Rare B meson decays to baryonic final states

21^{st} FPCP Conference at Lyon

Pablo Baladrón Rodríguez on behalf of LHCb Collaboration

Universidade de Santiago de Compostela, Instituto Galego de Física de Altas Enerxías

pablo.baladron.rodriguez@cern.ch

May-June 2023

Motivation

Unexpected rates in decays with $p\bar{p}$ pairs in the final state: threshold enhancement effect

Different yields for baryonic and purely mesonic decays, while purely baryonic 2-body decays are suppressed.

Threshold enhancement!

- $\mathcal{B}(\mathbf{B^0 \to \pi^+\pi^-}) = (5.1 \pm 0.2)\times10^{-6}$ $\approx$ $\mathcal{B}(\mathbf{B^0 \to p\bar{p}\,\pi^+\pi^-}) = (2.9 \pm 0.2)\times10^{-6}$
- $\mathcal{B}(\mathbf{B^0 \to K^+\pi^-}) = (2.0 \pm 0.1)\times10^{-6}$ $\approx$ $\mathcal{B}(\mathbf{B^0 \to p\bar{p}\,K^+\pi^-}) = (6.3 \pm 0.5)\times10^{-6}$
- $\mathcal{B}(\mathbf{B^0 \to K^+K^-}) = (7.8 \pm 0.5)\times10^{-8}$ $<$ $\mathcal{B}(\mathbf{B^0 \to p\bar{p}\,K^+K^-}) = (1.2 \pm 0.3)\times10^{-7}$
- $\mathcal{B}(\mathbf{B^0 \to p\bar{p}}) = (1.3 \pm 0.3)\times10^{-8}$ $\overset{?}{\approx}$ $\mathcal{B}(\mathbf{B^0 \to p\bar{p}\,p\bar{p}}) < (2.0)\times10^{-7}$
  [PRL 119 (2017) 23, 232001] [PRD 98 (2018) 7, 071102]

- $\mathcal{B}(\mathbf{B_s^0 \to \pi^+\pi^-}) = (7.0 \pm 1.0)\times10^{-7}$ $\approx$ $\mathcal{B}(\mathbf{B_s^0 \to p\bar{p}\,\pi^+\pi^-}) = (4.3 \pm 2.0)\times10^{-7}$
- $\mathcal{B}(\mathbf{B_s^0 \to K^+\pi^-}) = (5.8 \pm 0.7)\times10^{-6}$ $\approx$ $\mathcal{B}(\mathbf{B_s^0 \to p\bar{p}\,K^+\pi^-}) = (1.4 \pm 0.3)\times10^{-6}$
- $\mathcal{B}(\mathbf{B_s^0 \to K^+K^-}) = (2.7 \pm 0.2)\times10^{-5}$ $>$ $\mathcal{B}(\mathbf{B_s^0 \to p\bar{p}\,K^+K^-}) = (4.5 \pm 0.5)\times10^{-6}$
- $\mathcal{B}(\mathbf{B_s^0 \to p\bar{p}}) < 1.5\times10^{-8}$ $\overset{?}{\approx}$ $\mathcal{B}(\mathbf{B_s^0 \to p\bar{p}\,p\bar{p}})$ = ? (never searched for)
  [PRL 119 (2017) 23, 232001]

New measurements of purely baryonic B decays would provide new insight in the understanding of the non-trivial processes involved.

Theory landscape

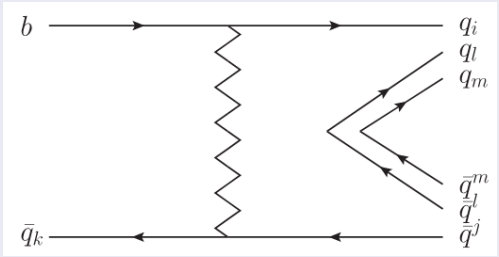
New Physics from penguin topologies vs. Residual QCD effects

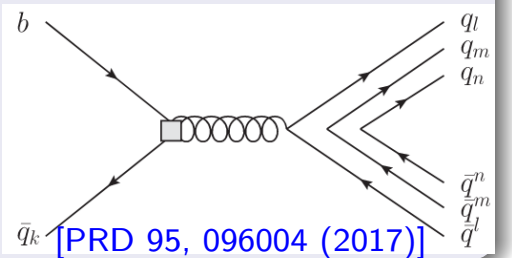
New physics from penguin topologies

W-Exchange and Penguin-Annihilation diagrams suppressed?

- **yes**: $\mathcal{B}(B_s^0 \to p\bar{p}) \to 0$
- **no**: $\mathcal{B}(B_s^0 \to p\bar{p}) \approx \mathcal{O}(10^{-8})$

[JHEP 2004, 035 (2020)]





[PRD 95, 096004 (2017)]

Residual QCD effects

Threshold enhancement on multi-body on the $m(p\bar{p}) = m(p) + m(\bar{p})$ region of the phase space. Several possible explanations:

- Resonance before threshold
- Final state interactions between the baryon pair
- ...

[Eur. Phys. J. C74 (2014) 3026]

Non-perturbative strong interactions combine with short-distance weak decays to produce final states that display non-trivial patterns.

Search for the rare hadronic decay $B_s^0 \to p\bar{p}$

Run 2 data: $6\, fb^{-1}$

PRD (Accepted) : arXiv:2206.06673

Introduction

Search for the rare hadronic decay $B_s^0 \to p\bar{p}$

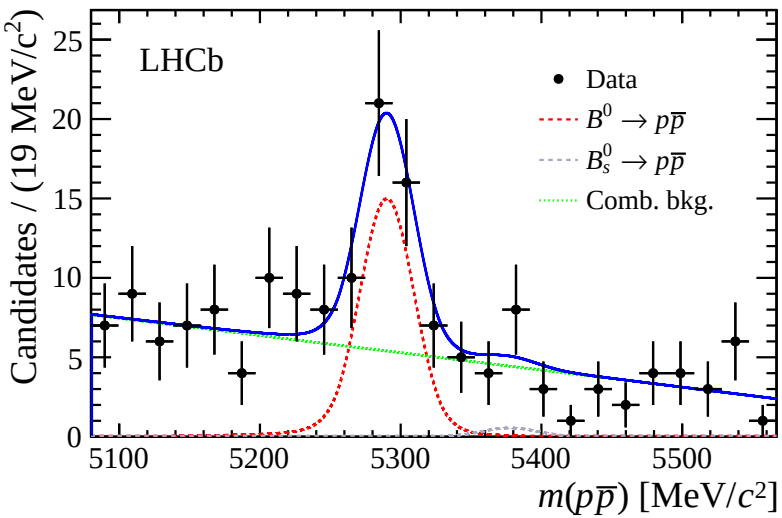
Previous results

LHCb Run 1 data: $3\,fb^{-1}$.

$\mathcal{B}(B^0 \to p\bar{p}) = (1.25 \pm 0.27 \pm 0.18) \times 10^{-8}$

$\mathcal{B}(B_s^0 \to p\bar{p}) < 1.5 \times 10^{-8}$ at 90% CL

[PRL 119 (2017) 232001]



Analysis strategy

$$\mathcal{B}(B^0_{(s)} \to p\bar{p}) = \frac{N(B^0_{(s)} \to p\bar{p})}{N(B^0 \to K^+\pi^-)} \times \frac{\varepsilon_{B^0 \to K^+\pi^-}}{\varepsilon_{B^0_{(s)} \to p\bar{p}}} \times \mathcal{B}(B^0 \to K^+\pi^-) \times \frac{f_d}{f_{d(s)}},$$

blinded signal region.

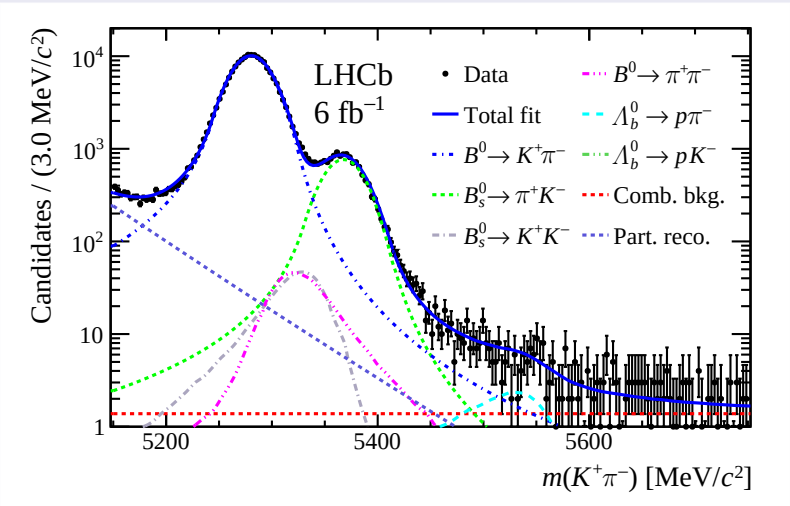
Selection and Signal Yields

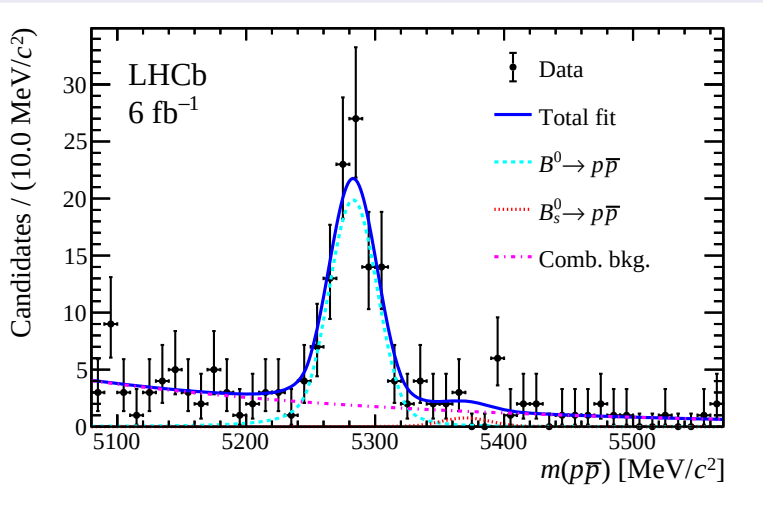
Search for the rare hadronic decay $B_s^0 \to p\bar{p}$

Selection: performed in 3 steps

- Previous cuts to ensure **good quality of tracks**.
- **PID**. Punzi FoM $= \frac{\varepsilon_{sig}}{\alpha/2+\sqrt{N_{bkg}}}$; $\alpha = 3$.
- **BDT** on topological variables to reduce the combinatorial background.

Signal yields from mass fits





$N(B^0 \to K^+\pi^-) = 179890 \pm 350$

$N(B^0 \to p\bar{p}) = 98 \pm 11 \quad N(B_s^0 \to p\bar{p}) = 4 \pm 5$

Results

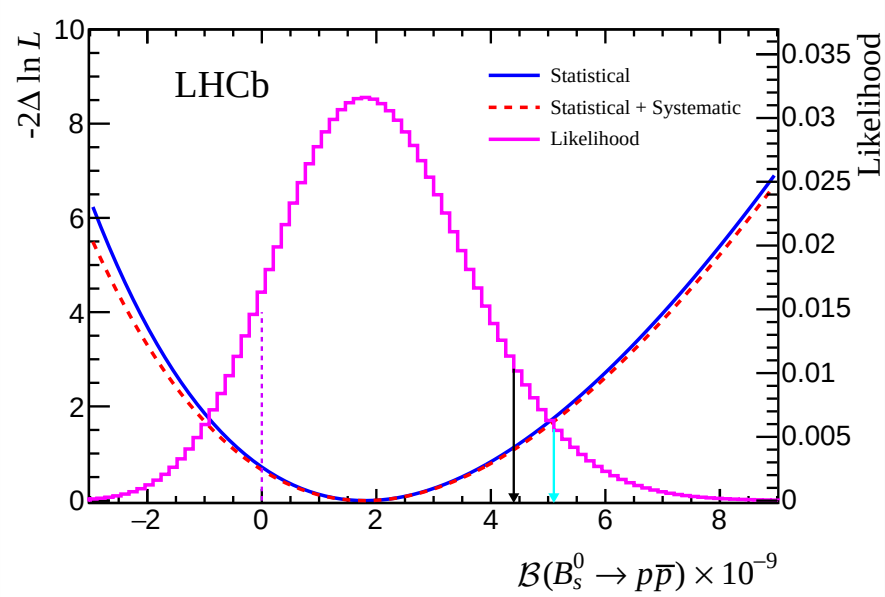
Search for the rare hadronic decay $B_s^0 \to p\bar{p}$

$B^0 \to p\bar{p}$, observation confirmed

- Run 2: $\mathcal{B}(\mathbf{B^0 \to p\bar{p}}) = (\mathbf{1.27 \pm 0.15 \pm 0.05 \pm 0.04}) \times \mathbf{10^{-8}}$
- Combination with Run 1: $\mathcal{B}(B^0 \to p\bar{p}) = (1.27 \pm 0.13 \pm 0.05 \pm 0.03) \times 10^{-8}$

$B_s^0 \to p\bar{p}$, upper limit improved by a factor ~ 4

- $\mathcal{B}(\mathbf{B_s^0 \to p\bar{p}}) < \mathbf{4.4\,(5.1) \times 10^{-9}}$ at **90% (95%) CL**



Searches for the rare hadronic decays $B^0 \to p\bar{p}p\bar{p}$ and $B_s^0 \to p\bar{p}p\bar{p}$

Run 1 + Run 2 data: $9\,fb^{-1}$

PRL (Accepted) : arXiv:2211.08847

Introduction

Searches for the rare hadronic decays $B^0 \to p\bar{p}p\bar{p}$ and $B_s^0 \to p\bar{p}p\bar{p}$

GOAL: **First observation** of a 4-body purely baryonic B meson decay

Previous results

- **BaBar**: $\mathcal{B}(B^0 \to p\bar{p}p\bar{p}) < 2.0\times10^{-7}$ at 90% CL. [PRD 98 (2018) 7, 071102]
- $B_s^0 \to p\bar{p}p\bar{p}$ expected to be further suppressed than B^0 mode.

Analysis strategy

Simultaneous fit to normalization and signal in different data taking periods, efficiencies obtained separately. **Unblinding** in 2 steps.

$$\mathcal{B}(B^0_{(s)} \to p\bar{p}p\bar{p}) =$$

$$\frac{N(B^0_{(s)} \to p\bar{p}p\bar{p})}{N(B^0_{(s)} \to J/\psi\, K^{*0}(\phi)} \times \frac{\varepsilon_{B^0_{(s)} \to J/\psi\, K^{*0}(\phi)}}{\varepsilon_{B^0_{(s)} \to p\bar{p}p\bar{p}}} \times \mathcal{B}_{vis}(B^0_{(s)} \to J/\psi\, K^{*0}(\phi))$$

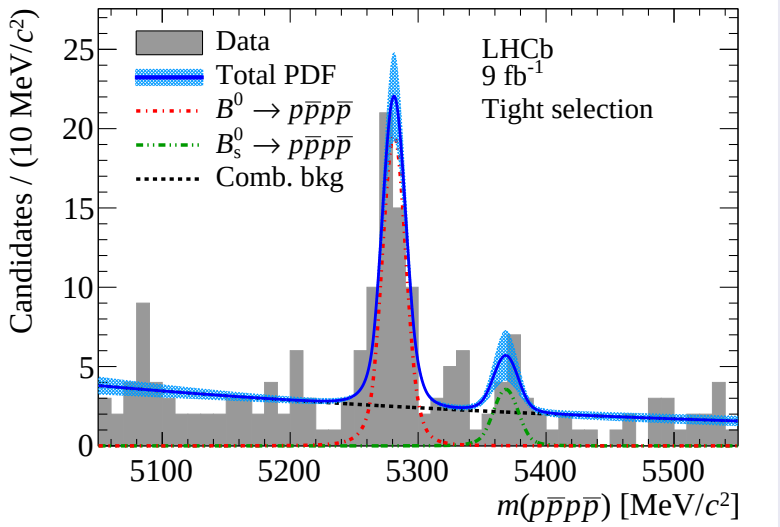
Selection and Signal Yields

Searches for the rare hadronic decays $B^0 \to p\bar{p}p\bar{p}$ and $B_s^0 \to p\bar{p}p\bar{p}$

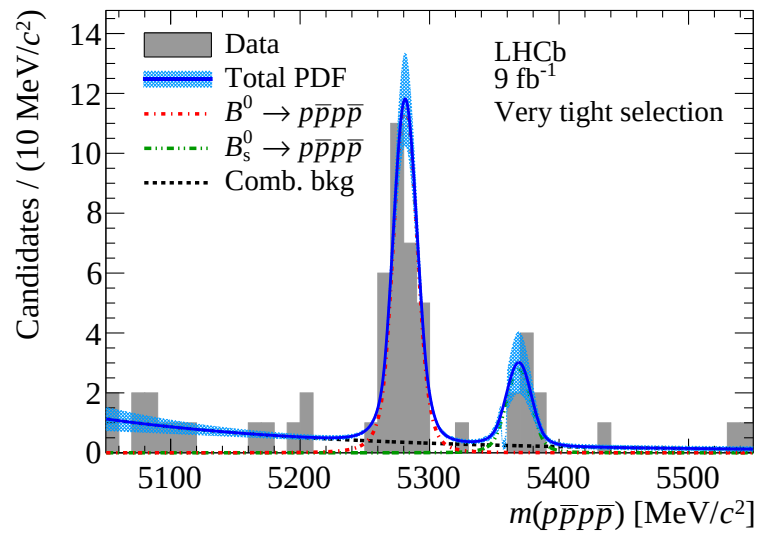
Selection: tight and very tight categories

- **PID**. Very tight cuts on PID are used to study the B_s^0 meson.
- χ^2_{IP} of the $B^0_{(s)}$ meson with respect to the origin vertex.

Signal yield: significance from independent fits



$N(B^0 \to p\bar{p}p\bar{p}) = 48 \pm 8 \quad (S > 9\sigma)$

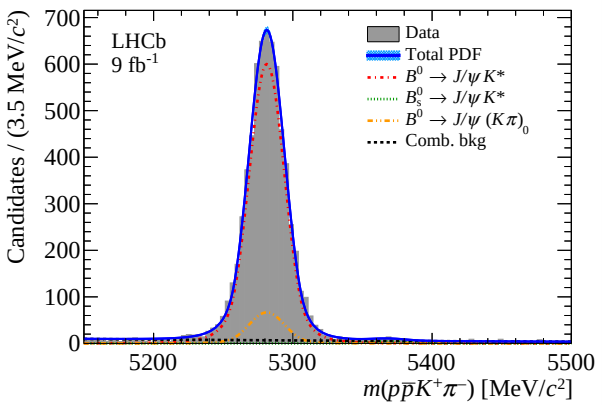


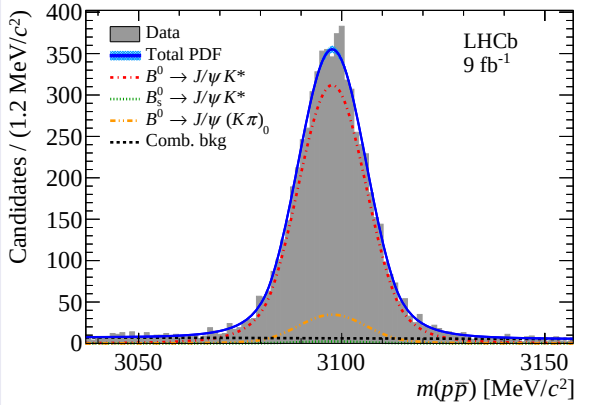
$N(B_s^0 \to p\bar{p}p\bar{p}) = 7.1 \pm 2.9 \quad (S = 4\sigma)$

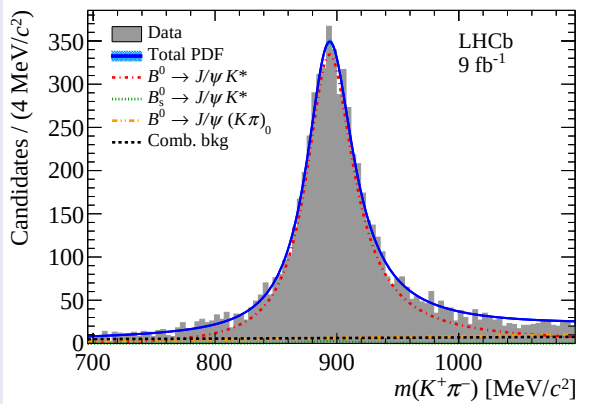
Normalization channel 3D fits

Searches for the rare hadronic decays $B^0 \to p\bar{p}p\bar{p}$ and $B_s^0 \to p\bar{p}p\bar{p}$

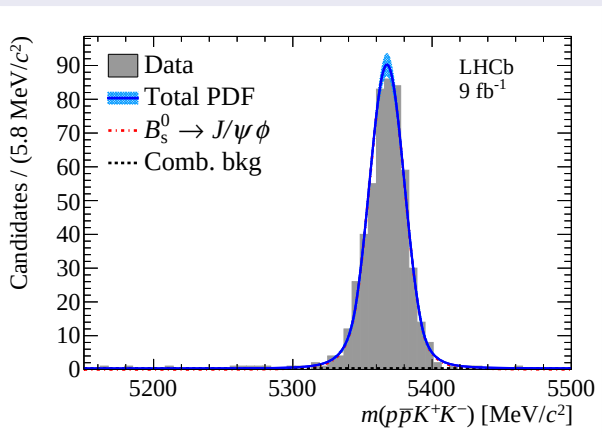
$B^0 \to J/\psi(p\bar{p})\, K^{*0}(K\pi)$

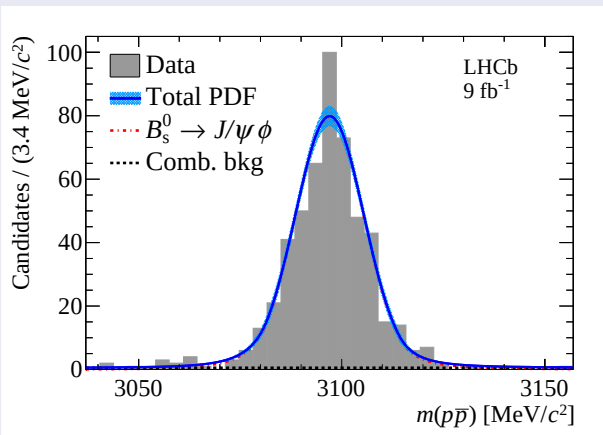


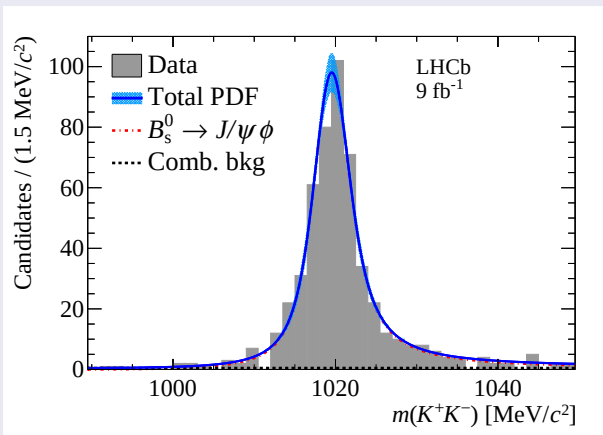




$B_s^0 \to J/\psi(p\bar{p})\, \phi(KK)$







Results

Searches for the rare hadronic decays $B^0 \to p\bar{p}p\bar{p}$ and $B_s^0 \to p\bar{p}p\bar{p}$

Simultaneous fit to signal and normalization channels on the different data-taking periods. Qualitative study for possible $c\bar{c}$ contributions.

Branching Fractions: B_s^0 unexpectedly large!

- Inclusive measurement: (tight and very-tight selections respectively)

$$\mathcal{B}(\mathbf{B^0 \to p\bar{p}p\bar{p}}) = (\mathbf{2.2 \pm 0.4 \pm 0.1 \pm 0.1}) \times \mathbf{10^{-8}}$$

$$\mathcal{B}(\mathbf{B_s^0 \to p\bar{p}p\bar{p}}) = (\mathbf{2.3 \pm 1.0 \pm 0.2 \pm 0.1}) \times \mathbf{10^{-8}}$$

- $c\bar{c}$ veto: (only statistical uncertainties)

$$\mathcal{B}(\mathbf{B^0 \to p\bar{p}p\bar{p}}) = (\mathbf{1.6 \pm 0.4}) \times \mathbf{10^{-8}}$$

$$\mathcal{B}(\mathbf{B_s^0 \to p\bar{p}p\bar{p}}) = (\mathbf{2.2 \pm 1.2}) \times \mathbf{10^{-8}}$$

Data is consistent with decays proceeding primarily through charmless transitions.
Qualitative examination: $\mathcal{B}(B^0 \to J/\psi\, p\bar{p}) \times \mathcal{B}(J/\psi \to p\bar{p}) = \mathcal{O}(10^{-9})$

Conclusion

- $B^0 \to p\bar{p}$ and $B_s^0 \to p\bar{p}$ measurements improves the extraction of tree and penguin amplitudes of charmless two-body baryonic B decays
- **First observation** of purely baryonic four-body $B_{(s)}$-meson decays! Unexpectedly large $\mathcal{B}(B_s^0 \to p\bar{p}p\bar{p})$ difficult to explain as a tree-level process, probe for non-perturbative QCD effects in B decays with baryon pairs
- LHCb Upgrade will benefit these analysis on **Run 3**:
  - Could yield the observation of $B_s^0 \to p\bar{p}$
  - Amplitude analysis on $B^0 \to p\bar{p}p\bar{p}$
  - Confirmation for the large $B_s^0 \to p\bar{p}p\bar{p}$ branching fraction
  - More baryonic lines can be studied, e.g.: $B^+ \to p\bar{\Lambda}$

back-up

Systematics

Search for the rare hadronic decay $B_s^0 \to p\bar{p}$

Source of systematic uncertainties	$B^0 \to p\bar{p}$	$B_s^0 \to p\bar{p}$
f_s/f_d	-	3.1
L0 trigger efficiency	1.0	1.0
Selection efficiency relative to $B^0 \to K^+\pi^-$	2.0	2.0
Tracking efficiency	1.9	1.9
PID efficiency	2.4	2.4
Fit model	1.0	22.0
Total	3.9	22.5

Systematics

Searches for the rare hadronic decays $B^0 \to p\bar{p}p\bar{p}$ and $B_s^0 \to p\bar{p}p\bar{p}$

Systematic source	$\mathcal{B}(B^0 \to p\bar{p}p\bar{p})$	$\mathcal{B}(B_s^0 \to p\bar{p}p\bar{p})$
Efficiencies (sample size)	5	3
Efficiencies (weights)	16	9
PID	8	3
Tracking	5	2
Fixed PDF parameters	5	2
Signal model	1	4
Background model	8	18
Total systematic	22	21
Normalisation $\mathcal{B}$	24	13

LHCb detector (upgrade)