First studies on rare $B \rightarrow hh$ decays
Today - report primarily on $B \rightarrow p p\bar{p}$

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University of Glasgow

LHCb CP Measurements WG meeting, CERN, 15 April 2008
Motivations
- theory and experimental review of (rare) charmless baryonic B decays
  - Brief reminder of Bd → KK and Bs → pp

First steps in the analysis of B → p pbar decays
- kinematics
- long tracks, “standard loose protons”

B → p pbar pre-selection: making of
- distributions of cut variables
- pre-selection cuts
- background and reduction factors
Theory review / B. R.s

Experimental review

Reminder from CP meeting 31/01/2008
Charmless baryonic $B$ decays: theoretical predictions

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow pp$</td>
<td>$4.2 \times 10^{-6}$</td>
<td>$1.2 \times 10^{-6}$</td>
<td>$7.0 \times 10^{-6}$</td>
<td>$2.9 \times 10^{-6}$</td>
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<tr>
<td>$B^0 \rightarrow nn$</td>
<td>$3.5 \times 10^{-7}$</td>
<td>$7.0 \times 10^{-6}$</td>
<td>$2.9 \times 10^{-5}$</td>
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<td>$B^- \rightarrow np$</td>
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<td>$1.7 \times 10^{-5}$</td>
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<td>$B^0 \rightarrow \Lambda \Lambda$</td>
<td>$2 \times 10^{-7}$</td>
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<tr>
<td>$B^- \rightarrow p\Delta^-$</td>
<td>$1.5 \times 10^{-4}$</td>
<td>$2.9 \times 10^{-7}$</td>
<td>$3.2 \times 10^{-4}$</td>
<td>$2.4 \times 10^{-6}$</td>
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<td>$B^0 \rightarrow p\Delta^-$</td>
<td>$7 \times 10^{-8}$</td>
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<td>$4.0 \times 10^{-6}$</td>
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<tr>
<td>$B^- \rightarrow n\Delta^-$</td>
<td>$1.1 \times 10^{-4}$</td>
<td>$2.7 \times 10^{-7}$</td>
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<td>$4.6 \times 10^{-7}$</td>
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<td>$B^0 \rightarrow n\Delta^0$</td>
<td>$1.0 \times 10^{-4}$</td>
<td>$1.0 \times 10^{-6}$</td>
<td>$4.0 \times 10^{-6}$</td>
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<td>$B^- \rightarrow \Lambda p$</td>
<td>$\approx 3 \times 10^{-6}$</td>
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<td>$B^0 \rightarrow \Lambda n$</td>
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<tr>
<td>$B^0 \rightarrow \Sigma^+ p$</td>
<td>$6 \times 10^{-6}$</td>
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<tr>
<td>$B^- \rightarrow \Sigma^0 p$</td>
<td>$3 \times 10^{-6}$</td>
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<td>$B^- \rightarrow \Sigma^+ \Delta^-$</td>
<td>$6 \times 10^{-6}$</td>
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<tr>
<td>$B^0 \rightarrow \Sigma^+ \Delta^-$</td>
<td>$6 \times 10^{-6}$</td>
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<tr>
<td>$B^- \rightarrow \Sigma^- \Delta^0$</td>
<td>$2 \times 10^{-6}$</td>
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</tbody>
</table>

Reminder from CP meeting 31/01/2008


Theoretical predictions do not really agree
Charmless baryonic B decays: measurements (1/2)

Heavy Flavor Averaging Group
Aug. 2007

Compilation of $B^+$ Baryonic Branching Fractions
All branching fractions are in units of $10^{-6}$; limits are 90% CL

In PDG2006    New since PDG2006 (preliminary)    New since PDG2006 (published)

<table>
<thead>
<tr>
<th>RPP #</th>
<th>Mode</th>
<th>PDG2006 Avg.</th>
<th>BABAR</th>
<th>Belle</th>
<th>CLEO</th>
<th>New Avg.</th>
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</thead>
<tbody>
<tr>
<td>286</td>
<td>$p\bar{p}\pi^+$</td>
<td>3.1$^{+0.8}_{-0.7}$</td>
<td>1.69$^{+0.29}<em>{-0.27}$ &amp; 1.68$^{+0.12}</em>{-0.12}$ &amp; &lt; 160 &amp; 1.69$^{+0.24}_{-0.22}$</td>
<td></td>
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<tr>
<td>289</td>
<td>$p\bar{p}K^+$</td>
<td>5.6$^{+1.0}_{-1.0}$</td>
<td>6.7$^{+0.5}<em>{-0.4}$ &amp; 5.98$^{+0.19}</em>{-0.19}$ &amp; 6.24$^{+0.32}_{-0.33}$</td>
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<tr>
<td>290</td>
<td>$\Theta^{++}\bar{p}$ *</td>
<td>&lt; 0.091</td>
<td>&lt; 0.09</td>
<td>&lt; 0.091</td>
<td>&lt; 0.09</td>
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<tr>
<td>291</td>
<td>$f_s(2221)K^+$ *</td>
<td>&lt; 0.41</td>
<td>&lt; 0.41</td>
<td>&lt; 0.41</td>
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<tr>
<td>292</td>
<td>$p\Lambda(1520)$</td>
<td>&lt; 1.5</td>
<td>&lt; 1.5</td>
<td>&lt; 1.5</td>
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</tr>
<tr>
<td>294</td>
<td>$p\bar{p}K^{*+}$</td>
<td>10.3$^{+3.6}_{-2.8}$ &amp; 1.7</td>
<td>5.3$^{+1.5}<em>{-1.3}$ &amp; 10.3$^{+3.6}</em>{-2.8}$ &amp; 6.6$^{+1.7}_{-1.7}$ &amp; &lt; 0.77</td>
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<tr>
<td>–</td>
<td>$f_s(2221)K^{*+}$ *</td>
<td>New</td>
<td>&lt; 0.77</td>
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<tr>
<td>295</td>
<td>$p\bar{\Lambda}$</td>
<td>&lt; 0.49</td>
<td>&lt; 0.32</td>
<td>&lt; 1.5</td>
<td>&lt; 0.32</td>
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<tr>
<td>–</td>
<td>$p\bar{\Lambda}\pi^0$ New</td>
<td>3.00$^{+0.34}_{-0.33}$</td>
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<tr>
<td>–</td>
<td>$p\bar{\Sigma}(1385)^0$ New</td>
<td>&lt; 0.47</td>
<td>&lt; 0.47</td>
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</tr>
<tr>
<td>–</td>
<td>$\Delta^{++}\bar{\Lambda}$ New</td>
<td>&lt; 0.82</td>
<td>&lt; 0.82</td>
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<tr>
<td>299</td>
<td>$\Lambda\Lambda\pi^+$</td>
<td>&lt; 2.8</td>
<td>&lt; 2.8 &amp; &lt; 2.8 &amp; &lt; 2.8</td>
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<tr>
<td>300</td>
<td>$\Lambda\Lambda K^+$</td>
<td>2.9$^{+0.3}_{-0.7}$ &amp; 0.4</td>
<td>2.9$^{+0.3}_{-0.7}$ &amp; 0.4</td>
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<tr>
<td>301</td>
<td>$\Delta^0 p$</td>
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<td>&lt; 1.42</td>
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<td>&lt; 150</td>
<td>&lt; 0.14</td>
<td>&lt; 150</td>
<td>&lt; 0.14</td>
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§Di-baryon mass is less than 2.85 GeV/GeV; † Charmonium decays to $p\bar{p}$ have been statistically subtracted.
† The charmonium mass region has been vetoed. * Product BF - daughter BF taken to be 100%: $\Theta(1540)^{++} \to K^{+}\bar{p}$ (pentaquark candidate);

Reminder from CP meeting 31/01/2008

LHCb CP WG Meeting, CERN, 15 April 2008

5/37
**Compilation of $B^0$ Baryonic Branching Fractions**

All branching fractions are in units of $10^{-5}$; limits are 90\% CL

<table>
<thead>
<tr>
<th>RPP#</th>
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<th>CLEO</th>
<th>New Avg.</th>
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</thead>
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<tr>
<td>266</td>
<td>$p\bar{p}$</td>
<td>&lt; 0.27</td>
<td>&lt; 0.27</td>
<td>&lt; 0.11 *</td>
<td>&lt; 1.4</td>
<td>&lt; 0.11</td>
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<tr>
<td>268</td>
<td>$p\bar{p}K^0$</td>
<td>2.1$^{+0.6}_{-0.4}$</td>
<td>3.0$^{+0.5}_{-0.3}$ †</td>
<td>2.40$^{+0.54}_{-0.44}$ ± 0.28 †</td>
<td>2.73$^{+0.47}_{-0.42}$</td>
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<td>269</td>
<td>$G^+\bar{p}$ *</td>
<td>&lt; 0.23</td>
<td>&lt; 0.05</td>
<td>&lt; 0.23</td>
<td>&lt; 0.05</td>
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<td>270</td>
<td>$p\bar{p}K^{*0}$</td>
<td>&lt; 7.6</td>
<td>1.47$^{+0.45}_{-0.40}$ †</td>
<td>&lt; 7.6 †</td>
<td>1.5$^{+0.6}_{-0.5}$</td>
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<td>271</td>
<td>$p\Lambda\pi^-$</td>
<td>2.6$^{+0.5}_{-0.4}$</td>
<td>3.30$^{+0.53}_{-0.31}$</td>
<td>3.23$^{+0.33}_{-0.28}$ ± 0.29 †</td>
<td>&lt; 13</td>
<td>3.25$^{+0.36}_{-0.34}$</td>
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<tr>
<td></td>
<td>$p\Sigma(1385)^-$</td>
<td>New</td>
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<td>&lt; 0.26</td>
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<tr>
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<td>$\Delta^0\Lambda$</td>
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<td>272</td>
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<td>&lt; 0.82</td>
<td>&lt; 0.82</td>
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<td>273</td>
<td>$p\Sigma^0\pi^-$</td>
<td>&lt; 3.8</td>
<td>&lt; 3.8</td>
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<tr>
<td>274</td>
<td>$\Lambda\bar{\Lambda}$</td>
<td>&lt; 0.69</td>
<td>&lt; 0.32</td>
<td>&lt; 1.2</td>
<td>&lt; 0.32</td>
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</table>

* Belle collab., hep-ex/0703048v1

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Reminder from CP meeting 31/01/2008

LHCb CP WG Meeting, CERN, 15 April 2008
Charmless baryonic B decays in LHCb

- Several 3-body decays observed by BaBar and/or Belle; e.g.:

\[ B^- \to p\Lambda\pi^- , \quad B^+ \to p\pi\pi^+ , \quad B^0 \to p\pi K^0 \]
\[ B^+ \to p\pi^* \ , \quad B^+ \to \Lambda\pi K^+ \ , \quad B^+ \to p\Lambda\gamma \]

- Branching fractions \( \sim 10^{-6} \)

- But no 2-body decays yet discovered! At least at the level of \( 10^{-7} \)-ish …

- Note: calculations tricky and not all “schools” in agreement …

- Glasgow group wants to change this and exploit large LHCb samples “from day 1”

- Focus first on the easiest: 2-body proton- antiproton final state!

- Will also study rare B \( \to hh \) decays

  - First studies done with DC04 data by Charlotte Newby (CERN-THESIS 2007-018)
  - Expect \( \sim 2000 \) \( B_d \to KK \) and \( B_s \to \pi\pi \) events per nominal year

  assuming branching ratios 10x smaller than \( B_d \to \pi\pi \), etc.
First steps in the analysis of $B \to p\bar{p}$ decays
Software versions

- B-decay DSTs produced with Brunel v30r14
- $b\bar{b}$ inclusive DSTs produced with Brunel v30r14
- Minimum bias DSTs produced with Brunel v30r17

- All analyses done with DaVinci v19r11p1

Side remark:
- on signal samples
- ~ half of the events do not have both B-daughters in the acceptance
Kinematics of decay

Distributions for events with both MC B-daughter protons are in LHCb acceptance
MC-truth distributions when both protons in acceptance

High $p$ and $p_{T}$ spectrum

$p$ of B-daughters

$p_{T}$ of B-daughters
Long tracks

Distributions for events with both MC B-daughter protons are in LHCb acceptance
Input tracks: « long tracks »

- **B signal sample contains ~ 32 long tracks per event**
- **On a B → p pbar sample just over 3 long tracks are real protons**
- **We should not have to deal with large combinatorics …**
  
  … provided the PID is excellent ;-)
Standard loose protons

Distributions for events with both MC B-daughter protons are in LHCb acceptance
On average, we start from ~ 3.4 long tracks that are real protons and the “standard loose” PID provides ~ 11 “standard loose protons”

Only ~2.9 “standard loose protons” are real protons

Proton PID inefficiencies account for the difference
Input particles: « standard loose protons » (2/5)

DLL(p-π) for MC-matched protons

DLL(p-K) for MC-matched protons
Input particles: « standard loose protons » (3/5)

Purity versus DLL(p-π)

Purity versus DLL(p-K)

Same as above for $p_T > 1$ GeV
A $p_T$ cut helps the PID
Input particles: « standard loose protons » (5/5)

- All loose protons
- Loose protons MC-matched to protons

- The B signal is indeed present even without any (pre-)selection
  … on a signal sample ;-)
Pre-selection: making of
Towards a pre-selection ...

- What variables do we have at hand?

- Let’s look at some distributions before any pre-selection …

- Well, nearly dummy cuts applied so as to be able to use the “DaVinci machinery” ;-
  - “standard loose protons” are defined with $\Delta \ln L_{p\pi} > -5$
  - minimum $p_T$ of B-daughters > 100 MeV
  - B-candidate invariant mass within 2 GeV
Distributions for signal and b-inclusive background (1/6)

Largest $p_T$ of B-daughters

Smallest $p_T$ of B-daughters

LHCb CP WG Meeting, CERN, 15 April 2008
Distributions for signal and b-inclusive background (3/6)

B-vertex $\chi^2$

<table>
<thead>
<tr>
<th>B-vertex $\chi^2$</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>16459</td>
<td>1.459</td>
<td>2.336</td>
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</table>

Arbitrary units

$10^{-1}$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12 \quad 14 \quad 16 \quad 18 \quad 20$
Distributions for signal and b-inclusive background (4/6)

B IPS

<table>
<thead>
<tr>
<th>B IPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
</tbody>
</table>

![Graph showing distributions with B IPS highlighted and table of statistics.](image)
Distributions for signal and b-inclusive background (5/6)

B distance-of-flight significance w.r.t primary vertex
B-candidate invariant mass

- Entries: 16459
- Mean: 5271
- RMS: 64.16
B invariant mass resolution on signal

This is promising …
Pre-selection

Goal:
- Define a loose set of cuts for stripping
- Keep as much signal as possible while rejecting as much background as possible

“Optimisation”:
- Vary a few of the cuts considered and check reduction factor on a b-bbar inclusive background
- Cross-check reduction factor on signal
- First look at reduction factor on minimum bias

At the end:
- Better knowledge of possible/potential sources of background
Pre-selection variables

Pre-selection cuts consist of various requirements:

- **Particle identification:**
  
  $p$-$\pi$ separation based on PID likelihood difference ($\Delta \ln L_{p\pi}$)

- **Topological:**
  
  clear separation of primary vertex and B-decay vertex
  
  B-daughters impact parameter (IP) and B-decay length significance

- **Kinematic:**
  
  minimal B-daughters transverse momentum

- **Vertexing:**
  
  $\chi^2$ of vertex fit to B-daughters

- **Mass:**
  
  mass window cut on invariant mass of B-daughters

- **Other cuts possible but not considered:** e.g. $p_T$ of B, $\Delta \ln L_{pK}$
Example of cut not considered: $p_T$ of B candidate
## Pre-selection cuts

<table>
<thead>
<tr>
<th>Cut variable</th>
<th>Cut value</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-mass window</td>
<td>± 600 MeV</td>
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<tr>
<td>min $p_T$ of each B-daughter</td>
<td>800 MeV</td>
</tr>
<tr>
<td>min $p_T$ of at least one B-daughter</td>
<td>1600 MeV</td>
</tr>
<tr>
<td>B-vertex $\chi^2$</td>
<td>&lt; 15</td>
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<tr>
<td>min IPS of each B-daughter</td>
<td>&gt; 3.5</td>
</tr>
<tr>
<td>min IPS of at least one B-daughter</td>
<td>&gt; 4.0</td>
</tr>
<tr>
<td>IPS of B-vertex</td>
<td>&lt; 6</td>
</tr>
<tr>
<td>B flight distance significance</td>
<td>&gt; 10</td>
</tr>
</tbody>
</table>
Backgrounds and reduction factors

Reduction factors:

- 3.5 on signal for ~2200 on b-bbar inclusive background
- No minimum bias event passed in a sample of 40k
  - clearly this needs to be checked on much larger a sample …
  - … keep fingers crossed …

Specific background:

- Looked at $B_s \rightarrow KK$, $B^0 \rightarrow KK$ and $\Lambda_b \rightarrow pK$:
  all contribute as background (main contributor is $\Lambda_b \rightarrow pK$)
- Note: Belle reports B-decay background to be negligible in their selection. They are dominated by $e^+e^- \rightarrow q\bar{q}$ background
- We just started looking at background. Much more to be done …
  - e.g.: do we need to apply DLL cuts at pre-selection level?
  - look at channels such as $B \rightarrow hh$ with misid., 3-body B-decays with 2 protons in final state, $\Lambda_b \rightarrow p+$anything, etc.
Path towards a selection
Investigating **TMVA** for cut optimisation

**Proof of principle only**
- arbitrary normalisation

Trained with
- samples: $B_s \rightarrow K^+K^-, B^0 \rightarrow K^+K^-, \Lambda_b \rightarrow pK^-$
- variables:
  - $B^0$: mass, vertex $\chi^2$, IPS, Flight distance signif.,
  - proton: $p_T$, IPS, proton ID

**TMVA response for classifier: Fisher**

<table>
<thead>
<tr>
<th>Normalized</th>
</tr>
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<tbody>
<tr>
<td>Signal</td>
</tr>
<tr>
<td>Background</td>
</tr>
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</table>

**Background rejection versus Signal efficiency**

<table>
<thead>
<tr>
<th>Background rejection</th>
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<tbody>
<tr>
<td>1.0</td>
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<tr>
<td>0.9</td>
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<td>0.8</td>
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<td>0.7</td>
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<tr>
<td>0.4</td>
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<tr>
<td>0.3</td>
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<tr>
<td>0.2</td>
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</table>

MVA Method:

- Fisher
Conclusions and outlook (1/2)

- No 2-body baryonic charmless decays observed so far, e.g.
  \[ B^0 \rightarrow p\bar{p}, \quad B^0 \rightarrow \Lambda\bar{\Lambda}, \quad B^+ \rightarrow p\bar{\Lambda} \]

- Theoretical calculations/predictions do not always agree
  - some limits already exclude certain models

- Focus for now on early measurement of \( pp \) mode: is easiest for LHCb
  - we could expect of order 1000-3000 events per nominal year?
  - first pre-selection is available and performance seems very reasonable

⇒ Possible observation by LHCb of first 2-body baryonic \( B \) decay

- We could also look e.g. at \( \Lambda \)’s … see the decays above …
Cross-check (stripping) pre-selection satisfies all requirements
And release the agreed-upon pre-selection

Work on a “final” selection starting from pre-selected events
  use TMVA for the optimisation task

Pay particular attention to protons particle identification
  not very much studied so far since LHCb benchmark channels do not contain protons
  Can anything be gained here?

In parallel will start work on $B^0 \rightarrow KK$ and $B_s \rightarrow \pi\pi$