Charmless *b*-hadron decays at LHCb

Irina Nasteva

Universidade Federal do Rio de Janeiro (UFRJ)

On behalf of the LHCb collaboration

HADRON 2021
Online, Mexico city, 28 July 2021

Outline

Motivations

Detector and analysis strategies

Recent measurements of CP violation in charmless:

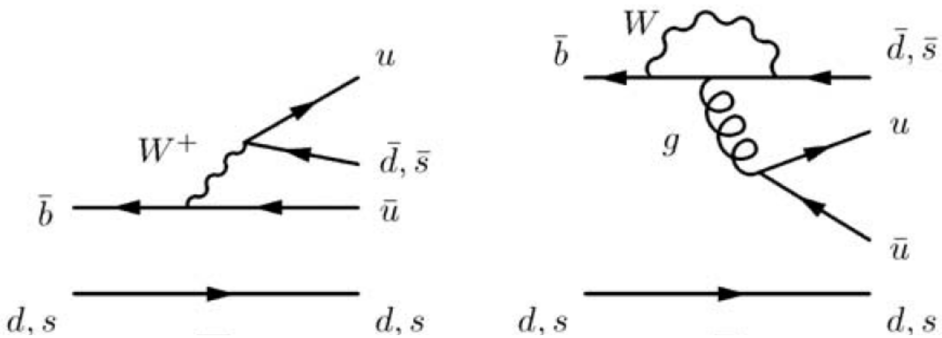
- Two-body *b*-meson decays
  - $B_{(s)}^0 \to h^+h^-$ (h= K,π) — JHEP 03 (2021) 075
  - $B^\pm \to K^\pm\pi^0$ — Phys. Rev. Lett. 126 (2021) 091802
- Three-body *b*-meson decays — Phys. Rev. D 102 (2020) 112010; Phys. Rev. D 90 (2014) 112004; Phys. Rev. Lett. 123 (2019) 231802; Phys. Rev. Lett. 124 (2020) 031801; Phys. Rev. D 101 (2020) 012006
  - $B^\pm \to h^\pm h^+ h^-$ (h= K,π)
- Three- and four-body *b*-baryon decays
  - $\Xi_b^- \to pK^-K^-$ — arXiv:2104.15074
  - $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ — Phys. Rev. D 102 (2020) 051101

Charmless b-hadron decays

- Charmless hadronic decays are suppressed in the Standard Model (SM).
- They proceed through $b \to u$ tree and $b \to s,d$ loop (penguin) transitions.
- Tree and penguin amplitudes are of similar size and have a relative weak phase, their interference can lead to CP violation in decay.
- New Physics particles could contribute to penguin loop and additional sources of CP violation.

Two-body *b*-meson decays:

- Large CP violation observed.
- CP violation in mixing (time-dependent) and decay.
- "Kπ puzzle".



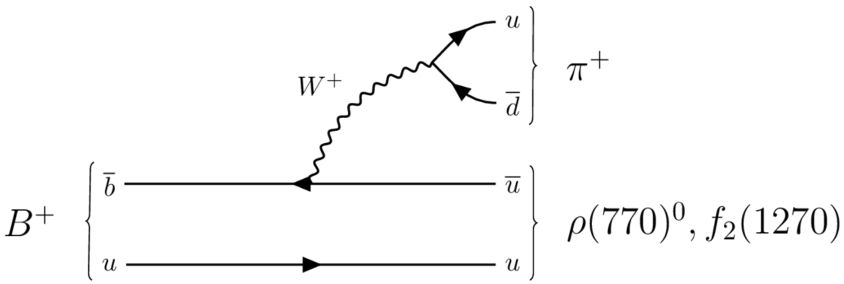
$B^0_{(s)} \to K^+K^-$
$B^0_{(s)} \to K^+\pi^-$
$B^0_{(s)} \to \pi^+\pi^-$

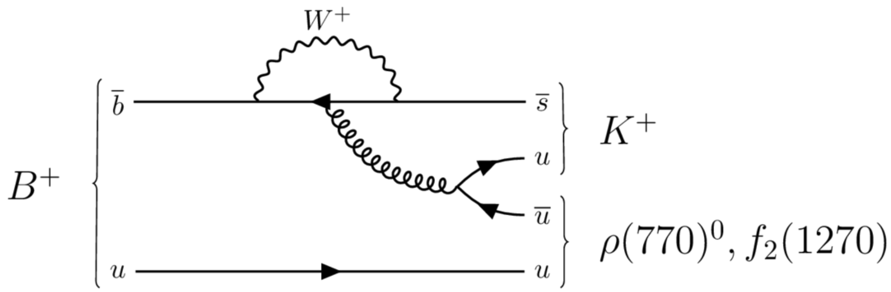
$B^\pm \to K^\pm\pi^0$

Charmless *b*-hadron decays

Three-body *b*-meson decays:

- Rich spectrum of resonant final states and large local CP asymmetries.

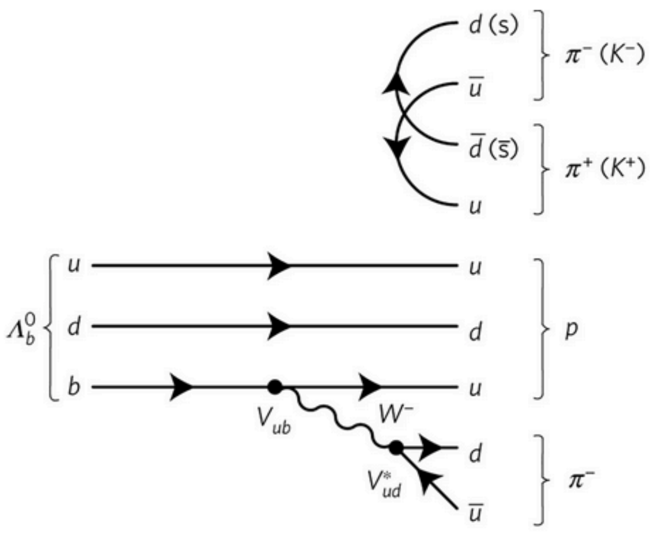


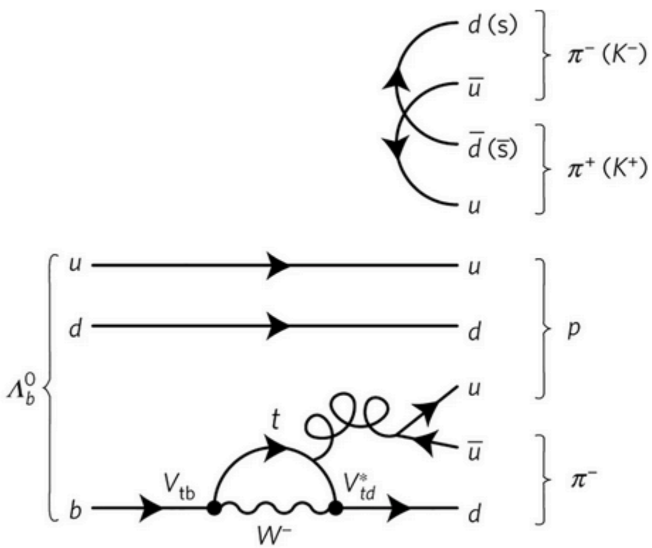


$B^{\pm} \to K^{\pm}K^{+}K^{-}$
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$
$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$
$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$

Three- and four-body *b*-baryon decays:

- No observation of CP violation yet, but have similar diagrams to *b*-mesons.

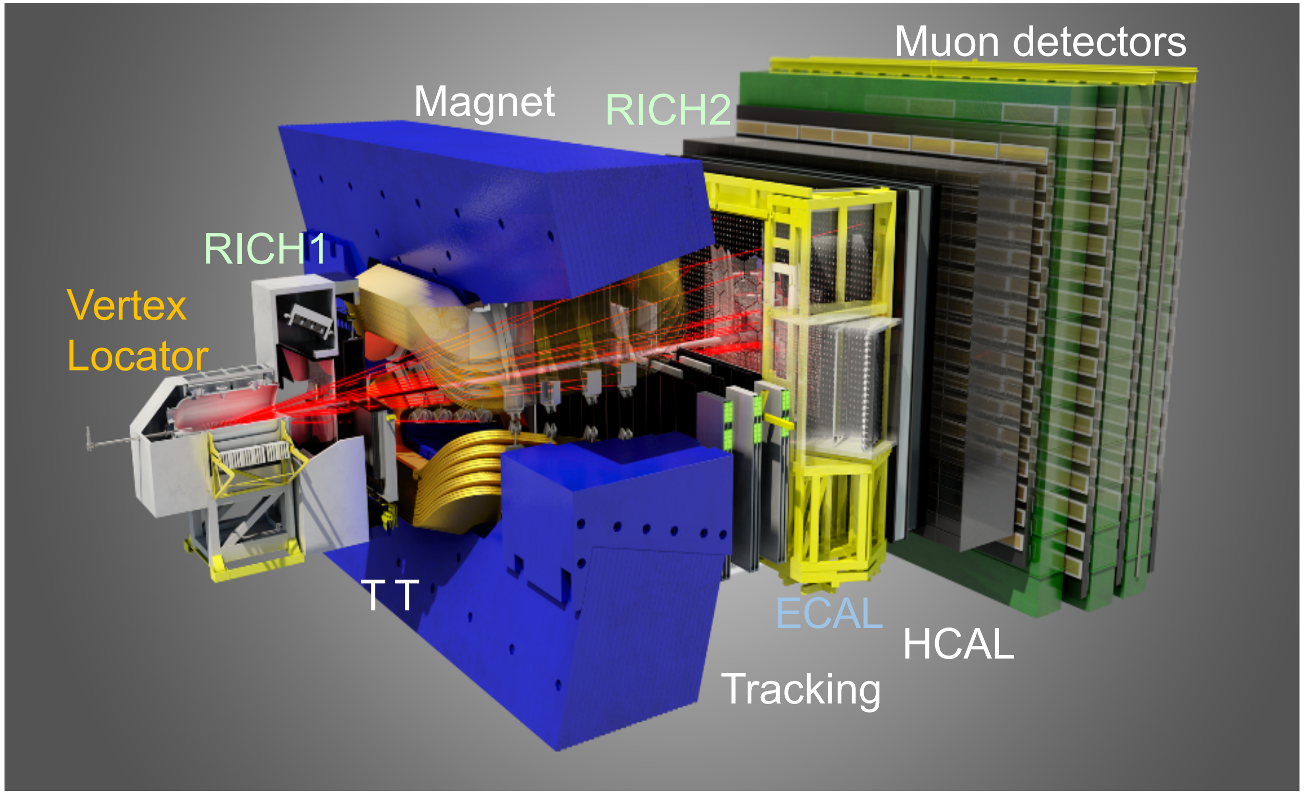




$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$
$\Lambda_b^0 \to p\pi^-K^+K^-$

$\Xi_b^- \to pK^-K^-$

Detector and analysis strategies



Int. J. Mod. Phys. A 30 1530022 (2015)

- Selection of displaced secondary vertices of charged hadrons in the VELO.
- Multivariate classifiers to reject combinatorial background.
- Particle identification of charged hadrons $\mathrm{K}^{\pm}, \pi^{\pm}, \mathrm{p}$ using RICH detector information.
- Photon and neutral pion reconstruction in the ECAL.
- Flavour tagging for neutral *b*-hadrons: based on particle charges, same-side and opposite-side.
- Amplitude analyses of multibody decays to explore the underlying dynamics.

Observation of CP violation in $B_{(s)}^0 \rightarrow h^+h^-$

arXiv:2012.05319
JHEP 03 (2021) 075

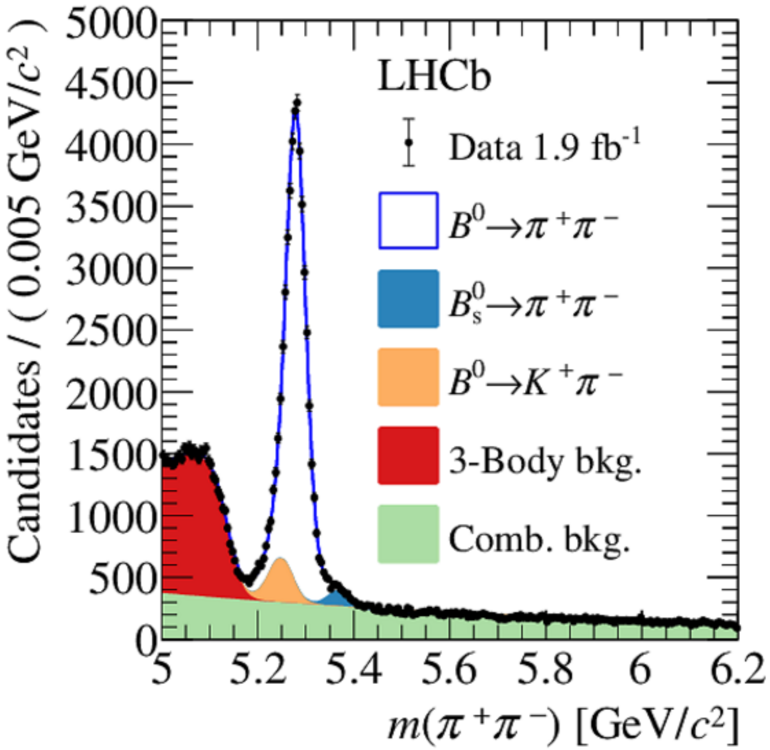
1.9 fb^{-1} Run II data

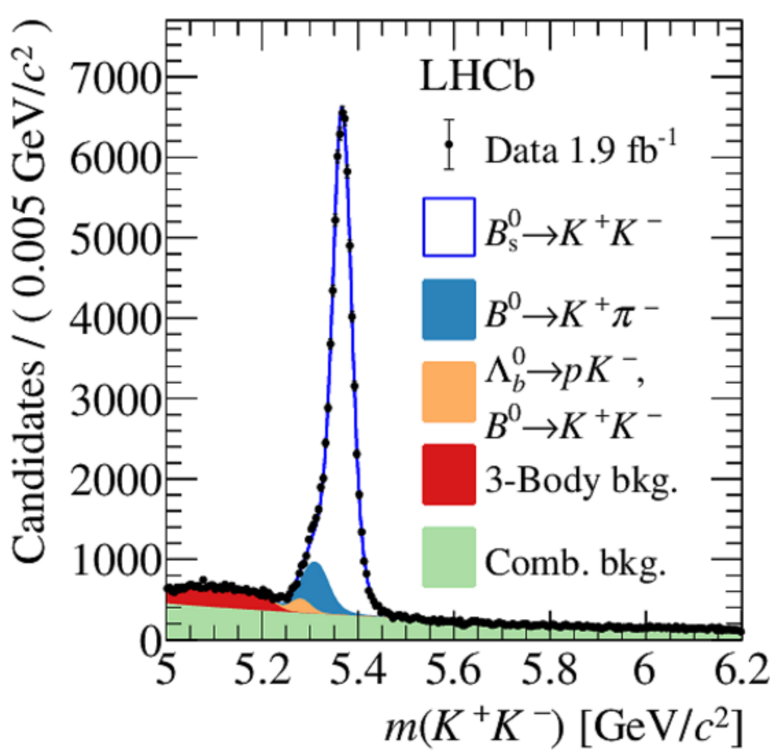
CP violation in $B_{(s)}^0 \to h^+h^-$

arXiv:2012.05319
JHEP 03 (2021) 075

- Updated measurement with partial Run 2 dataset and combination of results.
- Simultaneous fit to invariant mass, decay-time, flavour tagging decision and mistag probability for the three different final states: $K^{\pm}\pi^{\mp}$, $\pi^+\pi^-$ and K^+K^-.
- Probing direct and mixing-induced CP violation: $$A_f(t) = \frac{C_f \cos(\Delta m_s\, t) - S_f \sin(\Delta m_s\, t)}{\cosh(\Delta\Gamma\, t/2) + A_f^{\Delta\Gamma} \sinh(\Delta\Gamma\, t/2)}$$
- Time-dependent CP asymmetry measurement in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays.

45620
signal events



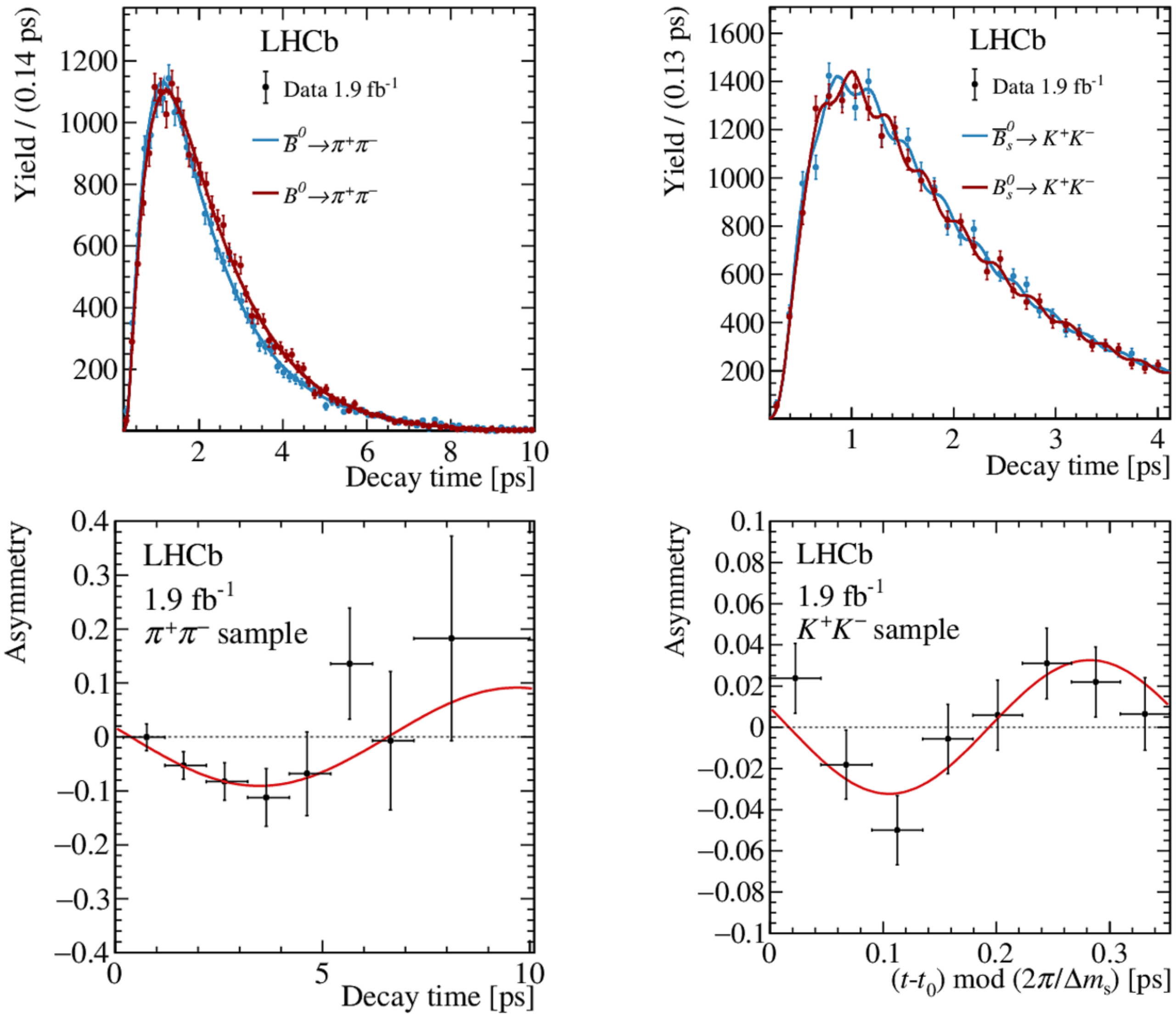


70310
signal events

Observation of CP violation in $B_{(s)}^0 \to h^+h^-$

arXiv:2012.05319
JHEP 03 (2021) 075

- Time-dependent CP asymmetry measurement in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays.



Fit results:

$$
\begin{aligned}
C_{\pi\pi} &= -0.311 \pm 0.045 \pm 0.015,\\
S_{\pi\pi} &= -0.706 \pm 0.042 \pm 0.013,\\
C_{KK} &= 0.164 \pm 0.034 \pm 0.014,\\
S_{KK} &= 0.123 \pm 0.034 \pm 0.015,\\
\mathcal{A}^{\Delta\Gamma}_{KK} &= -0.83 \pm 0.05 \pm 0.09,
\end{aligned}
$$

Most precise results from a single experiment.

First observation of time-dependent CP violation in B^0_s decays with 6.5σ.

Observation of CP violation in $B_{(s)}^0 \to K^+\pi^-$

arXiv:2012.05319
JHEP 03 (2021) 075

- Time-integrated CP asymmetry measurement in $B^0 \to K^+\pi^-$ and $B^0_s \to K^-\pi^+$ decays.

$$A_{CP} = \frac{\left|\overline{A}_{\overline{f}}\right|^2 - |A_f|^2}{\left|\overline{A}_{\overline{f}}\right|^2 + |A_f|^2}$$

- Results confirm CP violation observations:

$$A_{CP}^{B^0} = -0.0824 \pm 0.0033 \pm 0.0033,$$
$$A_{CP}^{B_s^0} = \quad 0.236 \pm 0.013 \pm 0.011.$$

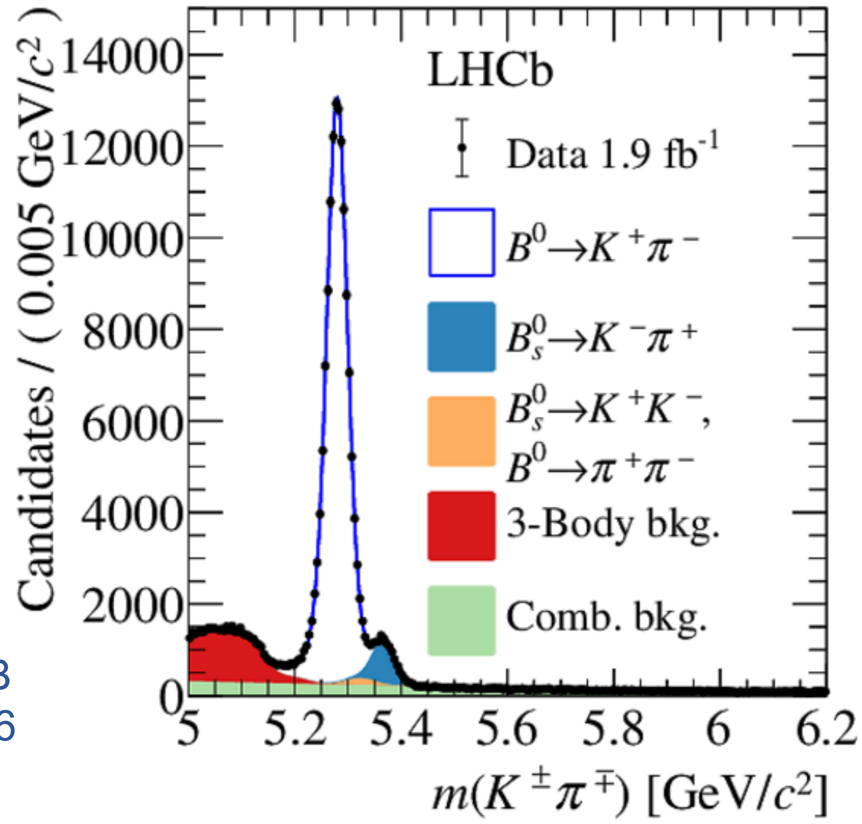
- A proposed test of the SM using the relation:

$$\Delta \equiv \frac{A_{CP}^{B^0}}{A_{CP}^{B_s^0}} + \frac{\mathcal{B}\left(B_s^0 \to K^-\pi^+\right)}{\mathcal{B}\left(B^0 \to K^+\pi^-\right)} \frac{\Gamma_s}{\Gamma_d} = 0$$

H.J.Lipkin, PLB 621 (2005) 126

- Agrees with 0 within 2σ:

$$\Delta = -0.085 \pm 0.025 \pm 0.035$$



140340 signal events

CP violation in $B^+ \to K^+\pi^0$

arXiv:2012.12789
Phys. Rev. Lett. 126 (2021) 091802

5.4 fb^{-1} Run II data

The $K\pi$ puzzle

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

- The family of 4 two-body B decays to a kaon and a pion can probe new physics.
- Studied extensively at B-factories, Tevatron and LHCb.

- Isospin symmetry in the SM imposes relations on amplitudes and asymmetries:
  - Asymmetries should be equal for $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$, however
  - Measurements so far are nonzero at 5.5σ.

$$A_{CP}(B^0 \to K^+\pi^-) = -0.84 \pm 0.004, \qquad A_{CP}(B^+ \to K^+\pi^0) = 0.040 \pm 0.021$$

HFLAV 2018

  - A more accurate sum rule is proposed:

$$A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

M. Gronau, PLB 627 (2005) 82

  - It predicts $A_{CP}(B^0 \to K^0\pi^0) = -0.150 \pm 0.032$, but measurement is compatible with zero.

CP violation in $B^+ \to K^+\pi^0$

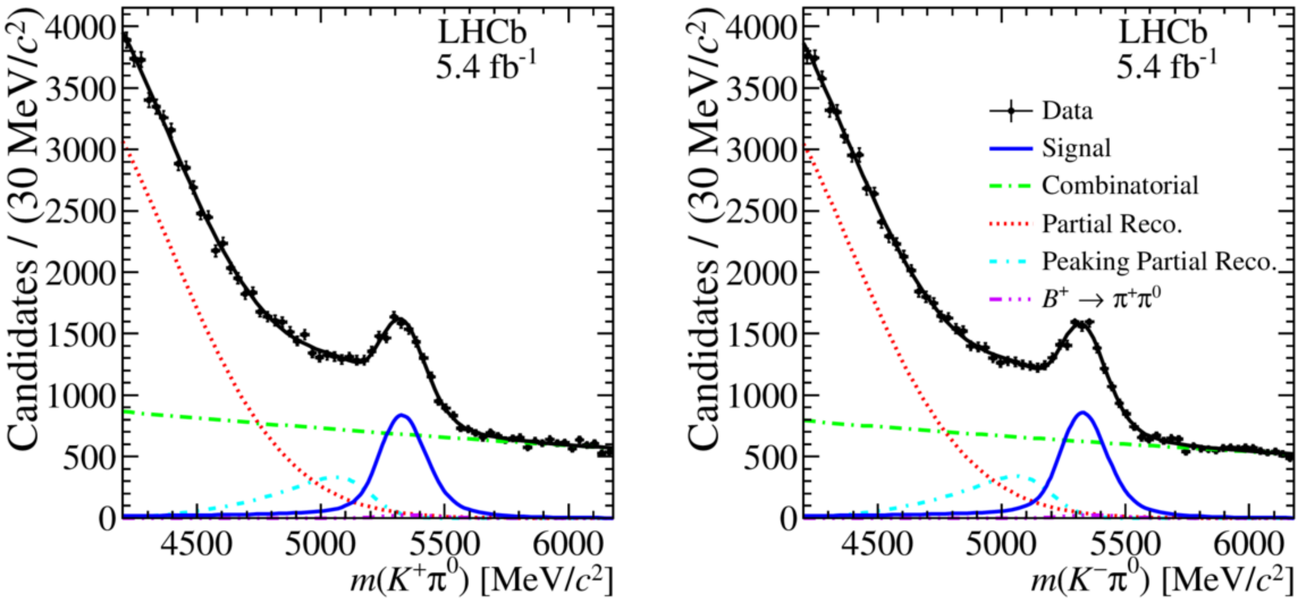
arXiv:2012.12789
Phys. Rev. Lett. 126 (2021) 091802

- First analysis of a one-track decay at a hadron collider.
- Measurement of the direct CP asymmetry: $A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003$

Together with the result

$$A_{CP}(B^0 \to K^+\pi^-) = -0.084 \pm 0.004$$

the updated difference is more than 8σ away from zero:



16680 signal events

$$\Delta A_{CP}(K\pi) = A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.115 \pm 0.014$$

The Kπ puzzle is confirmed and substantially enhanced!

Branching Fractions and CP violation in $B^+ \to h^+h^-h^+$

Phys. Rev. D 102 (2020) 112010
Phys. Rev. D 90 (2014) 112004
Phys. Rev. Lett. 123 (2019) 231802
Phys. Rev. Lett. 124 (2020) 031801
Phys. Rev. D 101 (2020) 012006

3 fb^{-1} Run I data

Branching fractions of $B^+ \to h^+h^-h^+$

arXiv:2010.11802
Phys. Rev. D 102 (2020) 112010

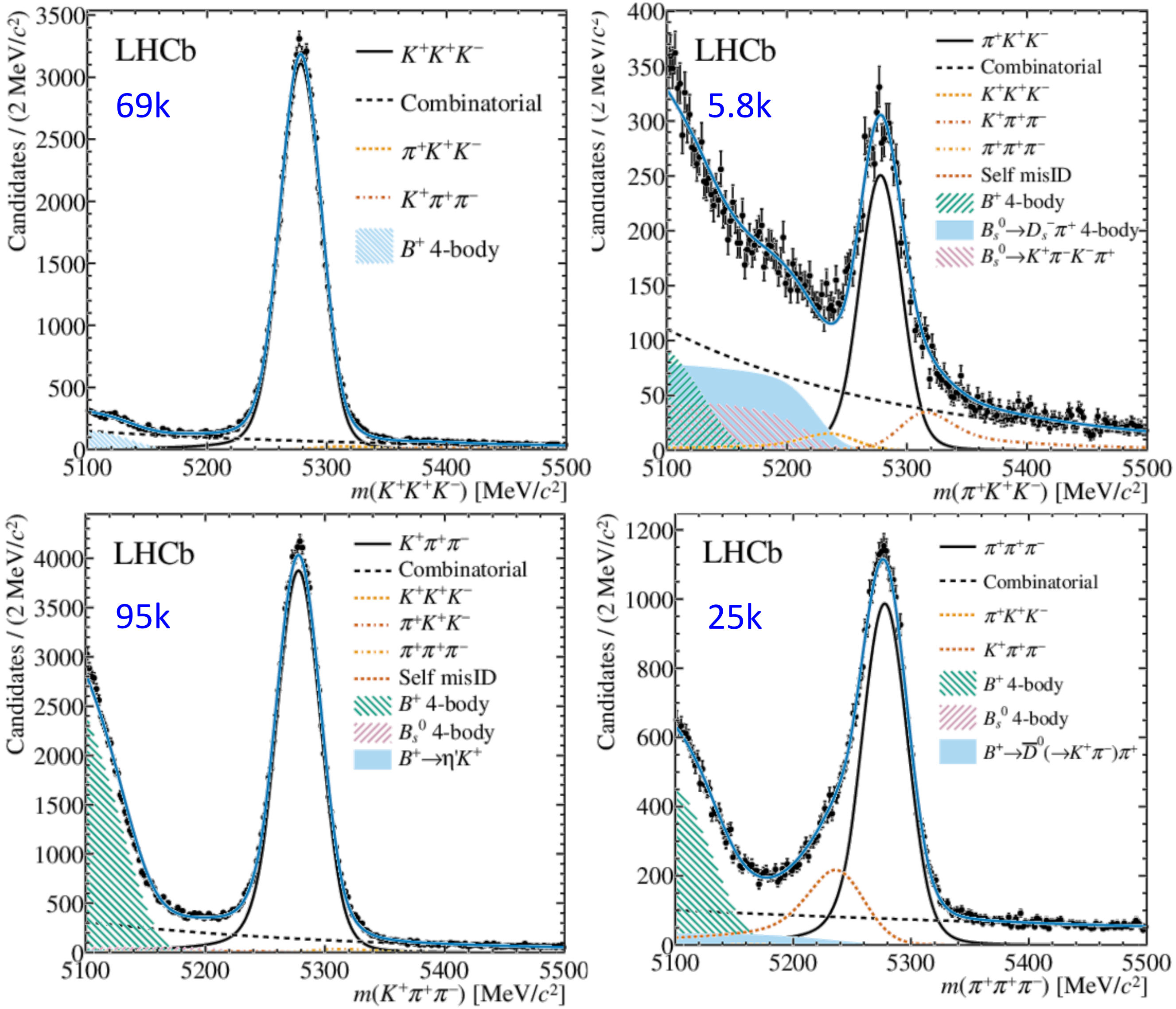
- Three-body B decays are of interest for CP violation and Dalitz plot analyses.
- Measurement of the branching fractions with Run I data.
- $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$, $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$, $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ relative to $B^{\pm} \to K^{\pm}K^{+}K^{-}$ decays.

$$\mathcal{B}(B^+ \to \pi^+ K^+ K^-)/\mathcal{B}(B^+ \to K^+ K^+ K^-) = 0.151 \pm 0.004\,(\text{stat}) \pm 0.008\,(\text{syst}),$$

$$\mathcal{B}(B^+ \to K^+ \pi^+ \pi^-)/\mathcal{B}(B^+ \to K^+ K^+ K^-) = 1.703 \pm 0.011\,(\text{stat}) \pm 0.022\,(\text{syst}),$$

$$\mathcal{B}(B^+ \to \pi^+ \pi^+ \pi^-)/\mathcal{B}(B^+ \to K^+ K^+ K^-) = 0.488 \pm 0.005\,(\text{stat}) \pm 0.009\,(\text{syst}).$$

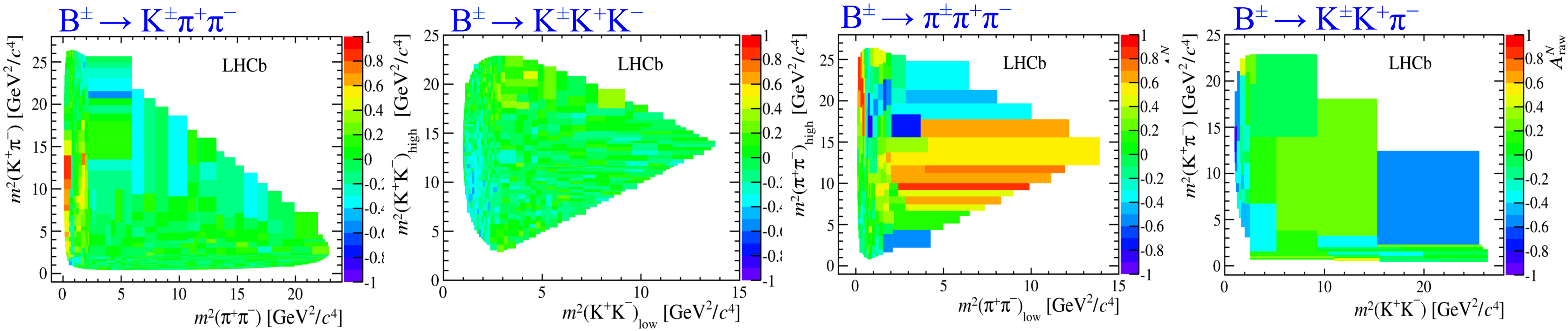
Significant improvement in the precision.



CP violation in $B^+ \to h^+h^-h^+$

arXiv:1408.5373
Phys. Rev. D 90 (2014) 112004

- Three-body B decays can proceed through a number of intermediate two-body resonances.
- Model-independent analysis of Run I data.
- Large integrated CP asymmetries and a rich pattern of local CP asymmetries.
- Motivation for further amplitude analyses to study the underlying dynamics.



$$A_{CP}(B^\pm \to K^\pm\pi^+\pi^-) = +0.025 \pm 0.004 \pm 0.004 \pm 0.007 \quad 2.8\sigma$$

$$A_{CP}(B^\pm \to K^\pm K^+K^-) = -0.036 \pm 0.004 \pm 0.002 \pm 0.007 \quad 4.3\sigma$$

$$A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) = +0.058 \pm 0.008 \pm 0.009 \pm 0.007 \quad 4.2\sigma$$

$$A_{CP}(B^\pm \to \pi^\pm K^+K^-) = -0.123 \pm 0.017 \pm 0.012 \pm 0.007 \quad 5.6\sigma$$

Integrated asymmetries

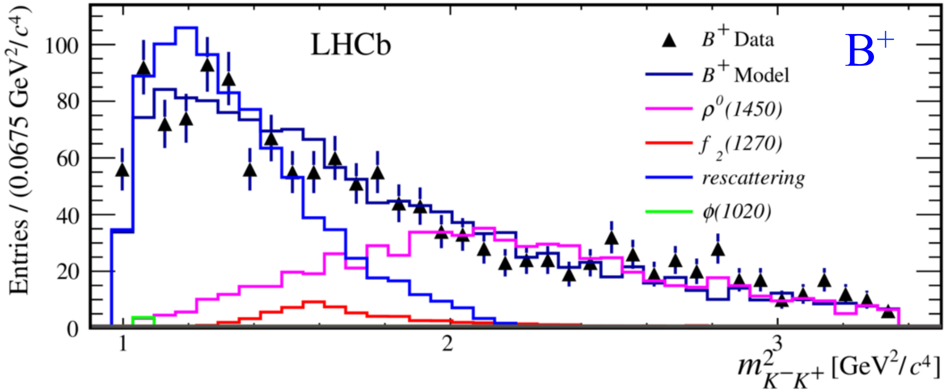
CP violation in $B^+ \to \pi^+ K^+ K^-$

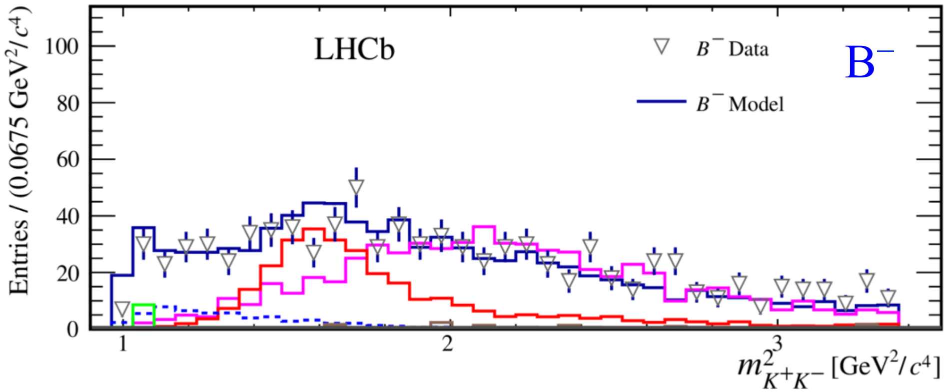
arXiv:1905.09244
Phys. Rev. Lett. 123 (2019) 231802

- First amplitude analysis of $B^+ \to \pi^+ K^+ K^-$ decays
- Isobar model.
- Dedicated amplitudes for rescattering and single pole form-factor.

$[1 + m^2(\pi^\pm K^\mp)/\Lambda^2]^{-1}$ Phys. Rev. D 71 (2005) 074016
Phys. Rev. D 92 (2015) 054010

	Contribution	Fit Fraction(%)	A_{CP}(%)
$K^+\pi^-$	$K^*(892)^0$	$7.5 \pm 0.6 \pm 0.5$	$+12.3 \pm 8.7 \pm 4.5$
	$K_0^*(1430)^0$	$4.5 \pm 0.7 \pm 1.2$	$+10.4 \pm 14.9 \pm 8.8$
	Single pole	$32.3 \pm 1.5 \pm 4.1$	$-10.7 \pm 5.3 \pm 3.5$
K^+K^-	$\rho(1450)^0$	$30.7 \pm 1.2 \pm 0.9$	$-10.9 \pm 4.4 \pm 2.4$
	$f_2(1270)$	$7.5 \pm 0.8 \pm 0.7$	$+26.7 \pm 10.2 \pm 4.8$
	Rescattering	$16.4 \pm 0.8 \pm 1.0$	$-66.4 \pm 3.8 \pm 1.9$
	$\phi(1020)$	$0.3 \pm 0.1 \pm 0.1$	$+9.8 \pm 43.6 \pm 26.6$





Dominant contributions in red.

$KK \leftrightarrow \pi\pi$ rescattering:
largest ever CP asymmetry for a single amplitude ~ −66%.

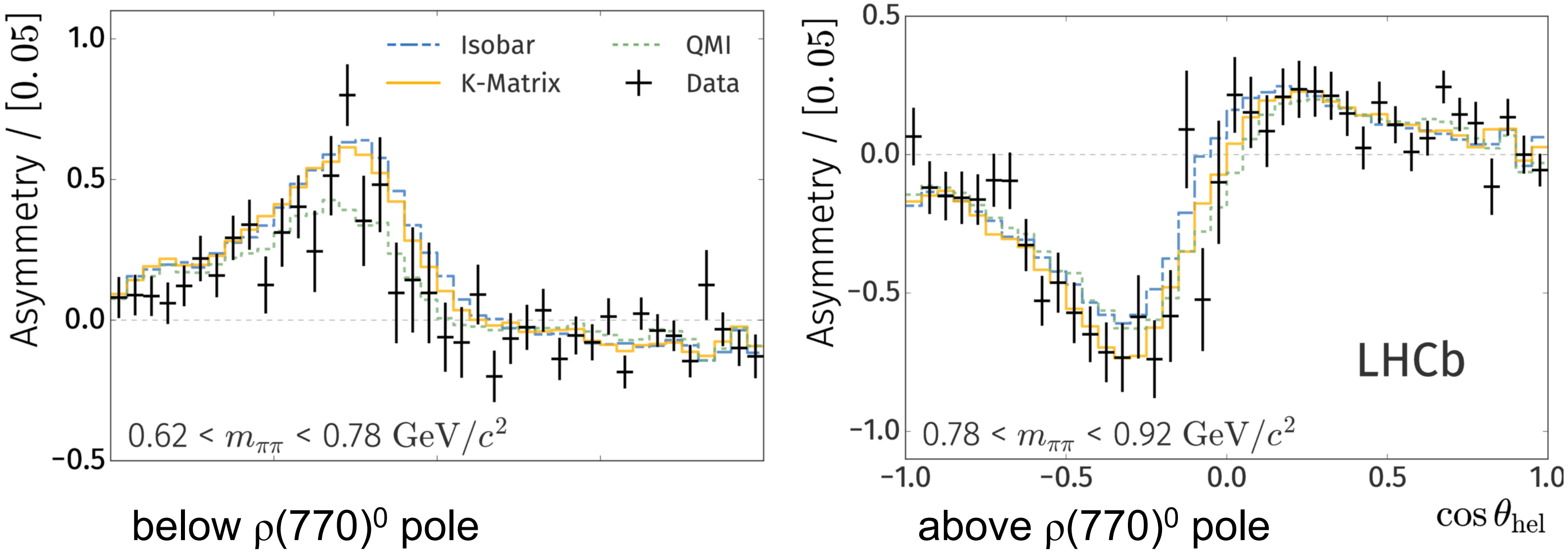
CP violation in $B^+ \to \pi^+\pi^+\pi^-$

Phys. Rev. Lett. 124 (2020) 031801
Phys. Rev. D 101 (2020) 012006

- Observation of several sources of CP violation in $B^+ \to \pi^+\pi^+\pi^-$ decays amplitude analysis.
- Three different S-wave models: isobar (sum of a σ-pole and $KK \leftrightarrow \pi\pi$ rescattering term); K-matrix (parameters from scattering data) and QMI formalism (in bins of $\pi\pi$ mass).
- Large CP asymmetries associated with scalar S-wave and tensor $f_2(1270)$.

$$A_{CP}(\text{S-wave}) = +0.144 \pm 0.018 \pm 0.021, \qquad A_{CP}(f_2(1270)) = +0.468 \pm 0.061 \pm 0.047$$

- Interference between P-wave $\rho(770)^0$ and S-wave with change of sign: CPV with >25σ.
- First observation of CP violation in the interference between two quasi-two-body decays.



below $\rho(770)^0$ pole — above $\rho(770)^0$ pole

Search for CP violation in $\Xi_b^- \to pK^-K^-$

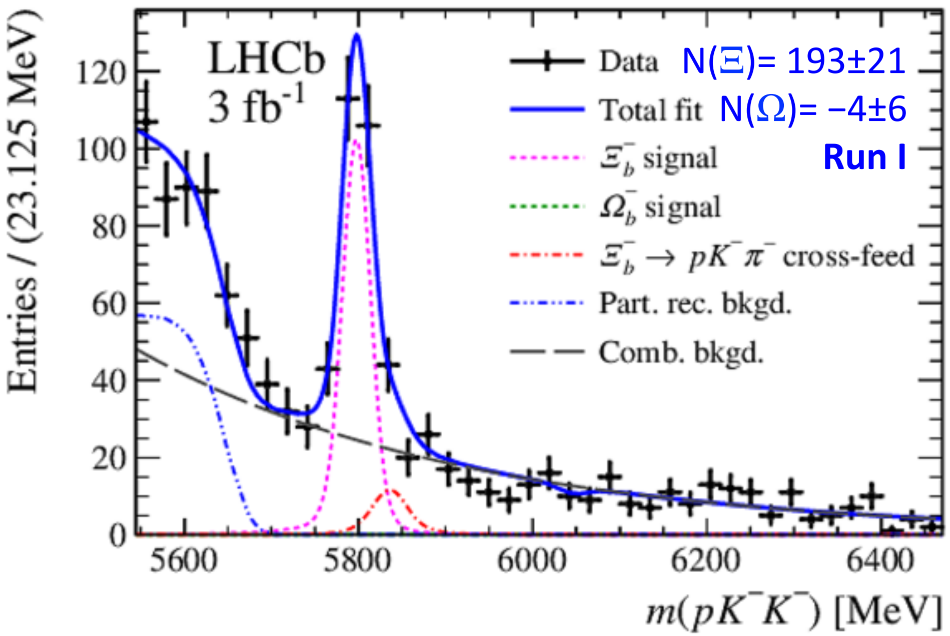
arXiv:2104.15074
Submitted to Phys. Rev. D

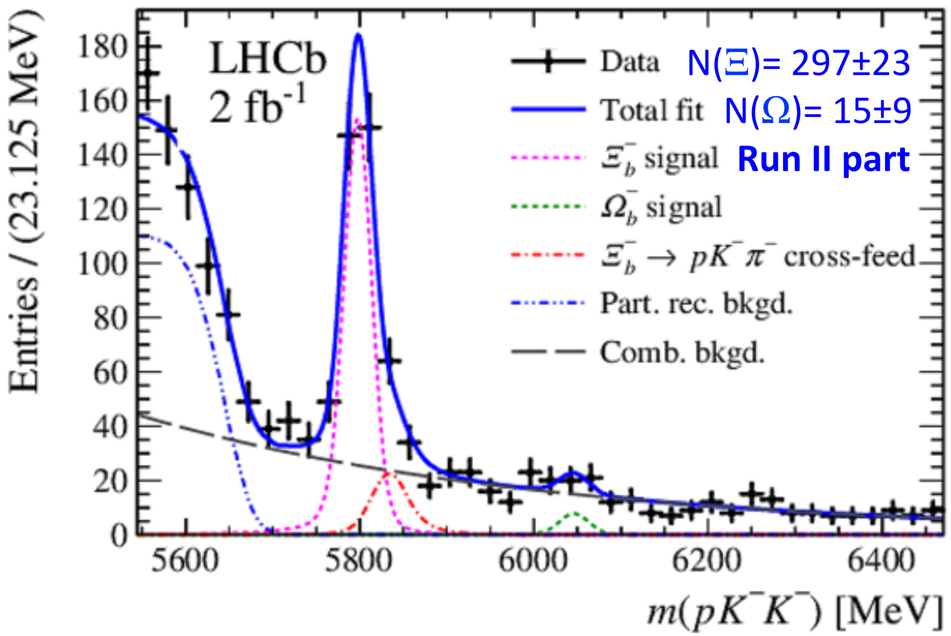
5 fb^{-1} Run I and Run II data

Search for CPV in $\Xi_b^- \to pK^-K^-$ decays

arXiv:2104.15074

- CP violation should also be present in *b*-baryon decays, special interest in 3-body.
- Run I and partial Run 2 datasets analysed separately.





- Also search for the previously unobserved $\Omega_b^- \to pK^-K^-$ decay.
- Upper limit on the ratio of fragmentation and branching fractions:

$$\mathcal{R} \equiv \frac{f_{\Omega_b^-}}{f_{\Xi_b^-}} \times \frac{\mathcal{B}(\Omega_b^- \to pK^-K^-)}{\mathcal{B}(\Xi_b^- \to pK^-K^-)} < 62\ (71) \times 10^{-3}$$

Search for CPV in $\Xi_b^- \rightarrow pK^-K^-$ decays

arXiv:2104.15074

- First amplitude analysis of any *b*-baryon allowing for CP violation effects.
- Studied many possible pK^- resonances, found 6 contributions.
- Measured fit fractions, interference fit fractions and CP-violating asymmetry:

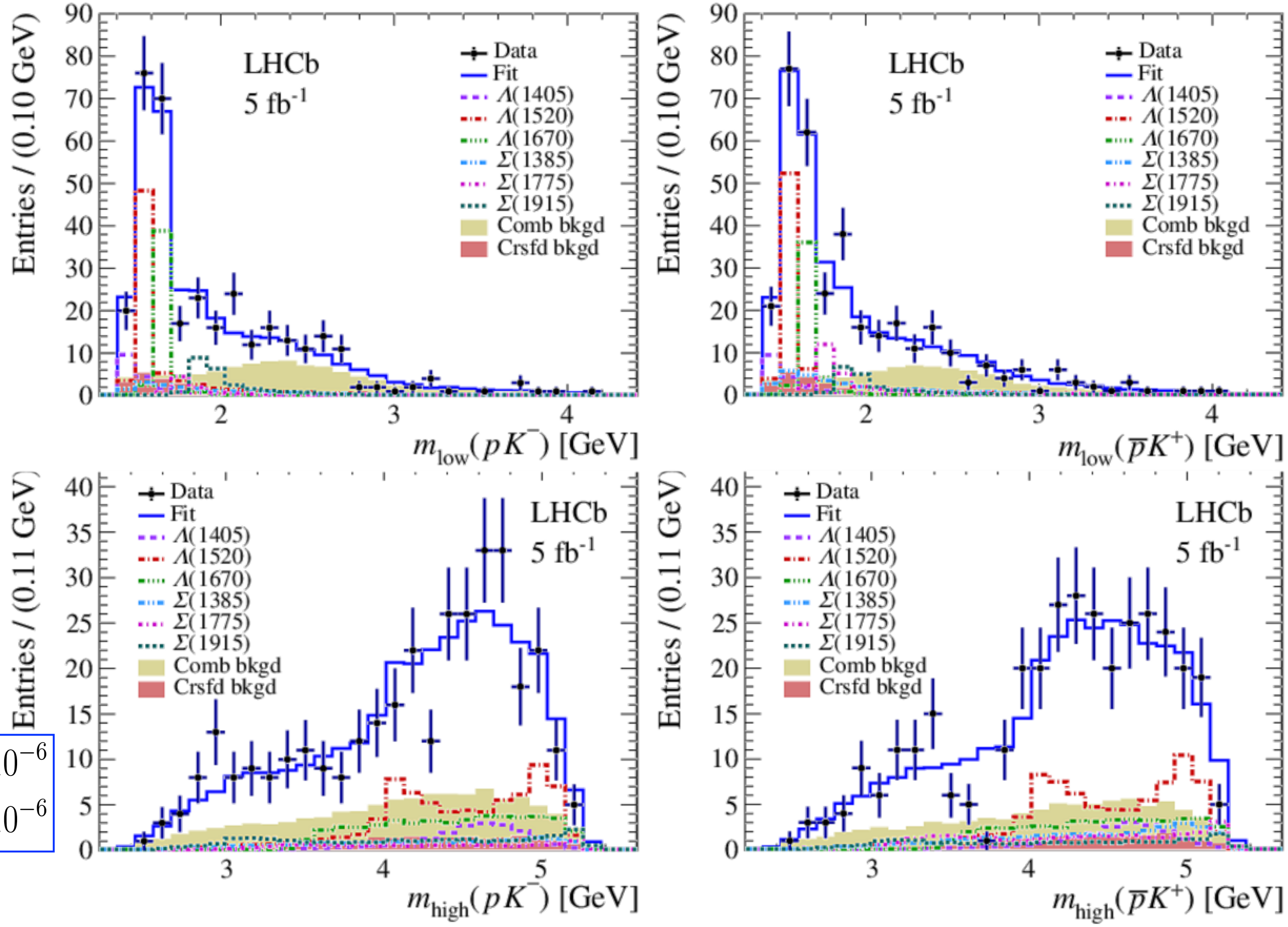
Component	A^{CP} (10^{-2})
$\Sigma(1385)$	-27 ± 34 (stat) ± 73 (syst)
$\Lambda(1405)$	-1 ± 24 (stat) ± 32 (syst)
$\Lambda(1520)$	-5 ± 9 (stat) ± 8 (syst)
$\Lambda(1670)$	3 ± 14 (stat) ± 10 (syst)
$\Sigma(1775)$	-47 ± 26 (stat) ± 14 (syst)
$\Sigma(1915)$	11 ± 26 (stat) ± 22 (syst)

- No significant CP asymmetry.
- Measurement of branching fractions of intermediate resonances.

$$\mathcal{B}(\Xi_b^- \rightarrow RK^-) = \mathcal{B}(\Xi_b^- \rightarrow pK^-K^-) \times \mathcal{F}_i \,.$$

$$\mathcal{B}\left(\Xi_b^- \rightarrow \Lambda(1520)K^-\right) = (0.76 \pm 0.09 \pm 0.08 \pm 0.30) \times 10^{-6}$$
$$\mathcal{B}\left(\Xi_b^- \rightarrow \Lambda(1670)K^-\right) = (0.45 \pm 0.07 \pm 0.13 \pm 0.18) \times 10^{-6}$$

significance >5σ



Search for CP violation and observation of P violation in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$

arXiv:1912.10741
Phys. Rev. D 102 (2020) 051101

6.6 fb^{-1} Run I and Run II data

Search for CP violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

arXiv:1912.10741
Phys. Rev. D 102 (2020) 051101

- Previously, evidence of CP violation (3.3σ) in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ from Run I, and first evidence in any baryon decay.
  Nat. Phys. 13, 391 (2017)
- Larger current data sample, optimised selection.
- Search for CP and P violation using two methods:
  1) Triple Product Asymmetries.
  2) Unbinned energy test method.
- Sensitive to global (1) and local (1,2) asymmetries.

Scalar triple products

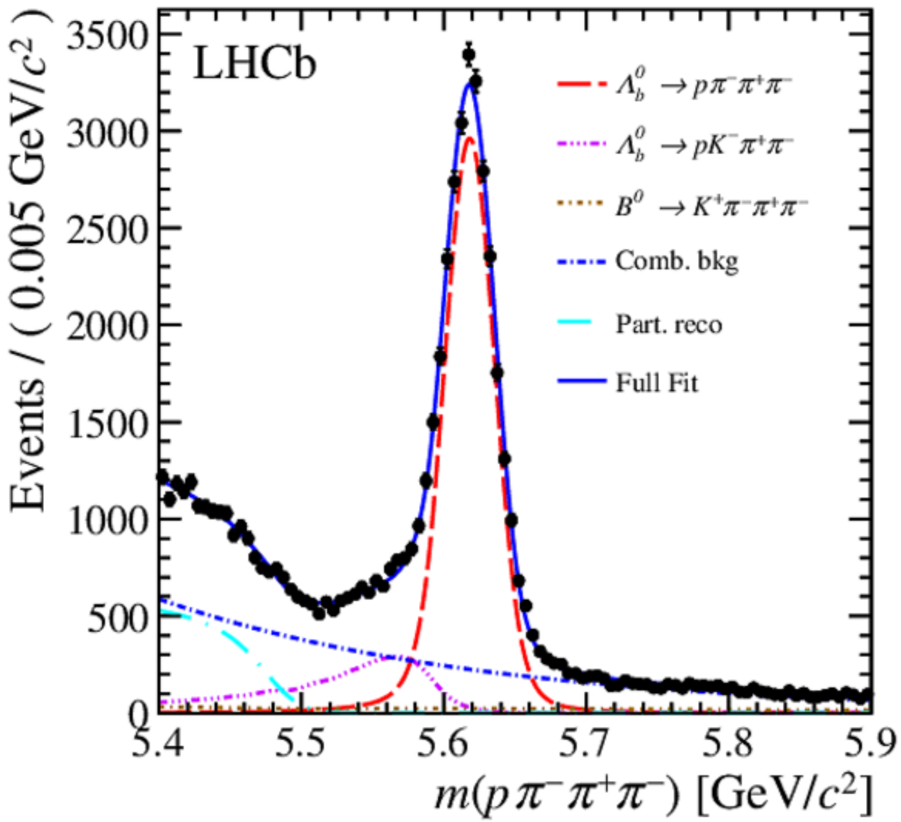
$$C_{\hat{T}} \equiv \vec{p}_p \cdot \left(\vec{p}_{\pi^-_{\text{fast}}} \times \vec{p}_{\pi^+}\right)$$

$$\overline{C}_{\hat{T}} \equiv \vec{p}_{\overline{p}} \cdot \left(\vec{p}_{\pi^+_{\text{fast}}} \times \vec{p}_{\pi^-}\right)$$

T-odd asymmetries

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

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



N(Λ)= 27600 signal events

CP-violating asymmetry
$$a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \overline{A}_{\hat{T}})$$

P-violating asymmetry
$$a_{P}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} + \overline{A}_{\hat{T}})$$

Observation of P violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

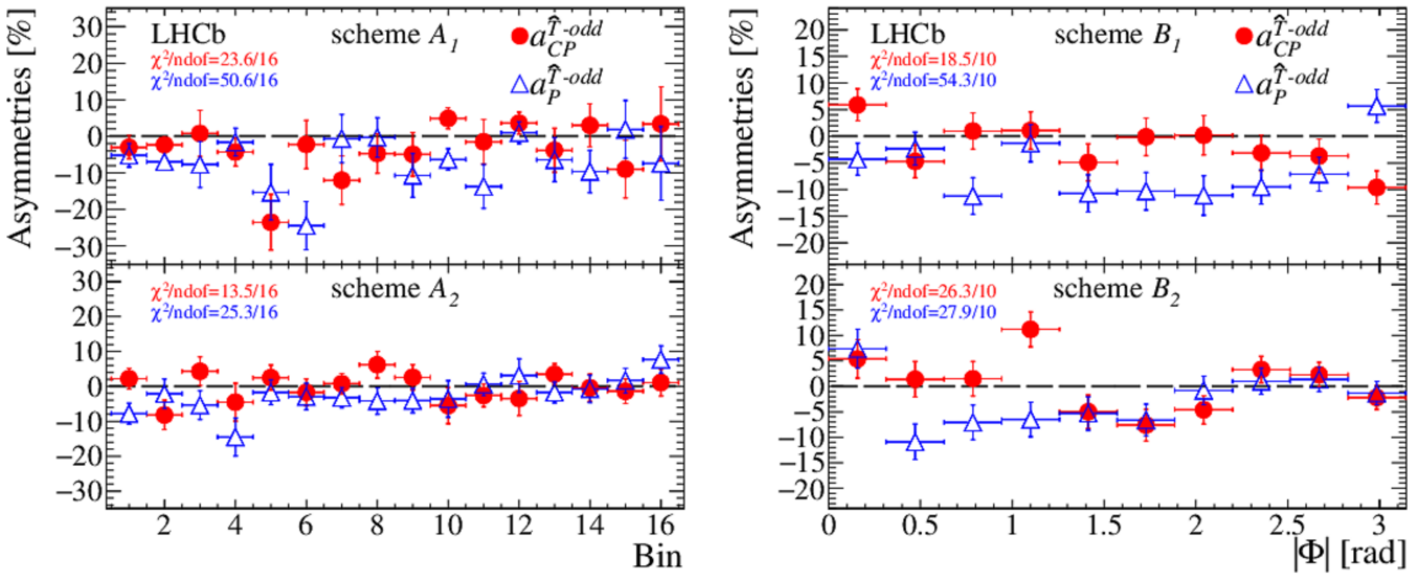
arXiv:1912.10741
Phys. Rev. D 102 (2020) 051101

- Triple product asymmetries integrated in phase space:
- Observation of Parity violation at 5.5σ.
- CP conserved at 2.9σ.

$$a_P^{\widehat{T}\text{-odd}} = (-4.0 \pm 0.7 \pm 0.2)\%$$

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

- Local asymmetries in two binning schemes of phase space:



Indication of local large P-violation contribution from $\Lambda_b^0 \to pa_1(1260)^-$ decay at 5.5σ.

- The energy test method also confirms local P violation (5.3σ) and CP conservation (3.0σ).

Conclusions

- Charmless *b*-meson and *b*-baryon decays provide a fertile environment for studies of CP violation, hadronic effects and searches for new physics.
- LHCb continues to produce fantastic measurements of these decay channels:
  - First observation of time-dependent CP violation in B_s^0 decays.
  - Enhancement of the Kπ puzzle.
  - Large asymmetries in three-body B^+ decays.
  - New searches in the *b*-baryon sector.
- More analyses of Run II data are underway.
- The upgraded LHCb detector will bring more new exciting results soon.