CP-violation measurements in beauty at LHCb Experiment and Prospects

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SILAFAE 2024 - Novembre 4-8.

Introduction

- **CP**-violation ➡ stands for **Charge Conjugation** - **Parity** symmetry violation (CPV)
- Explained in the Standard Model through the CKM mixing matrix (V_{CKM}) among families of quarks, <u>via the existence of one complex phase:</u>

the mixing matrix for quarks (V_{CKM}) is different from that of antiquarks ($V^{\dagger}_{CKM}$)!

$$\underset{\text{weak states}}{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}} = \overbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}^{\text{CKM matrix}} \underset{\text{mass states}}{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}$$

Unitary matrix with 3 real parameter +
1 complex phase

Matter and antimatter do not behave in the same way in nature:

- weak interactions are not invariant under **C**, **P** and **CP** transformation

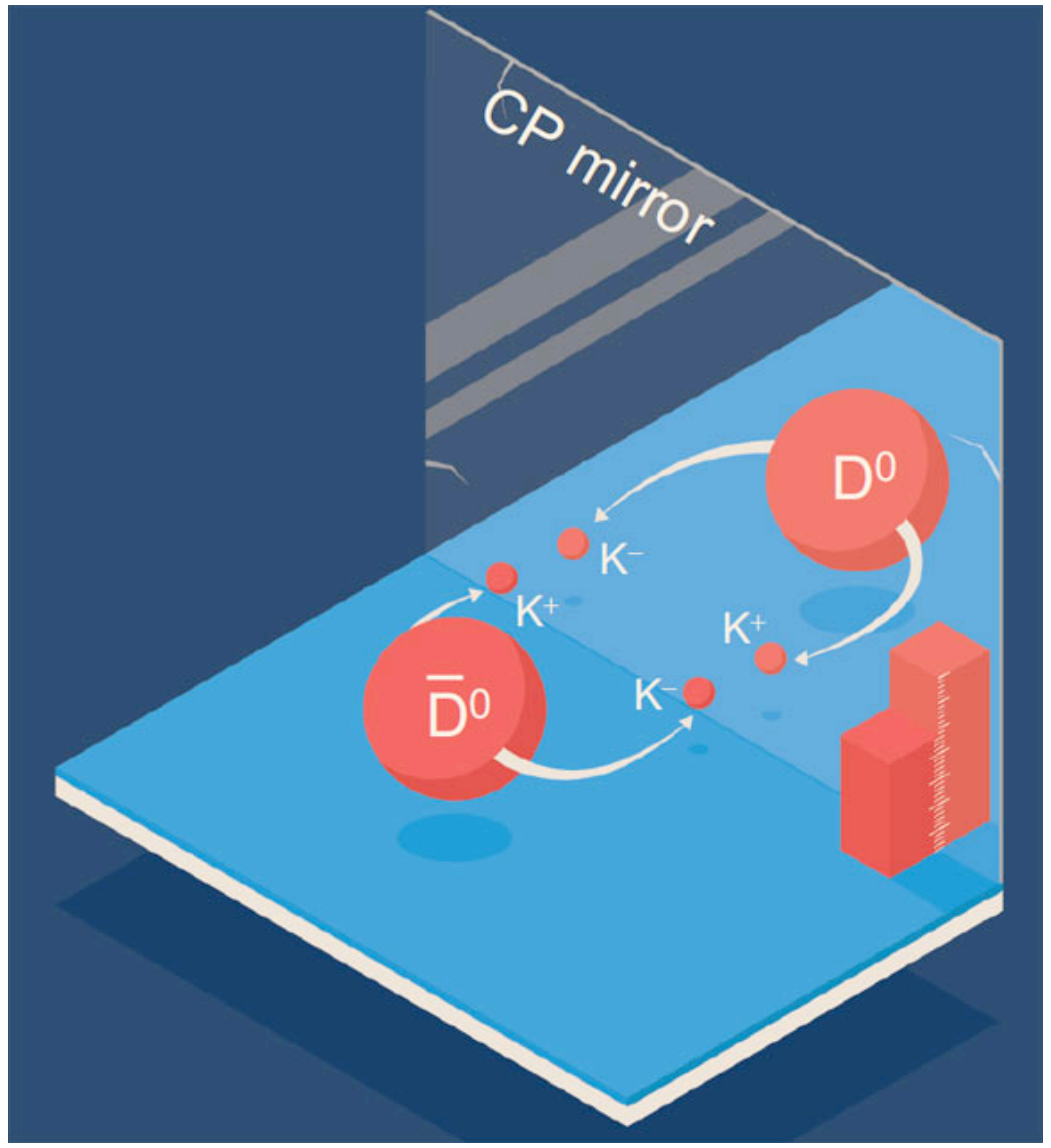


Image: CERN

Introduction

Experimentally discovered in **strange**, **charm** and **beauty** sectors.

The amount of matter-antimatter asymmetry still cannot all be explained within the SM: **we need to search for new sources of CPV!**

- Effects suppressed in the charm sector - CKM and GIM Mechanism
- B-physics most sensitive to CPV
- Baryonic sector - Still to be observed!

***CP*-violation Mechanism**	**Direct CP Violation:** $\lvert A \rvert^2 \neq \lvert \bar{A} \rvert^2$ **only mechanism for charged decays (as $B^{\pm}$ mesons and *b*-baryons)**
	CP violation by mixing: Related to the difference in rate oscillation between particle and anti-particle
	CP violation through the interference of decay amplitude and mixing

Introduction

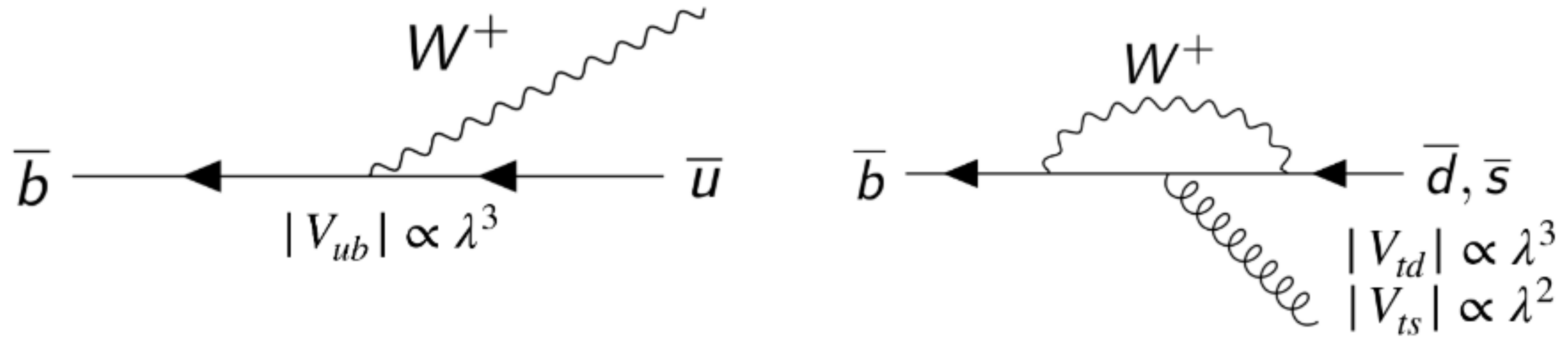
LHCb explores a very broad program for CPV studies

- I will focus on some B Charmless and B to Charmonia results

Charmless *B* decays

**B*-hadron decays without charm or charmonium contributions in their final state

Decays that involve transitions of the type $b \to u(s), b \to d$



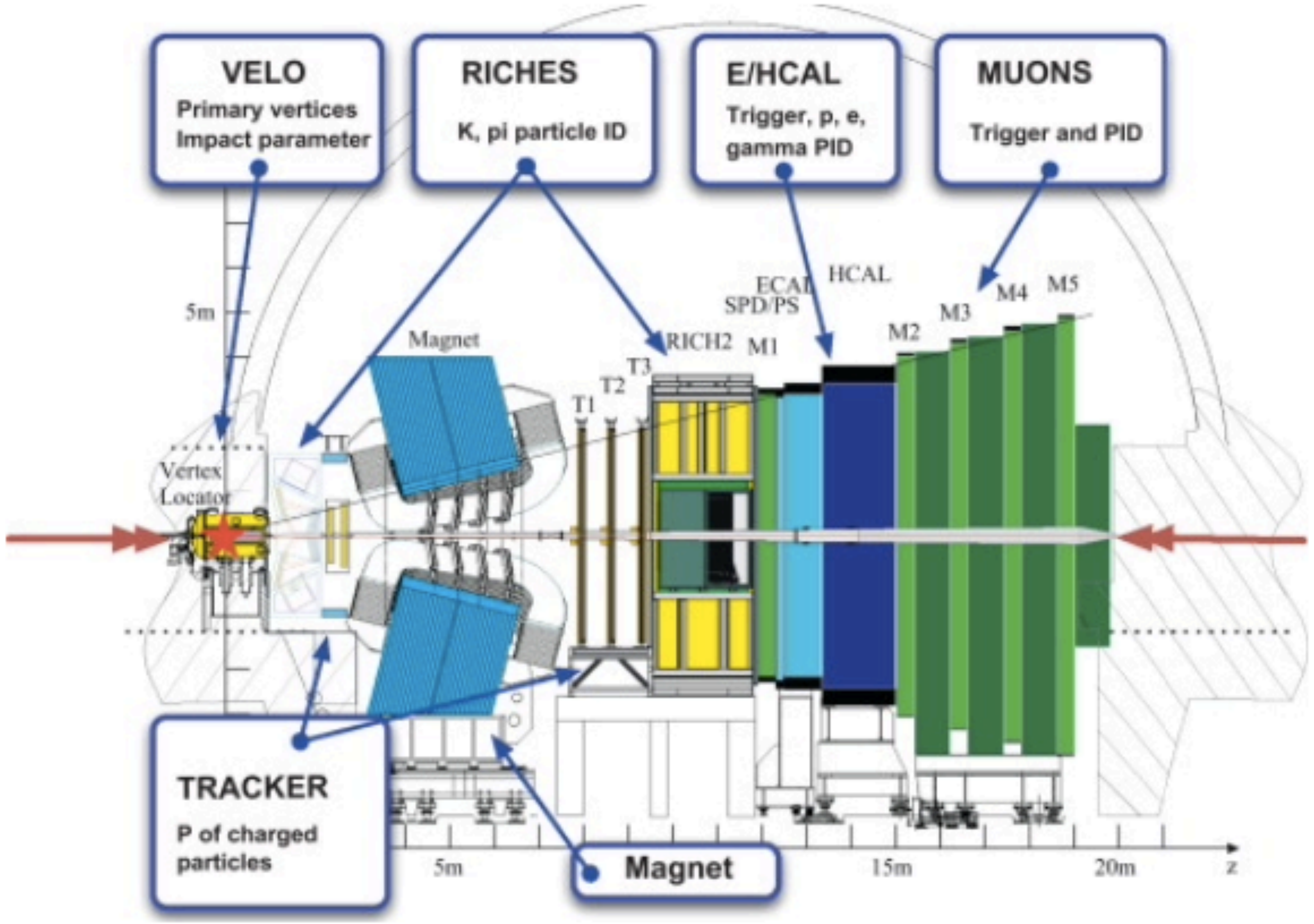
- Dominant tree-level and penguin diagram contributing in the order of magnitude
- Multi-body decays dominated by rich resonant structures
  - CP violation signatures localized in regions of phase space
  - Allow us to better understand the B-hadron dynamics

They offer a rich environment for CP violation studies

LHCb exploits Dalitz plot analyses, Time dependent/independent CPV analyses, Searched for unobserved decays of *B* mesons and baryons

The LHCb detector

- It is a single-arm forward spectrometer designed for the study of B and D mesons.
- It covers a pseudo-rapidity range of $2 < \eta < 5$
- run I data: $\mathcal{L} = 3.0\ \mathrm{fb}^{-1}$ from pp collisions at 7 TeV (2011) and 8 TeV (2012) in the center-of-mass-energy
- run II data: $\mathcal{L} = 6.0\ \mathrm{fb}^{-1}$ from pp collisions at 13 TeV (2015-2018)



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

CP asymmetries in $\Lambda_b^0 \to ph^-$ ([LHCb-PAPER-2024-048], in preparation)

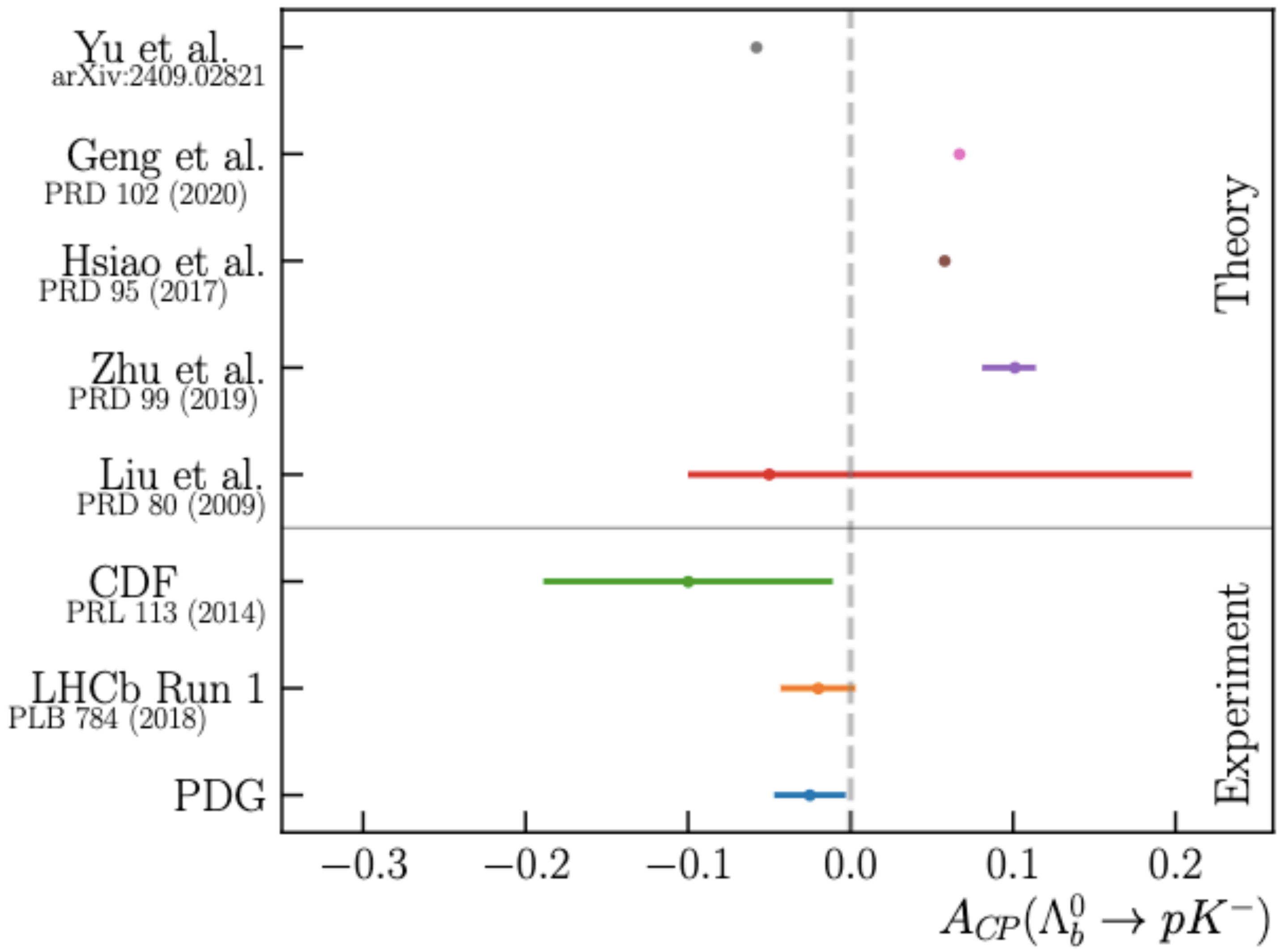
In the baryon sector, no evidence of CP violation has been observed so far

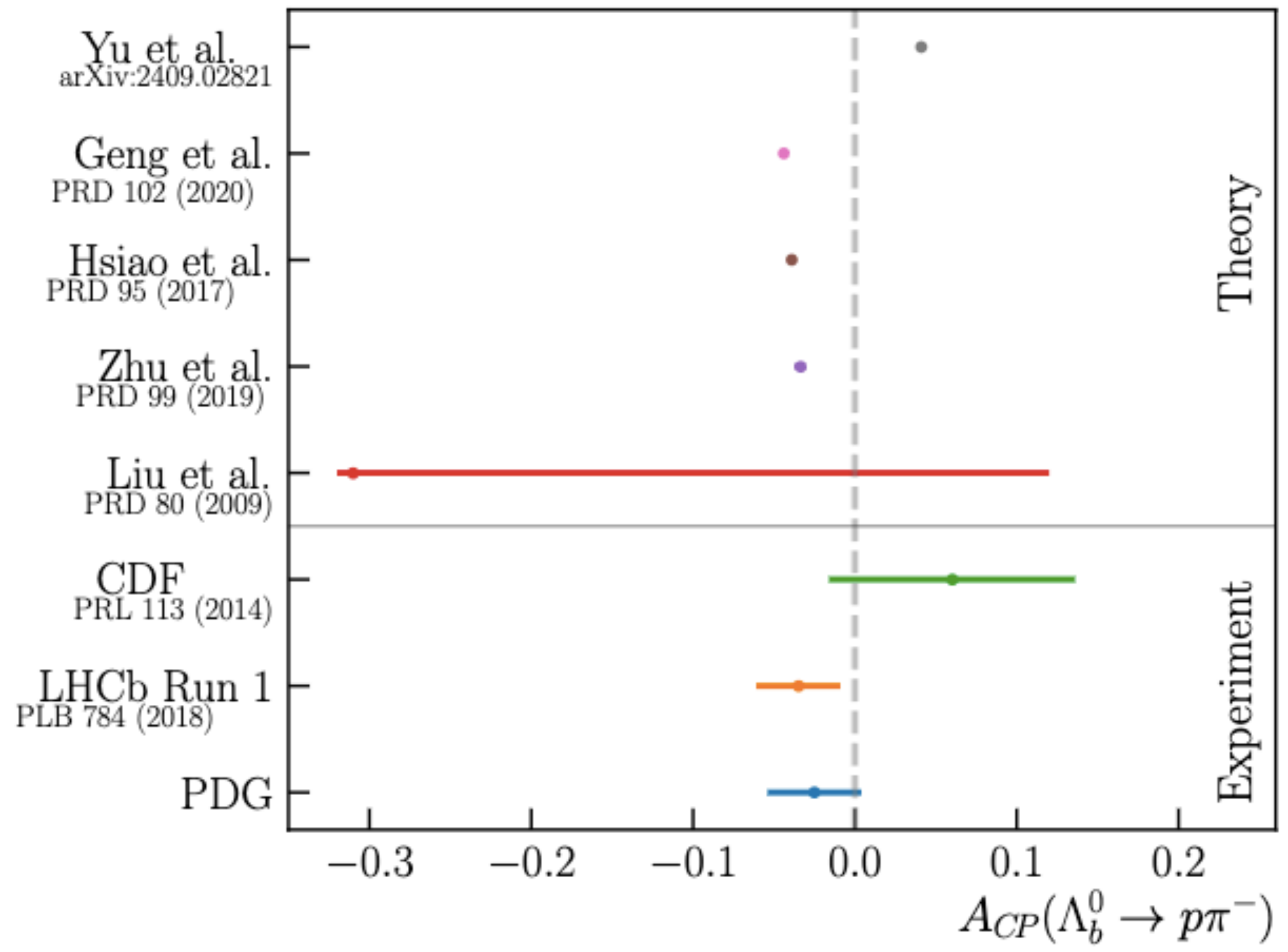
➡ $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ are promising laboratories for CPV searches

➡They are mediated at the same quark-level transitions as B_s^0/B^0, where CP violation is observed.

- World Average value dominated by LHCb

	$A_{CP}(\Lambda_b^0 \to pK^-)$	$A_{CP}(\Lambda_b^0 \to p\pi^-)$
CDF	$(-10 \pm 8 \pm 4)\%$	$(6 \pm 7 \pm 3)\%$
LHCb Run1	$(-2.0 \pm 1.3 \pm 1.9)\%$	$(-3.5 \pm 1.7 \pm 2.0)\%$
PDG	$(-2.5 \pm 2.2)\%$	$(-2.5 \pm 2.9)\%$





In this analysis it is presented the search for CPV $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$

- Update of Run 1 results, addition of Run 2 data
- Total Luminosity of 9 fb^{-1}

CP asymmetries in $\Lambda_b^0 \to ph^-$ ([LHCb-PAPER-2024-048], in preparation)

CP asymmetry is defined as

$$A_{CP} = \frac{\Gamma(\Lambda_b^0 \to f) - \Gamma(\overline{\Lambda_b^0} \to \bar{f})}{\Gamma(\Lambda_b^0 \to f) + \Gamma(\overline{\Lambda_b^0} \to \bar{f})},$$

where,
Γ : is the partial width of a given decay
f: represents pK^- or $p\pi^-$
$\bar{f}$: represents pK^+ or $p\pi^+$

Analysis Strategy

Run 1

Measurements updated

$$A_{CP}^{pK^-} = A_{raw}^{pK^-} - A_D^P - A_D^{K^-} - A_{PID}^{pK^-} - A_T^{pK^-} - A_p^{\Lambda_b^0}$$

$$A_{CP}^{p\pi^-} = A_{raw}^{p\pi^-} - A_D^P - A_D^{\pi^-} - A_{PID}^{p\pi^-} - A_T^{p\pi^-} - A_p^{\Lambda_b^0}$$

- Subtraction of nuisance asymmetries.
- Use of data-driven methods.

Run 2

Use of control sample $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$

$$A_{CP}^{pK^-} = \Delta A_{raw} - \Delta A_D^P - \Delta A_D^{K^-} - \Delta A_{PID} - \Delta A_p^{\Lambda_b^0} - \Delta A_T - A_D^{\pi^-} - A_D^{\pi^+} + A_{CP}^{\Lambda_c^+\pi^-}$$

$$A_{CP}^{p\pi^-} = \Delta A_{raw} - \Delta A_D^P - \Delta A_D^{\pi^-} - \Delta A_{PID} - \Delta A_p^{\Lambda_b^0} - \Delta A_T - A_D^{K^-} - A_D^{\pi^+} + A_{CP}^{\Lambda_c^+\pi^-}$$

- CP asymmetry of control channel expected to be zero. Also used to remove the $A_p(\Lambda_b^0)$
- ΔA : is the difference in the asymmetries in the signal and control mode

CP asymmetries in $\Lambda_b^0 \to ph^-$ ([LHCb-PAPER-2024-048], in preparation)

Analysis Strategy Run 2

CP asymmetries obtained from:

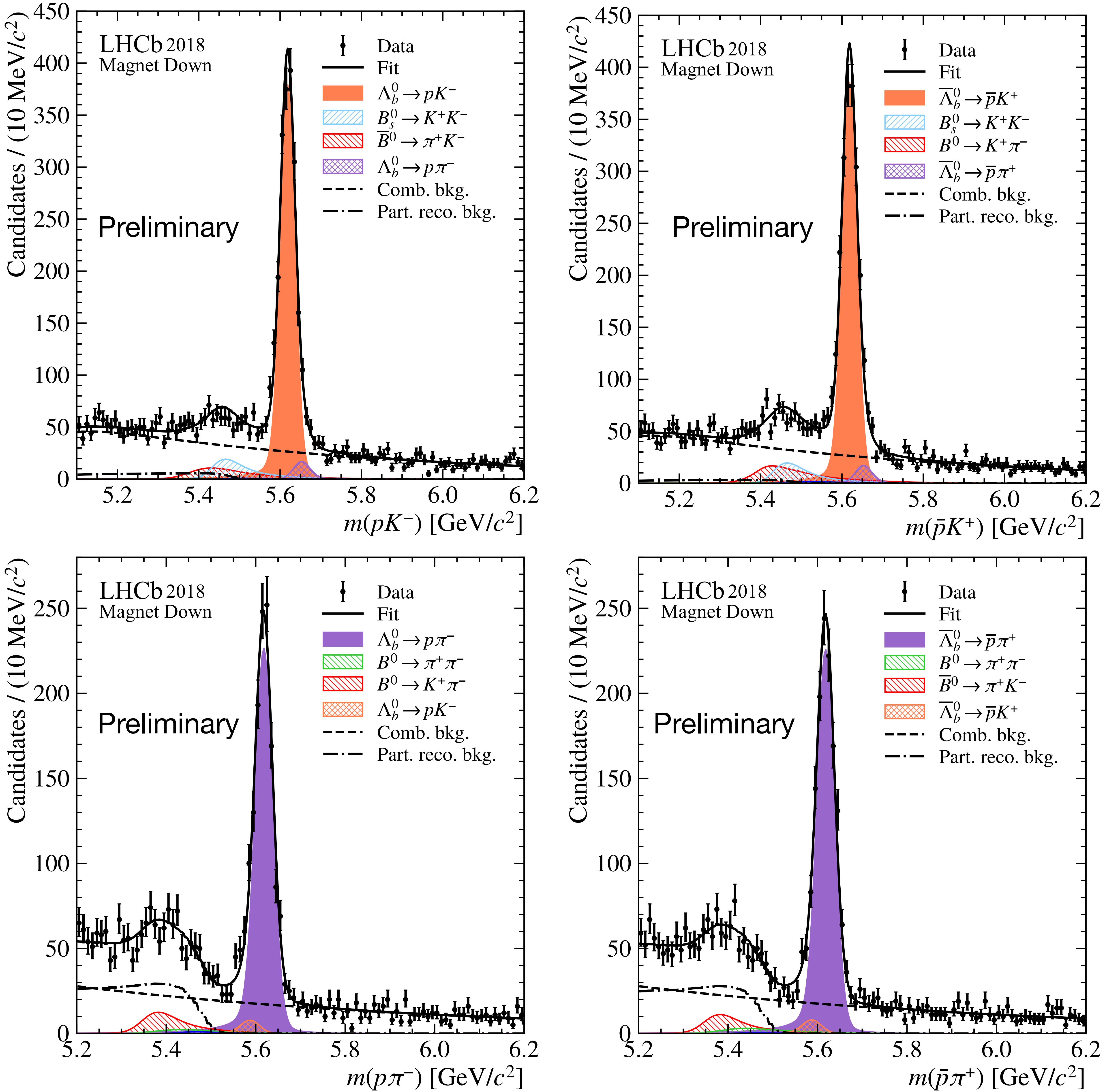
$$A_{CP}^{pK^-} = \Delta A_{raw} - \Delta A_D^P - \Delta A_D^{K^-} - \Delta A_{PID} - \Delta A_p^{\Lambda_b^0} - \Delta A_T - A_D^{\pi^-} - A_D^{\pi^+} + A_{CP}^{\Lambda_c^+\pi^-}$$

$$A_{CP}^{p\pi^-} = \Delta A_{raw} - \Delta A_D^P - \Delta A_D^{\pi^-} - \Delta A_{PID} - \Delta A_p^{\Lambda_b^0} - \Delta A_T - A_D^{K^-} - A_D^{\pi^+} + A_{CP}^{\Lambda_c^+\pi^-}$$

ΔA : is the difference in the asymmetries in the signal and control mode
A_{raw} : is the raw asymmetry
A_D^h : Asymmetry in the detection between *h* and its charge conjugate
A_{PID}: Asymmetry in the particle identification efficiencies in f and $\bar{f}$
A_T : Asymmetry in the trigger efficiencies in f and $\bar{f}$

- New data-driven techniques for trigger induced corrections
- Better control of uncertainties from PID

CP asymmetries in $\Lambda_b^0 \to ph^-$ ([LHCb-PAPER-2024-048], in preparation)



Raw asymmetry A_{raw}, obtained between the yields of $\Lambda_b^0 \to f$ and $\overline{\Lambda_b^0} \to \bar{f}$

$$A_{raw} = \frac{N(\Lambda_b^0 \to f) - N(\overline{\Lambda_b^0} \to \bar{f})}{N(\Lambda_b^0 \to f) + N(\overline{\Lambda_b^0} \to \bar{f})},$$

- An extended binned likelihood fit is performed for 12 subsets, based by year of data sample and magnet polarity

- Invariant mass distribution for the 2018 magDown sample.

NEW!

CP asymmetries in $\Lambda_b^0 \to ph^-$ ([LHCb-PAPER-2024-048], in preparation)

- CP asymmetries measurements in the 12 individual data-taking subsamples
- Computing their average, results in:

NEW!

Updated Run 1 results :

$$A_{CP}^{pK^-} = (-0.27 \pm 1.55(stat) \pm 0.57(syst))\,\%\,,$$
$$A_{CP}^{p\pi^-} = (-0.59 \pm 1.86(stat) \pm 0.53(syst))\,\%$$

New Run 2 results :

$$A_{CP}^{pK^-} = (-1.39 \pm 0.75(stat) \pm 0.41(syst))\,\%\,,$$
$$A_{CP}^{p\pi^-} = (0.42 \pm 0.93(stat) \pm 0.42(syst))\,\%$$

Combination of Run 2 measurements with Run 1 updated results:

$$A_{CP}^{pK^-} = (-1.14 \pm 0.67 \pm 0.36)\,\%\,,$$
$$A_{CP}^{p\pi^-} = (\,0.20 \pm 0.83 \pm 0.37)\,\%$$

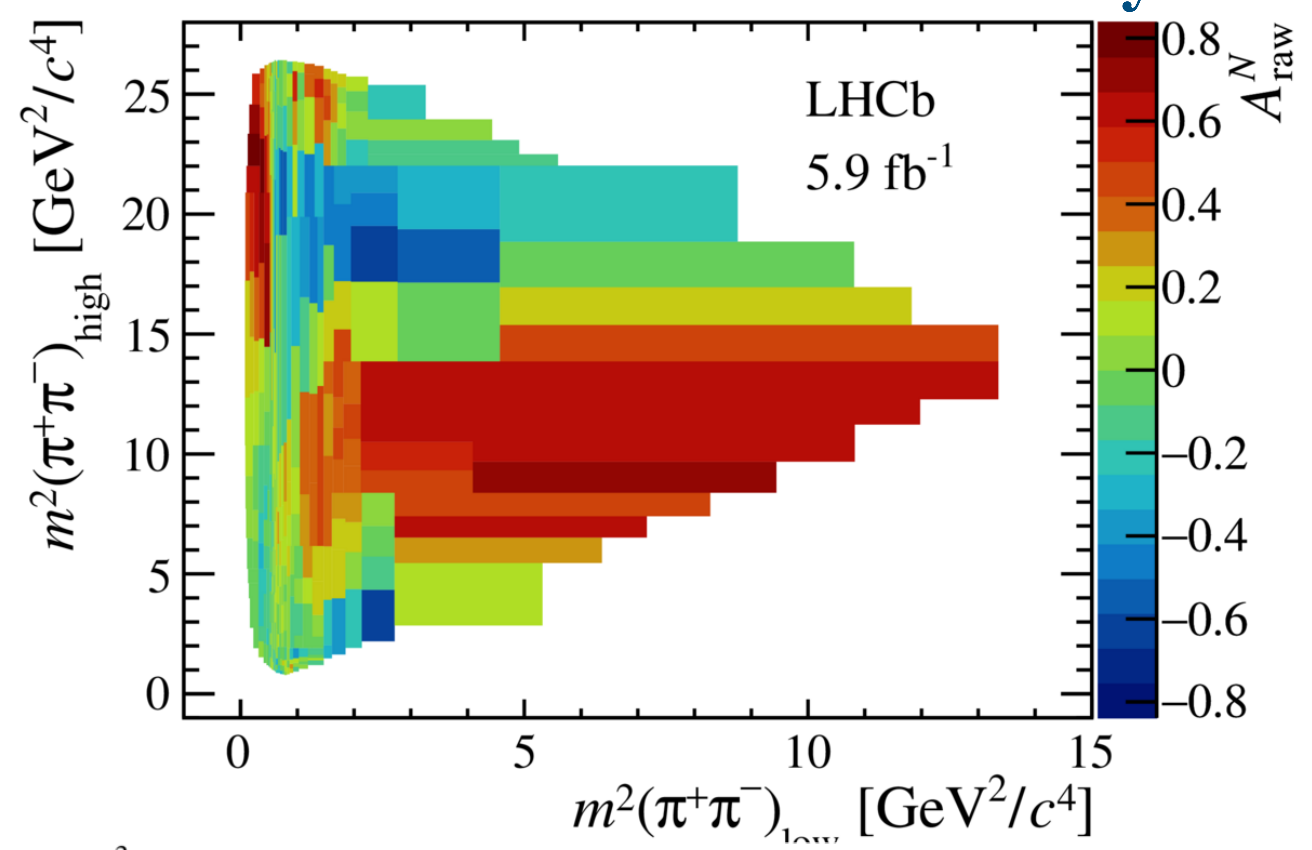
- **No evidence of CP violation**
- **Most precise measurement to date**
- **Improved precision by a factor of three**

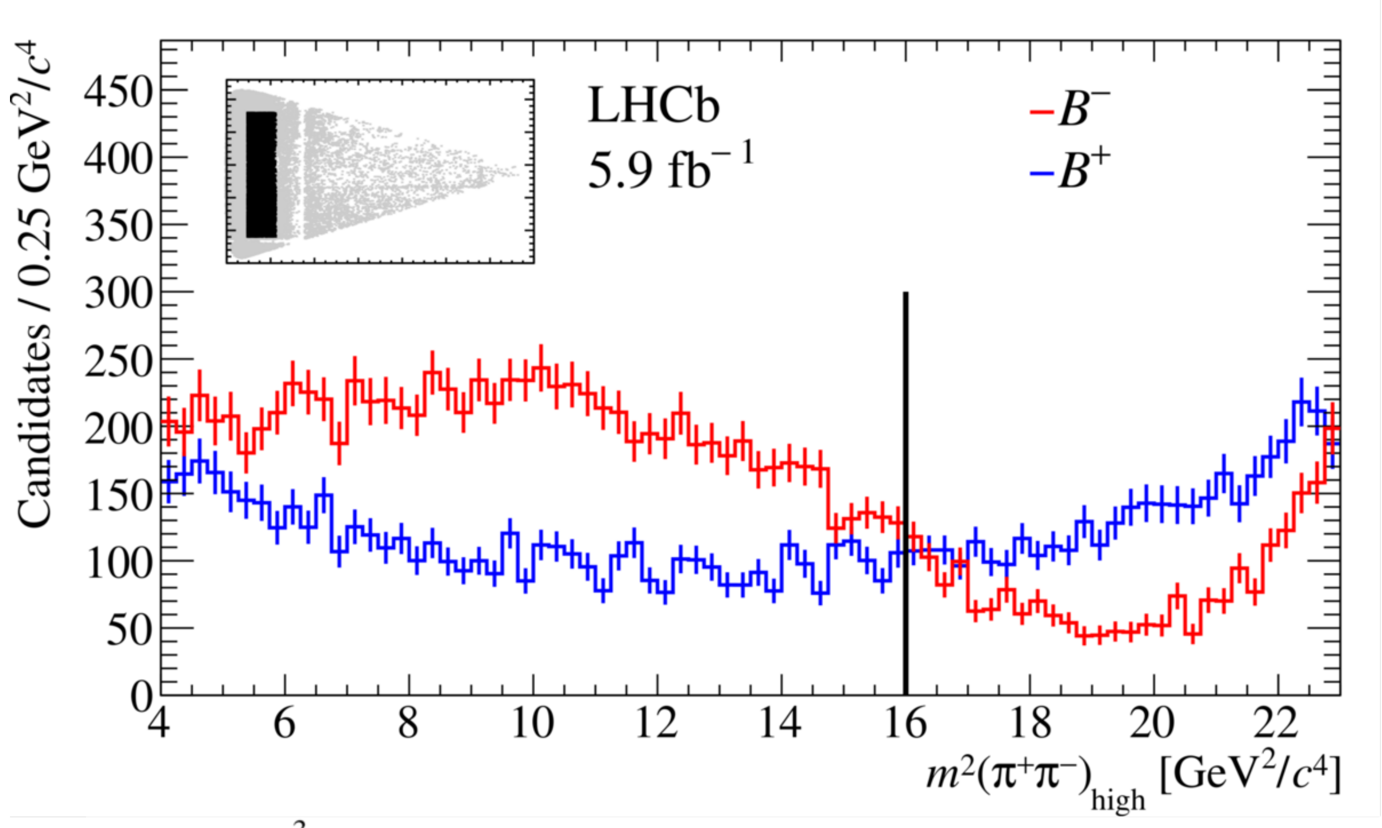
Study of Λ_b^0/Ξ_b^0 decays to $\Lambda h^+ h^{'-}$ decays [LHCb-PAPER-2024-043], in preparation

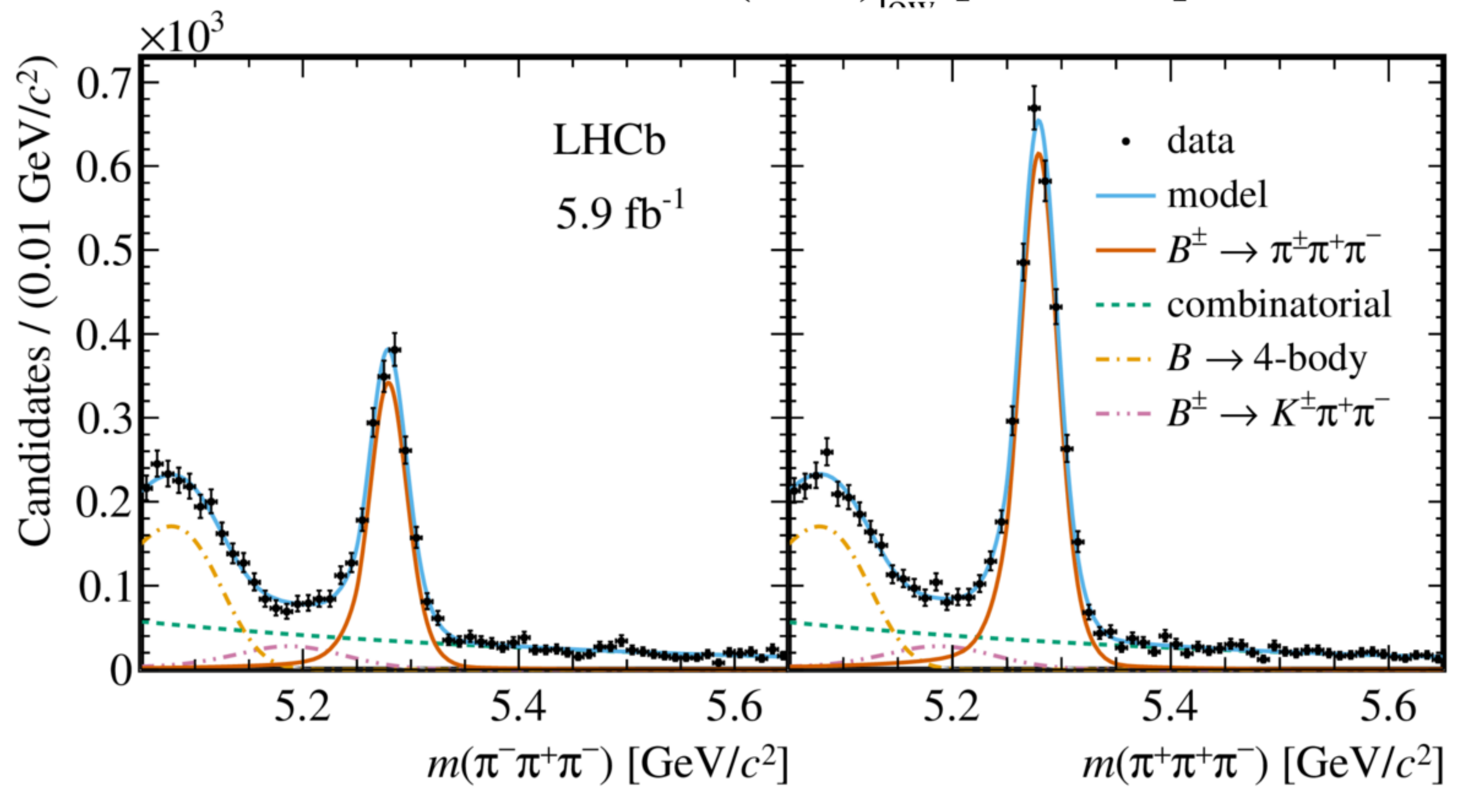
- Charmless three-body decays are excellent candidates for relative large CP violation effects to occur.
    - Intermediate states can interfere and can lead to complex signatures in the phase space

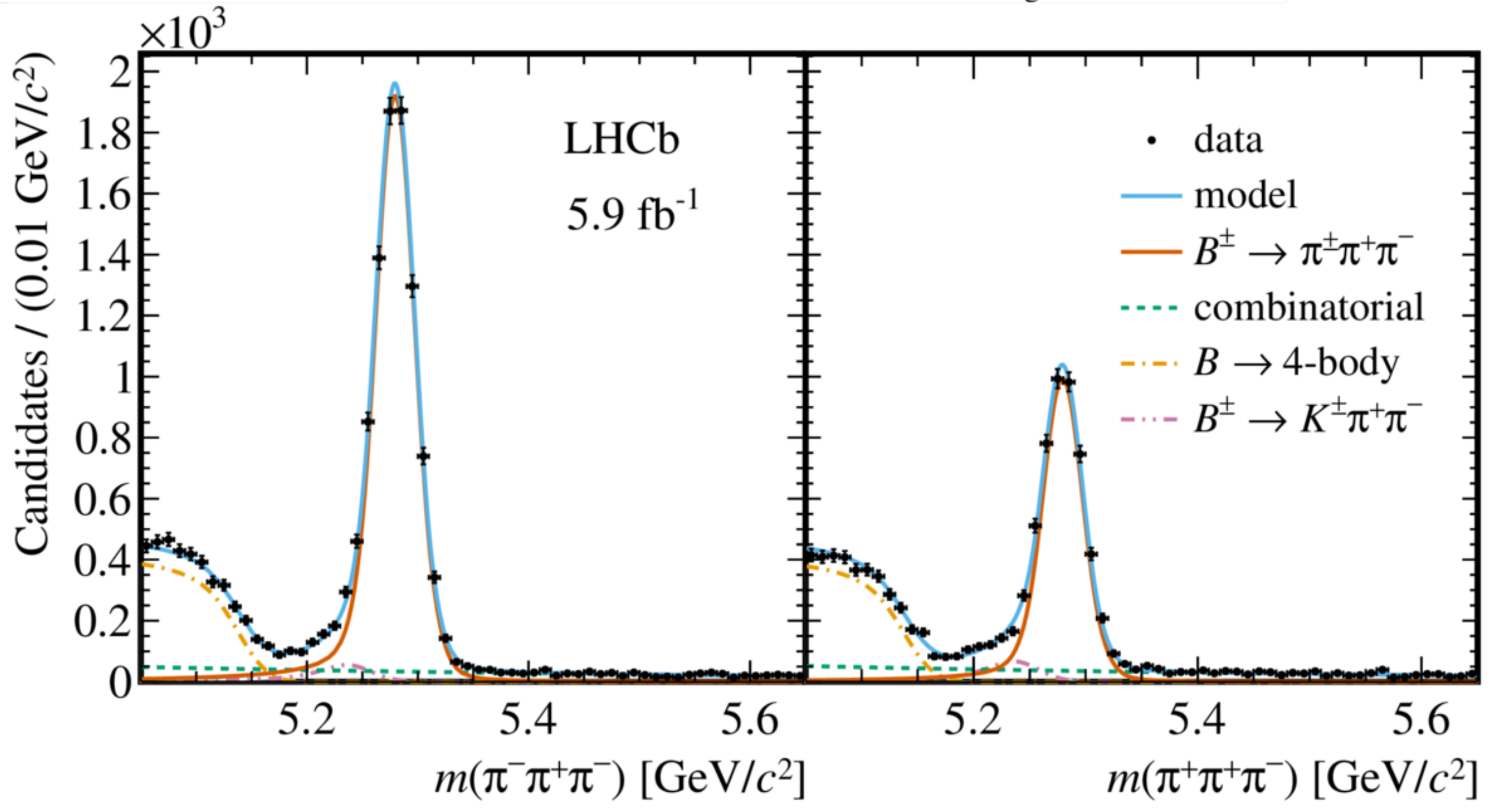
Three-body B mesons decays, has shown large integrated CP asymmetries and large CP asymmetries in regions of the phase space

Phys. Rev. D 108, 012008









Similar dynamics involved in
$\Lambda_b^0 \to \Lambda(\to p\pi^-)h^+h^{'-}, h = K, \pi$

⭐ **Interesting to place for CPV studies!**

Study of Λ_b^0/Ξ_b^0 decays to $\Lambda h^+ h^{'-}$ decays [LHCb-PAPER-2024-043], in preparation

- Analysis performed with $\mathscr{L} = 9\,fb^{-1}$, Run 1 + Run 2 data sample

Branching ratio measurements are performed in all channels:

$$\frac{\mathscr{B}(\Lambda_b^0/\Xi_b^0 \to \Lambda h^+ h^{'-})}{\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\,\pi^-)} = \frac{N_{\Lambda_b^0/\Xi_b^0 \to \Lambda h^+ h^{'-}}}{N_{\Lambda_b^0 \to \Lambda_c^+(\to\Lambda\pi^+)\,\pi^-}} \times \frac{\epsilon_{\Lambda_b^0 \to \Lambda_c^+(\to\Lambda\pi^+)\,\pi^-}}{\epsilon_{\Lambda_b^0/\Xi_b^0 \to \Lambda h^+ h^{'-}}} \times \frac{f_{\Lambda_b{}^0/\Xi_b^0}}{f_{\Lambda_b^0}}$$

- **Control mode** $\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\,\pi^-$
- **Used to reduce systematics uncertainties.**
- 6 BR measurements performed

Study of Λ_b^0/Ξ_b^0 decays to $\Lambda h^+ h^{'-}$ decays

[LHCb-PAPER-2024-043], in preparation

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Signal yields extracted from invariant mass fit

Efficiencies determined from simulations samples

Corrections applied using Data-driven techniques

Fragmentation fraction

Control mode

- $\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\,\pi^-$
- **Used to reduce systematics uncertainties.**
- 6 BR measurements performed

Study of Λ_b^0/Ξ_b^0 decays to $\Lambda h^+ h'^-$ decays

[LHCb-PAPER-2024-043], in preparation

- Branching fraction measurements results

NEW!

- $N = 1920 \pm 50$

  $\mathscr{B} = (10.7 \pm 0.3 \pm 0.4 \pm 1.1) \times 10^{-6}$

- $N = 618 \pm 32$

  $\mathscr{B} = (4.6 \pm 0.2 \pm 0.4 \pm 0.5) \times 10^{-6}$

- $N = 640 \pm 40$

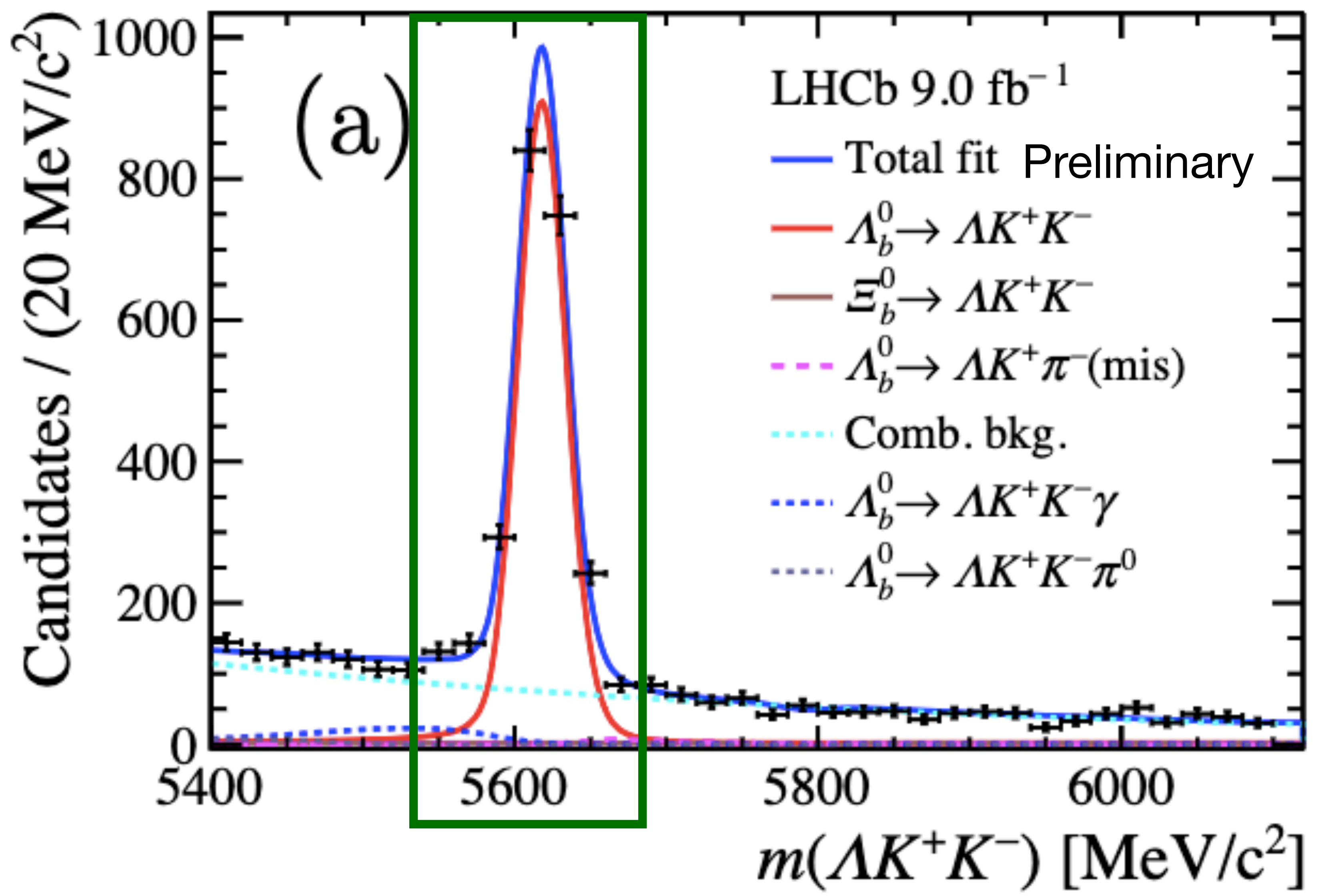
  $\mathscr{B} = (5.3 \pm 0.4 \pm 0.5 \pm 0.5) \times 10^{-6}$

Study of Λ_b^0/Ξ_b^0 decays to $\Lambda h^+ h'^-$ decays [LHCb-PAPER-2024-043], in preparation

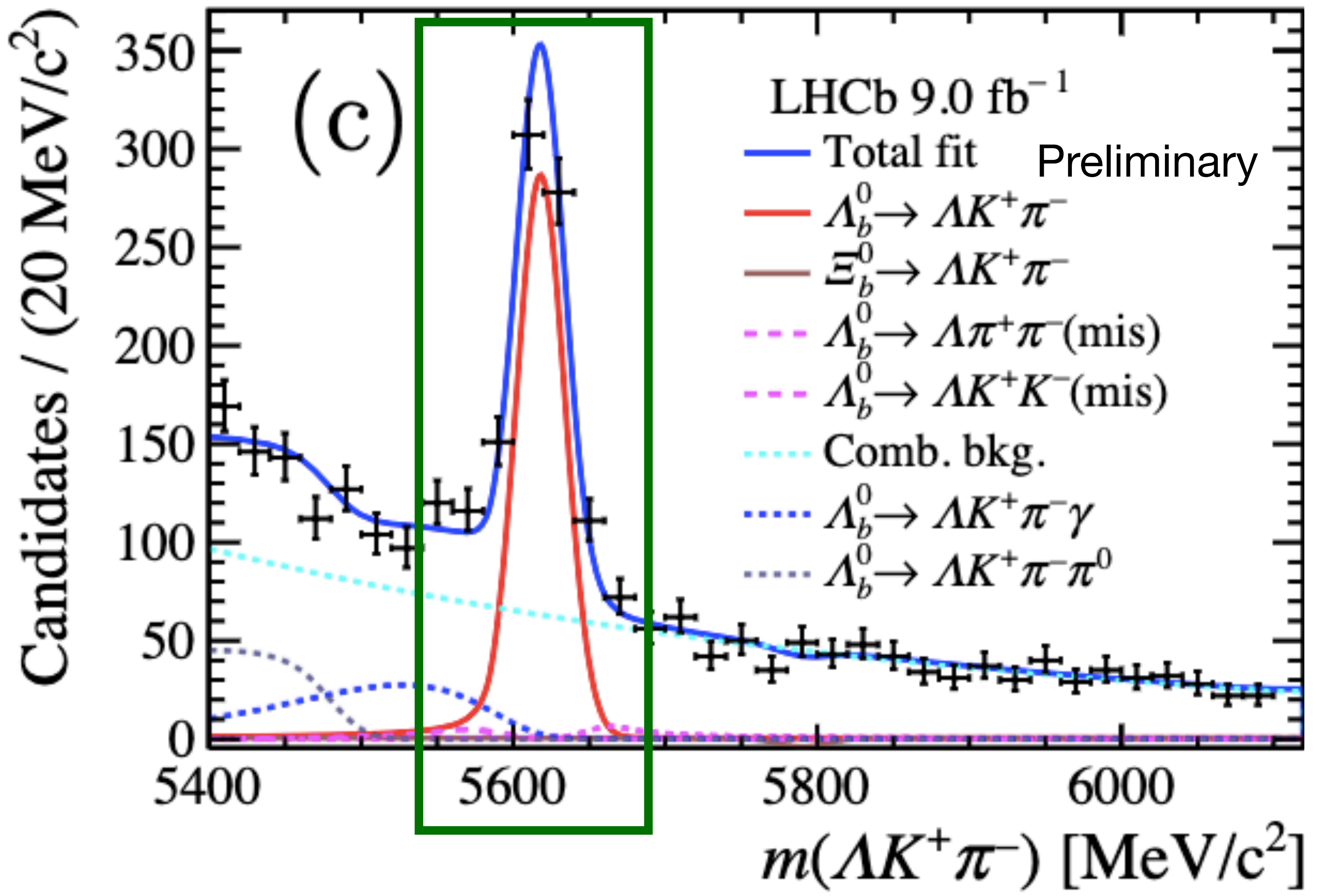
- Branching fraction measurements results

NEW!

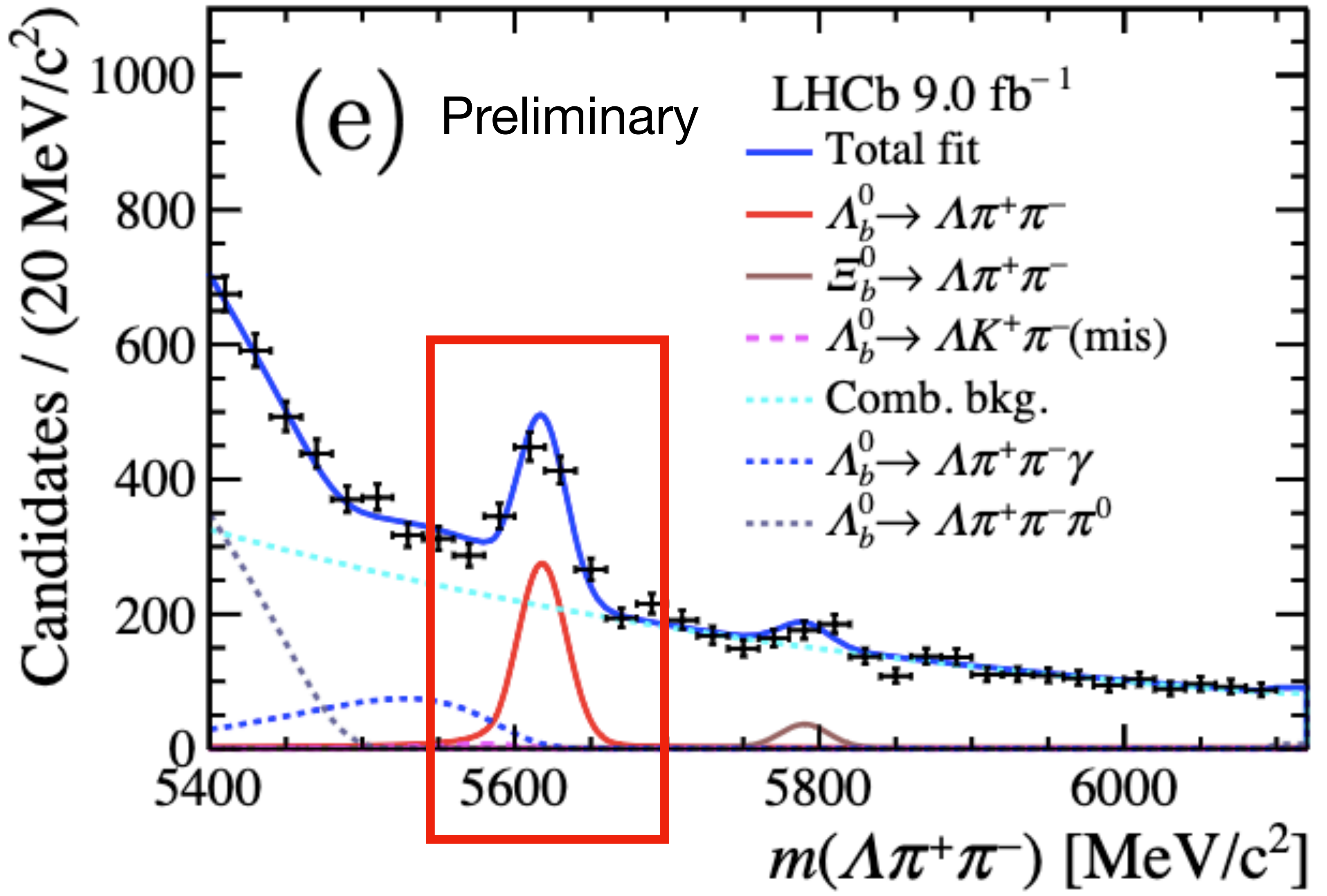
$\Lambda_b^0 \to \Lambda K^+ K^-$



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



$\Lambda_b^0 \to \Lambda \pi^+ \pi^-$



- $N = 1920 \pm 50$

$\mathscr{B} = (10.7 \pm 0.3 \pm 0.4 \pm 1.1) \times 10^{-6}$

Confirmation

- $N = 618 \pm 32$

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Confirmation

- $N = 640 \pm 40$

$\mathscr{B} = (5.3 \pm 0.4 \pm 0.5 \pm 0.5) \times 10^{-6}$

First Observation!

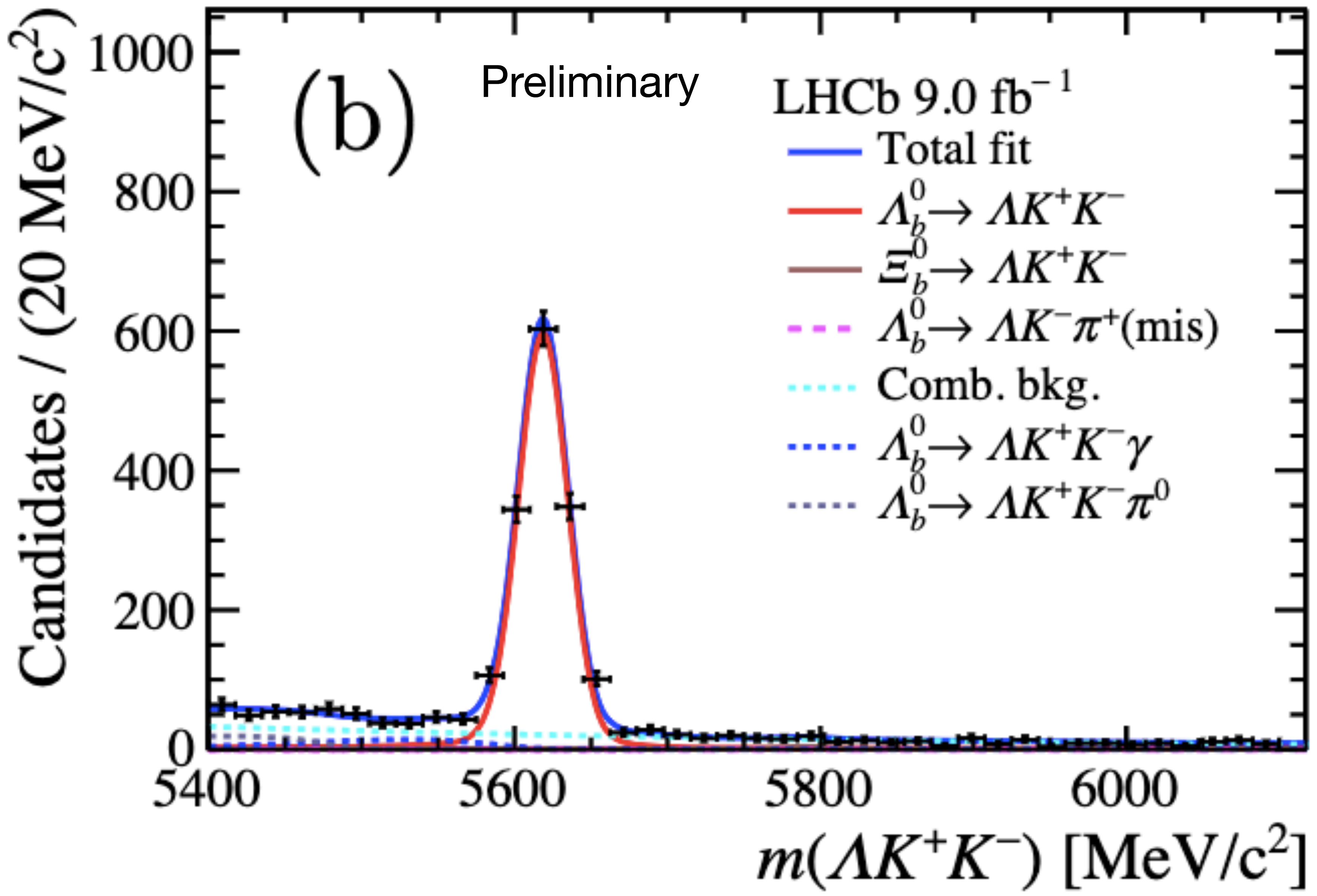
> 10 σ of significance

Study of Λ_b^0/Ξ_b^0 decays to $\Lambda h^+ h'^-$ decays [LHCb-PAPER-2024-043], in preparation

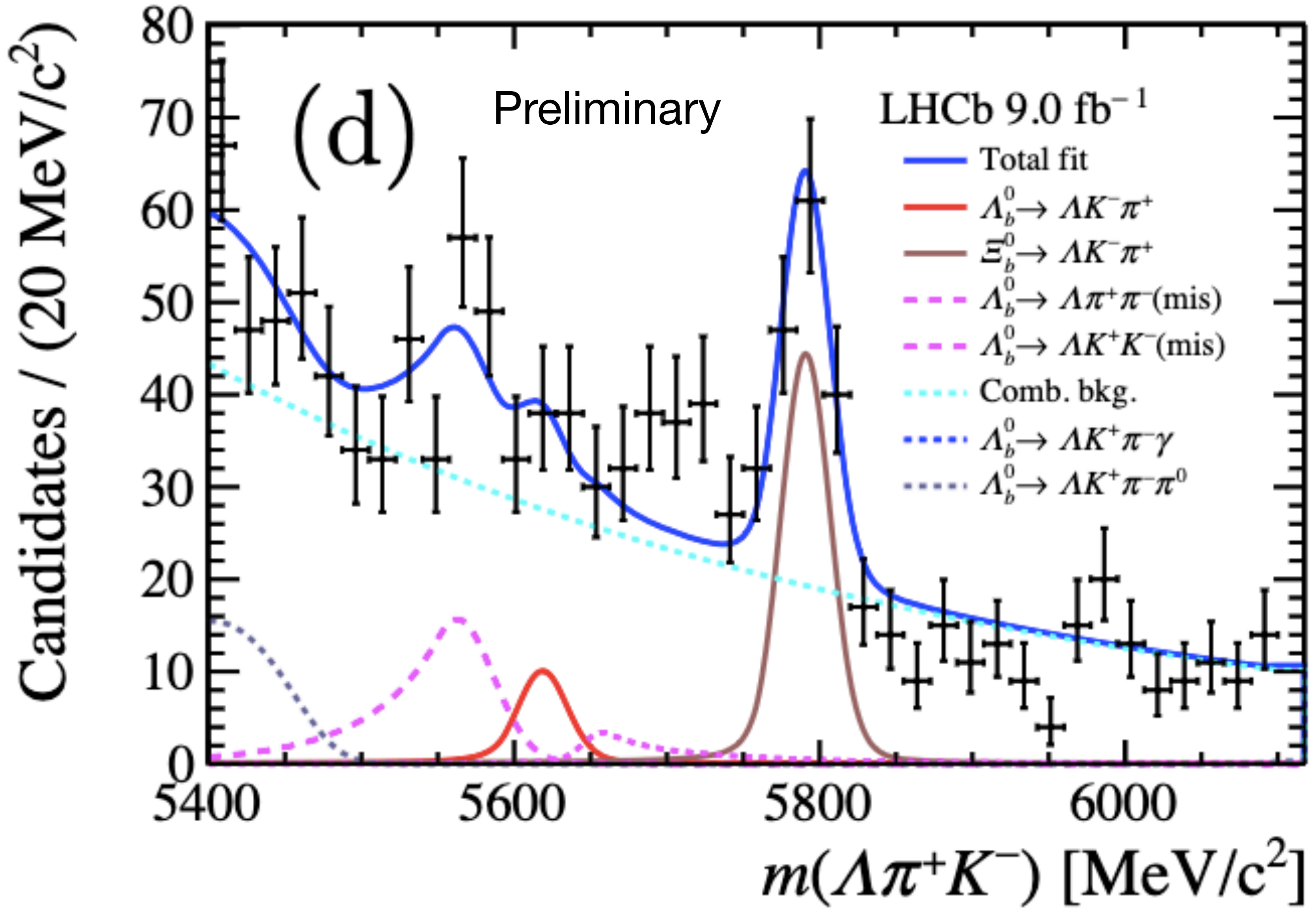
- Branching fraction measurements results

NEW!

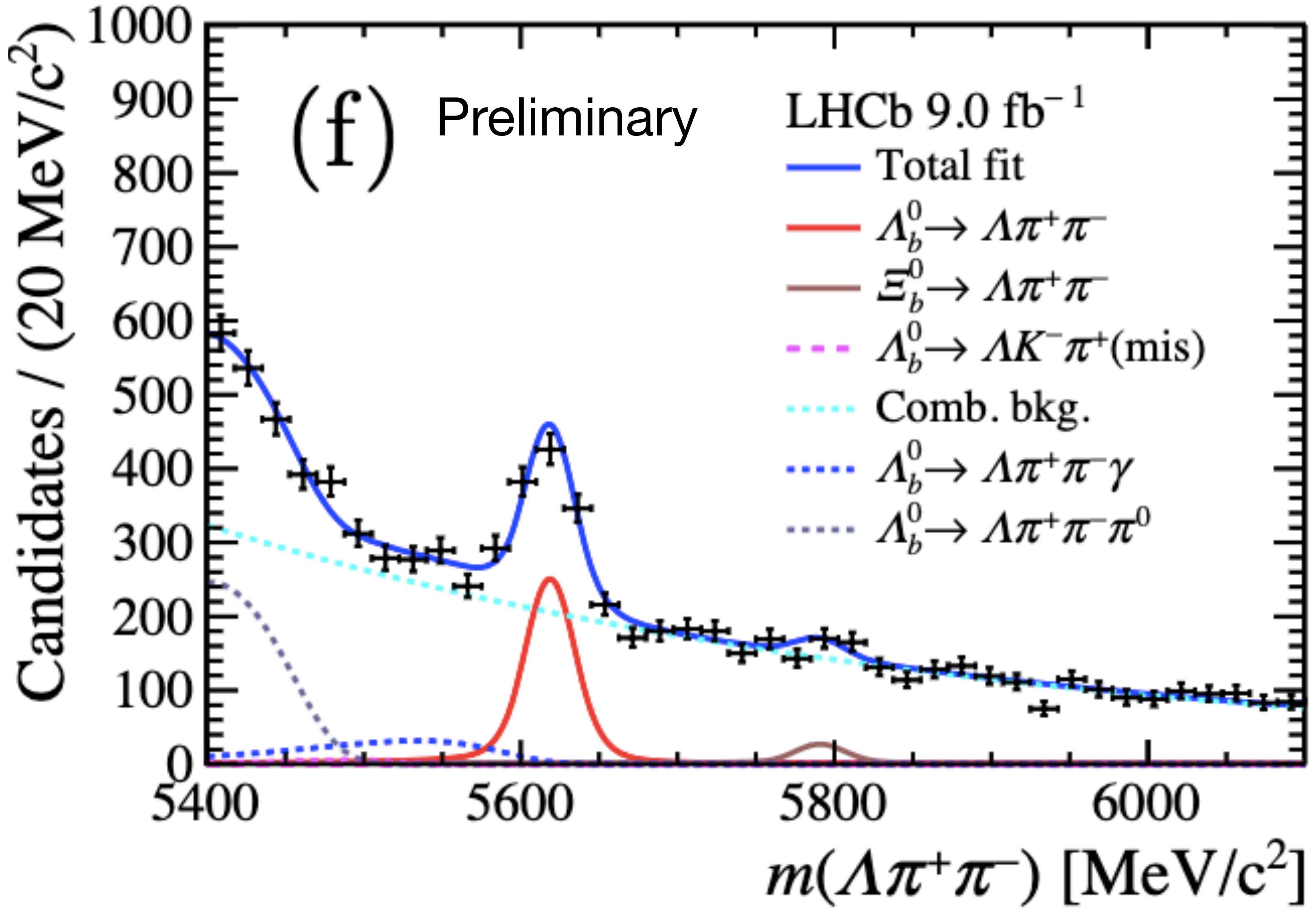
$\Xi_b^0 \to \Lambda K^+ K^-$



$\Xi_b^0 \to \Lambda K^- \pi^+$



$\Xi_b^0 \to \Lambda \pi^+ \pi^-$



- $N = 12 \pm 9$
  $\mathscr{B} < 2.4(2.8) \times 10^{-6}$ @ 90 % (95%) C.L
- $N = 119 \pm 15$
  $\mathscr{B} = (10.4 \pm 1.4 \pm 1.2 \pm 3.5) \times 10^{-6}$
- $N = 56 \pm 27$
  $\mathscr{B} = (11.0 \pm 2.6 \pm 1.4 \pm 3.8) \times 10^{-6}$

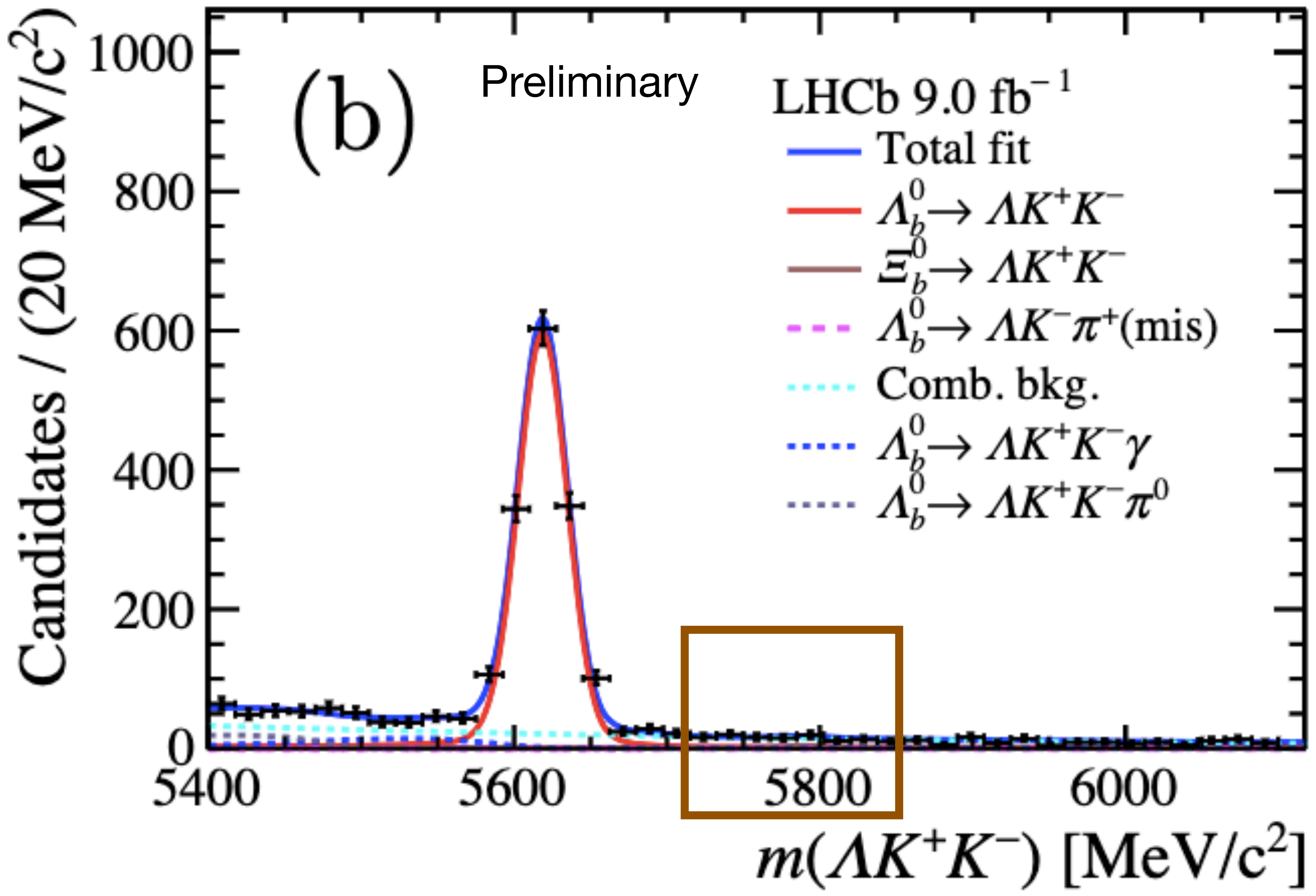
Study of Λ_b^0/Ξ_b^0 decays to $\Lambda h^+ h^{'-}$ decays

[LHCb-PAPER-2024-043], in preparation

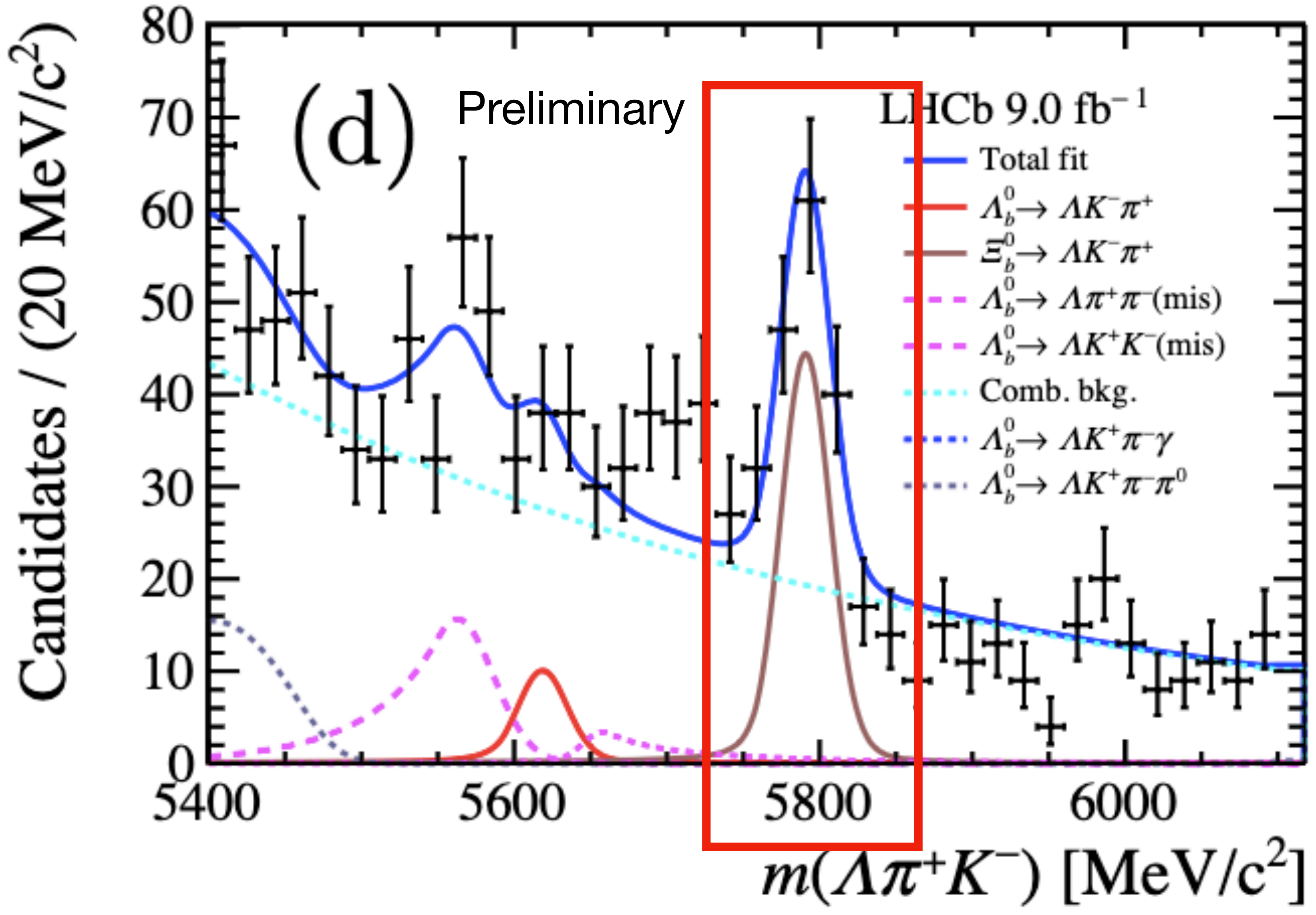
- Branching fraction measurements results

NEW!

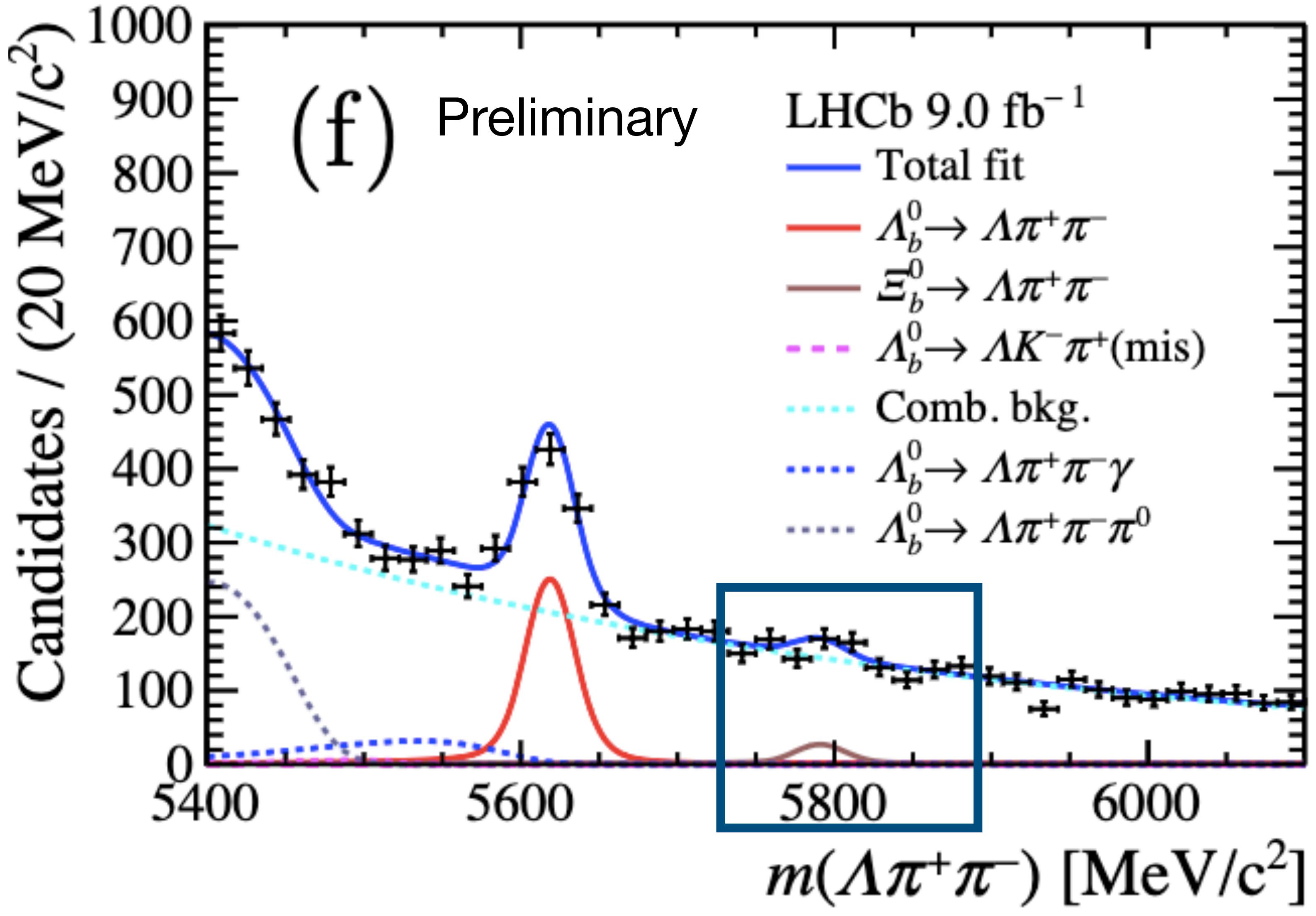
$\Xi_b^0 \to \Lambda K^+ K^-$



$\Xi_b^0 \to \Lambda K^- \pi^+$



$\Xi_b^0 \to \Lambda \pi^+ \pi^-$



- $N = 12 \pm 9$

$\mathscr{B} < 2.4(2.8) \times 10^{-6} @ 90\,\% \,(95\%)\, C.L$

No evidence

1.7 σ of significance

- $N = 119 \pm 15$

$\mathscr{B} = (10.4 \pm 1.4 \pm 1.2 \pm 3.5) \times 10^{-6}$

First Observation!

> 10 σ of significance

- $N = 56 \pm 27$

$\mathscr{B} = (11.0 \pm 2.6 \pm 1.4 \pm 3.8) \times 10^{-6}$

First evidence

4 σ of significance

Study of Λ_b^0/Ξ_b^0 decays to $\Lambda h^+ h'^-$ decays

[LHCb-PAPER-2024-043], in preparation

CP violation measurements: $\Delta A_{CP} = A_{CP}(\Lambda_b^0/\Xi_b^0 \to f) - A_{CP}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)$

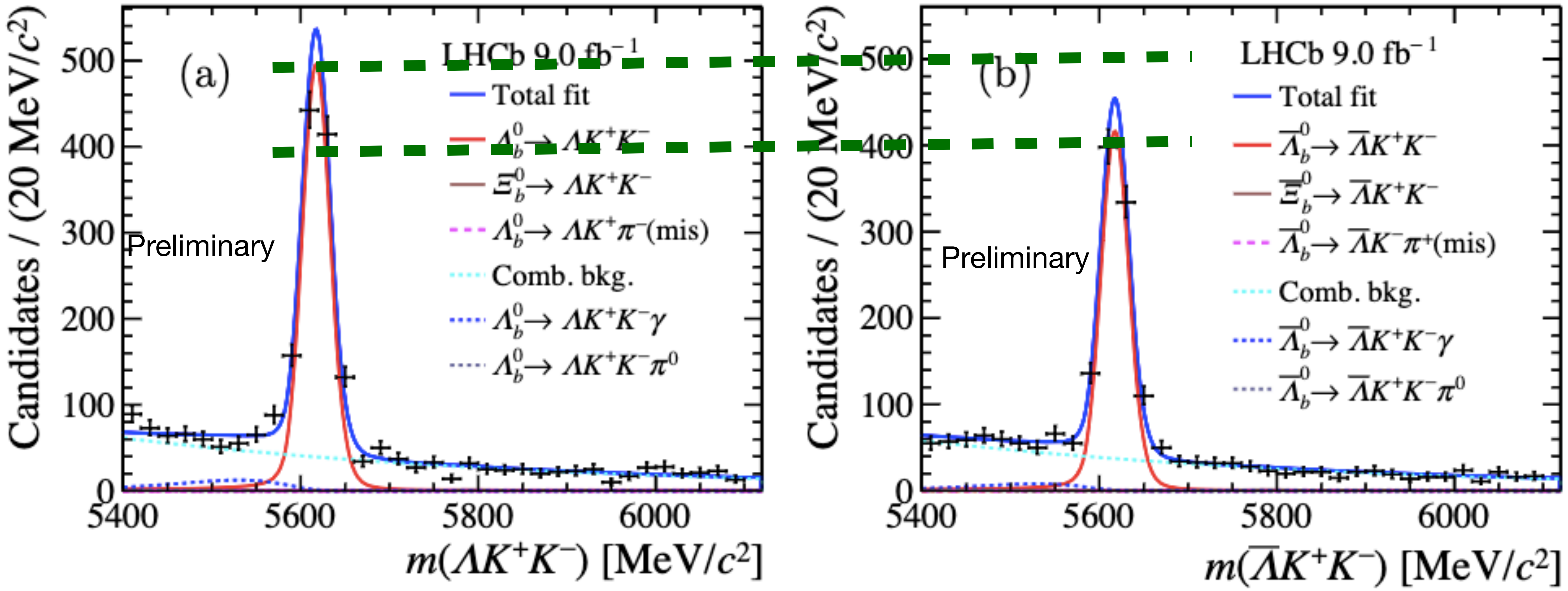
NEW!

$\Delta A_{CP}(\Lambda_b^0 \to \Lambda K^+ \pi^-) = -0.118 \pm 0.045 \pm 0.021,$ **2.4** σ

$\Delta A_{CP}(\Lambda_b^0 \to \Lambda \pi^+ \pi^-) = -0.013 \pm 0.053 \pm 0.018$ **0.2** σ

$\boxed{\Delta A_{CP}(\Lambda_b^0 \to \Lambda K^+ K^-) = 0.083 \pm 0.023 \pm 0.016}$ → **First Evidence of CP violation, $3.1\,\sigma$ of significance**

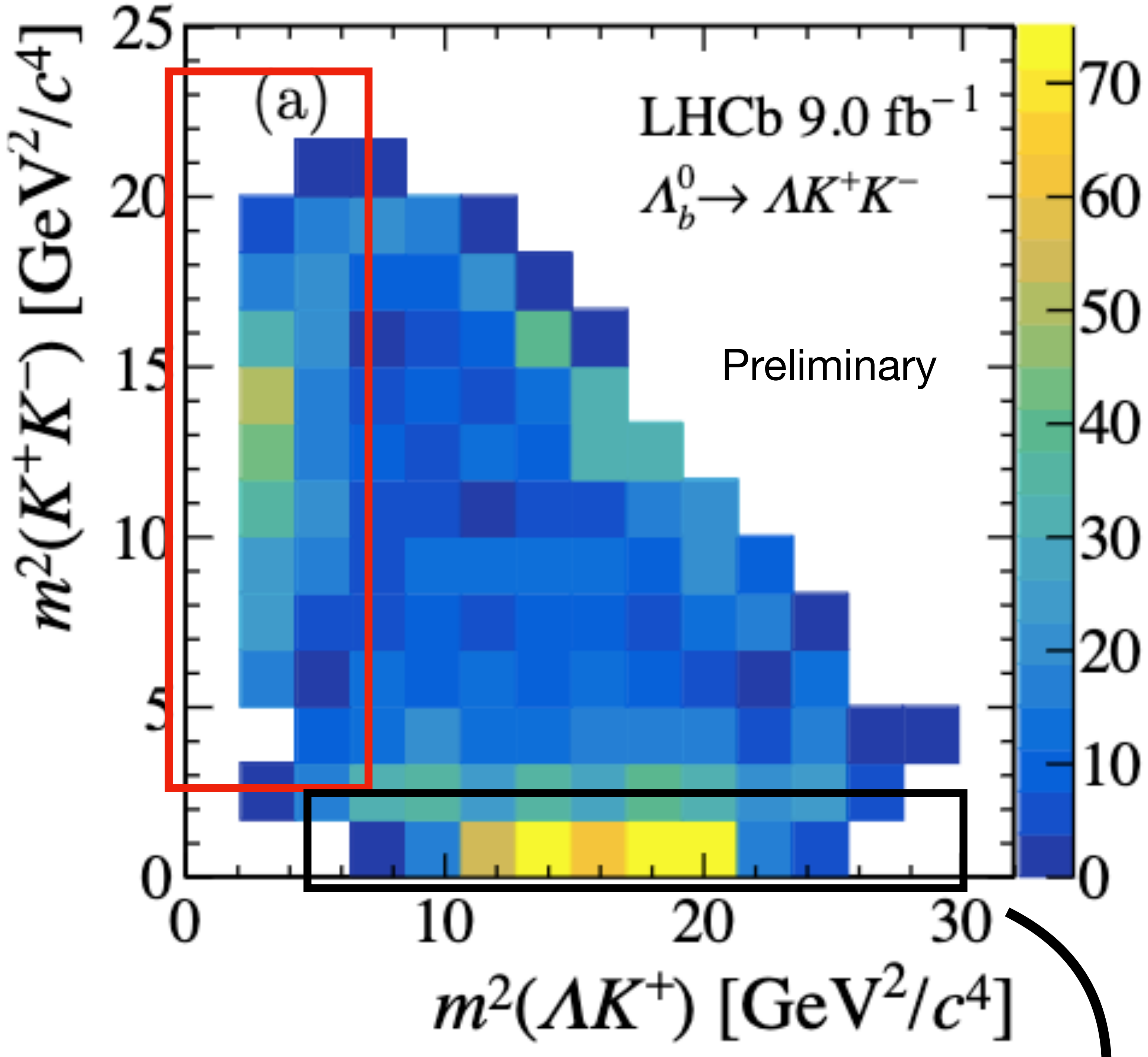
$\Delta A_{CP}(\Xi_b^0 \to \Lambda K^- \pi^+) = 0.27 \pm 0.12 \pm 0.05$ **2.1** σ



Study of Λ_b^0/Ξ_b^0 decays to $\Lambda h^+ h'^-$ decays

[LHCb-PAPER-2024-043], in preparation

$\Lambda_b^0 \to N^{*+}K^-$

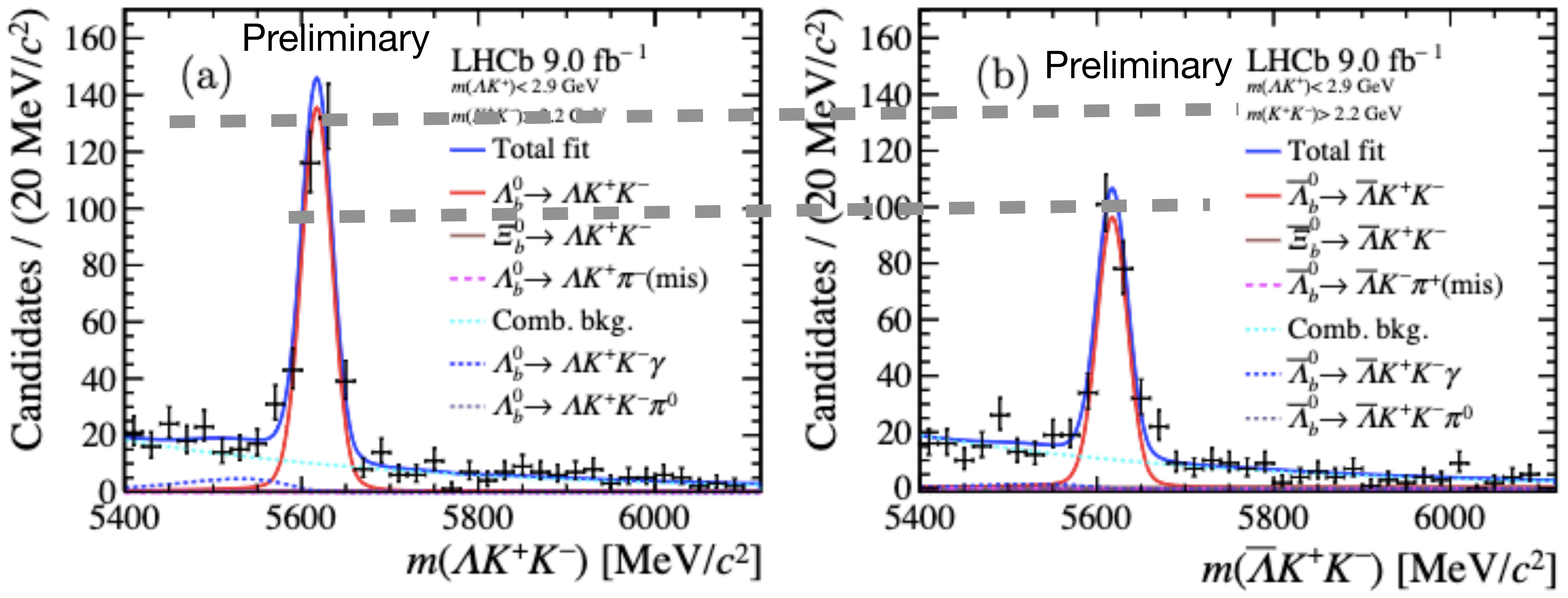


$\Lambda_b^0 \to \Lambda\phi$

Dalitz plot with background subtracted
with sPlot technique

NEW!

For the $\Lambda_b^0 \to N^{*+}K^-$ region



$\Delta A_{CP}(N^{*+}K^-) = 0.165 \pm 0.048 \pm 0.017$, **with** $3.2\,\sigma$

First evidence of CP violation in localized region

$\Delta A_{CP}(\Lambda\phi) = 0.150 \pm 0.055 \pm 0.021$, **consistent with zero in** $2.5\,\sigma$

[LHCb-PAPER-2024-031], in preparation

CP asymmetries and BF of $B^+ \to J/\psi\pi^+$ decays

- Analysis performed with Run 2 data set $\mathscr{L} = 6\,fb^{-1}$
- Measurements performed separately for 2016, 2017 and 2018 and then combined

- Measurement of CP asymmetry, using control channel $B^+ \to J/\psi K^+$

$$\Delta\mathcal{A}^{CP} \equiv \mathcal{A}^{CP}(B^+ \to J/\psi\pi^+) - \mathcal{A}^{CP}(B^+ \to J/\psi K^+).$$

- Ratio of Branching fractions defined as

$$\mathcal{R}_{K/\pi} \equiv \frac{\mathcal{B}(B^+ \to J/\psi\pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)},$$

- Sizable direct CP violation up to the percent level could arise from interference between the tree and penguin contributions

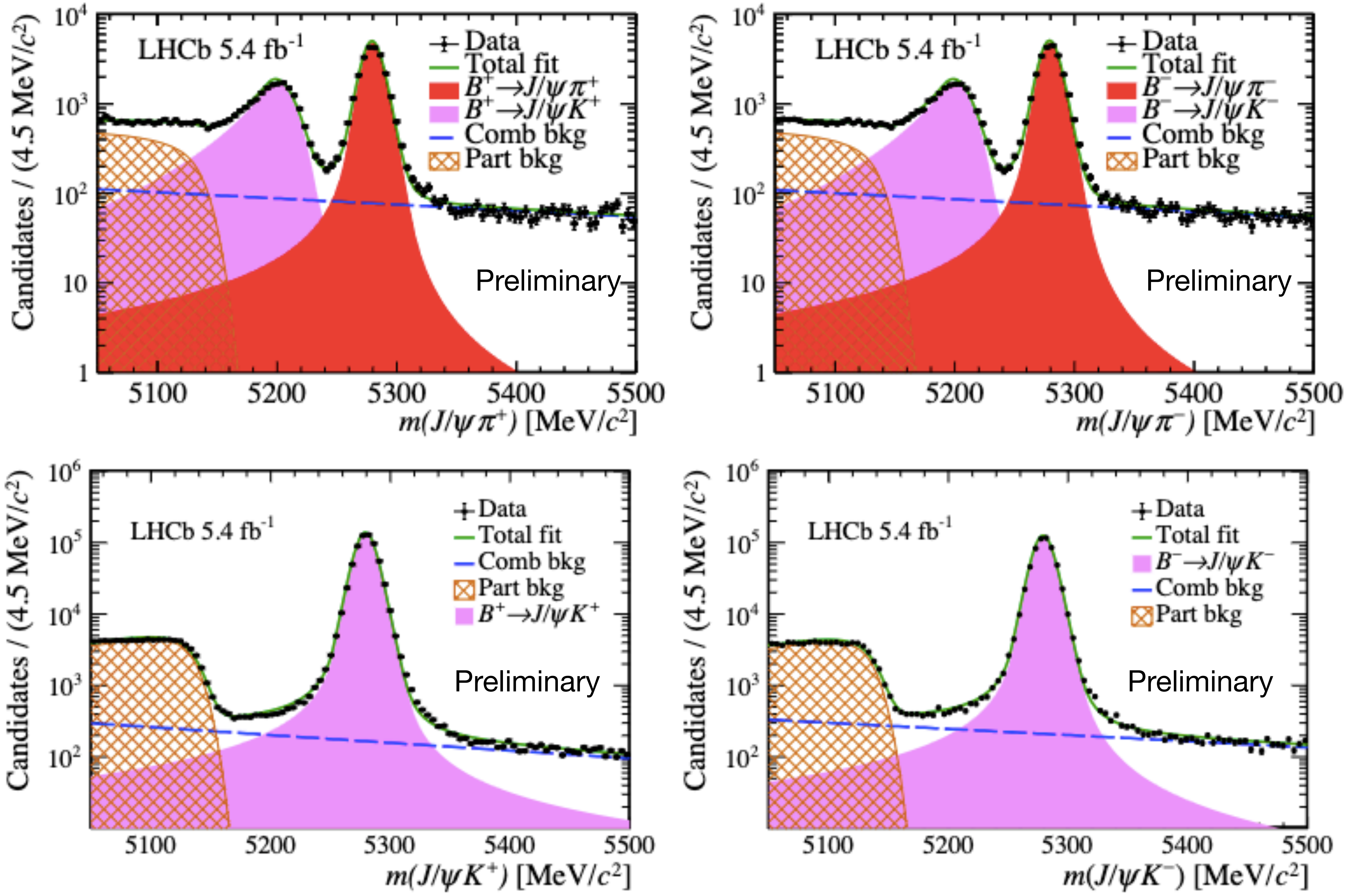
  ➡ still not observed

- LHCb previous measurements are consistent with CP conservation.

CP asymmetries and BF of $B^+ \to J/\psi\pi^+$ decays

Invariant mass fit to signal and control channel

NEW!



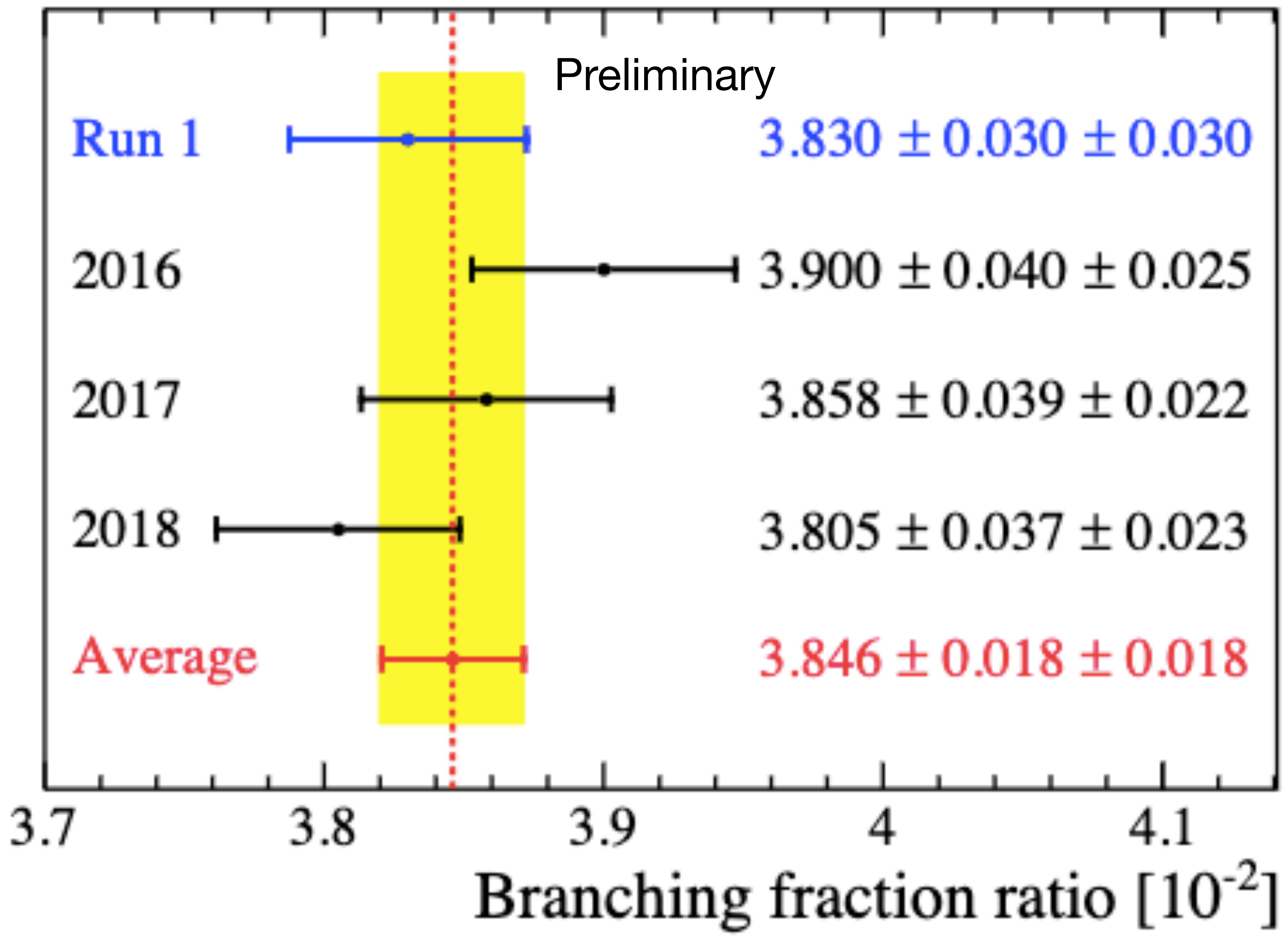
Combined 2016-2018 data sample

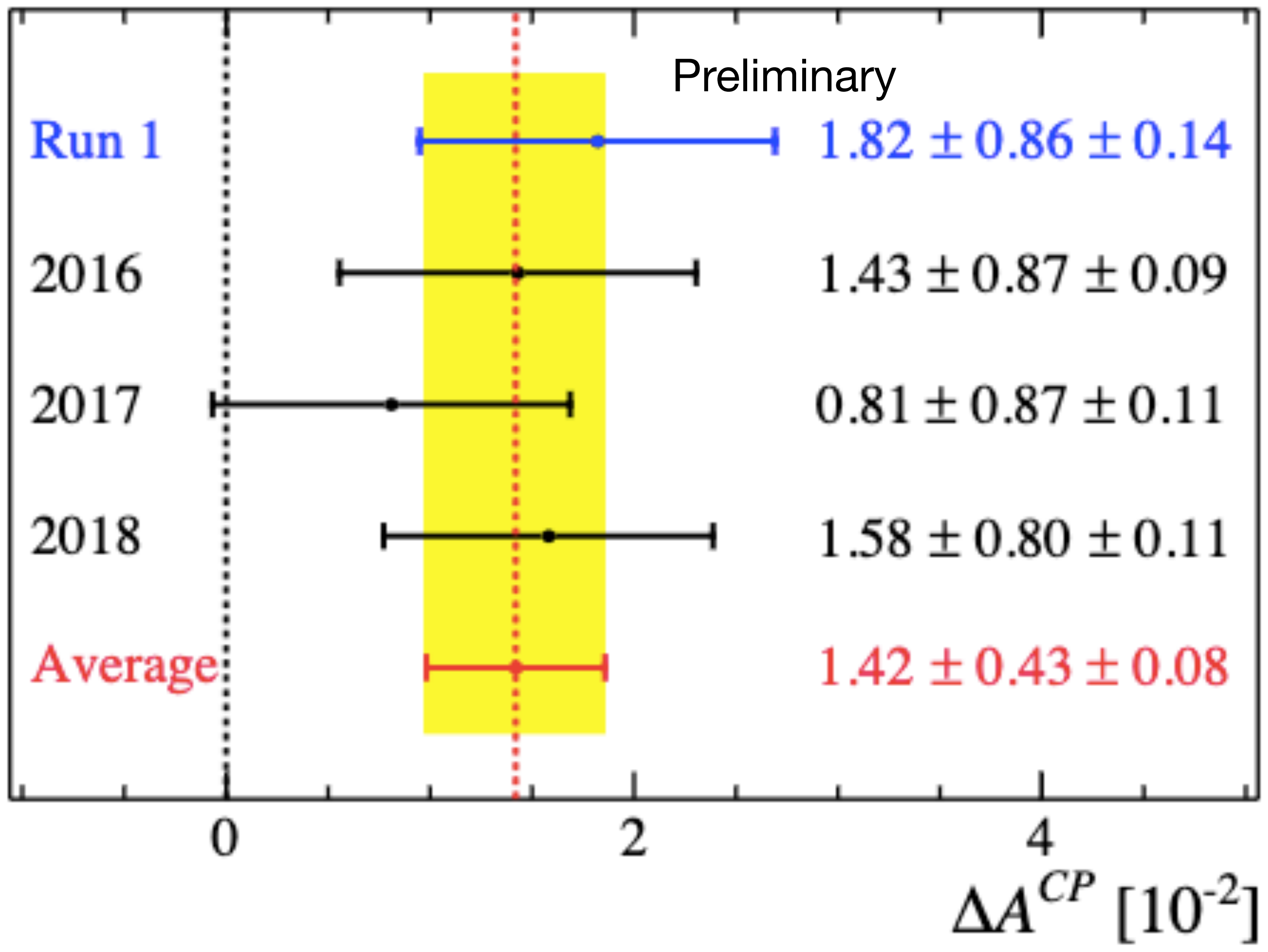
Measurements results:

$$\mathcal{R}_{K/\pi} = \begin{cases} (3.900 \pm 0.040 \pm 0.025) \times 10^{-2} & (2016) \\ (3.858 \pm 0.039 \pm 0.022) \times 10^{-2} & (2017) \\ (3.805 \pm 0.037 \pm 0.023) \times 10^{-2} & (2018), \end{cases}$$

$$\Delta\mathcal{A}^{CP} = \begin{cases} (1.43 \pm 0.87 \pm 0.09) \times 10^{-2} & (2016) \\ (0.81 \pm 0.87 \pm 0.11) \times 10^{-2} & (2017) \\ (1.58 \pm 0.80 \pm 0.11) \times 10^{-2} & (2018), \end{cases}$$

CP asymmetries and BF of $B^+ \to J/\psi\pi^+$ decays





NEW!

Measurements results:

- Provides the **first evidence of direct CP violation** in beauty to charmonia, with 3.2 σ
- The ΔA^{CP} and $\mathscr{R}_{K/\pi}$ can help to control effects of penguin contributions in the golden channel $B^0 \to J/\psi K^0$ affecting the determination of CP-violating phase 2β.

Summary

- A lot of work ongoing in the LHCb experiment, with a very broad program in the search for *CP*-asymmetries in b hadrons.

- Most precise measurements for of CP asymmetry for $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$

- **First evidence of direct CP violation** in baryon decays $\Lambda_b^0 \to \Lambda K^+ K^-$ decays

- **First evidence of direct CP violation** in beauty to charmonia decays

- More data to come in the Run 3 era, further studies in the pipeline, improvement in precision measurements.

Thank you!