Study of the charmless baryonic decay of b hardons at LHCb

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Outline

- Introduction
- Charmless baryonic decay of B meson
  - Two body decay
  - Multibody decay
- Charmless baryonic decay of B_c^+
- Search for CPV in charmless decay of Λ_b^0
- Conclusion and outlook

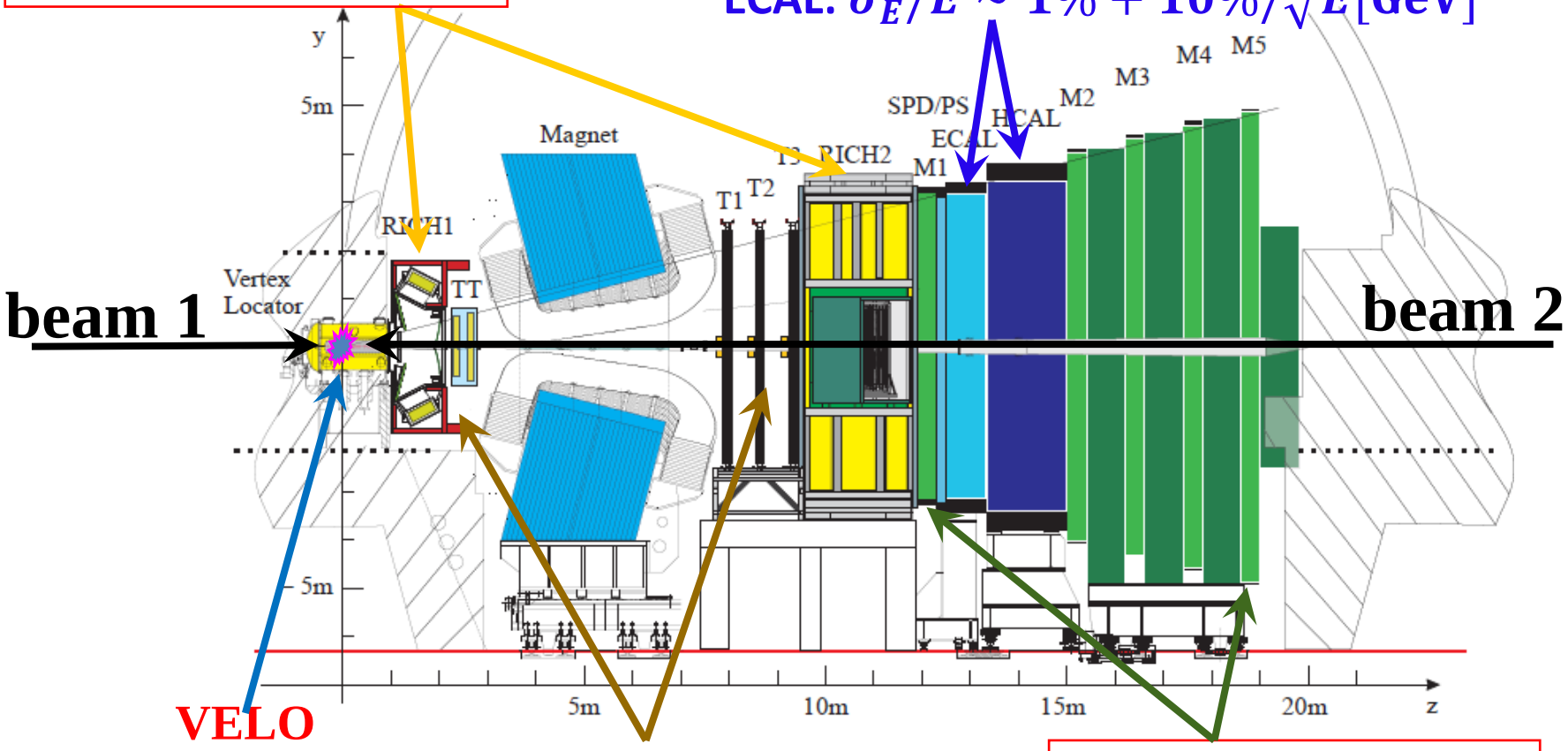
LHCb detector

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

Pseudorapidity acceptance
$2 < \eta < 5$

RICH1 & RICH2
$\epsilon(K \to K) \sim 95\%$
$\pi \to K$ mis-id: $\sim 5\%$

Calorimeters
ECAL: $\sigma_E/E \sim 1\% + 10\%/\sqrt{E[\text{GeV}]}$

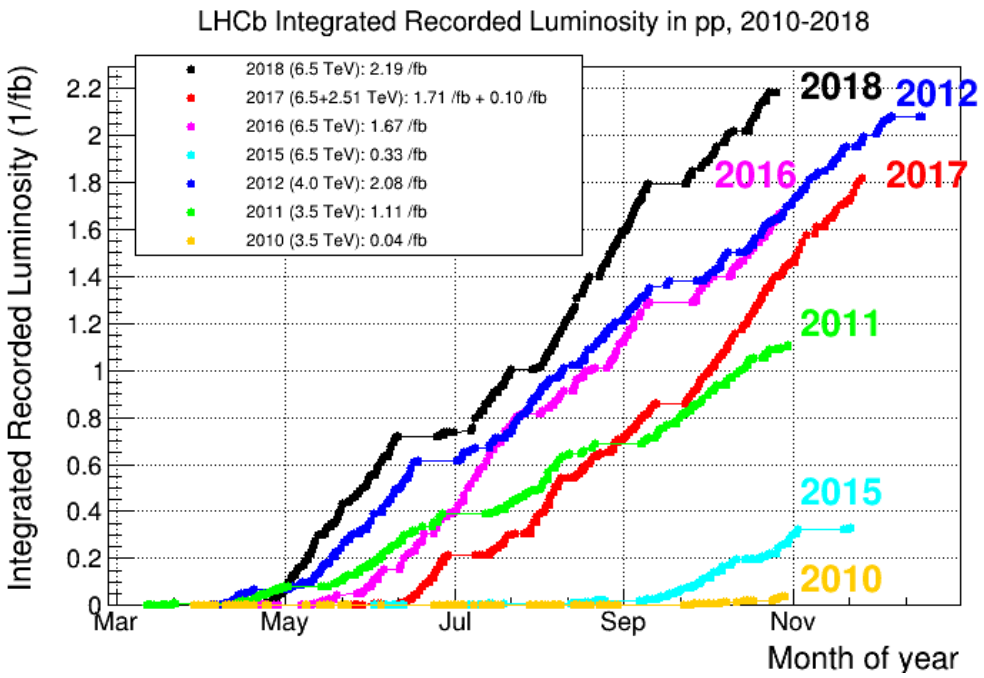


VELO
$\sigma_{IP} \sim 20$ μm
Decay time resolution: 45 fs (τ)~1.5 p

Tracking System
$\Delta p/p = 0.5\%@5$ GeV/c
to $1\%@200$ GeV/c

Muon System
$\epsilon(\mu \to \mu) \sim 97\%$
$\pi \to \mu$ mis-id: $1 \sim 3\%$

LHCb data



RUN-I

1 fb^{-1} of pp collisions at 7 TeV

2 fb^{-1} of pp collisions at 8 TeV

RUN-II (2015~2018 13 TeV)

$\boldsymbol{\sigma}$(RUN-II)$\approx$ $\mathbf{2}\boldsymbol{\sigma}$(RUN-I)

- **All *b* hadrons:**

  $\boldsymbol{B^0}, \boldsymbol{B^{\pm}}, \boldsymbol{B_s^0}, \boldsymbol{B_c^{\pm}}$ …

	B^0	B^+	B_s^0	***b* baryons (Λ_b …)**	B_c^+
Fraction(%)	40	40	10	10	0.1
Component	$\bar{b}d$	$\bar{b}u$	$\bar{b}s$	bqq	$\bar{b}c$

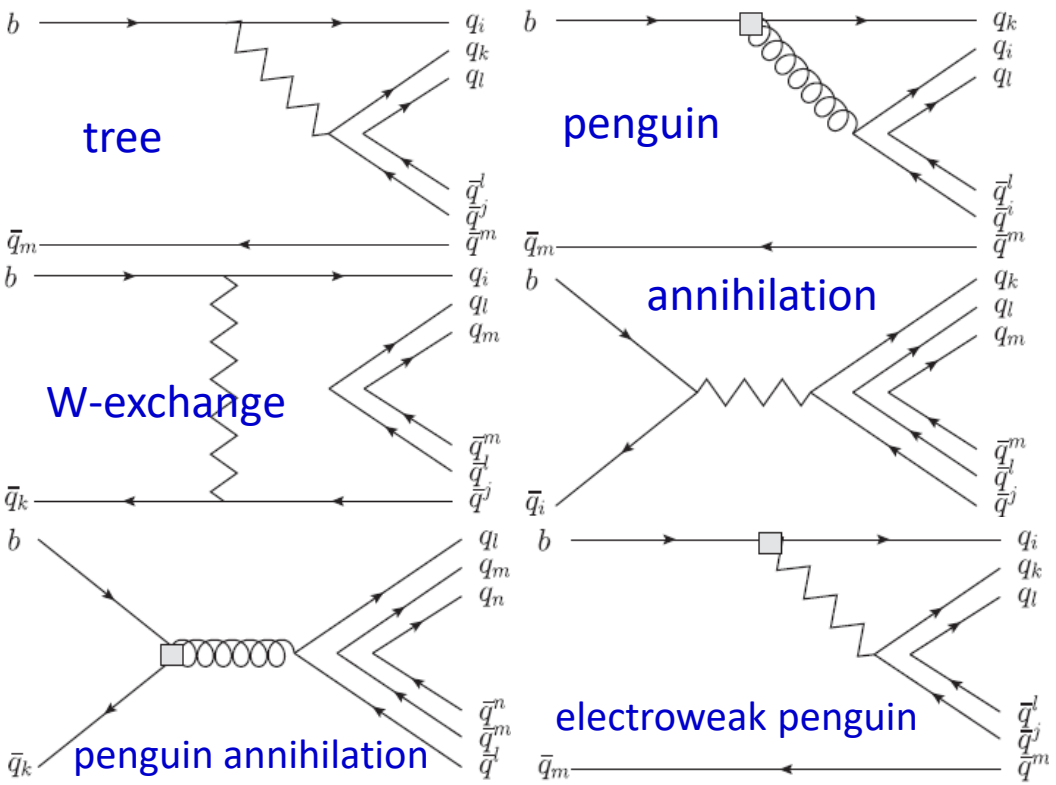
PRD 85.032008

Two body charmless baryonic decays of B

- Provides information on the dynamics of B decays and tests QCD based models of the hadronization process

- Discriminate the available models and makes it possible to extract both tree and penguin amplitudes of charmless two body baryonic decays

Phys. Rev. D 95, 096004 (2017)



- $B^0 \to p\bar{p}$ and $B^+ \to p\bar{\Lambda}$ as input to predict all other $B \to \mathfrak{B}_1\mathfrak{B}_2$

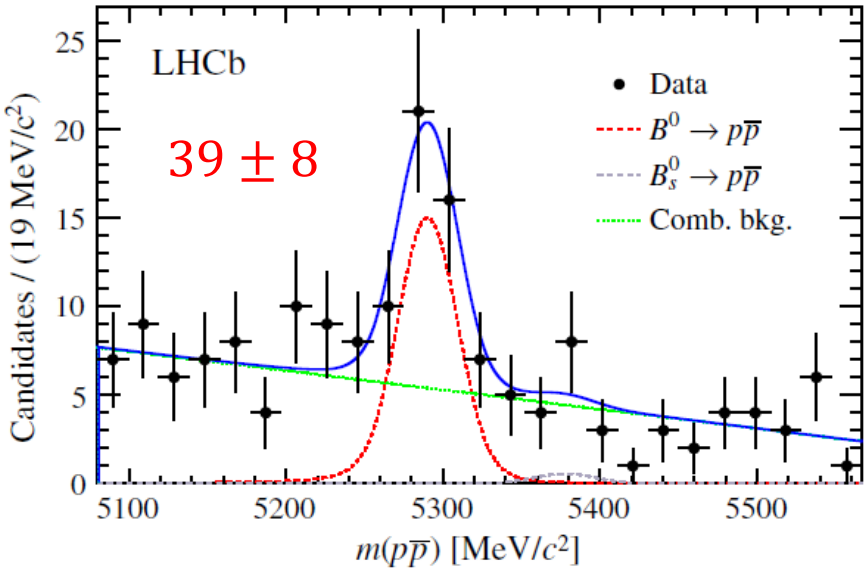
- Baryonic B decays are also interesting in the study of CP violation

- Pure penguin modes are expected to be sensitive to new physics contributions

First observation of $B^0 \to p\bar{p}$ with RUN-I data

- $B^0 \to K^+\pi^-$ as a normalization mode

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



- $\mathcal{B}(B^0 \to p\bar{p}) = (1.25 \pm 0.27 \pm 0.18) \times 10^{-8}$
- $\mathcal{B}(B^0_s \to p\bar{p}) < 1.5 \times 10^{-8}$@90% CL

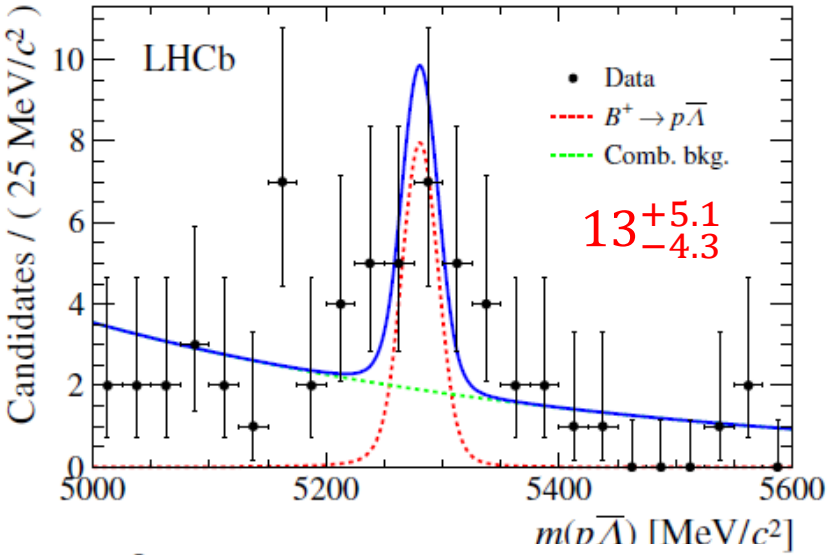
PRL 119, 232001 (2017)

- $\mathcal{B}(B^0 \to p\bar{p})$ is compatible with recent theoretical calculations
- $\mathcal{B}(B^0_s \to p\bar{p})$ measurement will make it possible to quantitatively compare the models
  - **Phys. Rev. D 91, 077501 (2015), Phys. Rev. D 95, 096004 (2017)**
- $B^0_s \to p\bar{p}$ would provide valuable information on whether contributions from the exchange (annihilation) processes
  - **JHEP 04(2020)035**

Evidence for $B^+ \to p\bar{\Lambda}$ with RUN-I data

JHEP 04(2017)162

- $B^+ \to K_s^0 \pi^+$ as a normalization mode
- $\mathcal{B}(B^+ \to p\bar{\Lambda}) = (2.4^{+1.0}_{-0.8} \pm 0.3) \times 10^{-7}$
- The first evidence for this decay process (4.1σ)



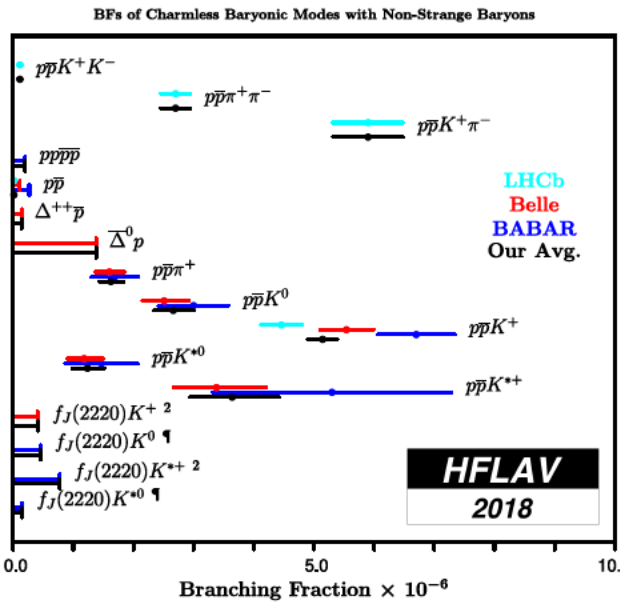
$$\mathcal{B}(B^+ \to p\bar{\Lambda}) = \frac{N(B^+ \to p\bar{\Lambda})}{N(B^+ \to K^0_S\pi^+)} \frac{\epsilon_{B^+\to K^0_S\pi^+}}{\epsilon_{B^+\to p\bar{\Lambda}}} \frac{\mathcal{B}(K^0_S \to \pi^+\pi^-)}{\mathcal{B}(\Lambda \to p\pi^-)} \mathcal{B}(B^+ \to K^0_S\pi^+)$$

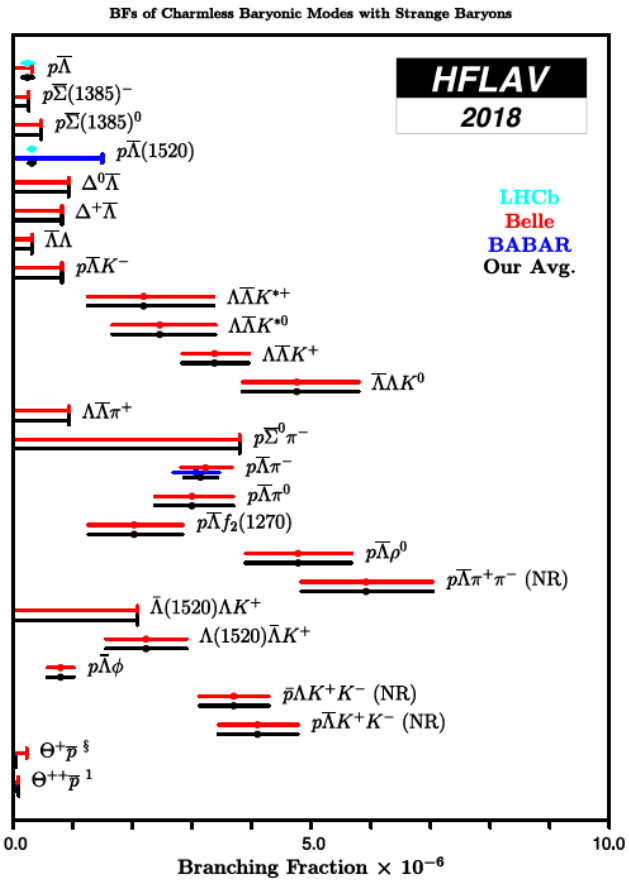
- Compatible with the theoretical predictions
  - **Phys. Rev. D 66 (2002) 014020, , Phys. Rev. D 89 (2014) 056003**
- In tension with calculations based on QCD sum rules (**Nucl. Phys. B 345 (1990) 137**) and factorization (**Phys. Rev. D 91 (2015) 077501**)

Multibody charmless baryonic decays of B

- The decays of B mesons into multiple baryon final states are still far from being fully understood
- $\mathcal{B}(B \to \mathfrak{B}_1\mathfrak{B}_2X) \gg \mathcal{B}(B \to \mathfrak{B}_1\mathfrak{B}_2)$, where $\mathfrak{B}$ represents a generic baryon
- $\mathcal{B}(B \to \mathfrak{B}_1\mathfrak{B}_2X) = (6.8 \pm 0.5 \pm 0.3)\%$, sum of all measurements lest than 1%（**PDG**）
  - **Z. Phys. C56, 1–6(1992)**
- $B \to \mathfrak{B}_1\mathfrak{B}_2\mathfrak{B}_3\mathfrak{B}_4$ decay mode never be oberved
  - $B \to pppp\ (2.9\sigma)$

Phys. Rev. D 98, 071102 (2018)



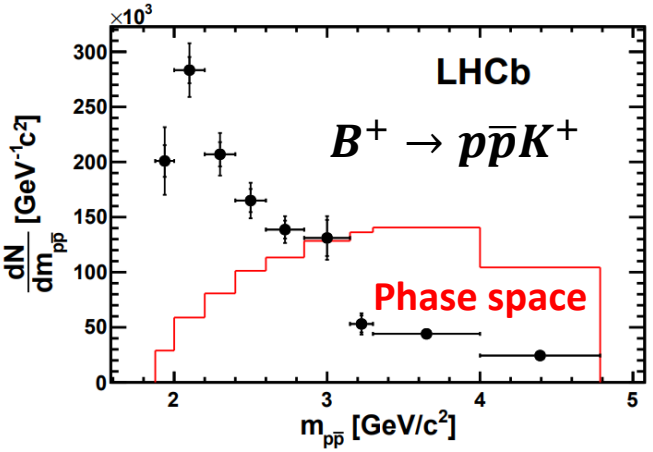


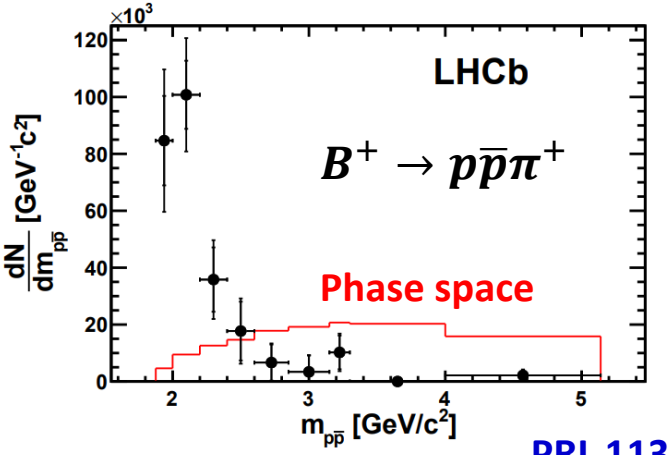
Charmless baryonic $B^+$and B^0 modes branching fractions reported by HFLAV

Threshold enhancement and CP asymmetry

- Many channels have the special feature: baryon-antibaryon pair peaks near threshold

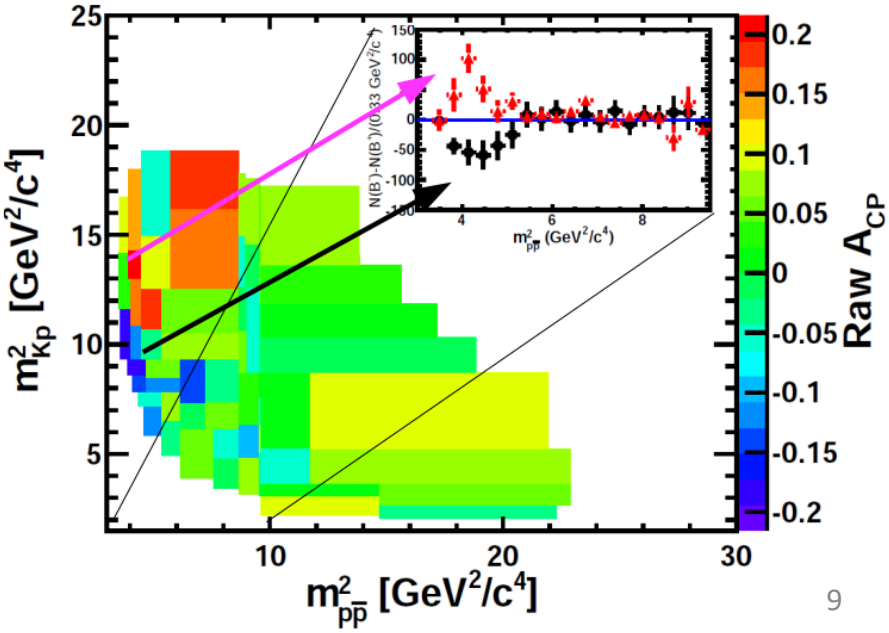
PRD 88, 052015 (2013)





PRL 113, 141801 (2014)

- 4σ CP asymmetry effect near-threshold with sign-flip near the zero crossing of the cosine of the light meson angle in $p\bar{p}$ frame ($\Delta A_{cp} \sim 4.7\sigma$), pointing to interfering J=0 and J=1 type waves

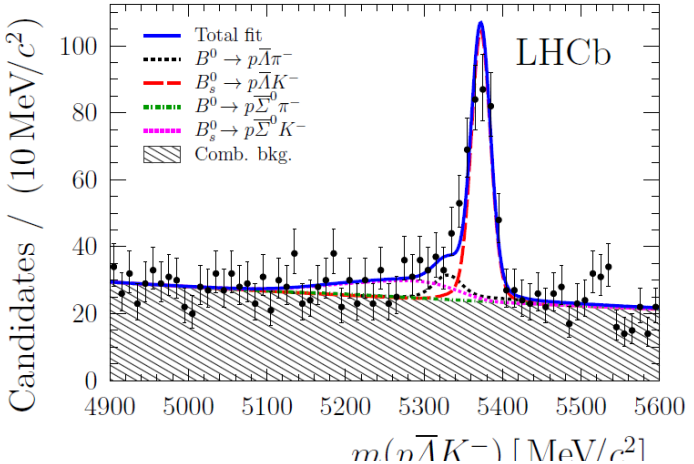


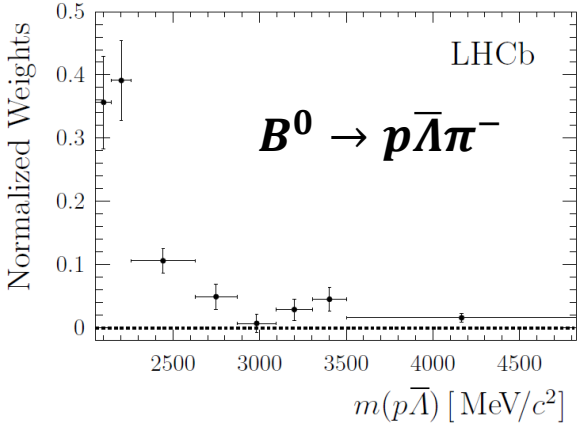
First observation of $B_s^0 \to p\bar{\Lambda}K^-$ with RUN-I data

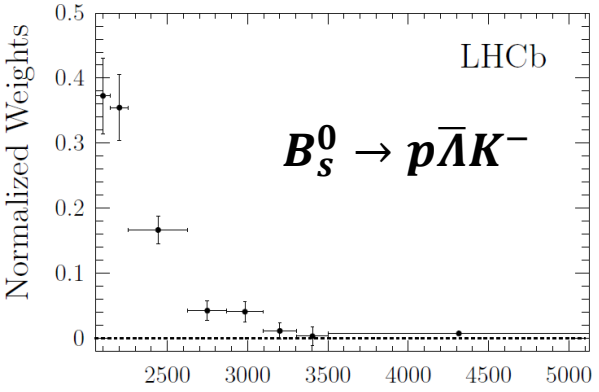
- Theoretical prediction: $\sim 10^{-6}$
- Theorey predict a large CPV asymmetry: 10% in $B^0 \to p\bar{\Lambda}\pi^-$
  - Int. J. Mod. Phys. A23 (2008) 3290
- $B^0 \to p\bar{\Lambda}\pi^-$ as a normalization mode

$$\mathcal{B}(B_s^0 \to p\bar{\Lambda}K^-) + \mathcal{B}(B_s^0 \to \bar{p}\Lambda K^+)$$
$$= [5.46 \pm 0.61 \pm 0.57 \pm 050(\mathcal{B}) \pm 0.32(f_s/f_d)]$$
$$\times 10^{-6}$$

- $m(p\bar{\Lambda})$ are already efficiency-corrected and background-subtracted
- Observed the $p\bar{\Lambda}$ threshold enhancement



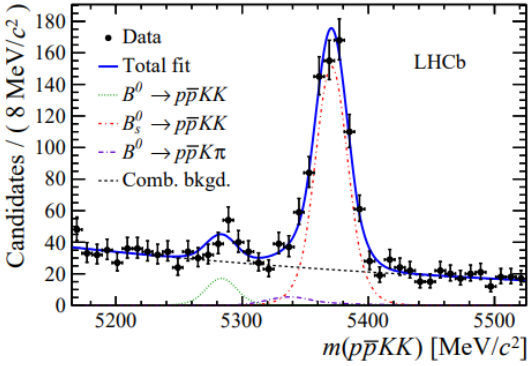


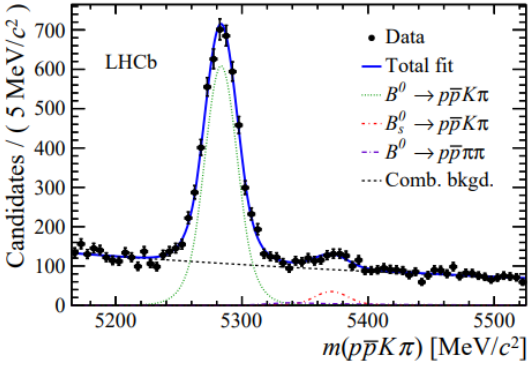


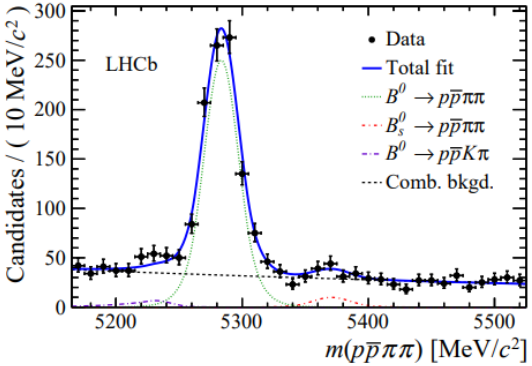
Phys. Rev. Lett. 119 (2017) 041802

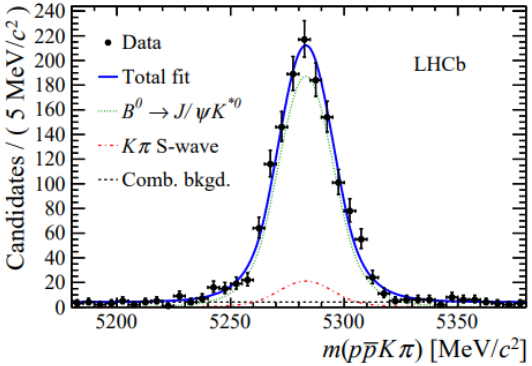
First observation of $B^0_{(s)} \to p\bar{p}h^+h^-$ with RUN-I data

Phys. Rev. D 96 (2017) 051103







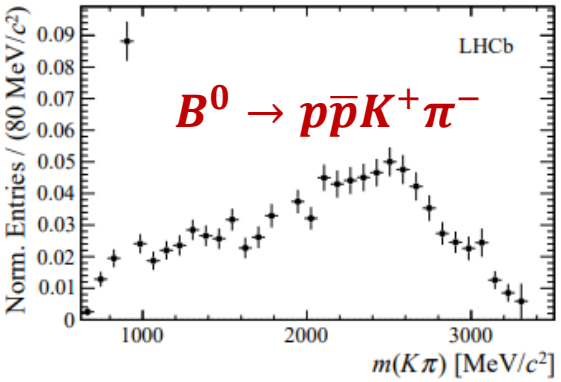


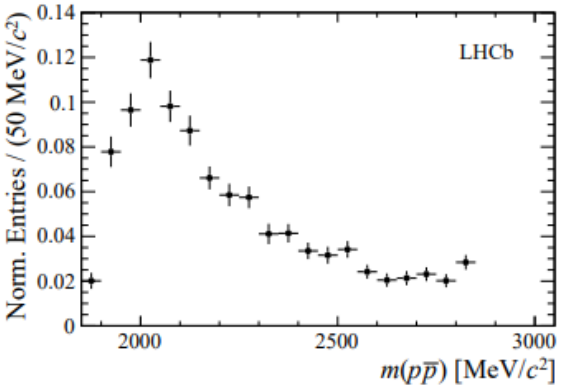
- $m(p\bar{p}) < 2.85\ \mathrm{GeV}/c^2$
- $B^0 \to J/\psi(\to p\bar{p})K^*(892)$ as a normalization mode

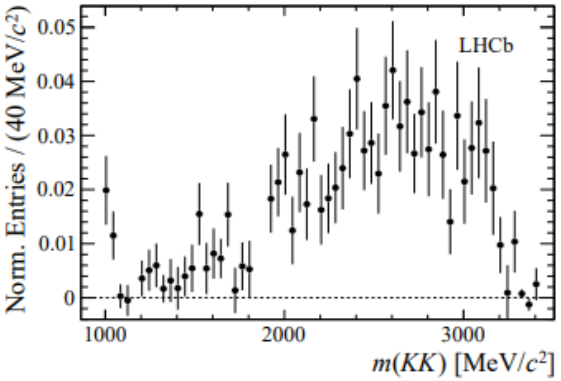
Decay channel	Yield $\mathcal{N}$	Significance $[\sigma]$	Branching fraction / 10^{-6}
$B^0 \to p\bar{p}KK$	68 ± 17	4.1	$0.113 \pm 0.028 \pm 0.011 \pm 0.008$
$B^0 \to p\bar{p}K\pi$	4155 ± 83	> 25	$5.9 \pm 0.3 \pm 0.3 \pm 0.4$
$B^0 \to p\bar{p}\pi\pi$	902 ± 35	> 25	$2.7 \pm 0.1 \pm 0.1 \pm 0.2$
$B^0_s \to p\bar{p}KK$	635 ± 32	> 25	$4.2 \pm 0.3 \pm 0.2 \pm 0.3 \pm 0.2$
$B^0_s \to p\bar{p}K\pi$	246 ± 39	6.5	$1.30 \pm 0.21 \pm 0.11 \pm 0.09 \pm 0.08$
$B^0_s \to p\bar{p}\pi\pi$	39 ± 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 ± 45	–	–

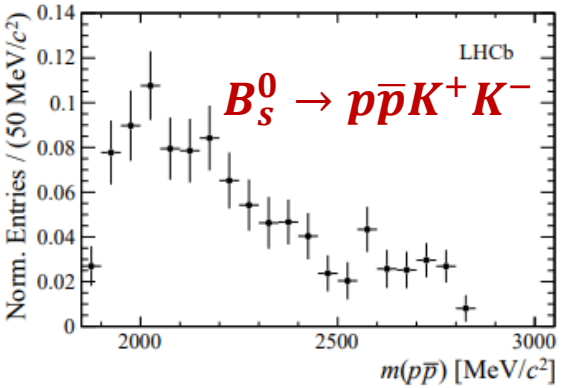
The $p\bar{p}$ threshold enhancement

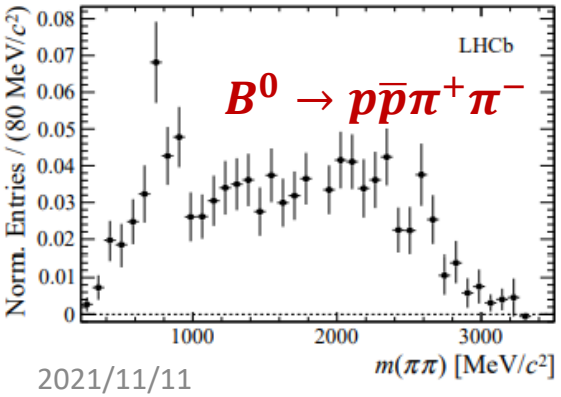
Phys. Rev. D 96 (2017) 051103

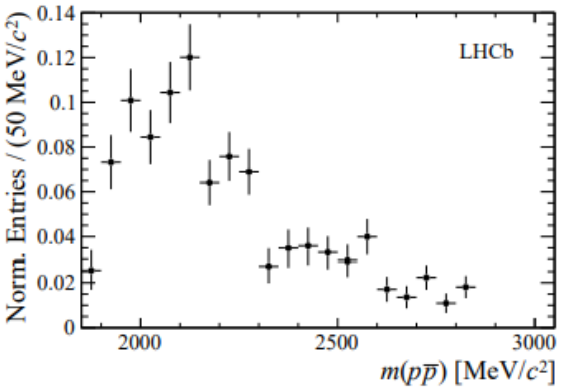










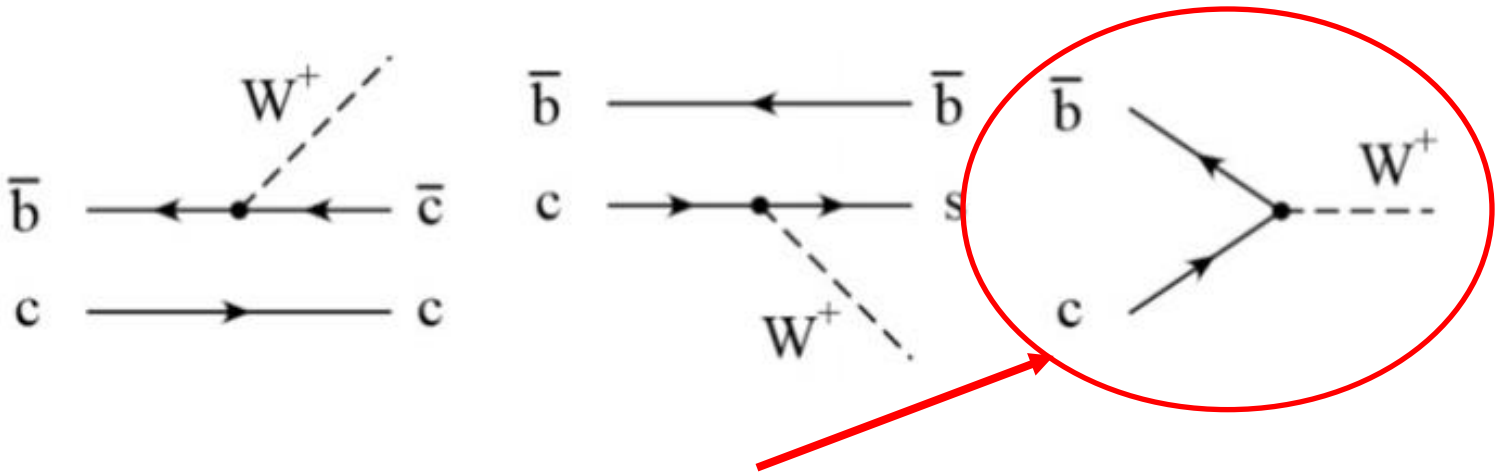


- $m(p\bar{p})$ are already efficiency-corrected and background-subtracted
- Vetoed D^0
- Confirmed the threshold enhancement of $B_s^0 \to p\bar{\Lambda}K^-$

Charmless baryonic decay of B_c^+

- Unique state that contains two heavy quarks of different flavors

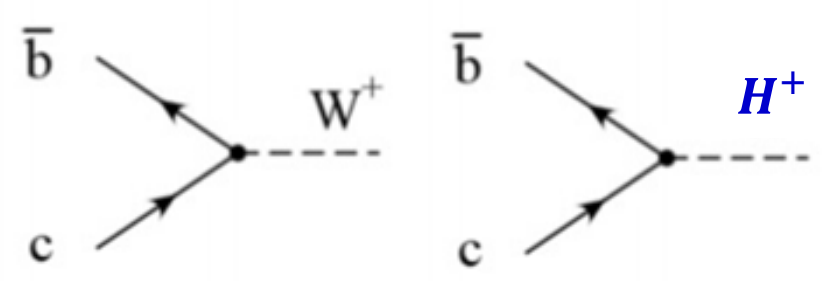
- Rich decay modes
  1. *b* quark decay ~20%
  2. *c* quark decay ~70%
  3. annihilation decay ~10%



- Charmless baryonic decay provide a good test-bed for the study of the W-exchange topology

Search for $B_c^+ \to p\bar{p}\pi^+$ with Run-I data

- In the SM, theoretical prediction B_c^+ annihilation decays :10^{-8}~10^{-6}
- Any significant enhancement could indicate the particles beyond the SM (like H^+)

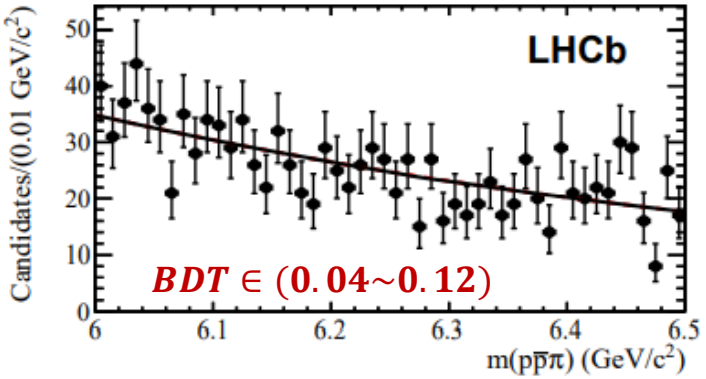


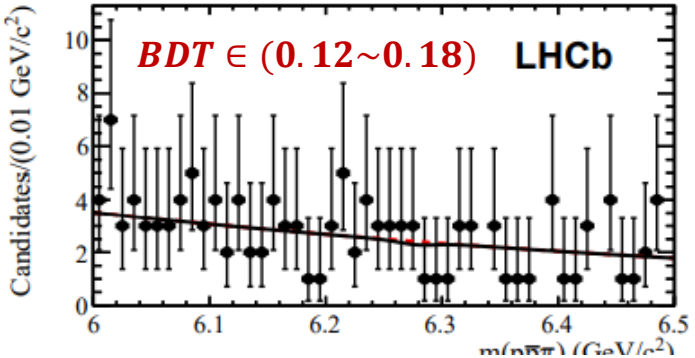
- $B^+ \to p\bar{p}\pi^+$ as a normalization mode

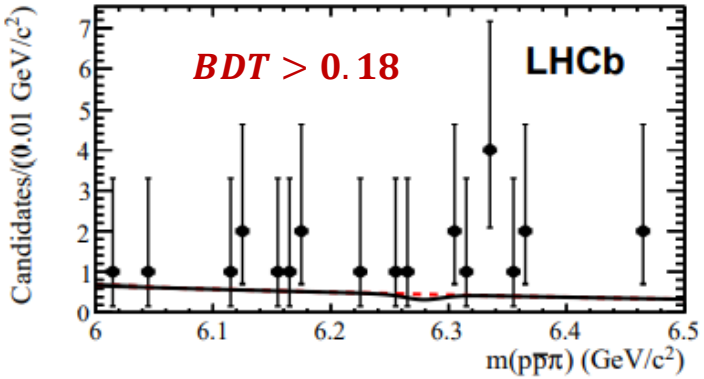
$$R_f \equiv \frac{\sigma(B_c^+)}{\sigma(B^+)} \times \mathcal{B}(B_c^+ \to f)$$

- $m(p\bar{p}) < 2.85\ \mathrm{GeV}/c^2$

$$R_p < 3.6 \times 10^{-8}$$







Phys. Lett. B 759 (2016) 313

Search for CPV in charmless decay of b baryon

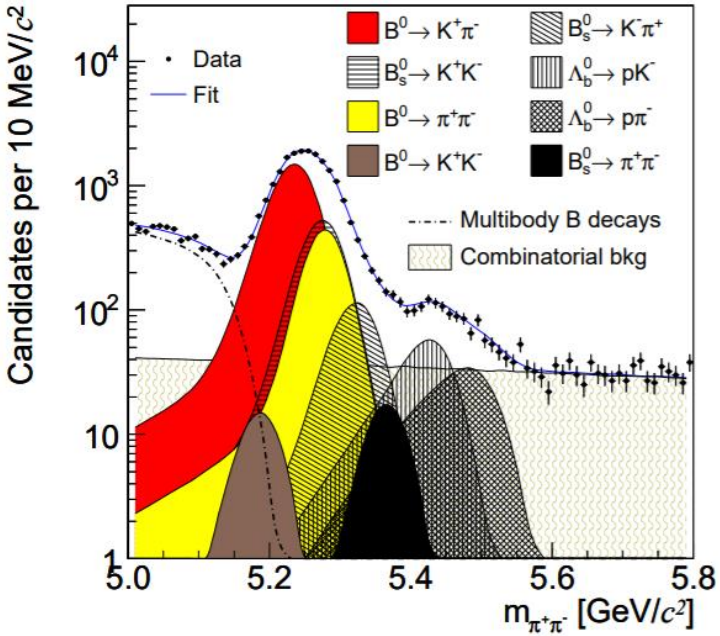
- CPV never observed in baryon decays to now
- LHCb has the unique possibility to search for CPV in b baryon decays where sizeable CPV effects are expected in the Standard Model
- Triple product asymmetries (TPA) used in search for CPV in $\Lambda_b \to ph^-h^+h^- and\ \Xi_\mathrm{b} \to p\pi^+K^-K^-$
  - The first evidence of CPV in the baryon sector(3.3σ in $\Lambda_b \to p\pi^-\pi^+\pi^-$)
  - Nature Phys. 13 (2017) 391-396(detail in back up)
- Perform measurements in regions of phase space for increased sensitivity to localised CP violation effects. Different strong phases at play

Search for direct CPV in $\Lambda_b^0 \to ph^-$

- Predictions for the CP asymmetries in $\Lambda_b^0 \to ph^-$ about 30%
  - A. Ali, G. Kramer, and C.-D. L, Phys. Rev. D58 (1998) 094009
  - Y. K. Hsiao and C. Q. Geng, Phys. Rev. D91(2015) 116007
  - $A_{cp}(\Lambda_b \to p\pi^-) - A_{cp}(\Lambda_b \to pK^-) \approx -0.26$

$$A_{CP} = \frac{N_{\Lambda_b} - N_{\bar{\Lambda}_b}}{N_{\Lambda_b} + N_{\bar{\Lambda}_b}}$$

- The first measurements of these by CDF

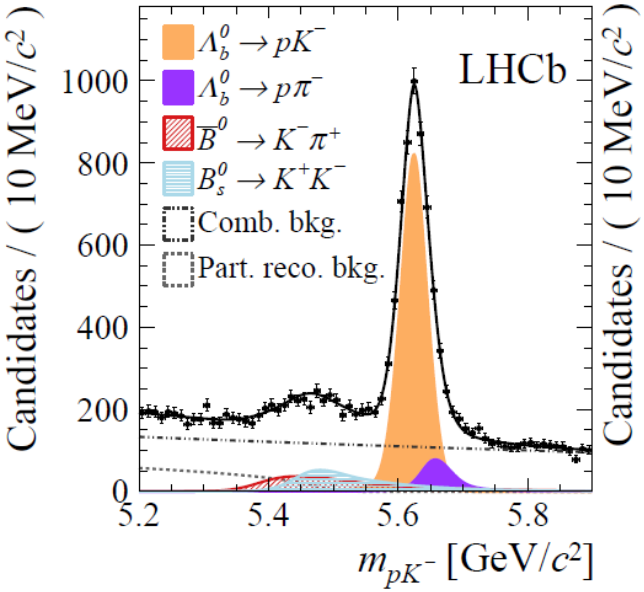


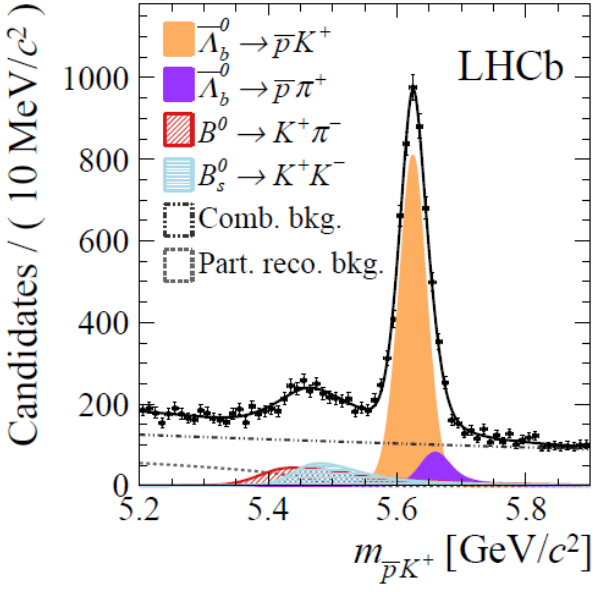
Phys. Rev. Lett. 113 (2014)242001

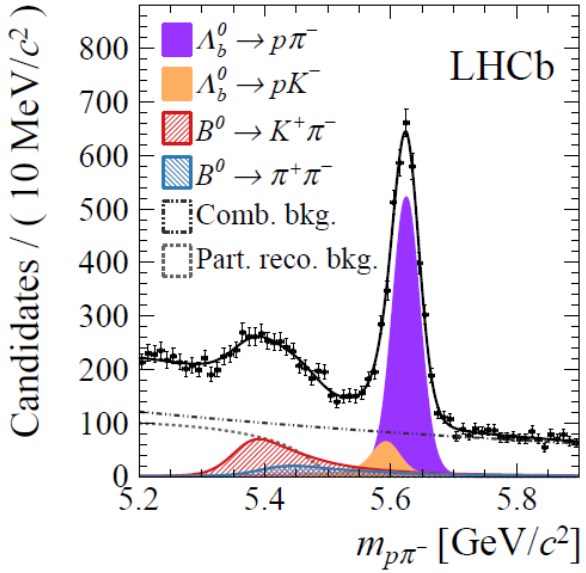
Decay	$\mathcal{N}_{b\to f}$	$\mathcal{N}_{\bar{b}\to \bar{f}}$	$\mathcal{A}(b \to f)$
$B^0 \to K^+\pi^-$	5313 ± 109	6348 ± 117	$-0.083 \pm 0.013 \pm 0.004$
$B_s^0 \to K^-\pi^+$	560 ± 51	354 ± 46	$+0.22 \pm 0.07 \pm 0.02$
$\Lambda_b^0 \to p\pi^-$	242 ± 24	206 ± 23	$+0.06 \pm 0.07 \pm 0.03$
$\Lambda_b^0 \to pK^-$	271 ± 30	324 ± 31	$-0.10 \pm 0.08 \pm 0.04$

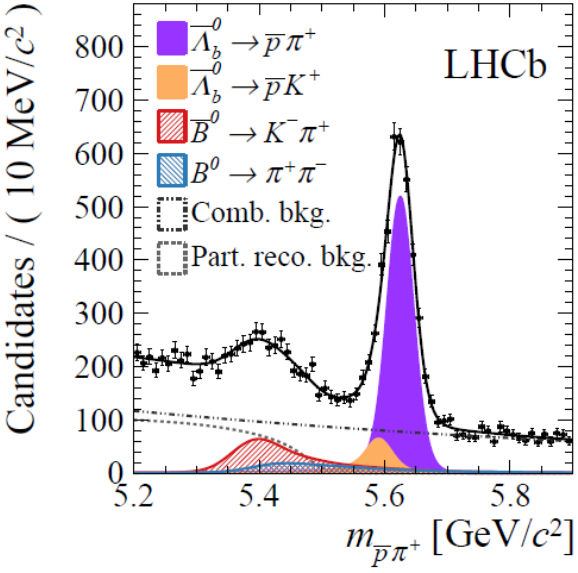
- The asymmetries were found to be compatible with zero within an uncertainty of 8 to 9%
- $A_{cp}(\Lambda_b^0 \to p\pi^-) - A_{cp}(\Lambda_b^0 \to pK^-) = 0.16 \pm 0.12$

Search for direct CPV in $\Lambda_b^0 \to ph^-$ with RUN-I data









$$A_{cp}^{pK^-} = -0.020 \pm 0.013 \pm 0.019$$

$$A_{cp}^{p\pi^-} = -0.035 \pm 0.017 \pm 0.020$$

$$A_{cp}^{p\pi^-} - A_{cp}^{pK^-} = 0.014 \pm 0.022 \pm 0.010$$

- No CP-violation
- Much improved precision with CDF

Phys. Lett. B 787 (2018) 124-133

Search for CPV using TPA

- Triple products in Λ_b rest frame

  $\hat{T}$ = motion reversal operator

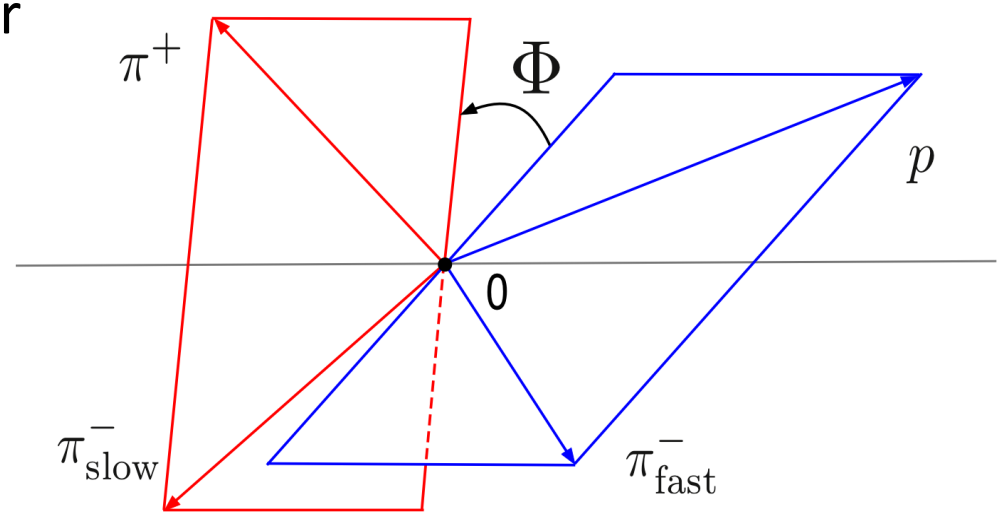
$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h^-} \times \vec{p}_{h^+}) \propto \sin\Phi$$

$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h^+} \times \vec{p}_{h^-}) \propto \sin\overline{\Phi}$$

- $\hat{T}$ – odd asymmetries:

$$A_{\hat{T}} = \frac{N_{\Lambda_b^0}(C_{\hat{T}} > 0) - N_{\Lambda_b^0}(C_{\hat{T}} < 0)}{N_{\Lambda_b^0}(C_{\hat{T}} > 0) + N_{\Lambda_b^0}(C_{\hat{T}} < 0)},$$

$$\overline{A}_{\hat{T}} = \frac{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} > 0) - N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} < 0)}{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} > 0) + N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} < 0)}$$



CP-violating observable: $a_{CP}^{\hat{T}-\text{odd}} = \frac{1}{2}(A_{\hat{T}} - A_{\bar{\hat{T}}})$

P-violating observable: $a_{P}^{\hat{T}-\text{odd}} = \frac{1}{2}(A_{\hat{T}} + A_{\bar{\hat{T}}})$

Sensitivity to CPV

- $A_{\hat{T}}, A_{\bar{\hat{T}}}, a_{CP}^{\hat{T}-\mathrm{odd}}$ and $a_{P}^{\hat{T}-\mathrm{odd}}$ are insensitive to
  - particle/antiparticle production asymmetries
  - detector-induced charge asymmetries
  - reduced systematic uncertainties

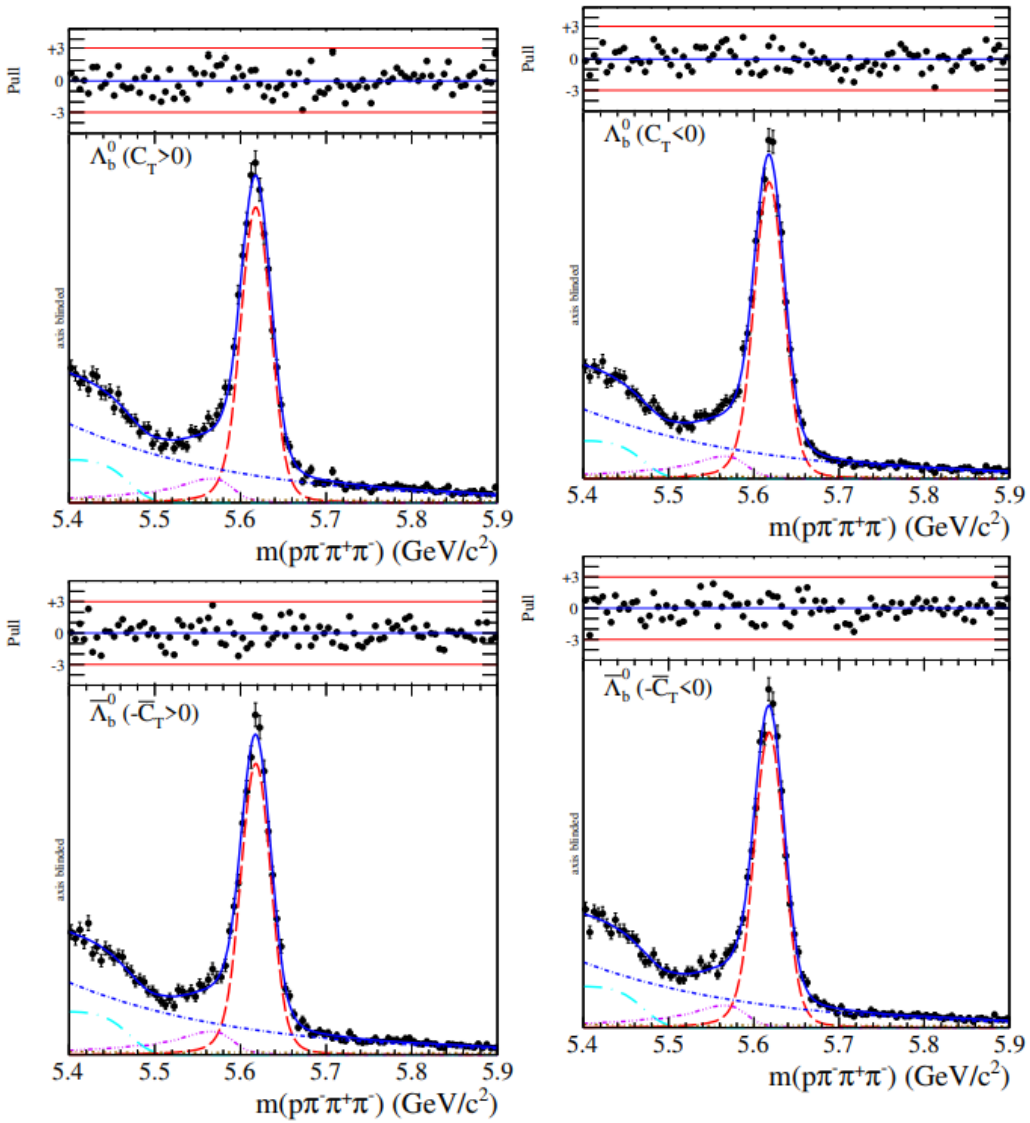
- Complementary approach to A_{CP} analysis

$$A_{CP} = \frac{N_{\Lambda_b} - N_{\bar{\Lambda}_b}}{N_{\Lambda_b} + N_{\bar{\Lambda}_b}}$$

- Sensitive to potential new physics effects:
  - W. Bensalem, A. Datta, and D. London, New physics effects on triple product correlations in Λb decays, Phys. Rev. D66 (2002) 094004, arXiv:hep-ph/0208054

CPV measurements in $\Lambda_b \to p\pi^-\pi^+\pi^-$

(2011,2012,2015,2016,2017) $\mathbf{6.6\ fb^{-1}}$



- Signal Yield: 27687
- RUN-I signal yield: 6636

$$A_{\hat{T}} = \frac{N_{\Lambda_b^0}(C_{\hat{T}} > 0) - N_{\Lambda_b^0}(C_{\hat{T}} < 0)}{N_{\Lambda_b^0}(C_{\hat{T}} > 0) + N_{\Lambda_b^0}(C_{\hat{T}} < 0)},$$

$$\overline{A}_{\hat{T}} = \frac{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} > 0) - N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} < 0)}{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} > 0) + N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} < 0)}$$

$$a_{CP}^{\hat{T}-\mathrm{odd}} = (-0.7 \pm 0.7 \pm 0.2)\%$$

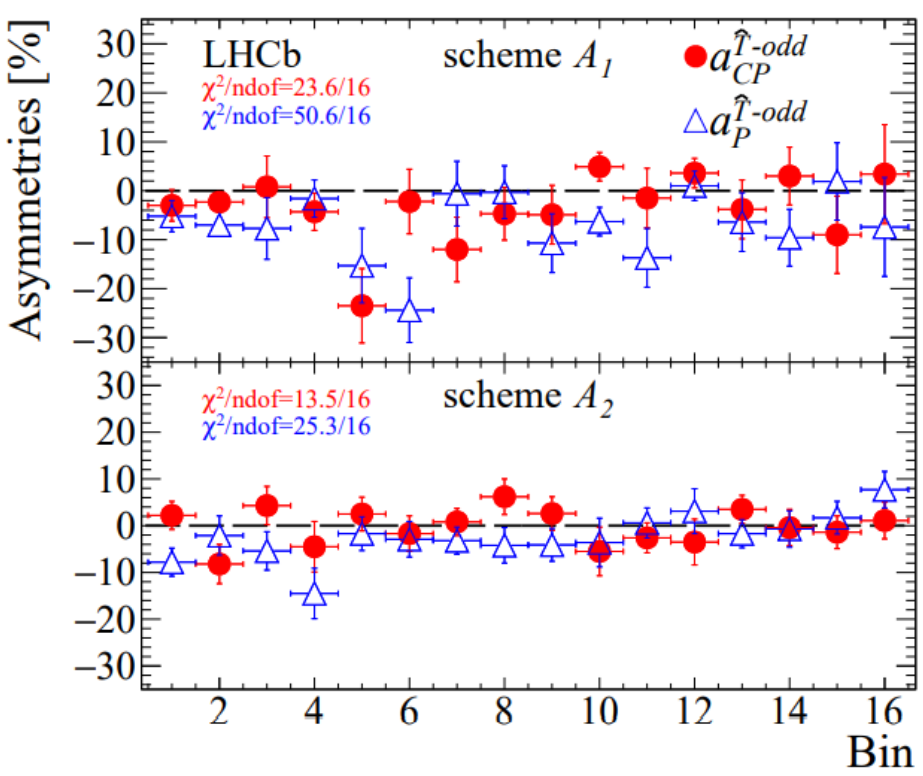
$$a_{P}^{\hat{T}-\mathrm{odd}} = (-4.0 \pm 0.7 \pm 0.2")\%$$

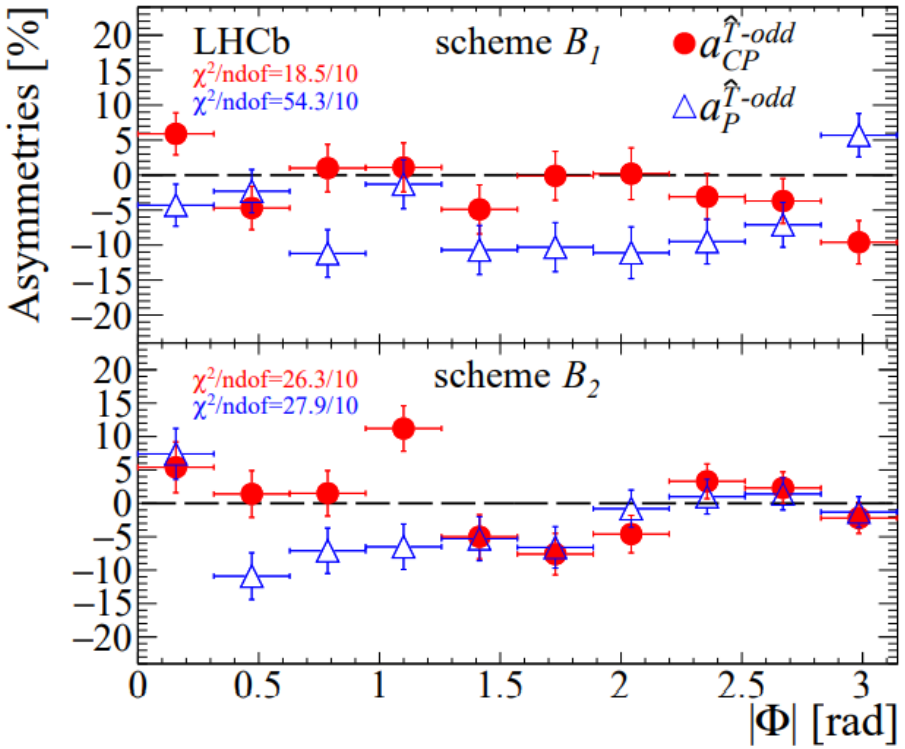
Phys. Rev. D 102 (2020) 051101

Measurement asymmetries in phase space regions

Scheme A: on dominant resonances: $\Delta^{++}, N^*, \rho(770)$

Scheme B: on Φ angle between decay planes $\pi^+\pi^-_{slow}$ and $p\pi^-_{fast}$





Phys. Rev. D 102 (2020) 051101

- No CP-violation
- Violation of P symmetry is observed

Conclusions and Outlook

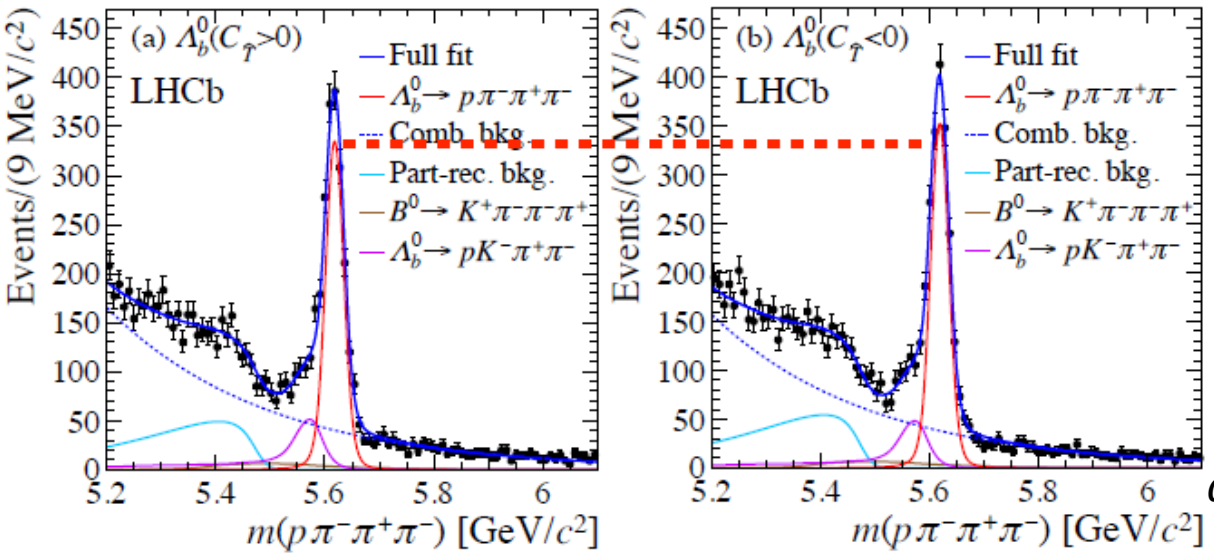
- Many results on b hardon charmless baryonic decay by LHCb
  - First observation of $B^0 \to p\bar{p}$, evidence for $B^+ \to p\bar{\Lambda}$
  - First observation of $B^0_{(s)} \to p\bar{p}h^+h^-$
  - $\mathcal{B}(B_c^+ \to p\bar{p}\pi^+) < 3.6 \times 10^{-8}$ @90% CL
  - No direct CPV in $\Lambda_b^0 \to ph^-$
  - No CPV in $\Lambda_b \to p\pi^-\pi^+\pi^-$
- More analyses based on RUN-I and RUN-II data are still under way
  - Search for $B_s^0 \to p\bar{p}, B^+ \to p\bar{\Lambda}$
  - Search for $B^0_{(s)} \to p\bar{p}p\bar{p}, B^+ \to \bar{\Lambda}pp\bar{p}$
  - CPV of $B^0_{(s)} \to p\bar{p}h^+h^-$
  - Search for $\Lambda_b^0 \to \Lambda p\bar{p}$ ……

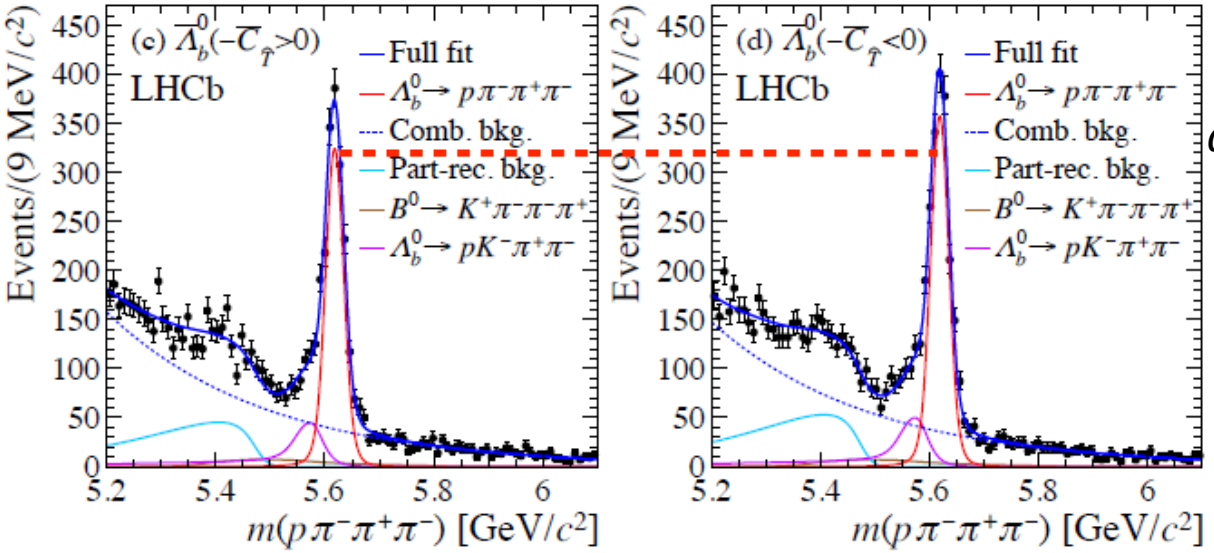
Thank you!

Back up

CPV measurements in $\Lambda_b \to p\pi^-\pi^+\pi^-$, $\Lambda_b \to p\pi^-K^+K^-$

Run-I, 3 fb^{-1}





$$A_{\hat{T}} = \frac{N_{\Lambda_b^0}(C_{\hat{T}}>0) - N_{\Lambda_b^0}(C_{\hat{T}}<0)}{N_{\Lambda_b^0}(C_{\hat{T}}>0) + N_{\Lambda_b^0}(C_{\hat{T}}<0)},$$

$$\overline{A}_{\hat{T}} = \frac{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}>0) - N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}<0)}{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}>0) + N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}<0)}$$

For $\Lambda_b \to p\pi^-\pi^+\pi^-$

$a_{CP}^{\hat{T}\text{-odd}} = (1.15 \pm 1.45 \pm 0.32)\%$

$a_P^{\hat{T}\text{-odd}} = (-3.71 \pm 1.45 \pm 0.32)\%$

For $\Lambda_b \to p\pi^-K^+K^-$

$a_{CP}^{\hat{T}\text{-odd}} = (-0.93 \pm 4.54 \pm 0.42)\%$

$a_P^{\hat{T}\text{-odd}} = (3.62 \pm 4.54 \pm 0.42)\%$

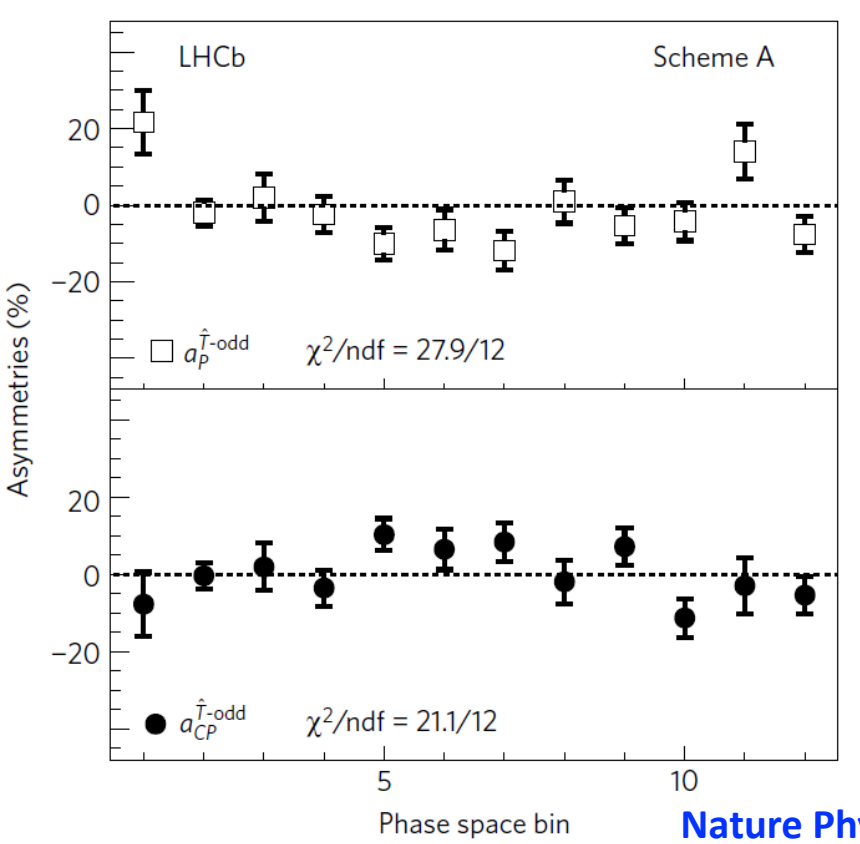
Phase space integrated results consistent with P or CP symmetry

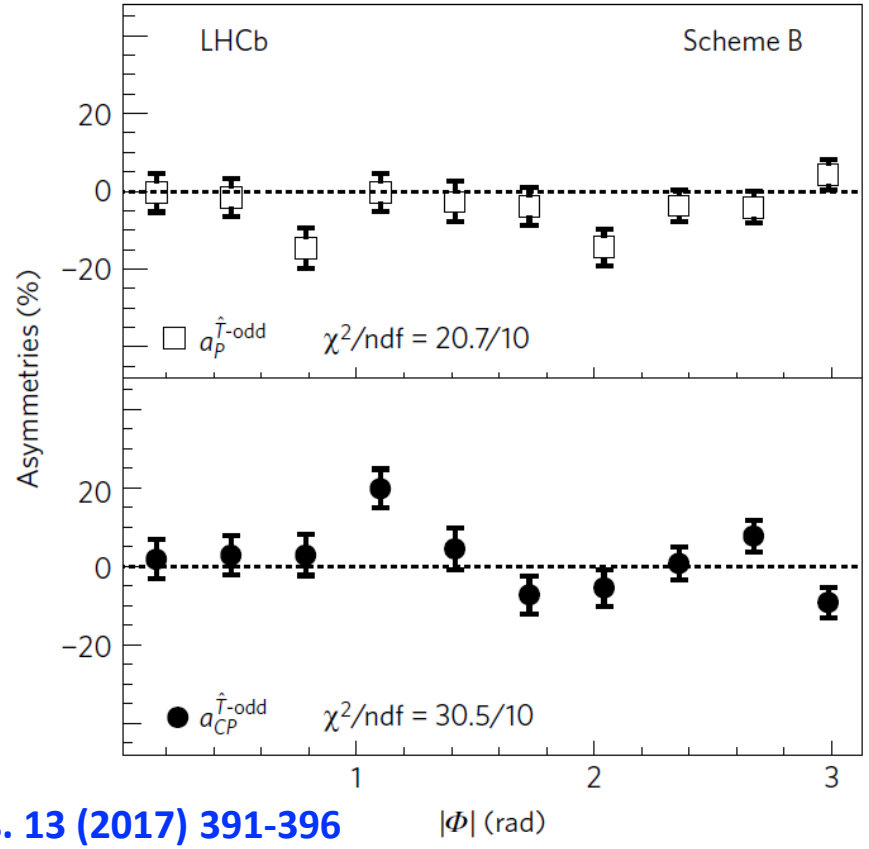
Nature Phys. 13 (2017) 391-396

Measurement asymmetries in phase space regions

Scheme A: on dominant resonances: $\Delta^{++}, N^*, \rho(770)$

Scheme B: on Φ angle between decay planes $\pi^+\pi^-_{slow}$ and $p\pi^-_{fast}$

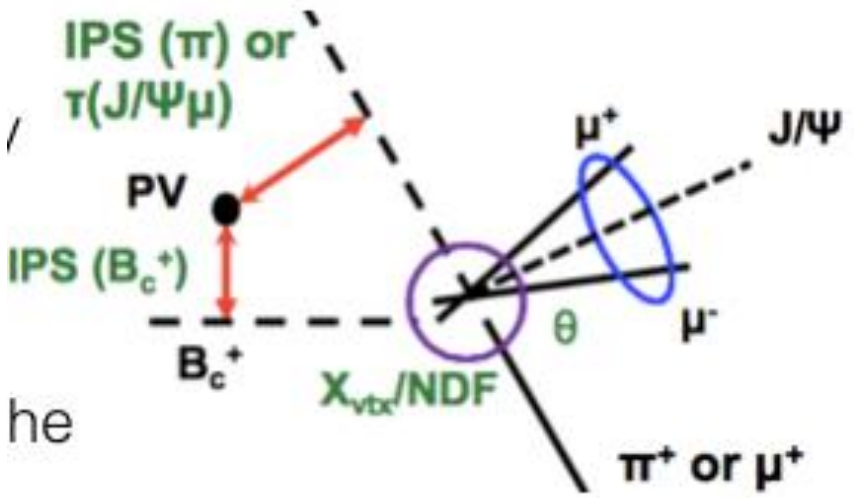




Nature Phys. 13 (2017) 391-396

- Combined 3.3σ deviation from CP symmetry
  - The first evidence of CPV in the baryon sector

Multivariate analysis



- IPS(B_c^+), IPS(J/ψ), IPS(H), IPS($\mu^{\pm}$), PT(J/ψ), PT(H), PT($\mu^{\pm}$) ,Bc_τ, Bc_L, $\chi^2_{DTF}(B_c^+)$