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Outline

- Physics case
- LHCb experiment
- Two body modes: $B \to hh(*)$, $B \to pp$, $(B \to \phi K^*)$
- Three body modes: $B \to hhh$, $B \to pph$
- Conclusion

(*) $h = \pi$ or $K$
Physics case: why are charmless decays interesting?

- Charmless = everything that is not $b \rightarrow c$

$\begin{array}{cccc}
 & d & s & b \\
 u & \text{white} & \text{blue} & \text{black} \\
 c & \text{blue} & \text{black} & \text{white} \\
 t & \text{white} & \text{black} & \text{white} \\
\end{array}$

- $b \rightarrow s,d$ loop (penguin) and $b \rightarrow u$ tree transitions

  - Sensitivity to small CKM matrix elements

- Small branching fractions

  - Sensitivity to deviations from SM: new physics (heavy particles in loops)

- CP asymmetries: another probe of NP

\[ A_{CP} = \frac{\Gamma(B(B_{(s)}^0 \rightarrow f^-) - \Gamma(B(B_{(s)}^0 \rightarrow f^+))}{\Gamma(B(B_{(s)}^0 \rightarrow f^-) + \Gamma(B(B_{(s)}^0 \rightarrow f^+))} \]

\[ A_{CP}(t) = \frac{\Gamma(B \rightarrow f_{CP}(t)) - \Gamma(B \rightarrow f_{CP}(t))}{\Gamma(B \rightarrow f_{CP}(t)) + \Gamma(B \rightarrow f_{CP}(t))} = C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t) \]

\[ \cosh\left(\frac{\Delta m_{d(s)} t}{2}\right) - A_f \sinh\left(\frac{\Delta m_{d(s)} t}{2}\right) \]

- Limitation from theoretical hadronic uncertainties due to form factors, etc...: combine different modes and use (flavour) symmetries. Studying amplitudes in Dalitz analyses is a plus for disentangling contributions.
LHCb detector

Forward spectrometer
Coverage: 1.8 < η < 4.9

Tracking stations
Calorimeters

Reconstruction of vertices

Cherenkov ring imaging detectors for PID
Muon stations

4 T.m
Direct CPV in $B^0 \rightarrow K\pi$

$B_d^0 \rightarrow K\pi$ and $B_s^0 \rightarrow K\pi$ U-spin related


- Combined fits to signals and cross-feeds. Use of data-based PID calibration to disentangle the contributions

Very carefully corrections to the raw asymmetries:

- Correction for detection asymmetry using $D^* \rightarrow D^0 (hh) \pi$ control samples in data

- Correction for production asymmetry extracted from study of the time dependence of raw $A_{CP}$

Main systematics: detection asymmetry and backgrounds

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

$A_{CP}(B_s^0 \rightarrow K^-\pi^+) = 0.27 \pm 0.04$ (stat) $\pm 0.01$ (syst)

Improved

First observation of direct CP in Bs system
CP asym. and rates in $B^\pm \rightarrow K^0_s h^\pm$

Provides complementary information to $B^0 \rightarrow K\pi$ for the extraction of $\gamma$ angle using U-spin symmetry e.g, R.Fleischer Eur. Phys. J. C52 (2007) 267

For detection and production asymmetries, use $J/\Psi K^\pm$ as a control channel, with similar selection + correct for $K/\pi$ differences

$$\frac{\mathcal{B}(B^+ \rightarrow K^0_s K^+)}{\mathcal{B}(B^+ \rightarrow K^0_s \pi^+)} = 0.064 \pm 0.009 \text{ (stat.)} \pm 0.004 \text{ (syst.)}$$

$$\mathcal{A}^{CP}(B^+ \rightarrow K^0_s \pi^+) = -0.022 \pm 0.025 \text{ (stat.)} \pm 0.010 \text{ (syst.)}$$

$$\mathcal{A}^{CP}(B^+ \rightarrow K^0_s K^+) = -0.21 \pm 0.14 \text{ (stat.)} \pm 0.01 \text{ (syst.)}$$

### Diagram

- **B$^-$**
  - $K^0_s \pi^-$ invariant mass [GeV/c$^2$]
  - Candidates / 0.02 GeV/c$^2$

- **B$^+$**
  - $K^0_s \pi^+$ invariant mass [GeV/c$^2$]
  - Candidates / 0.02 GeV/c$^2$

- **B$^-$**
  - $K^0_s K^-$ invariant mass [GeV/c$^2$]
  - Candidates / 0.02 GeV/c$^2$

- **B$^+$**
  - $K^0_s K^+$ invariant mass [GeV/c$^2$]
  - Candidates / 0.02 GeV/c$^2$
$B^0 \rightarrow \pi^+\pi^-$ and $B^0_s \rightarrow K^+K^-$

Same U-spin interplay as in $B^0_{(s)} \rightarrow K\pi$

First measurement

$C_{\pi\pi} = -0.38 \pm 0.15 \text{ (stat)} \pm 0.02 \text{ (syst)}$

$S_{\pi\pi} = -0.71 \pm 0.13 \text{ (stat)} \pm 0.02 \text{ (syst)}$

$C_{KK} = 0.14 \pm 0.11 \text{ (stat)} \pm 0.03 \text{ (syst)}$

$S_{KK} = 0.30 \pm 0.12 \text{ (stat)} \pm 0.04 \text{ (syst)}$
Evidence of $B^0 \to pp$

Tree dominated $B^0 \to pp$ vs. penguin dominated $B_s^0 \to pp$

$B^0 \to K^+\pi^-$ used for normalization

Decision trees used for discrimination. Detailed PID and two-body + three-body backgrounds modeling

$\Gamma(B^0 \to pp) = (1.47^{+0.71}_{-0.53}) \times 10^{-8}$ 3.3σ significance: FIRST EVIDENCE

Nothing significant for $B_s^0 \to pp$ (improved limits, though)
First observation of $B_s^0 \rightarrow \phi K^{*0}$

Relative suppression $|V_{td}/V_{ts}|^2$

$\overline{B}_d^0 \rightarrow \phi \overline{K}^{*0}$ natural normalization channel

Branching fraction and polarization analysis

$B(B_s^0 \rightarrow \phi \overline{K}^{*0}) = (1.10 \pm 0.24(\text{stat}) \pm 0.14(\text{syst}) \pm 0.08(\text{fd/fs})) \times 10^{-6}$

Sig: 6.1σ: first observation!
3x$|V_{td}/V_{ts}|^2$ scaling

Longitudinal fraction

$f_0 = 0.51 \pm 0.15 (\text{stat}) \pm 0.07 (\text{syst})$

Similar to $\overline{B}_d^0 \rightarrow \phi \overline{K}^{*0}$, differs from $\overline{B}_d^0 \rightarrow K^{*0}\overline{K}^{*0}$
Direct CPV in $B^\pm \to K^\pm h^+ h^-$ - inclusive

**arXiv:1306.1246**


Partially reconstructed bkg from 4-body decays.
Detection and production asymmetries determined with $B^\pm \to J/\Psi (\mu\mu)K^\pm$ evts passing same selection
Minor trigger differences accounted for

\[ A_{CP} = A_{raw} - A_\Delta \]
\[ A_\Delta = A_{raw}(J/\psi K) - A_{CP}(J/\psi K) \]

**Inclusive asymmetries:**

\[
A_{CP}(B^\pm \to K^\pm \pi^+ \pi^-) = 0.032 \pm 0.008 \pm 0.004 \pm 0.007 \quad 2.8\sigma
\]

\[
A_{CP}(B^\pm \to K^\pm K^+ K^-) = -0.043 \pm 0.009 \pm 0.003 \pm 0.007 \quad 3.7\sigma
\]
Direct CPV in $B^\pm \rightarrow K^\pm h^+ h^-$ - regions

Map of the asymmetry in the Dalitz plane: low $\pi\pi$ and $KK$-low mass regions exhibit high asymmetries, oppositely correlated. Not clearly related to resonances.

Anti-correlated huge asymmetries Point to $\pi\pi \leftrightarrow KK$ FSI effects

$$A_{CP}^{reg}(K\pi\pi) = 0.678 \pm 0.078 \pm 0.032 \pm 0.007,$$

$$A_{CP}^{reg}(KKK) = -0.226 \pm 0.020 \pm 0.004 \pm 0.007$$
Direct CPV in $B^\pm \rightarrow \pi^\pm h^+ h^-$ - similar results

Inclusive asymmetries:

$$A_{CP}(B^\pm \rightarrow \pi^\pm \pi^+ \pi^-) = +0.120 \pm 0.020\text{(stat)} \pm 0.019\text{(syst)} \pm 0.007(J/\psi K^\pm)$$

$$A_{CP}(B^\pm \rightarrow K^+ K^- \pi^\pm) = -0.153 \pm 0.046\text{(stat)} \pm 0.019\text{(syst)} \pm 0.007(J/\psi K^\pm)$$

Similar anti-correlated huge asymmetries at low $\pi\pi$ and KK mass regions exhibit high asymmetries, oppositely correlated.

Final results being published
**B^{±}→p p h^{±} dynamics and CP asymmetries**

**Baryonic counterpart of B^{±}→h^{+} h^{-} h^{±}**

Similar selection to B^{±}→h^{+} h^{-} h^{±}

Difference in PID only

Background: combinatorial and cross-feed. A small (p p)K* component part. reco

- **Study of differential spectra**: pp, neutral Kp masses, cosine of the helicity angle. Chase any peculiar structure
- **Use of B^{±}→J/Ψ (p p)K^{±} as a control channel**
- **Asymmetries for B^{±}→p p K^{±}**

\[ N(B^{±}→p p K^{±}) = 7029±139 \]
\[ N(B^{±}→p p \pi^{±}) = 656±70 \]
B^{±} \rightarrow \bar{p}p\bar{p}h^{±} spectra

pp mass spectra derived after removing charmonium contributions

Confirmation of low m(pp) enhancement seen in B factories for this case and in other contexts

Opposite behaviour for light meson – proton correlations pp\pi obeys to short-distance picture, ppK not. Long distance effects?
B$^\pm \rightarrow p\bar{p}h^\pm$ dynamics

Background subtracted Dalitz distributions

B$^\pm \rightarrow p\bar{p}K^\pm$

B$^\pm \rightarrow p\bar{p}\pi^\pm$

ηc, J/Ψ, Ψ(2S)

(Kp)$^0$ threshold activity

Low pp enhancement differently distributed between p\bar{p}K and p\bar{p}\pi

Possible pp structure near 2 GeV/c$^2$ for B$^\pm \rightarrow p\bar{p}K^\pm$

Further investigations with more data and upgrade of the analysis
$B^{\pm} \to ppK^{\pm}$ Kp resonance...

$\bar{p}pK^{\pm}$ spectrum near Kp threshold

Kp distribution after subtraction of non-B background

$\Lambda(1520)$

Kp spectrum systematically studied with non-resonant and resonant components

Combined fit gives $N(B^{\pm} \to \Lambda(1520)p) = 47^{+12}_{-11}$

Combined significance $> 5.1\sigma$

First observation of two-body charmless baryonic decay

\[ \frac{B(B^+ \to \Lambda(1520) \to K^+\bar{p})p}{B(B^+ \to J/\psi \to \bar{p}pK^+)} = 0.041^{+0.011}_{-0.010} \text{ (stat)} \pm 0.001 \text{ (syst)} \]

\[ B(B^+ \to \Lambda(1520)p) = (3.9^{+1.0}_{-0.9} \text{ (stat)} \pm 0.1 \text{ (syst)} \pm 0.3 \text{ (BF)}) \times 10^{-7} \]

...and asymmetries

Inclusive asymmetry $A_{CP}(ppK^{\pm}) = -0.022 \pm 0.031 \pm 0.007$

Charmless ($m(pp) < 2.85$ GeV/$c^2$) $A_{CP}(ppK^{\pm}) = -0.047 \pm 0.036 \pm 0.007$

No significant asymmetry in any projection of the Dalitz plane
$B^0 \rightarrow K^0_h h'^+ h'^-$

$B^0$ goes through loop penguins, $B_s^0$ through suppressed tree
Establish signals, then CP violating angle extraction in the future
Normalization to $B^0 \rightarrow K_s \pi^+ \pi^-$
Selection adds the complication of the $K_s$ displaced vertex
decaying in vertex locator or tracking stations
Veto background from $D$ and charmonium resonances.
- $B^0 \rightarrow K_s K^+ \pi^-$ confirmed
- first observation of $B_s^0 \rightarrow K_s K^+ \pi^-$ and $B_s^0 \rightarrow K_s \pi^+ \pi^-$

\[
B (B_s^0 \rightarrow K_s^0 \pi^+ \pi^-) = (14.3 \pm 2.8 \pm 1.8 \pm 0.6) \times 10^{-6}
\]
\[
B (B_s^0 \rightarrow K_s^0 K^+ \pi^-) = (73.6 \pm 5.7 \pm 6.9 \pm 3.0) \times 10^{-6}
\]
$B_{s}^{0} \rightarrow K_{s} h^{+} h^{-}$ - dynamics

Differences show up in $B_{s}^{0} \rightarrow K_{s} K^{+} \pi^{-}$

Further details will show up with more statistics and full amplitude analysis.
Conclusion and outlook

- Lots of (new) results (all not shown here) on two-body and three-body decays
  - Improvements, evidences and observations on branching fractions
- Big CP asymmetries showing up, globally and locally
- Combined amplitude analyses will help extracting CKM parameters (angles) in the future
  - Three-body modes have shown to be an interesting ground for that
  - FSI effects could be sized and interpreted with the help of old hh scattering data (e.g arXiv:1307.8164, Bediaga, Frederico, Lourenço)
- Charmless baryonics ramping up: B decays, but also other baryons
  - e.g: search for $\Lambda_b \rightarrow \Lambda \eta'$ decay (LHCb-CONF-2013-010)
- Most of the analyses shown are being upgraded (method and/or statistics)
- Whether we test (remaining) loosely constrained sectors of SM or probe NP, charmless modes are a privileged tool