Charmless b-hadron decays at LHCb

- **Focus on 3/4-body CPV results**
- **A few rare decay results**
- **Selective**

⇒ Publications

Jike Wang (On behalf of the LHCb collaboration)

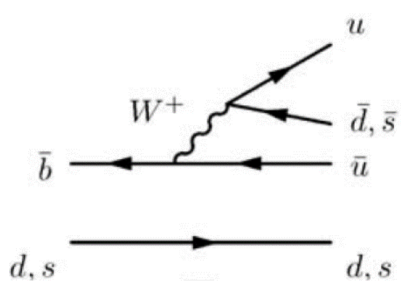
Wuhan University

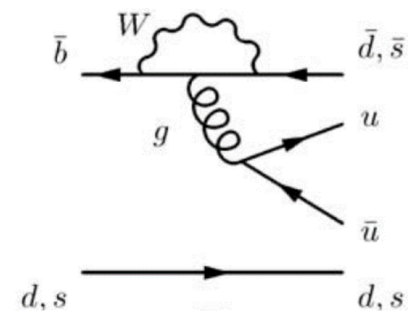
Charmless hadronic decays

- Charmless hadronic decays are suppressed in the SM
- They proceed e.g. through b → u tree and b → s,d loop (penguin) transitions.
- New Physics could contribute to penguin loop as additional sources of CPV

- **Two-body charmless b-meson decays:**

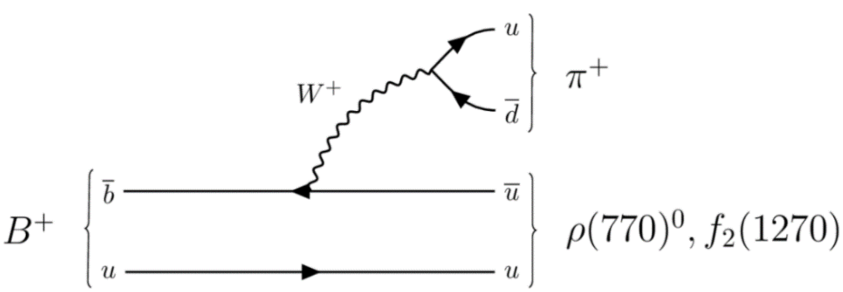
  ⇒ Large CPV observed.

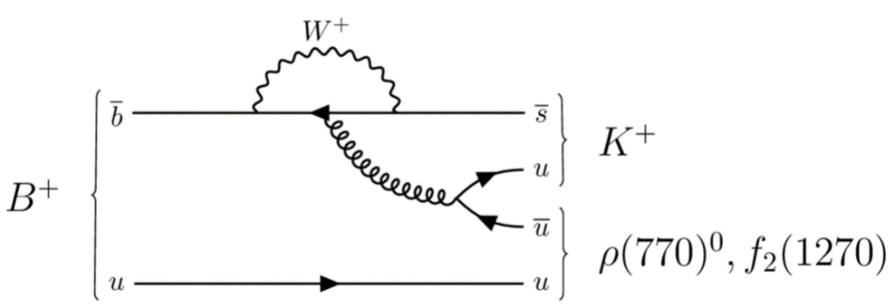




- **Three/four-body charmless b-hadron decays:**

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





Direct CPV in $B^{\pm} \to h^{\pm}h'^{+}h'^{-}$ and $B^{\pm} \to h^{\pm}h^{+}h^{-}$

- The role of short/long distance contributions to the generation of the strong-phase differences:

  ⇒ is long-standing debate

  ⇒ for direct *CPV*, and three-body decays offer a way of answering

- With 5.9 fb^{-1} 13 TeV pp collision data with the LHCb 2015-2018

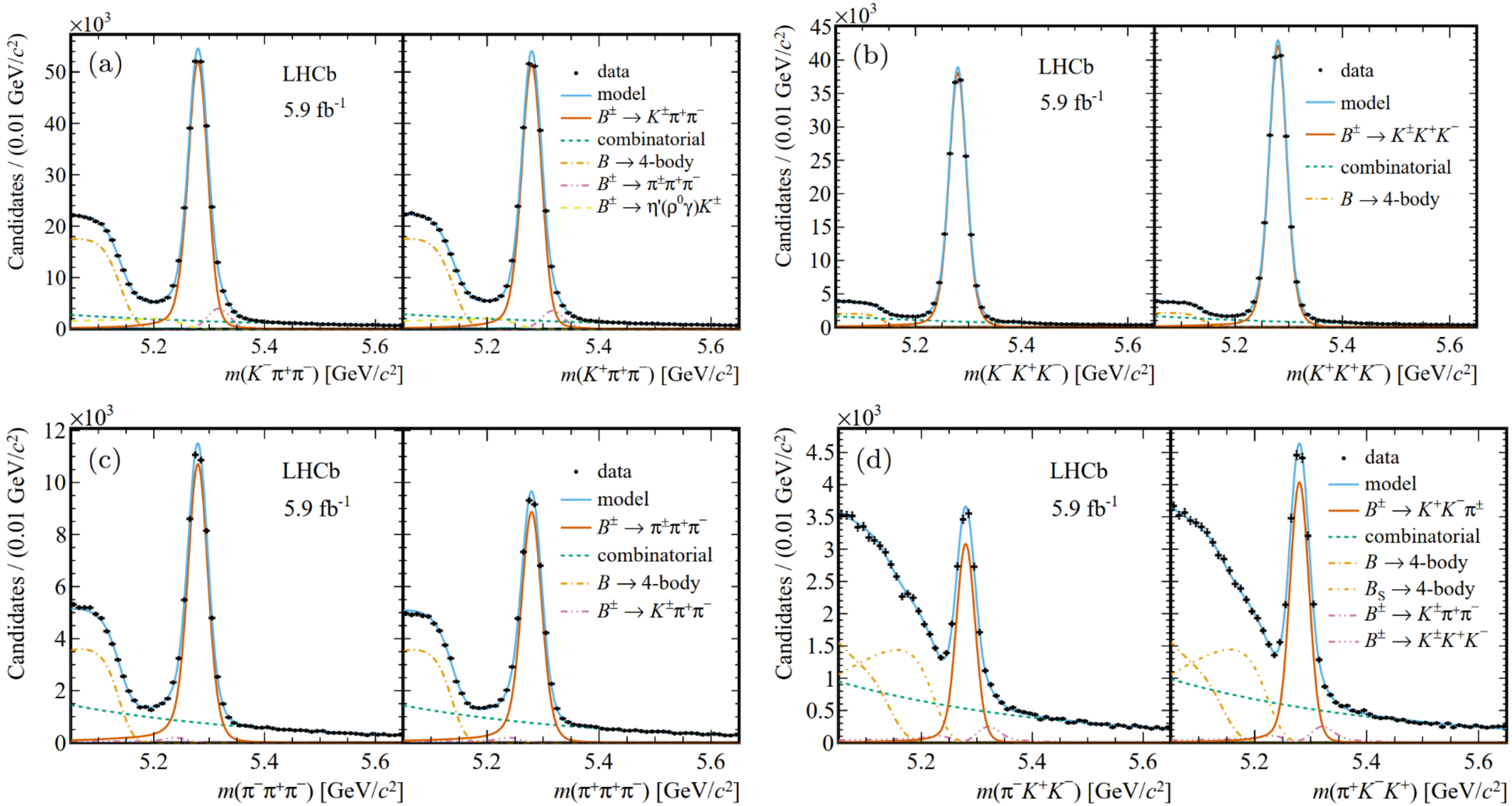
  ⇒ previously observed CP asymmetry in $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ decays is confirmed,

  ⇒ CP asymmetries are observed with a significance of $> 5\sigma$ in the $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to K^{\pm}K^{+}K^{-}$ decays,

  ⇒ while the CP asymmetry of $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ is confirmed to be compatible with 0

arXiv:2206.07622

Direct CPV in $B^{\pm} \to h^{\pm}h'^{+}h'^{-}$ and $B^{\pm} \to h^{\pm}h^{+}h^{-}$



$A_{CP}(\boldsymbol{B}^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = +0.011 \pm 0.002 \pm 0.003 \pm 0.003 \Rightarrow$ Consistent with *CP* conservation

$A_{CP}(\boldsymbol{B}^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.037 \pm 0.002 \pm 0.002 \pm 0.003$ 8.5σ

$A_{CP}(\boldsymbol{B}^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +0.080 \pm 0.004 \pm 0.003 \pm 0.003$ 14.1σ

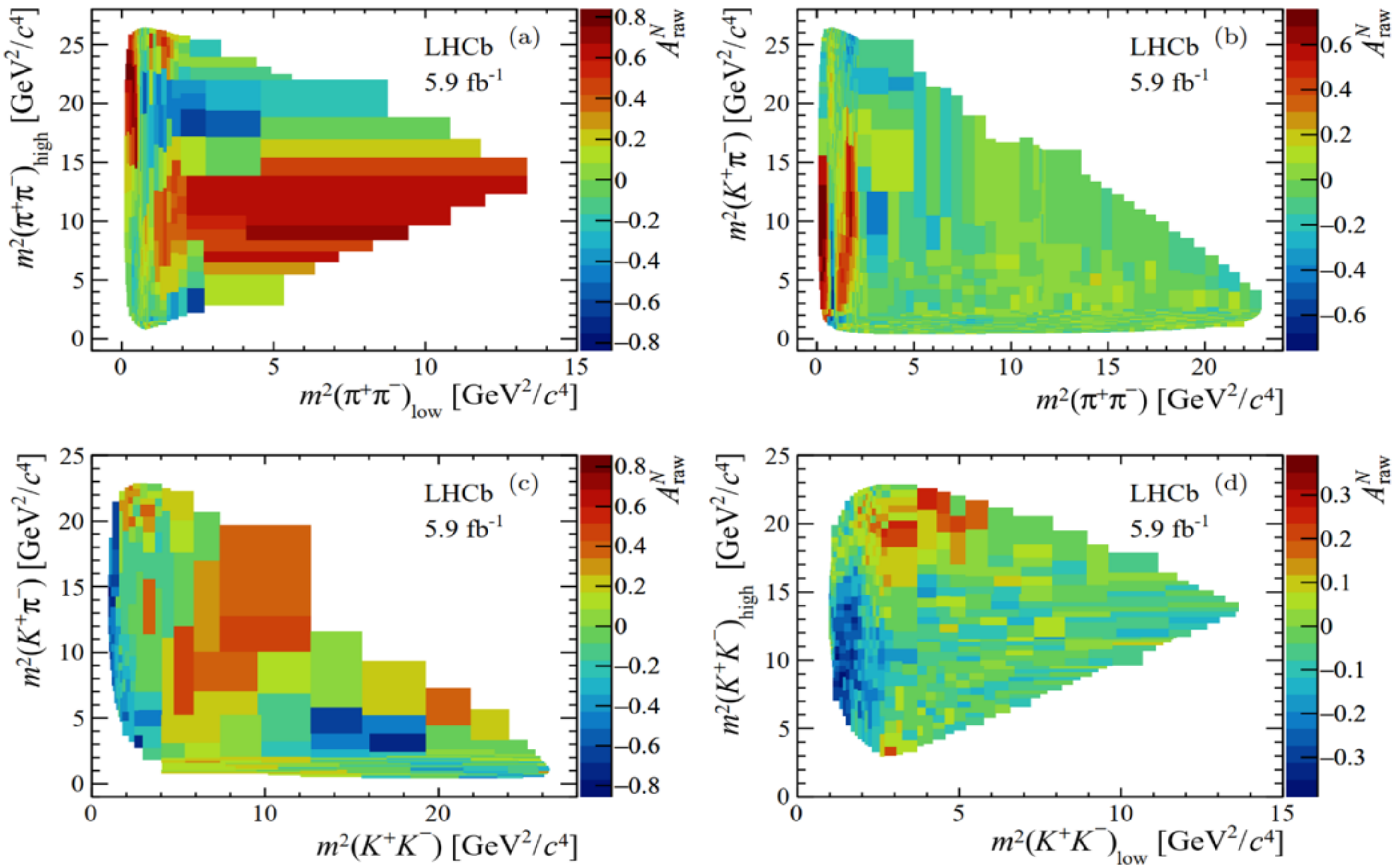
$A_{CP}(\boldsymbol{B}^{\pm} \to \pi^{\pm}K^{+}K^{-}) = -0.114 \pm 0.007 \pm 0.003 \pm 0.003$ 13.6σ

} **first observation**

arXiv:2206.07622

Direct CPV in $B^{\pm} \to h^{\pm}h'^{+}h'^{-}$ and $B^{\pm} \to h^{\pm}h^{+}h^{-}$

- Three-body decays can proceed through a number of intermediate two-body resonances.
- Large integrated CP asymmetries and a rich pattern of local CP asymmetries.



- Need further amplitude analyses to study the underlying dynamics. arXiv:2206.07622

Search for Direct CPV in $B^{\pm} \to PV$

- Theoretical developments using different approaches have resulted in many predictions for CP asymmetries.

  ⇒ Many of these are focused on charmless two-body and quasitwo-body B-meson decays, in particular those to two pseudoscalar mesons ($\boldsymbol{B \to PP}$) and to a pseudoscalar and a vector meson ($\boldsymbol{B \to PV}$)

- **5 different $B \to PV$ decays from 4 final states:** $\boldsymbol{B^{\pm}} \to K^{\pm}\pi^{+}\pi^{-}$, $\boldsymbol{B^{\pm}} \to K^{\pm}K^{+}K^{-}$, $\boldsymbol{B^{\pm}} \to \pi^{\pm}\pi^{+}\pi^{-}$, $\boldsymbol{B^{\pm}} \to \pi^{\pm}K^{+}K^{-}$

  ⇒ $\boldsymbol{B^{\pm}} \to \rho(770)^{0}K^{\pm}$, $\boldsymbol{B^{\pm}} \to \rho(770)^{0}\pi^{\pm}$, $\boldsymbol{B^{\pm}} \to K^{*}(892)^{0}\pi^{\pm}$, $\boldsymbol{B^{\pm}} \to K^{*}(892)^{0}K^{\pm}$, $\boldsymbol{B^{\pm}} \to \phi(1020)K^{\pm}$

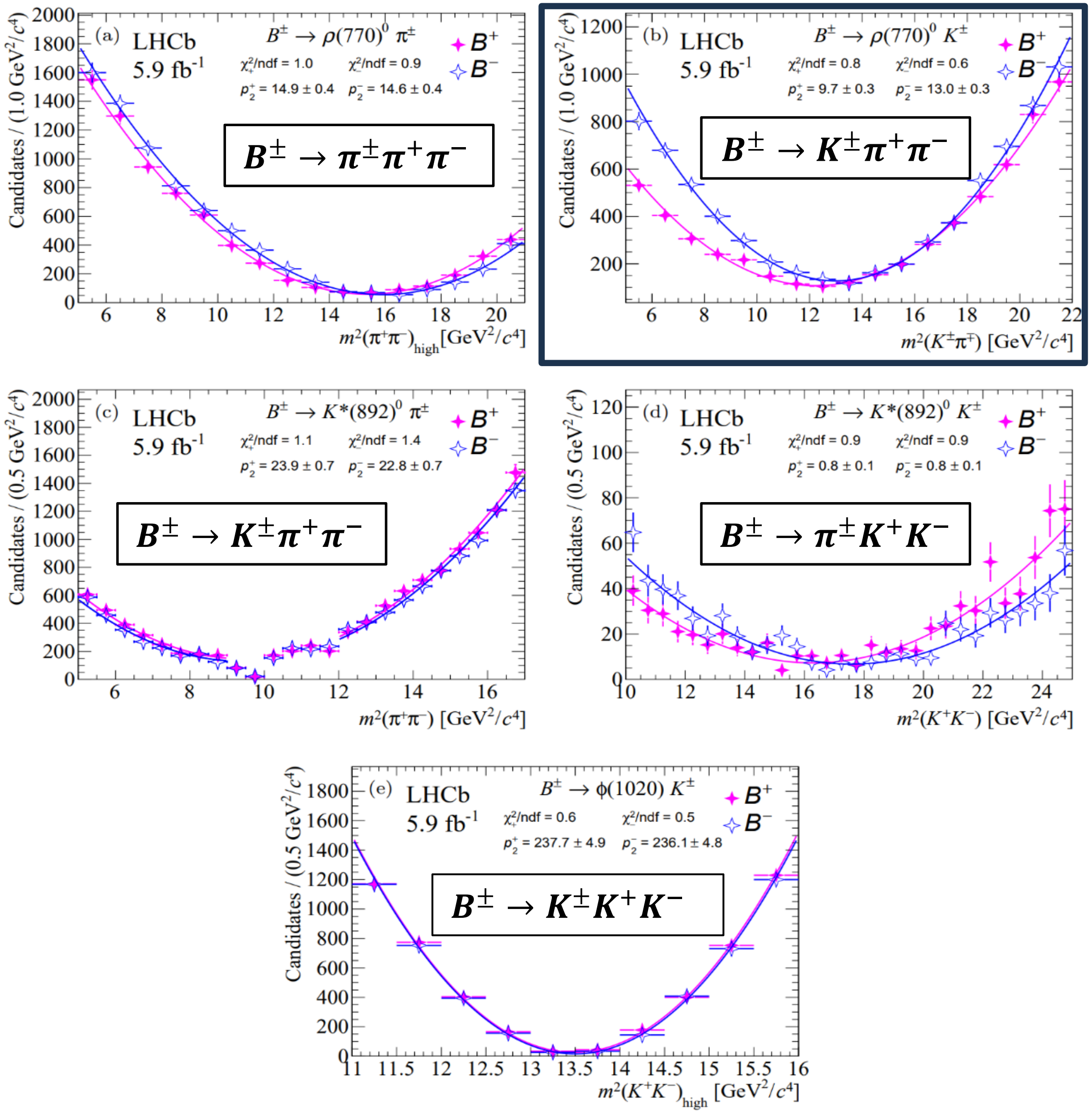
- With 5.9 fb^{-1} 13 TeV pp data, recorded with the LHCb 2015-2018:

  ⇒ $A_{CP}(\boldsymbol{B^{\pm}} \to \rho(770)^{0}K^{\pm}) = +0.150 \pm 0.019 \pm 0.011$, **first observation**

  ⇒ For the other four decay channels, compatible with zero

arXiv:2206.02038

Search for Direct CPV in $B^{\pm} \to PV$



- In $B^{\pm} \to R(h_1^- h_1^+) h_3^{\pm}$ $s_{\perp}$ for $m^2\ (h_1^- h_3^+)$ in different final states
  - $\Rightarrow$ reflects the angular distribution of the decay products
- B^+ and B^-

arXiv:2206.02038

Search for Direct CPV in $B^{\pm} \to PV$

- **Summary of measurements for:**

$\boldsymbol{B}^{\pm} \to R(h_1^- h_1^+) h_3^{\pm}$

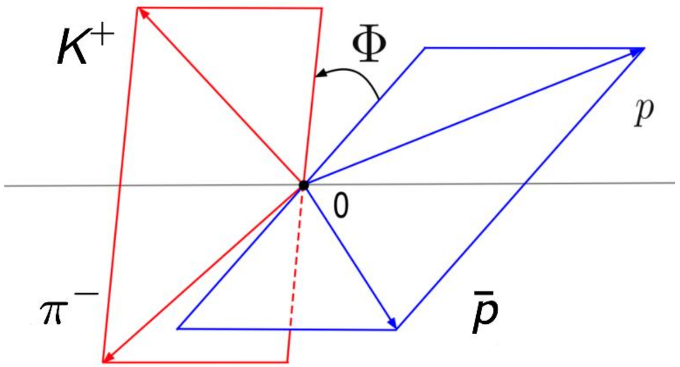
Decay channel	This work	Previous measurements
$B^{\pm} \to (\rho(770)^0 \to \pi^+\pi^-)\pi^{\pm}$	$-0.004 \pm 0.017 \pm 0.009$	$+0.007 \pm 0.011 \pm 0.016$ (LHCb [20,21])
$B^{\pm} \to (\rho(770)^0 \to \pi^+\pi^-)K^{\pm}$	$+0.150 \pm 0.019 \pm 0.011$	$+0.44 \pm 0.10 \pm 0.04$ (BaBar [28]) $+0.30 \pm 0.11 \pm 0.02$ (Belle [22])
$B^{\pm} \to (K^*(892)^0 \to K^{\pm}\pi^{\mp})\pi^{\pm}$	$-0.015 \pm 0.021 \pm 0.012$	$+0.032 \pm 0.052 \pm 0.011$ (BaBar [28]) $-0.149 \pm 0.064 \pm 0.020$ (Belle [22])
$B^{\pm} \to (K^*(892)^0 \to K^{\pm}\pi^{\mp})K^{\pm}$	$+0.007 \pm 0.054 \pm 0.032$	$+0.123 \pm 0.087 \pm 0.045$ (LHCb [19])
$B^{\pm} \to (\phi(1020) \to K^+K^-)K^{\pm}$	$+0.004 \pm 0.014 \pm 0.007$	$+0.128 \pm 0.044 \pm 0.013$ (BaBar [26])

The LHCb results

arXiv:2206.02038

Search for CPV using $\hat{T}$–odd in $B^0 \to p\bar{p}K^+\pi^-$

- Great interest to further search *CPV* in **baryonic *B* decays** (besides the $B^+ \to p\bar{p}K^+$), up to ~20% are predicted
- search for *CP* and *P* violation based on triple-product asymmetries in the charmless region of the $B^0 \to p\bar{p}K^+\pi^-$, with 8.4 fb^{-1} pp collision data at LHCb



- Define:

$$C_{\hat{T}} = \vec{p}_{K^+} \cdot (\vec{p}_{\pi^-} \times \vec{p}_p), \quad \bar{C}_{\hat{T}} = \vec{p}_{K^-} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\bar{p}}).$$

- The two $\hat{T}$**–odd** triple product asymmetries are defined as:

$$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}, \quad \bar{A}_{\hat{T}} = \frac{\bar{N}(-\bar{C}_{\hat{T}} > 0) - \bar{N}(-\bar{C}_{\hat{T}} < 0)}{\bar{N}(-\bar{C}_{\hat{T}} > 0) + \bar{N}(-\bar{C}_{\hat{T}} < 0)},$$

- The *CP*- and *P*-violating observables are then constructed as:

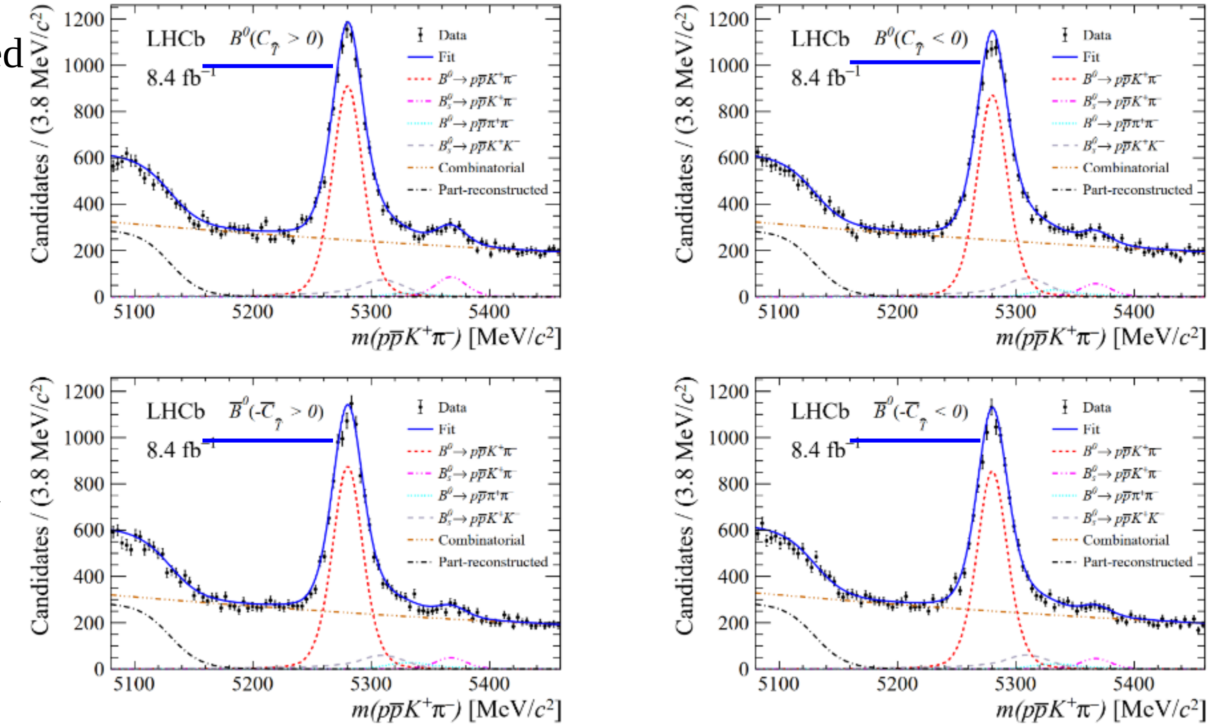
$$a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}}), \quad a_{P}^{\hat{T}\text{-odd}} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}}).$$

⇒ insensitive to particle-antiparticle production and detector-induced asymmetries

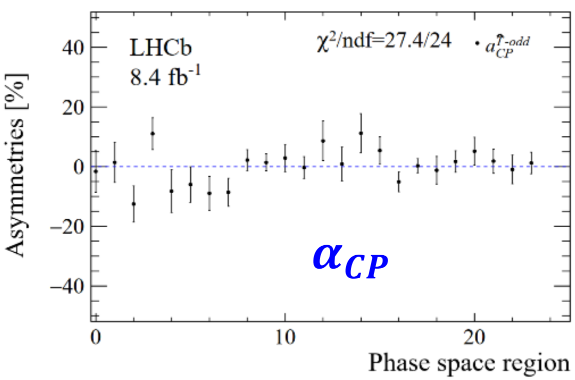
arXiv:2205.08973

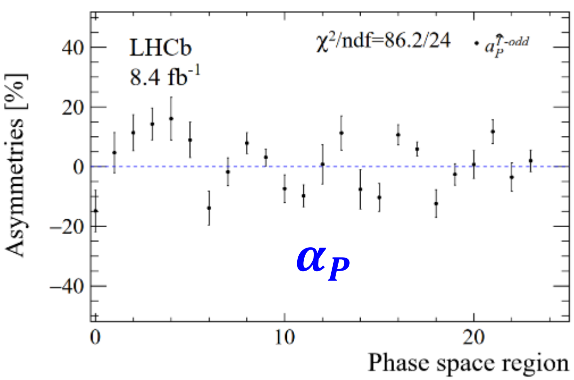
Search for CPV using $\hat{T}$–odd in $B^0 \to p\bar{p}K^+\pi^-$

- Fitting the phase-space integrated data divided according to the **B flavor and sign** of the product
- Main sources of cross-feed BGs are due to $\boldsymbol{B^0 \to p\bar{p}K^+K^-}$ **and** $\boldsymbol{B^0 \to p\bar{p}\pi^+\pi^-}$ decays, where a kaon or a pion is misidentified.



- Regions chosen before examining the data to avoid biases. The phase space is divided into **24 regions**





arXiv:2205.08973

Search for CPV using $\widehat{T}$–odd in $B^0 \to p\bar{p}K^+\pi^-$

- The measured phase-space **integrated** asymmetries are:

$$a_P^{\hat{T}\text{-odd}} = (1.49 \pm 0.85 \pm 0.08)\%,$$
$$a_{CP}^{\hat{T}\text{-odd}} = (0.51 \pm 0.85 \pm 0.08)\%,$$

- Both are consistent with *P* and *CP* conservation.

- Measurements **in regions of the phase space** the ***CP*-symmetry**:

  ⇒ **1.1 σ** deviation

- For ***P*-symmetry** ⇒ **5.8σ deviation**

- Significant *P*-asymmetries are observed in the region of low $p\bar{p}$ mass and near the $K^*(892)^0$ resonance.

arXiv:2205.08973

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

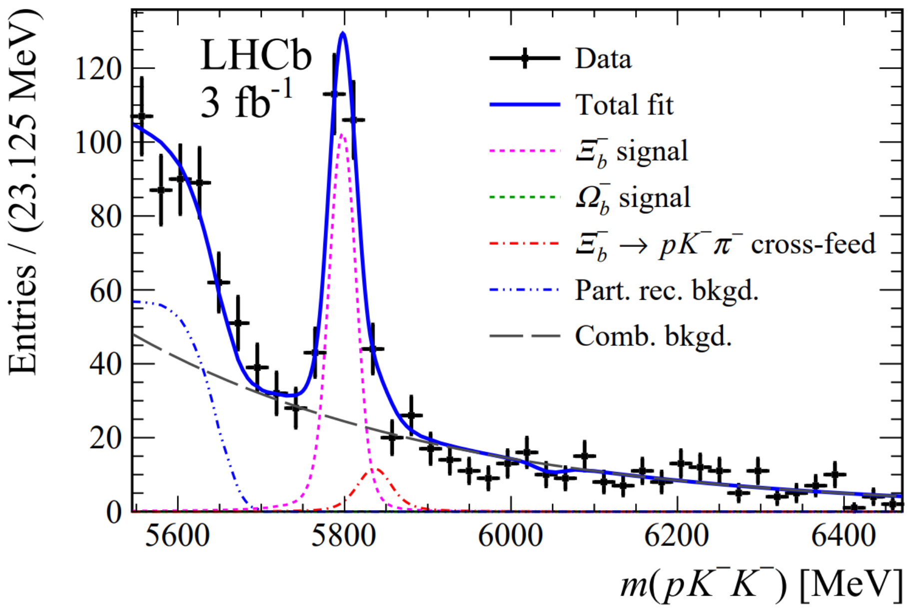
- Breaking of CP symmetry has not yet been observed in the properties of any baryon.

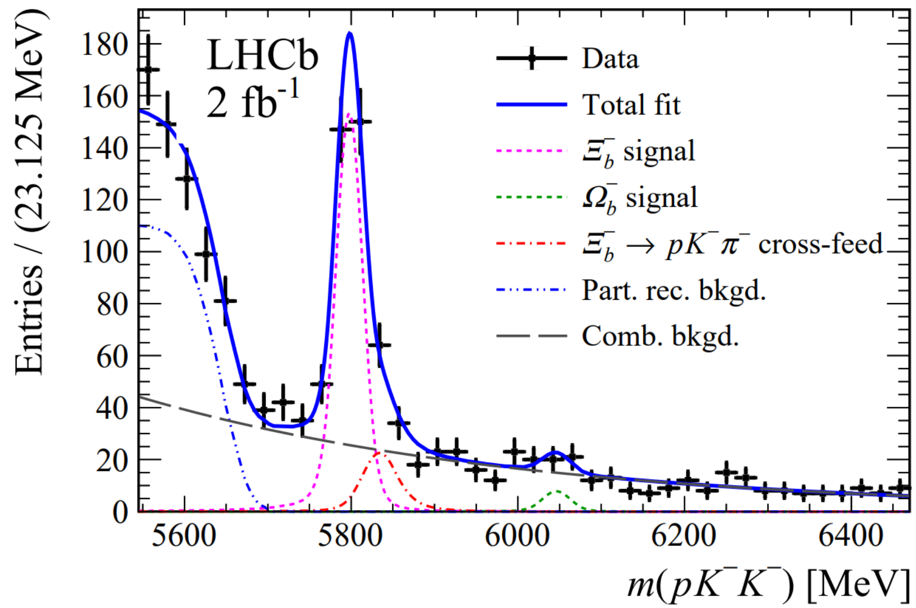
- In light of the large CPV observed in charmless decays of B mesons, it is of great interest to extend the range of searches in b-baryon decays.

- The first amplitude analysis of $\Xi_b^- \to pK^-K^-$ decays is reported. This is also the first amplitude analysis of any b-baryon decay mode allowing for CPV effects.

Phys. Rev. D 104, 052010

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





- Distributions of pK^-K^- invariant mass for $\boldsymbol{X_b^-}$ candidates in (left) Run 1 and (right) Run 2 data; Also search for the previously unobserved $\boldsymbol{\Omega_b^- \to pK^-K^-}$ decay.

Parameter	Run 1	Run 2
$\Xi_b^- \to pK^-K^-$ yield	193 ± 21	297 ± 23
$\Omega_b^- \to pK^-K^-$ yield	-4 ± 6	15 ± 9
Partially reconstructed background yield	231 ± 34	442 ± 36
Combinatorial background yield	721 ± 50	775 ± 51

Phys. Rev. D 104, 052010

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

- Studied many possible pK^- resonances, **got 6**
- Measured CPV asymmetry:

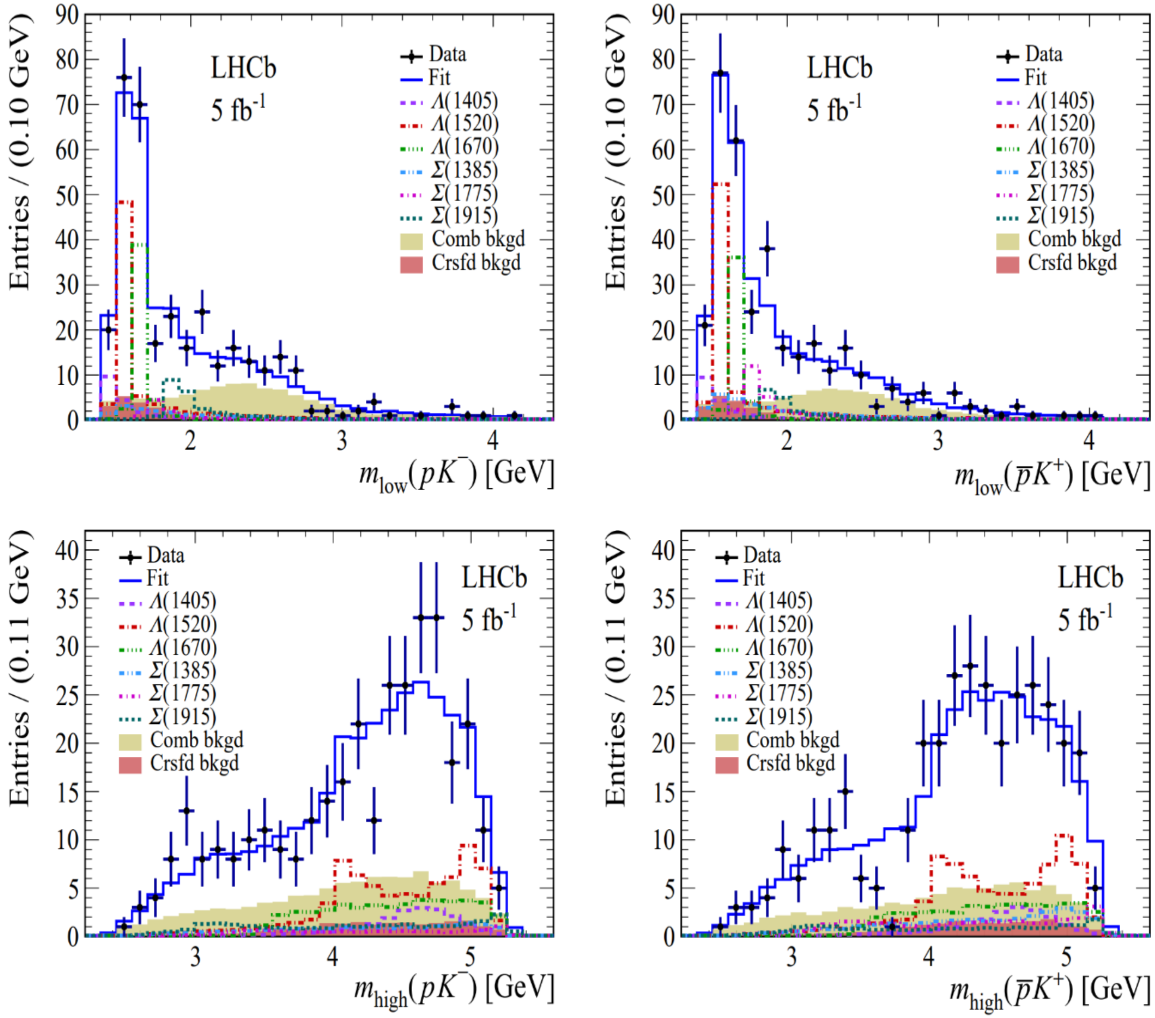
  $\Rightarrow$ all consistent with 0

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)

- Measured BRs:

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

The following two > 5 σ:

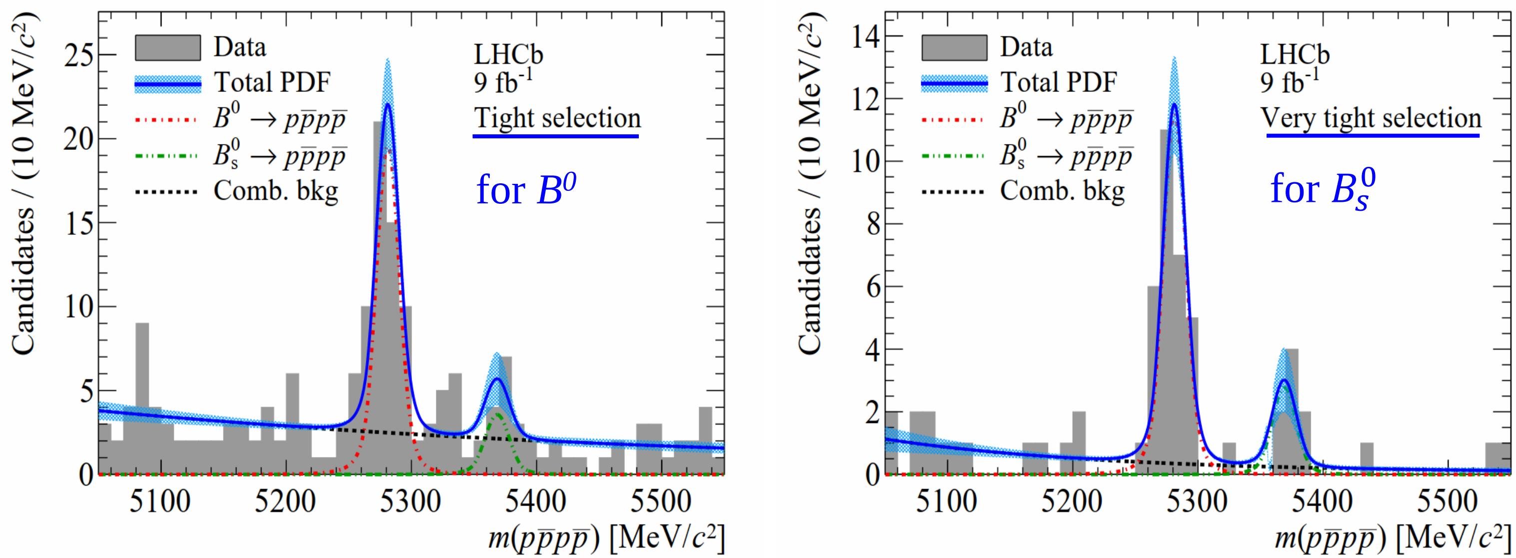


$$\mathcal{B}\left(\Xi_b^- \to \Lambda(1520)K^-\right) = (0.76 \pm 0.09 \pm 0.08 \pm 0.30) \times 10^{-6}\,,$$
$$\mathcal{B}\left(\Xi_b^- \to \Lambda(1670)K^-\right) = (0.45 \pm 0.07 \pm 0.13 \pm 0.18) \times 10^{-6}\,,$$

Phys. Rev. D 104, 052010

The rare hadronic decay $B^0_{(s)} \to p\bar{p}p\bar{p}$

- No reliable prediction for $B^0_{(s)} \to p\bar{p}p\bar{p}$ for now, a first measurement of the corresponding BR would give better understand the underlying dynamics
- The BRs of multi-body baryonic decay modes may be significantly increased due to a threshold enhancement effect in the m(baryon-antibaryon) , while two-body baryonic decays (such as $B^0_{(s)} \to p\bar{p}$) are suppressed
- B^0 / B^0_s: **significance of 9.3σ and 4.0σ**



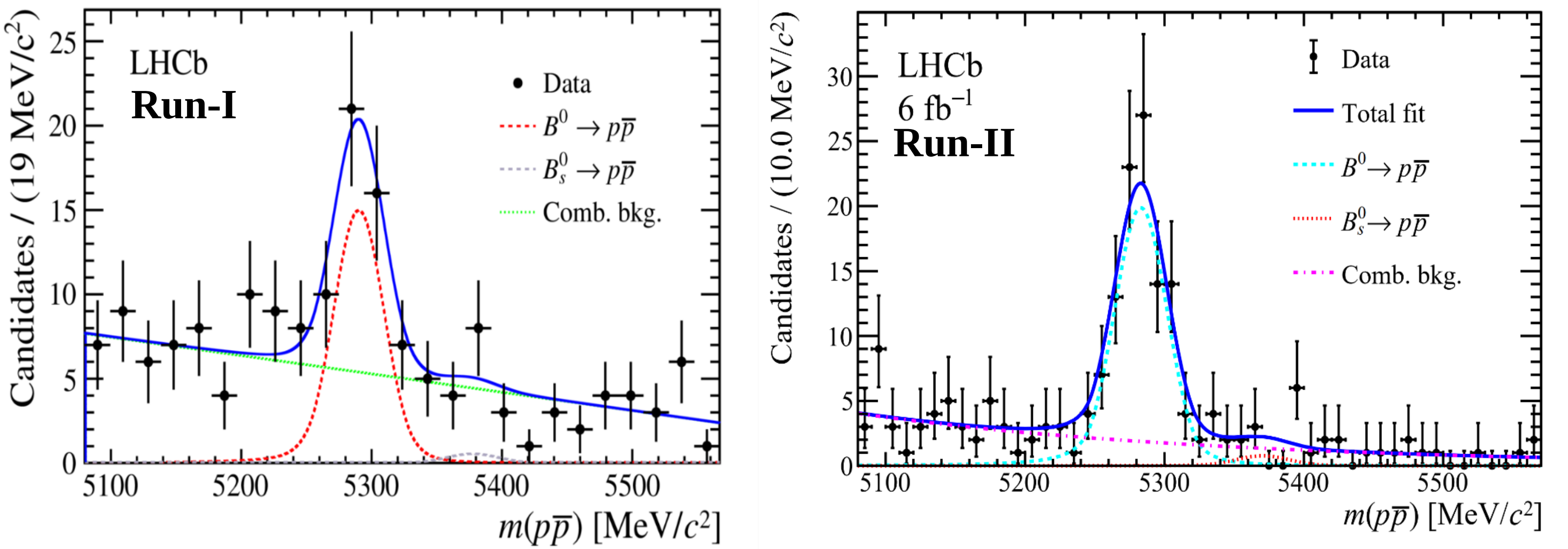
- Results: BR($B^0 \to p\bar{p}p\bar{p}$)= (2.2±0.4±0.1) $\times 10^{-8}$ and BR($B^0_s \to p\bar{p}p\bar{p}$)= (2.2±1.0±0.2) $\times 10^{-8}$

arXiv:2211.08847

The rare hadronic decay $B^0 \to p\bar{p}$

- Two-body baryonic decays are suppressed, only few charmless two-body baryonic decays have been observed:

  $\Rightarrow B^+ \to p\,\bar{\Lambda}(1520)$, $B^+ \to p\,\bar{\Lambda}$ and $B^0 \to p\bar{p}$ modes.



$$\mathcal{B}(B^0_{(s)} \to p\bar{p}) = \frac{N(B^0_{(s)} \to p\bar{p})}{N(B^0 \to K^+\pi^-)} \times \frac{\varepsilon_{B^0\to K^+\pi^-}}{\varepsilon_{B^0_{(s)}\to p\bar{p}}} \times \mathcal{B}(B^0 \to K^+\pi^-) \times \frac{f_d}{f_{d(s)}}, \qquad (1)$$

- Run-I result: BR($B^0 \to p\bar{p}$)= $(1.25\pm0.27\pm0.18)\times10^{-8}$
- Run-II result: BR($B^0 \to p\bar{p}$)= $(1.27\pm0.15\pm0.05)\times10^{-8}$

Also see talk by Irene Bachiller about the $B_s^0 \to p\bar{p}$ search arXiv:2206.06673

Summary

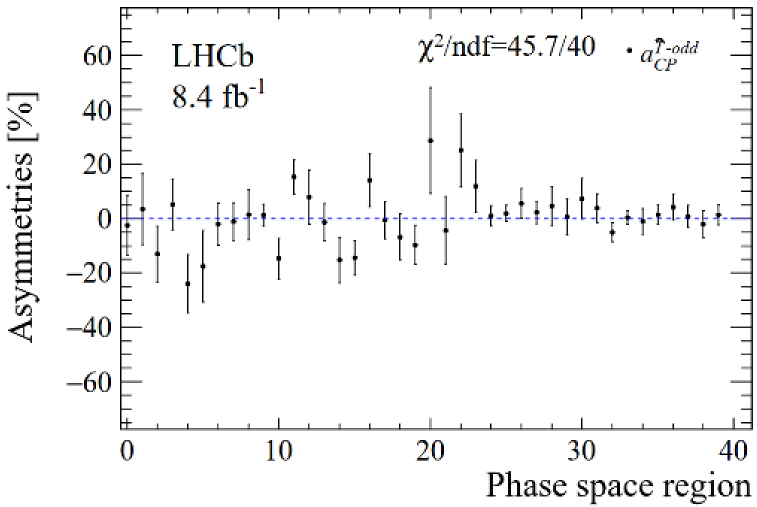
- LHCb provides ideal environment for charmless b-meson and b-baryon decays for studies of CP violation, hadronic effects and searches for new physics.

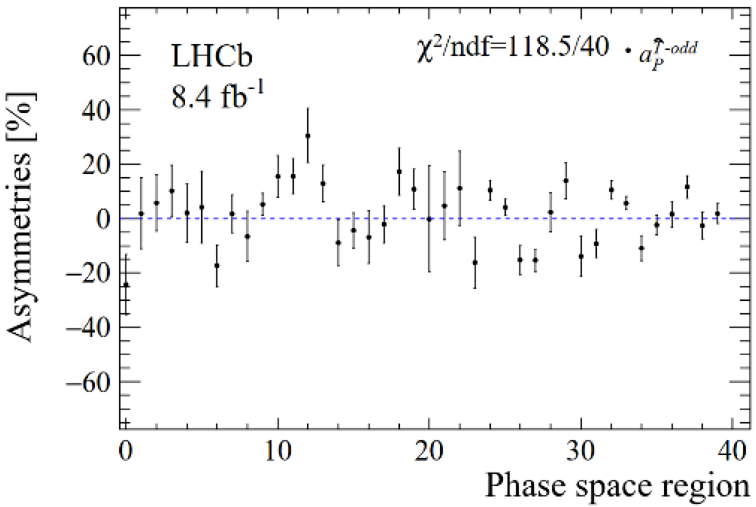
- More results are coming on the way; the upgraded LHCb detector will also bring more new exciting results soon.

Thanks for your listening!

Search for CPV using $\widehat{T}$–odd in $B^0 \to p\bar{p}K^+\pi^-$

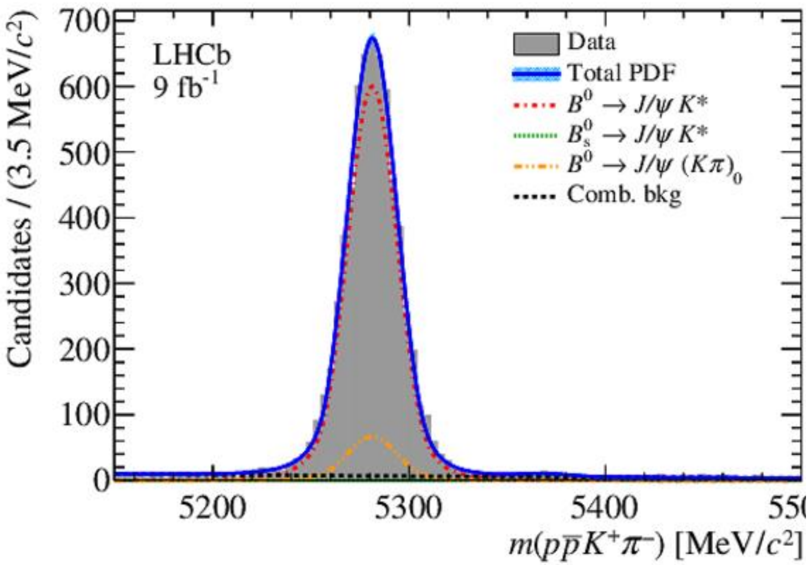
The phase space is divided into 40 regions

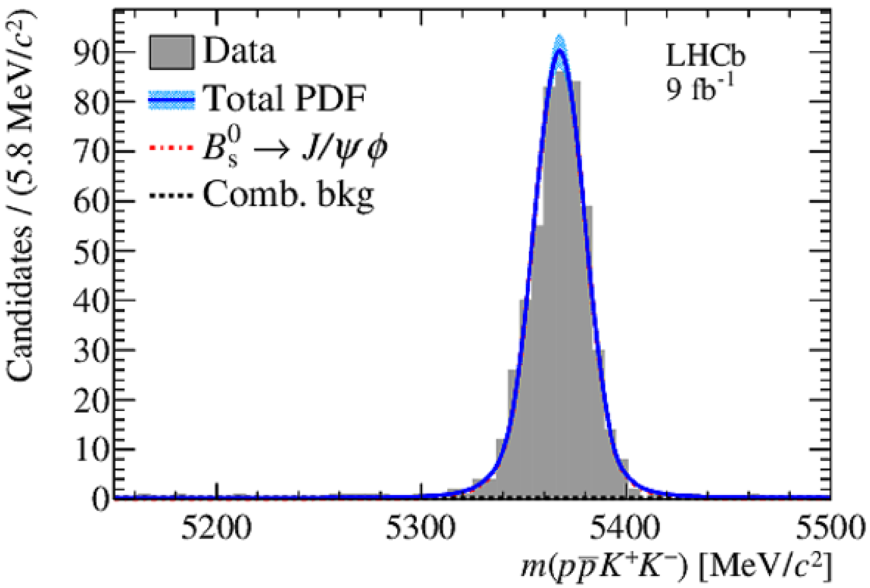




The rare hadronic decay $B^0_{(s)} \to p\bar{p}p\bar{p}$

- The branching fractions are measured relative to the topologically similar normalisation decays： $B^0 \to J/\psi(\to p\bar{p})K^{*0}(\to K\pi)$ and $B^0_s \to J/\psi(\to p\bar{p})\phi(\to KK)$
- Results: BR($B^0 \to p\bar{p}p\bar{p}$)= $(2.2\pm0.4\pm0.1)\times10^{-8}$ and BR($B^0_s \to p\bar{p}p\bar{p}$)= $(2.2\pm1.0\pm0.2)\times10^{-8}$





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