



Measurements of CPV and mixing in beauty decays to charmless and charmonia final states

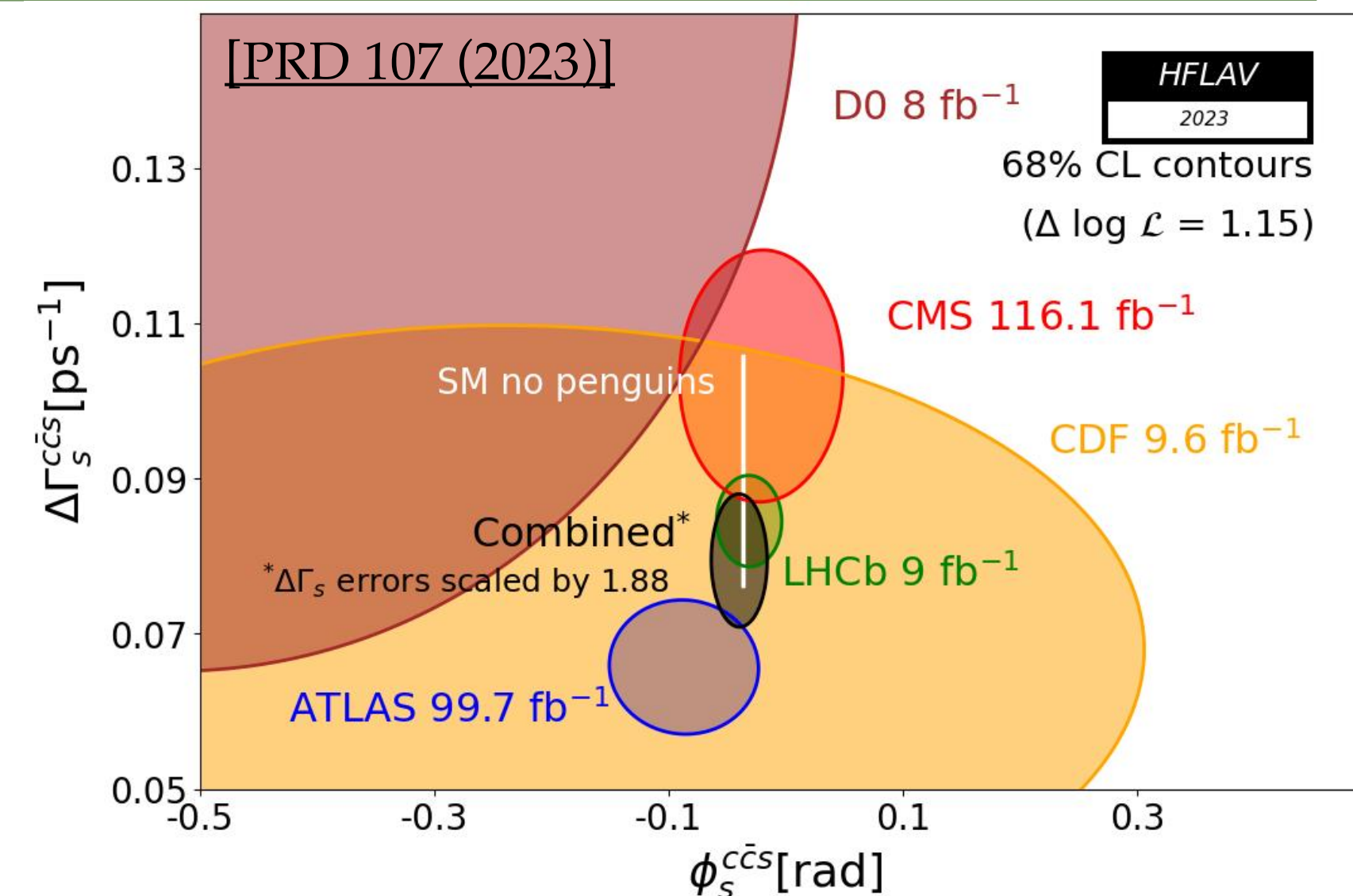
Andrea Villa, on behalf of the LHCb Collaboration

Implications of LHCb measurements and future prospects, 23-25 October 2024

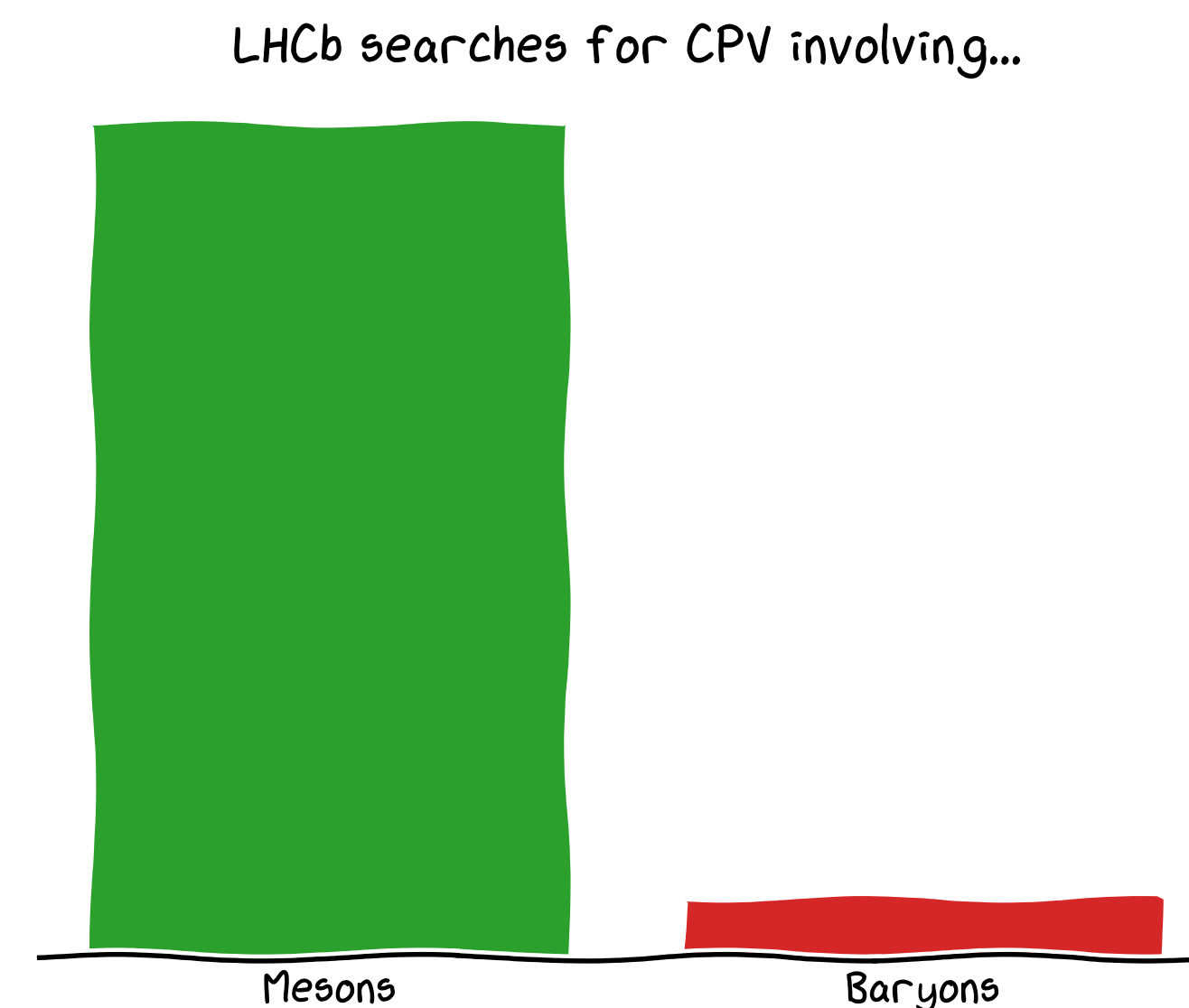
LHCb
LHCb

Introduction

- Beauty to charmonia decays:
 - Allow to measure CKM angle β and weak phases $\phi_{(s)}$
 - Stringent tests of the SM and powerful probes for New Physics
 - Today: CP asymmetry and branching fraction of $B^+ \rightarrow J/\psi\pi^+$ decays
[LHCb-PAPER-2024-031], in preparation



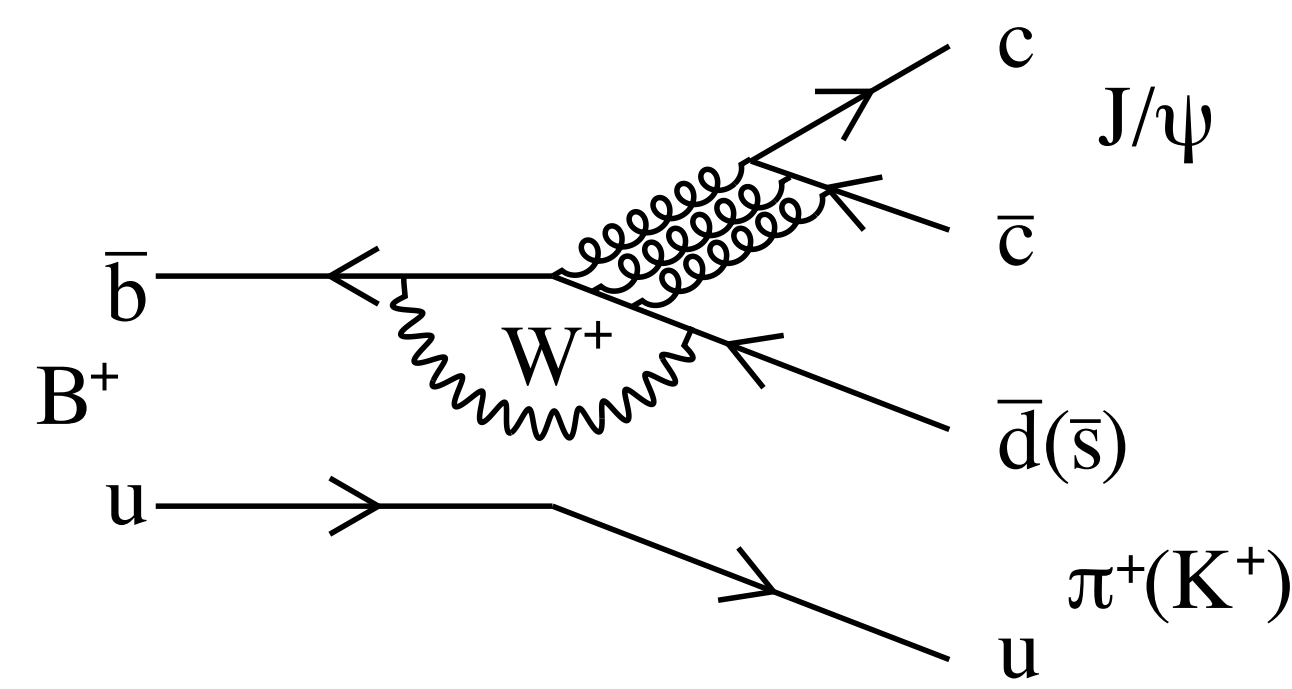
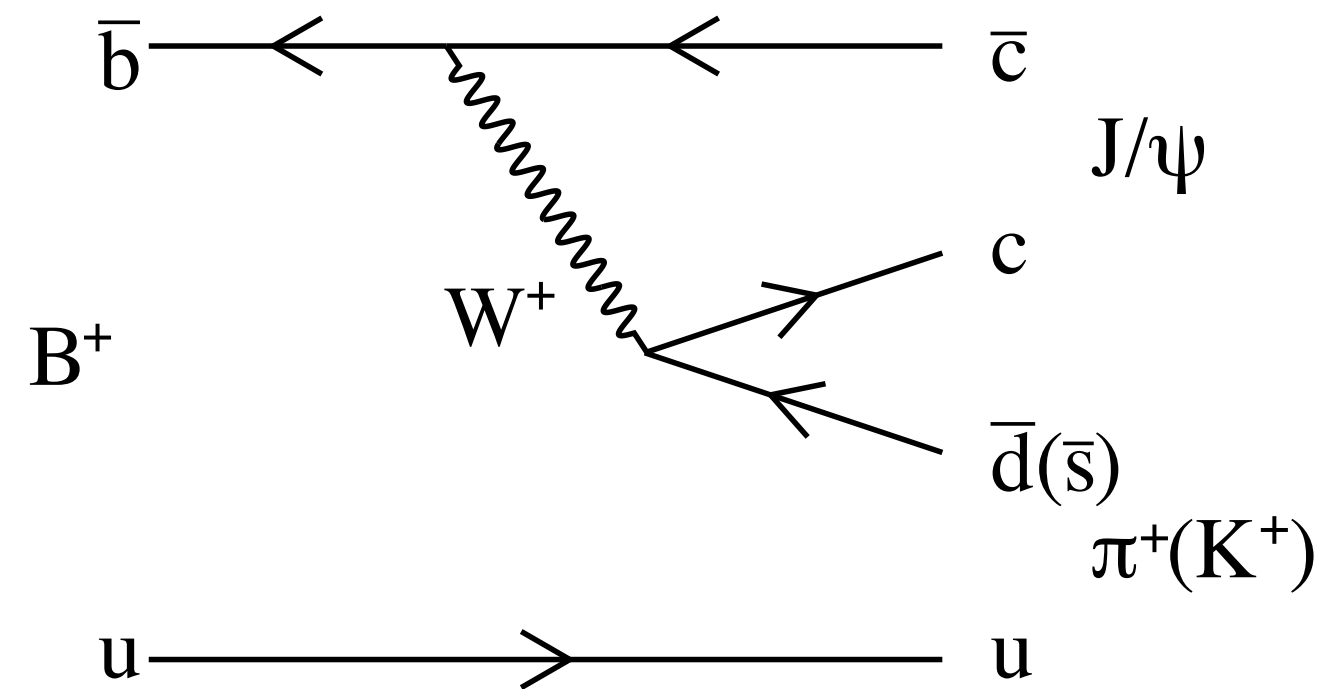
- Charmless decays of beauty baryons:
 - Overlooked in favour of mesons until now
 - Avoiding charm final-states allows for sizeable penguin contributions \rightarrow possible CPV enhancement
 - Today:
 CP asymmetries with $\Lambda_b^0 \rightarrow ph^-$ decays
[LHCb-PAPER-2024-048], in preparation
Study of Λ_b^0 and Ξ_b^0 decays to $\Lambda h^+ h'^-$ final states
[LHCb-PAPER-2024-043], in preparation



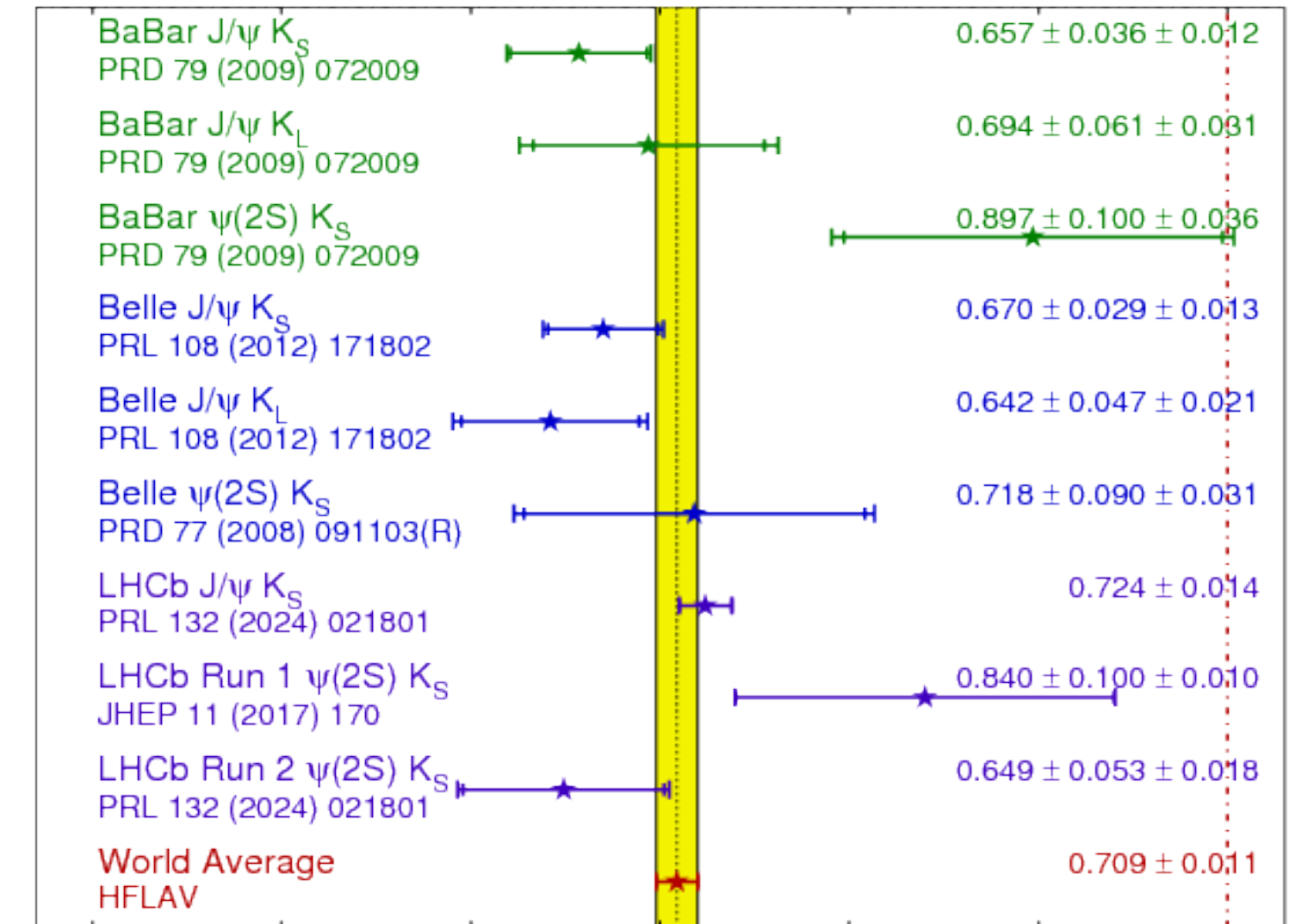
CP asymmetry and branching fraction of $B^+ \rightarrow J/\psi\pi^+$ decays

- $b \rightarrow c\bar{c}d$ decay
- Less CKM-suppression for penguin diagrams
 \longrightarrow **CPV enhancement** from interference? [PRD 49 (1994)]
 [PRD 52 (1995)]
- Can improve understanding of penguin contribution to $b \rightarrow c\bar{c}s$ transitions (β from $B^0 \rightarrow J/\psi K^0$)

[PRL 95 (2005)] [JHEP 03 (2015)]
 [PRD 79 (2009)] [JPG 48 (2021)]



$\sin(2\beta) \equiv \sin(2\phi_1)$ **HFLAV**
 Moriond 2024
 PRELIMINARY



[PRD 107 (2023)]

CP asymmetry and branching fraction of $B^+ \rightarrow J/\psi\pi^+$ decays

New!

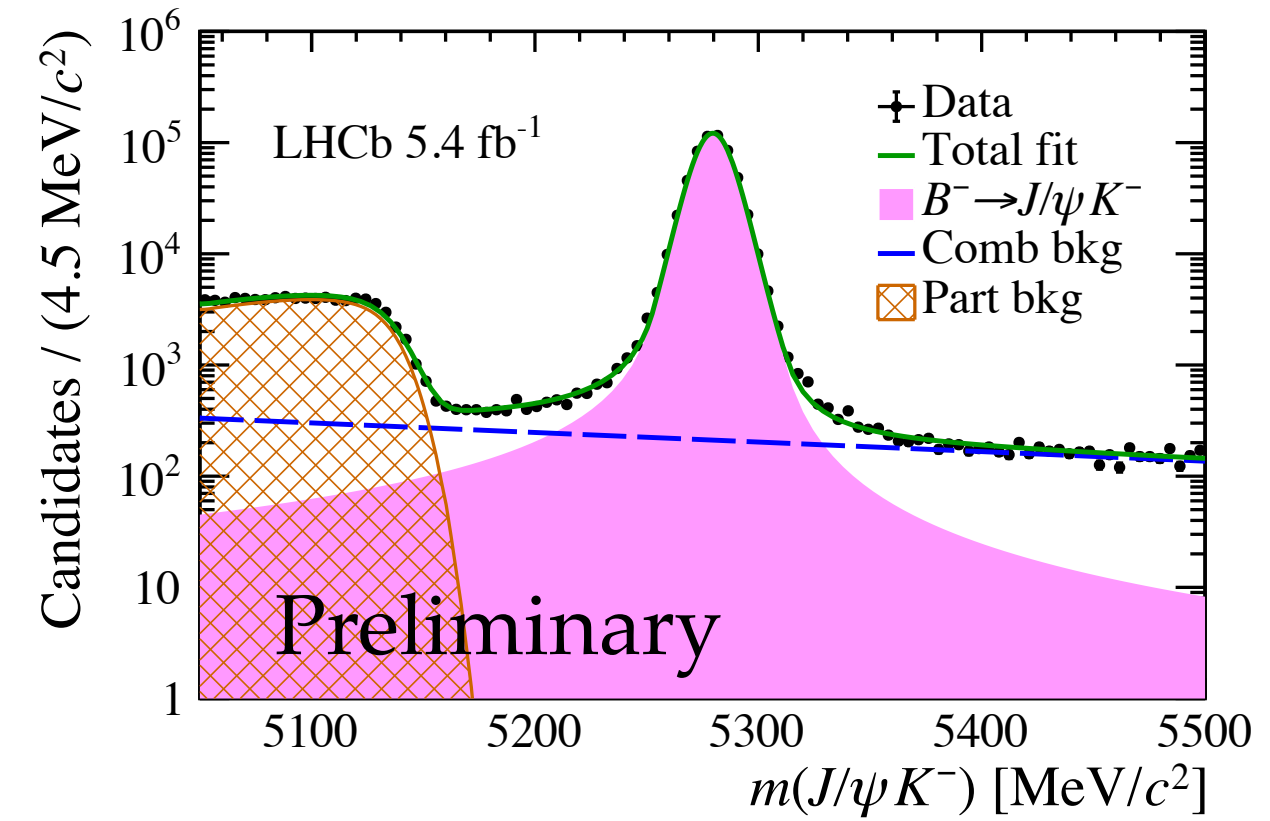
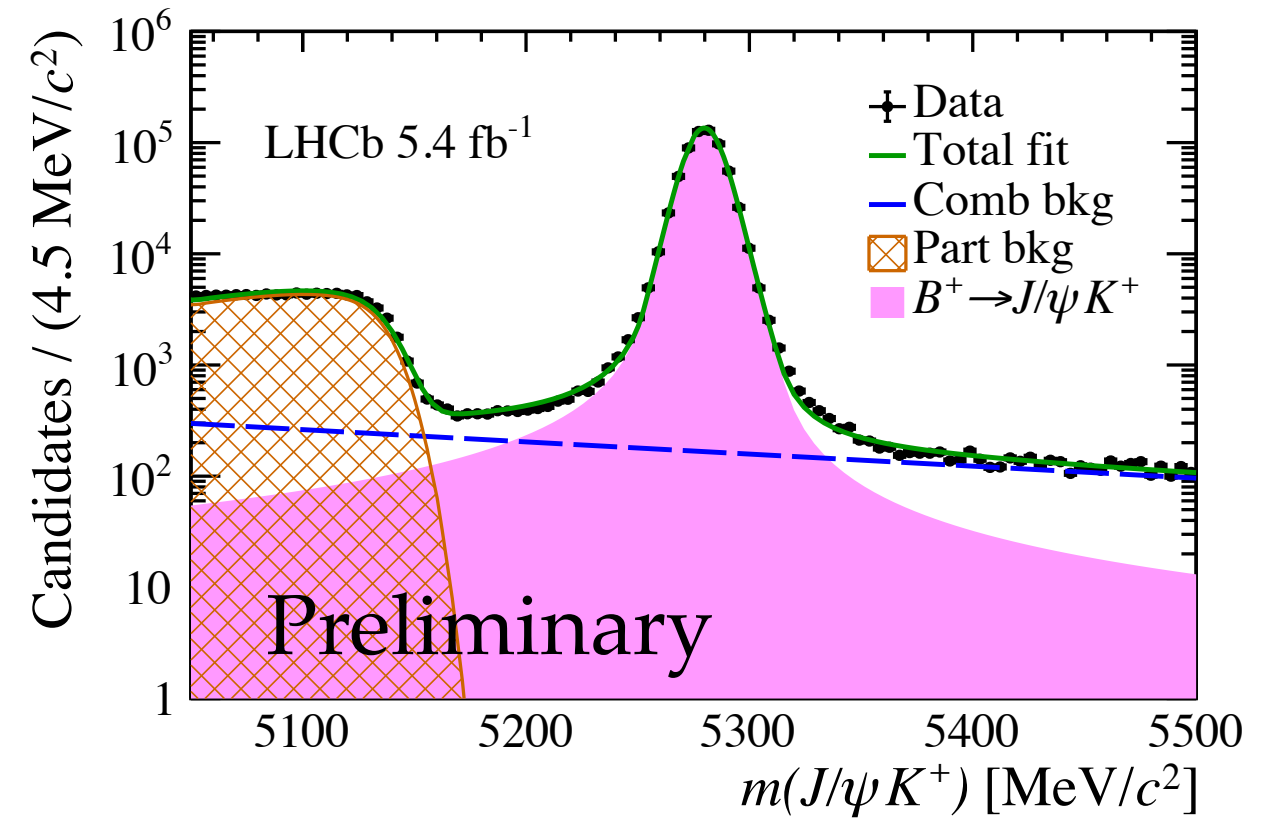
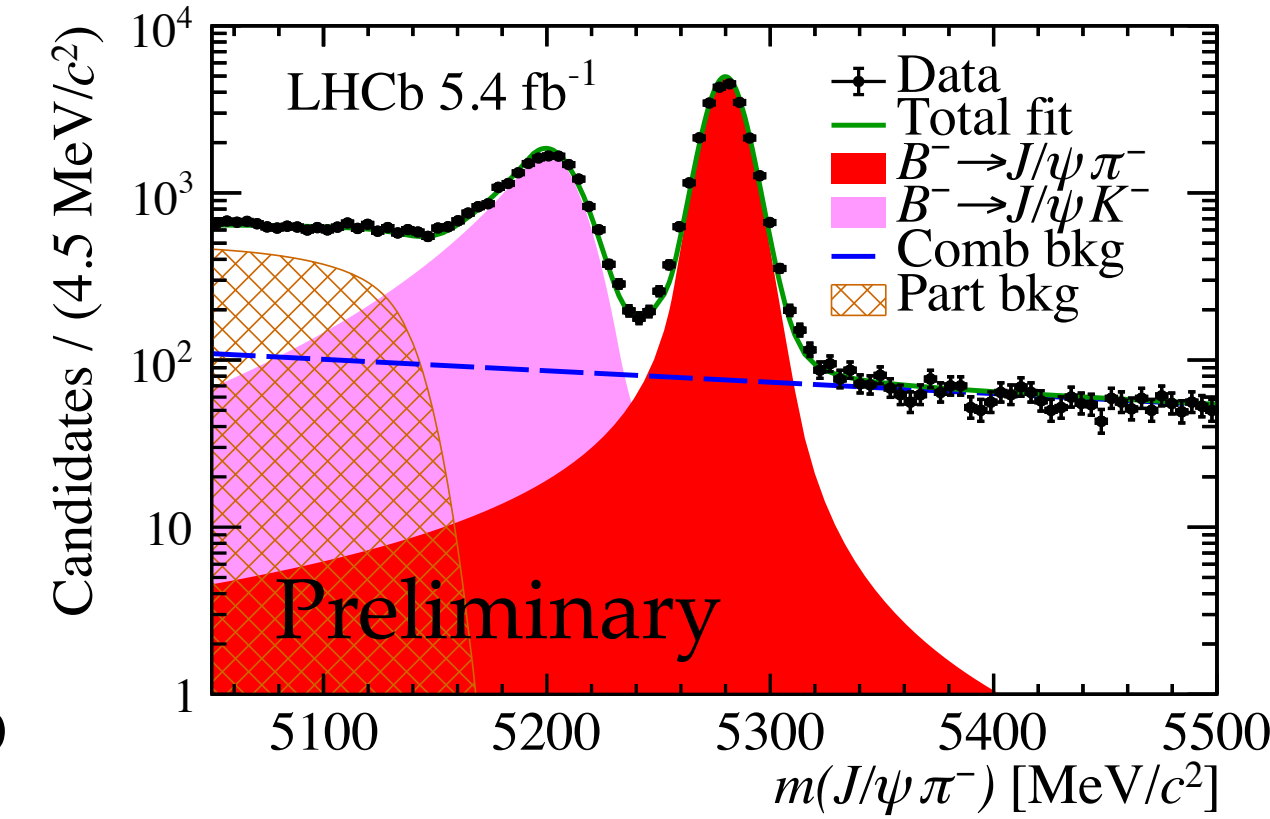
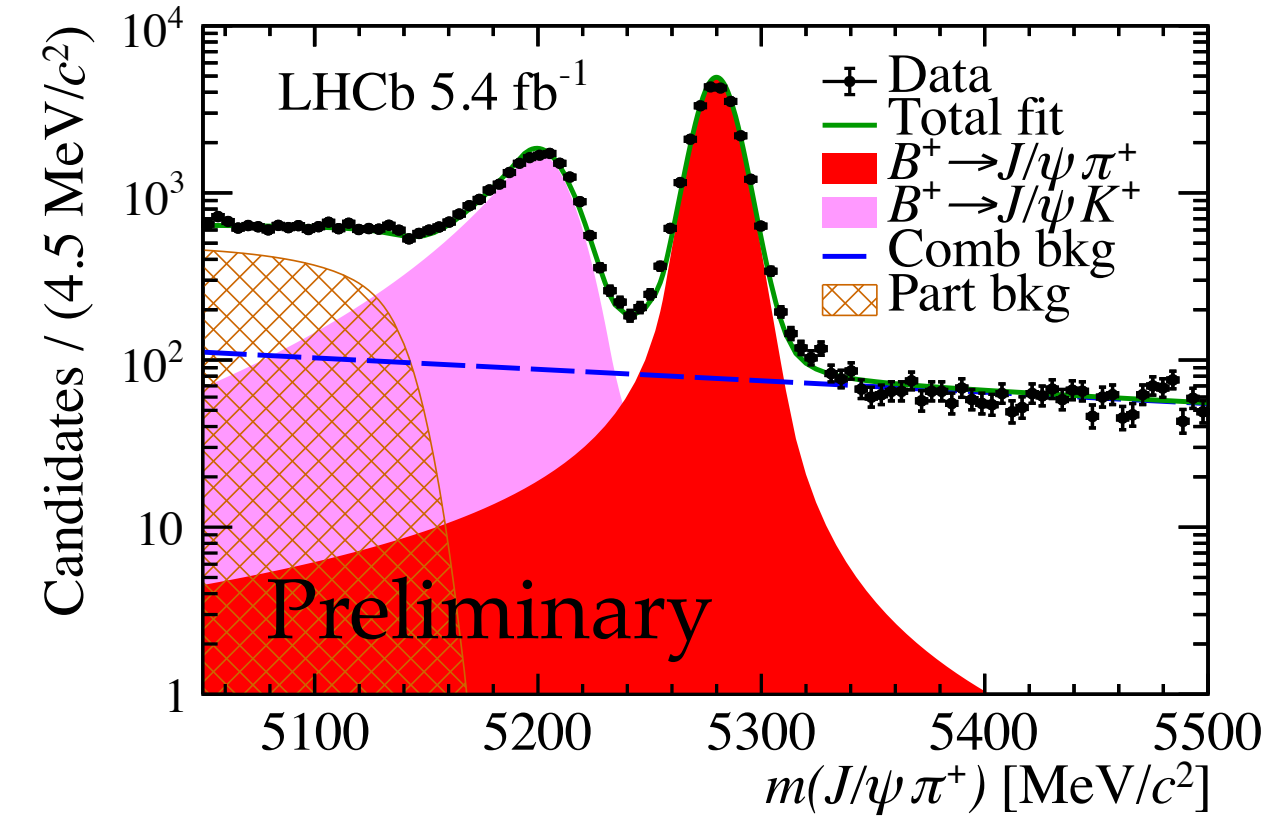
[LHCb-PAPER-2024-031], in preparation

- New measurement of BF and CP asymmetry with LHCb Run 2 dataset ($\mathcal{L} = 6 \text{ fb}^{-1}$)
- Measured relative to control sample of $B^+ \rightarrow J/\psi K^+$ decays:

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

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

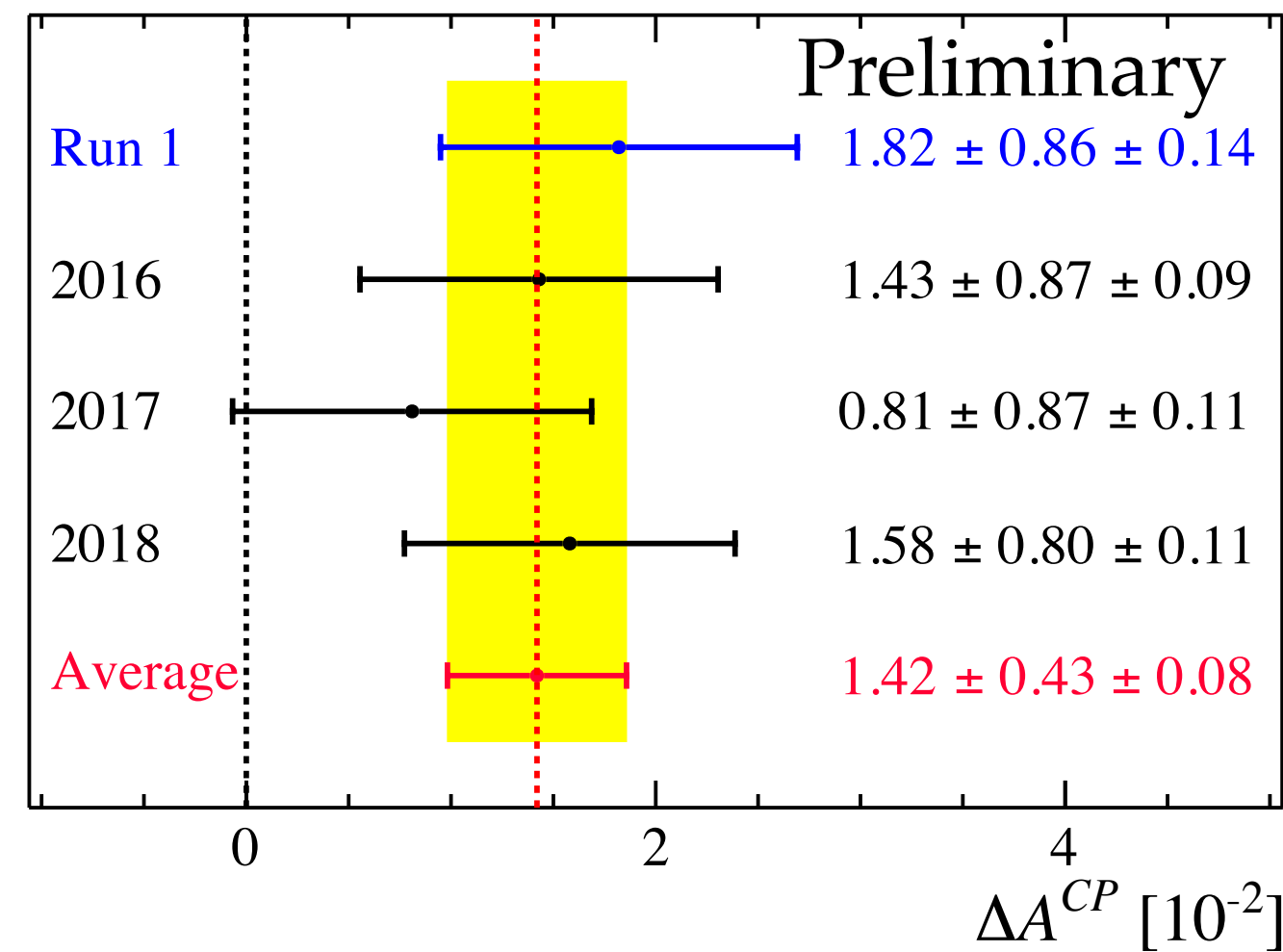
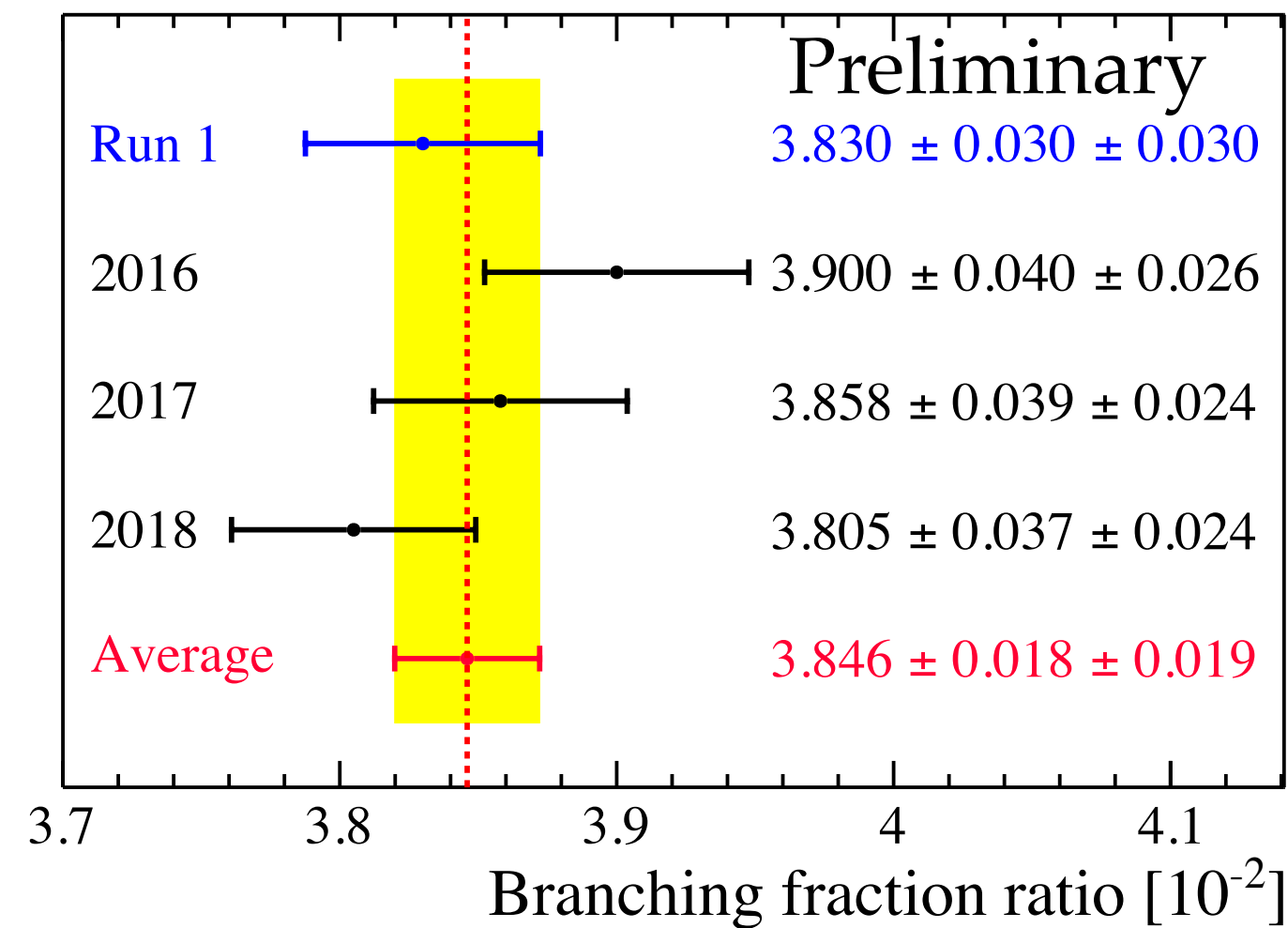
- Many systematic uncertainties **cancel**
- Performed separately for 2016, 2017, and 2018 subsamples and then combined



CP asymmetry and branching fraction of $B^+ \rightarrow J/\psi\pi^+$ decays

New!

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



- Using Run-1 $A_{CP}(B^+ \rightarrow J/\psi K^+)$:

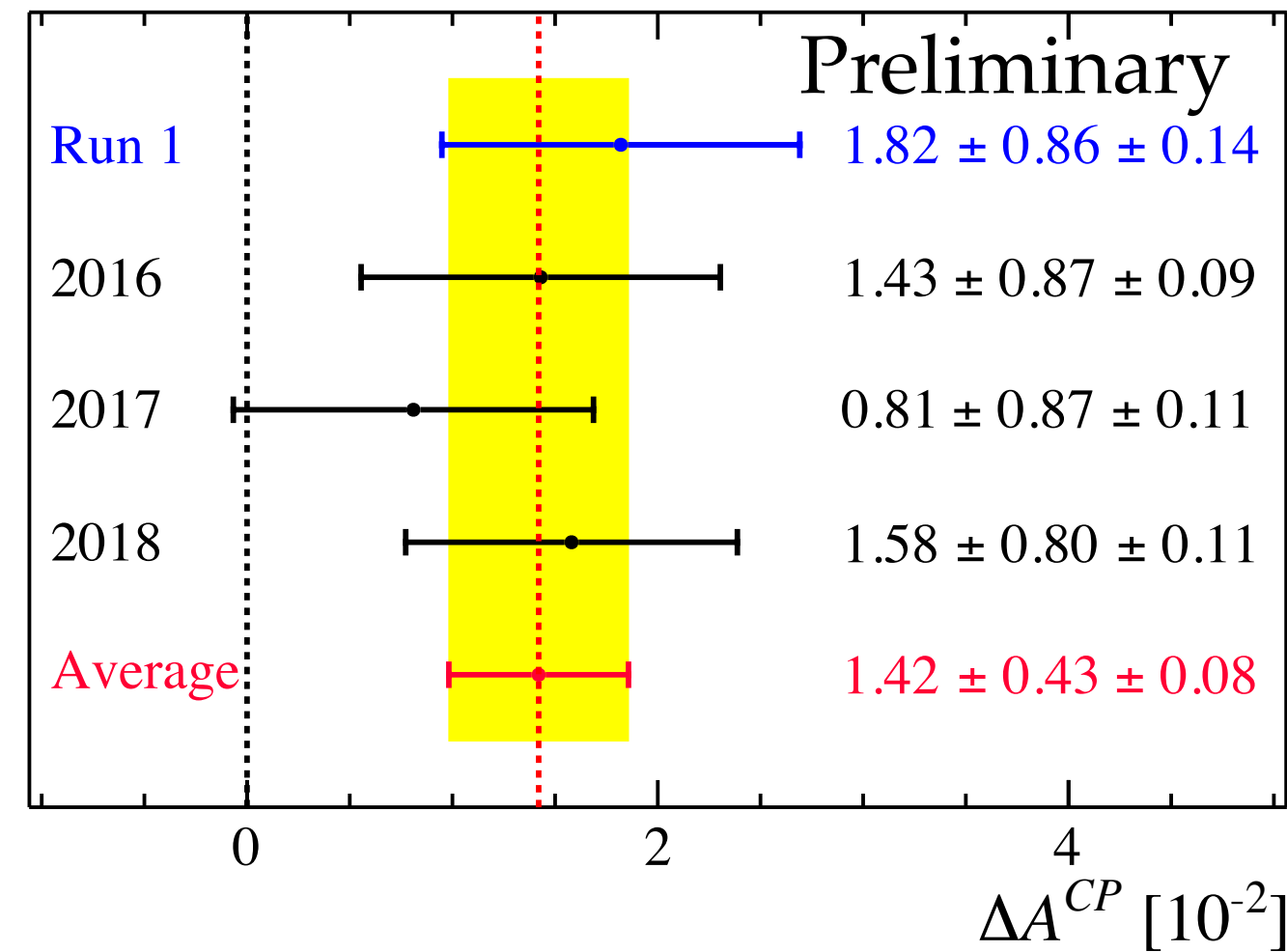
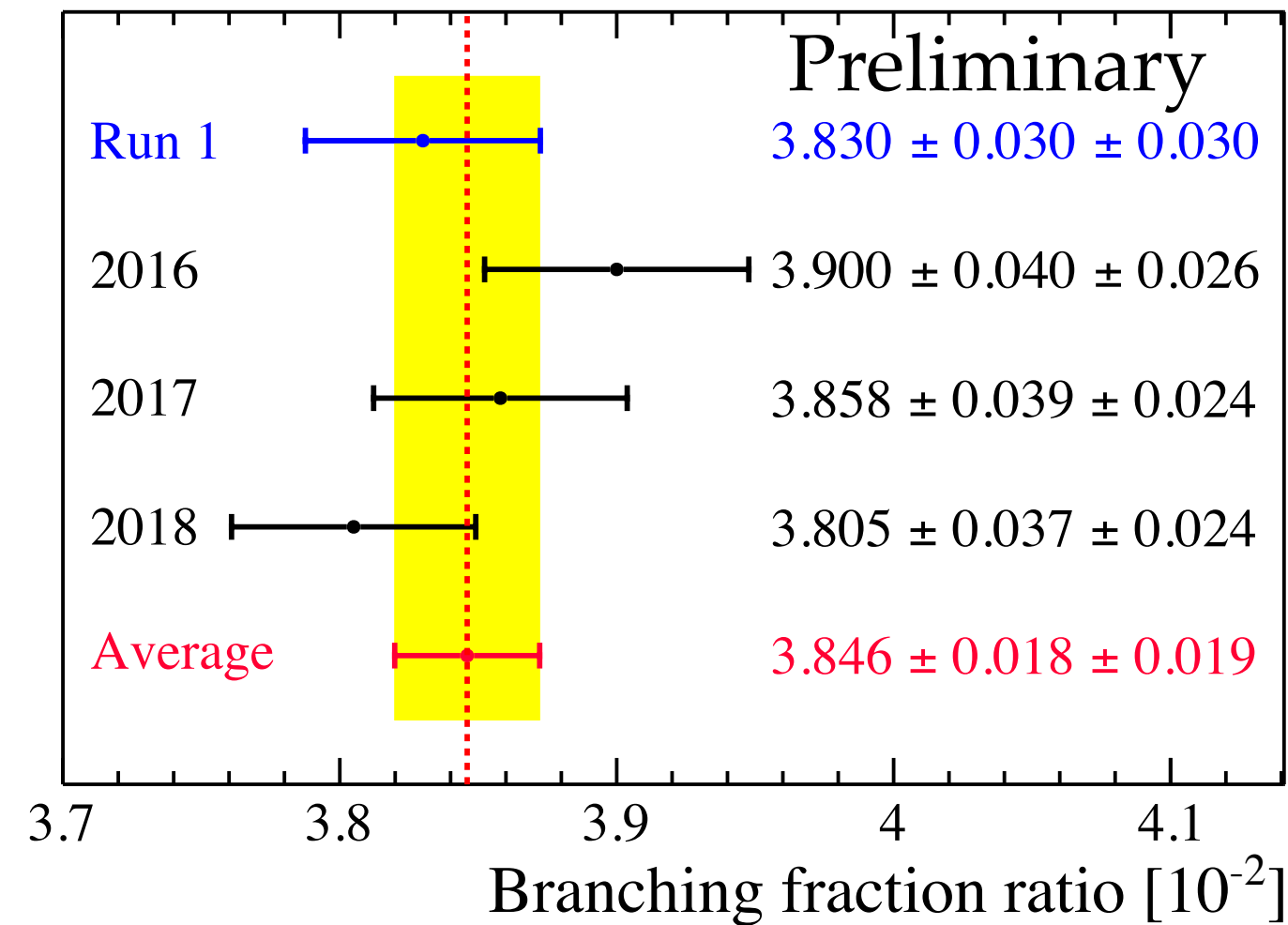
$$\mathcal{A}^{CP}(B^+ \rightarrow J/\psi\pi^+) = (1.51 \pm 0.50 \pm 0.08) \times 10^{-2}$$

- First evidence of direct CP violation in beauty to charmonia decays (3.2σ)**

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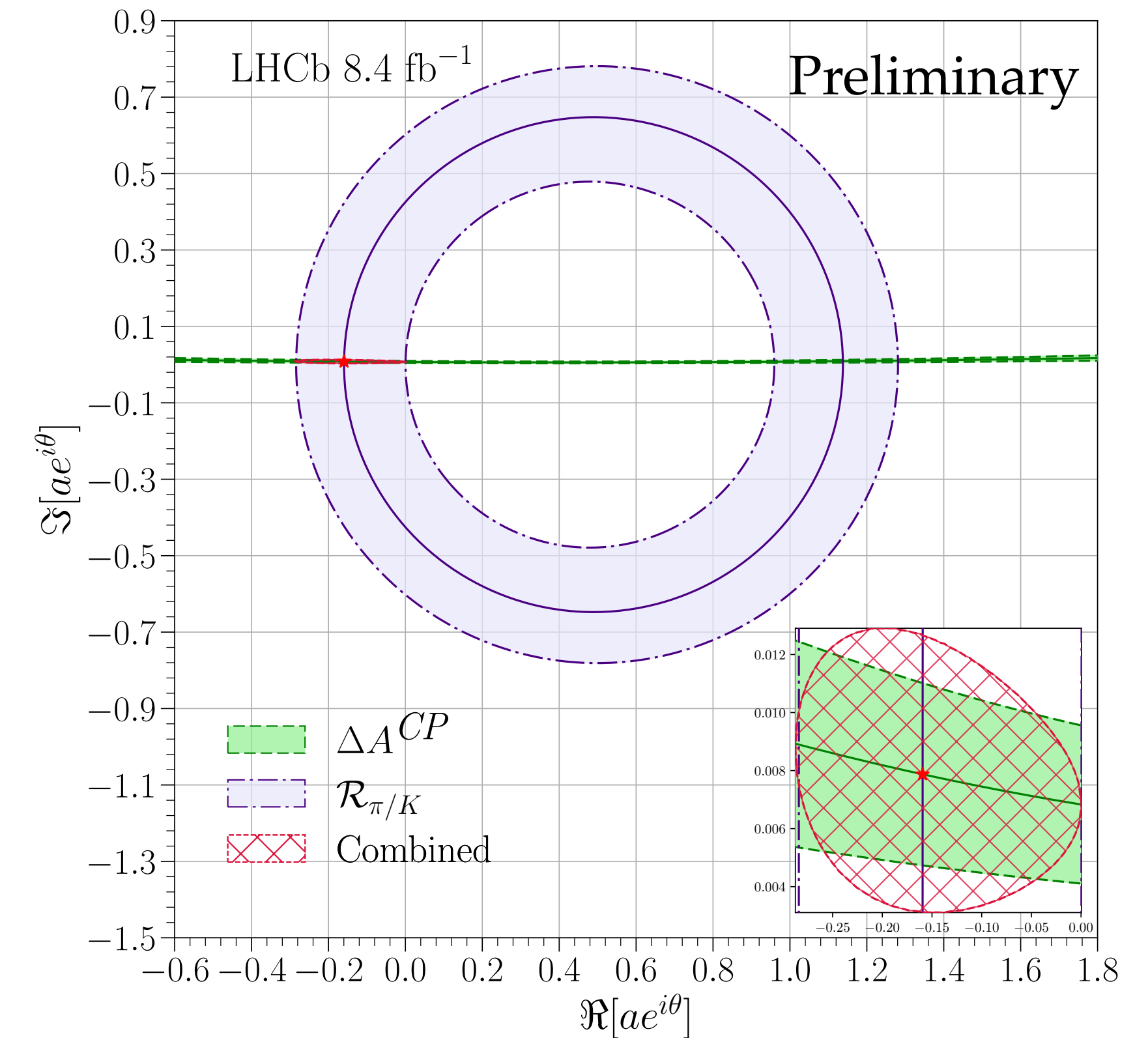
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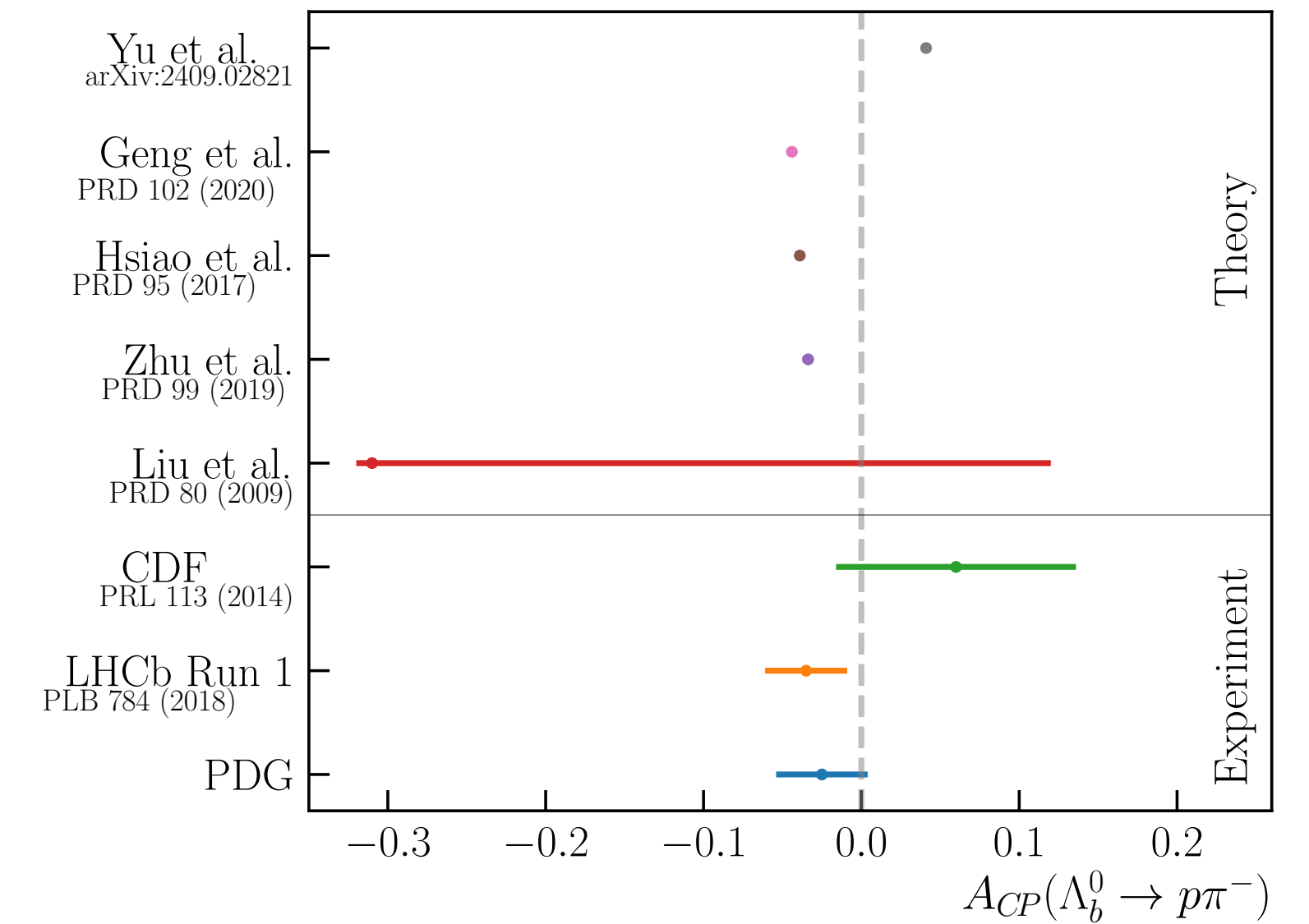
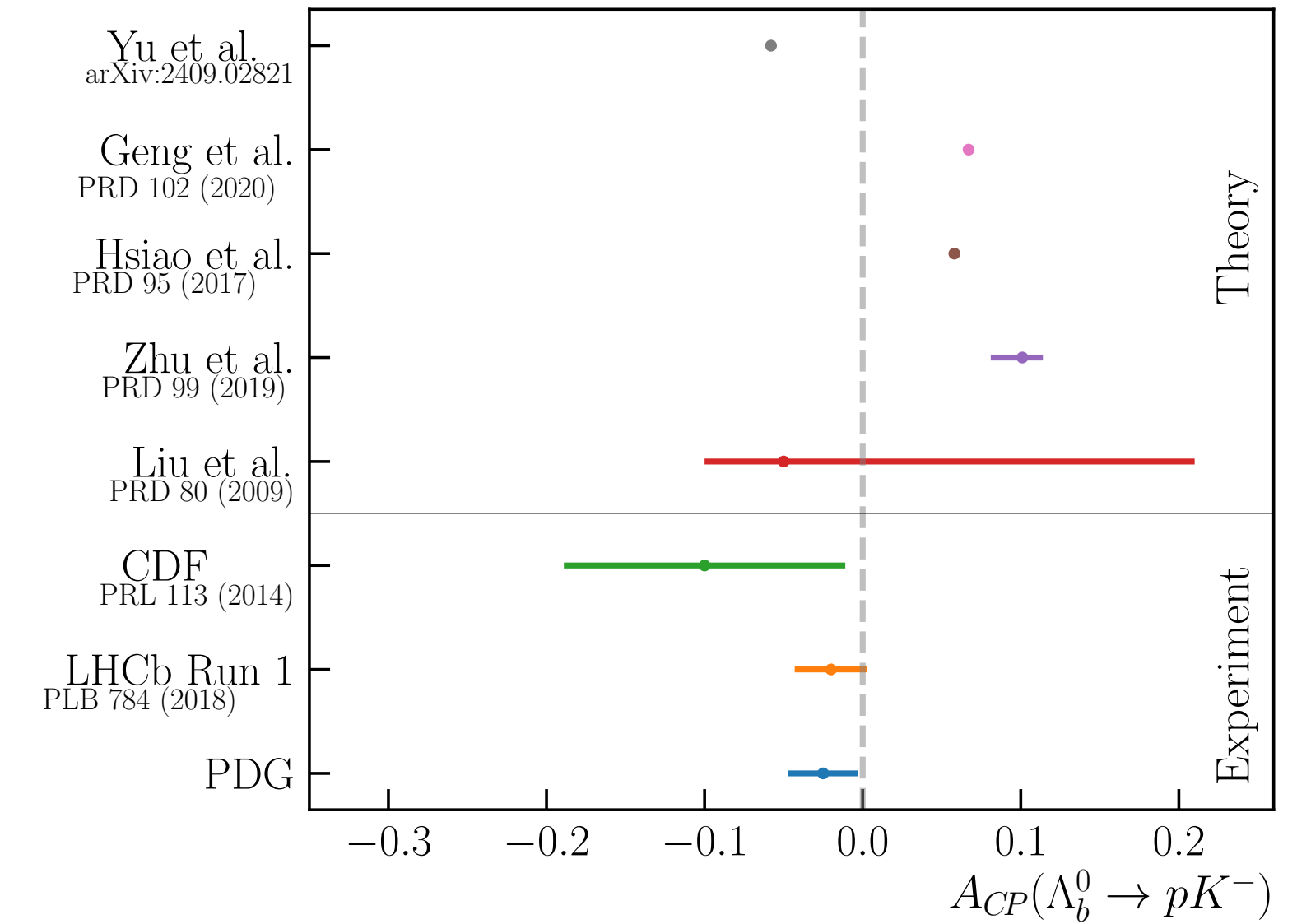
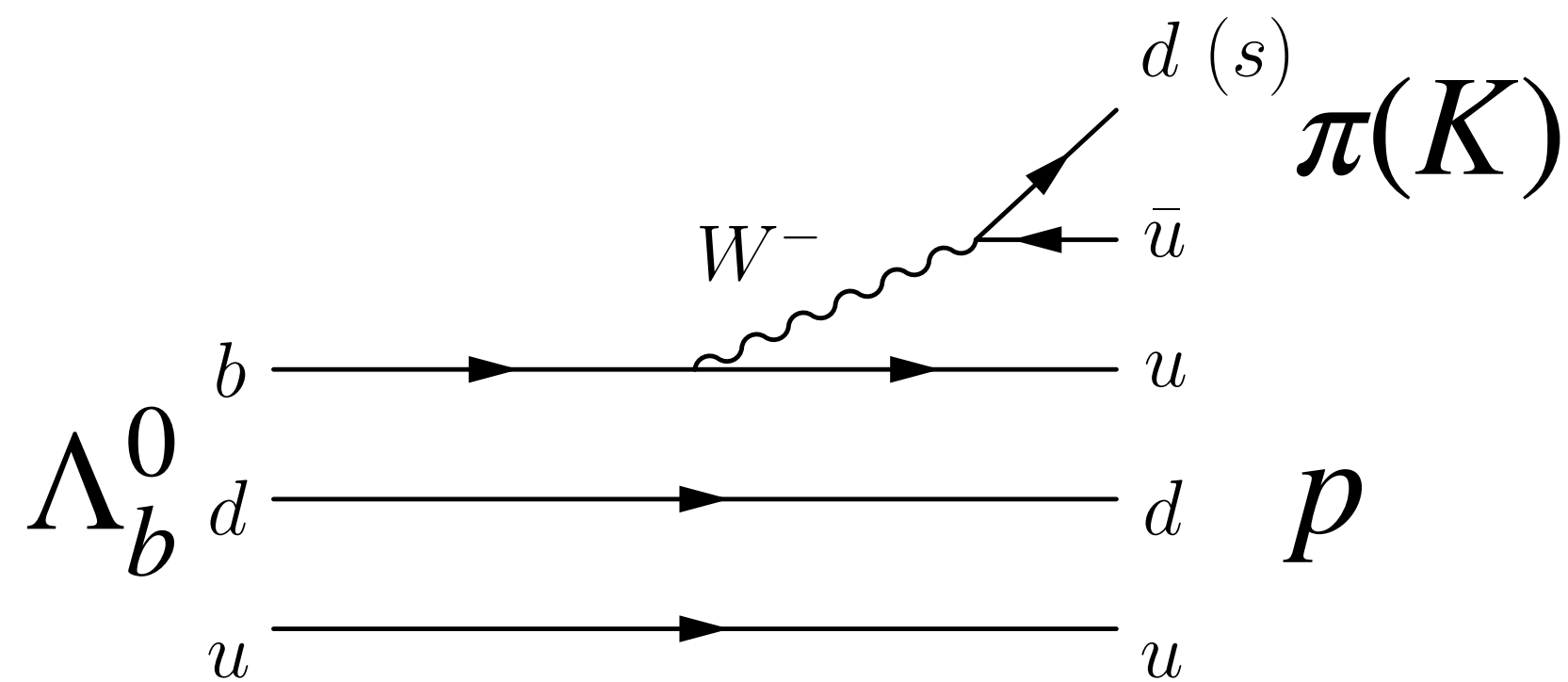
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- Constraints on size (a) and strong phase (θ) of penguin-to-tree contribution (assuming $SU(3)$ conservation)



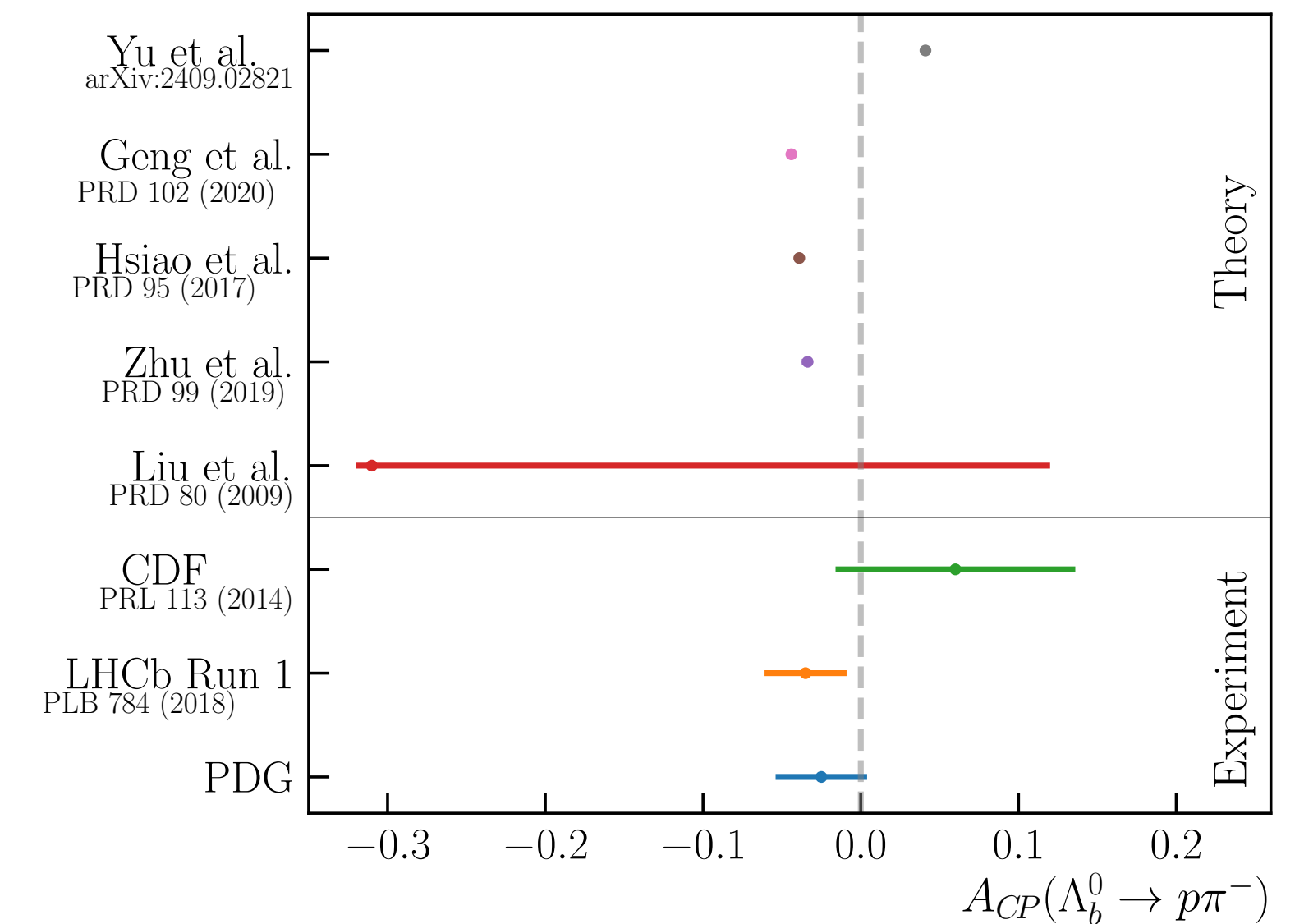
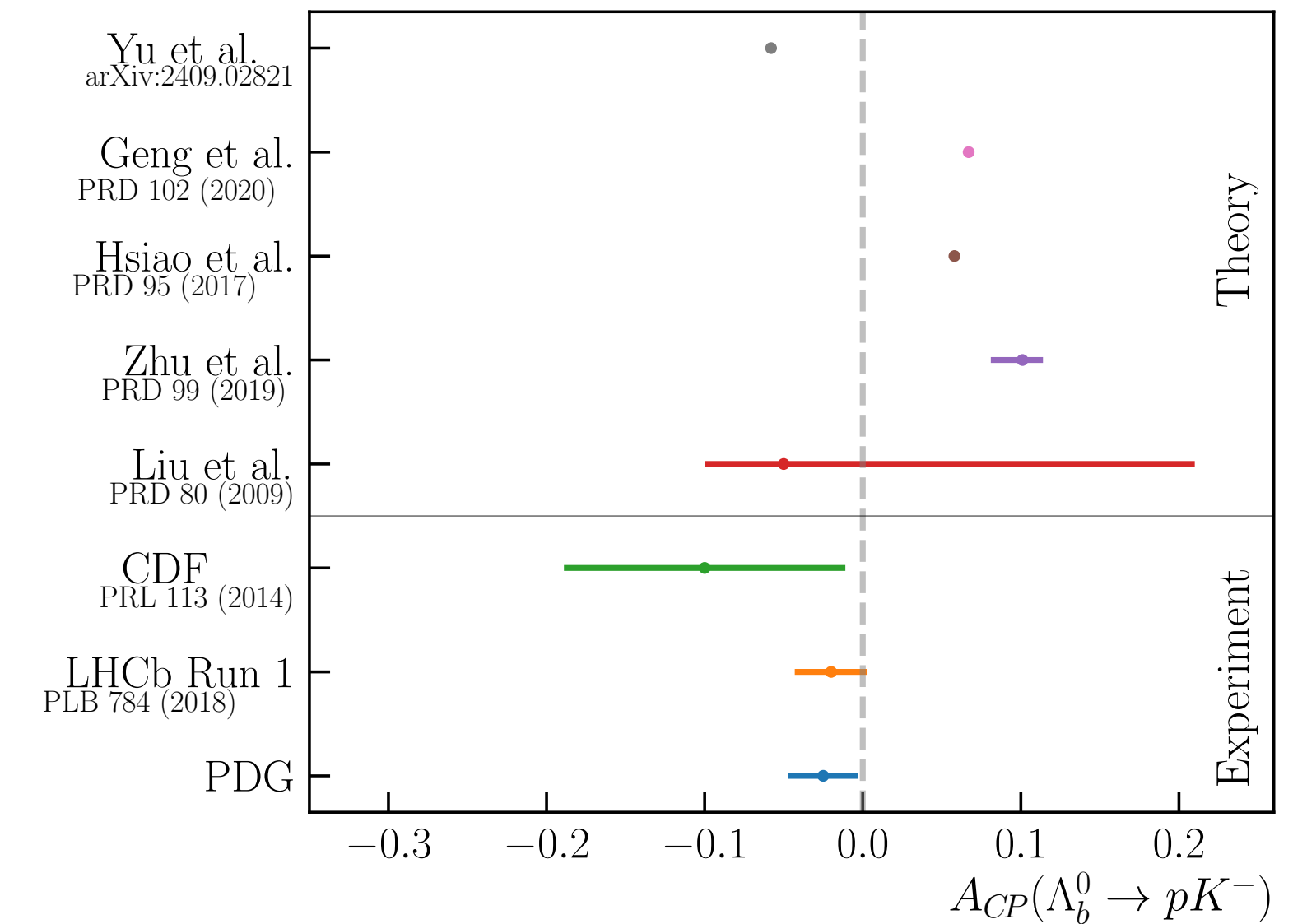
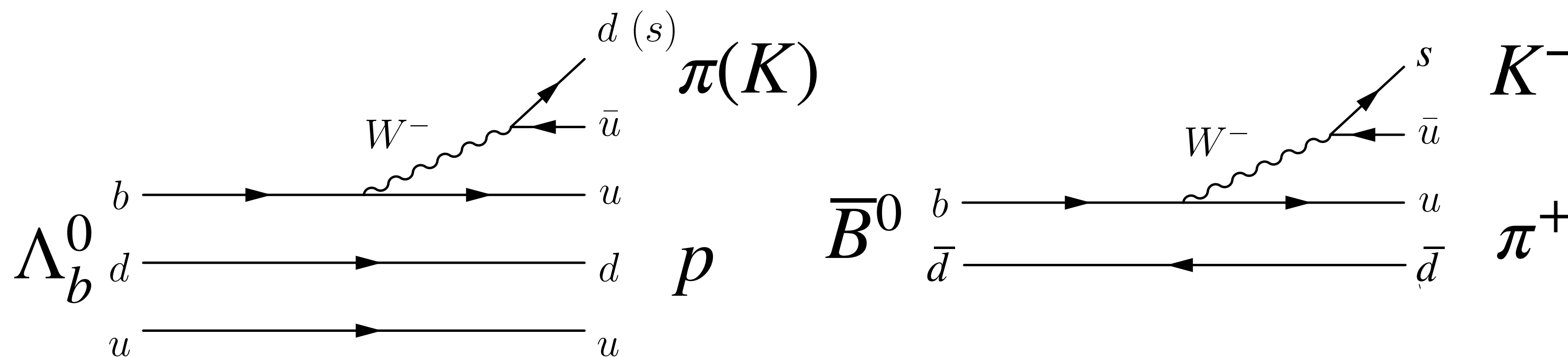
Measurement of CP asymmetries with $\Lambda_b^0 \rightarrow ph^-$ decays

- CPV in baryons still relatively **unexplored**
- Tree-level transition suppressed \rightarrow penguin contribution to $\Lambda_b^0 \rightarrow ph^-$ could enhance CP -violating effects



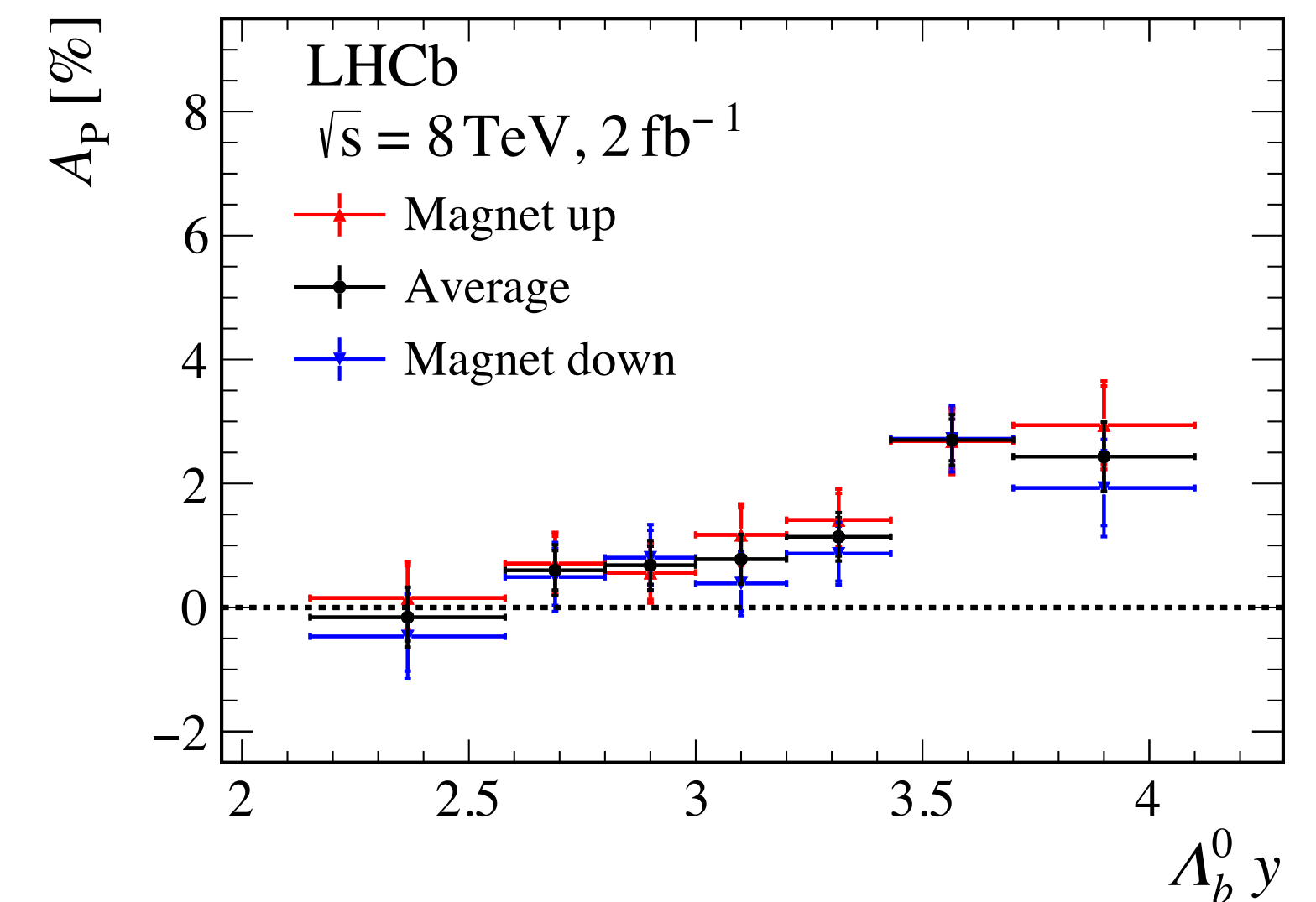
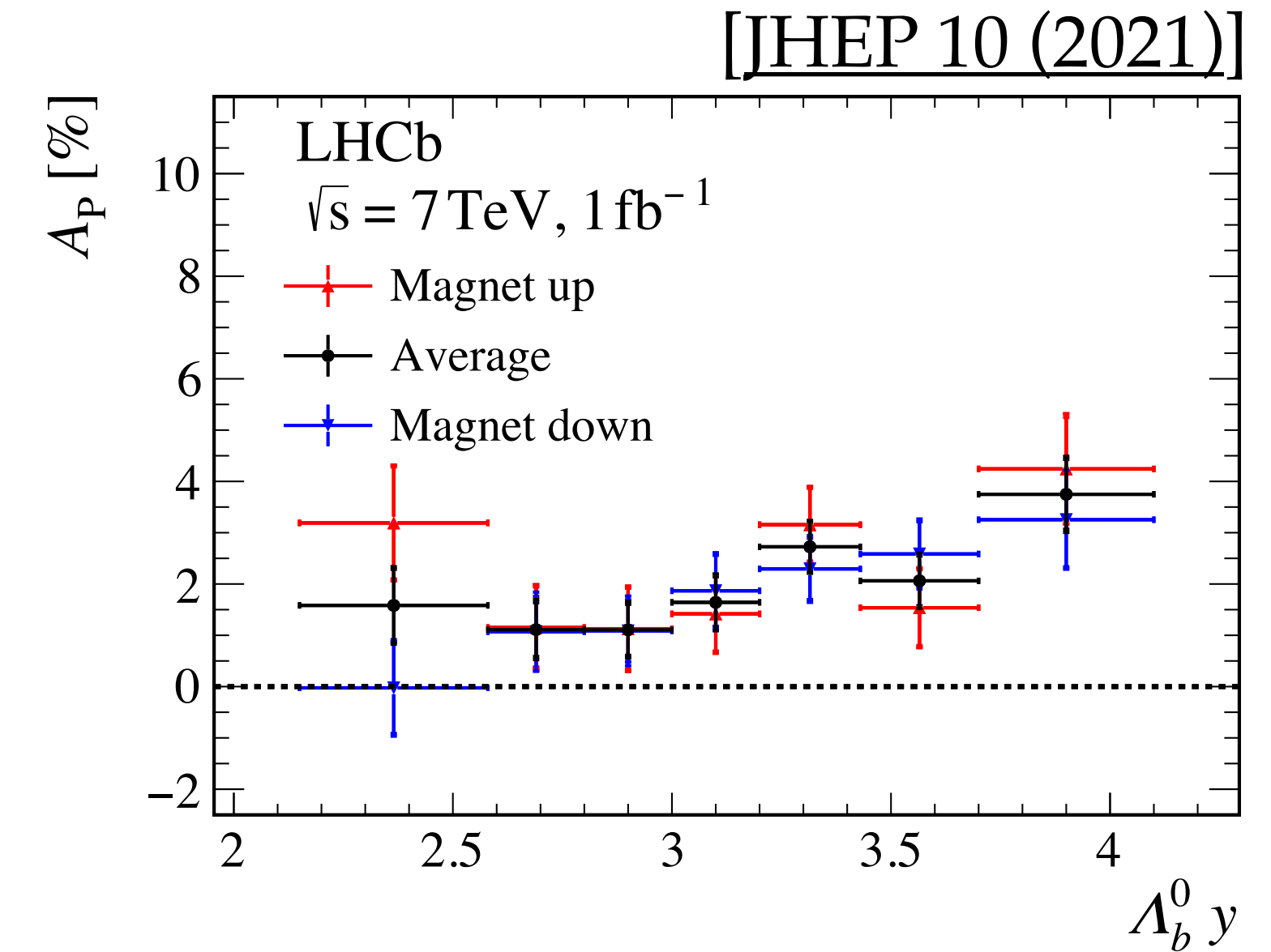
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- Similar diagrams to $B^0 \rightarrow K^+\pi^-$ ($A_{CP} = 8\%$) [PRD 98 (2018)]



Measurement of CP asymmetries with $\Lambda_b^0 \rightarrow ph^-$ decays

- **Update** of Run 1 measurement and addition of Run 2 sample ($\mathcal{L} = 9 \text{ fb}^{-1}$)
- Run 1 precision improved thanks to $A_P(\Lambda_b^0)$ and $A_{det}(p)$ measurement
- Run 2: $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ **control sample** to remove $A_P(\Lambda_b^0)$ contribution
- New **data-driven** techniques for trigger-induced corrections
- Better control of uncertainties from PID



Measurement of CP asymmetries with $\Lambda_b^0 \rightarrow ph^-$ decays

New!

[LHCb-PAPER-2024-048], in preparation

- New Run 2 measurement:

$$A_{CP}(\Lambda_b^0 \rightarrow pK^-) = (-1.39 \pm 0.75(\text{stat}) \pm 0.41(\text{syst})) \%$$

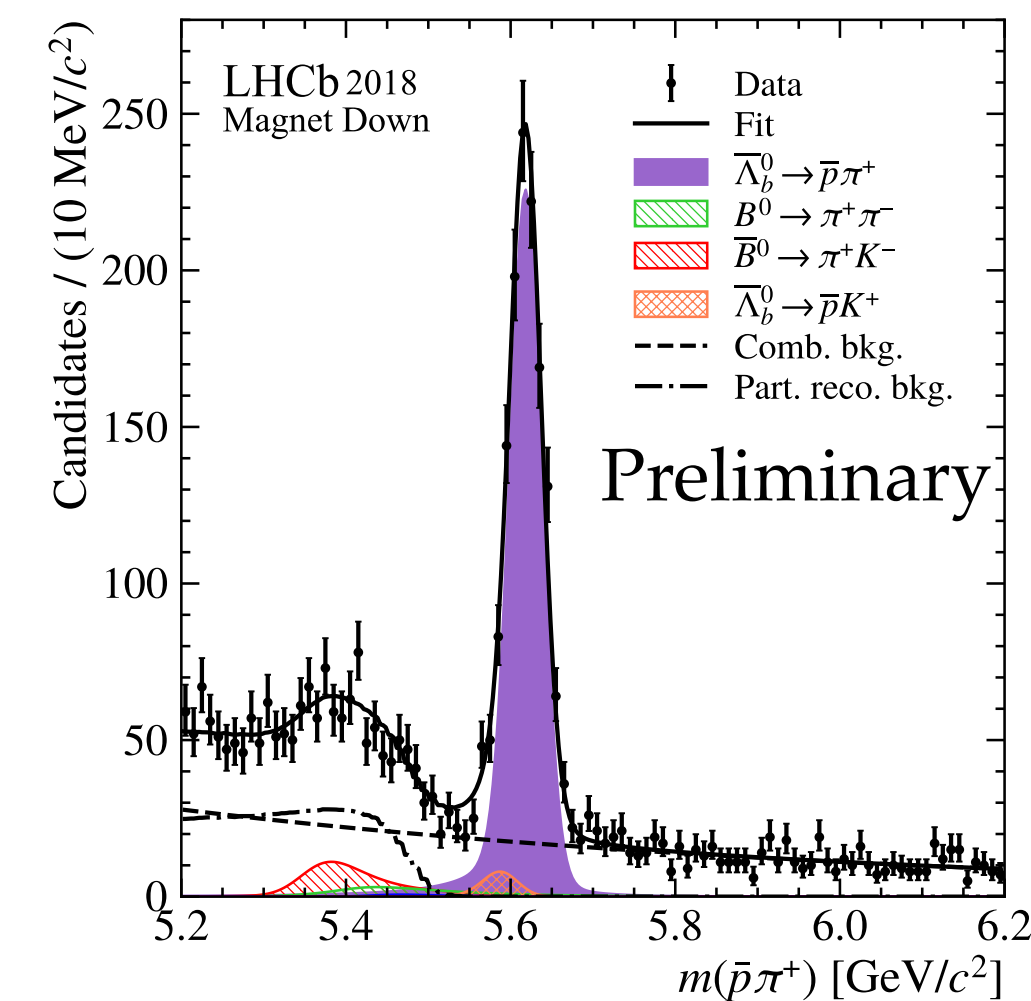
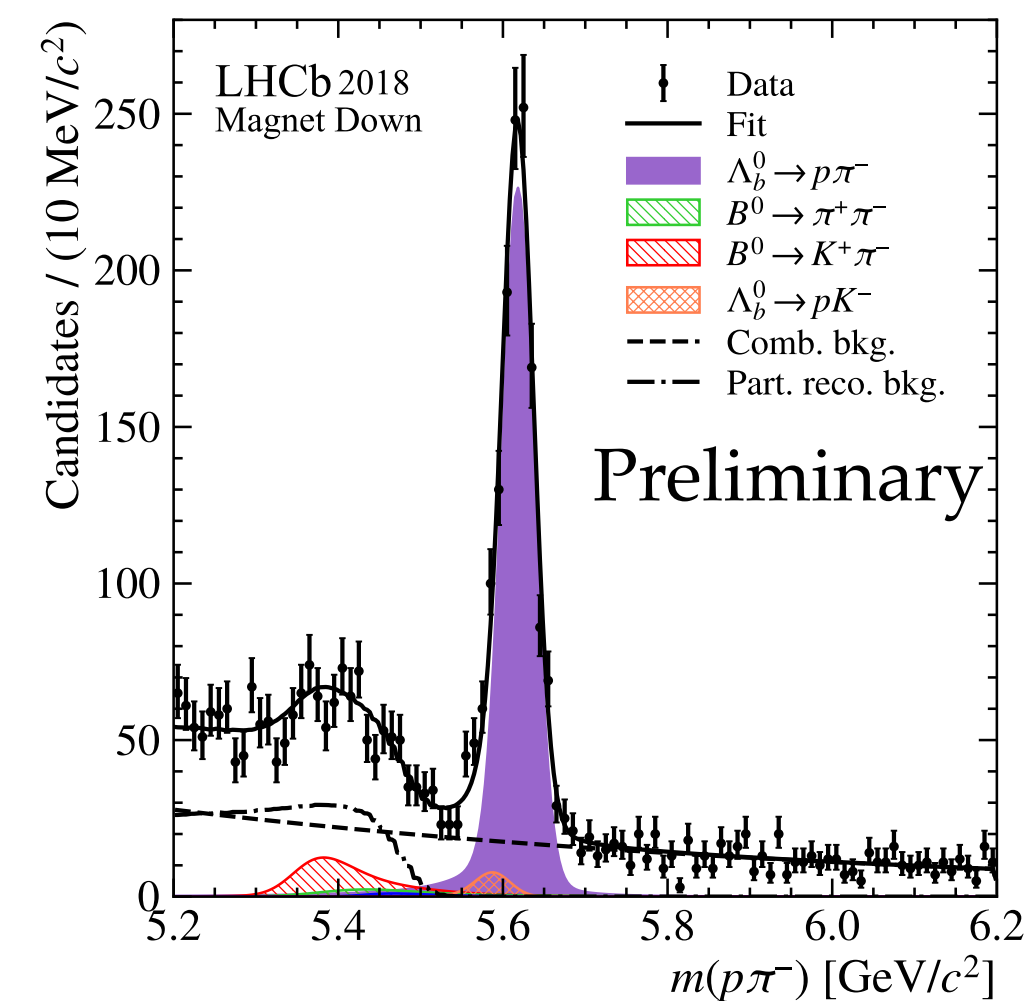
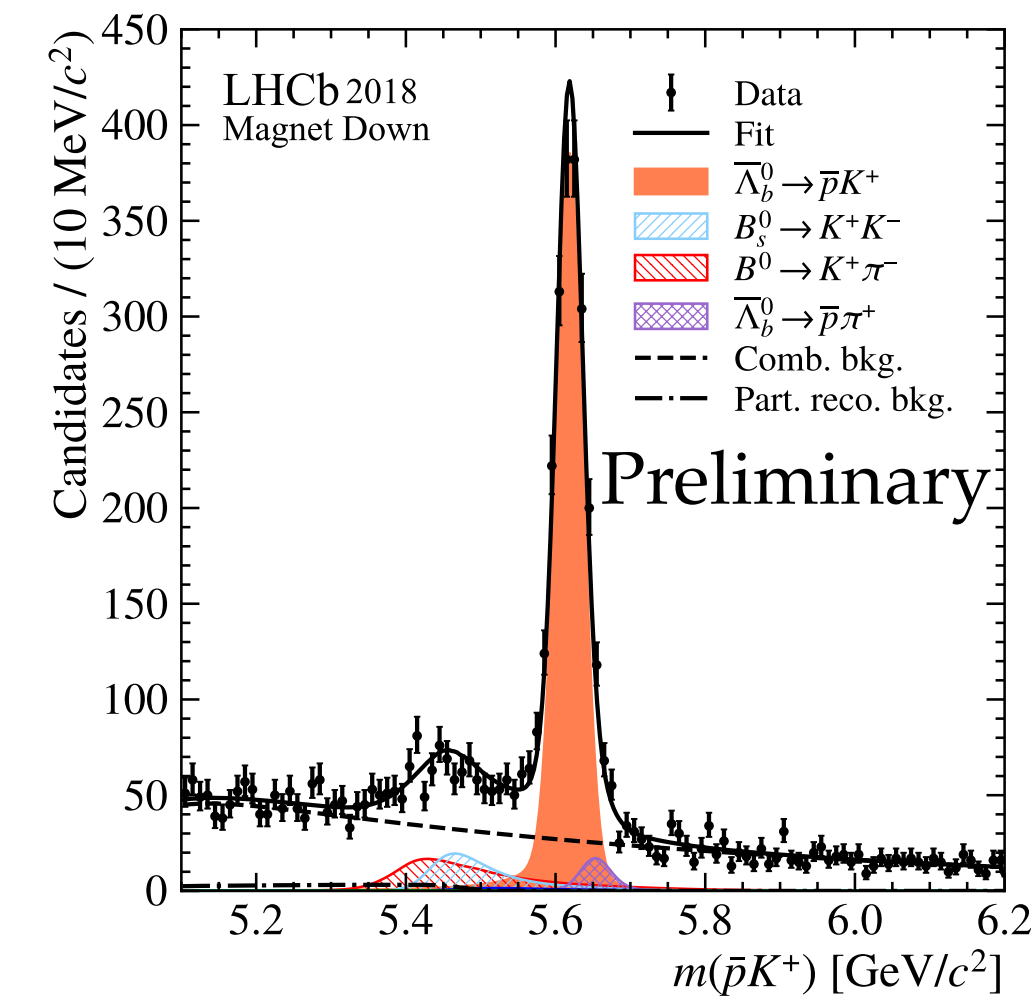
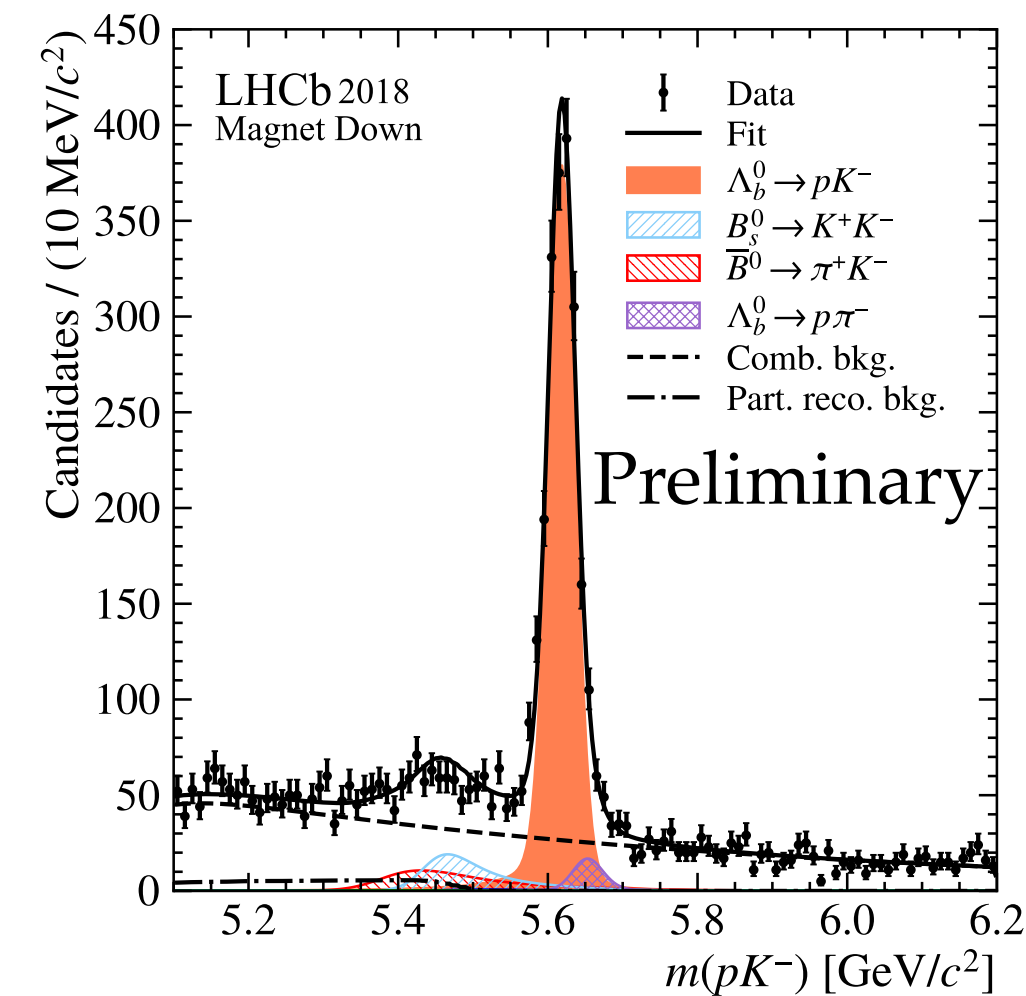
$$A_{CP}(\Lambda_b^0 \rightarrow p\pi^-) = (0.42 \pm 0.93(\text{stat}) \pm 0.42(\text{syst})) \%$$

- Combination with **updated** Run 1 results:

$$A_{CP}(\Lambda_b^0 \rightarrow pK^-) = (-1.14 \pm 0.67 \pm 0.36) \%$$

$$A_{CP}(\Lambda_b^0 \rightarrow p\pi^-) = (0.20 \pm 0.83 \pm 0.37) \%$$

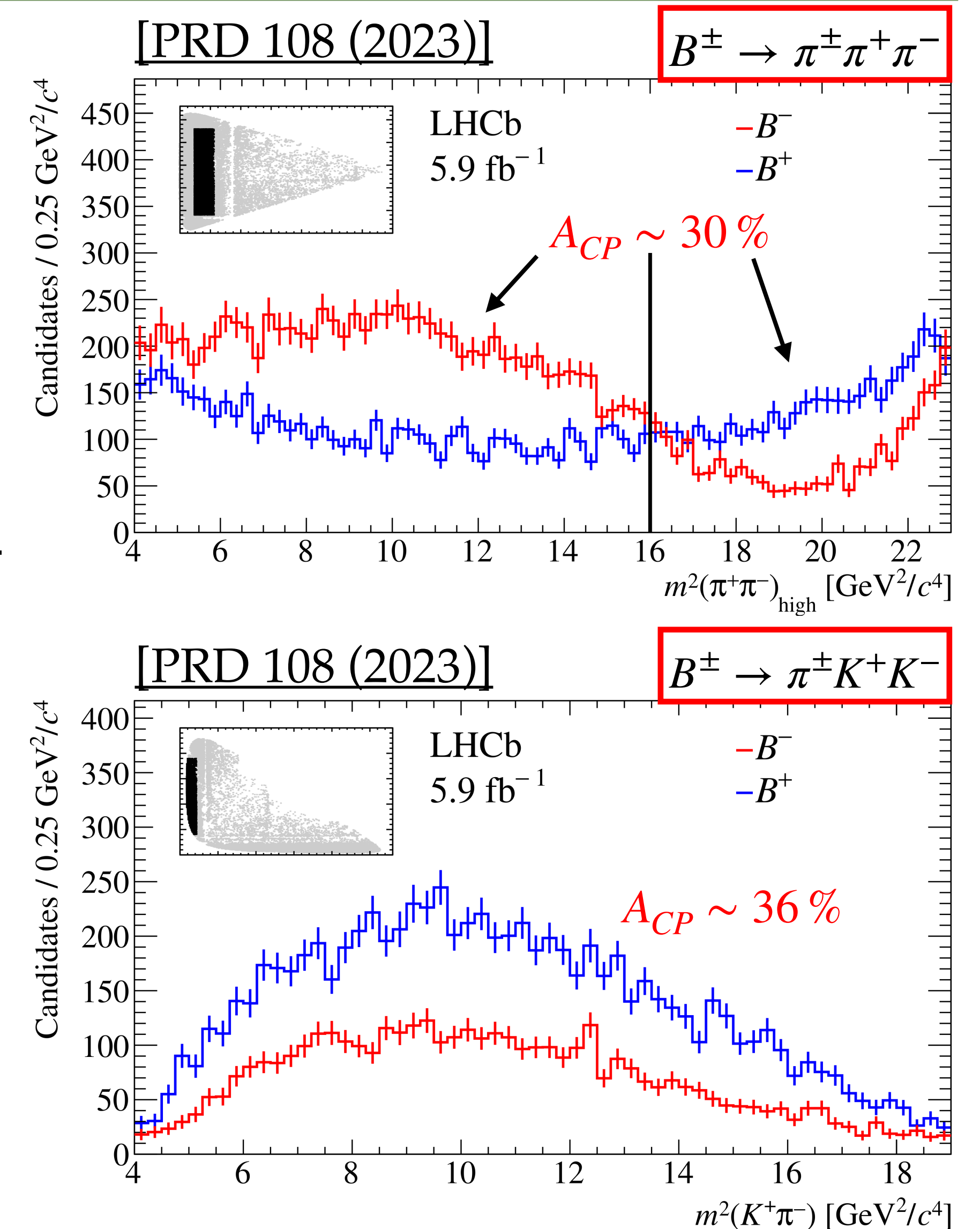
- **No evidence** of CP violation
- Not dominated by systematics anymore
- $3 \times$ improvement over current PDG average



Study of Λ_b^0 and Ξ_b^0 decays to $\Lambda h^+ h'^-$ final states

- **Large CPV** found in $\pi\pi \leftrightarrow KK$ rescattering regions of $B^\pm \rightarrow h^\pm h'^+ h''^-$ decays
- Light resonances could play a role in CPV ?
- Similar dynamics involved in $\Lambda_b^0/\Xi_b^0 \rightarrow \Lambda h^+ h'^-$ decays
- BF predictions: $10^{-7} - 10^{-6}$
 A_{CP} predictions: $0 - 4\%$

[PRD 58 (1998)] [PRD 69 (2004)] [EPJC 76 (2016)]
 [PRD 95 (2017)] [PRD 99 (2019)] [PRD 107 (2023)]



Study of Λ_b^0 and Ξ_b^0 decays to $\Lambda h^+ h'^-$ final states

- New LHCb study of $\Lambda_b^0/\Xi_b^0 \rightarrow \Lambda(\rightarrow p\pi^-)h^+h'^-$ with the full Run 1+2 dataset ($\mathcal{L} = 9 \text{ fb}^{-1}$)

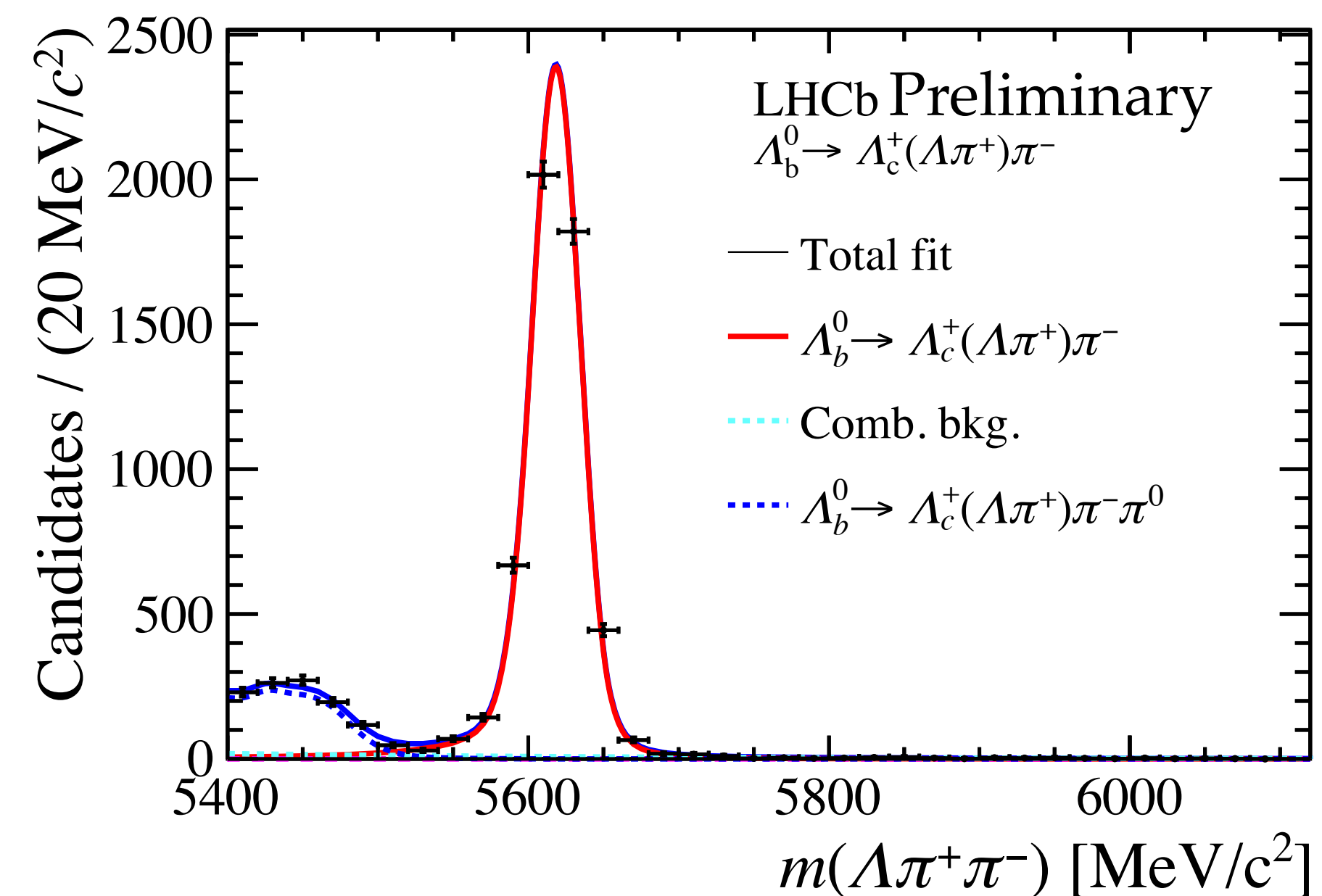
- Measurement of all 6 BF s and CP asymmetries in 4 of the channels

- $\Lambda_b^0 \rightarrow \Lambda_c^+(\rightarrow \Lambda\pi^+)\pi^-$ used for normalisation

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

$$\Delta A_{CP}(\Lambda_b^0/\Xi_b^0 \rightarrow f) = A_{CP}(\Lambda_b^0/\Xi_b^0 \rightarrow f) - A_{CP}(\Lambda_b^0 \rightarrow \Lambda_c^+(\rightarrow \Lambda\pi^+)\pi^-)$$

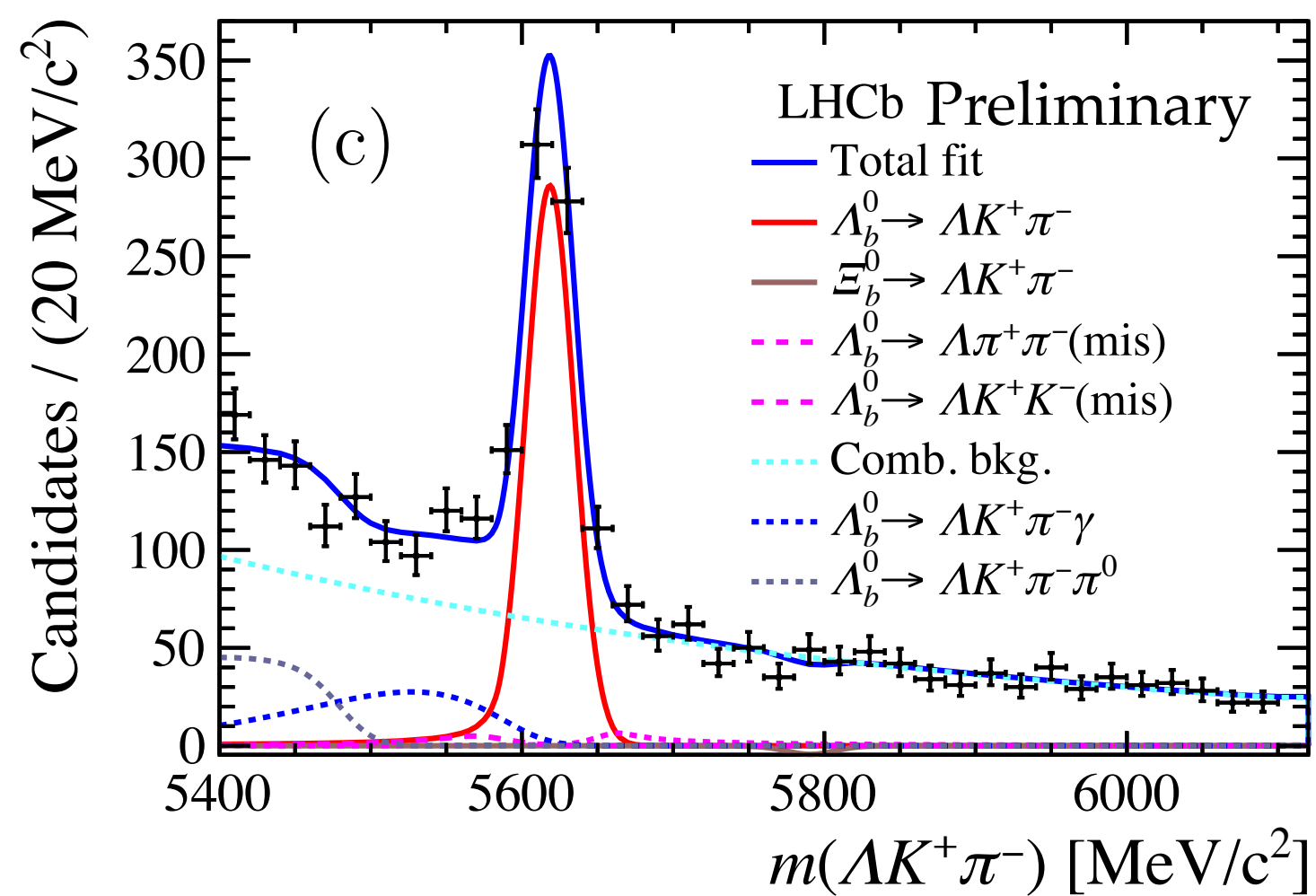
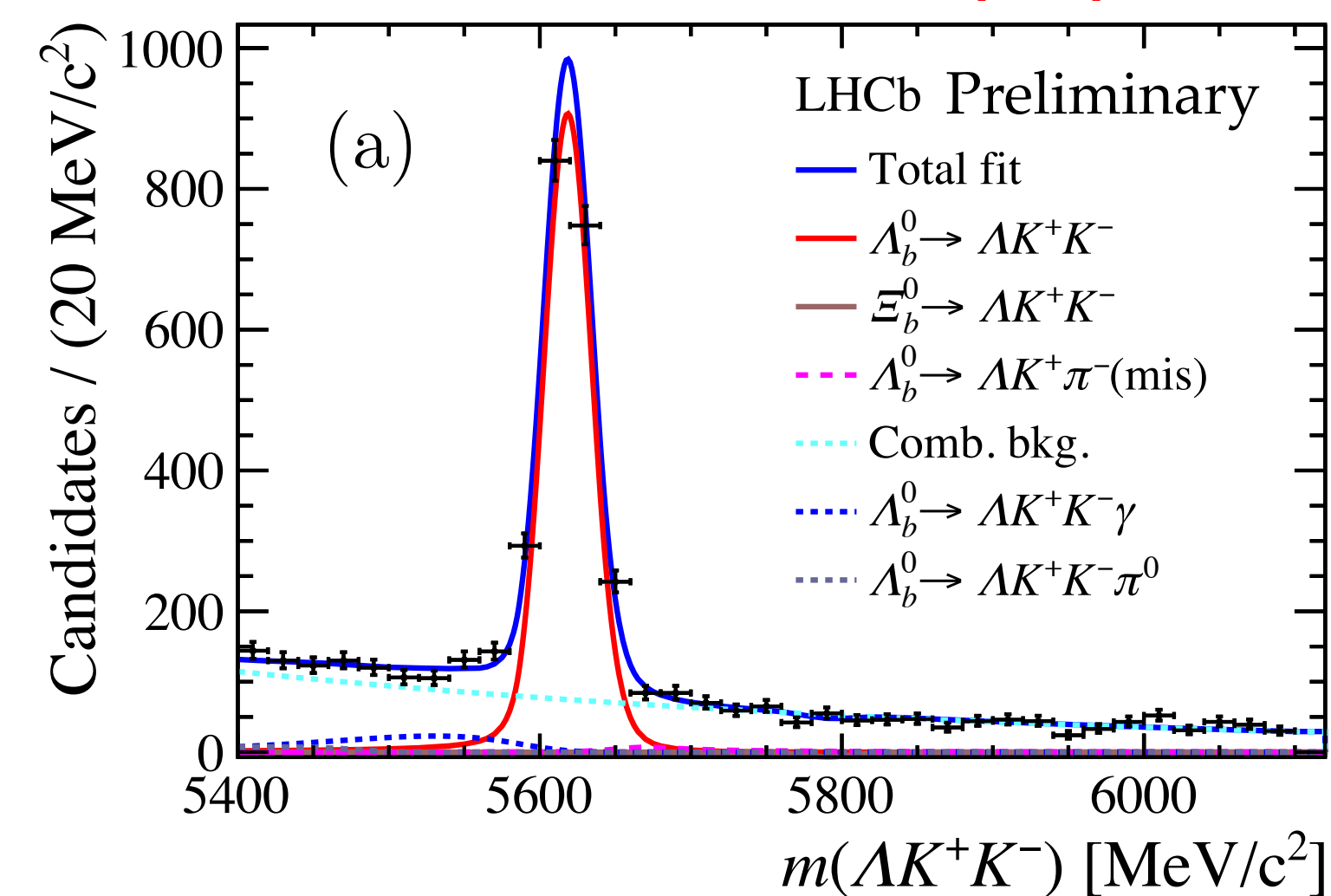
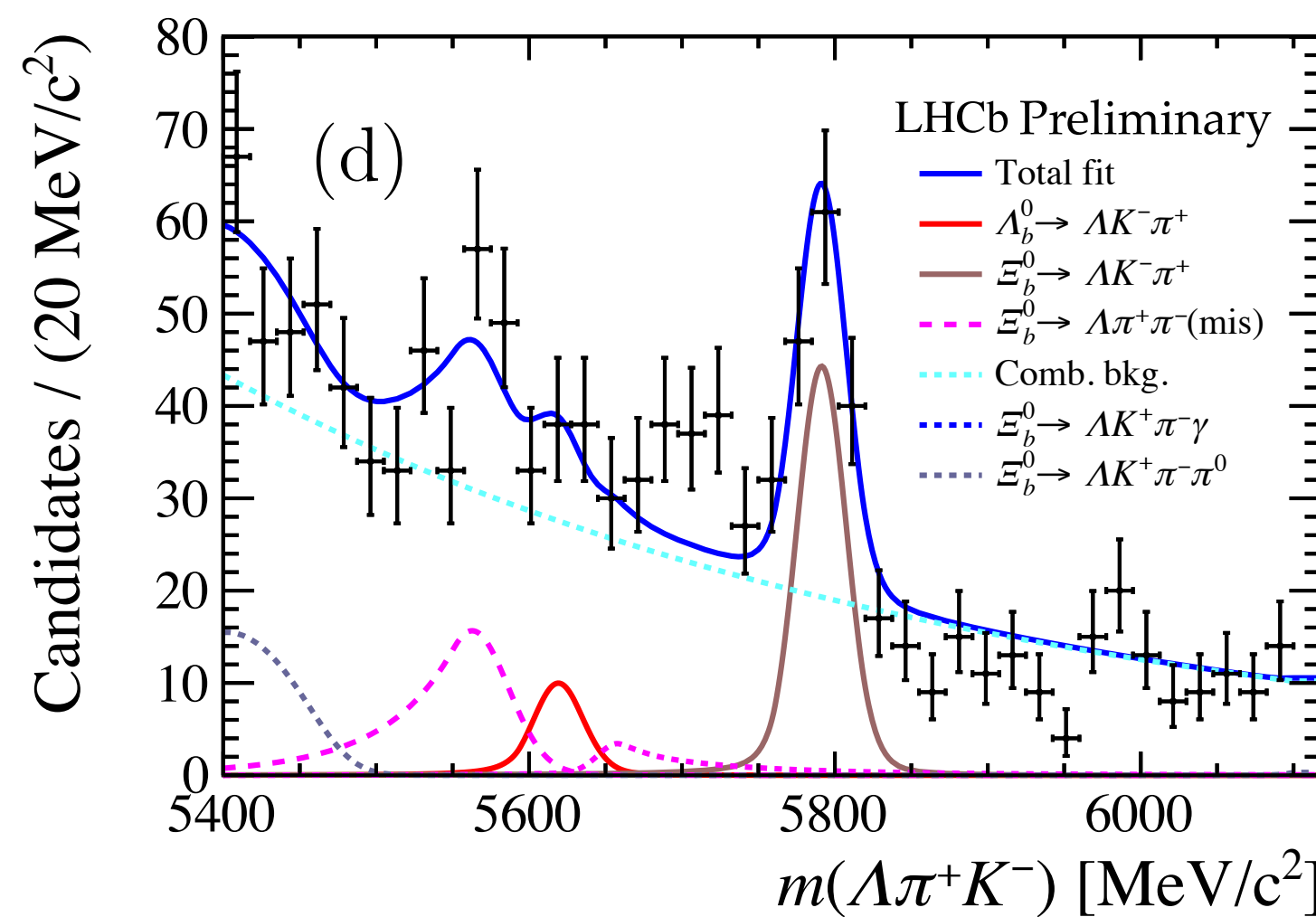
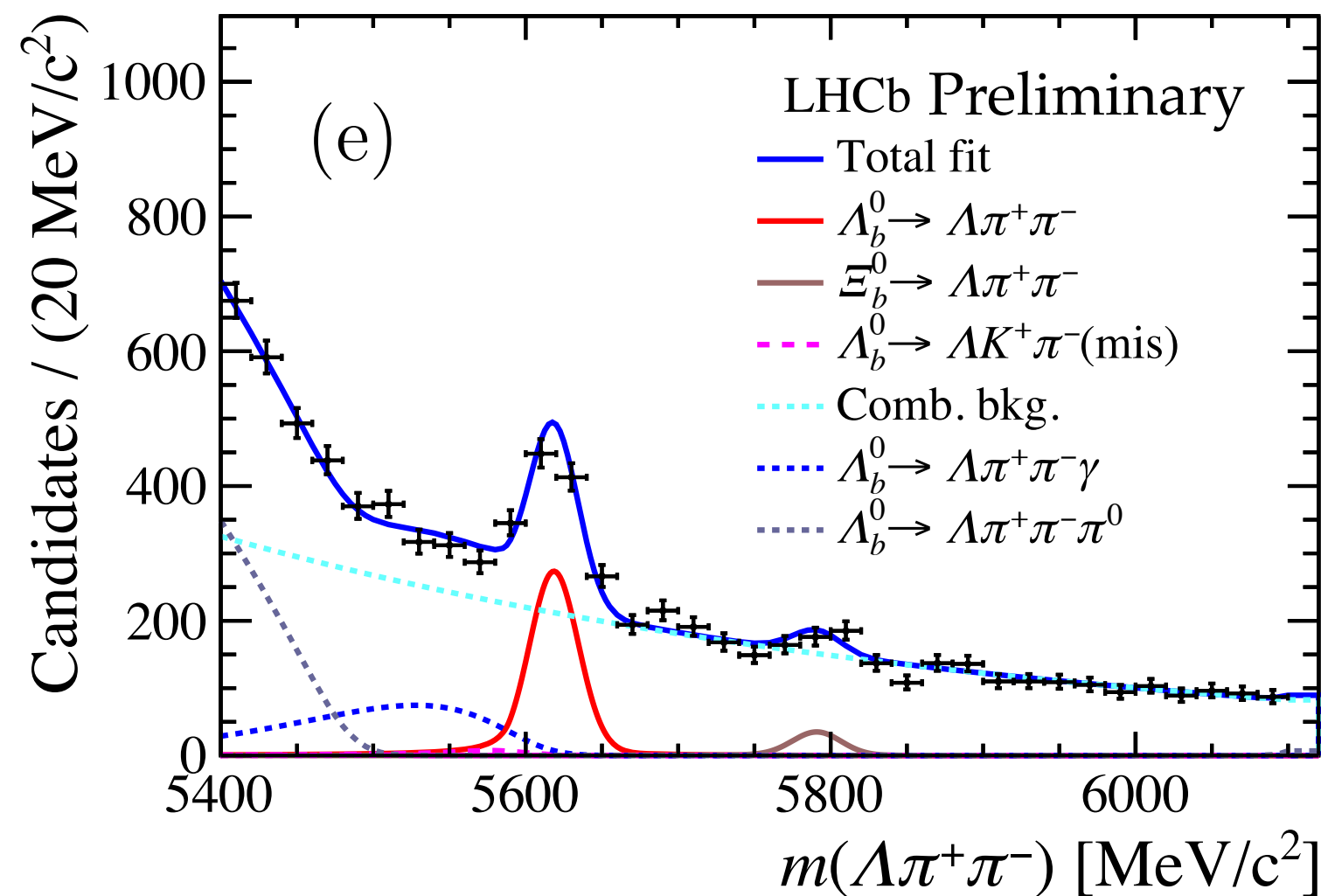
[LHCb-PAPER-2024-043], in preparation



Study of Λ_b^0 and Ξ_b^0 decays to $\Lambda h^+ h'^-$ final states

New!

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



$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda\pi^+\pi^-) = (5.3 \pm 0.4 \pm 0.5 \pm 0.5(\text{norm})) \times 10^{-6}$$

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda K^+\pi^-) = (4.6 \pm 0.2 \pm 0.4 \pm 0.5(\text{norm})) \times 10^{-6}$$

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda K^+K^-) = (10.7 \pm 0.3 \pm 0.4 \pm 1.1(\text{norm})) \times 10^{-6}$$

$$\mathcal{B}(\Xi_b^0 \rightarrow \Lambda\pi^+\pi^-) = (11.0 \pm 2.6 \pm 1.4 \pm 3.8(\text{norm})) \times 10^{-6}$$

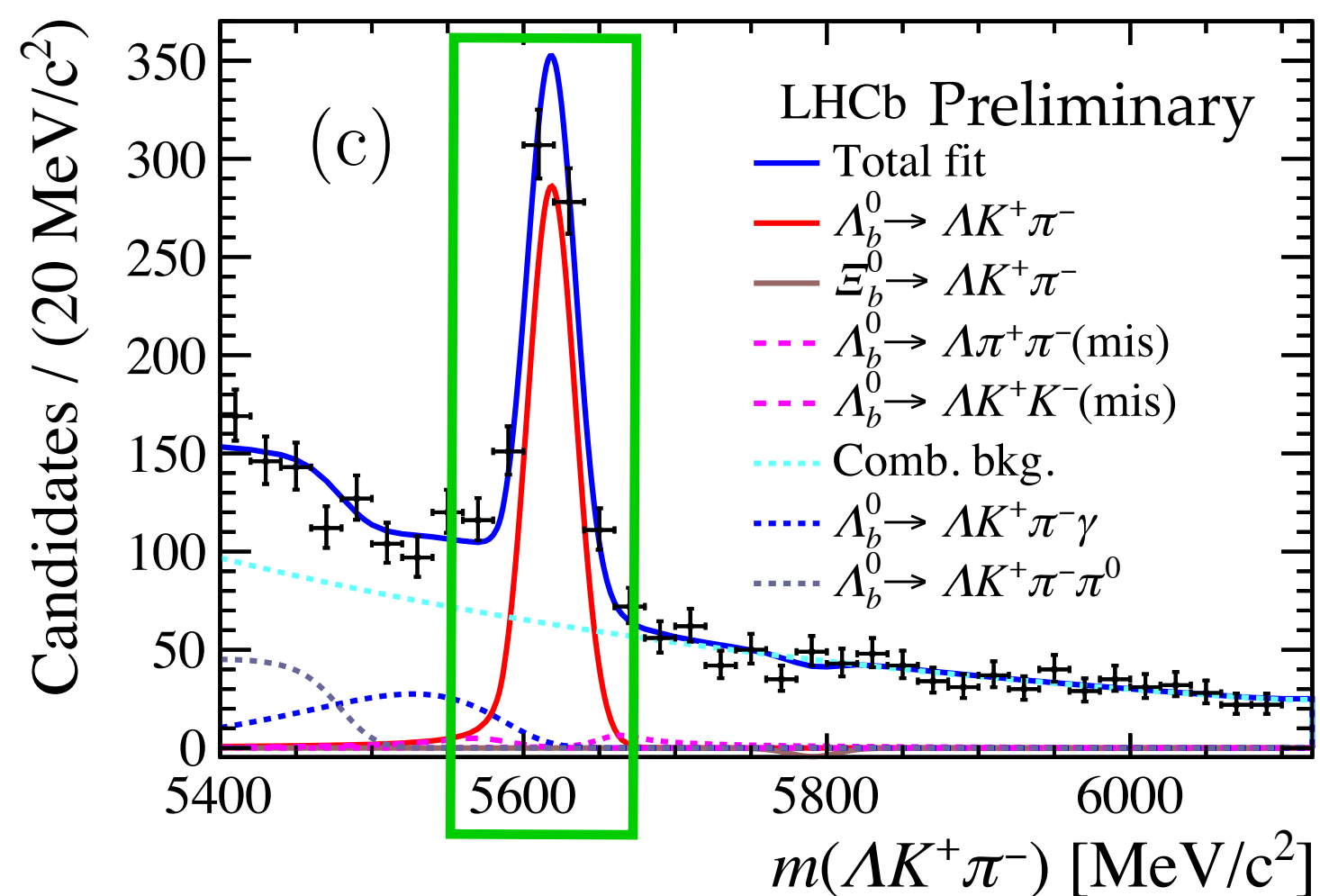
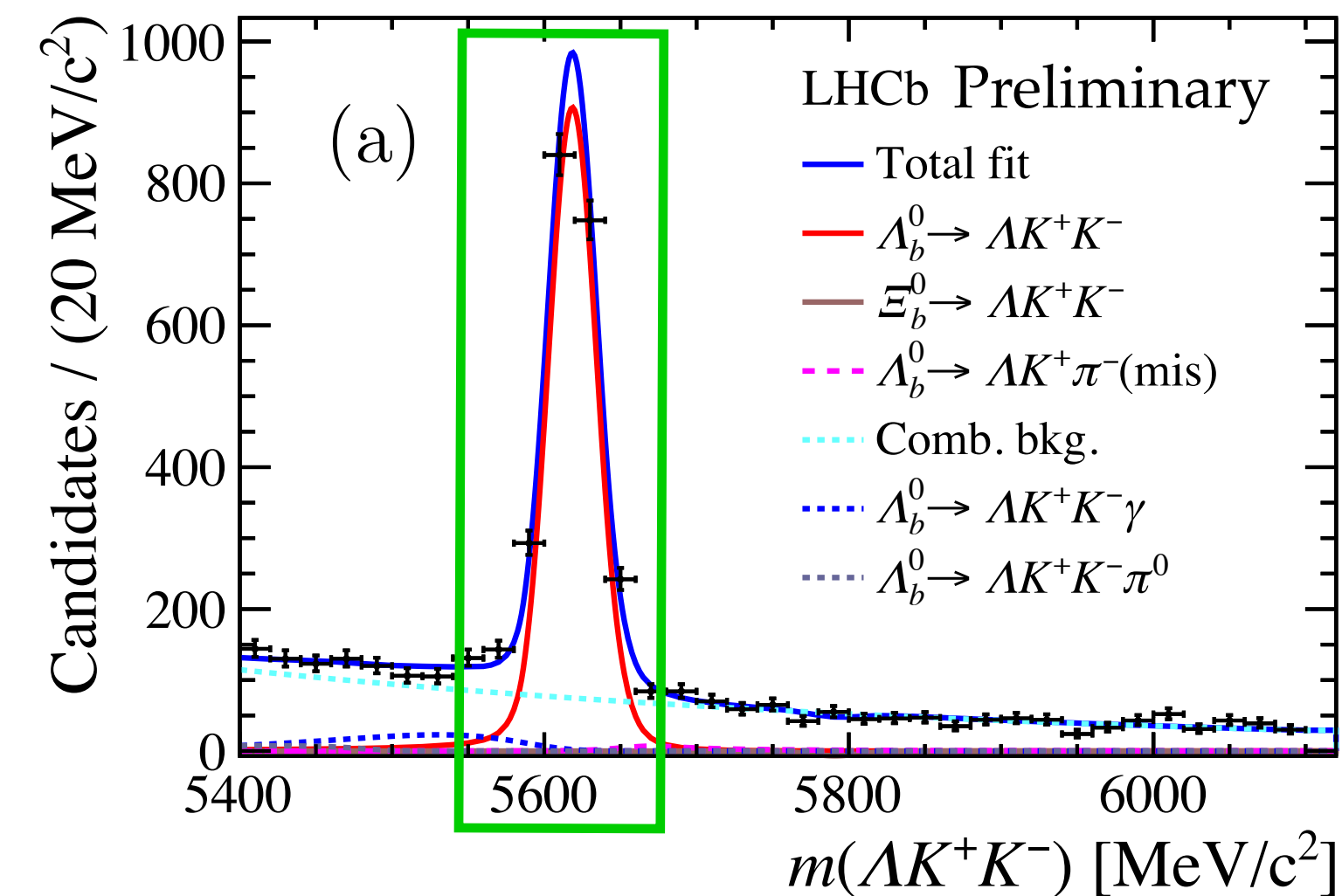
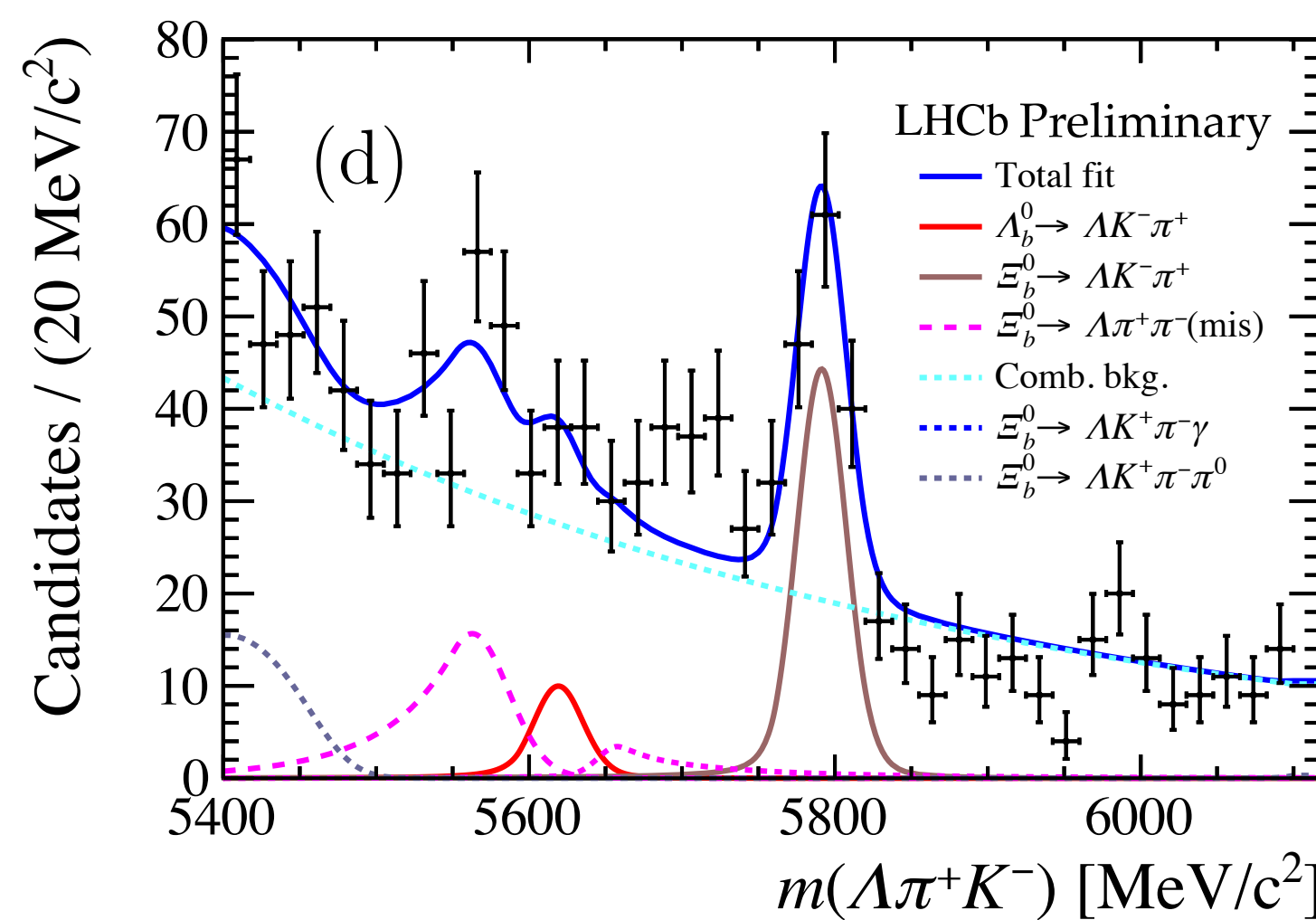
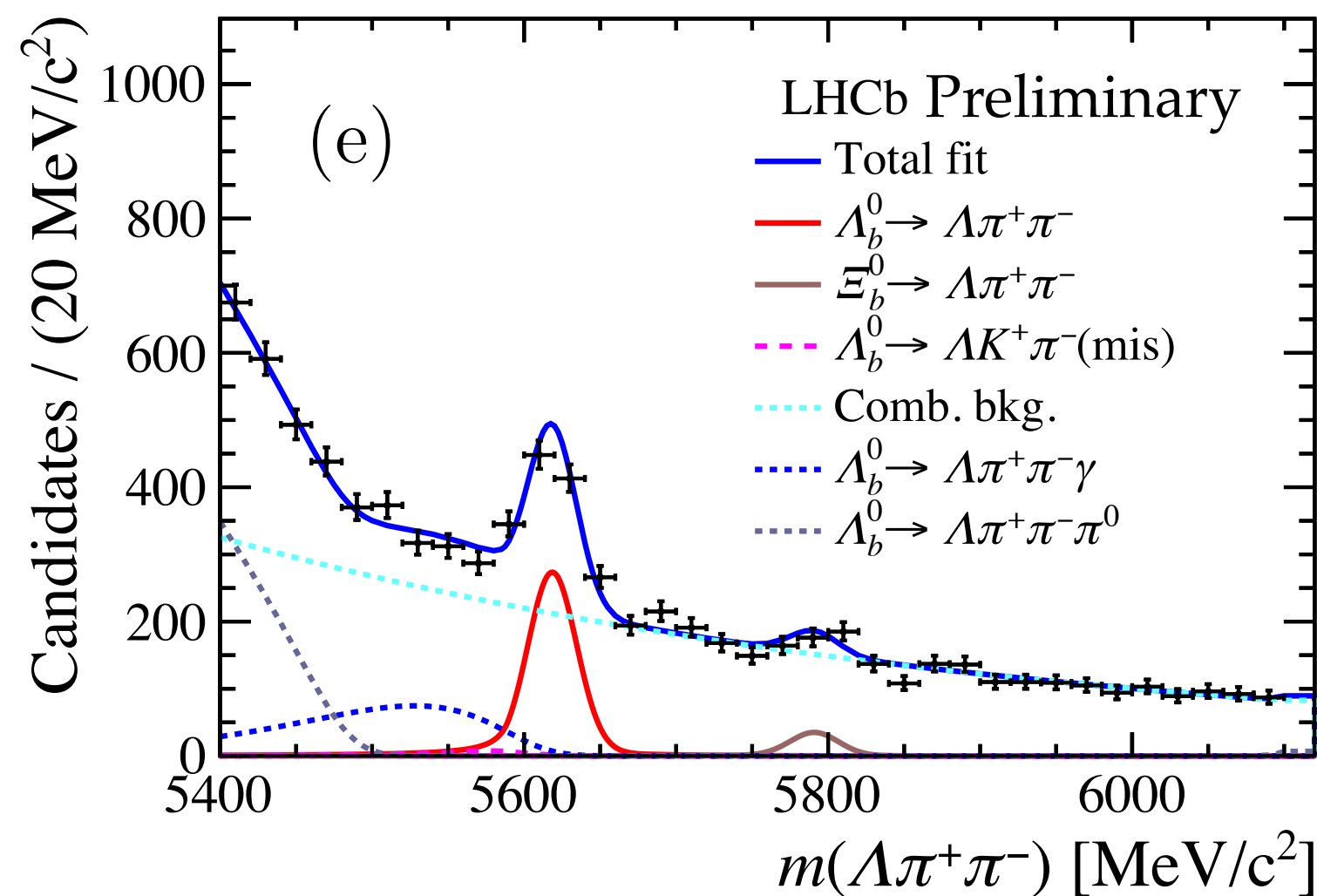
$$\mathcal{B}(\Xi_b^0 \rightarrow \Lambda K^-\pi^+) = (10.4 \pm 1.4 \pm 1.2 \pm 3.5(\text{norm})) \times 10^{-6}$$

$$\mathcal{B}(\Xi_b^0 \rightarrow \Lambda K^-K^+) < 2.4 \times 10^{-6} \text{ (90\% CL)}$$

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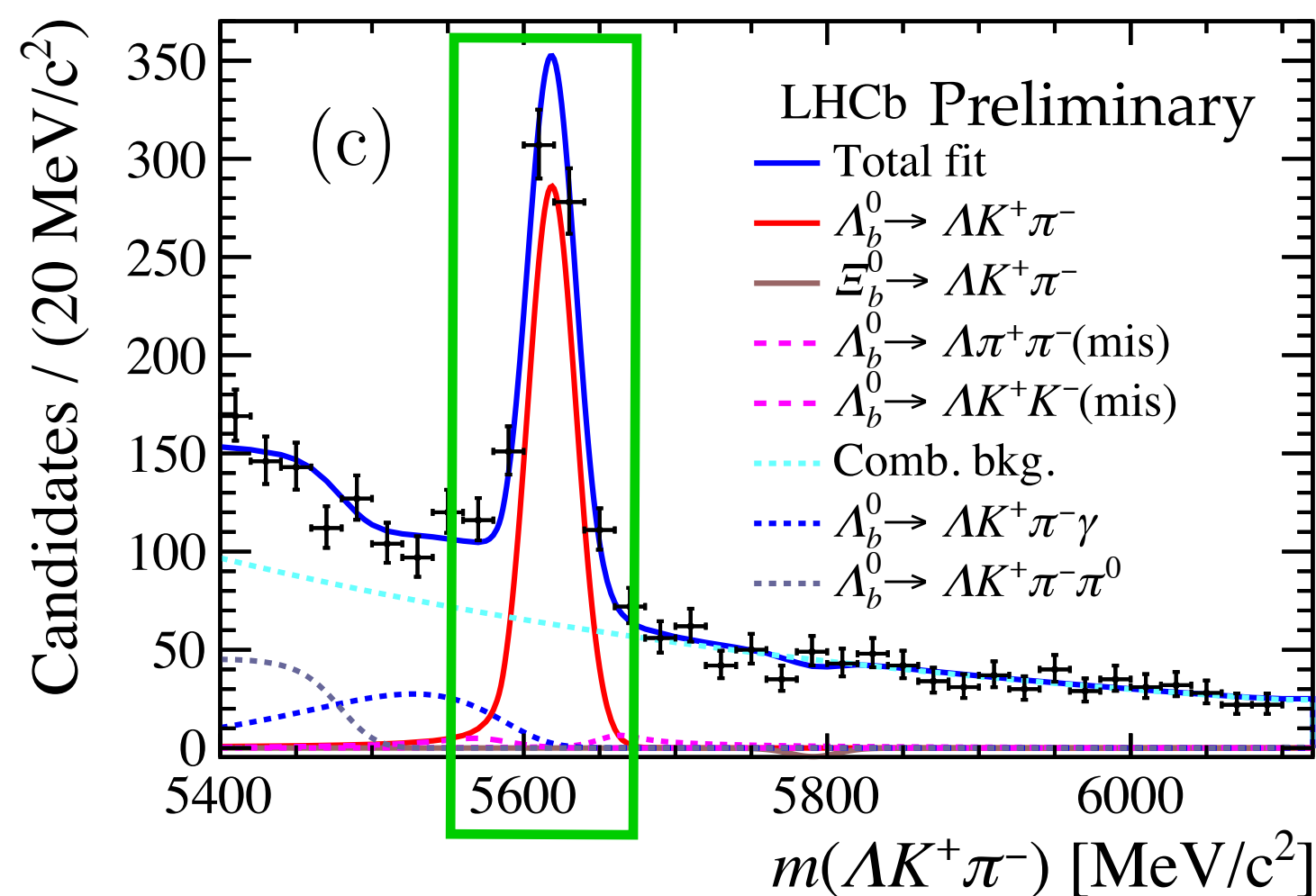
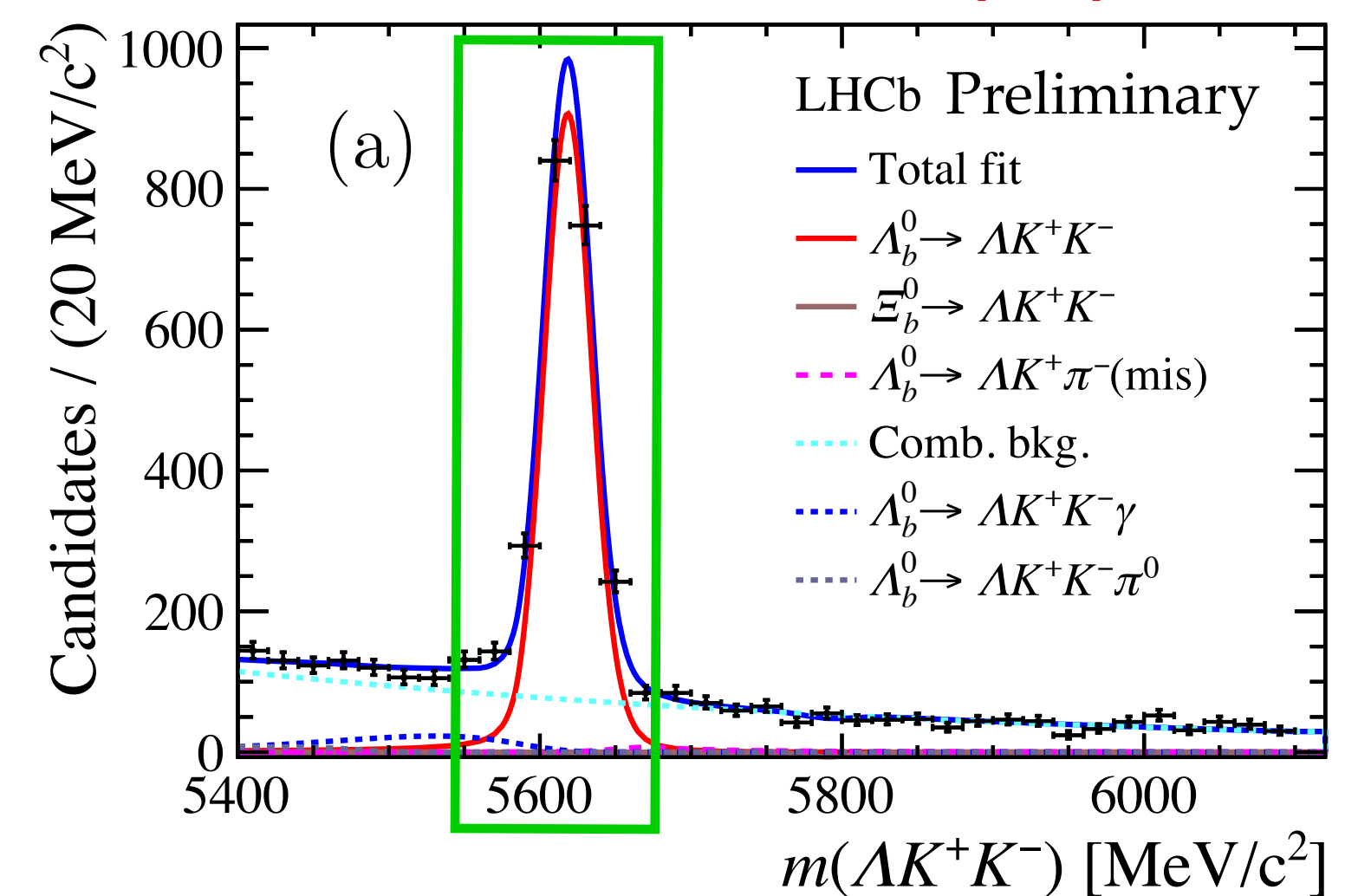
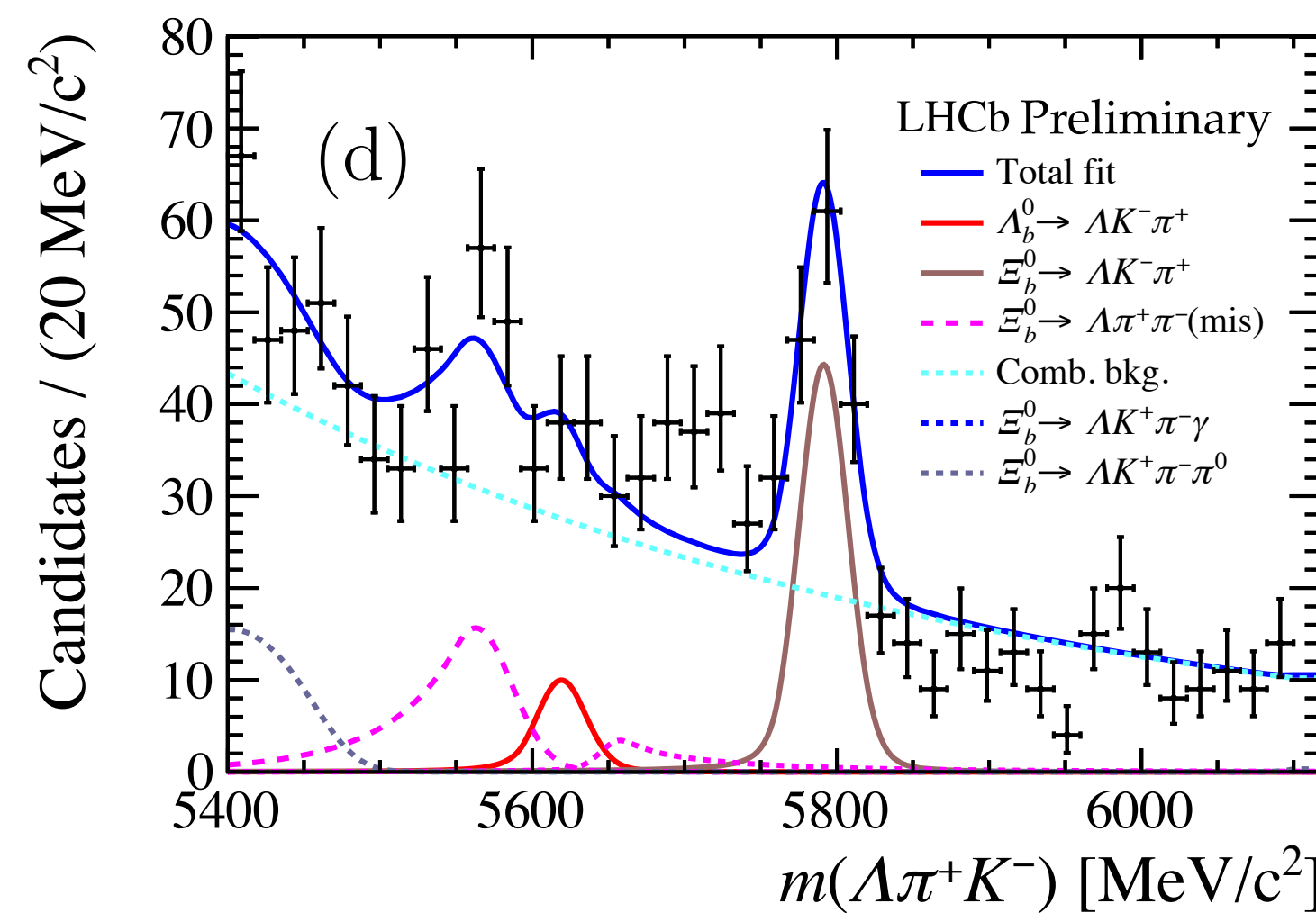
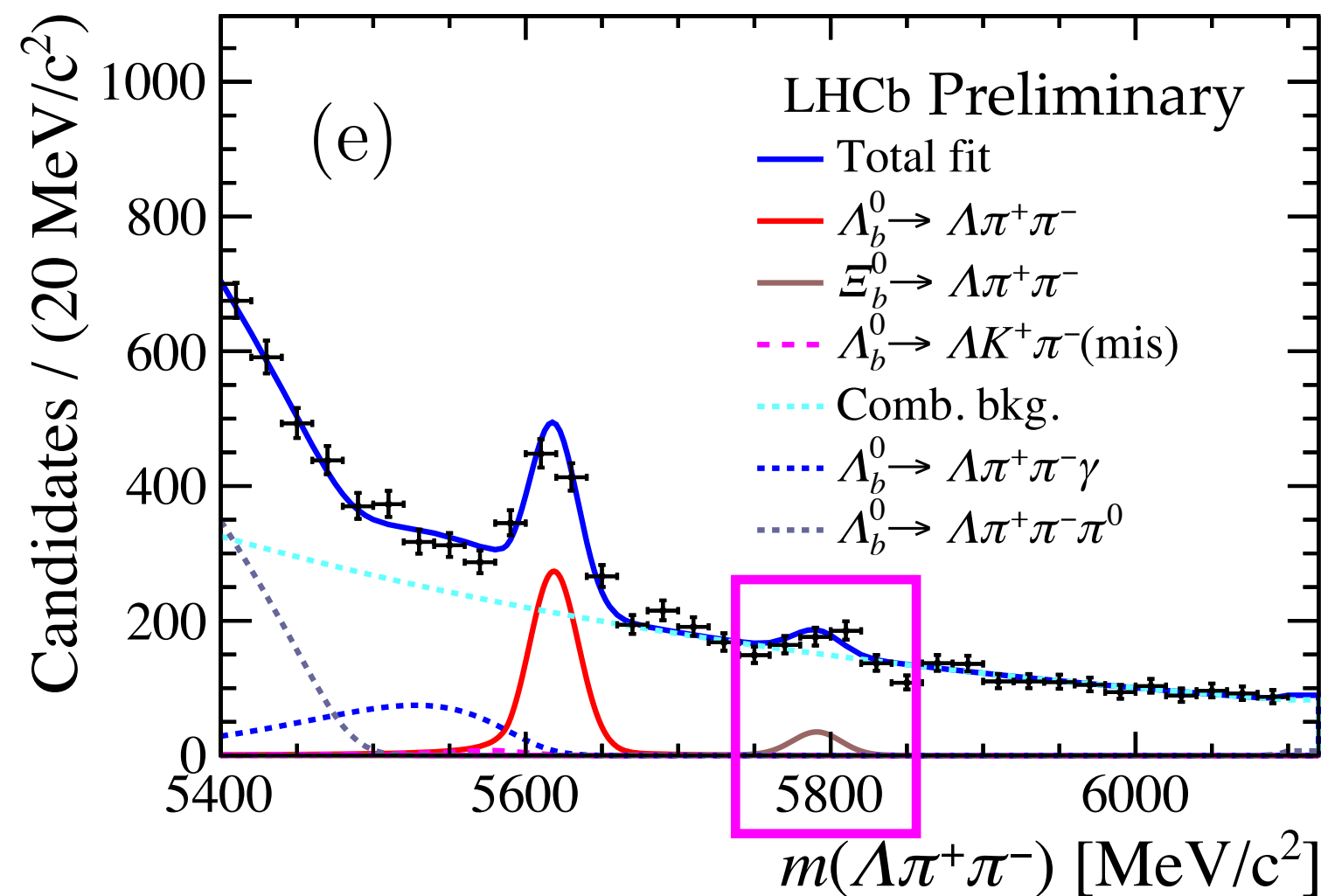
Confirmed

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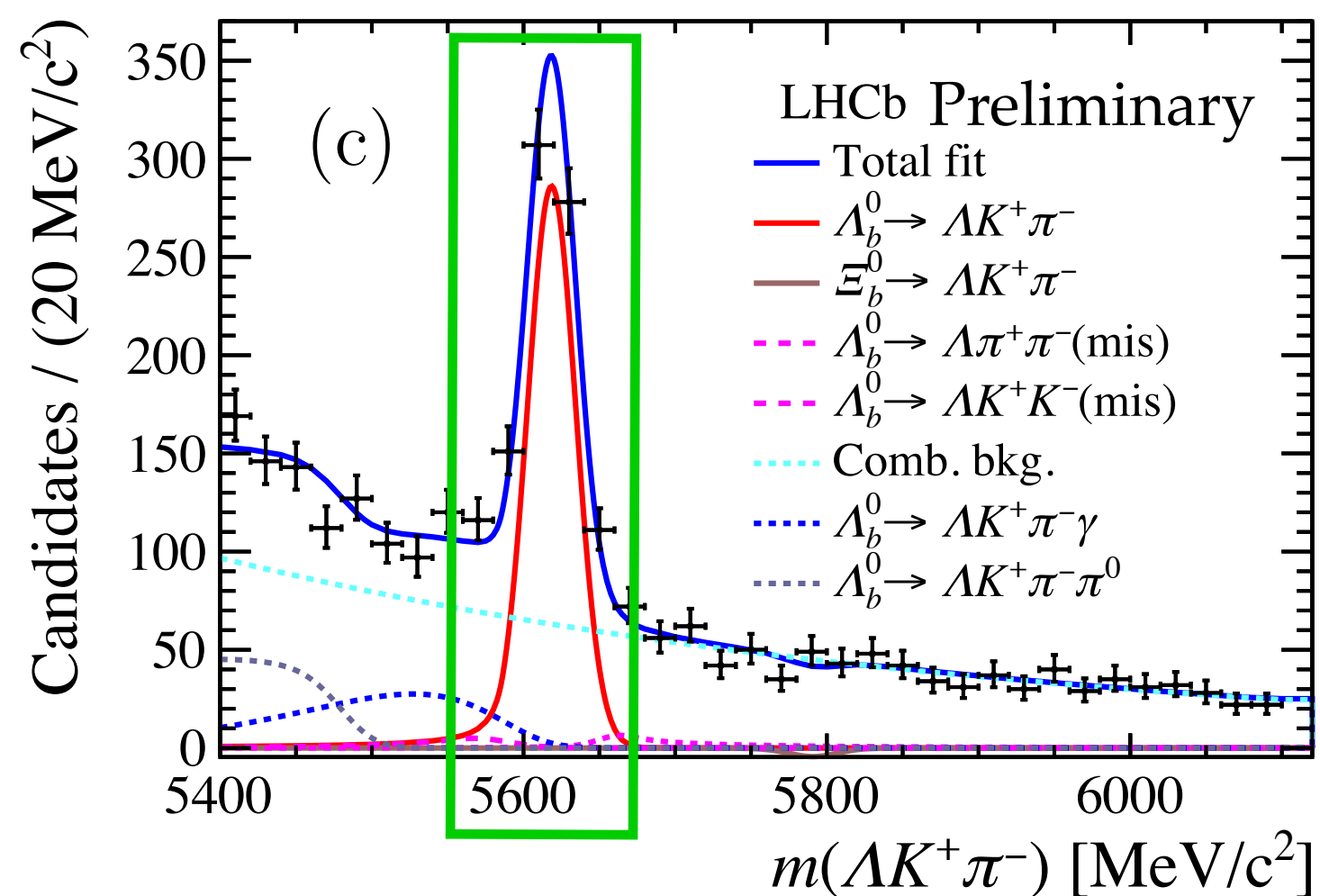
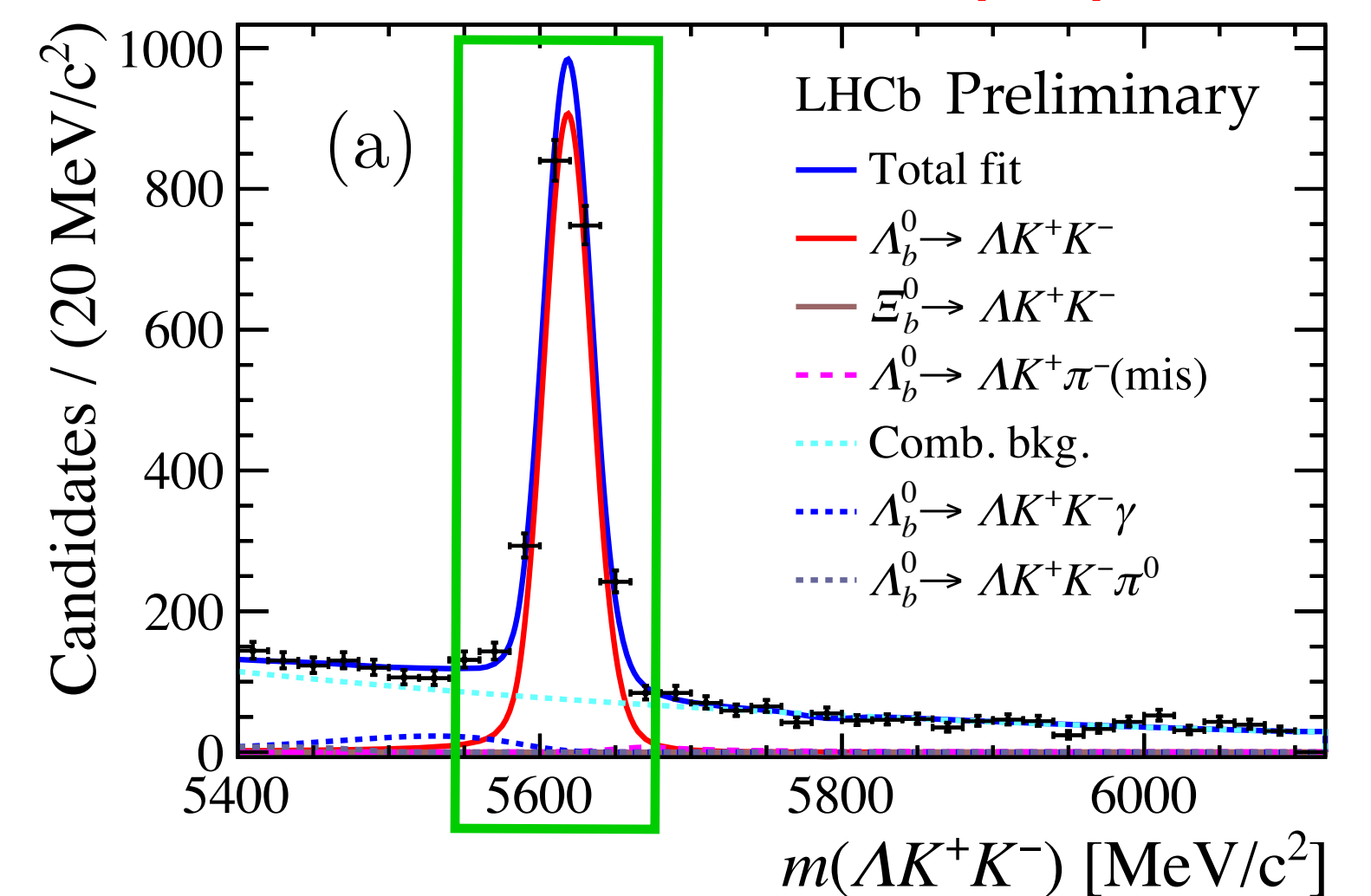
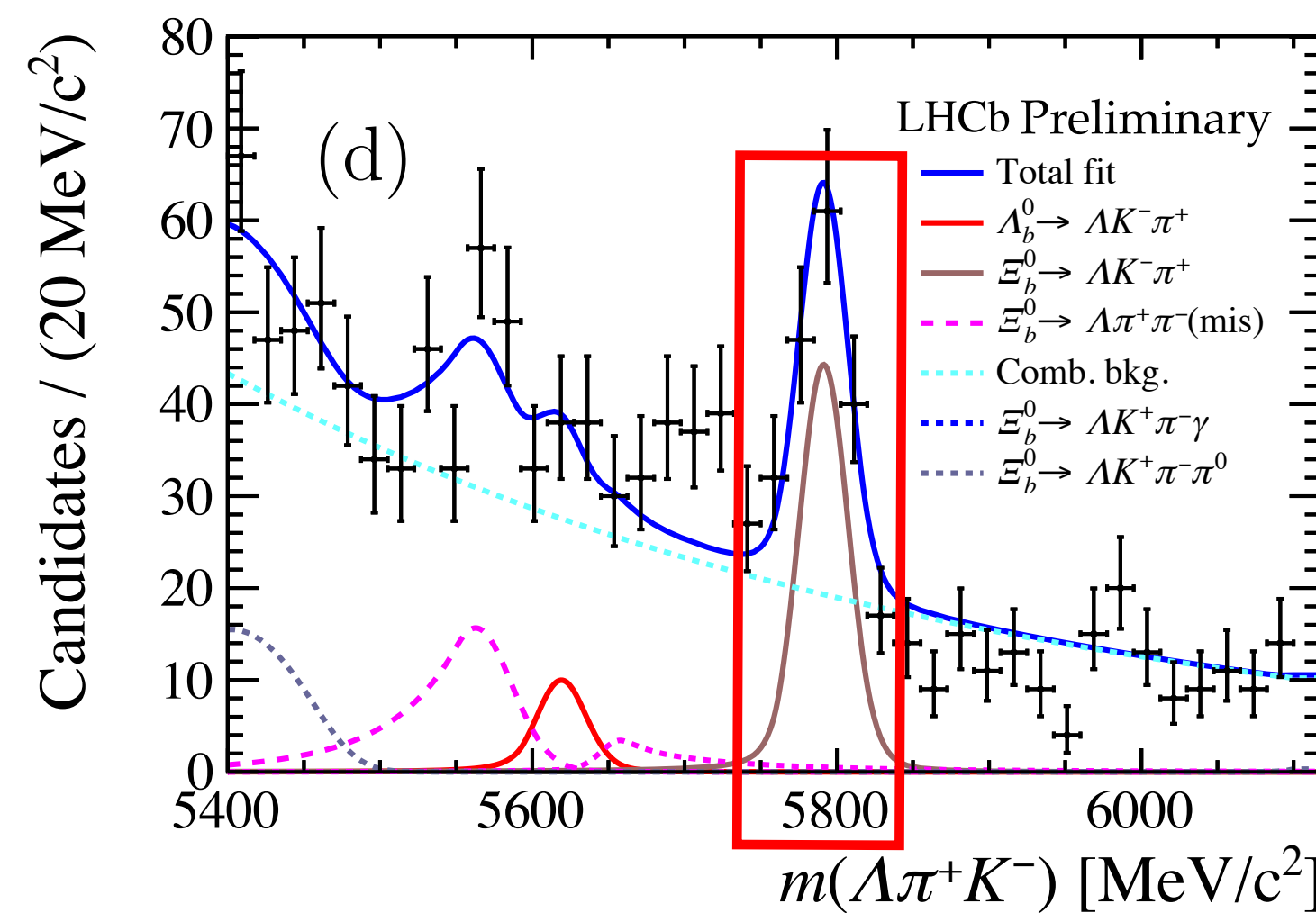
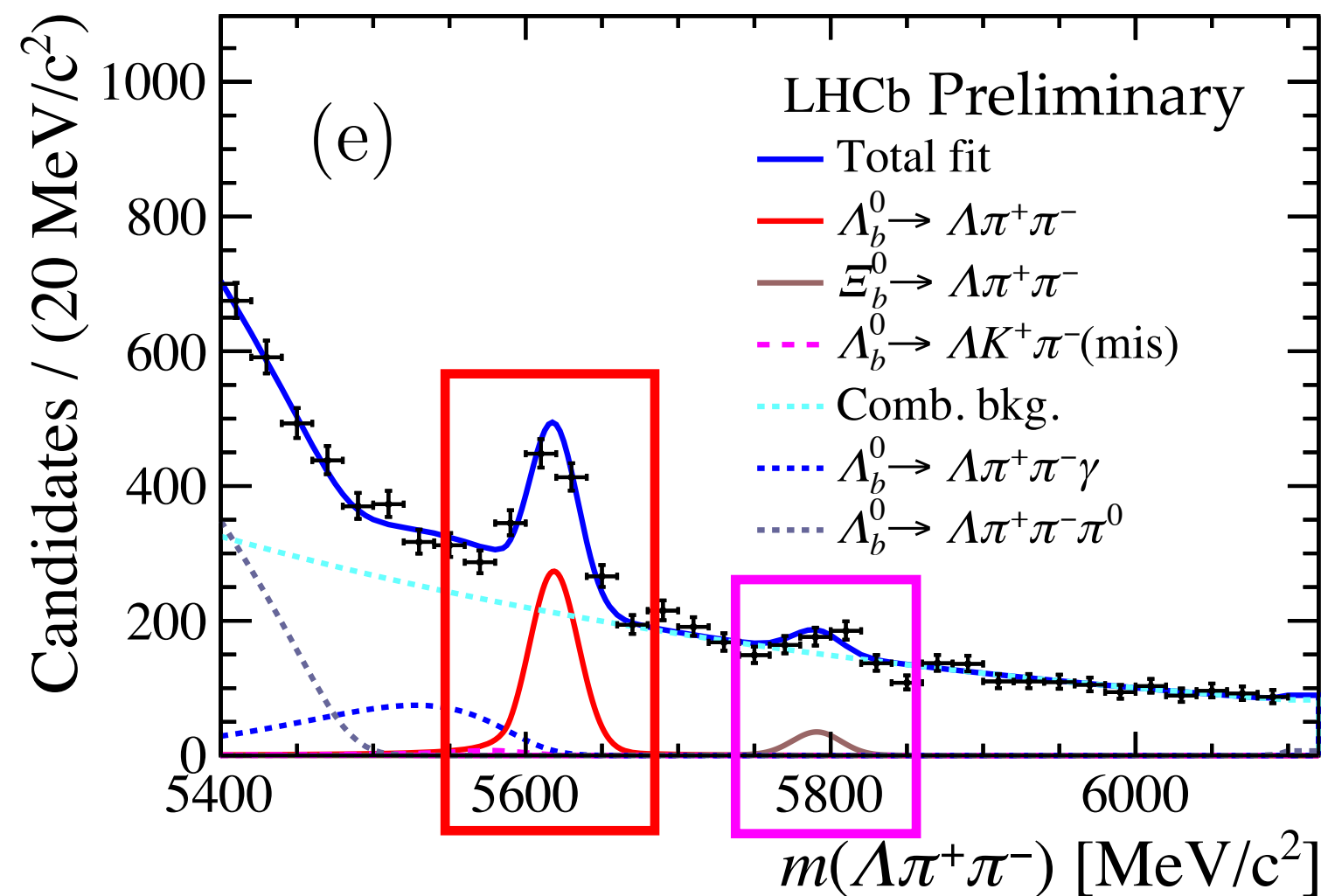
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First evidence (4σ)

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First observation

Confirmed

Confirmed

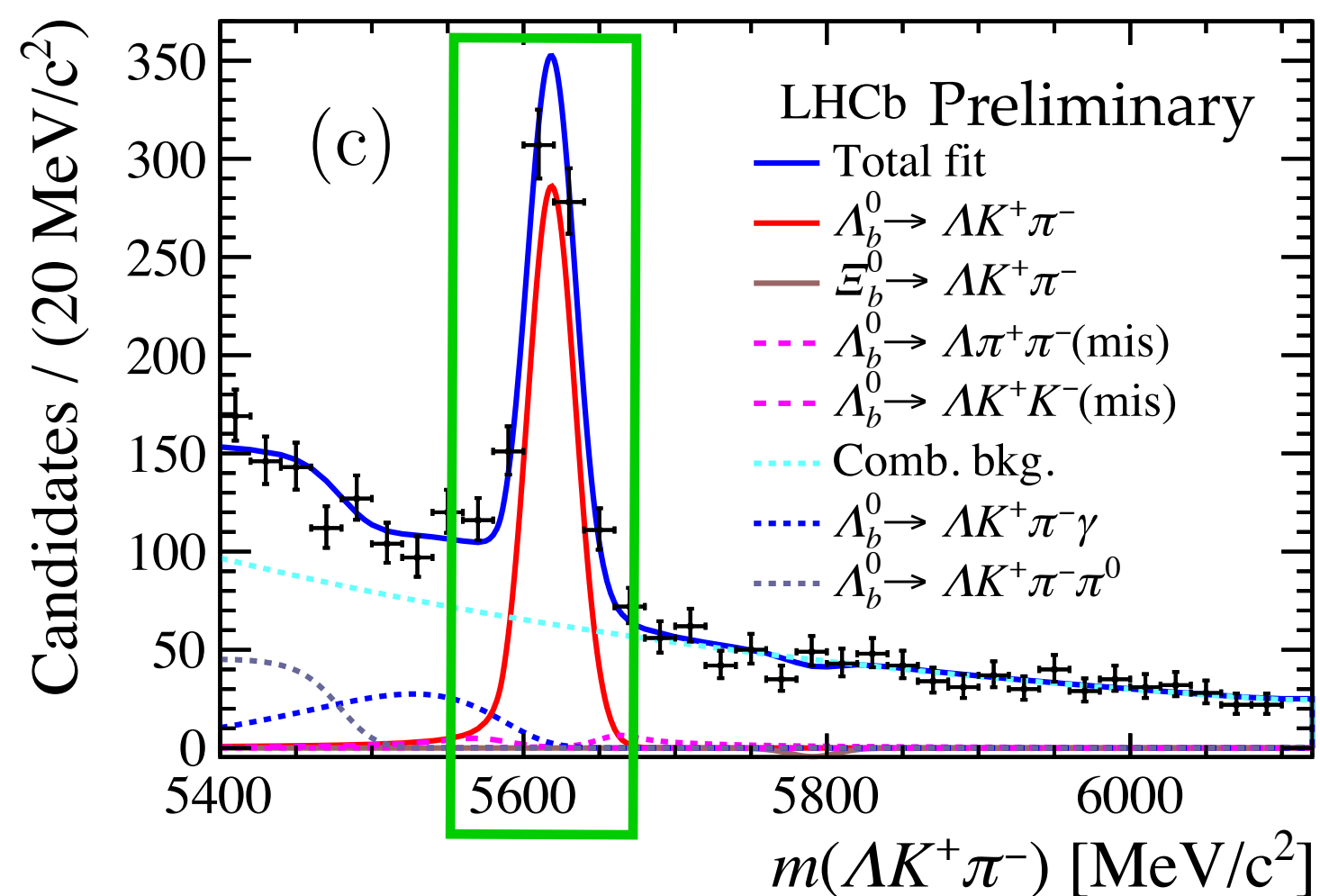
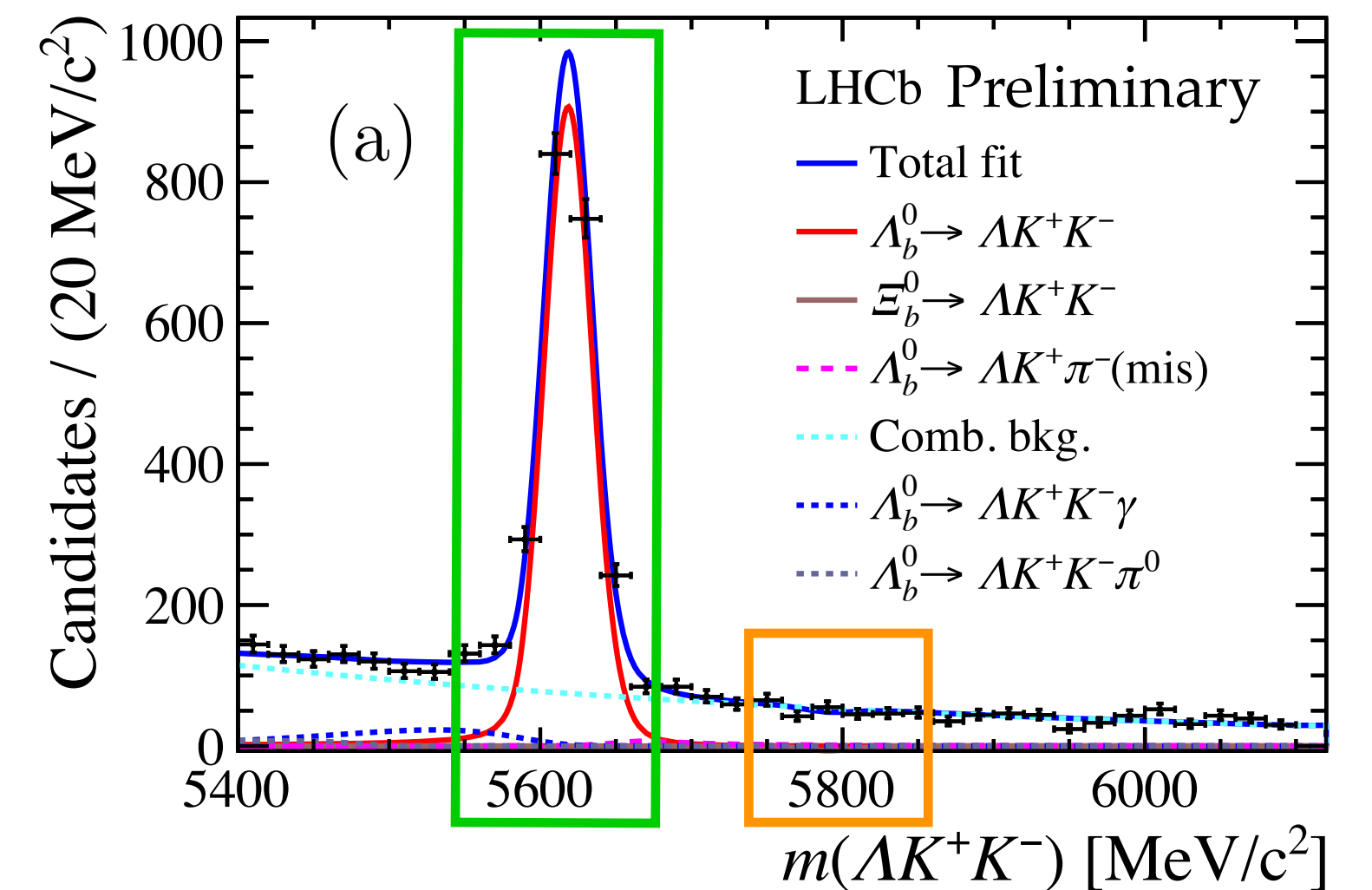
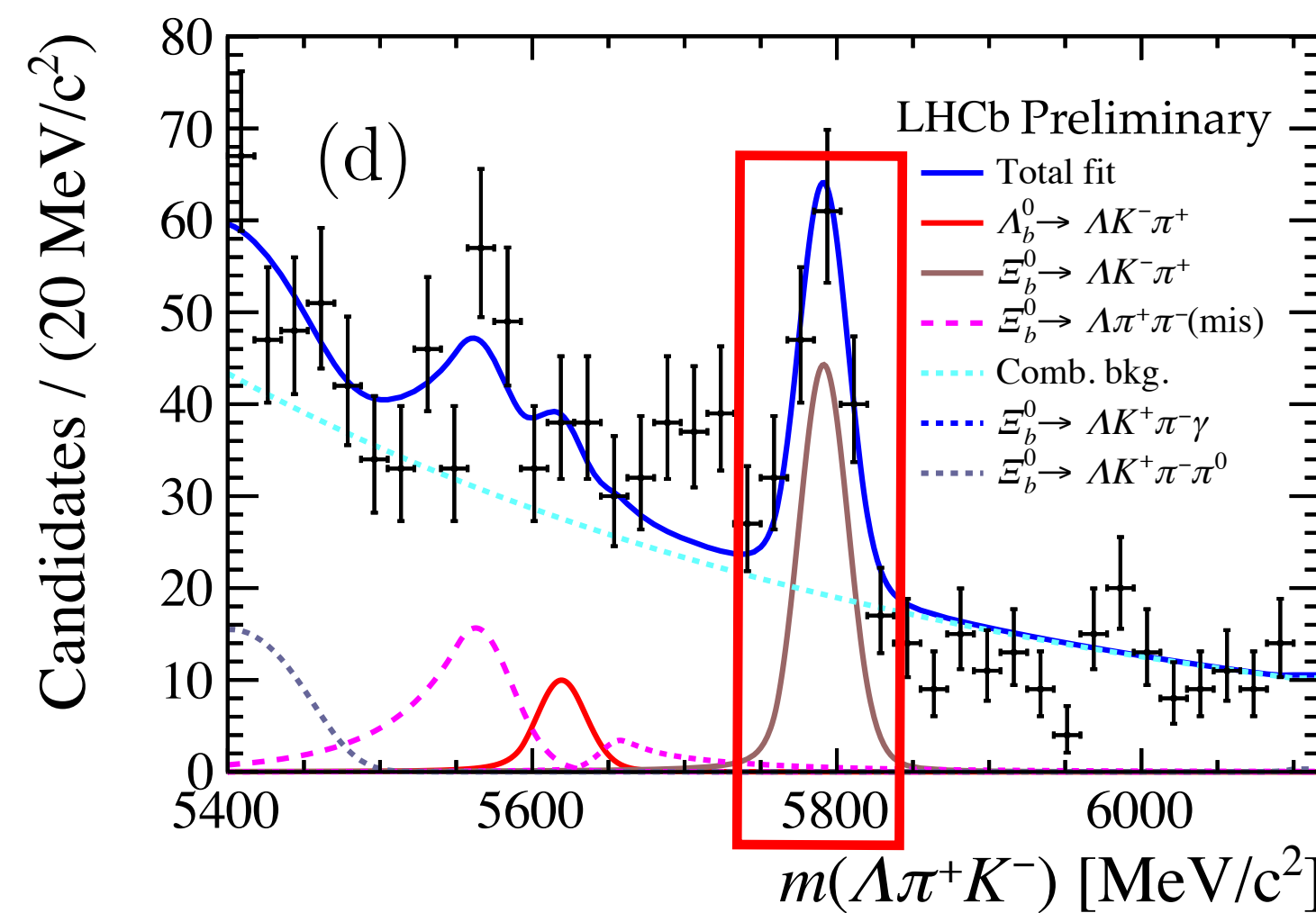
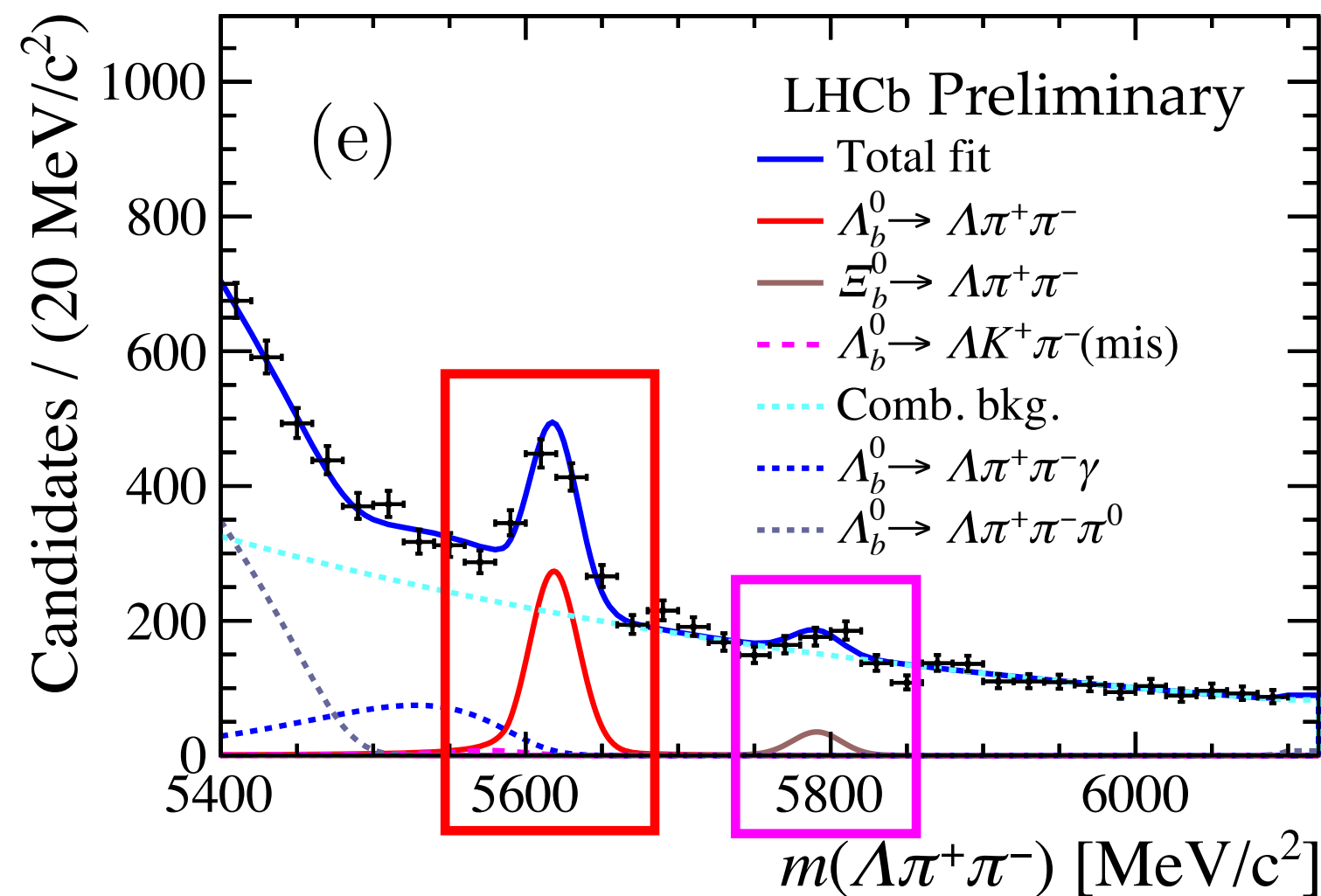
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$$\mathcal{B}(\Xi_b^0 \rightarrow \Lambda K^- \pi^+) = (10.4 \pm 1.4 \pm 1.2 \pm 3.5(\text{norm})) \times 10^{-6}$$

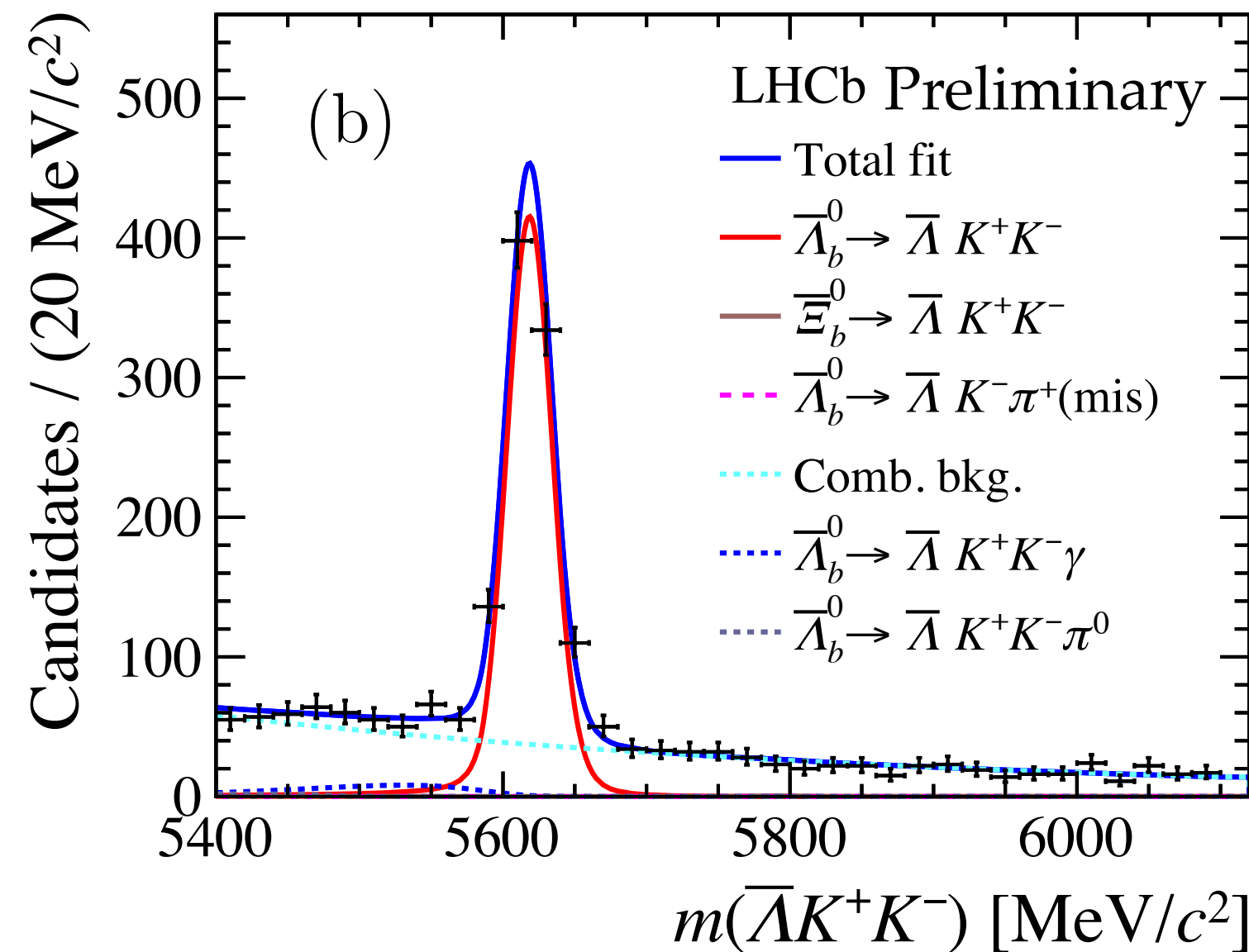
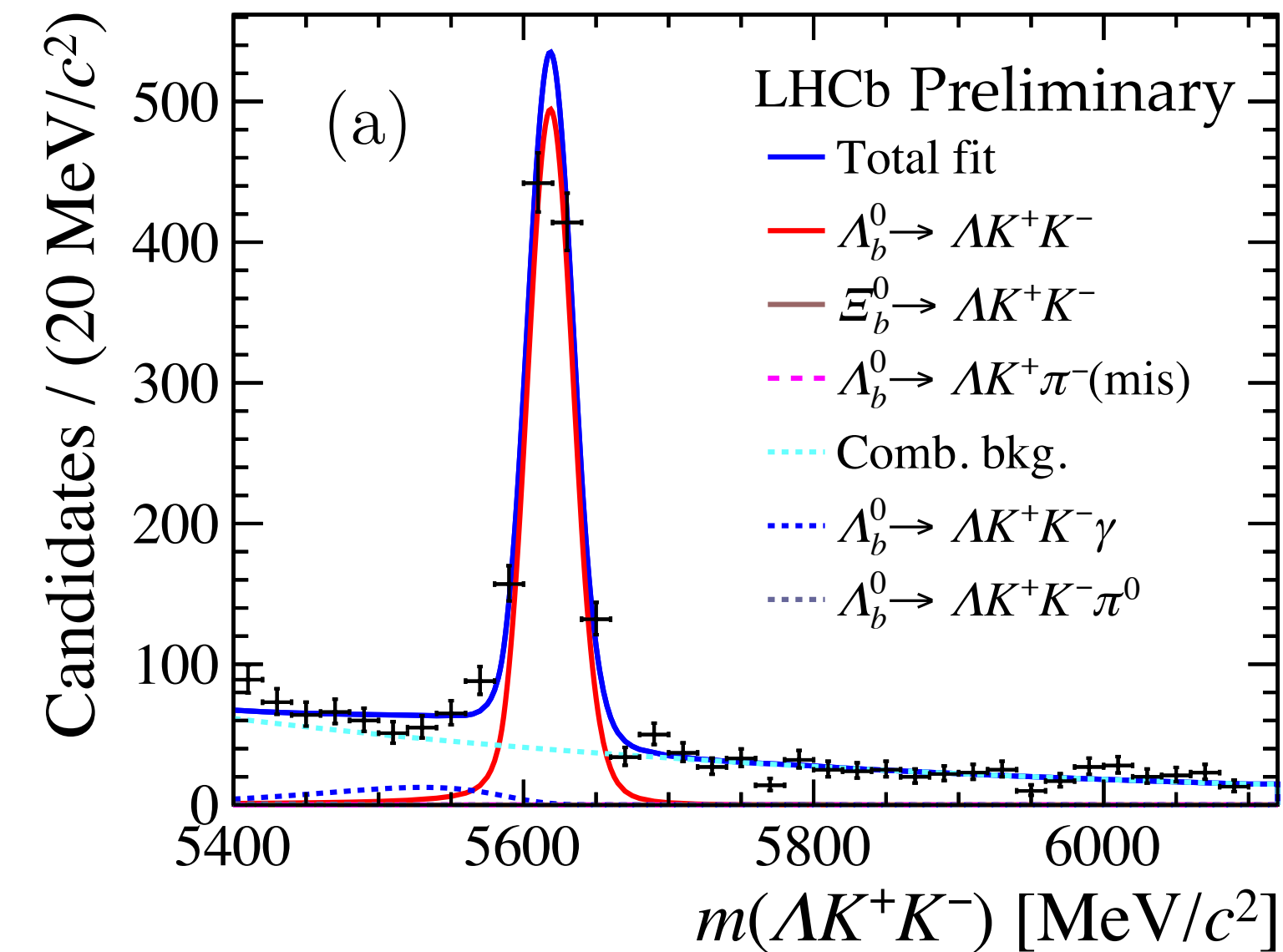
First observation

$$\mathcal{B}(\Xi_b^0 \rightarrow \Lambda K^- K^+) < 2.4 \times 10^{-6} \text{ (90\% CL)}$$

No evidence

Study of Λ_b^0 and Ξ_b^0 decays to $\Lambda h^+ h'^-$ final states

New!



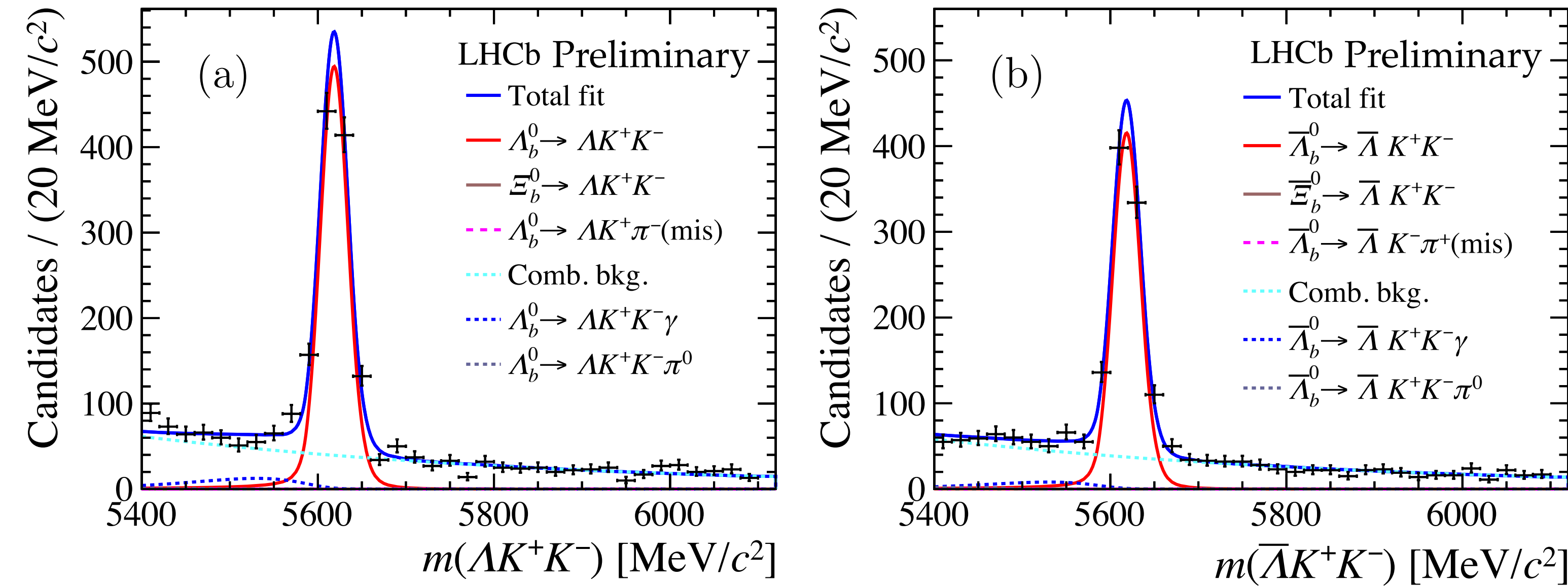
[LHCb-PAPER-2024-043], in preparation

• Run 1&2 results:

$$\begin{aligned} \Delta \mathcal{A}^{CP} (\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-) &= -0.013 \pm 0.053 \pm 0.018, \\ \Delta \mathcal{A}^{CP} (\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-) &= -0.118 \pm 0.045 \pm 0.021, \\ \Delta \mathcal{A}^{CP} (\Lambda_b^0 \rightarrow \Lambda K^+ K^-) &= 0.083 \pm 0.023 \pm 0.016, \\ \Delta \mathcal{A}^{CP} (\Xi_b^0 \rightarrow \Lambda K^- \pi^+) &= 0.27 \pm 0.12 \pm 0.05, \end{aligned}$$

Study of Λ_b^0 and Ξ_b^0 decays to $\Lambda h^+ h'^-$ final states

New!



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

- Run 1&2 results:

$$\Delta\mathcal{A}^{CP} (\Lambda_b^0 \rightarrow \Lambda\pi^+\pi^-) = -0.013 \pm 0.053 \pm 0.018,$$

$$\Delta\mathcal{A}^{CP} (\Lambda_b^0 \rightarrow \Lambda K^+\pi^-) = -0.118 \pm 0.045 \pm 0.021,$$

$$\Delta\mathcal{A}^{CP} (\Lambda_b^0 \rightarrow \Lambda K^+ K^-) = 0.083 \pm 0.023 \pm 0.016,$$

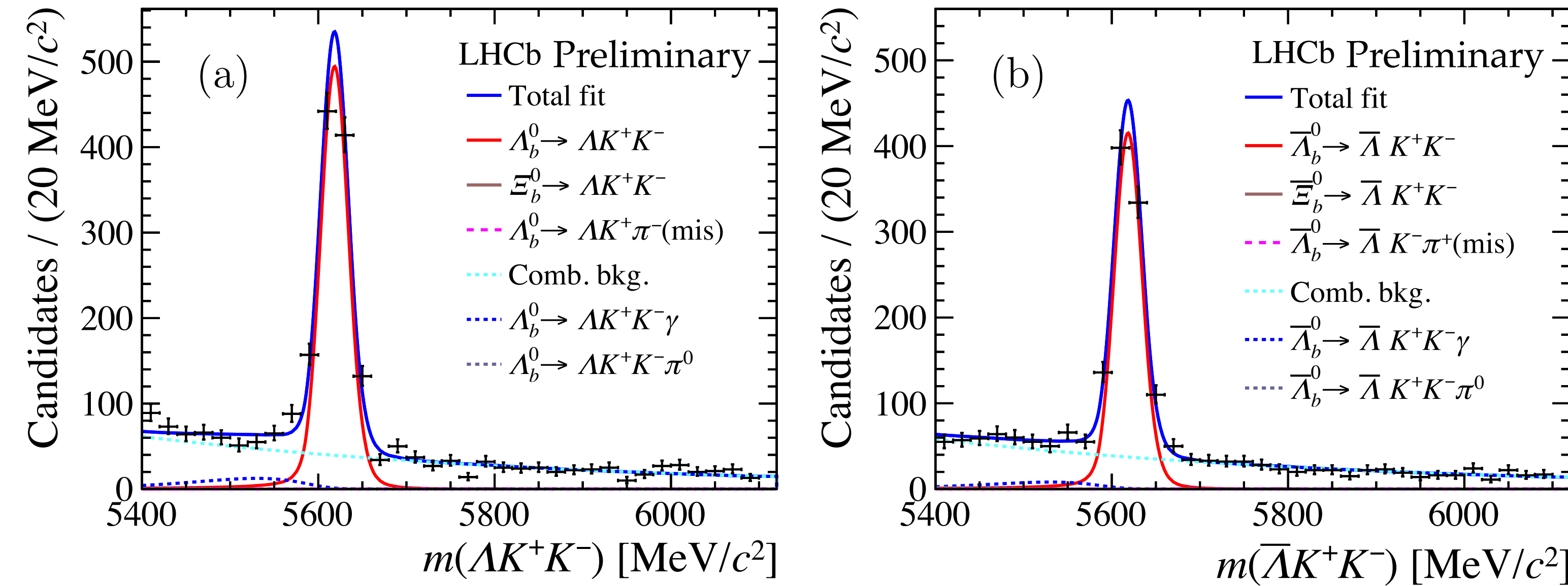
$$\Delta\mathcal{A}^{CP} (\Xi_b^0 \rightarrow \Lambda K^-\pi^+) = 0.27 \pm 0.12 \pm 0.05,$$

- First evidence of direct CP violation in baryon decays (3.1σ)

Study of Λ_b^0 and Ξ_b^0 decays to $\Lambda h^+ h'^-$ final states

New!

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



Run 1&2 results:

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \rightarrow \Lambda\pi^+\pi^-) = -0.013 \pm 0.053 \pm 0.018,$$

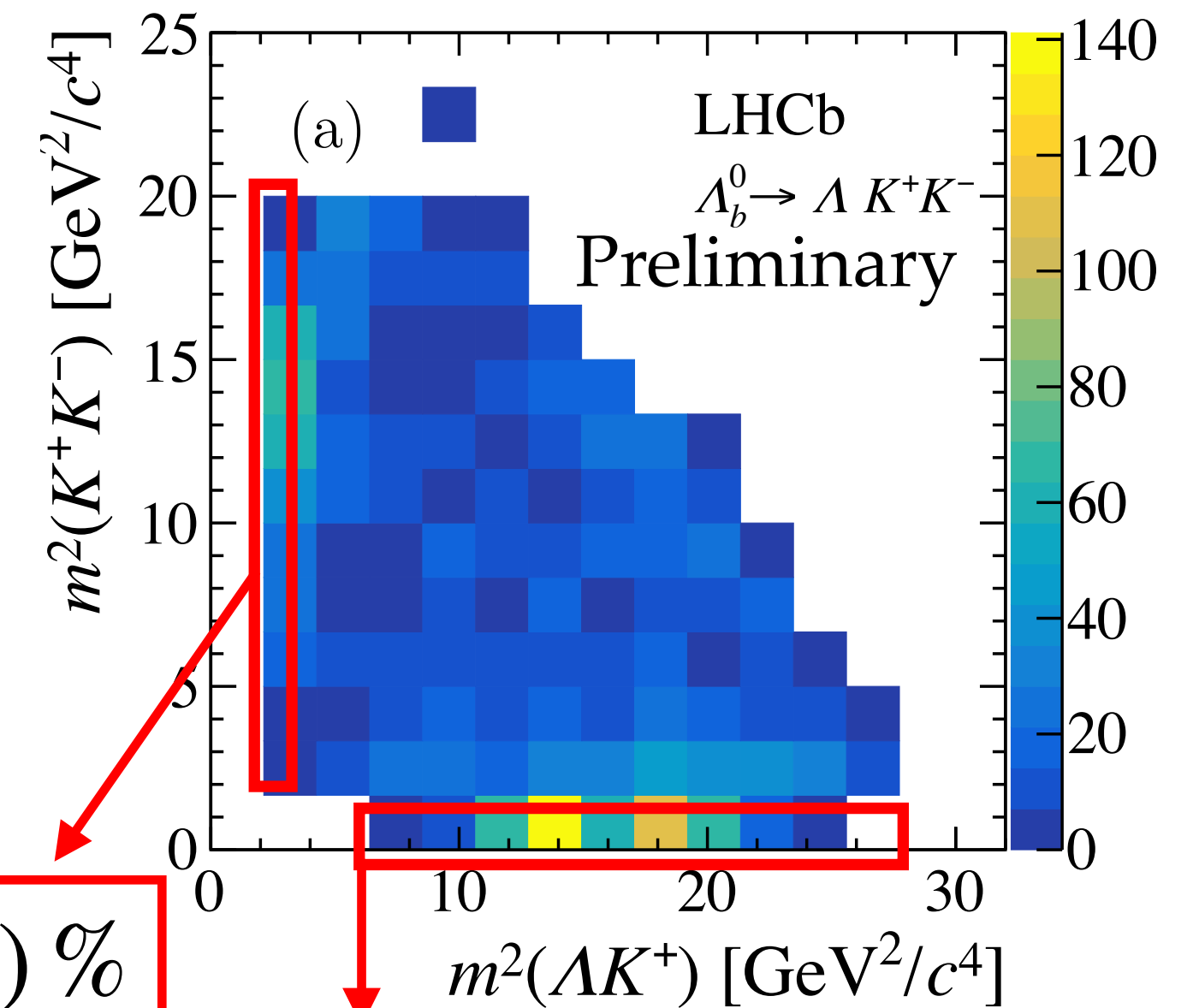
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \rightarrow \Lambda K^+\pi^-) = -0.118 \pm 0.045 \pm 0.021,$$

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \rightarrow \Lambda K^+K^-) = 0.083 \pm 0.023 \pm 0.016,$$

$$\Delta\mathcal{A}^{CP}(\Xi_b^0 \rightarrow \Lambda K^-\pi^+) = 0.27 \pm 0.12 \pm 0.05,$$

- **First evidence** of direct CP violation in baryon decays (3.1σ)

- Possible interpretation: enhancement from $N^{*+} \rightarrow \Lambda K^+$ (3.2σ) and $\phi \rightarrow K^+K^-$ resonances

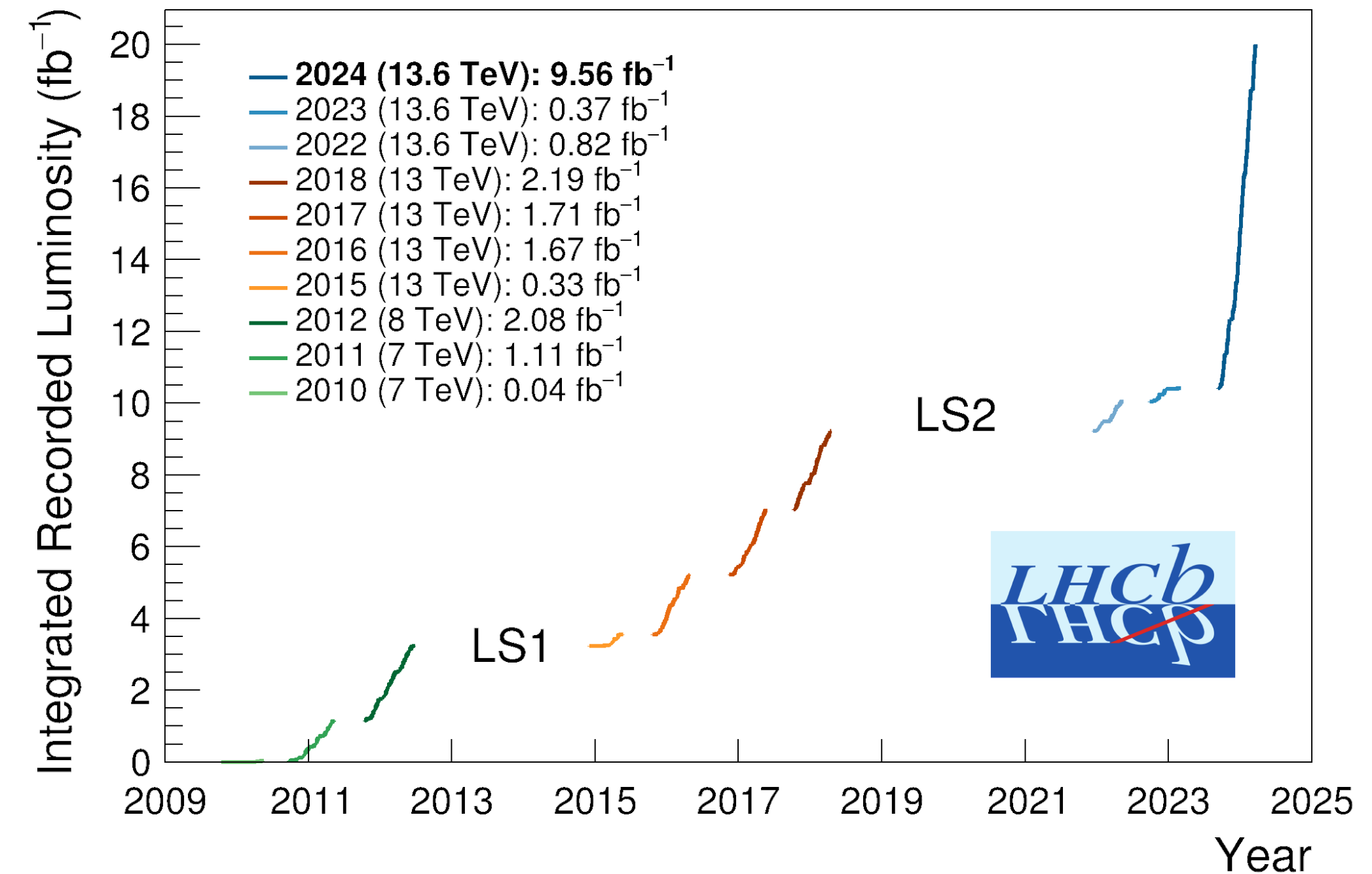


$$\Delta A_{CP} = (16.5 \pm 5.1) \%$$

$$\Delta A_{CP} = (15.0 \pm 5.9) \%$$

Conclusions

- **First evidence** of **direct CP** violation in beauty to charmonia decays
- Best measurements of $A_{CP}(\Lambda_b^0 \rightarrow pK^-)$ and $A_{CP}(\Lambda_b^0 \rightarrow p\pi^-)$
- **First evidence** of **direct CP** violation in **baryon** decays $\Lambda_b^0 \rightarrow \Lambda K^+ K^-$
 - If confirmed, may provide useful insights on sources of *CPV* in baryon dynamics
- Huge increase in sample size expected for Run 3 with higher hadronic selection efficiencies → **stay tuned!**



BACKUP

CP asymmetry and branching fraction of $B^+ \rightarrow J/\psi\pi^+$ decays

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

	Branching fraction ratio			CP asymmetry difference		
	2016	2017	2018	2016	2017	2018
	[%]	[%]	[%]	$[10^{-2}]$	$[10^{-2}]$	$[10^{-2}]$
Mass fit	0.22	0.16	0.21	0.04	0.06	0.04
Trigger efficiency	0.40	0.39	0.37	-	-	-
Material budget	0.30	0.30	0.30	-	-	-
Simulation correction	0.17	0.15	0.14	-	-	-
PID	0.29	0.22	0.29	0.06	0.07	0.08
Detection asymmetry	-	-	-	0.05	0.05	0.05
Production asymmetry	-	-	-	0.02	0.02	0.02
Total	0.64	0.58	0.61	0.09	0.11	0.11

CP asymmetry and branching fraction of $B^+ \rightarrow J/\psi\pi^+$ decays

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

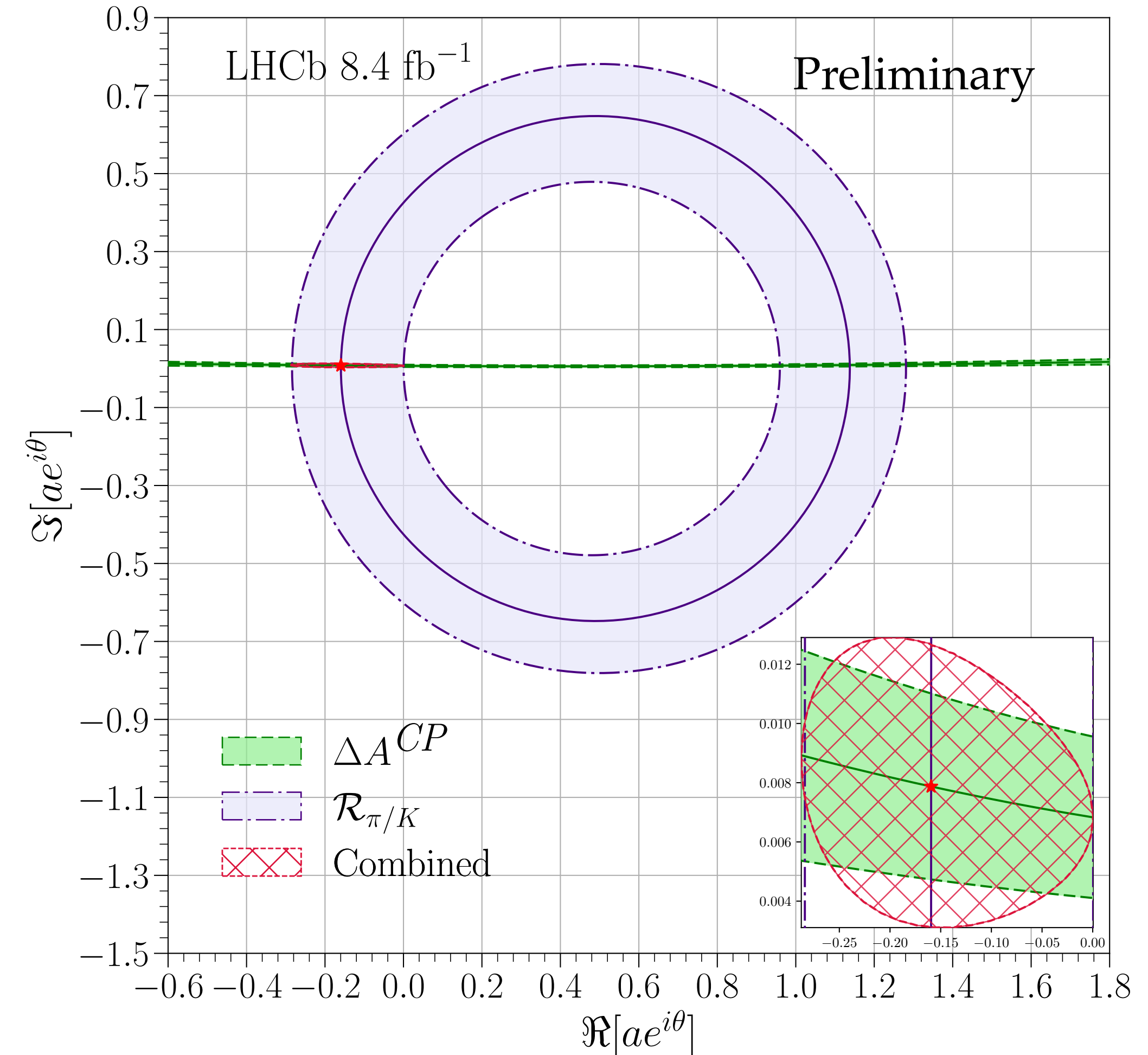
- Write amplitudes as

$$A(B^+ \rightarrow J/\psi\pi^+) = -V_{us}A \left(1 + ae^{i\theta}e^{i\gamma}\right)$$

$$A(B^+ \rightarrow J/\psi K^+) = (1 - V_{us}^2/2)A' \left(1 + \frac{V_{us}}{1 - V_{us}^2}a'e^{i\theta'}e^{i\gamma}\right)$$

- Assuming SU(3) conservation, $a = a'$ and $\theta = \theta'$

- Using $A'/A = 1.32 \pm 0.07$ [JPG 48 (2021)] and $\gamma = (64.6 \pm 2.8)^\circ$ [JHEP 12 (2021)]



Measurement of CP asymmetries with $\Lambda_b^0 \rightarrow ph^-$ decays

[LHCb-PAPER-2024-048], in preparation

	Run 1		Run 2	
	$\Lambda_b^0 \rightarrow pK^-$	$\Lambda_b^0 \rightarrow p\pi^-$	$\Lambda_b^0 \rightarrow pK^-$	$\Lambda_b^0 \rightarrow p\pi^-$
Fit model	0.05	0.15	0.05	0.15
Particle identification	0.25	0.25	0.15	0.16
TIS trigger	0.12	0.11	0.04	0.04
TOS hardware trigger	0.20	0.21	0.10	0.10
TOS software trigger	0.33	0.32	0.20	0.20
Proton detection	0.10	0.10	0.04	0.04
Kaon detection	0.25	-	0.10	0.03
Pion detection	-	0.10	0.04	0.04
Λ_b^0 production	0.12	0.13	-	-
Control sample size	-	-	0.28	0.28
Total systematic	0.57	0.53	0.41	0.42
Statistical	1.55	1.86	0.75	0.93

Study of Λ_b^0 and Ξ_b^0 decays to $\Lambda h^+ h'^-$ final states

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

- Branching fractions:

Channel	PhSp	Fit	Veto	PID	Control	Eff.	Total.
$\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$	0.091	0.049	0.007	0.005	0.042	0.017	0.113
$\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-$	0.076	0.026	0.009	0.001	0.034	0.015	0.089
$\Lambda_b^0 \rightarrow \Lambda K^+ K^-$	0.026	0.020	0.005	0.004	0.018	0.014	0.041
$\Xi_b^0 \rightarrow \Lambda \pi^+ \pi^-$	0.112	0.110	0.021	0.004	0.056	0.018	0.168
$\Xi_b^0 \rightarrow \Lambda K^- \pi^+$	0.102	0.076	0.003	0.002	0.029	0.014	0.131
$\Xi_b^0 \rightarrow \Lambda K^+ K^-$	0.100	0.992	0.504	0.001	0.024	0.021	1.117

- CP asymmetries

Channel	Fit	Shape	Correction	Control	Veto	Total
$\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$	0.007	0.005	0.009	0.013	0.004	0.018
$\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-$	0.011	0.005	0.010	0.013	0.002	0.021
$\Lambda_b^0 \rightarrow \Lambda K^+ K^-$	0.003	0.002	0.009	0.013	0.002	0.016
$\Xi_b^0 \rightarrow \Lambda K^+ \pi^-$	0.022	0.009	0.043	0.013	0.006	0.051