Charmless multi-body $b$ decays at LHCb

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On behalf of the LHCb experiment

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This talk covers some recent highlights in this sector from LHCb

- CPV measurements in charmless three-body decays involving $K^0_S$
  

- Searches for $CP$ violation in $b$-baryon multi-body decays and 4-body decays BR
  
  [i.e. $\Lambda^0_b \to p\{K,\pi\}, \Lambda^0_b \to \{\Lambda, K^0\}hh, \Lambda^0_b \to p3h$]
  
  [JHEP 098 (2018) 2018]

- Searches for $CP$ violation in the baryonic sector
  
  [Preliminary: LHCb-PAPER-2018-001]
Charmless three-body decays to final states containing a long-lived particle

LHCb results: $\mathcal{L} = 3\text{ fb}^{-1} - 2011 + 2012$ dataset

Updated branching fraction of $B^0(s) \to K^0 h^+ h^-$ decays

[JHEP 11 (2017) 027]

Dalitz plot analysis of $B^0 \to K^0 \pi^+ \pi^-$ decays

Three-body decays containing $K^0_s$

Many channels have been already explored in the B-factories which has a great range of interesting features

- Transitions mediated by $b \rightarrow u$ (tree) and/or $b \rightarrow d,s$ (penguin) diagrams

- Several comparable amplitudes can give rise to (via interference) large $CP$ violation

- Deviations of observables from their expected values in the SM could indicate NP contributions

- Potential to measure all three UT angles
  
  \[e.g. \beta\text{-angle } B^0 \rightarrow K^0_S \pi^+ \pi^- , B^0 \rightarrow K^0_S K^+ K^-\]

- Rich spectrum of final/resonant states can be further disentangled via amplitude analysis
Recent results from $B^0_{(s)} \to K^0 h^+ h^-'$ decays

- BF measurements updated with 3 fb$^{-1}$
  
  $\mathcal{B}(B^0_{s} \to K^0 K^+ K^-) \in [0.4 - 2.5] \times 10^{-6}$ at 90% C.L.

- Long term: time-dependent amplitude analysis for CKM-phases measurement
- Short term: time-integrated analysis
  [sensitive to $\Sigma$ in flavour-specific contributions]
Dalitz plot analysis of $B^0 \rightarrow K^0 \pi^+ \pi^-$

Analysis performed with ~3.2k signal events and purity of 85-95%

Backgrounds due to Combinatorial (3-13%) and cross-feed (2-3%)

Signal region: $\pm 3\sigma$ around nominal mass is considered for the Dalitz plot fit

Quasi-flavour-specific final state
Amplitude analysis most commonly performed in the “Isobar Model”, in which the total amplitude is approximated as coherent sum of quasi-two-body contributions:

\[
\mathcal{A}(m_{ij}^2, m_{jk}^2) = \sum_{l=1}^{N} c_l F_l(m_{ij}^2, m_{jk}^2)
\]

\( c_l \): complex coefficients describing the relative magnitude and phase of the different isobars

\( F_l \): dynamical amplitudes that contain the lineshape and spin-dependence of the hadronic part

Many observables can be accessed: Re\((c_l)\) and Im\((c_l)\) or \(|c_l|\) and arg\((c_l)\); or derived quantities such as BF and A\(_{CP}\)

Resonance mass term (e.g. Breit-Wigner) Barrier factors - \( p, q \): momenta of bachelor and resonance Angular probability distribution
Dalitz plot analysis of $B^0 \rightarrow K^0\pi^+\pi^-$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Parameters</th>
<th>Lineshape</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^-$</td>
<td>$m_0 = 891.66 \pm 0.26$</td>
<td>RBW</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 50.8 \pm 0.9$</td>
<td></td>
</tr>
<tr>
<td>$(K\pi)_0^-$</td>
<td>$\text{Re}(\lambda_0) = 0.204 \pm 0.103$</td>
<td>EFKLLM</td>
</tr>
<tr>
<td></td>
<td>$\text{Im}(\lambda_0) = 0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\text{Re}(\lambda_1) = 1$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\text{Im}(\lambda_1) = 0$</td>
<td></td>
</tr>
<tr>
<td>$K_2^*(1430)^-$</td>
<td>$m_0 = 1425.6 \pm 1.5$</td>
<td>RBW</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 98.5 \pm 2.7$</td>
<td></td>
</tr>
<tr>
<td>$K^*(1680)^-$</td>
<td>$m_0 = 1717 \pm 27$</td>
<td>Flatté</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 332 \pm 110$</td>
<td></td>
</tr>
<tr>
<td>$f_0(500)$</td>
<td>$m_0 = 513 \pm 32$</td>
<td>RBW</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 335 \pm 67$</td>
<td></td>
</tr>
<tr>
<td>$\rho(770)^0$</td>
<td>$m_0 = 775.26 \pm 0.25$</td>
<td>GS</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 149.8 \pm 0.8$</td>
<td></td>
</tr>
<tr>
<td>$f_0(980)$</td>
<td>$g_\pi = 0.165 \pm 0.025$</td>
<td>Flatté</td>
</tr>
<tr>
<td></td>
<td>$g_K = 0.695 \pm 0.119$</td>
<td></td>
</tr>
<tr>
<td>$f_0(1500)$</td>
<td>$m_0 = 1505 \pm 6$</td>
<td>RBW</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 109 \pm 7$</td>
<td></td>
</tr>
<tr>
<td>$\chi_{c0}$</td>
<td>$m_0 = 3414.75 \pm 0.31$</td>
<td>RBW</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_0 = 10.5 \pm 0.6$</td>
<td></td>
</tr>
<tr>
<td>Nonresonant (NR)</td>
<td></td>
<td>Phase space</td>
</tr>
</tbody>
</table>

EFKLLM: $R_j(m) = F(m) \left( \frac{\lambda_0}{m^2} + \lambda_1 \right)$

Asymmetry observable derived from usual isobar parameters

$$A_{\text{raw}} = \frac{|\bar{c}_j|^2 - |c_j|^2}{|\bar{c}_j|^2 + |c_j|^2}$$

The $CP$ asymmetry is related to the raw asymmetry by $A_{\text{CP}} = A_{\text{raw}} - A_{\Delta}$


$A_{\Delta} = A_P(B^0) + A_D(\pi)$

(-0.35 $\pm$ 0.81)\% 0.25\%

Fit fractions:

$$F_i = \frac{\int \int_{DP} |c_i F_i(s_+, s_-)|^2 ds_+ ds_-}{\int \int_{DP} \sum_j |c_j F_j(s_+, s_-)|^2 ds_+ ds_-}$$
Dalitz plot fit results

\[ A_{CP}(K^*(892)^-\pi^+) = -0.308 \pm 0.060 \pm 0.011 \pm 0.012 \]
\[ A_{CP}((K\pi)_0^-\pi^+) = -0.032 \pm 0.047 \pm 0.016 \pm 0.027 \]
\[ A_{CP}(K^*_2(1430)^-\pi^+) = -0.29 \pm 0.22 \pm 0.09 \pm 0.03 \]
\[ A_{CP}(K^*(1680)^-\pi^+) = -0.07 \pm 0.13 \pm 0.02 \pm 0.03 \]
\[ A_{CP}(f_0(980)K^0_S) = 0.28 \pm 0.27 \pm 0.05 \pm 0.14 \]

First observation of \( CP \) violation in \( B^0 \to K^*(892)\pi \) with \(~6\) sigma

Previous world average
\[ A(K^*(892)\pi) = -0.23 \pm 0.06 \]

The resonance state $K^*(1680)$ has been included in the model (not seen in previous analyses)

No signature of $f_2(1270)$

Alternative LASS modelling for the S-wave has been examined:

$$-2\Delta \ln L = 85$$

No systematic is assigned to the choice of the model, but only uncertainties associated to fixed parameters

### Dalitz plot fit results

<table>
<thead>
<tr>
<th>Fit fractions:</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{F}(K^*(892)^-\pi^+)$</td>
<td>9.43 ± 0.40 ± 0.33 ± 0.34 %</td>
</tr>
<tr>
<td>$\mathcal{F}((K\pi)_{0}^0\pi^+)$</td>
<td>32.7 ± 1.4 ± 1.5 ± 1.1 %</td>
</tr>
<tr>
<td>$\mathcal{F}(K_2^*(1430)^-\pi^+)$</td>
<td>2.45 ± 0.10 ± 0.08 ± 0.14 ± 0.12 %</td>
</tr>
<tr>
<td>$\mathcal{F}(K^*(1680)^-\pi^+)$</td>
<td>7.34 ± 0.30 ± 0.31 ± 0.06 %</td>
</tr>
<tr>
<td>$\mathcal{F}(f_0(980)K^0_S)$</td>
<td>18.6 ± 0.8 ± 0.7 ± 1.2 %</td>
</tr>
<tr>
<td>$\mathcal{F}(\rho(770)^0 K^0_S)$</td>
<td>3.8 ± 1.1 ± 0.7 ± 0.4 %</td>
</tr>
<tr>
<td>$\mathcal{F}(f_0(500)K^0_S)$</td>
<td>0.32 ± 0.40 ± 0.08 ± 0.19 ± 0.23 %</td>
</tr>
<tr>
<td>$\mathcal{F}(f_0(1500)K^0_S)$</td>
<td>2.60 ± 0.54 ± 1.28 ± 0.60 %</td>
</tr>
<tr>
<td>$\mathcal{F}(\chi_{c0}K^0_S)$</td>
<td>2.23 ± 0.40 ± 0.32 ± 0.22 ± 0.13 %</td>
</tr>
<tr>
<td>$\mathcal{F}(K^0_S\pi^+\pi^-)^{NR}$</td>
<td>24.3 ± 1.3 ± 3.7 ± 4.5 %</td>
</tr>
</tbody>
</table>
Searches for \( CP \) violation in \( b \)-baryon decays

LHCb results: \( \mathcal{L} = 3 \text{ fb}^{-1} - 2011 + 2012 \) dataset

Searches for \( CP \) in multi-body decays

[JHEP 04 (2014) 087, JHEP 05 (2016) 08]

BR measurements of \( \Lambda^0_b \) and \( \Xi^0_b \) decays

[LHCb, JHEP 1802 (2018) 098]
**CP violation in the baryonic sector**

Phenomenon well established in the meson sector, *i.e.* Kaon and B$^{±,0(s)}$ decays: no deviation from the SM has been seen

As-of-yet no CP violation in $b$-baryons has been observed, though the CKM mechanism predicts sizeable amount of violation

At LHCb $b$-baryons are collected in unprecedented quantities → opens a new field in flavour physics for precision measurements

Same underlying short distance physics for $b$-baryons and $B$ mesons but with different spin and QCD structure
**CP violation in the baryonic sector**

*CP violation in decay*: only type available in the baryonic sector (no mixing due to baryon number conservation)

This observable can be measured by comparing yields between baryon/anti-baryon:

\[
A_{CP} = \frac{N(A \rightarrow f) - N(\bar{A} \rightarrow \bar{f})}{N(A \rightarrow f) + N(\bar{A} \rightarrow \bar{f})} \propto \sin (\delta_1 - \delta_2) \sin (\varphi_1 - \varphi_2)
\]

- Contributions from at least two amplitudes: \(e.g. \ A_1 e^{i\delta_1} e^{i\phi_1}, A_2 e^{i\delta_2} e^{i\phi_2}\)
- Need non-vanishing strong and weak phase difference
- Sensitive to baryon-antibaryon production asymmetries
- Sensitive to charged particle reconstruction asymmetries
Beauty baryon: two-body case

Simplest decay modes: $\Lambda_{b}^{0} \rightarrow pK^{-}, p\pi$

[―CDF, PRL 113, 242001 (2014)―]

Ongoing analysis - expected approximately 10x CDF statistics

Potentially large CPV effects in charmless decays

[―Phys. Rev. D 91, 116007 (2015)―]

<table>
<thead>
<tr>
<th>Decay</th>
<th>$A(b \rightarrow f)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_{b}^{0} \rightarrow p\pi^{-}$</td>
<td>$+0.06 \pm 0.07 \pm 0.03$</td>
</tr>
<tr>
<td>$\Lambda_{b}^{0} \rightarrow pK^{-}$</td>
<td>$-0.10 \pm 0.08 \pm 0.04$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>decay</th>
<th>our result</th>
<th>pQCD [5]</th>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{2}A_{CP}(\Lambda_{b} \rightarrow pK^{-})$</td>
<td>$5.8 \pm 0.2 \pm 0.1$</td>
<td>$-5^{+26}_{-5}$</td>
<td>$-10 \pm 8 \pm 4$ [8]</td>
</tr>
<tr>
<td>$10^{2}A_{CP}(\Lambda_{b} \rightarrow p\pi^{-})$</td>
<td>$-3.9 \pm 0.2 \pm 0.0$</td>
<td>$-31^{+43}_{-1}$</td>
<td>$6 \pm 7 \pm 3$ [8]</td>
</tr>
<tr>
<td>$10^{2}A_{CP}(\Lambda_{b} \rightarrow pK_{s}^{-})$</td>
<td>$19.6 \pm 1.3 \pm 1.0$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$10^{2}A_{CP}(\Lambda_{b} \rightarrow p\rho^{-})$</td>
<td>$-3.7 \pm 0.3 \pm 0.0$</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
Beauty baryon: multi-body decays

Limited information available in two-body decays: i.e. BF and $A_{CP}$
Additional information can be obtained via multi-body decays ($n > 2$)

- CPV in $\Lambda^0_b \rightarrow pK^0\pi$ decays [LHCb, JHEP 04 (2014) 087]
  
  [Note that amplitude analysis (Dalitz plot) of this mode can access the intermediate channel $pK^* - SM\ CP$ violation expected to be $\sim 20\%$]

- CPV in $\Lambda^0_b \rightarrow \Lambda h^+h^-$ decays [LHCb, JHEP 05 (2016) 08]

- Triple-product asymmetry in $\Lambda^0_b \rightarrow \Lambda\phi$ decays [LHCb, PLB 759 (2016) 282]

- CPV in $\Lambda^0_b \rightarrow J/\psi\pi$ and $J/\psi pK^-$ decays [LHCb, JHEP 07 (2014) 103]

- CPV in $\Lambda^0_b \rightarrow pK^-\mu^+\mu^-$ decays [LHCb, JHEP 06 (2017) 108]

All measurements consistent with CP symmetry!
Search for \(CP\) violation in 4-body decays


Integrated and triple-product asymmetry measurements in \(\Lambda_{b}^{0}(\Xi_{b}^{0}) \rightarrow p\pi[\pi\pi, K\bar{K}, K\pi]\)

Transitions with both tree and penguin amplitudes at comparable magnitude

Tree diagram \(\propto V_{ub} \sim \lambda^3\)

Penguin diagram \(\propto \sum_{x=u,c,t} V_{bx} V_{xd} \sim \lambda^3\)

First step: determine the signal yields for these channels
BR measurements of $\Lambda^0_b$, $\Xi^0_b \rightarrow p3h$

BR wrt the $\Lambda^0_b \rightarrow \Lambda^+ c\pi$ channel [First observations]

$$
\frac{\mathcal{B}(X_b \rightarrow phh''')}{\mathcal{B}(A^0_b \rightarrow \Lambda^+_c\pi^-)} \cdot \frac{f_{X_b}}{f_{A^0_b}} = \frac{\epsilon_{\text{geo.}}^{A^0_b \rightarrow \Lambda^+_c\pi^-} \cdot \epsilon_{\text{sel.}}^{X_b \rightarrow phh'''}}{\epsilon_{\text{geo.}}^{X_b \rightarrow phh'''} \cdot \epsilon_{\text{sel.}}^{X_b \rightarrow phh'''} \cdot \frac{1}{\mathcal{N}_{X_b \rightarrow phh'''}} \cdot \frac{1}{\mathcal{N}_{A^0_b \rightarrow \Lambda^+_c\pi^-}}}
$$

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[R. Coutinho (UZH) - Beauty 2018]
Searches for *CP* violation in four body *b*-baryon decays

LHCb results: $\mathcal{L} = 3 \text{ fb}^{-1}$ – 2011 + 2012 dataset

**Searches for CPV in $\Lambda^0_b (\Xi^0_b) \rightarrow p h^+ h^- h''^-$ decays**

**CP violation in the baryonic sector**

**Triple product asymmetry:** use momenta of any 3 final particles in 4-body decays

\[
C_{\tilde{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \propto \sin \Phi, \text{ for } \Lambda_b^0
\]

\[
\overline{C}_{\tilde{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}) \propto \sin \overline{\Phi}, \text{ for } \Lambda_b^0
\]

- \( h_1 = \pi, h_2 = K \) for \( \Lambda_b^0 \to p\pi^-K^+K^- \)
- \( h_1 = \pi_{\text{fast}}, h_2 = \pi_{\text{slow}} \) for \( \Lambda_b^0 \to p\pi^-\pi^+\pi^- \)

**P-odd asymmetries:**

\[
A_{\tilde{T}}(C_{\tilde{T}}) = \frac{N(C_{\tilde{T}}>0) - N(C_{\tilde{T}}<0)}{N(C_{\tilde{T}}>0)+N(C_{\tilde{T}}<0)}, \text{ for } \Lambda_b^0
\]

\[
\overline{A}_{\tilde{T}}(\overline{C}_{\tilde{T}}) = \frac{\overline{N}(-C_{\tilde{T}}>0) - \overline{N}(-C_{\tilde{T}}<0)}{\overline{N}(-C_{\tilde{T}}>0)+\overline{N}(-C_{\tilde{T}}<0)}, \text{ for } \Lambda_b^0
\]

**CP violation observable**

\[
a_{CP}^{\tilde{T}-\text{odd}} = \frac{1}{2} (A_{\tilde{T}} - \overline{A}_{\tilde{T}})
\]

**P-violating observable**

\[
a_{P}^{\tilde{T}-\text{odd}} = \frac{1}{2} (A_{\tilde{T}} + \overline{A}_{\tilde{T}})
\]

The \( A_{\tilde{T}}, \overline{A}_{\tilde{T}}, a_{P}^{\tilde{T}-\text{odd}} \) and \( a_{CP}^{\tilde{T}-\text{odd}} \) observables are largely unaffected by \( A_D \) and \( A_P \).
**CP violation measurements in** $\Lambda_0^b \rightarrow p\pi[p^+\pi^-,K^+K^-]$

$\Lambda_0^b : C_T > 0$

$\Lambda_0^b : C_T < 0$

\[ A_T(C_T) = \frac{N(C_T > 0) - N(C_T < 0)}{N(C_T > 0) + N(C_T < 0)} , \text{ for } \Lambda_0^b \]

\[ \bar{A}_T(\bar{C}_T) = \frac{\bar{N}(\bar{C}_T > 0) - \bar{N}(\bar{C}_T < 0)}{\bar{N}(\bar{C}_T > 0) + \bar{N}(\bar{C}_T < 0)} , \text{ for } \Lambda_0^b \]

Phase space integrated asymmetries for $\Lambda_0^b \rightarrow p\pi[p^+\pi^-]$

$\hat{a}_{P}^{T-\text{odd}} = (-3.71 \pm 1.45 \pm 0.32)\%$

$\hat{a}_{CP}^{T-\text{odd}} = (1.15 \pm 1.45 \pm 0.32)\%$

Consistent with hypothesis of P and CP symmetry

Similar results are found for the less sensitive mode $p\pi^+K^+K^-$
Phase-space \( CP \) violation in \( \Lambda_{0b} \to p\pi\pi^+\pi^- \)

Binning A: based on dominant resonant structures, \textit{e.g.} \( \Delta^{++}, N^* \) and \( \rho(770) \)

- LHCb Scheme A
  - \( a_{P}^{T}\text{-odd} \)
    - \( \chi^2/\text{ndf}=27.9/12 \)
  - \( a_{CP}^{T}\text{-odd} \)
    - \( \chi^2/\text{ndf}=21.1/12 \)

Binning B: function of the angle between the decay planes \( \pi^+\pi^-\text{slow} \) and \( p\pi^-\text{fast} \)

- LHCb Scheme B
  - \( a_{P}^{T}\text{-odd} \)
    - \( \chi^2/\text{ndf}=20.7/10 \)
  - \( a_{CP}^{T}\text{-odd} \)
    - \( \chi^2/\text{ndf}=30.5/10 \)

First evidence for \( CP \) violation with 3.3 standard deviations!
Measurements in $\Lambda^0_b \rightarrow pK[\pi\pi,KK]$, $\Xi^0_b \rightarrow pK\pi K$

Integrated and triple-product asymmetry measurements in dominant modes

<table>
<thead>
<tr>
<th>$\Lambda^0_b \rightarrow pK^-\pi^+\pi^-$</th>
<th>$\Lambda^0_b \rightarrow pK^-K^+K^-$</th>
<th>$\Xi^0_b \rightarrow pK^-K^{-}\pi^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_P^{T_{\text{odd}}}$ (%)</td>
<td>$a_{CP}^{T_{\text{odd}}}$ (%)</td>
<td></td>
</tr>
<tr>
<td>$-0.60 \pm 0.84 \pm 0.31$</td>
<td>$-1.56 \pm 1.51 \pm 0.32$</td>
<td>$-3.04 \pm 5.19 \pm 0.36$</td>
</tr>
<tr>
<td>$-0.81 \pm 0.84 \pm 0.31$</td>
<td>$1.12 \pm 1.51 \pm 0.32$</td>
<td>$-3.58 \pm 5.19 \pm 0.36$</td>
</tr>
</tbody>
</table>

Results are found to be compatible with $P$ and $CP$ symmetries
Measurements in $\Lambda_{b}^{0} \rightarrow pK[\pi\pi, KK]$

**Binning A:** dominant resonances, e.g. $\Delta^{++}$, $K^{*}(892)$ and $f_0(980)$

**Binning B:** angle between the decay planes $pK$ and $\pi\pi$

**Asymmetries [%]**

<table>
<thead>
<tr>
<th>Phase space region</th>
<th>$a_{CP}^{\text{odd}}$</th>
<th>$\chi^2$/ndf</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb [PRELIMINARY]</td>
<td>$a_{CP}^{\text{odd}}$</td>
<td>7.2/14</td>
</tr>
<tr>
<td>(a)</td>
<td>$a_{CP}^{\text{odd}}$</td>
<td>13.0/14</td>
</tr>
</tbody>
</table>

**Measurements in regions of the phase space are also found to be consistent with the conservation of both $P$ and $CP$ symmetries**

[PRELIMINARY, LHCb-PAPER-2018-001]
General conclusions

- Enormous wealth of physics to be found in multi-body hadronic decays (e.g. CKM phase measurements, CP violation)

- First observation of CP violation in $B^0 \to K^*(892)\pi$ decays

- Searches for CPV $b$-baryons are still in the early stages but with increased data from the LHC this area is becoming more of interest

- CP violation is expected in the baryon sector and first evidence in $\Lambda^0_b \to p\pi\pi^+\pi$ decays has been seen by LHCb
  - Still many interesting results are foreseen with LHCb Run-I dataset (e.g. $B^0_s$ and $b$-baryon DP analyses, $B^+_c$ decays)
  - Run-II dataset will provide unprecedented insights in this field
Spectrometer mainly dedicated to heavy flavour physics

LHCb Integrated Recorded Luminosity in pp, 2010-2017

[3 fb⁻¹ Run-I (2011/12) at 7/8 TeV]
[3.7 fb⁻¹ Run-II (2015-17) at 13 TeV]

Dalitz plot analysis features

Intensity along bands indicates magnitude and the spin of the given resonance

Angular distribution of resonance related to Legendre Polynomials

Amplitude analysis can access:

- Relative phases between states
- Sensitivity to CP violating effects
- Resolve ambiguities in weak phases
- Hadron spectroscopy

Particle Data Group Collaboration
PRD 86 (2012) 010001
Dalitz plot analysis features

Intensity along bands indicates magnitude and the spin of the given resonance

Amplitude analysis can access:
- Relative phases between states
- Sensitivity to CP violating effects
- Resolve ambiguities in weak phases
- Hadron spectroscopy

Particle Data Group Collaboration
PRD 86 (2012) 010001

Toy simulation using Laura++ package:
Detector acceptance modelling

Since each detector has its own acceptance, such effects need to be properly accommodated when performing a Dalitz plot fit.

- Two general approaches: 2-D polynomial (or similar) function or a 2-D histogram.

\[ \mathcal{L} = \prod_{l=1}^{N_{\text{evts}}} \frac{e(m_{ij}^2, m_{jk}^2) \left| \sum_{m=1}^{N_R} c_m F_m(m_{ij}^2, m_{jk}^2) \right|^2}{\int_{\text{DP}} e(m_{ij}^2, m_{jk}^2) \left| \sum_{m=1}^{N_R} c_m F_m(m_{ij}^2, m_{jk}^2) \right|^2 \, d\text{DP}} \]

LHCb general strategy has been based on Spline these distributions in the squared DP.
Detector acceptance modelling

Preferential co-ordinate transformation to improve sensitivity modelling in the DP borders
Background contributions

Contributions from different backgrounds can be presented and need to be modelled

\[
\mathcal{L} = \prod_{l=1}^{N_{\text{events}}} \frac{\epsilon(m_{ij}^2, m_{jk}^2) \left| \sum_{m=1}^{N_R} c_m F_m(m_{ij}^2, m_{jk}^2) \right|^2}{\int_{DP} \epsilon(m_{ij}^2, m_{jk}^2) \left| \sum_{m=1}^{N_R} c_m F_m(m_{ij}^2, m_{jk}^2) \right|^2 dDP} + \frac{\sum_{m=1}^{N_B} |k_m|^2 |B_m(m_{ij}^2, m_{jk}^2)|^2}{\int_{DP} \sum_{m=1}^{N_B} |k_m|^2 |B_m(m_{ij}^2, m_{jk}^2)|^2 dDP}
\]

**Signal (Coherent)**

**Background (Incoherent)**
**Kπ invariant mass modelling**

- **K*(892) resonance** - Relativistic Breit-Wigner

- **Kπ S-wave** contribution

  Toy simulation using Laura++ package
  arXiv:1711.09854

  ![Graph](image)

  


  \[
  R_j(s) = \frac{\sqrt{s}}{q \cot \delta_B - i\theta} + e^{2i\delta_B} \frac{m_0 \Gamma_0 \frac{m_0}{q_0}}{(m_0^2 - s) - i m_0 \Gamma_0 \frac{q_0}{\sqrt{s} \frac{m_0}{q_0}}}
  \]

- **EFKLLM lineshape** [PRD 79 (2009) 094005]

  \[
  R_j(m) = F(m) \left( \frac{c_0}{m^2} + c_1 \right)
  \]

- **κ + K*0(1430) resonance** [Flatté]

  NR parametrisation [PRD 92 (2015) 054010]

  \[
  R_j(s) = \frac{1}{1 + \frac{s}{\Lambda^2}}
  \]

  Single model κ + K*0(1430) + K*0(1950)
  [arXiv:1701.04881]

  Others (non DP), polynomial expansion [PRD 93 (2016) 074025]
Search for $CP$ violation in $\Lambda_{b}^{0} \rightarrow \{\Lambda,K^{0}\}hh$

Studies of $b$-baryon decays is still at an early stage, although LHCb interesting has been significantly increasing.

First observation (8.6 $\sigma$) of the $\Lambda_{b}^{0} \rightarrow K^{0}p\pi^{-}$ decay has been obtained with 1 fb$^{-1}$

- Phase space integrated asymmetry:
  \[ A^{CP}(\Lambda_{b}^{0} \rightarrow K^{0}_{S}p\pi^{-}) = 0.22 \pm 0.13{\text{(stat.)}} \pm 0.03{\text{(syst.)}} \]

- Search for local (binned) asymmetries, i.e. similar to the $B^{\pm} \rightarrow h^{\pm}h^{+}h^{-}$

Possible contribution from $\Lambda_{b}^{0} \rightarrow pK^{*-}$

R. Coutinho (UZH) - Beauty 2018
Results for $\Lambda^0_b(\Xi^0_b) \to \Lambda h^+h^-$ decays

First observation of the decays $\Lambda^0_b \to \Lambda K^+\pi^- (8.1\sigma)$ and $\Lambda^0_b \to \Lambda K^+K^- (15.8\sigma)$ with 3 fb$^{-1}$

$$\mathcal{A}_{CP}(\Lambda^0_b \to \Lambda K^+\pi^-) = -0.53 \pm 0.23 \text{ (stat)} \pm 0.11 \text{ (syst)}$$

$$\mathcal{A}_{CP}(\Lambda^0_b \to \Lambda K^+K^-) = -0.28 \pm 0.10 \text{ (stat)} \pm 0.07 \text{ (syst)}$$
Towards [more] charmless DP analyses

Efforts on understanding the large asymmetries seen in $B^+ \rightarrow h^+ h^+ h^+$ decays

$$A_{\text{raw}}^{CP} (B^\pm \rightarrow \pi^\pm \pi^\mp \pi^-) = 0.584 \pm 0.082 \pm 0.027 \pm 0.007$$

$$A_{\text{reg}}^{CP} (B^\pm \rightarrow \pi^\pm K^+ K^-) = -0.648 \pm 0.070 \pm 0.013 \pm 0.007$$

R. Coutinho (UZH) - Beauty 2018
Towards [more] charmless DP analyses

- DP analysis is clearly required, in particular to understand the origin of the strong phase difference
- Such analyses are currently ongoing at LHCb!
  \[i.e. (1) \ B^\pm \to \pi^\pm \pi^\mp \pi^\pm, \ (2) \ B^\pm \to \pi^\pm K^+ K^- \ldots\]
- Unprecedented statistics (e.g. 5-200 K events for \(B^\pm \to \pi^\pm K^+ K^-\), \(K^\pm \pi^+ \pi^-\)): simplified theoretical descriptions are no longer sufficient
  - How to model non-resonant contributions, final state interaction, re-scattering effects? Connect two (or all) different final states?
  - How to obtain an accurate description of the S-wave?
    \[e.g. \text{for } B^\pm \to \pi^\pm K^+ K^- \text{ already limited, } \ NR+ \ K^*_0(1430) \text{ or } \kappa + K^*_0(1430)\text{?} \]
Towards [more] charmless DP analyses

Many other channels that have never been explored in the B-factories are gradually being investigated

- Untagged time-integrated analysis of $B^0_s \rightarrow K^0_s K\pi$ decays
  - Only flavour averaged fit fractions
  - Modelling of S-wave of crucial relevance, \textit{i.e.} LASS/EFKLLM
- Amplitude analysis of $\Lambda_b \rightarrow K^0_s p\pi$ – Large $A_{CP}(pK^*) \sim 20\%$ predicted

[PRD 91 (2015) 11, 116007]
BR measurements of $\Lambda^0_b$, $\Xi^0_b \rightarrow p3h$

BR wrt the $\Lambda^0_b \rightarrow \Lambda^+_c\pi^-$ channel [First observations]

\[
\frac{\mathcal{B}(X_b \rightarrow phh''')}{\mathcal{B}(A^0_b \rightarrow \Lambda^+_c\pi^-)} \cdot \frac{f_{X_b}}{f_{A^0_b}} = \frac{\epsilon_{\text{geo.}}^{\Lambda^0_b \rightarrow \Lambda^+_c\pi^-}}{\epsilon_{\text{geo.}}^{X_b \rightarrow phh'''}} \cdot \frac{\epsilon_{\text{sel.}}^{\Lambda^0_b \rightarrow \Lambda^+_c\pi^-}}{\epsilon_{\text{sel.}}^{X_b \rightarrow phh'''}} \cdot \frac{\epsilon_{\text{PID}}^{\Lambda^0_b \rightarrow \Lambda^+_c\pi^-}}{\epsilon_{\text{PID}}^{X_b \rightarrow phh'''}} \cdot \frac{1}{\epsilon_{\text{veto}}^{X_b \rightarrow phh'''}} \cdot \frac{N_{X_b \rightarrow phh'''}}{N_{A^0_b \rightarrow \Lambda^+_c\pi^-}}
\]

Using the world average $\text{BR}(\Lambda^0_b \rightarrow \Lambda^+_c\pi)$ and $\text{BR}(\Lambda^+_c \rightarrow pK\pi)$

\[
\mathcal{B}(A^0_b \rightarrow p\pi^-\pi^+\pi^-) = (1.90 \pm 0.06 \pm 0.10 \pm 0.16 \pm 0.07) \cdot 10^{-5}
\]

\[
\mathcal{B}(A^0_b \rightarrow pK^-\pi^+\pi^-) = (4.55 \pm 0.08 \pm 0.20 \pm 0.39 \pm 0.17) \cdot 10^{-5}
\]

\[
\mathcal{B}(A^0_b \rightarrow pK^-K^+\pi^-) = (0.37 \pm 0.03 \pm 0.04 \pm 0.03 \pm 0.01) \cdot 10^{-5}
\]

\[
\mathcal{B}(A^0_b \rightarrow pK^-K^+K^-) = (1.14 \pm 0.03 \pm 0.07 \pm 0.10 \pm 0.05) \cdot 10^{-5}
\]

\[
\mathcal{B}(\Xi^0_b \rightarrow pK^-\pi^+\pi^-) \cdot f_{\Xi^0_b}/f_{A^0_b} = (1.72 \pm 0.21 \pm 0.25 \pm 0.15 \pm 0.07) \cdot 10^{-6}
\]

\[
\mathcal{B}(\Xi^0_b \rightarrow pK^-\pi^+K^-) \cdot f_{\Xi^0_b}/f_{A^0_b} = (1.56 \pm 0.16 \pm 0.19 \pm 0.13 \pm 0.06) \cdot 10^{-6}
\]

\[
\mathcal{B}(\Xi^0_b \rightarrow pK^-K^+K^-) \cdot f_{\Xi^0_b}/f_{A^0_b} \in [0.11-0.25] \cdot 10^{-6} \text{ at 90\% C.L.}
\]