CP-violation in decay

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LHCb Implications Workshop

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CP-violation in decay

- $b$-hadron decays without charm in the final state can have similar sized tree ($A_1$) and penguin ($A_2$) contributions
- Maximise potential for CP violation in decay (different weak phases, $\phi = \phi_1 - \phi_2$)
- Multi-body final states also proceed via numerous intermediate resonances - variation in strong phase, $\delta = \delta_1 - \delta_2$, across Dalitz plot

$$ A_{CP} = \frac{2|A_1||A_2| \sin \delta \sin \phi}{|A_1|^2 + |A_2|^2 + 2|A_1||A_2| \cos \delta \cos \phi} $$

See talk by F.Dordei for additional CPV measurements
• In principle, the most promising investigations are in multi-body decays - many techniques used to analyse them:

  • Phase-space integrated CP-asymmetries [arXiv:1603.00413]
  • Amplitude fits - three and four-body
  • Binned phase-space asymmetries [arXiv:1408.5373]
  • Kernel based two-sample hypothesis testing (‘Energy test’) [arXiv:1410.4170]

• All of these used in upcoming searches for CP-violation, using the decays described in this talk
$B^0_{(s)} \rightarrow K^0_S h^+ h^- \text{ branching fractions}$

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

- Loop-dominated avenue to measure the CKM angle $\beta$, via $B \rightarrow \phi K^0_S$ (or $B \rightarrow \rho^0 K^0_S$, ...) [arXiv:hep-ph/9704277].

- Can also obtain the CKM angle $\gamma$ from isospin or flavour SU(3) symmetry relations between decay modes [arXiv:hep-ph/0601233, arXiv:1303.0846].

- Arguments can also be reversed to provide information on hadronic parameters in $B \rightarrow K^* \pi$ [arXiv:1704.01596].

\begin{align*}
\sin(2\beta_{\text{eff}}) &= \sin(2\phi_1) \\
\begin{array}{|c|c|}
\hline
B_{\text{ecs}} & \text{World Average} \\
\hline
\phi K^0 & 0.69 \pm 0.02 \\
\eta^0 K^0 & 0.74 \pm 0.11 \\
\bar{K}^0 K_S K_S & 0.63 \pm 0.06 \\
\bar{\pi}^0 K^0 & 0.72 \pm 0.19 \\
\rho^0 K_S & 0.57 \pm 0.17 \\
\omega K_S & 0.54 \pm 0.21 \\
f_{\bar{q}} K_S & 0.71 \pm 0.21 \\
f_{\bar{q}} K_S & 0.69 \pm 0.10 \\
f_{\bar{q}} K_S & 0.48 \pm 0.53 \\
f_{\bar{q}} K_S & 0.20 \pm 0.53 \\
\kappa^0 \pi^0 K_S & 0.72 \pm 0.71 \\
\omega \pi^0 K_S & 0.97 \pm 0.06 \\
\pi^0 K_S & 0.01 \pm 0.33 \\
K^+ K^0 K^0 & 0.68 \pm 0.06 \\
\hline
\end{array}
\end{align*}

HFLAV Summer 2016
$B_{(s)}^0 \rightarrow K_S^0 h^+ h^-$ branching fractions

- All $B^0 \rightarrow K_S^0 h^+ h^-$ decays observed at the B-factories [arXiv:1003.0640].

- $B^0_s \rightarrow K_S^0 \pi^+ \pi^-$ and $B^0_s \rightarrow K_S^0 K^\pm \pi^\mp$ observed with 1fb$^{-1}$ of 2011 LHCb data [arXiv:1307.7648].

- Aim for the 3fb$^{-1}$ update is to make the most precise measurement of the branching fractions, and make an observation of $B^0_s \rightarrow K_S^0 K^+ K^-$. $K_S^0$-mesons reconstructed from two downstream or long tracks.
$B^0_{(s)} \to K_S^0 h^+ h^-$ branching fractions

Yields:

- $B^0 \to K_S^0 \pi^+ \pi^-$: $4177 \pm 80$
- $B^0 \to K_S^0 K^\pm \pi^\mp$: $421 \pm 29$
- $B^0 \to K_S^0 K^+ K^-$: $1818 \pm 49$
- $B^s \to K_S^0 \pi^+ \pi^-$: $220 \pm 22$
- $B^s \to K_S^0 K^\pm \pi^\mp$: $1668 \pm 50$
$B_{(s)}^0 \rightarrow K_S^0 h^+ h^-$ branching fractions

- Selection separately optimised for the search for $B_S^0 \rightarrow K_S^0 K^+ K^-$ (dashed blue curve):

Yield of $19 \pm 7$ events ($2.5\sigma$ stat. + syst.)

- Efficiencies calculated using simulated data, using the corresponding background subtracted phase-space distributions - data-driven corrections for particle ID, L0 trigger, and tracking

- Dominant systematics from the combinatorial background fit model, and the knowledge of the L0 trigger efficiencies
\( B^0_{(s)} \rightarrow K^0_S h^+ h^- \) branching fractions


- Background subtracted
Branching fractions measured relative to $B^0 \rightarrow K^0_{S}\pi^+\pi^-$, using the world average value (minus LHCb) of $\mathcal{B}(B^0 \rightarrow K^0_{S}\pi^+\pi^-) = (4.96 \pm 0.20) \times 10^{-5}$:

\[
\begin{align*}
\mathcal{B}(B^0 \rightarrow \overline{K}^0 K^{\pm}\pi^{\mp}) &= (6.1 \pm 0.5 \pm 0.7 \pm 0.3) \times 10^{-6}, \\
\mathcal{B}(B^0 \rightarrow K^0 K^{+}K^{-}) &= (27.2 \pm 0.9 \pm 1.6 \pm 1.1) \times 10^{-6}, \\
\mathcal{B}(B^0_s \rightarrow K^{0}\pi^{+}\pi^{-}) &= (9.5 \pm 1.3 \pm 1.5 \pm 0.4) \times 10^{-6}, \\
\mathcal{B}(B^0_s \rightarrow \overline{K}^0 K^{\pm}\pi^{\mp}) &= (84.3 \pm 3.5 \pm 7.4 \pm 3.4) \times 10^{-6}, \\
\mathcal{B}(B^0_s \rightarrow K^0 K^{+}K^{-}) &\in [0.4 - 2.5] \times 10^{-6} \text{ at 90\% C.L.}
\end{align*}
\]

where the first uncertainty is statistical, the second systematic, and the third due to $\mathcal{B}(B^0 \rightarrow K^0_{S}\pi^+\pi^-)$. The confidence interval for $B^0_s \rightarrow K^0_{S}K^{+}K^{-}$ is obtained using the Feldman-Cousins method.
$\bar{B}^0 \rightarrow K_S^0 \pi^+ \pi^-$ amplitude analysis

[LHCb-PAPER-2017-033, To be submitted to PRL]
\( \bar{B}^0 \rightarrow K^0_S \pi^+ \pi^- \) time independent

- Time-integrated, untagged analysis - first step towards measurements of \( \beta_{\text{eff}} \) in a time-dependent analysis
- B-factory measurements found evidence for negative CP-asymmetry in the decay of \( \bar{B}^0 \rightarrow K^*(892)^- \pi^+ \) [arXiv:1105.0125, arXiv:0905.3615, arXiv:0811.3665]
- Selection identical to the branching fraction analysis described previously
- Combinatorial background taken from sideband, \( m(K^0_S \pi^+ \pi^-) > 5450 \text{ MeV} \), and dominant cross-feed \( (B^0_s \rightarrow K^0_S K^\mp \pi^\mp) \) Dalitz-plot distribution taken from data
\[ B^0 \rightarrow K_S^0 \pi^+ \pi^- \text{ time independent} \]

- Amplitude model parameterised in terms of invariant-mass pairs \( m_{K_S^0 \pi^+}^2 \) and \( m_{K_S^0 \pi^-}^2 \) \((s^+ \text{ and } s^-)\),

\[
A = \sum_{j}^{N} c_j F_j (s^+, s^-),
\]

Form of \( F \) given by:

\[
F(s^+, s^-) \propto T(s^+, s^-) \cdot Z(s^+, s^-, L) \cdot X(s^+, s^-, L)
\]

- \( T(s^+, s^-) \): Mass distribution in \( m_{K_S^0 \pi^\pm} \) or \( m_{\pi^+ \pi^-} \) (lineshape)

- \( Z(s^+, s^-, L) \): Spin term, resonance spin \( L \) (using Zemach tensors)
  - proportional to Legendre polynomial

- \( X(s^+, s^-, L) \): Centrifugal barrier term (Blatt-Weisskopf)
$\bar{B}^0 \rightarrow K_S^0 \pi^+ \pi^-$ time independent

- A built by starting with those contributions identified in the B-factory analyses
- Contributions are added (or removed) depending on the likelihood, goodness of fit, or component magnitude

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^-$</td>
<td>Relativistic Breit–Wigner</td>
</tr>
<tr>
<td>$(K\pi)_0$</td>
<td>Model from QCDF (EFKLLM, arXiv:0902.3645)</td>
</tr>
<tr>
<td>$K^*_2(1430)^-$</td>
<td>Relativistic Breit–Wigner</td>
</tr>
<tr>
<td>$K^*(1680)^-$</td>
<td>Flatté</td>
</tr>
<tr>
<td>$f_0(500)$</td>
<td>Relativistic Breit–Wigner</td>
</tr>
<tr>
<td>$\rho(770)^0$</td>
<td>Gounaris–Sakurai</td>
</tr>
<tr>
<td>$f_0(980)$</td>
<td>Flatté</td>
</tr>
<tr>
<td>$f_0(1500)$</td>
<td>Relativistic Breit–Wigner</td>
</tr>
<tr>
<td>$\chi_{c0}$</td>
<td>Relativistic Breit–Wigner</td>
</tr>
</tbody>
</table>

- Plus a flat non-resonant contribution
For quasi-flavour-specific final states, the CP asymmetry from the isobar coefficients

\[ A_{CP}^{\text{isobar}} = \frac{|\bar{c}_j|^2 - |c_j|^2}{|\bar{c}_j|^2 + |c_j|^2} \]

is corrected for the \( B^0 / B^0 \) production asymmetry of approximately \(-0.35\%\) (and the pion detection asymmetry is consistent with zero).

Quasi-two-body branching fractions are obtained using the fit fraction of each contribution - the relative intensity if only a single component contributed

\[ FF_i = \frac{\int_{DP} |c_i F_i|^2 ds^+ ds^-}{\int_{DP} |\sum_j c_j F_j|^2 ds^+ ds^-} \]
$\bar{B}^0 \rightarrow K^0_S \pi^+ \pi^-$ fit projections

- Significant asymmetry in the $K^*(892)^\pm$ region!
- Systematic uncertainties arise from knowledge of the fit yield, the variation of the signal efficiency and background across the Dalitz plot, the fixed model parameters, modelling the S-wave components, and marginal contributions to the amplitude.
After applying efficiency corrections (same as branching fraction analysis), and correcting for production asymmetry:

\[
\mathcal{A}_{CP}(\bar{B}^0 \rightarrow K^*(892)^-\pi^+) = -0.308 \pm 0.060 \pm 0.011 \pm 0.012
\]

- Approximately 6σ from zero - first observation of CP violation in this mode

- Also measure \(\mathcal{A}_{CP}\) for other decays:

\[
\begin{align*}
\mathcal{A}_{CP}((K\pi)^*_-\pi^+) &= -0.032 \pm 0.047 \pm 0.016 \pm 0.027 \\
\mathcal{A}_{CP}(K_2^*(1430)^-\pi^+) &= -0.29 \pm 0.22 \pm 0.09 \pm 0.03 \\
\mathcal{A}_{CP}(K^*(1680)^-\pi^+) &= -0.07 \pm 0.13 \pm 0.02 \pm 0.03 \\
\mathcal{A}_{CP}(f_0(980)K^0_S) &= 0.28 \pm 0.27 \pm 0.05 \pm 0.14
\end{align*}
\]

where uncertainties are statistical, systematic (experimental) and systematic (DP model)
\[ \Lambda_{b}^{0}(\Xi_{b}^{0}) \rightarrow ph^{-}h^{+}h^{-} \text{ decays} \]

[LHCb-PAPER-2017-034, To be submitted to JHEP]
\( \Lambda_b^0(\Xi_b^0) \to p h^- h^+ h^- \) decays

- Tree and loop contributions similar magnitude - potential for large CPV in decay
- Previous publication by LHCb on triple-product asymmetries - evidence for CP violation (3.3\( \sigma \)) in the decay of \( \Lambda_b^0 \to p \pi^- \pi^+ \pi^- \) [arXiv:1609.05216]
\[ \Lambda_b^0(\Xi_b^0) \rightarrow p h^- h^+ h^- \] branching fractions

- Only use candidates independent of a trigger decision on signal - avoid biasing phase-space
- Simultaneous fit to all final states, constraining \((\pi \leftrightarrow K)\) cross-feed
- \(m(\Xi_b^0) - m(\Lambda_b^0)\) constrained to the world-average value

[\text{LHCb-PAPER-2017-034, to be submitted to JHEP}]
$\Lambda_{b}^{0}(\Xi_{b}^{0}) \rightarrow ph^{-}h^{+}h^{-}$ branching fractions

- Background contribution from multibody $B$ decays estimated by a fit to the spectrum following a proton mass hypothesis swap

- Dominant systematic uncertainty on the branching fractions arises from the variation of the efficiency across the phase-space

[LHCb-PAPER-2017-034, to be submitted to JHEP]
Branching fractions are measured relative to $\Lambda_b^0 \to \Lambda_c^+ (pK^- \pi^+) \pi^-$,

$$
\begin{align*}
B(\Lambda_b^0 \to p\pi^- \pi^+ \pi^-) &= (1.90 \pm 0.06 \pm 0.10 \pm 0.16 \pm 0.07) \cdot 10^{-5}, \\
B(\Lambda_b^0 \to pK^- \pi^+ \pi^-) &= (4.55 \pm 0.08 \pm 0.20 \pm 0.39 \pm 0.17) \cdot 10^{-5}, \\
B(\Lambda_b^0 \to pK^- K^+ \pi^-) &= (0.37 \pm 0.03 \pm 0.04 \pm 0.03 \pm 0.01) \cdot 10^{-5}, \\
B(\Lambda_b^0 \to pK^- K^+ K^-) &= (1.14 \pm 0.03 \pm 0.07 \pm 0.10 \pm 0.05) \cdot 10^{-5},
\end{align*}
$$

where uncertainties are statistical, systematic, and from the $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ and $\Lambda_c^+ \to pK^- \pi^+$ branching fractions. Results for $\Xi_b^0$

$$
\begin{align*}
B(\Xi_b^0 \to pK^- \pi^+ \pi^-) \cdot f_{\Xi_b^0} / f_{\Lambda_b^0} &= (1.72 \pm 0.21 \pm 0.25 \pm 0.15 \pm 0.07) \cdot 10^{-6}, \\
B(\Xi_b^0 \to pK^- \pi^+ K^-) \cdot f_{\Xi_b^0} / f_{\Lambda_b^0} &= (1.56 \pm 0.16 \pm 0.19 \pm 0.13 \pm 0.06) \cdot 10^{-6}, \\
B(\Xi_b^0 \to pK^- K^+ K^-) \cdot f_{\Xi_b^0} / f_{\Lambda_b^0} &\in [0.11 - 0.25] \cdot 10^{-6} \text{ at } 90 \% \text{ C.L.}
\end{align*}
$$

are a product of the branching fraction and ratio of the production fractions of $\Xi_b^0$ and $\Lambda_b^0$ baryons ($f_{\Xi_b^0} / f_{\Lambda_b^0}$). The interval on $\Xi_b^0 \to pK^- K^+ K^-$ branching fraction is obtained using the Feldman-Cousins method.
$B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$

time-dependent analyses

[LHCb-CONF-2016-018]
\(B^0 \rightarrow \pi^+\pi^-\) and \(B^0_s \rightarrow K^+K^-\) time-dependent analyses [LHCb-CONF-2016-018]

- Time-dependent measurement of CP violation in \(B^0 \rightarrow \pi^+\pi^-\) and \(B^0_s \rightarrow K^+K^-\) using 3fb\(^{-1}\) of data - supersedes 1fb\(^{-1}\) LHCb measurement [arXiv:1308.1428]

- Can extract CKM angles \(\gamma\) and \(\beta_s\) via U-spin symmetry [arXiv:1408.4368]

- For

\[
\mathcal{A}(t) = \frac{\Gamma_{\overline{B}^0_{(s)} \rightarrow f}(t) - \Gamma_{B^0_{(s)} \rightarrow f}(t)}{\Gamma_{\overline{B}^0_{(s)} \rightarrow f}(t) + \Gamma_{B^0_{(s)} \rightarrow f}(t)} = \frac{-C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t)}{\cosh(\frac{\Delta \Gamma_{d,s}}{2} t) + A_f^{\Delta \Gamma} \sinh(\frac{\Delta \Gamma_{d,s}}{2} t)}
\]

extract parameters corresponding to

\[
C_f \equiv \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \quad S_f \equiv \frac{2\text{Im}\lambda_f}{1 + |\lambda_f|^2}, \quad A_f^{\Delta \Gamma} \equiv -\frac{2\text{Re}\lambda_f}{1 + |\lambda_f|^2},
\]

\[
\lambda_f \equiv \frac{q}{p} \frac{\bar{A}_f}{A_f}.
\]
$B^0 \rightarrow \pi^+\pi^-$ and $B^0_S \rightarrow K^+K^-$ time-dependent analyses [LHCb-CONF-2016-018]

• $N(B^0 \rightarrow \pi^+\pi^-) = 28\,652 \pm 226$

• $N(B^0 \rightarrow K^+K^-) = 36\,840 \pm 222$

• Flavour tagging calibrated using $B^0_S \rightarrow K^\pm\pi^\mp$ - all final states fitted simultaneously
\(B^0 \rightarrow \pi^+\pi^-\) and \(B^0_S \rightarrow K^+K^-\) time-dependent analyses [LHCb-CONF-2016-018]

\[
\begin{align*}
C_{\pi^+\pi^-} &= -0.24 \pm 0.07 \pm 0.01, \\
S_{\pi^+\pi^-} &= -0.68 \pm 0.06 \pm 0.01, \\
C_{K^+K^-} &= 0.24 \pm 0.06 \pm 0.02, \\
S_{K^+K^-} &= 0.22 \pm 0.06 \pm 0.02, \\
A_{K^+K^-}^{\Delta} &= -0.75 \pm 0.07 \pm 0.11,
\end{align*}
\]

- Consistent with B-factory values - most precise value of \(S_{\pi^+\pi^-}\)
- \((S_{K^+K^-}, C_{K^+K^-})\) differs from \((0, 0)\) at a level of 4.6\(\sigma\)
- Ongoing work to include additional (‘same side’) flavour taggers, update for Run 2 LHCb data, and measure CKM parameters
Search for $B^+ \rightarrow D_s^+ K^+ K^-$ decays

[LHCb-PAPER-2017-032, To be submitted to JHEP]
$B^+ \rightarrow D_s^+ K^+ K^-$ decays

- $B^+ \rightarrow D_s^+ \phi$ proceeds primarily via annihilation diagram in SM - predictions of branching fraction $\mathcal{O}(10^{-7})$
- Additional diagrams contribute in extensions to SM - enhance branching fractions and/or CP asymmetries
- Update previous measurement $(3.0 \text{fb}^{-1})$ to $4.7 \text{fb}^{-1}$

- Selection of $\phi$ enhanced with cut on helicity angle of $|\cos \theta_{\text{hel}}| > 0.4$ - background approximately uniform, efficiency of 82% for signal
- $D_s^+ \rightarrow K^+ K^- \pi^+$ used for $B^+ \rightarrow D_s^+ K^+ K^-$ search, additionally $D_s^+ \rightarrow K^+ \pi^- \pi^+$ and $D_s^+ \rightarrow \pi^+ \pi^- \pi^+$ for $B^+ \rightarrow D_s^+ \phi$
\( B^+ \rightarrow D^+_s K^+ K^- \) decays

- Total \( B^+ \rightarrow D^+_s K^+ K^- \) yield of 443 ± 29 - first observation
- \( B^+ \rightarrow D^+_s K^+ K^- \) efficiencies corrected using the background subtracted phase-space distribution, \( B^+ \rightarrow D^+_s \phi \) assumed to have no variation

- Dominant systematic uncertainties are from the knowledge of the relative efficiencies (for \( B^+ \rightarrow D^+_s K^+ K^- \)), and background fit PDFs and the assumption that \( B^+ \rightarrow D^+_s K^+ K^- \) proceeds purely via \( f_0(980) \) or \( a_0(980) \)
$B^+ \rightarrow D_s^+ K^+ K^-$ decays

- Background subtracted and efficiency corrected $m(D_s^+ K^-)$ (left) and $m(K^+ K^-)$ (right)
- Branching fraction measurements (normalised to $B^+ \rightarrow D_s^+ D^0 (K^+ K^-)$):

$$B(B^+ \rightarrow D_s^+ K^+ K^-) = (7.1 \pm 0.5 \pm 0.6 \pm 0.7) \times 10^{-6}$$

$$B(B^+ \rightarrow D_s^+ \phi) < 4.4 (4.9) \times 10^{-7}, \text{ at } 90(5)\% \text{ confidence}$$

- Uncertainties are statistical, systematic, and on the resonance and normalisation branching fractions.
Summary
Summary

- Most precise measurements of the $B_{(s)}^0 \rightarrow K_S^0 h^+ h^-$ branching fractions, but are yet to observe $B_s^0 \rightarrow K_S^0 K^+ K^-$

- Untagged, time-integrated amplitude analysis of $\bar{B}^0 \rightarrow K_S^0 \pi^+ \pi^-$ performed, and CP violation observed for the first time in the decay of $\bar{B}^0 \rightarrow K^*^- \pi^+$ at a level of $6\sigma$

- First observations of many four-body $b$-baryon decay modes, with a large number of candidates - perfect for further investigations of CPV in baryon decays

- Updated time-dependent study of $B^0 \rightarrow \pi^+ \pi^-$ and $B_s^0 \rightarrow K^+ K^-$ decays, with evidence for CPV in $B_s^0 \rightarrow K^+ K^-$ decays

- First observation of $B^+ \rightarrow D_s^+ K^+ K^-$, and limit on $\mathcal{B}(B^+ \rightarrow D_s^+ \phi)$

- Many more results on these and other topics coming soon!
Backup
$\bar{B}^0 \rightarrow K^0_S \pi^+ \pi^-$
\[ T(m) = F(m) \left( \frac{c_0}{m^2} + c_1 \right) \]

- F(m) form factors
- \( c_0, c_1 \) left free in fit (phase of one fixed here)
- Parameterises the full invariant-mass range
CPV in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ decays

With $C^\hat{T} = p_p \cdot (p_{h_1^-} \times p_{h_2^+})$, and $\bar{C}^\hat{T} = p_{\bar{p}} \cdot (p_{h_1^+} \times p_{h_2^-})$:

$$A^\hat{T}(C^\hat{T}) = \frac{N(C^\hat{T} > 0) - N(C^\hat{T} < 0)}{N(C^\hat{T} > 0) + N(C^\hat{T} < 0)},$$

$$\bar{A}^\hat{T}(\bar{C}^\hat{T}) = \frac{\bar{N}(-\bar{C}^\hat{T} > 0) - \bar{N}(-\bar{C}^\hat{T} < 0)}{\bar{N}(-\bar{C}^\hat{T} > 0) + \bar{N}(-\bar{C}^\hat{T} < 0)},$$

$$a^\hat{T}_{CP-\text{odd}} = \frac{1}{2} (A^\hat{T} - \bar{A}^\hat{T}) ,$$
\[ \Lambda^0_b(\Xi^0_b) \rightarrow p h^- h^+ h^- \text{ decays} \]

- Simultaneous fit yields:

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Signal yield</th>
<th>S/B</th>
<th>±3σ range (MeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Lambda^0_b \rightarrow p\pi^- \pi^+ \pi^- )</td>
<td>1809 ± 48</td>
<td>4.9 ± 0.3</td>
<td>[5573.9, 5674.6]</td>
</tr>
<tr>
<td>( \Lambda^0_b \rightarrow pK^- \pi^+ \pi^- )</td>
<td>5193 ± 76</td>
<td>7.7 ± 0.4</td>
<td>[5574.4, 5674.2]</td>
</tr>
<tr>
<td>( \Lambda^0_b \rightarrow pK^- K^+ \pi^- )</td>
<td>444 ± 30</td>
<td>0.71 ± 0.06</td>
<td>[5577.4, 5671.1]</td>
</tr>
<tr>
<td>( \Lambda^0_b \rightarrow pK^- K^+ K^- )</td>
<td>1706 ± 46</td>
<td>8.1 ± 0.7</td>
<td>[5579.0, 5674.6]</td>
</tr>
<tr>
<td>( \Xi^0_b \rightarrow pK^- \pi^+ \pi^- )</td>
<td>183 ± 22</td>
<td>0.59 ± 0.09</td>
<td>[5747.9, 5846.2]</td>
</tr>
<tr>
<td>( \Xi^0_b \rightarrow pK^- \pi^+ K^- )</td>
<td>199 ± 21</td>
<td>0.8 ± 0.1</td>
<td>[5747.4, 5846.2]</td>
</tr>
<tr>
<td>( \Xi^0_b \rightarrow pK^- K^+ K^- )</td>
<td>27 ± 14</td>
<td>0.14 ± 0.08</td>
<td>[5752.7, 5840.8]</td>
</tr>
<tr>
<td>( \Lambda^0_b \rightarrow (\Lambda^+_c \rightarrow pK^- \pi^+) \pi^- )</td>
<td>16518 ± 133</td>
<td>-</td>
<td>[5573.7, 5674.8]</td>
</tr>
</tbody>
</table>
$B^0 \rightarrow \pi^+ \pi^-$ and $B^0_s \rightarrow K^+ K^-$ time-dependent analyses

- Time-dependent asymmetry $B^0 \rightarrow \pi^+ \pi^-$ (left), $B^0_s \rightarrow K^+ K^-$ (right):
$B^+ \rightarrow D^+_s K^+ K^-$ fit categories
Production asymmetries, 8TeV

![Graph 1: $A^p(B^+)$](image1)

![Graph 2: $A^p(B^0)$](image2)

$LHCb \quad \sqrt{s} = 8 \text{ TeV}$
An aside on S-wave

• Accurate S-wave models very important, e.g., in $B^+ \to \pi^+\pi^+\pi^-$ Dalitz-plot (from arXiv:1408.5373)

• Characteristic of CPV in interference between S and P-wave

• S-wave can be modelled using different approaches as cross-check (e.g., K-matrix, isobar model, model independent, ...)

• Experimenting with better motivated S-wave descriptions (e.g., unitarity conserving K-matrix models)