# Charmless baryonic weak-decay processes

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Workshop on multibody charmless B-hadron decays
LPNHE, Paris, June 6th 2018

# Charmless b-hadron decays – some triumphs and puzzles

**Take-away message: charmless decays have been providing a wealth of important results in Flavour Physics !**

*Triumphs*

- ❑ 1st observation of CP violation in $B_s$ mesons
- ❑ Observation of the largest CP violation effects, in 3-body $B^+$ decays
- ❑ 1st evidence for CP violation in baryonic B decays
- ❑ 1st evidence for CP violation in the decay of a baryon

*Puzzles / features*

- ❑ K-$\pi$ puzzle in 2-body B decays
- ❑ Polarisation puzzle in $B \to V\, V$ decays
  - Unexpectedly small longitudinal polarisation component in $B \to \phi\, K^*$ decays
- ❑ Threshold enhancement in baryonic B decays

# *Baryonic decays: a bit of history and motivation …*

# $1^{st}$ evidence for B decay to a charmless baryonic final state

(Belle Collaboration)

We report the observation of the decay mode $B^{\pm} \rightarrow p\bar{p}K^{\pm}$ based on an analysis of 29.4 fb$^{-1}$ of data collected by the Belle detector at KEKB. This is the first example of a $b \rightarrow s$ transition with baryons in the final state. The $p\bar{p}$ mass spectrum in this decay is inconsistent with phase space and is peaked at low mass. The branching fraction for this decay is measured to be $\mathcal{B}(B^{\pm} \rightarrow p\bar{p}K^{\pm}) = (4.3^{+1.1}_{-0.9}(\text{stat}) \pm 0.5(\text{syst})) \times 10^{-6}$. We also report upper limits for the decays $B^0 \rightarrow p\bar{p}K_S$ and $B^{\pm} \rightarrow p\bar{p}\pi^{\pm}$.

$$\mathcal{B}(B^{+} \rightarrow p\bar{p}K^{+}) = (4.3^{+1.1}_{-0.9}(\text{stat}) \pm 0.5(\text{syst})) \times 10^{-6}$$

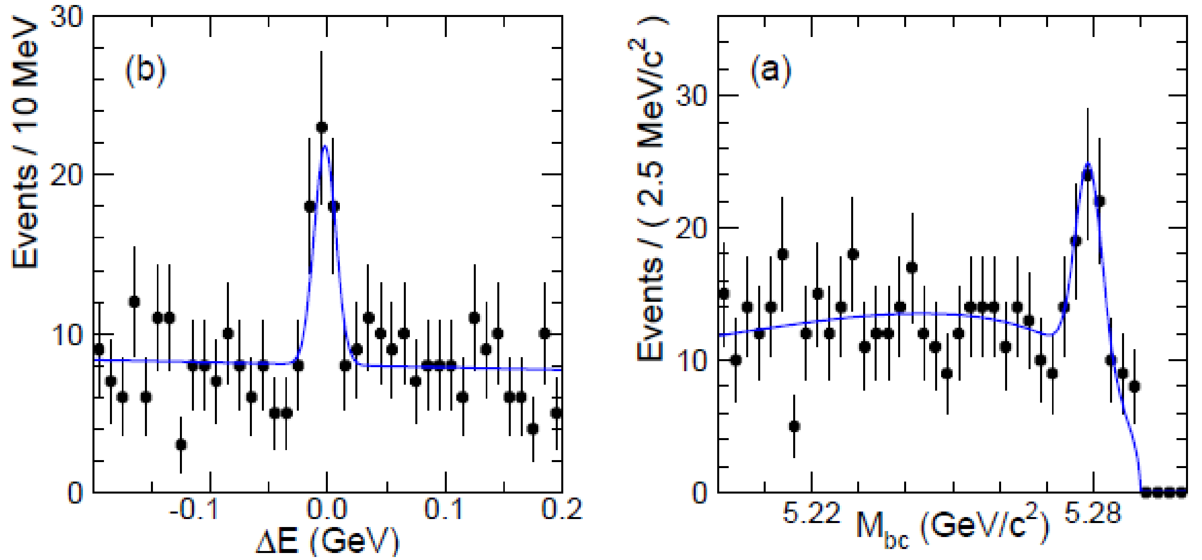



FIG. 1. (a) $\Delta E$ and (b) $M_{\text{bc}}$ distributions for $B^{+} \rightarrow p\bar{p}K^{+}$ candidates.

**Phys. Rev. Lett. 88, 181803 (2002)**

# Baryonic B decays – motivation

- ❑ **Inclusive branching fraction (BF) to baryonic final states ~ 7% of B-meson total width !**
  - **- Most decay modes still to be studied / observed**
  - **- Large variety of final states possible thanks to a large B mass**

- ❑ **Threshold enhancement in baryon-antibaryon system observed in many decay modes**

  **[see e.g. "The physics of the B factories", Eur. Phys. J. C74 (2014) 3026]**

- ❑ **Many-body final states tend to have a larger BF than 3- and 2-body final states**

$$\mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-) \gg \mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^0) \gg \mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \overline{p}),$$

$$\begin{aligned} & \mathcal{B}(\overline{B} \to \mathfrak{B}_{1c} \overline{\mathfrak{B}}_{2c}) \sim 10^{-3} \\ \gg & \mathcal{B}(\overline{B} \to \mathfrak{B}_c \overline{\mathfrak{B}}) \sim 10^{-5} \\ \gg & \mathcal{B}(\overline{B} \to \mathfrak{B}_1 \overline{\mathfrak{B}}_2) \lesssim 10^{-6} \end{aligned}$$

- ❑ **Theoretical description is a challenge and various models "in competition"**
  - **- Theshold enhancement not fully understood**

# Baryonic B decays – short history & highlights

CLEO

- 1997: 1st observation of baryonic B decays [PRL 79, 3125 (1997)]

B factories

- 2002: 1st observation of a charmless baryonic B decay, $B^+ \to p\,\overline{p}\,K^+$ [PRL 88, 181803 (2002)]
- 2013: 1st evidence for a baryonic $B_s$ decay, $B_s^0 \to \overline{\Lambda}_c^-\,\Lambda\,\pi^-$ [Phys. Lett. B 726 (2013)]
- Many $B^0$ and $B^+$ baryonic decays observed and studied, with charm in the final state, or charmless
- Experimental observation of threshold enhancement in baryon-antibaryon invariant mass in several decay modes

LHC(b)

- 2013: 1st observation of a 2-body charmless baryonic mode: $B^+ \to p\,\overline{\Lambda}(1520)$ [PRL 113, 141801 (2014)]

  1st evidence for CP violation in a baryonic B decay, seen in $B^+ \to p\,\overline{p}\,K^+$ [PRL 113, 141801 (2014)]

  1st evidence for very suppressed $B^0 \to p\,\overline{p}$ with 2011 data analysis [JHEP 10 (2013) 005]
- 2014: 1st observation of a baryonic $B_c^+$ decay, $B_c^+ \to J/\varphi\,p\,\overline{p}\,\pi^+$ [PRL 113, 152003 (2014)]
- 2016: 1st evidence for suppressed $B^+ \to p\,\overline{\Lambda}$ [JHEP 04 (2017) 162]

  1st observation of a baryonic $B_s^0$ decay, $B_s^0 \to p\,\overline{\Lambda}\,K^-$ [arXiv:1704.07908 [hep-ex]]

  Observation of charmless $B_{(s)}^0 \to p\,\overline{p}\,h^+h'^-$ decays [arXiv:1704.08497 [hep-ex]]
- 2017: 1st observation of a purely baryonic $B^0$ decay, $B^0 \to p\,\overline{p}$ [arXiv:1709.01156 [hep-ex]]

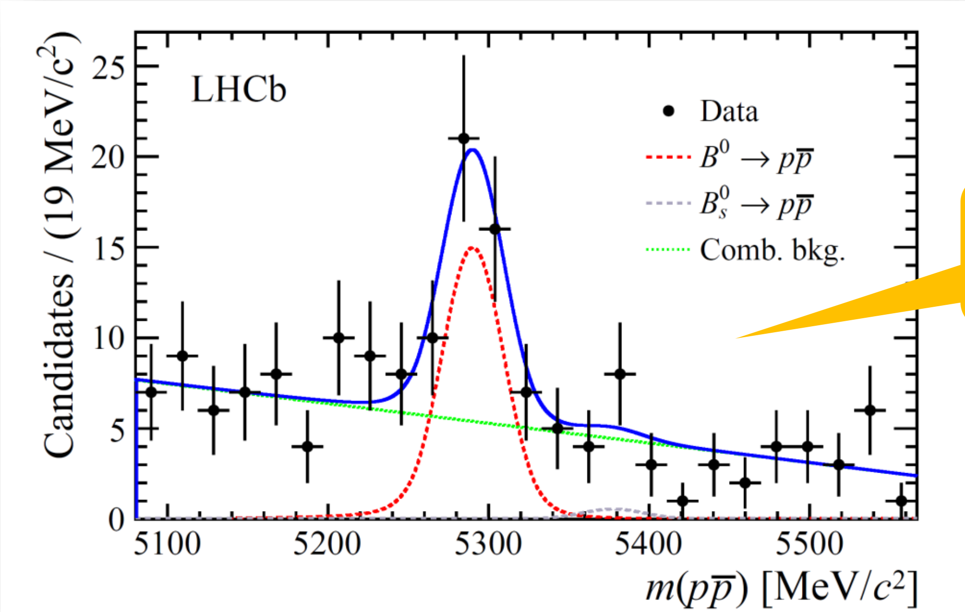
# Rare modes

➡ *Rare baryonic = typically 2-body decays … but only?*
$B^0_{(s)} \to p\,\bar{p}$

# First observation of $B^0 \to p\,\bar{p}$

PRL 119, 232001 (2017)

❑ Rarest $B^0$ decay ever observed, and also rarest hadronic B decay ever observed !




Clear peak !

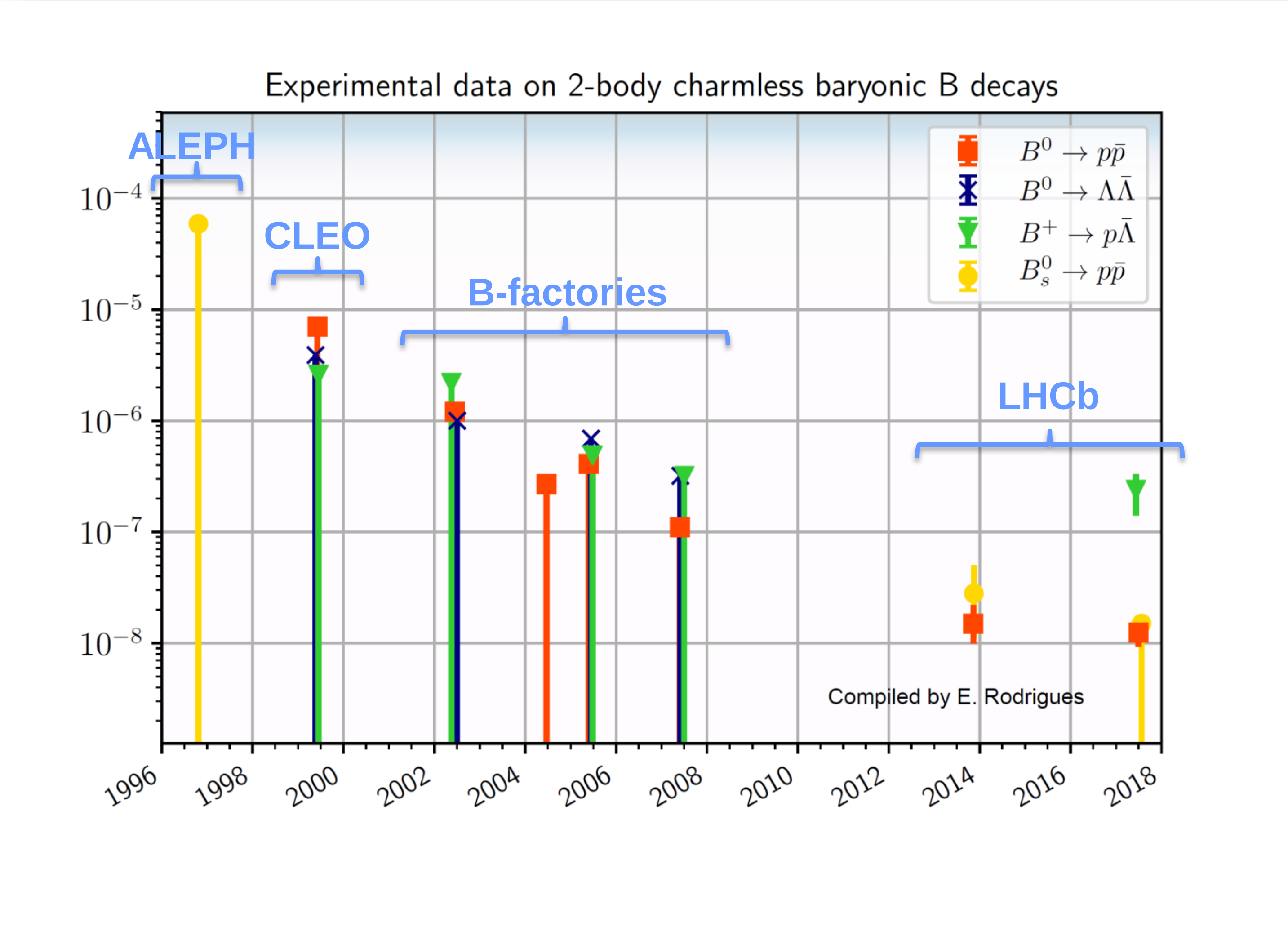
$$N(B^0 \to p\bar{p}) = 39 \pm 8$$
$$N(B_s^0 \to p\bar{p}) = 2 \pm 4$$

❑ Statistical significance = 6.0σ
- 5.3σ with systematic uncertainties included

❑ First observation of a charmless 2-body baryonic $B^0$ decay !

$$\mathcal{B}(B^0 \to p\bar{p}) = (1.25 \pm 0.27 \pm 0.18) \times 10^{-8}$$
$$\mathcal{B}(B_s^0 \to p\bar{p}) < 1.5 \times 10^{-8} \text{ at } 90\% \text{ confidence level}$$

# Where do we stand for 2-body decays ?




**Upper limits** **1st evidences or observations**

# Baryonic $B_s$ decays

$B^0_{(s)} \to p\,\overline{\Lambda}\,h^-$

$B^0_{(s)} \to p\,\overline{p}\,h^+\,h^{(\prime)-}$

# Search for baryonic $B_s$ decays – motivation recap

- **Baryonic decays of B mesons had been observed for all B species *except* the $B_s$ meson !**
  - **Only evidence of $B_s^0 \to \overline{\Lambda}_c^- \Lambda \pi^-$ by Belle** [Phys. Lett. B 726 (2013) 206]

- **2-body modes are rather suppressed ⇒ exploit 3-body final states (and 4-body states …)**

- **$B_s^0 \to p \overline{\Lambda} K^-$ seen as a good candidate given that the related mode $B^0 \to p \overline{\Lambda} \pi^-$ has a large BF ~ 3 x $10^{-6}$ and is well studied**

- **Experimental situation for $B_{(s)}^0 \to p \overline{\Lambda} h^-$ decays and cousins :**

| Decay Channel | BaBar $\mathcal{B}$ or UL | Belle $\mathcal{B}$ or UL |
|---|---|---|
| $B^0 \to p\overline{\Lambda}\pi^-$ | $(3.07 \pm 0.39) \times 10^{-6}$ [18] | $(3.23\,^{+0.33}_{-0.29} \pm 0.29) \times 10^{-6}$ [19] |
| $B^0 \to p\overline{\Lambda}K^-$ | - | $< 8.2 \times 10^{-7}$ [16] |
| $B_s^0 \to p\overline{\Lambda}K^-$ | - | - |
| $B_s^0 \to p\overline{\Lambda}\pi^-$ | - | - |
| $B^0 \to p\overline{\Sigma}^0\pi^-$ | - | $< 3.8 \times 10^{-6}$ [16] |
| $B_s^0 \to p\overline{\Sigma}^0 K^-$ | - | - |

- **No theoretical predictions were available before the LHCb experimental results became public**

# $1^{st}$ obs of a baryonic $B_s$ decay – fit projections

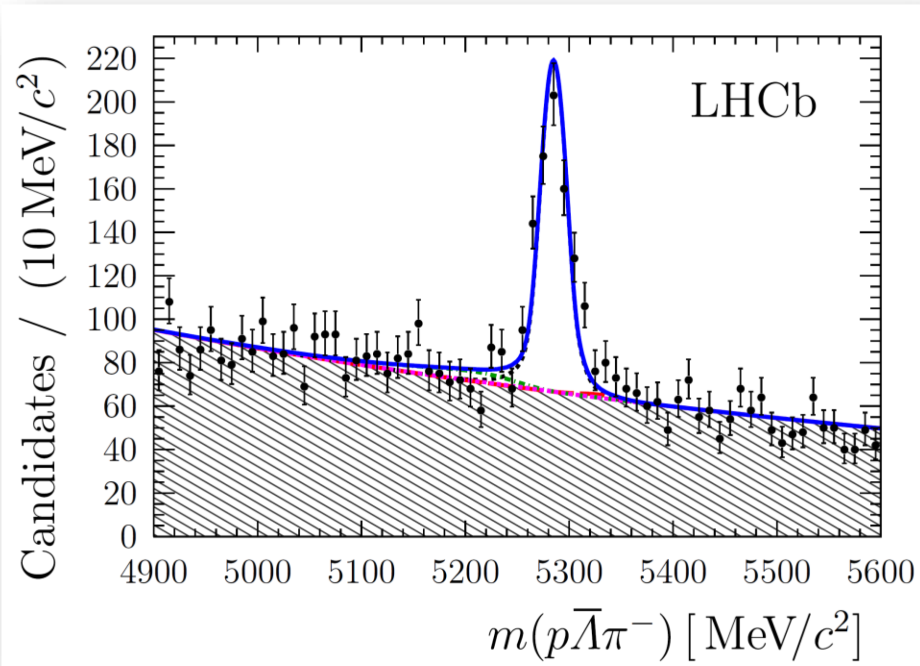
PRL 119, 041802 (2017)

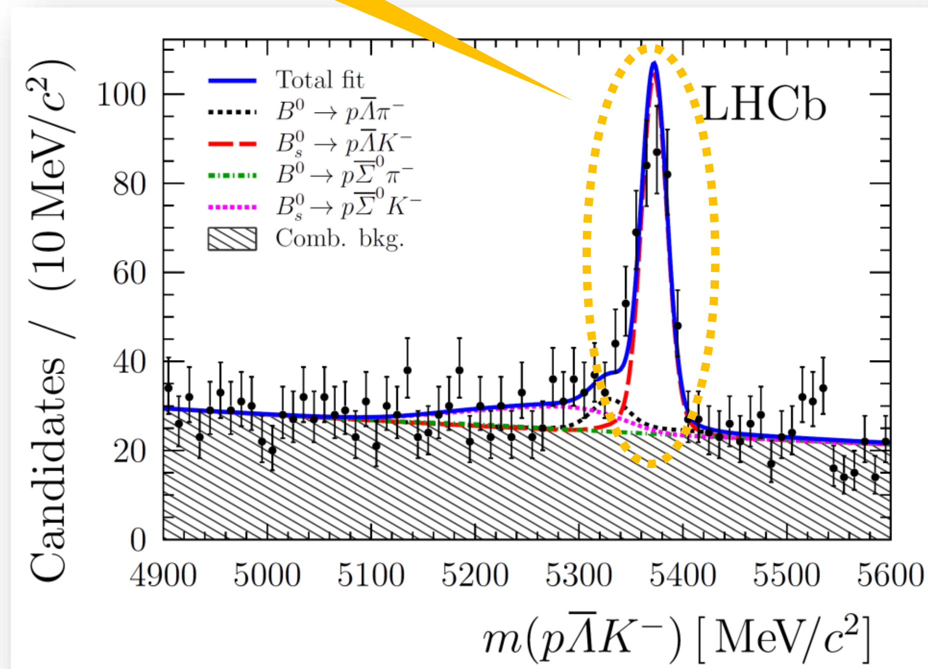
❑ **LHCb analysis on full run-I data sample**

$B^0 \to p\,\overline{\Lambda}\,\pi$

$1^{st}$ observation !

$B_s \to p\,\overline{\Lambda}\,K$



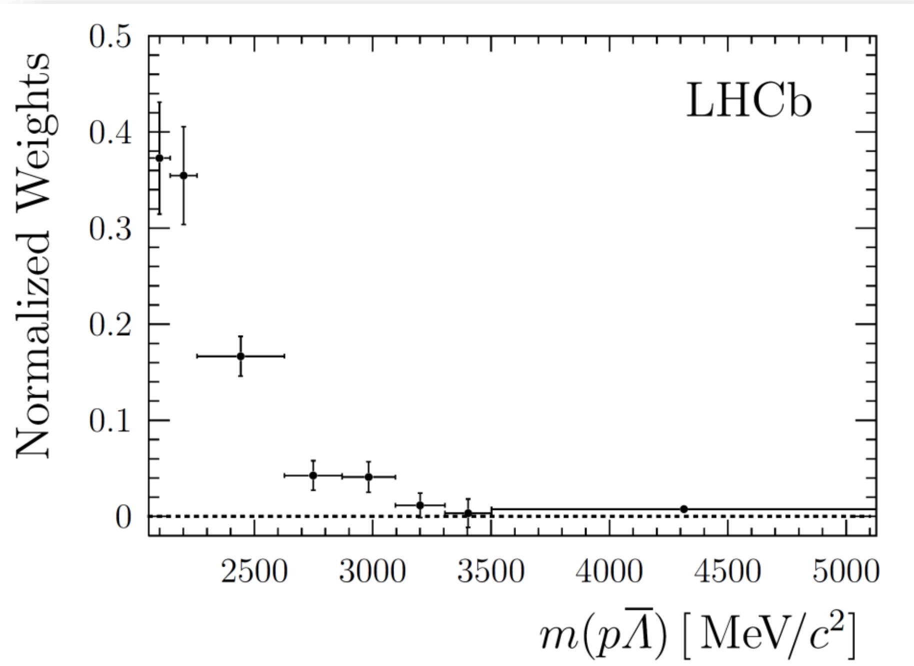

$$N(B_s^0 \to p\overline{\Lambda}K^-) = 234 \pm 29$$
$$N(B^0 \to p\overline{\Lambda}\pi^-) = 519 \pm 28$$

# $1^{st}$ obs of a baryonic $B_s$ decay – 2-part. proj.

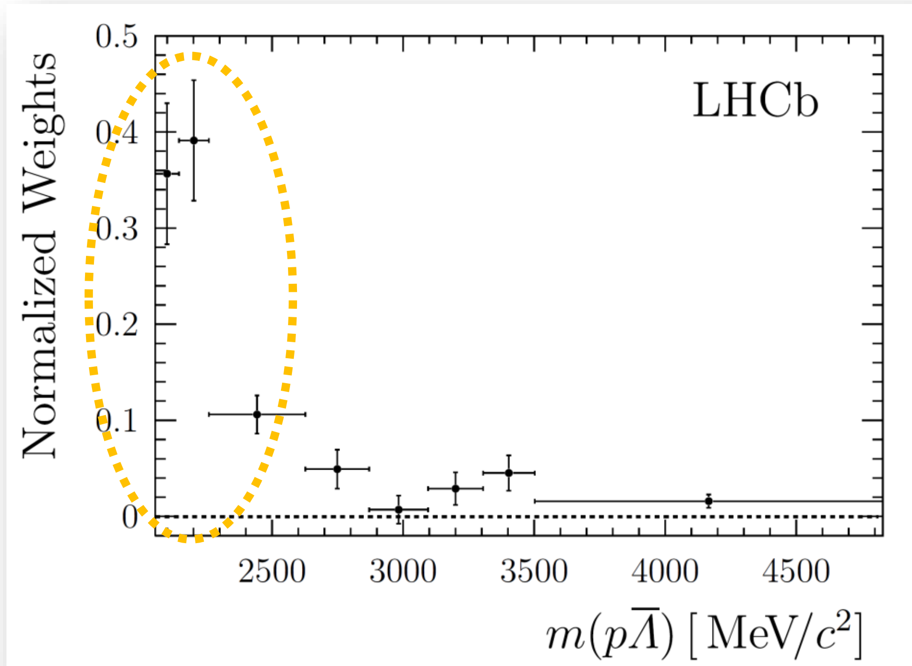
PRL 119, 041802 (2017)

$1^{st}$ observation of threshold enhancement in baryonic $B_s$ decays

$B^0 \to p \bar{\Lambda} \pi$




$B_s \to p \bar{\Lambda} K$



# First observation of a baryonic $B_s$ decay

PRL 119, 041802 (2017)

- ❑ First observation of a baryonic $B_s$ decay !
- ❑ With a statistical significance > 15σ

- ❑ Branching fraction determined to be

$$\mathcal{B}(B_s^0 \to p\overline{\Lambda}K^-)+\mathcal{B}(B_s^0 \to \overline{p}\Lambda K^+) = \left[5.46 \pm 0.61 \pm 0.57 \pm 0.50(\mathcal{B}) \pm 0.32(f_s/f_d)\right] \times 10^{-6}$$

Uncertainty on $B^0 \to p\overline{\Lambda}\pi$ branching fraction

Uncertainty on ratio of fragmentation probabilities

- ❑ Result opens a new area of research on baryonic B decays
  - So far baryonic $B_s^0$ decays had only been theo. studied [PRD 91 (2015) 077501; PRD 89 (2014) 056003] in the case of 2-body final states following the 1st evidence for $B^0 \to p\,\overline{p}$ reported by LHCb in 2013 [JHEP 10 (2013) 005] and in charmed baryonic decays [EPJ C 75 (2015) 101]
- ❑ Decay-time-dependent CP violation measurements interesting with this unique baryonic decay … !

# Time-dependent CPV in baryonic B decays

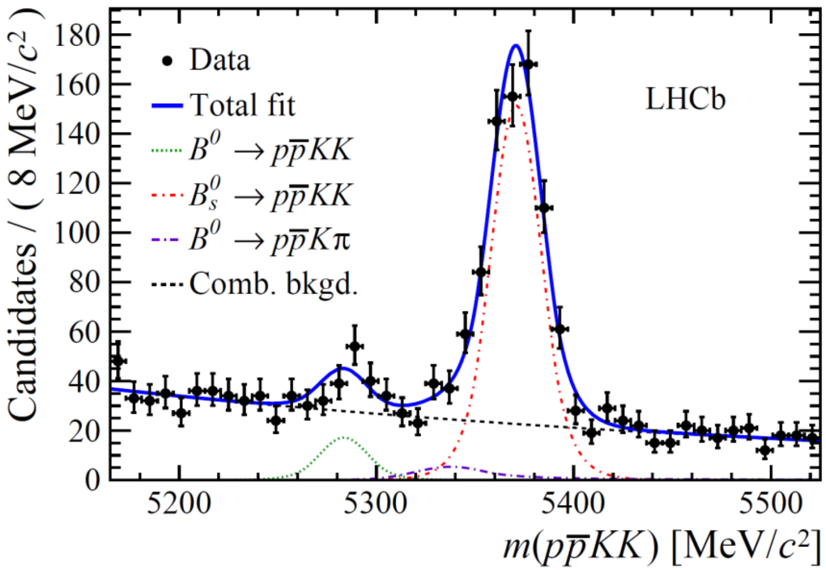
PLB 767 (2016) 205

- $B^0 \to p\,\overline{\Lambda}\,\pi^-$ is flavour-specific, unlike $B_s^0 \to p\,\overline{\Lambda}\,K^-$ :
  (in some analogy with $B_s^0 \to D_s^+\pi^-$ and $B_s^0 \to D_s^+K^-$)
- All 4 processes $B_s^0\,,\overline{B}_s^0 \to p\,\overline{\Lambda}\,K^-,\ \overline{p}\,\Lambda\,K^+$ are possible
  ⇒ need for a flavour-tagged time-dependent analysis to disentangle all contributions
- First case realised of a baryonic B decay where
  time-dependent CP violation measurements are relevant
- Ratio of amplitudes predicted to be large
  ⇒ potentially large CP violating asymmetries !
- Typical TDCPV analyses require data samples of minimum ≈ 1.0 – 1.5 k events
  ⇒ need full data sample to be collected in LHCb's run II

  (Extrapolation from run-I analysis assuming a two-fold increase in the b production cross-section between run I and run II)

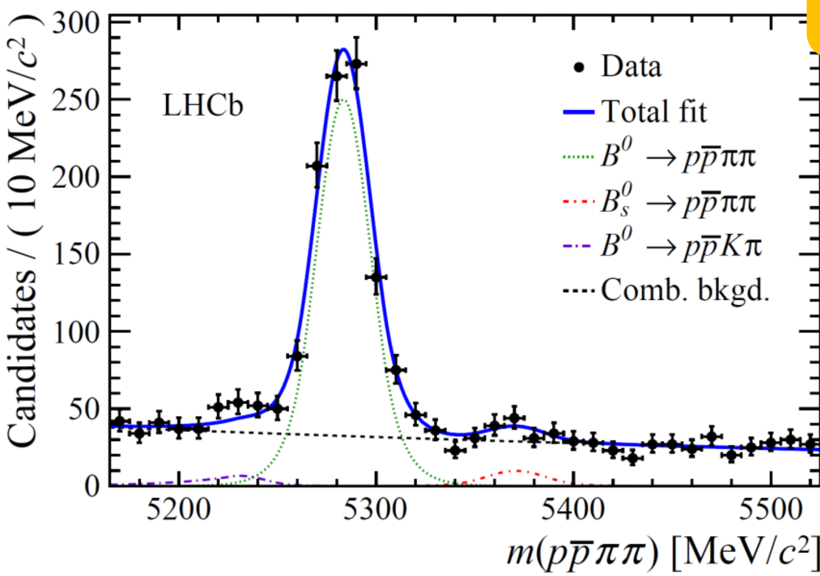
# $B^0_{(s)} \to p\,\overline{p}\,h^+\,h'^-$

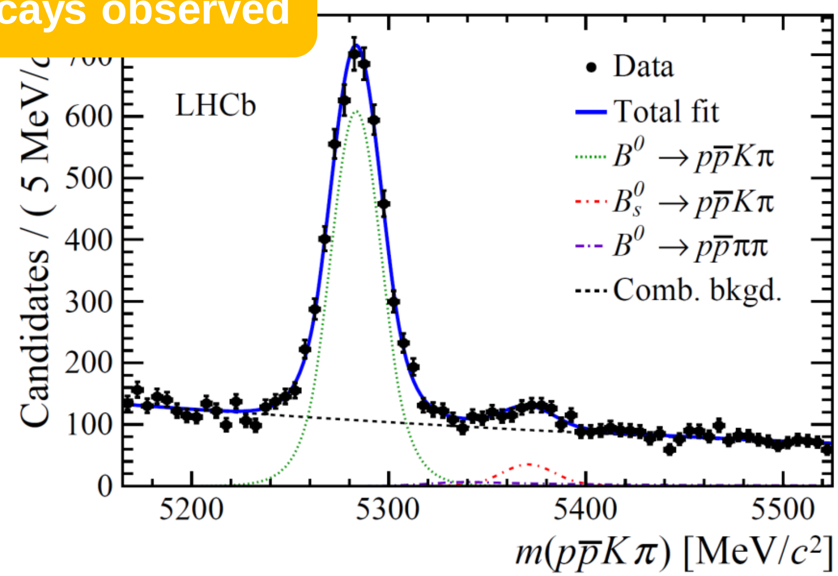
PRD 96, 051103(R) (2017)




| Decay channel | Yield $\mathcal{N}$ | Significance $[\sigma]$ |
|---|---|---|
| $B^0 \to p\overline{p}KK$ | $68 \pm 17$ | 4.1 |
| $B^0 \to p\overline{p}K\pi$ | $4155 \pm 83$ | $> 25$ |
| $B^0 \to p\overline{p}\pi\pi$ | $902 \pm 35$ | $> 25$ |
| $B^0_s \to p\overline{p}KK$ | $635 \pm 32$ | $> 25$ |
| $B^0_s \to p\overline{p}K\pi$ | $246 \pm 39$ | 6.5 |
| $B^0_s \to p\overline{p}\pi\pi$ | $39 \pm 16$ | 2.6 |
| $B^0 \to J/\psi K^*(892)^0$ | $1216 \pm 45$ | – |

**Yet more baryonic $B_{(s)}$ decays observed**

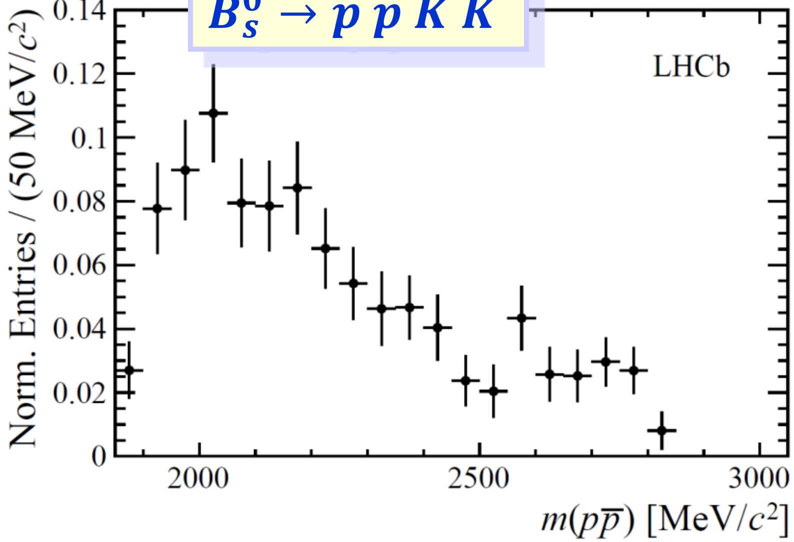


# $B^0_{(s)} \to p\,\overline{p}\,h^+\,h'^-$ – threshold enhancement

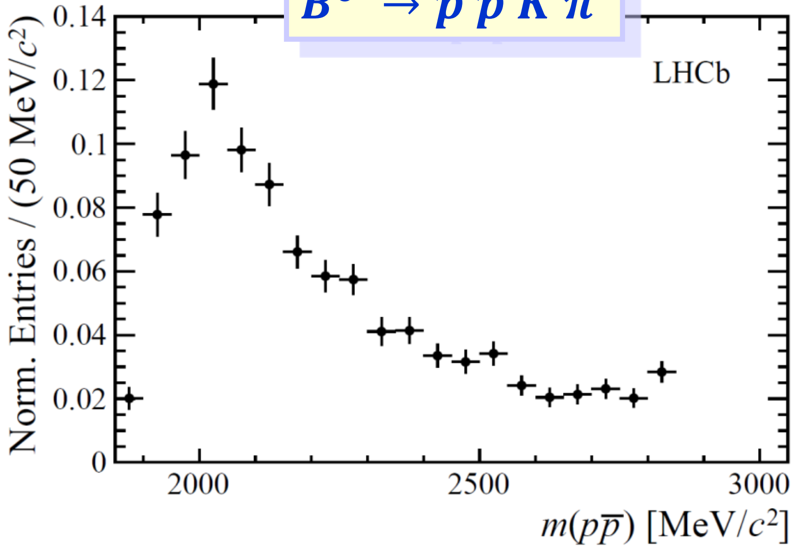
**PRD 96, 051103(R) (2017)**

$B^0_s \to p\,\overline{p}\,K\,K$

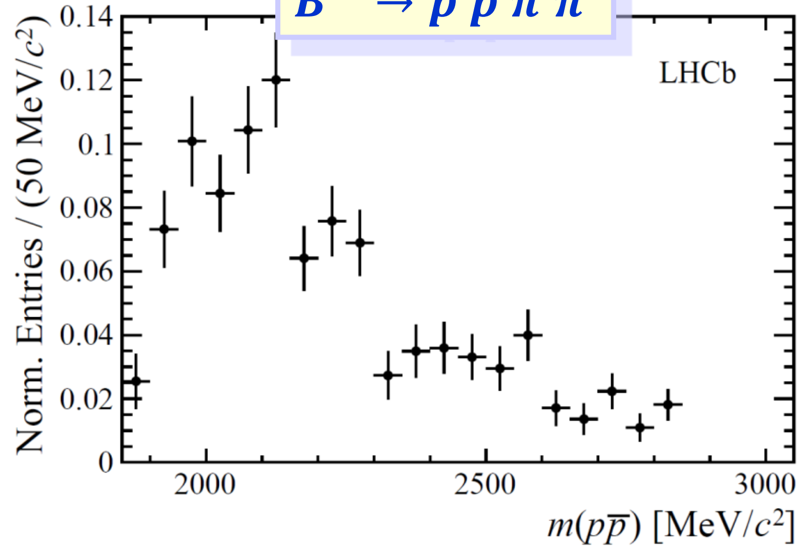



- ❑ Efficiency-corrected and background-subtracted sPlot'ed dist'ons
- ❑ Clear threshold enhancement
  - Confirmation of thresh. enhancement in baryonic $B^0_s$ decays

$B^0 \to p\,\overline{p}\,K\,\pi$




$B^0 \to p\,\overline{p}\,\pi\,\pi$



# $B^0_{(s)} \to p\,\overline{p}\,h^+\,h'^-$ decays – branching fractions

**PRD 96, 051103(R) (2017)**

- **3 first observations and 1 first evidence !**

| Decay channel | Yield $\mathcal{N}$ | Significance $[\sigma]$ | Branching fraction / $10^{-6}$ | | | | |
|---|---|---|---|---|---|---|---|
| $B^0 \to p\overline{p}KK$ | $68 \pm 17$ | 4.1 | $0.113$ | $\pm 0.028$ | $\pm 0.011$ | $\pm 0.008$ | |
| $B^0 \to p\overline{p}K\pi$ | $4155 \pm 83$ | $> 25$ | $5.9$ | $\pm 0.3$ | $\pm 0.3$ | $\pm 0.4$ | |
| $B^0 \to p\overline{p}\pi\pi$ | $902 \pm 35$ | $> 25$ | $2.7$ | $\pm 0.1$ | $\pm 0.1$ | $\pm 0.2$ | |
| $B^0_s \to p\overline{p}KK$ | $635 \pm 32$ | $> 25$ | $4.2$ | $\pm 0.3$ | $\pm 0.2$ | $\pm 0.3$ | $\pm 0.2$ |
| $B^0_s \to p\overline{p}K\pi$ | $246 \pm 39$ | 6.5 | $1.30$ | $\pm 0.21$ | $\pm 0.11$ | $\pm 0.09$ | $\pm 0.08$ |
| $B^0_s \to p\overline{p}\pi\pi$ | $39 \pm 16$ | 2.6 | $0.41$ | $\pm 0.17$ | $\pm 0.04$ | $\pm 0.03$ | $\pm 0.02$ |
| $B^0 \to J/\psi K^*(892)^0$ | $1216 \pm 45$ | – | – | | | | |

- **90% C.L. upper limit set on non-significant signal**

$$\mathcal{B}(B^0_s \to p\overline{p}\pi\pi) < 6.6 \times 10^{-7} \text{ at 90\% confidence level}$$

- **Ratios of BFs also determined:**

| | | | | |
|---|---|---|---|---|
| $\mathcal{B}(B^0 \to p\overline{p}KK)/\mathcal{B}(B^0 \to p\overline{p}K\pi)$ | $0.019$ | $\pm 0.005$ | $\pm 0.002$ | |
| $\mathcal{B}(B^0 \to p\overline{p}\pi\pi)/\mathcal{B}(B^0 \to p\overline{p}K\pi)$ | $0.46$ | $\pm 0.02$ | $\pm 0.02$ | |
| $\mathcal{B}(B^0_s \to p\overline{p}K\pi)/\mathcal{B}(B^0 \to p\overline{p}K\pi)$ | $0.22$ | $\pm 0.04$ | $\pm 0.02$ | $\pm 0.01$ |
| $\mathcal{B}(B^0_s \to p\overline{p}K\pi)/\mathcal{B}(B^0_s \to p\overline{p}KK)$ | $0.31$ | $\pm 0.05$ | $\pm 0.02$ | |

# *Purely baryonic 4-body decays*

# Purely baryonic multibody decays – $B^0_{(s)} \to p\,\overline{p}\,p\,\overline{p}$

- All seen charmless baryonic 2-body decays are rare, to very rare, e.g. $B^0 \to p\,\overline{p}$
- Having in mind the hierarchy in baryonic B decays, can this suppression be alleviated in multi-body purely baryonic decays, where there is no meson to recoil against the baryon-antibaryon pair?

- Decay mode(s) $B^0_{(s)} \to p\,\overline{p}\,p\,\overline{p}$ are the obvious 1st candidates to investigate
- Does a back-to-back $(p\,\overline{p})$-pair configuration happen very often here?
- Does one observe a threshold enhancement across the phase space? Symmetrically?

- For reference, BaBar had looked for $\overline{B}^0 \to \Lambda_c^+\,\overline{p}\,\overline{p}\,p$ [PRD 89, 071102 (2014)]
- Otherwise area of B decays to 2 baryon-antibaryon pairs is totally to be explored … except …

# BaBar search for $B^0 \to p\,\bar{p}\,p\,\bar{p}$

arXiv:1803.10378

- BaBar took (for now) the lead in searches for purely baryonic multi-body B decays …

- Search with full data set
- Hint of a signal, with a significance of 2.9σ
- Branching fraction:

$$\mathcal{B}(B^0 \to pp\bar{p}\bar{p}) = (1.1{\pm}0.5{\pm}0.2)\times 10^{-7}$$

- 90% C.L. upper limit @ $2\text{x}10^{-7}$

- What can LHCb say here …

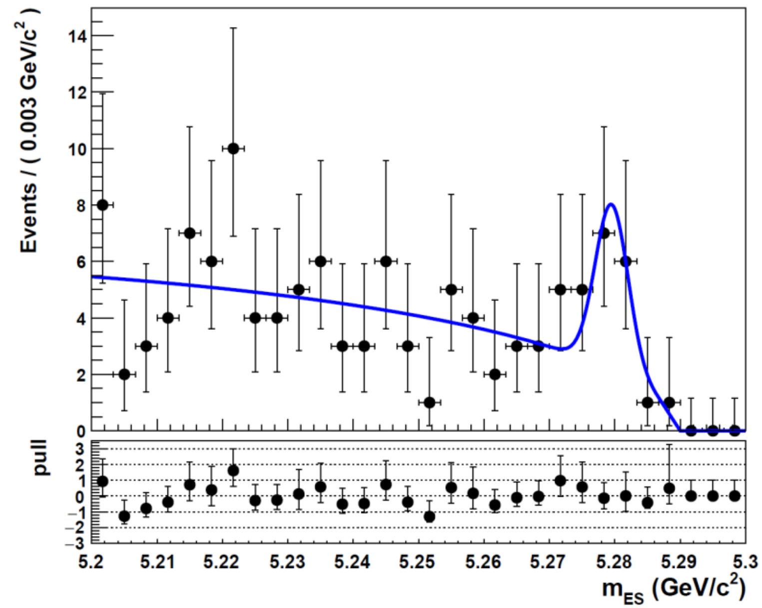



FIG. 3. Fit to the data $m_{\rm ES}$ distribution (dots) in the interval $5.2 < m_{\rm ES} < 5.3$ GeV/$c^2$. The bottom plot shows the pull distribution, which is the bin-by-bin difference between the data and fitted distribution normalized by the corresponding statistical uncertainty from the fit.

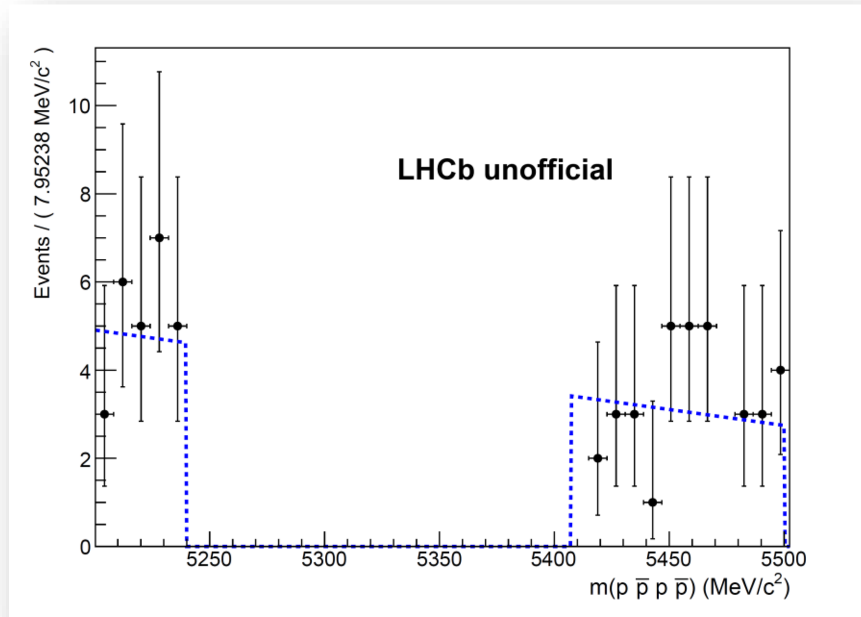
# Ongoing LHCb search for $B^0 \rightarrow p\,\overline{p}\,p\,\overline{p}$ !

- Search to be performed on full run I+II data sample
- Given typical reconstruction and selection efficiencies in LHCb, we have a real change to observe at least the $B^0$ mode !

- As an appetizer, VERY PRELIMINARY, and hence UNOFFICIAL spectrum with both $B^0$ and $B_s$ signal regions blinded

- Note:
  Remarkably, there is no multivariate selection here. Particle identification and a cut on B-vertex quality is enough !

**LHCb unofficial, run I data**



# *Purely baryonic decay processes*

# Purely baryonic decay processes

- ❑ **Decay processes involving only spin-carrying particles**
  **⇒ very interesting testbed for CP violation**
- ❑ **Totally new and unexplored area, both theoretically and experimentally !**
- ❑ **Experimental study fully on LHCb hands for the foreseeable future**

- ❑ **First exploratory work on the theoretical side in collaboration with Profs. C.Q. Geng & Y.K. Hsiao**
  **- "Exploring the simplest purely baryonic decay processes"** **[Phys. Rev. D 94, 014027 (2016)]**

- ❑ **The simplest decay is $\Lambda_b \to p\,\overline{p}\,n$ ! Only spin-1/2 baryons involved**
  **- Unique decay for obvious reasons**
- ❑ **Could also consider decays of heavier b baryons …**

# $\Lambda_b \to p\,\bar{p}\,n$ – predictions

PRD 94, 014027 (2016)

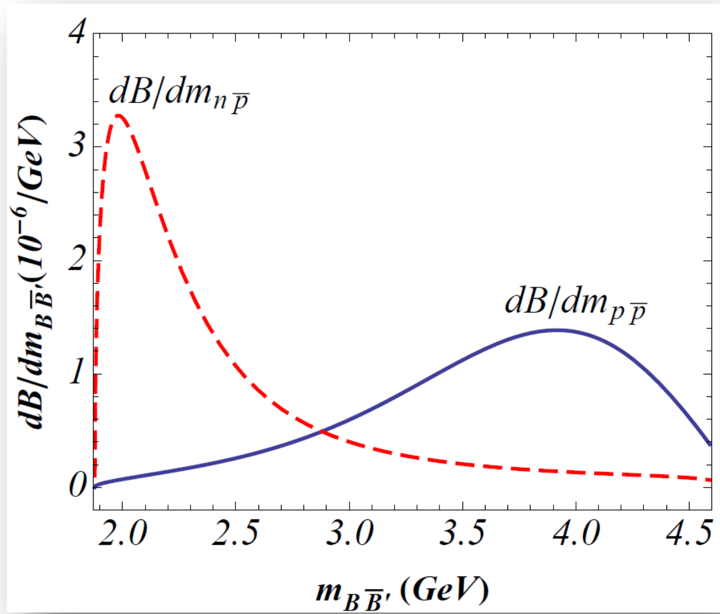
❑ Branching fraction typical for a charmless final state :

$$\mathcal{B}(\Lambda_b^0 \to p\bar{p}n) = (2.0^{+0.3}_{-0.2}) \times 10^{-6}$$

❑ Threshold enhancement predicted
- Typical for a baryonic decay

❑ But of course it is not accessible experimentally as it depends on the neutron

❑ The other possible distribution, for the neutron-proton pair, should not present any threshold enhancement



# "Roadmap" for purely baryonic decay processes

arXiv:1806.00861

- Kind of roadmap article released to the arXiv … yesterday !
- Discusses simplest purely baryonic decays for all b-baryons
- Most modes are out of reach until we get data with an upgraded LHCb detector
- Best bets are

| | Branching fraction | $\mathcal{A}_{CP} = \frac{\Gamma(\mathbf{B}_h \to \mathbf{B}_{l_1}\bar{\mathbf{B}}_{l_2}\mathbf{B}_{l_3}) - \Gamma(\bar{\mathbf{B}}_h \to \bar{\mathbf{B}}_{l_1}\mathbf{B}_{l_2}\bar{\mathbf{B}}_{l_3})}{\Gamma(\mathbf{B}_h \to \mathbf{B}_{l_1}\bar{\mathbf{B}}_{l_2}\mathbf{B}_{l_3}) + \Gamma(\bar{\mathbf{B}}_h \to \bar{\mathbf{B}}_{l_1}\mathbf{B}_{l_2}\bar{\mathbf{B}}_{l_3})}$ |
|---|---|---|
| $\Lambda_b^0 \to \Lambda p\bar{p}$ | $(3.2^{+0.8}_{-0.3} \pm 0.4 \pm 0.7\ ) \times 10^{-6}$ | $(3.4 \pm 0.1 \pm 0.1 \pm 1.0)\%$ |
| $\Xi_b^0 \to \Lambda p\bar{p}$ | $(1.4 \pm 0.1 \pm 0.1 \pm 0.4) \times 10^{-7}$ | $(-13.0 \pm 0.5 \pm 1.5 \pm 1.1)\%$ |

- Striking difference for predicted threshold enhancement

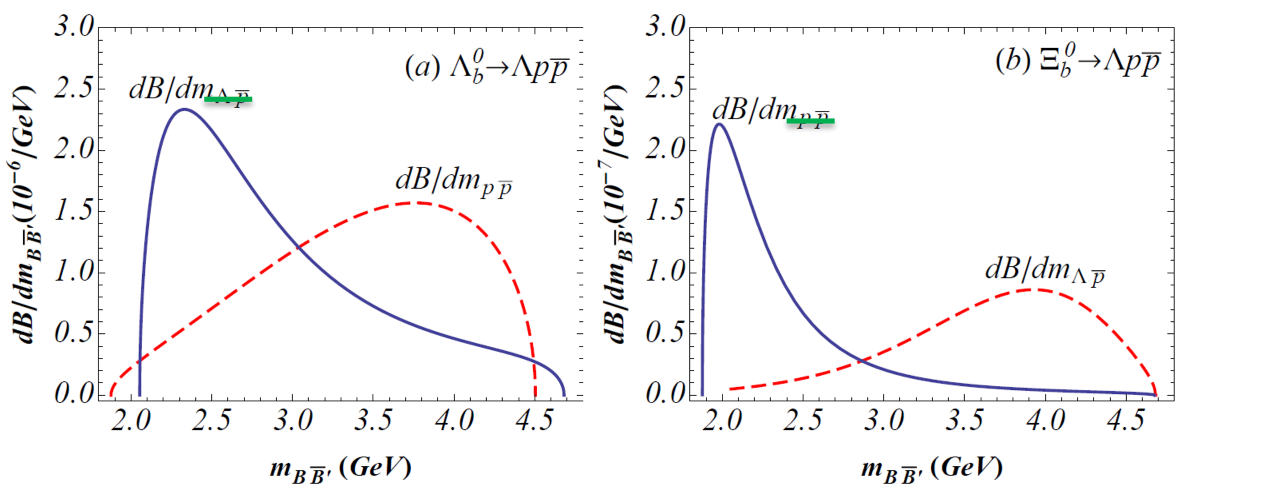



Figure 1: The dibaryon invariant mass spectra for the (a) $\Lambda_b^0 \to \Lambda p\bar{p}$ and (b) $\Xi_b^0 \to \Lambda p\bar{p}$ decays.

# *Spectroscopy*

# Spectroscopy with baryonic decays

- ❑ b-hadron decays have been extensively used to study resonances and even exotics
  - Many B → D X decays used in B-factories and LHCb for excited D-meson spectroscopy
  - E.g. $\Lambda_b^0 \to D^0 p\, \pi$ to study $\Lambda_c^+$ excited states (1701.07873v3 [hep-ex])
  - Pentaquarks in $\Lambda_b^0 \to J/\psi\, p\, K$ (PRL 115 (2015) 072001)
  - Charm-full baryonic decays
  - Etc.

- ❑ Charmless decays also have a word to say here ! E.g.:
  - Study of charmonium-like states
  - Study of relatively little known $\Lambda\bar{\Lambda}$ system (charmonium decays)
  - Interesting modes:

    $B_{(s)}^{0,+} \to \Lambda\,\bar{\Lambda}\,(light\ meson)$

    $\Lambda_b^0, \Xi_b^0 \to \Lambda\,\bar{\Lambda}\,\Lambda$
  - OK, this is looking into the future ;-)!

**Observation of $\Xi_c(2930)^0$ and updated measurement of $B^- \to K^-\Lambda_c^+\bar{\Lambda}_c^-$ at Belle**

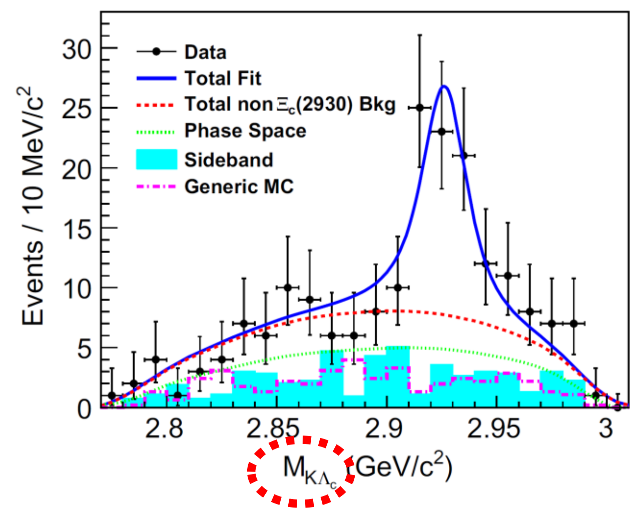



**Fig. 4** The $M_{K^-\Lambda_c^+}$ distribution of the selected data candidates, with fit results superimposed. Dots with error bars are the data, the solid blue line is the best fit, the dashed red line is the total non-$\Xi_c(2930)$ backgrounds, the dotted green line is the phase space contribution, the shaded cyan histogram is from the normalized $\Lambda_c^+$ and $\bar{\Lambda}_c^-$ mass side-bands, and the dot-dashed magenta line is the sum of the MC-simulated contributions from the normalized $e^+e^- \to q\bar{q}$ and $\Upsilon(4S) \to B\bar{B}$ generic-decay backgrounds

**Eur. Phys. J. C (2018) 78**

# *Semileptonic decays*

# Semileptonic baryonic B decays

PRD 89, 011101 (2014)

- Belle found 1st evidence for decays $B^+ \to p\,\bar{p}\,l\,\nu$ with a combined significance of 3.2σ (assuming e-μ lepton universality)
- 90% C.L. upper limit:

$$\mathcal{B}(B^- \to p\bar{p}\ell^-\bar{\nu}_\ell) < 9.6 \times 10^{-6}$$

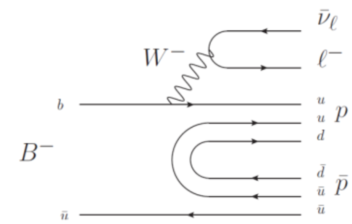



FIG. 1: Leading diagram for $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$ decay.

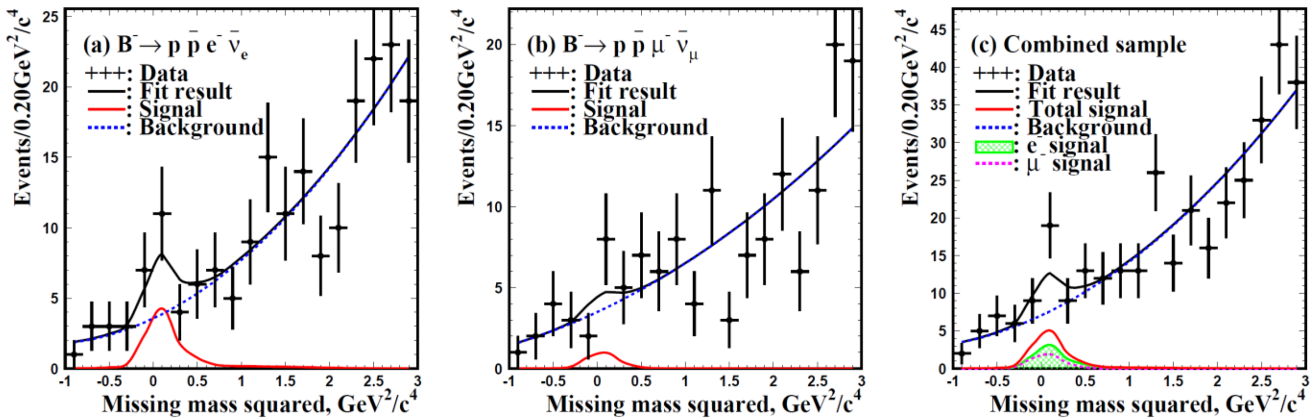



FIG. 2: Fitted missing mass squared distributions for (a) $B^- \to p\bar{p}e^-\bar{\nu}_e$, (b) $B^- \to p\bar{p}\mu^-\bar{\nu}_\mu$ and (c) the combined fit. Points with error bars represent data, while the curves denote various components of the fit: signal (solid red), total background (dashed blue), and the sum of all components (solid black). The hatched green area denotes the signal fit component from $B^- \to p\bar{p}e^-\bar{\nu}_e$ and the dashed purple curve that from $B^- \to p\bar{p}\mu^-\bar{\nu}_\mu$.

# Semileptonic baryonic B decays

- ❑ **Can in the future be used to study lepton flavour universality**

- ❑ **Can also help in the determination of Vub, see Phys. Lett. B 755 (2016) 418**


A B S T R A C T

We use the exclusive baryonic $B$ decays to determine the Cabibbo–Kobayashi–Maskawa (CKM) matrix element $V_{ub}$. From the relation $|V_{ub}|^2/|V_{cb}|^2 = (\mathcal{B}_\pi/\mathcal{B}_D)\mathcal{R}_{ff}$ based on $B^- \to p\bar{p}\pi^-$ and $\bar{B}^0 \to p\bar{p}D^0$ decays, where $|V_{cb}|$ and $\mathcal{B}_\pi/\mathcal{B}_D \equiv \mathcal{B}(B^- \to p\bar{p}\pi^-)/\mathcal{B}(\bar{B}^0 \to p\bar{p}D^0)$ are the data input parameters, while $\mathcal{R}_{ff}$ is the one fixed by the $B \to p\bar{p}$ transition matrix elements, we find $|V_{ub}| = (3.48^{+0.87}_{-0.63} \pm 0.40 \pm 0.07) \times 10^{-3}$ with the errors corresponding to the uncertainties from $\mathcal{R}_{ff}$, $\mathcal{B}_\pi/\mathcal{B}_D$ and $|V_{cb}|$, respectively. Being independent of the previous results, our determination of $|V_{ub}|$ has the central value close to those from the exclusive $\bar{B} \to \pi\ell\bar{\nu}_\ell$ and $\Lambda_b \to p\mu^-\bar{\nu}_\mu$ decays, but overlaps the one from the inclusive $\bar{B} \to X_u\ell\bar{\nu}_\ell$ with the current uncertainties. The extraction of $|V_{ub}|$ in the baryonic $B$ decays is clearly very useful for the complete determination of the CKM matrix elements as well as the exploration of new physics.

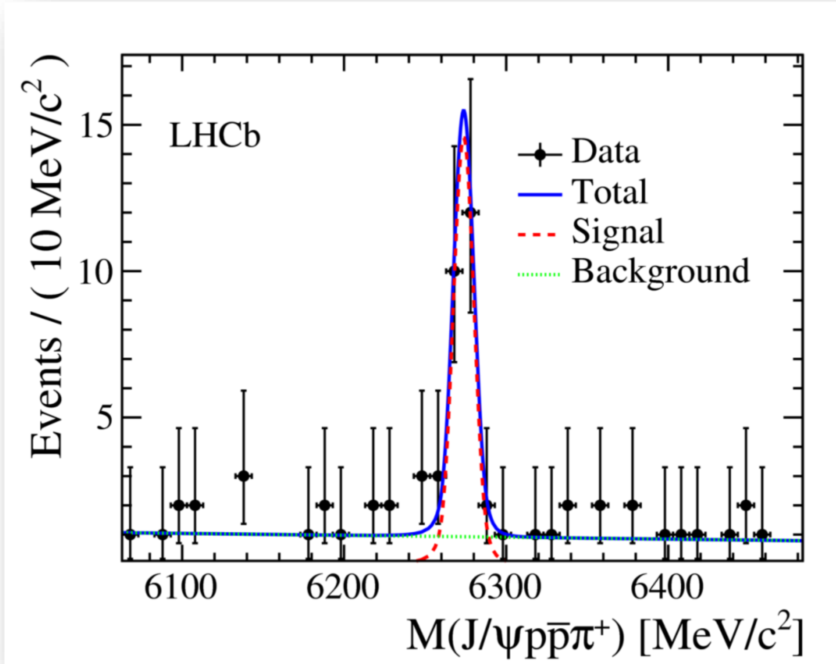
# Baryonic $B_c$ decays

➡ $B_c^+ \to p\,\bar{p}\,\pi^+$

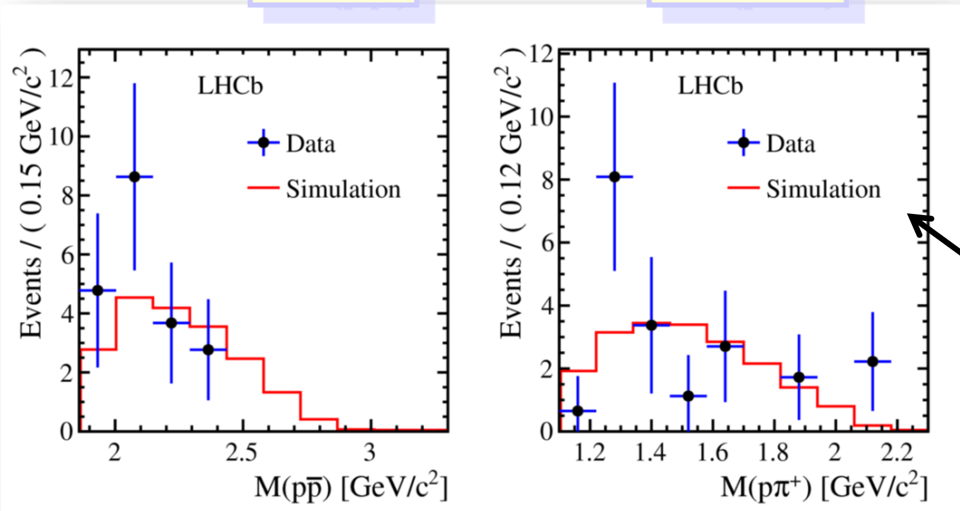
# Recap – 1st observation of a baryonic $B_c^+$ decay

PRL 113 (2014) 153003

- **Signal significance : 7.3σ**
- **LHCb,full run-I data sample (3 fb$^{-1}$)**




$m(p\bar{p})$ $m(p\pi^+)$




**Simulation =**
**using a phase space model**

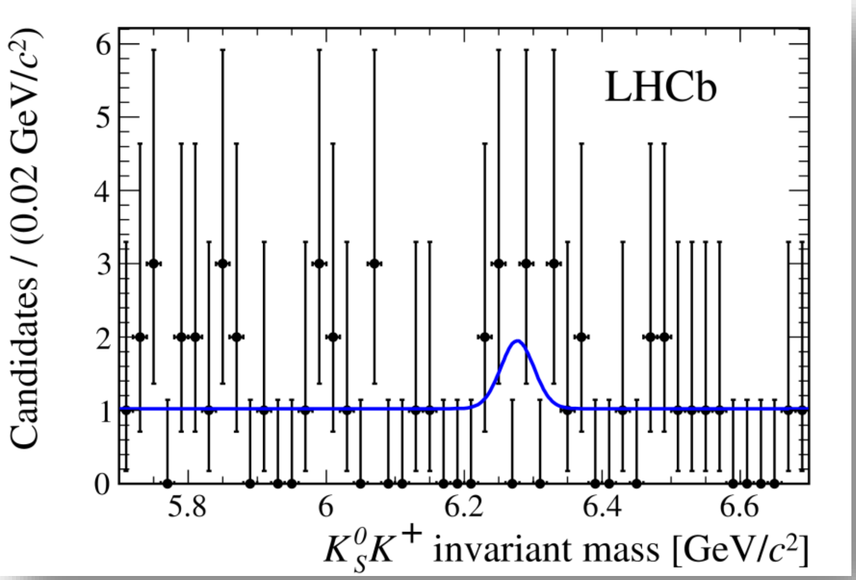
# Charmless (baryonic) $B_c^+$ decays - motivation

- Charmless $B_c$ decays proceed exclusively through annihilation !
- Rather suppressed, but natural ground to study annihilation processes …

- LHCb already performed search for 2-body decay $B_c^+ \to K_S^0 K^+$
  - 90% C. L. upper limit

$$\frac{f_c}{f_u} \cdot \frac{\mathcal{B}(B_c^+ \to K_S^0 K^+)}{\mathcal{B}(B^+ \to K_S^0 \pi^+)} < 5.8 \times 10^{-2}$$

Phys. Lett. B 726 (2013) 646-655




- Searches for 3-body modes seem natural
- Decays $B_c^+ \to K\, K\, \pi^+$ and $B_c^+ \to p\, \bar{p}\, \pi^+$ among simplest modes
  - Due to Cabibbo suppression $\left|\frac{V_{us}}{V_{ud}}\right| \sim 0.2$ , final states with no net strangeness dominate

# Search for $B_c^+ \to p\,\overline{p}\,\pi^+$

PLB 759 (2016) 313-321

## *Motivation*

- 1[st] search for a charmless baryonic $B_c^+$ decay

## *Analysis*

- Full run-I data sample (3 $fb^{-1}$)
- Branching fraction relative to that of $B^+ \to p\,\overline{p}\,\pi^+$
- Measurement sensitivity enhanced by considering 3 MVA regions
- 95% C.L. upper limit

$$\frac{f_c}{f_u} \times \mathcal{B}(B_c^+ \to p\overline{p}\pi^+) < 3.6 \times 10^{-8}$$

- In the charmless region $\mathrm{m}(p\overline{p}) < 2.85$ GeV , i.e. in annihilation region
- In the kinematic region $p_T(B) < 20$ GeV and region $2.0 < y(B) < 4.5$

➡ ***A broad study of charmless $B_c$ decays requires the LHCb upgrade …***

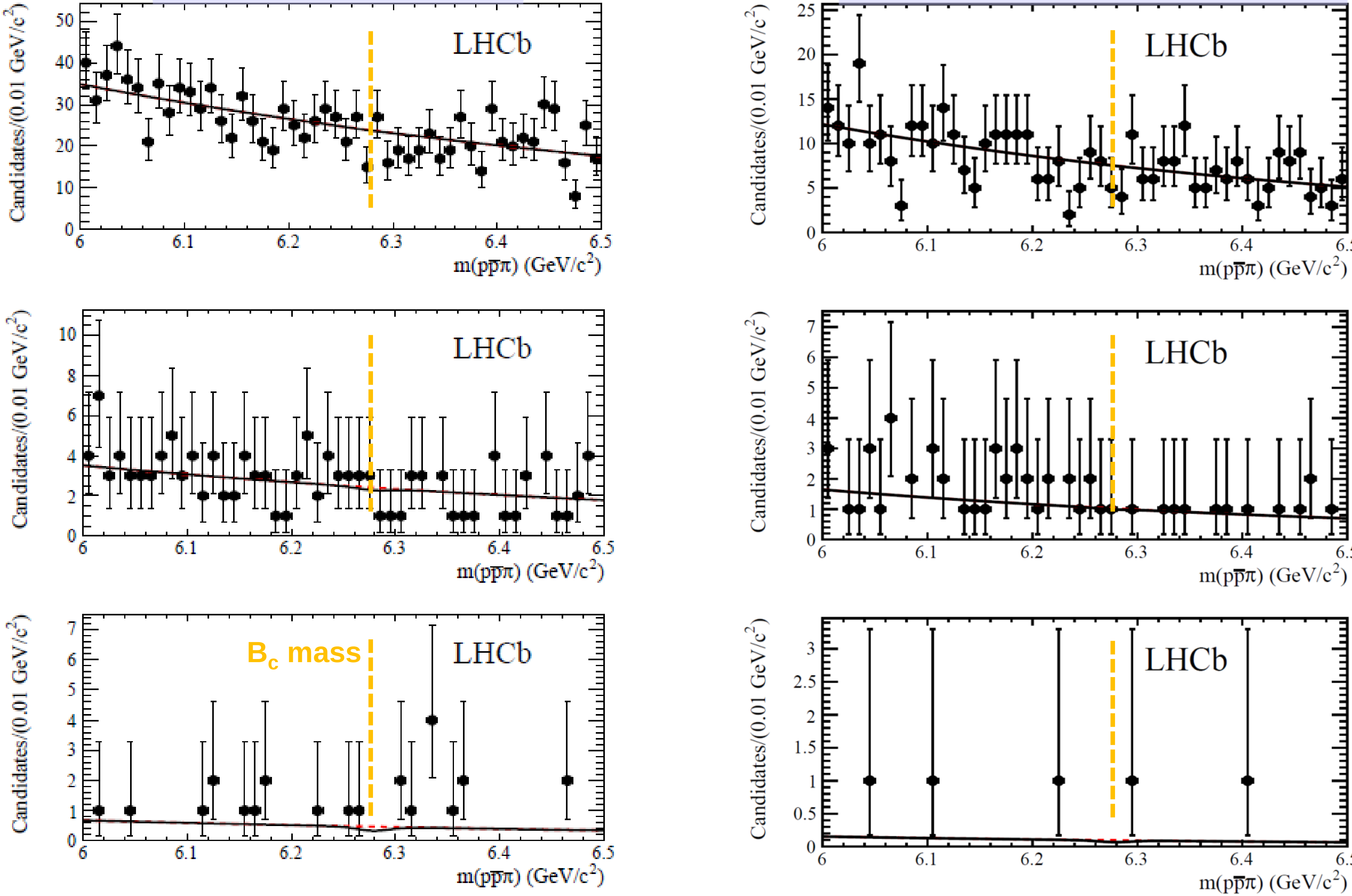
# Search for $B_c^+ \to p\,\overline{p}\,\pi^+$

PLB 759 (2016) 313-321

$m(p\overline{p}) < 2.85$ GeV

$2.85 < m(p\overline{p}) < 3.15$ GeV

MVA selection regions



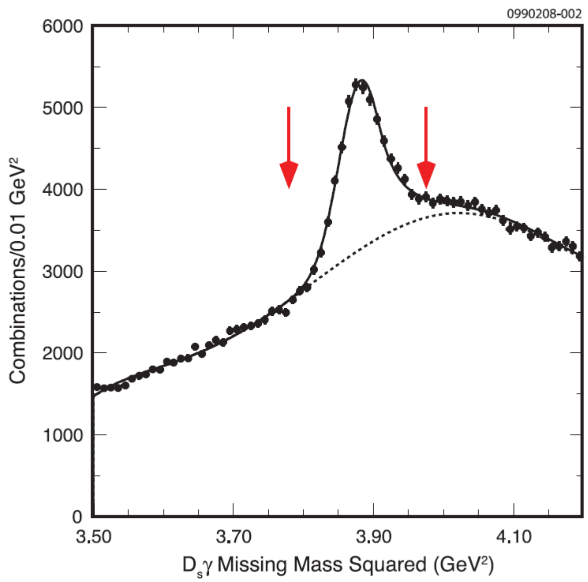
# *Baryonic D-meson decays*

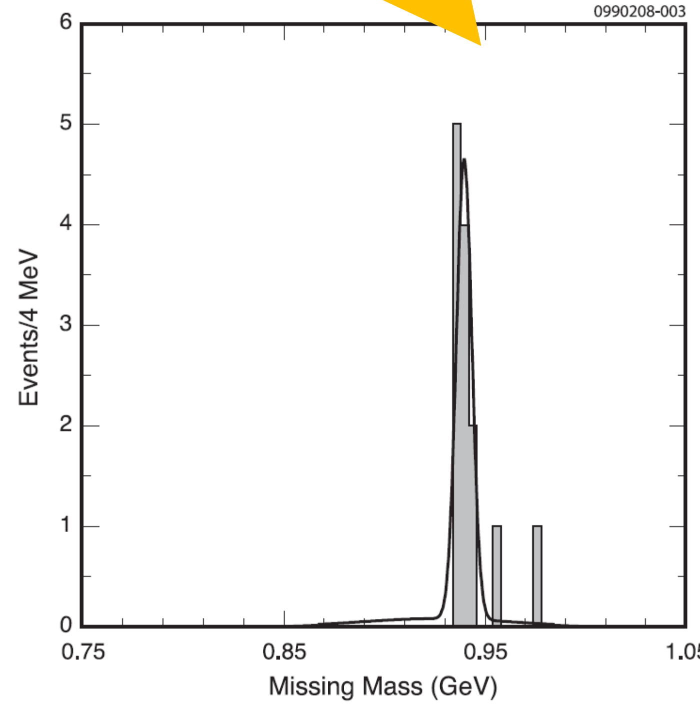
# The unique decay $D_s \to p\,\bar{n}$

PRL 100, 181802 (2008)

- Only kinematically allowed hadronic baryonic decay of a D meson !
- Beautiful search & observation by CLEO

1[st] observation of only possible D-meson baryonic decay




$$\mathcal{B}(D_s^+ \to p\bar{n}) = (1.30 \pm 0.36^{+0.12}_{-0.16}) \times 10^{-3}$$

- BF was naively expected to be of order $10^{-6}$ !

# The unique decay $D_s \to p \bar{p} e \nu$

Phys. Lett. B 780 (2018) 100

- Only semileptonic baryonic D-meson decay physically allowed !

$$m_{D_s^+} - 2m_p \approx 82 \text{ MeV}$$

- Final state only accessible via final-state rescattering
- Consider meson with comparable amount of light- and strange-quark components to alleviate OZI suppression
  - Meson exchanges from η, η', f0(980), X(1835)
- Branching fraction predicted in the range $10^{-9} - 10^{-8}$
- LHCb can do it !

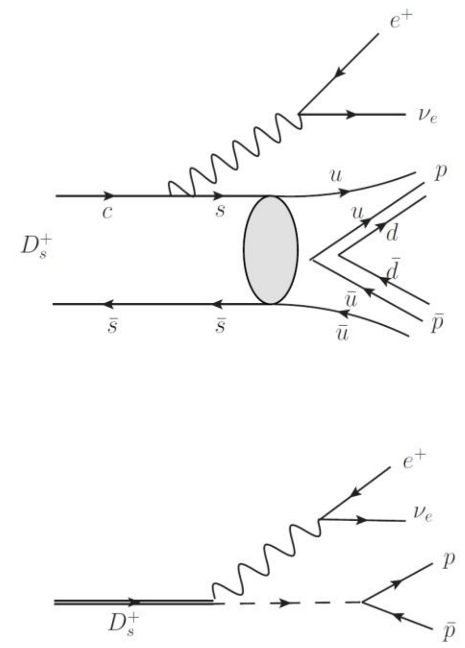



FIG. 1. Diagrams for the $D_s^+ \to p\bar{p}e^+\nu_e$ decay via meson exchanges. The upper panel depicts the quark diagram with a bulk denoting the neutral meson with $q\bar{q}$ and $s\bar{s}$ components, while the lower one is the meson exchange (denoted by dashed line) diagram at the hadron level.

# ***Final remarks***

# In short

- **LHCb is very active in the study of charmless b-hadron decays**
- **In particular, it has been providing a plethora of important results with baryonic decays**

- **Baryonic B decays still surprising us after almost 2 decades since first interest by community**

- **Run II is providing a lot more statistics**
- **The LHCb detector and data collection flow is much improved also !**
- ***Expect a lot and hope for surprises !***

- **Some studies will require the upgraded LHCb detector …**

# Back-up slides

# Charmless b-hadron decays programme (not comprehensive)

CKM matrix

Generalised factorisation

Dynamics of heavy flavour decays

Quark mixing

Discovery channels

$b \to (d,s)$ loop

CP violation

$b \to u$ tree

Theory

**Charmless b-hadron decays**

Experiment

$B \to P\,P$

$B \to P\,V$

Branching fractions

Time-(in)dependent measurements

$B \to V\,V$

3-body

CP asymmetries

baryonic

2-body

many-body

Lifetimes

# Search for 2-body modes – motivation

- ❑ 2-body baryonic B decays are rather suppressed ⇒ need LHCb, as not seen @ B factories
- ❑ 1st evidence for $B^0 \to p\,\overline{p}$ with 2011 data analysis **[JHEP 10 (2013) 005]**
- ❑ 1st observation of a 2-body charmless baryonic mode: $B^+ \to p\,\overline{\Lambda}(1520)$ **[PRL 113, 141801 (2014)]**

⇒ Important to confirm and/or improve knowledge of these very rare decays $B^0_{(s)} \to p\,\overline{p}$

⇒ $B^+ \to p\,\overline{\Lambda}$ seems like the next obvious decay mode to look for

- ❑ Phenomenologically speaking, the $B^0 \to p\,\overline{p}$ BF measured in the 2011 data analysis was yet smaller than expected
  ⇒ raised interest:
  most recent calculations explain a BF ~ $10^{-8}$ for the $B^0$ mode
  **[Phys. Rev. D91 (2015) 077501; Phys. Rev. D91 (2015) 036003]**

# $B_s^0 \to p\,\overline{\Lambda}\,K^-$

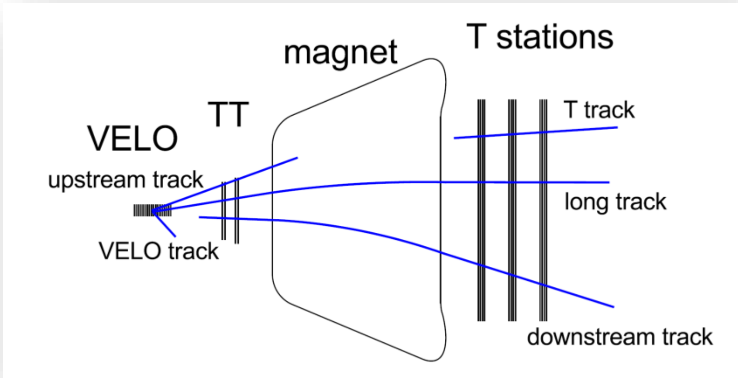
PRL 119, 041802 (2017)

### *Analysis strategy*

- **Branching fraction measured relative to normalisation mode $B^0 \to p\,\overline{\Lambda}\,\pi^-$**
  - **- Topologically identical decay, large branching fraction**

$$\mathcal{B}(B_s^0 \to p\overline{\Lambda}K^-) + \mathcal{B}(B_s^0 \to \overline{p}\Lambda K^+) = \frac{f_d}{f_s}\,\frac{N(B_s^0 \to p\overline{\Lambda}K^-)}{N(B^0 \to p\overline{\Lambda}\pi^-)}\,\frac{\epsilon_{B^0 \to p\overline{\Lambda}\pi^-}}{\epsilon_{B_s^0 \to p\overline{\Lambda}K^-}}\,\mathcal{B}(B^0 \to p\overline{\Lambda}\pi^-)$$

- **Similar selection for both decay modes**




### *Data*

- **Analysis on full run-I data sample**
- **Data split according to year and $V^0$ reconstruction category (*long* or *downstream* tracks)**
  - **- Studies proved a viable procedure to merge all subsamples for the mass fit**
- **Decay chain fitted with $V^0$ mass constrained**

# $B_s^0 \to p\,\overline{\Lambda}\,K^-$ – background studies

PRL 119, 041802 (2017)

*Background studies*

❑ Non resonant decays mode $B \to p\,\overline{p}\,\pi h$ ⇒ suppressed by $\Lambda$ selection

❑ Resonant decays:

- Charmonia decaying to $p\,\overline{p}$ ⇒ suppressed by $\Lambda$ selection
- Final states with a $K_S$ instead of a $\Lambda$ baryon ⇒ no contribution from such decays found in data

❑ Cross-feed from misidentification:

- Pion-kaon misID between signal and control modes ⇒ crucial in fits since part of signal model
- Proton-pion/kaon misID from $\Lambda_b \to \Lambda\,p\,\overline{p}$ ⇒ suppressed thanks to small branching fraction & small tails into signal region

❑ Partially reconstructed backgrounds:

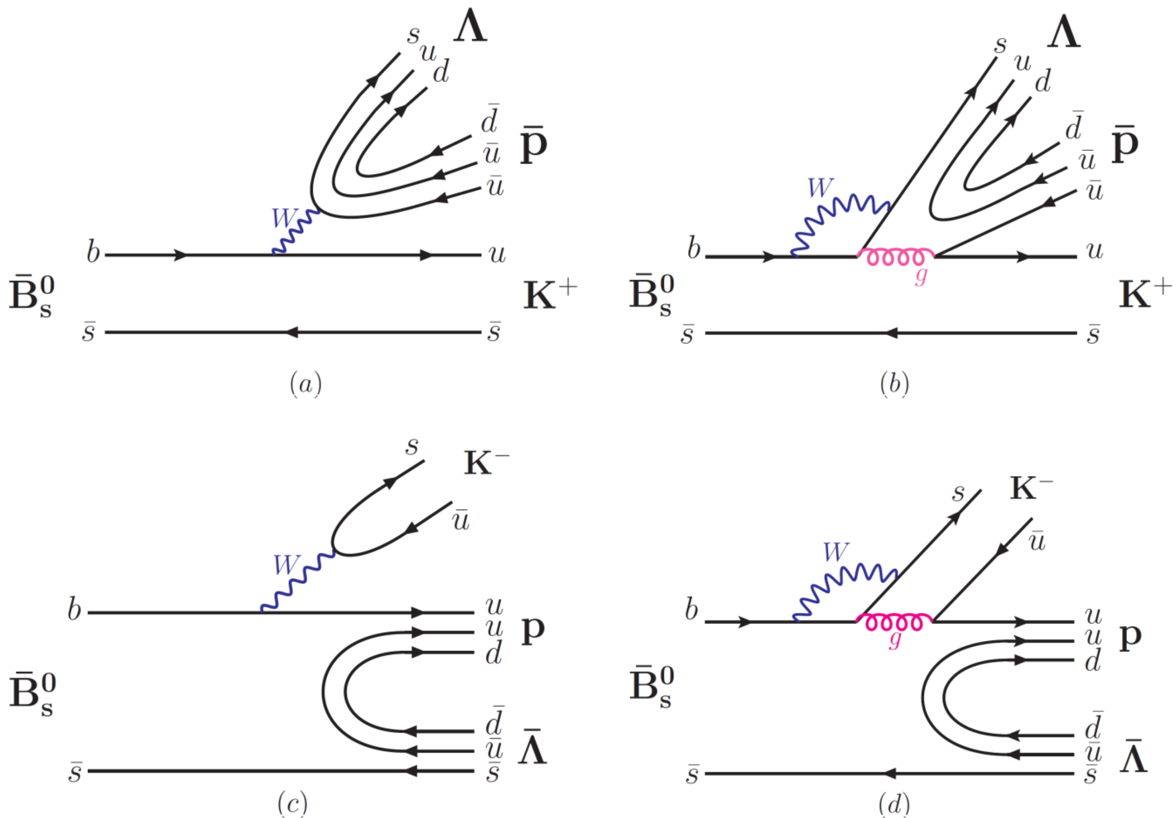
- $B^0_{(s)} \to p\,\overline{\Sigma}^0\,h^-$ ⇒ can sneak under signal peaks given small Σ-L mass difference ~ 77 MeV
- $B^0 \to p\,\overline{\Lambda}\,\rho^-$ , $B_s \to p\,\overline{\Lambda}\,K^*$ ⇒ largely suppressed by selection

*Fit strategy*

❑ Simultaneous fit to the 8 spectra : 2 final states x 2 years x 2 $\Lambda$ reconstruction categories

# $B_s^0 \to p\,\overline{\Lambda}\,K^-$ pheno paper – Feynman diagrams

- $B^0 \to p\,\overline{\Lambda}\,\pi^-$ is flavour-specific, unlike $B_s^0 \to p\,\overline{\Lambda}\,K^-$ :
  (in some analogy with $B_s^0 \to D_s^+\pi^-$ and $B_s^0 \to D_s^+K^-$)




(Not a comprehensive list of diagrams)

FIG. 1. Feynman diagrams for three-body baryonic $\bar{B}_s^0$ decays, where (a,b) depict $\bar{B}_s^0 \to \bar{p}\Lambda K^+$ while (c,d) depict $\bar{B}_s^0 \to p\bar{\Lambda}K^-$.

# $B_s^0 \to p\,\overline{\Lambda}\,K^-$ pheno paper – some predictions

**PLB 767 (2016) 205**

## ❑ Branching fractions :

$$\mathcal{B}(\bar{B}_s^0 \to \bar{p}\Lambda K^+) = (3.75 \pm 0.81^{+0.67}_{-0.31} \pm 0.01) \times 10^{-6}$$

$$\mathcal{B}(\bar{B}_s^0 \to p\bar{\Lambda} K^-) = (1.31 \pm 0.32^{+0.22}_{-0.10} \pm 0.01) \times 10^{-6}$$

$$\mathcal{B}(\bar{B}_s^0 \to p\bar{\Lambda} \pi^-) = (2.79 \pm 1.37^{+0.64}_{-0.30} \pm 0.17) \times 10^{-7}$$

**(Uncertainties from form factors, non-factorizable effects, CKM matrix elements)**

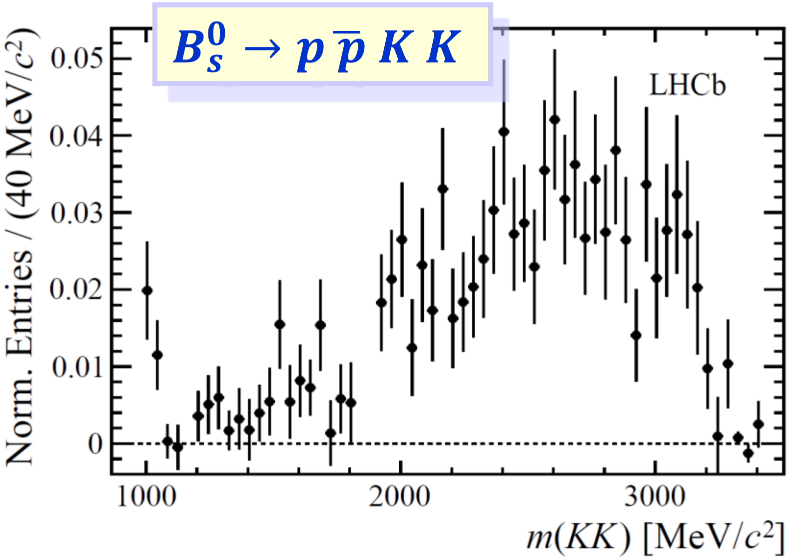
## ❑ BF relations :

$$\mathcal{B}(\bar{B}_s^0 \to \bar{p}\Lambda K^+) \simeq (f_K/f_\pi)^2(\tau_{B_s^0}/\tau_{B^0})\mathcal{B}(\bar{B}^0 \to \bar{p}\Lambda\pi^+)$$

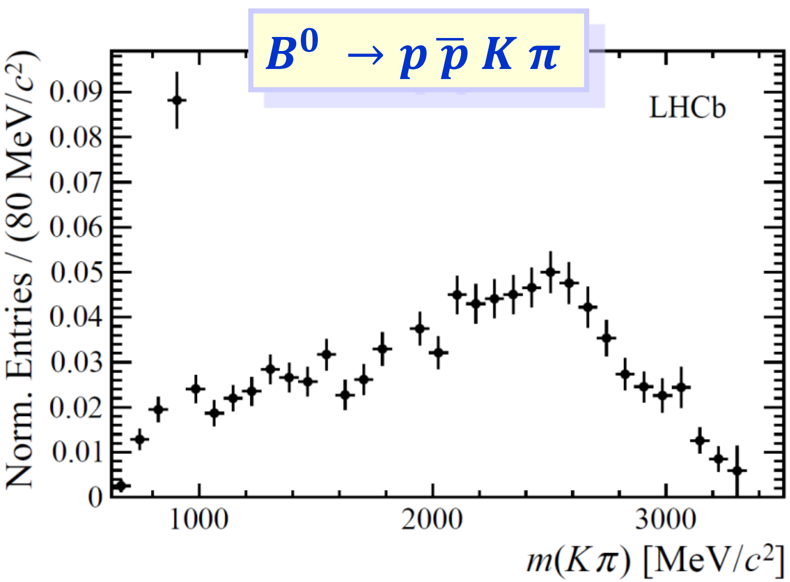
$$\frac{\mathcal{B}(\bar{B}_s^0 \to p\bar{\Lambda}\pi^-)}{\mathcal{B}(\bar{B}_s^0 \to p\bar{\Lambda}K^-)} \simeq \frac{\mathcal{B}(B^- \to p\bar{p}\pi^-)}{\mathcal{B}(B^- \to p\bar{p}K^-)}$$

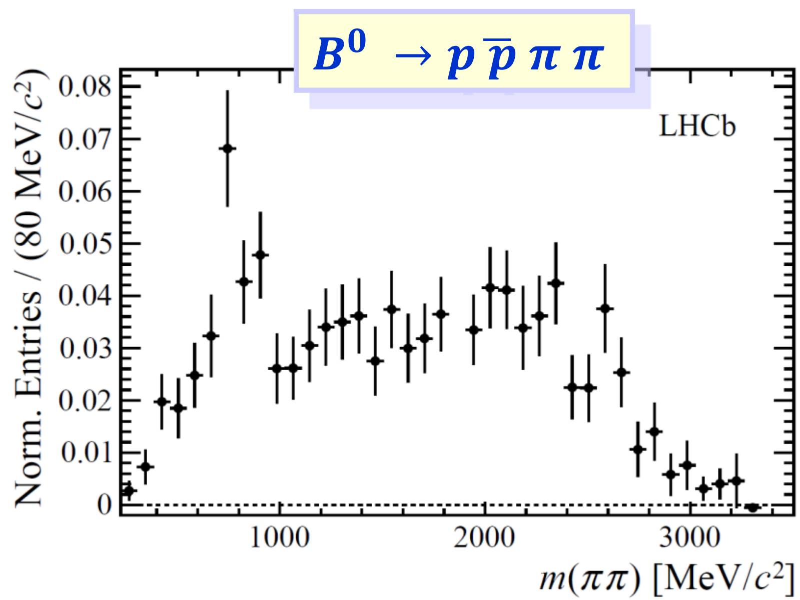
# $B^0_{(s)} \to p\,\bar{p}\,h^+\,h'^-$ – 2-particle projections

PRD 96, 051103(R) (2017)




- Efficiency-corrected and background-subtracted sPlot'ed dist'ons
- Vector mesons clearly visible in all 3 distributions
- A proper study would require an amplitude analysis …

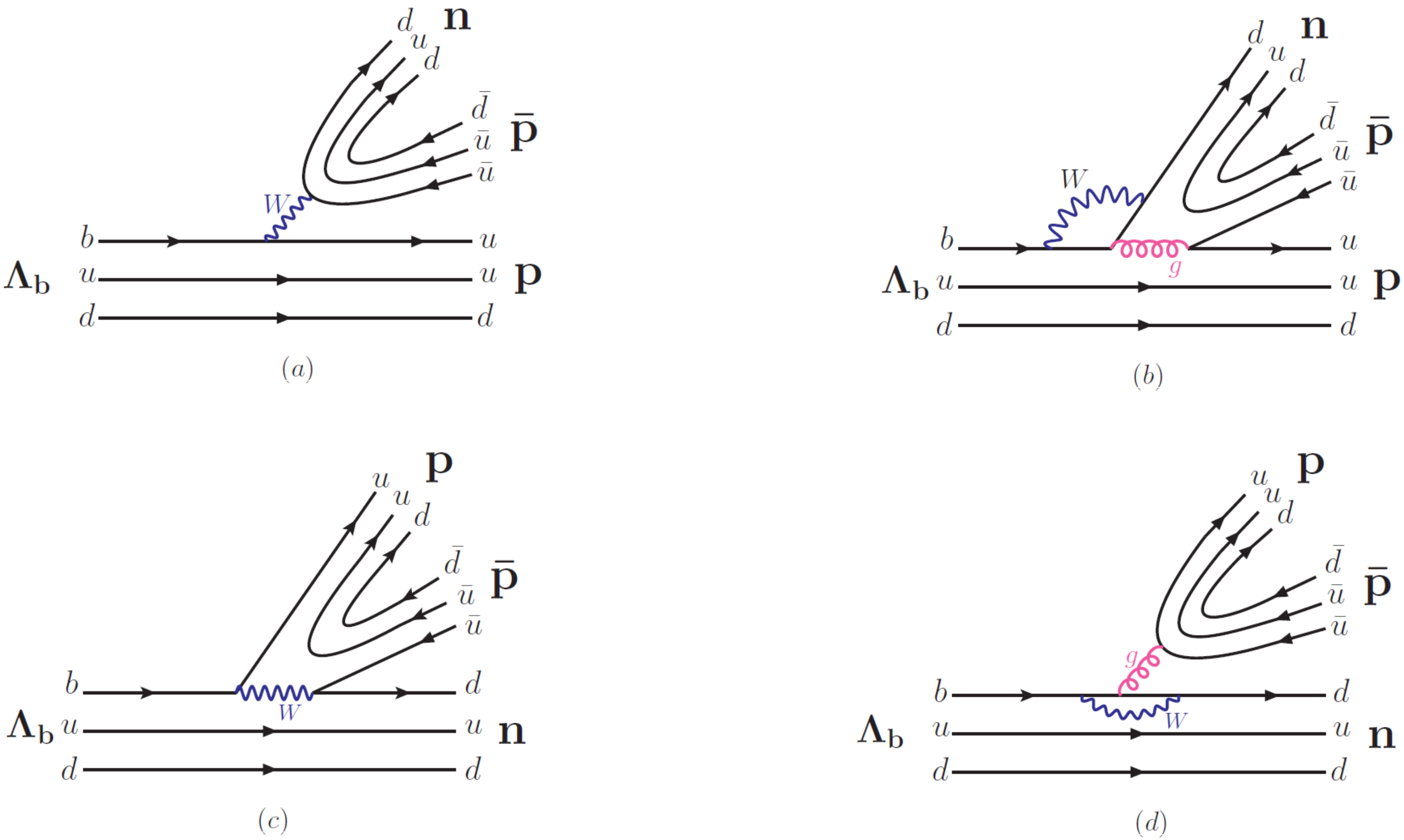


# *Charmless b-baryon decays*

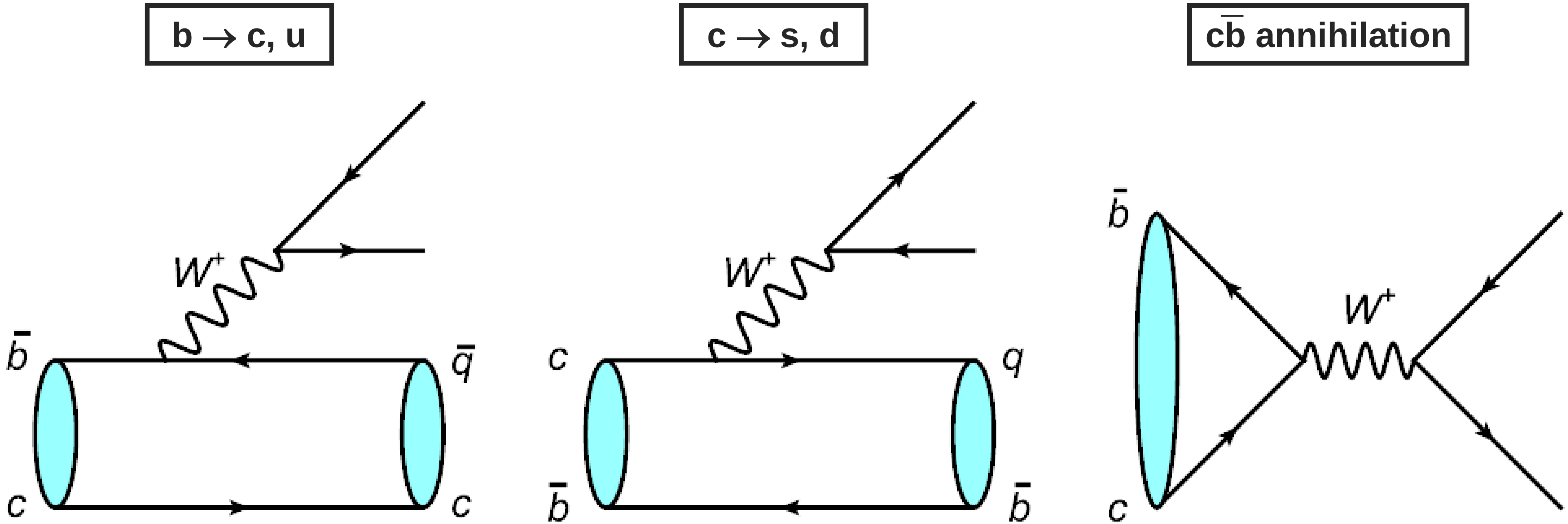
# $\Lambda_b \to p\,\bar{p}\,n$ – Feynman diagrams

PRD 94, 014027 (2016)]




- ❑ **Assume top-left diagram is dominating,**
  **and bottom-left diagram is main non-factorisable effect, expected to be small**

# Charmless $B_c^+$ decays - motivation




***Charmless $B_c$ decays proceed exclusively through annihilation !***

***Rather suppressed but natural ground to study annihilation processes …***