Search for the two-body charmless baryonic B-decays $B^0 \longrightarrow p\bar{p}$ and $B_s^0 \longrightarrow p\bar{p}$ at LHCb

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Motivation

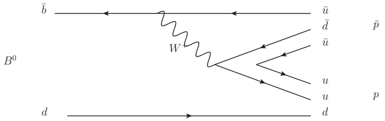
Why search for $B^0_{(s)} \to p\overline{p}$?

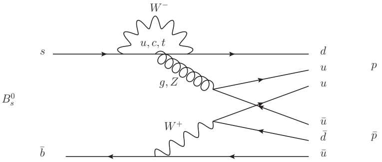
- Many 3-body modes known and studied e.g. by BaBar and Belle, with typical branching fractions (BFs) $\sim 10^{-6}$
- Several B to 2 charmless mesons decays have been observed
- Only one 2-body charmless baryonic decay mode observed, $B^+ \to p\overline{\Lambda}(1520)$ (Phys. Rev. D 88, 052015)
- $B^0_{(s)} \to p\overline{p}$ predicted to be the simplest mode
- Previous searches had probed down to BFs $\sim 10^{-7}$ (CLEO, SLAC, KEK-B)
- LHCb can probe further than these previous experiments

Theory

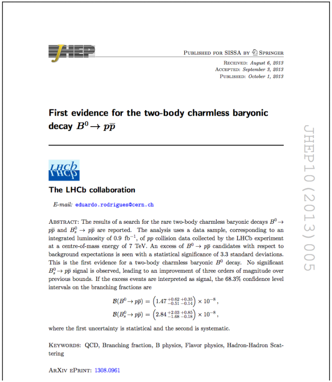
2-body modes prove difficult to calculate theoretically, models predict BFs of order $10^{-7} - 10^{-6}$ depending on which model used (e.g. quantum chromodynamics sum rules, diquark model, pole model)

- $B^0 \to p\bar{p}$ decay dominated by $b \to u$ tree-level process (left).
- $B^0_s \to p\bar{p}$ cannot decay via simple tree-level process $\to$ suppressed with contributions from topologies such as penguin (right), box and W-exchange





2011 Analysis



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First evidence for the two-body charmless baryonic decay $B^0 \to p\bar{p}$

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ABSTRACT: The results of a search for the rare two-body charmless baryonic decays $B^0 \to p\bar{p}$ and $B_s^0 \to p\bar{p}$ are reported. The analysis uses a data sample, corresponding to an integrated luminosity of 0.9 fb^{-1}, of pp collision data collected by the LHCb experiment at a centre-of-mass energy of 7 TeV. An excess of $B^0 \to p\bar{p}$ candidates with respect to background expectations is seen with a statistical significance of 3.3 standard deviations. This is the first evidence for a two-body charmless baryonic B^0 decay. No significant $B_s^0 \to p\bar{p}$ signal is observed, leading to an improvement of three orders of magnitude over previous bounds. If the excess events are interpreted as signal, the 68.3% confidence level intervals on the branching fractions are

$$\mathcal{B}(B^0 \to p\bar{p}) = \left(1.47\,^{+0.62}_{-0.51}\,^{+0.35}_{-0.14}\right) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to p\bar{p}) = \left(2.84\,^{+2.03}_{-1.68}\,^{+0.85}_{-0.18}\right) \times 10^{-8},$$

where the first uncertainty is statistical and the second is systematic.

KEYWORDS: QCD, Branching fraction, B physics, Flavor physics, Hadron-Hadron Scattering

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- Results published in JHEP (doi:10.1007/JHEP10(2013)005)
- Analysis uses $0.92\,\text{fb}^{-1}$ of proton-proton collision data at CoM energy of 7 TeV, 90% of the full 2011 data set

Analysis strategy

- Relative BF measurement using $B^0 \to K^+\pi^-$ normalisation channel (extra f_d/f_s factor for $B_s^0 \to p\overline{p}$)

$$\mathcal{B}(B^0 \to p\overline{p}) = \frac{N(B^0 \to p\overline{p})}{N(B^0 \to K^+\pi^-)} \frac{\epsilon_{B^0 \to K^+\pi^-}}{\epsilon_{B^0 \to p\overline{p}}} \mathcal{B}(B^0 \to K^+\pi^-) \quad (1)$$

- Measure ratio of efficiencies between signal and normalisation channels
- Number of triggered and selected events

$$N = \int \mathcal{L}\,\mathrm{d}t \cdot \sigma_{b\overline{b}} \cdot 2 \cdot f_q \cdot \mathcal{B}_{\mathrm{vis}} \cdot \epsilon_{\mathrm{tot}} \quad (2)$$

- Blind analysis. Signal region $[5230, 5417]\,\mathrm{MeV}/c^2$ blinded

$B^0_{(s)} \to p\bar{p}$ Event Selection

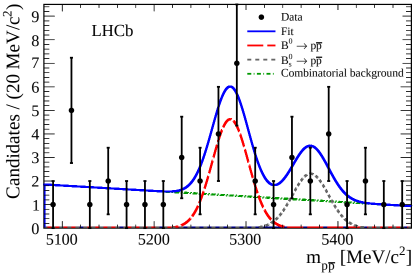
- Events selected efficiently using specific hadronic decay triggers
- Kinematic selection applied to exploit the characteristic topology of two-body decays
- Boosted decision tree (BDT) multivariate analysis (MVA) selection, using a mixture of B candidate and daughter variables
- Particle identification (PID) requirements applied to discriminate proton tracks from kaons and pions
- BDT and PID selections optimised using Punzi Figure of Merit:

$$\text{FoM} = \frac{\epsilon_{B^0 \to p\bar{p}}^{\text{BDT/trig, PID/BDT}}}{{}^{a}/_{2} + \sqrt{B^{\text{BDT/trig, PID/BDT}}}} \tag{3}$$

- a defines the target level of significance (in σ). Here choose $a = 3$
- Background yield estimated for 90% sample within signal region

$B^0_{(s)} \to p\bar{p}$ Mass fit

45 events observed across the $p\bar{p}$ mass spectrum, $[5080, 5480]\,\mathrm{MeV}/c^2$, after the selection



- Physics backgrounds studied extensively and found to be negligible
- $B^0_{(s)} \to p\bar{p}$ signal mass shapes each described by a Gaussian function with identical widths assumed for the two signals
- Combinatorial background described by a linear function

Signal yields across the full mass spectrum are:

- $N(B^0 \to p\bar{p}) = 11.42 \pm 4.25$ stat.
- $N(B^0_s \to p\bar{p}) = 5.70 \pm 3.38$ stat.

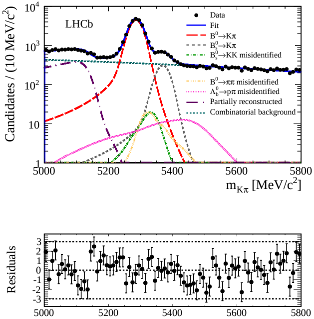
Signal regions defined as $\pm 50\,\mathrm{MeV}/c^2$ window around the fitted $B^0_{(s)} \to p\bar{p}$ mass peaks

$B^0 \to K^+\pi^-$ selection

- Normalisation channel for $B^0_{(s)} \to p\overline{p}$
- Identical trigger requirements as $B^0_{(s)} \to p\overline{p}$ selection
- Purely cut based selection utilising several of the same variables used in the $B^0_{(s)} \to p\overline{p}$ selection and BDT
- PID selection to discriminate kaons and pions, cut efficiency of 42%
- Overall ratio of efficiencies for $B^0 \to p\overline{p}$ wrt $B^0 \to K^+\pi^-$ is 0.60

$B^0 \to K^+\pi^-$ Mass fit

58009 events observed across the $K^+\pi^-$ mass spectrum, $[5000, 5800]\,\mathrm{MeV}/c^2$, after the selection

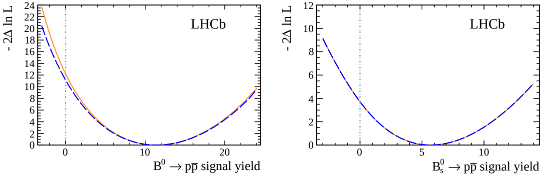


- Background contributions from misidentified $B_s^0 \to K^+K^-$, $B^0 \to \pi^+\pi^-$ and $\Lambda_b^0 \to p\pi^-$ as well as partially reconstructed and combinatorial backgrounds
- $B^0 \to K^+\pi^-$, $B_s^0 \to \pi^+K^-$ signal mass shapes each described by the sum of two Crystal Ball (CB) functions
- Misidentified backgrounds modelled with non-parametric PDFs
- Partially reconstructed backgrounds modelled with the sum of two exponentially-modified Gaussian (EMG) functions
- Combinatorial background described by a linear function

$B^0 \to K^+\pi^-$ Signal yield across the full mass spectrum:
$N(B^0 \to K^+\pi^-) = 24961 \pm 193$ stat.

Signal Significances

$B^0_{(s)} \to p\bar{p}$ signal significances using Wilks' theorem: $\sqrt{-2\ln(L_{S+B}/L_B)}$
L_{S+B} and L_B are the likelihoods from the baseline fit and the fit without the signal component, respectively



- Orange, statistical uncertainty only
- Blue, statistical and systematic uncertainties combined

Total significances:

$B^0 \to p\bar{p}$, 3.3σ $\to$ Evidence!

$B^0_s \to p\bar{p}$, 1.9σ

Confidence Limits

- Use Feldman-Cousins (FC) frequentist method to construct 68.3% and 90% CL intervals on $B^0_{(s)} \to p\overline{p}$ BFs
- FC method naturally provides one- or two-sided limits eliminating the risk of "flip-flopping"
- CL interval bands determined via simulation studies and taking into account systematic uncertainties
- Final 68.3% and 90% CL intervals:

$$\mathcal{B}(B^0 \to p\overline{p}) = (1.47\,^{+0.62}_{-0.51}\,^{+0.35}_{-0.14}) \times 10^{-8} \quad \text{at} \quad 68.3\% \quad \text{CL},$$

$$\mathcal{B}(B^0 \to p\overline{p}) = (1.47\,^{+1.09}_{-0.81}\,^{+0.69}_{-0.18}) \times 10^{-8} \quad \text{at} \quad 90\% \quad \text{CL},$$

$$\mathcal{B}(B^0_s \to p\overline{p}) = (2.84\,^{+2.03}_{-1.68}\,^{+0.85}_{-0.18}) \times 10^{-8} \quad \text{at} \quad 68.3\% \quad \text{CL},$$

$$\mathcal{B}(B^0_s \to p\overline{p}) = (2.84\,^{+3.57}_{-2.12}\,^{+2.00}_{-0.21}) \times 10^{-8} \quad \text{at} \quad 90\% \quad \text{CL},$$

First uncertainties are statistical and the second are systematic

Summary

- Two-sided confidence limits applied to $B^0 \to p\bar{p}$ and $B_s^0 \to p\bar{p}$ BFs for the first time
- Excess of $B^0 \to p\bar{p}$ candidates wrt. background expectations of 3.3σ
- First evidence for a two-body charmless baryonic B^0 decay
- No significant $B_s^0 \to p\bar{p}$ signal observed
- Upper limit on $B_s^0 \to p\bar{p}$ BF improves previous result by 3 orders of magnitude
- Measured $B^0 \to p\bar{p}$ BF excludes all existing theoretical predictions!
- Results motivate renewed theoretical calculations in this sector

Updated 2011+2012 dataset $B^0_{(s)} \to p\bar{p}$ analysis

Work currently under way on an updated $B^0_{(s)} \to p\bar{p}$ search using the full 2011 and 2012 combined pp collision data set

Suite of improvements planned following the 2011 analysis:

- Retain 100% of available data for analysis
- Change of MVA method $\to$ multilayer perceptron neural net (MLP ANN)
- Asymmetric PID selection $\to$ looser cut on least proton-like daughter to boost signal efficiency
- Normalisation channel event selection to mirror $B^0_{(s)} \to p\bar{p}$ selection more closely, reducing systematic uncertainty on ratio of efficiencies
- Simultaneous invariant mass fit in bins of MVA output

Aim to improve signal yield to observe 5σ significance in $B^0 \to p\bar{p}$

Search for $B^+ \to p\overline{\Lambda}$

Analysis within LHCb to search for $B^+ \to p\overline{\Lambda}$, the next simplest two-body baryonic mode after $B^0_{(s)} \to p\overline{p}$

- Analysis on full 2011 and 2012 combined data set
- Aiming to make a relative BF measurement, with $B^+ \to \pi^+ K^0_S$ as normalisation channel
- Extensive background studies required
- MVA methods required to reject large amount of combinatorial background
- Long Λ lifetime ($\tau = 2.6 \times 10^{-10}$s) and differences in detector performance between 2011 and 2012 add additional layers of complexity to the analysis

Backup Slides

BDT input variables

11 variables used in $B^0_{(s)} \to p\overline{p}$ BDT selection

- $\ln(B$ vertex $\chi^2/\text{nDoF})$;
- $\ln(B$ vertex IP $\chi^2)$;
- $\cos(B$ direction angle), the cosine of the B direction angle (the so-called DIRA variable);
- A_{p_T}, the p_T asymmetry of the B within a cone of radius[1] $R = 0.6$ around the B, given by

$$A_{p_\mathrm{T}} = \frac{{p_\mathrm{T}}^B - {p_\mathrm{T}}^\mathrm{cone}}{{p_\mathrm{T}}^B + {p_\mathrm{T}}^\mathrm{cone}} \quad , \tag{4}$$

  with ${p_\mathrm{T}}^\mathrm{cone}$ being the p_T of the vector sum of all tracks measured within the cone radius $R = 0.6$ around the B, except for the B-daughter particles;
- ln(distance in z between the B-decay vertex and the related PV);
- B-daughters' distance of closest approach (DOCA);
- Minimum of the daughters' p_T;
- Sum of the daughters' p_T;
- Minimum of the daughters' $\ln(\text{IP } \chi^2)$;
- Maximum of the daughters' $\ln(\text{IP } \chi^2)$;
- Minimum of the daughters' cone multiplicities within the cone of radius $R = 0.6$ around the daughters. The daughter cone multiplicity is calculated as the number of particles within the cone around each B-daughter.

[1] The cone radius is defined in (η, ϕ) as $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

Systematic Uncertainties

The full table of $B^0_{(s)} \to p\overline{p}$ and $B^0 \to K^+\pi^-$ systematic uncertainties:

Table: Relative systematic uncertainties contributing to the $B^0_{(s)} \to p\overline{p}$ branching fractions. The total corresponds to the sum of all contributions added in quadrature.

Source	Value (%)		
	$B^0 \to p\overline{p}$	$B^0_s \to p\overline{p}$	$B^0 \to K^+\pi^-$
$B^0 \to K^+\pi^-$ branching fraction	–	–	2.8
Trigger efficiency relative to $B^0 \to K^+\pi^-$	2.0	2.0	–
Selection efficiency relative to $B^0 \to K^+\pi^-$	8.0	8.0	–
PID efficiency	10.6	10.7	1.0
Yield from mass fit	6.8	4.6	1.6
f_s/f_d	–	7.8	–
Total	15.1	16.3	3.4