi^+ \pi^-)_{J_1} (\pi^+ \pi^-)_{J_2}$ candidates where both $\pi^+ \pi^-$ pairs satisfy $m_{\pi\pi} < 1.1$GeV
- Find approximately 630 $B^0$ events
- Also see $\sim$100 $B_s$ events – first observation of this decay mode
Amplitude analysis

- An untagged analysis assuming CP conservation
- Consider the following contributions:
  - **P-wave**: \(\rho(770), \omega(782)\)
  - **S-wave**: \(f_0(500), f_0(980), \text{NR}\)
  - **D-wave**: \(f_2(1270)\)
- **First observation of** \(B^0 \rightarrow \rho^0 \rho^0\)
- No evidence of \(B^0 \rightarrow \rho^0 f_0(980)\) reported by Belle
- Find longitudinal fraction in agreement with BaBar:

\[
  f_L = 0.745^{+0.048}_{-0.058} \text{ (stat)} \pm 0.034 \text{ (syst)}
\]

- Measure BF (using \(B^0 \rightarrow \phi K^{*0}\) as normalisation):

\[
  \mathcal{B}(B^0 \rightarrow \rho^0 \rho^0) = (0.94 \pm 0.17 \text{ (stat)} \pm 0.09 \text{ (syst)} \pm 0.06 \text{ (BF)}) \times 10^{-6}
\]

- Dominant systematic uncertainties are again the angular acceptance and mass lineshapes
BaBar analysis of $B^+ \rightarrow K_S^0 \pi^+ \pi^0$

- Approx. 32,000 candidates after all selection
- Maximum likelihood fit to $m_{ES}, \Delta E,$ Boosted Decision Tree (event topology) and DP
- Large correlations between DP position and kinematic variables
- Signal PDFs parameterised as function of DP position
- Signal yield of $1014 \pm 63$ (statistical uncertainty only)
### BFs and Phases

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>$B \left(10^{-6}\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0\pi^+\pi^0$</td>
<td>$45.9 \pm 2.6 \pm 3.0^{+8.6}_{-0.0}$</td>
</tr>
<tr>
<td>$K^*(892)^0\pi^+$</td>
<td>$14.6 \pm 2.4 \pm 1.4^{+0.3}_{-0.4}$</td>
</tr>
<tr>
<td>$K^*(892)^+\pi^0$</td>
<td>$9.2 \pm 1.3 \pm 0.6^{+0.3}_{-0.5}$</td>
</tr>
<tr>
<td>$K^*_0(1430)^0\pi^+$</td>
<td>$50.0 \pm 4.8 \pm 6.1^{+2.7}_{-2.6}$</td>
</tr>
<tr>
<td>$K^*_0(1430)^+\pi^0$</td>
<td>$17.2 \pm 2.4 \pm 1.5^{+0.0}_{-1.8}$</td>
</tr>
<tr>
<td>$\rho(770)^+K^0$</td>
<td>$9.4 \pm 1.6 \pm 1.1^{+0.0}_{-2.6}$</td>
</tr>
</tbody>
</table>

- First measurement of inclusive $K^0\pi^+\pi^0$ and $K^*_0(1430)^+\pi^0$ BFs
- First uncertainty is statistical, second systematic, and third due to the signal model
- Sensitivity to relative phases depends strongly on overlap in DP and effects of mis-reconstruction in the corners
- Smaller uncertainties for pairs of parallel resonances

### Relative phase (degrees)

<table>
<thead>
<tr>
<th>Reference amplitude</th>
<th>$K^*(892)^0\pi^+$</th>
<th>$K^*(892)^+\pi^0$</th>
<th>$(K\pi)^0\pi^+$</th>
<th>$(K\pi)^+\pi^0$</th>
<th>$\rho(770)^+K^0_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to K^*(892)^0\pi^+$</td>
<td>0</td>
<td>$-95 \pm 43$</td>
<td>174 ± 11</td>
<td>$-89 \pm 43$</td>
<td>$-122 \pm 43$</td>
</tr>
<tr>
<td>$B^+ \to K^*(892)^+\pi^0$</td>
<td>$-90 \pm 42$</td>
<td>6 ± 10</td>
<td>$63 \pm 37$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^+ \to (K\pi)^0\pi^+$</td>
<td>0</td>
<td>96 ± 42</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^+ \to (K\pi)^+\pi^0$</td>
<td>$-32 \pm 25$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^+ \to \rho(770)^+K^0_S$</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
BFs and Phases

<table>
<thead>
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<th>$B \times 10^{-6}$</th>
</tr>
</thead>
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</tr>
<tr>
<td>$\rho(770)^+ K^0$</td>
<td>$9.4 \pm 1.6 \pm 1.1^{+0.0}_{-2.6}$</td>
</tr>
</tbody>
</table>

Simulation

Large uncertainty indicates gaining CKM constraints will be difficult
Comparison of $K\pi$ and $K^*\pi$

- Using world average values for all $K\pi$ and $K^{*+}\pi^-$ asymmetries and BaBar average of their two results for $K^{*+}\pi^0$ (from arXiv:1501.00705 [hep-ex])
- Gives $\Delta A_{CP}(K^*\pi) \equiv A_{CP}(K^{*+}\pi^0) - A_{CP}(K^{*+}\pi^-) = -0.16 \pm 0.13$
  - Consistent with zero
- Uncertainty much improved but still too large to be conclusive

BaBar, Belle
BaBar, Belle, CDF, LHCb
BaBar only!
BaBar, Belle
$B^0_s \rightarrow \phi \phi$ branching fraction

- Reoptimised selection wrt previous analysis
- $B^0 \rightarrow \phi K^{*0}$ used as normalisation channel and results of previous amplitude analysis used to determine the S-wave contribution
- Branching fraction measured to be (world’s most precise determination):
  \[
  \mathcal{B}(B^0_s \rightarrow \phi \phi) = (1.84 \pm 0.05 \text{ (stat)} \pm 0.07 \text{ (syst)} \pm 0.11 \text{ (}$f_s/f_d$) \pm 0.12 \text{ (norm)}) \times 10^{-5}
  \]
- World’s best upper limit also determined for the corresponding $B^0$ decay:
  \[
  \mathcal{B}(B^0 \rightarrow \phi \phi) < 2.8 \times 10^{-8} \quad (@90\%\ CL)
  \]
Table 1: Sensitivities of the LHCb upgrade to key observables. The current sensitivity is compared to that expected after 5 fb$^{-1}$ and that which will be achieved with 50 fb$^{-1}$ by the upgraded experiment, all assuming $\sqrt{s} = 14$ TeV. Note that at the upgraded LHCb, the yield/fb$^{-1}$ in hadronic $B$ and $D$ decays will be higher on account of the software trigger.

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Pre-LHCb precision</th>
<th>LHCb (5 fb$^{-1}$)</th>
<th>Upgrade (50 fb$^{-1}$)</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluonic penguin</td>
<td>$S(B_s \rightarrow \phi\phi)$</td>
<td>-</td>
<td>0.08</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$S(B_s \rightarrow K^{*0}\bar{K}^{*0})$</td>
<td>-</td>
<td>0.07</td>
<td>0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>$S(B^0 \rightarrow \phi K^0_S)$</td>
<td>0.17</td>
<td>0.15</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>$B_s$ mixing</td>
<td>$\phi_s$ $(B_s \rightarrow J/\psi\phi)$</td>
<td>0.35</td>
<td>0.019</td>
<td>0.006</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$S(B_s \rightarrow \phi\gamma)$</td>
<td>-</td>
<td>0.07</td>
<td>0.02</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>$A^{\Delta\Gamma_s}(B_s \rightarrow \phi\gamma)$</td>
<td>-</td>
<td>0.14</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>E/W penguin</td>
<td>$A_T^{(2)}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$</td>
<td>-</td>
<td>0.14</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>$s_0 A_{FB}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$</td>
<td>-</td>
<td>4%</td>
<td>1%</td>
<td>7%</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$B(B_s \rightarrow \mu^+\mu^-)$</td>
<td>-</td>
<td>30%</td>
<td>8%</td>
<td>&lt; 10%</td>
</tr>
<tr>
<td></td>
<td>$B(B^0 \rightarrow \mu^+\mu^-)$</td>
<td>-</td>
<td>-</td>
<td>$\sim 35%$</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Unitarity triangle angles</td>
<td>$\gamma$ $(B \rightarrow D^{(<em>)}K^{(</em>)})$</td>
<td>$\sim 20^\circ$</td>
<td>$\sim 4^\circ$</td>
<td>0.9$^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma$ $(B_s \rightarrow D_s K)$</td>
<td>-</td>
<td>$\sim 7^\circ$</td>
<td>1.5$^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta$ $(B^0 \rightarrow J/\psi K^0)$</td>
<td>1$^\circ$</td>
<td>0.5$^\circ$</td>
<td>0.2$^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm CPV</td>
<td>$A_{T}$</td>
<td>$2.5 \times 10^{-3}$</td>
<td>$2 \times 10^{-4}$</td>
<td>$4 \times 10^{-5}$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$A_{CP}^{dir}(K\bar{K}) - A_{CP}^{dir}(\pi\pi)$</td>
<td>$4.3 \times 10^{-3}$</td>
<td>$4 \times 10^{-4}$</td>
<td>$8 \times 10^{-5}$</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 16: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with 50 fb\(^{-1}\) by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities. Note that the current sensitivities do not include new results presented at ICHEP 2012 or CKM2012.

<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^0_s) mixing</td>
<td>(2\beta_s (B^0_s \to J/\psi \phi))</td>
<td>0.10 [138]</td>
<td>0.025</td>
<td>0.008</td>
<td>(\sim 0.003)</td>
</tr>
<tr>
<td></td>
<td>(2\beta_s (B^0_s \to J/\psi f_0(980)))</td>
<td>0.17 [214]</td>
<td>0.045</td>
<td>0.014</td>
<td>(\sim 0.01)</td>
</tr>
<tr>
<td></td>
<td>(a_{s1})</td>
<td>(6.4 \times 10^{-3}) [43]</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</td>
<td>(2\beta_{s_{\text{eff}}} (B^0_s \to \phi \phi))</td>
<td>–</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Penguins</td>
<td>(2\beta_{s_{\text{eff}}} (B^0_s \to K^{*0} 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^0 \to \phi K_S^0))</td>
<td>0.17 [43]</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^0_s \to \phi \gamma))</td>
<td>–</td>
<td>0.09</td>
<td>0.02</td>
<td>(&lt; 0.01)</td>
</tr>
<tr>
<td></td>
<td>(\tau_{s_{\text{eff}}} (B^0 \to \phi \gamma) / \tau_{B_S^0})</td>
<td>–</td>
<td>5%</td>
<td>1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak penguins</td>
<td>(S_3 (B^0 \to K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4))</td>
<td>0.08 [67]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>(s_0 A_{FB} (B^0 \to K^{*0} \mu^+ \mu^-))</td>
<td>25% [67]</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 [76]</td>
<td>0.08</td>
<td>0.025</td>
<td>(\sim 0.02)</td>
</tr>
<tr>
<td></td>
<td>(B(B^+ \to \pi^+ \mu^+ \mu^-)/B(B^+ \to K^+ \mu^+ \mu^-))</td>
<td>25% [85]</td>
<td>8%</td>
<td>2.5%</td>
<td>(\sim 10%)</td>
</tr>
<tr>
<td>Higgs penguins</td>
<td>(B(B^0_s \to \mu^+ \mu^-))</td>
<td>(1.5 \times 10^{-9}) [13]</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 \to \mu^+ \mu^-)/B(B^0_s \to \mu^+ \mu^-))</td>
<td>–</td>
<td>(\sim 100%)</td>
<td>(\sim 35%)</td>
<td>(\sim 5%)</td>
</tr>
<tr>
<td>Unitarity triangle angles</td>
<td>(\gamma (B \to D(\ast) K(\ast)))</td>
<td>(\sim 10-12^\circ) [244,258]</td>
<td>4(^\circ)</td>
<td>0.9(^\circ)</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>(\gamma (B^0_s \to D_s K))</td>
<td>–</td>
<td>11(^\circ)</td>
<td>2.0(^\circ)</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>(\beta (B^0 \to J/\psi K^0_S))</td>
<td>0.8(^\circ) [43]</td>
<td>0.6(^\circ)</td>
<td>0.2(^\circ)</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>(A_\Gamma)</td>
<td>(2.3 \times 10^{-3}) [43]</td>
<td>(0.40 \times 10^{-3})</td>
<td>(0.07 \times 10^{-3})</td>
<td>–</td>
</tr>
<tr>
<td>CP violation</td>
<td>(\Delta A_{CP})</td>
<td>(2.1 \times 10^{-3}) [18]</td>
<td>(0.65 \times 10^{-3})</td>
<td>(0.12 \times 10^{-3})</td>
<td>–</td>
</tr>
</tbody>
</table>
Figure 5: Different processes populating the phase space of the $B_c^+ \rightarrow K^+K^-\pi^+$ decay: (a) pure annihilation, (b) $B_c^+ \rightarrow D^0(\rightarrow K^-\pi^+)K^+$, (c) $B_c^+ \rightarrow B_s^0(\rightarrow K^+K^-)\pi^+$, $B^0(\rightarrow \pi^+K^-)K^+$ and (d) charmonium $B_c^+ \rightarrow [\bar{c}c](\rightarrow K^-K^+)\pi^+$ mode.