Charmless Hadronic $B$ Decays at LHCb

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(on behalf of the LHCb collaboration)
Outline

• Overview of LHCb detector

• Physics opportunities in charmless hadronic $B$ decays at LHCb
  – Measurement of $\gamma$ in decays involving penguins
    • Using $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$
    • Using $B^{+/0} \to K^{+/0}\pi^+\pi^-$ and $B_d \to K_S\pi^+\pi^-$
  – Search for rare decay modes
    – Many other analyses not covered here
      • e.g. $\alpha$ measurement with $B_d \to \rho\pi$, $\rho\rho$ and $\pi\pi$
The \textit{LHCb} Detector

- Take advantage of $B$ production at LHC
  \begin{itemize}
  \item $\sigma_{\bar{b}b} \approx 500\mu b \rightarrow 10^{12} b\bar{b}$ pairs in 2fb$^{-1}$ (nominal year @ $2 \times 10^{32}$cm$^{-2}$s$^{-1}$)
  \item Produce all $B$ species: $B^+, B_d, B_s, B_c, \Lambda_b, \ldots$
  \end{itemize}

- Use trigger(*) to cope with high event rate
  \begin{itemize}
  \item \textit{Level 0}: hardware trigger on high $p_T/E_T$ leptons or hadrons
  \item \textit{High Level Trigger}: matches L0 object to track with displaced vertex, then runs inclusive & exclusive selections
  \end{itemize}

(*) see talk on Friday by L. de Paula
Hadronic Modes at **LHCb**

- **Vertex Locator (VeLo):** Si strip detector giving $\sigma_t \approx 40\text{fs}$; allows displaced vertex trigger and time-dependent $B_s$ studies

- **Cherenkov Counters (RICH):** Excellent $p/K/\pi$ separation for $2<p<100\text{GeV}$; can separate out final states

**PID example:** $B_s \rightarrow K^+K^-$ oscillations with $2\text{fb}^{-1}$

$B_{d} \rightarrow \pi^+\pi^-$ residual width = $39\text{fs}$

Without RICH PID

With RICH PID

Mass resoln $\approx 17\text{MeV}$

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Current Status of γ

- Least well constrained parameter of the “db” unitarity triangle.
- Indirect measurement from fit to apex gives $\gamma = (66.8^{+5.4}_{-3.8})^\circ$.
- Direct measurements from time-independent analyses of $B^{+/-} \to D^{0(*)}K^{+/-(*)}$ ("tree-only" decays) give $\gamma = (70^{+27}_{-29})^\circ$
  - Analysis method (ADS/GLW/GGSZ) depends on D decay mode.
- Such tree-only decays expected to give SM value for $\gamma$.

Following talk (S. Ricciardi) will discuss how LHCb can improve on current $\gamma$ measurements using tree-only decays.
LHCb γ Strategy

• Measurements of γ from decays involving both tree and penguin amplitudes are sensitive to New Physics effects
  – Compare to SM “standard candle” γ value from tree-only decays.
  – Significant disagreement would be unambiguous sign of NP.

• Prospects for two such measurements have been studied by LHCb
  – Combined Dalitz analysis of $B^{+/0} \to K^{+/0}\pi^+\pi^-$ and $B_d \to K_S\pi^+\pi^-$ (method: I. Bediaga et al, Phys. Rev. D 76 (073011) 2007).
Measuring $\gamma$ with $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$

B→hh at LHCb

- Studies of two-body charmless hadronic ("B→hh") decays at LHCb summarised as part of forthcoming "physics book".
  - Including selection/bkg studies, calibration/systematics, and γ extraction.
- ε_{geo} acceptance ∼21%, ε_{selection(no PID)} ∼18%, ε_{trigger} ∼36% ⇒ ε_{total} ∼1.4%

<table>
<thead>
<tr>
<th>Channel</th>
<th>2fb⁻¹ Yield (no PID)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B_d → π⁺π⁻</td>
<td>59k</td>
</tr>
<tr>
<td>B_d → K⁺π⁻</td>
<td>217k</td>
</tr>
<tr>
<td>B_s → K⁻π⁺</td>
<td>15k</td>
</tr>
<tr>
<td>B_s → K⁺K⁻</td>
<td>72k</td>
</tr>
<tr>
<td>Λ_b → pπ⁻</td>
<td>7k</td>
</tr>
<tr>
<td>Λ_b → pK⁻</td>
<td>11k</td>
</tr>
<tr>
<td>3-body bkg</td>
<td>[76k,186k]@68% C.L.</td>
</tr>
<tr>
<td>Combinatorial bkg</td>
<td>[106k,226k]@68% C.L.</td>
</tr>
</tbody>
</table>

Expected total mass distribution (ππ hypothesis) with 0.2fb⁻¹

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Some Calibrations for $B \rightarrow hh$

- Proper time resolution model is Gaussian with mean and width depending on per-event proper time error $\sigma_\tau$
  - Model can be determined on data using $B_s \rightarrow K^-\pi^+$ (if mistag is known).

- PID likelihood calibrated using $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$ and $\Lambda \rightarrow p\pi^-$.  

- Proper time acceptance distorted by IP cuts in trigger and selection
  - Can be determined on data by “swimming” the B to build up event-by-event acceptance (top hat).

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\[ \gamma \text{ from } B_d \rightarrow \pi^+\pi^-, \ B_s \rightarrow K^+K^- \]

- Direct and mixing induced CP asymmetries measured using tagged, time-dependent analysis:
  \[
  \frac{\Gamma(B \rightarrow f) - \Gamma(\bar{B} \rightarrow f)}{\Gamma(B \rightarrow f) + \Gamma(\bar{B} \rightarrow f)} = \frac{A_{CP}^{dir} \cos(\Delta m t) - A_{CP}^{mix} \sin(\Delta m t)}{\cosh(\Delta \Gamma t / 2) - A_{\Delta \Gamma} \sinh(\Delta \Gamma t / 2)}
  \]

- Have 4 asymmetries depending on 7 physics parameters: \( A_{\pi\pi}^{dir} = f_1(d, \theta, \gamma) \), \( A_{\pi\pi}^{mix} = f_2(d, \theta, \gamma, \phi_d) \), \( A_{KK}^{dir} = f_3(d', \theta', \gamma) \), \( A_{KK}^{mix} = f_4(d', \theta', \gamma, \phi_s) \).

- \( d (d') \) is related to the ratio of the magnitudes of the penguin and tree contributions for the \( B_d (B_s) \) decay, while \( \theta (\theta') \) is related to the difference in their strong phases.

- Assume U-Spin (d\(\leftrightarrow\)s) symmetry \( \Rightarrow d = d' \) and \( \theta = \theta' \)

- Take \( \phi_d \) from \( J/\psi K_S \) \( \Rightarrow \) system becomes soluble.
LHCb B→hh Fit Approach

- Fit for branching ratios, lifetimes, CP asymmetries, and detector parameters is made in all B→hh channels simultaneously (68 free parameters)
  - Mass and PID likelihoods used to separate modes.

- With 2fb⁻¹ of data, each of the four CP asymmetries from B_d→π⁺π⁻ and B_s→K⁺K⁻ will be measured with a statistical uncertainty of ≈0.04.
- For the extraction of γ, A^{dir}(KK) can be replaced with A_{CP}(B_d→K⁺π⁻), since they are expected to be equal given U-spin symmetry, and the uncertainty on A_{CP}(B_d→K⁺π⁻) with 2fb⁻¹ will be <0.01 (systematics dominated).
LHCb Sensitivity to $\gamma$

- Extraction of $\gamma$ allows for some U-spin breaking, with $0.8 < d'/d < 1.2$ and $-20^\circ < \theta' - \theta < 20^\circ$.
- SM solution for $\gamma$ is isolated by imposing the condition $\theta > 90^\circ$.
- With 2fb$^{-1}$, find $\sigma_\gamma = 7^\circ$, $\sigma_{\phi_s} = 0.05$ rad, $\sigma_d = 0.13$ and $\sigma_\theta = 7^\circ$.

- Alternative strategy would be to constrain $\phi_s$ (expect $\sigma_{\phi_s} \approx 0.03$ rad from $B_s \rightarrow J/\psi \phi$ with 2fb$^{-1}$) and release one of the U-spin constraints $d=d'$ or $\theta=\theta'$. 

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Measuring $\gamma$ with $B^{+/−} \rightarrow K^{+/−}\pi^{+}\pi^{−}$ and $B_d \rightarrow K_S \pi^{+}\pi^{−}$

• Tree amplitudes in three-body charmless hadronic decays involve $V_{ub}$
  – Probe $\gamma$ using interference between intermediate resonances
• $B^{+/-} \rightarrow K^{*0}\pi^{+/-}$ penguin only; $B_d \rightarrow K^{*+}\pi^-$ penguin and tree
  – Extract penguin amplitude ($V_{tb}V_{ts}^*P$) via standard Dalitz analysis of $B^{+/-} \rightarrow K^{+/-}\pi^+\pi^-$
  – Use this as input to untagged Dalitz analysis of $B_d \rightarrow K_S\pi^+\pi^-$ to extract tree amplitude ($V_{ub}V_{us}^*T$)
  – Tagging not required as resonance interference regions for $B_d$ and $\bar{B}_d$ are distinct
  – Parameters extracted relative to contribution from $\chi_{c0}K$ (common contribution to $B_d$ and $B^{+/-}$)

Resonances: $K^{*}(892)^{+/-}$, $K^{*}(1430)^{+/-}$, $\rho(770)^0$, $f_0(980)$, $\chi_{c0}$
\[ \text{B}^+/→K^+/−\pi^+π^−, \text{B}_d→K_S\pi^+\pi^- \text{ at LHCb} \]

- Selection: want to avoid tight cuts on \( p_T \) as this lowers efficiency in corner of Dalitz plot, where some of the resonances lie
  - Trade-off between minimising bias and reducing combinatoric bkg

<table>
<thead>
<tr>
<th>Channel</th>
<th>B.R.</th>
<th>( \epsilon_{\text{selection}} )</th>
<th>2 fb(^{-1}) yield (no HLT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{B}^+→K^+\pi^+\pi^- )</td>
<td>( 5.5\times10^{-5} )</td>
<td>1.1%</td>
<td>494k</td>
</tr>
<tr>
<td>( \text{B}_d→K_S\pi^+\pi^- )</td>
<td>( 2.2\times10^{-5} )</td>
<td>0.5%</td>
<td>90k</td>
</tr>
</tbody>
</table>

- Lower efficiency for \( \text{B}_d→K_S\pi^+\pi^- \) due to lower \( K_S \) reconstruction efficiency
  - 25% decay in VeLo \( \Rightarrow \) good efficiency/resolution
  - 50% decay between VeLo and TT Stations \( \Rightarrow \) poorer efficiency/resolution
  - 25% decay downstream of TT Stations \( \Rightarrow \) track lost

- Sensitivity to \( \gamma \) : idealised toy MC study (no background or detector effects)
  estimates \( \sigma_\gamma \sim 5^\circ \) (stat. only) with 2 fb\(^{-1}\).
Rare Hadronic $B$ Decays at LHCb

• Baryonic mode $B_d \rightarrow p\bar{p}$ unobserved $\implies$ SM predictions close to being ruled out
  – If true B.R. close to current limit ($1.1\times10^{-7}$), expect evidence with $\sim0.2\,\text{fb}^{-1}$ (2010 run)
  – Also expect to observe $B_d \rightarrow K^+K^-$ and $B_s \rightarrow \pi^+\pi^-$ (penguin annihilation and W exchange only) with $\sim1\,\text{fb}^{-1}$ (if SM B.R.s).

• $B^+ \rightarrow K^-\pi^+\pi^+$ and $B^+ \rightarrow K^+K^+\pi^-$ highly suppressed in SM
  – B.R.s $O(10^{-14})$ and $O(10^{-11})$ respectively.

• Can be strongly enhanced by NP effects
  – e.g. $\text{B.R.}(B^+\rightarrow K^-\pi^+\pi^+)\sim10^{-6}$ ($\approx$ current B.R. limit) with $Z'$.

• If such enhancements are present, LHCb may be able to make an observation.
Conclusions

- LHCb has a rich physics programme using charmless hadronic decays:
  - Measure $\gamma$ from decays with penguins and compare to SM value from tree-only decays
    - Expect $\sigma_\gamma = 7^\circ$ after 2fb$^{-1}$ from analysis using $B_d \rightarrow \pi^+\pi^-$, $B_s \rightarrow K^+K^-$
    - Measurement with $B^{+/0} \rightarrow K^{+/0}\pi^+\pi^-$ and $B_d \rightarrow K_S\pi^+\pi^-$ should be competitive (effect of backgrounds and systematics to be checked).
  - Search for undiscovered rare decays
    - Expect to observe $B_s \rightarrow \pi^+\pi^-$, $B_d \rightarrow K^+K^-$ and $B_d \rightarrow p\bar{p}$ with early data, whether SM branching ratio or not
    - Can observe $B^+ \rightarrow K^-\pi^+\pi^+$, $B^+ \rightarrow K^+K^+\pi^-$ if B.R. strongly enhanced by NP.
- Measure $\alpha$ using $B_d \rightarrow \rho\pi$, $\rho\rho$, and $\pi\pi$
  - Expect $\sigma_\alpha$(stat) $\sim 5^\circ$ after 2fb$^{-1}$ (dominated by $\rho\pi$).
- We are awaiting the first collisions…
Backup Slides
More Calibrations for $B \rightarrow hh$

- PID calibrated using PID-unbiased samples of $D^{*+} \rightarrow D^0 (\rightarrow K^-\pi^+)\pi^+$ and $\Lambda \rightarrow p\pi$:
  - Dedicated stream in trigger
  - Re-weight likelihood distribution for $B$ using $p$ and $p_T$ distributions.

- Tagging performance for $B_d$ measured using flavour-specific $B_d \rightarrow K^+\pi^-$
  - For $B_s$ tagging, $B_s \rightarrow K^-\pi^+$ has less statistics and is sensitive to proper time resolution
  - Can study $B_d$-$B_s$ difference in other modes (e.g. $B_d \rightarrow D^-\pi^+$ and $B_s \rightarrow D_s\pi^+$)
  - Can also calibrate using per-event mistag.

DLL distributions: $B_d \rightarrow \pi^+\pi^-$, $
\pi$ from $D \rightarrow K\pi$
before reweighting,
$
\pi$ from $D \rightarrow K\pi$
after reweighting.

Per-event mistag for $B_d \rightarrow K^+\pi^-$
Measuring $\alpha$ with $B_d \to \pi^+\pi^-\pi^0$

- $\alpha$ can be measured via a tagged Dalitz analysis of $B_d \to \pi^+\pi^-\pi^0$
  - Dominant submodes are $\rho^+\pi^-$, $\rho^-\pi^+$ and $\rho^0\pi^0$
  - Isospin symmetry used to extract $\alpha$, tree/penguin amplitudes and strong phases.
- Multivariate selection used, $\varepsilon_{\text{total}} \sim 0.07\%$. Expected $2\text{fb}^{-1}$ yield is $14k$, with $B/S \sim 1$.
- $2\text{fb}^{-1}$ toy experiment gives $\alpha = (97^{+9}_{-4})^\circ$ (stat. only)

Effect of $E_T$ cut on $\pi^0$

Time evolution of tagged Dalitz plots

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