Search for CPV in charmless decays of beauty baryons at LHCb

INFN BOLOGNA

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LHCb

The School of Athens, Raphael

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Introduction

- *CP* violation arises from complex phase in CKM matrix
- Observed in a many meson decays over the last 60 years
- Still no observation in baryon decays
- *CP* effects seem to be smaller there, why?

Indirect CPV in $K_L \to \pi^+\pi^-$
[PRL 13 (1964)]

Direct CPV in $K_S^0 \to \pi^+\pi^-/\pi^0\pi^0$
[IJMP A (2000)]

CPV in B^0 decays
[PRL 87 (2001)] [PRL 87 (2001)]

CPV in B^+ decays
[PLB 712 (2012)]

CPV in B_s^0 decays
[PRL 110 (2013)]

CPV in D^0 decays
[PRL 122 (2019)]

⋮

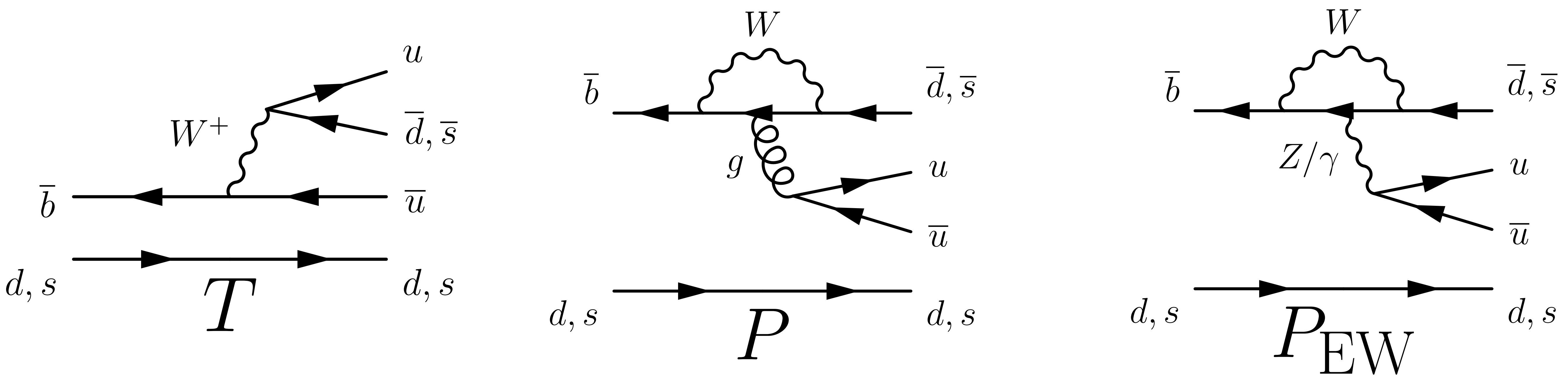
CPV in baryons?

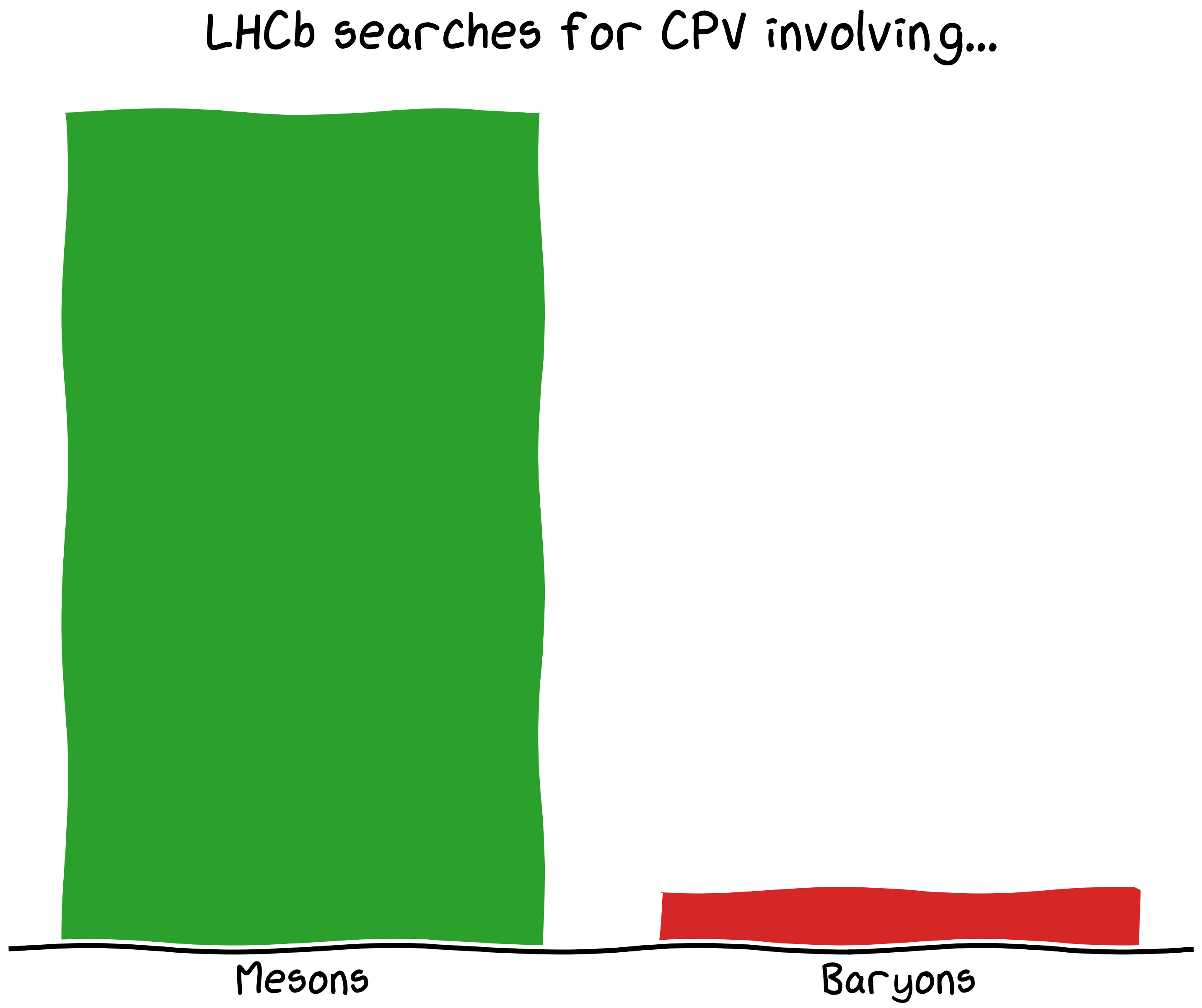
Introduction

- Charmless decays of beauty baryons are a promising direction
- Tree-level transitions suppressed → interference with penguin contributions might enhance *CPV*
- Theoretical predictions difficult because of large QCD uncertainties
- Overlooked in favour of mesons until now

$$\begin{array}{c|ccc} & d & s & b \\ \hline u & 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ c & -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ t & A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{array}$$

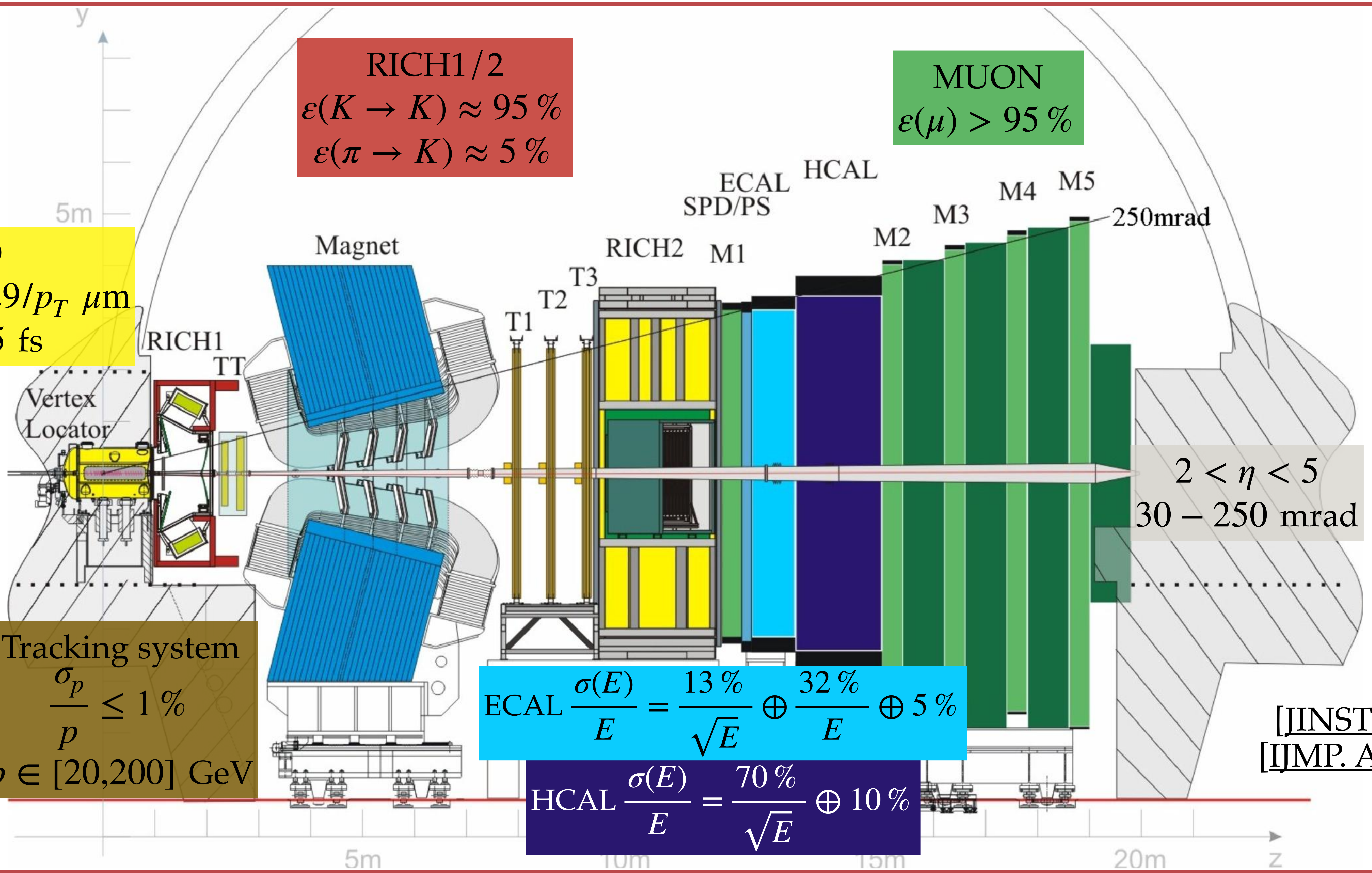
$$\boxed{\frac{V_{ub}}{V_{cb}} \approx 0.1}$$





The LHCb detector (Run 1-2)

Run 1: $\mathscr{L} = 3\ \mathrm{fb}^{-1}$, $\sqrt{s} = 7{,}8$ TeV
Run 2: $\mathscr{L} = 6\ \mathrm{fb}^{-1}$, $\sqrt{s} = 13$ TeV



RICH1/2
$\varepsilon(K \to K) \approx 95\,\%$
$\varepsilon(\pi \to K) \approx 5\,\%$

MUON
$\varepsilon(\mu) > 95\,\%$

VELO
$\sigma(IP) = 15 + 29/p_T\ \mu\mathrm{m}$
$\sigma(t) \approx 45$ fs

$2 < \eta < 5$
$30 - 250$ mrad

Tracking system
$\frac{\sigma_p}{p} \leq 1\,\%$
$p \in [20{,}200]$ GeV

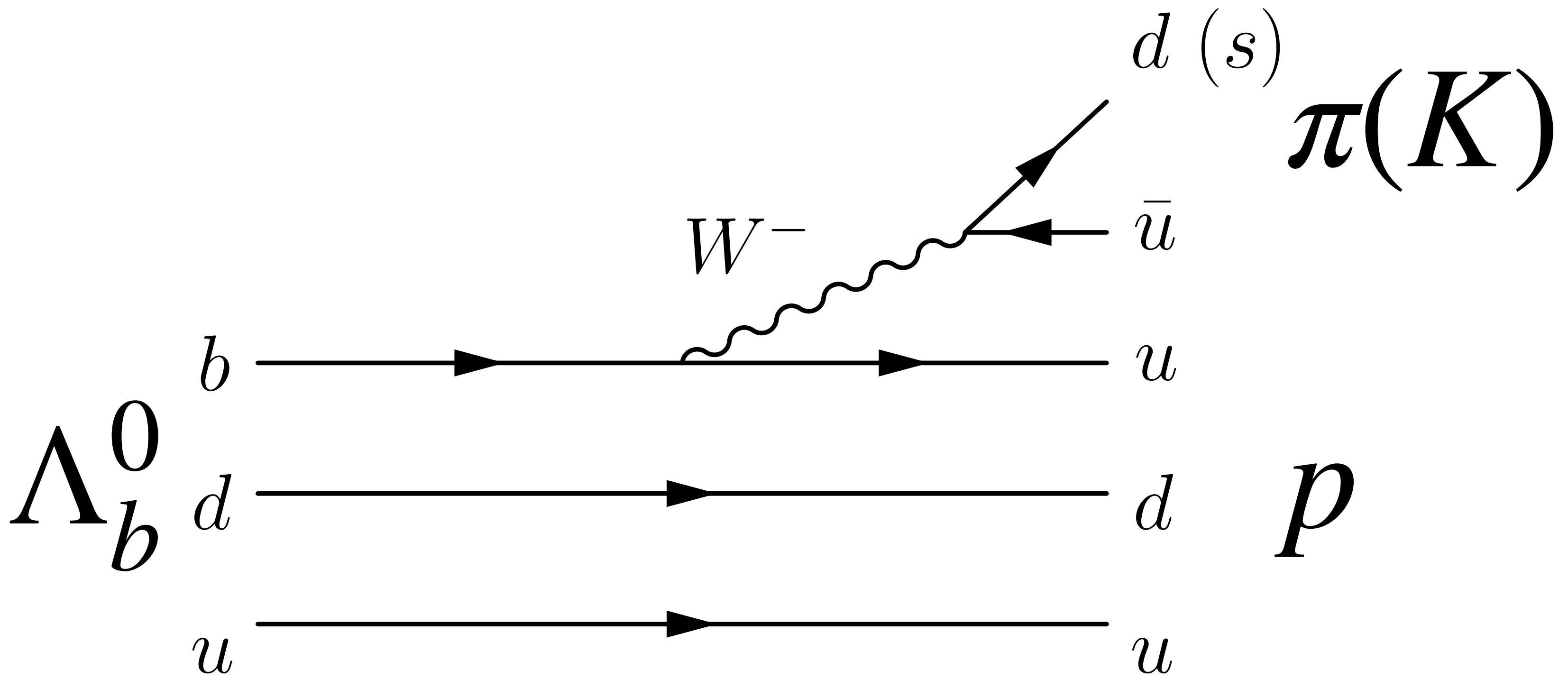
ECAL $\frac{\sigma(E)}{E} = \frac{13\,\%}{\sqrt{E}} \oplus \frac{32\,\%}{E} \oplus 5\,\%$

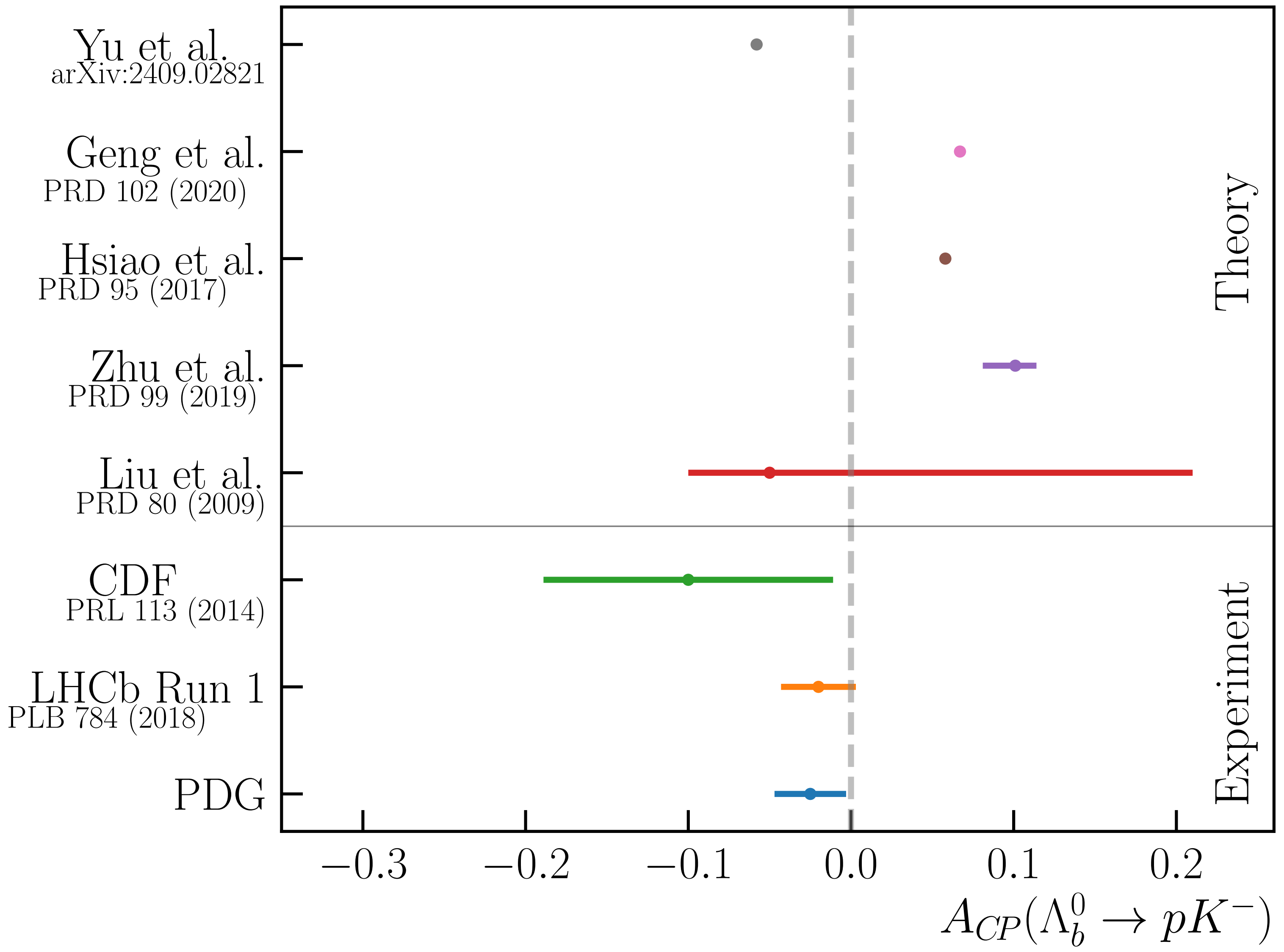
HCAL $\frac{\sigma(E)}{E} = \frac{70\,\%}{\sqrt{E}} \oplus 10\,\%$

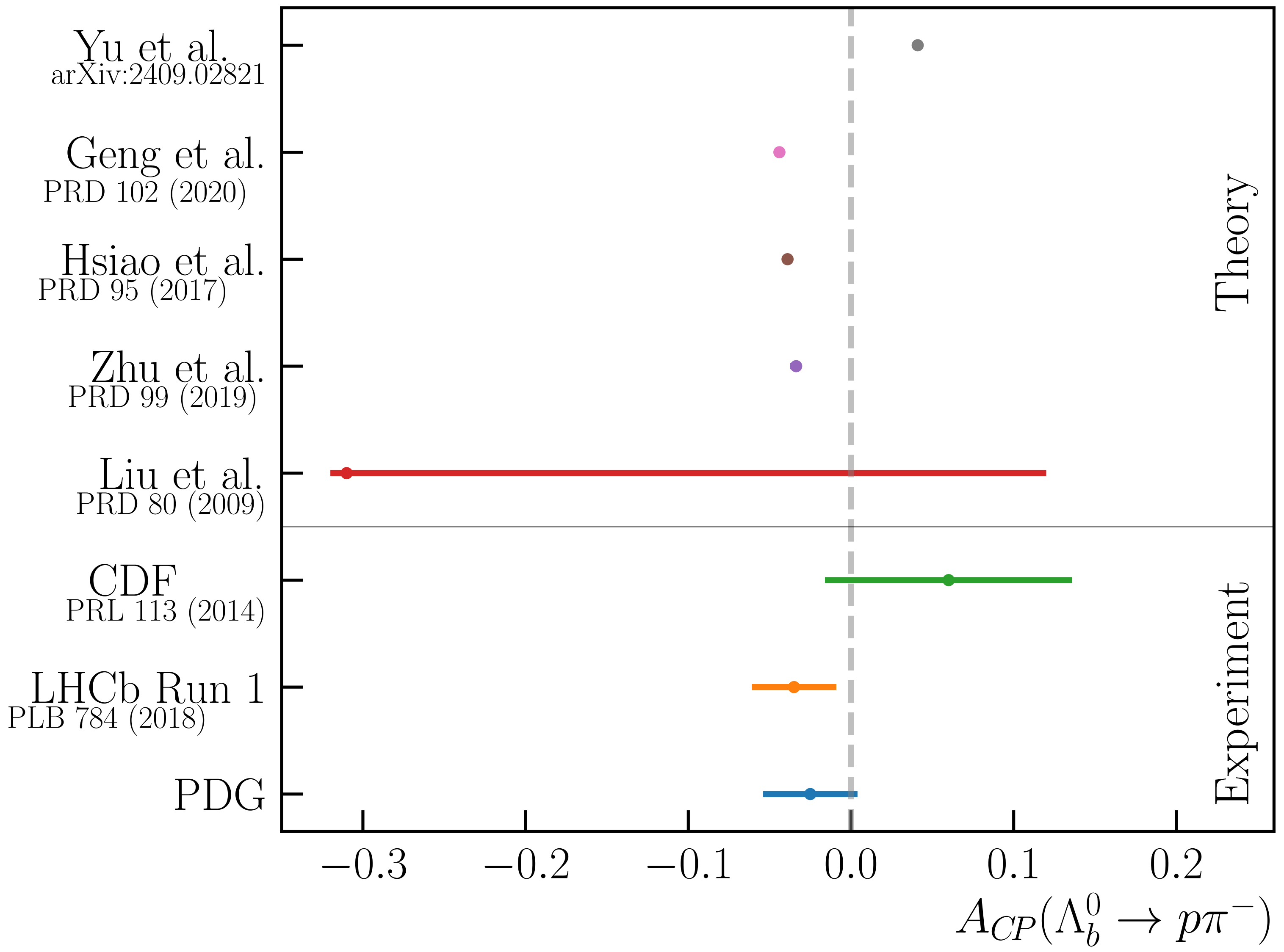
[JINST 3 (2008)]
[IJMP. A30 (2015)]

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

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

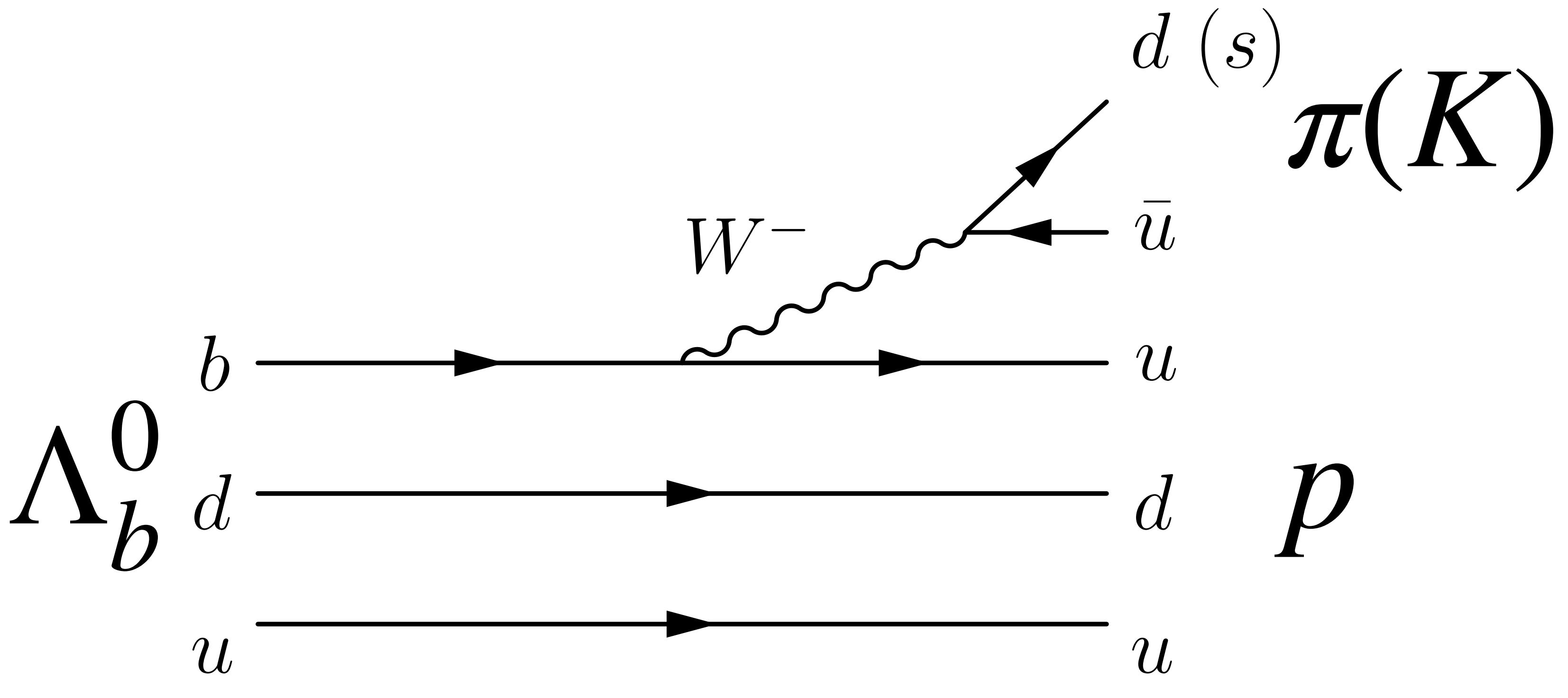


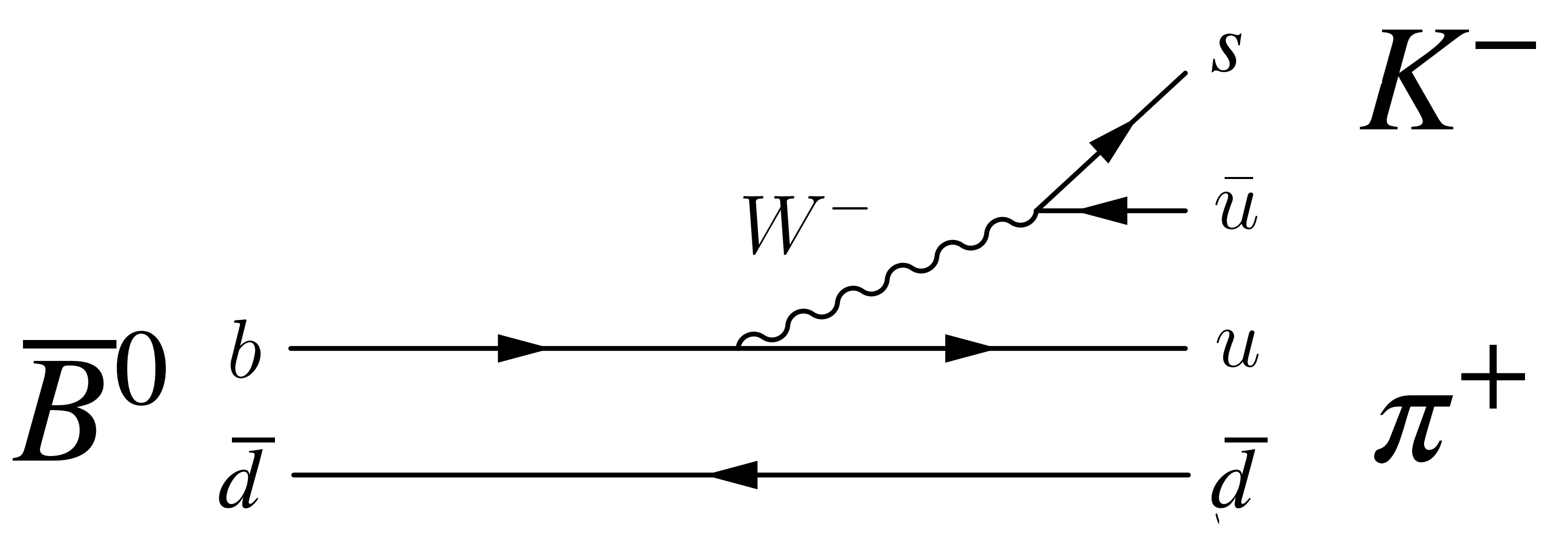


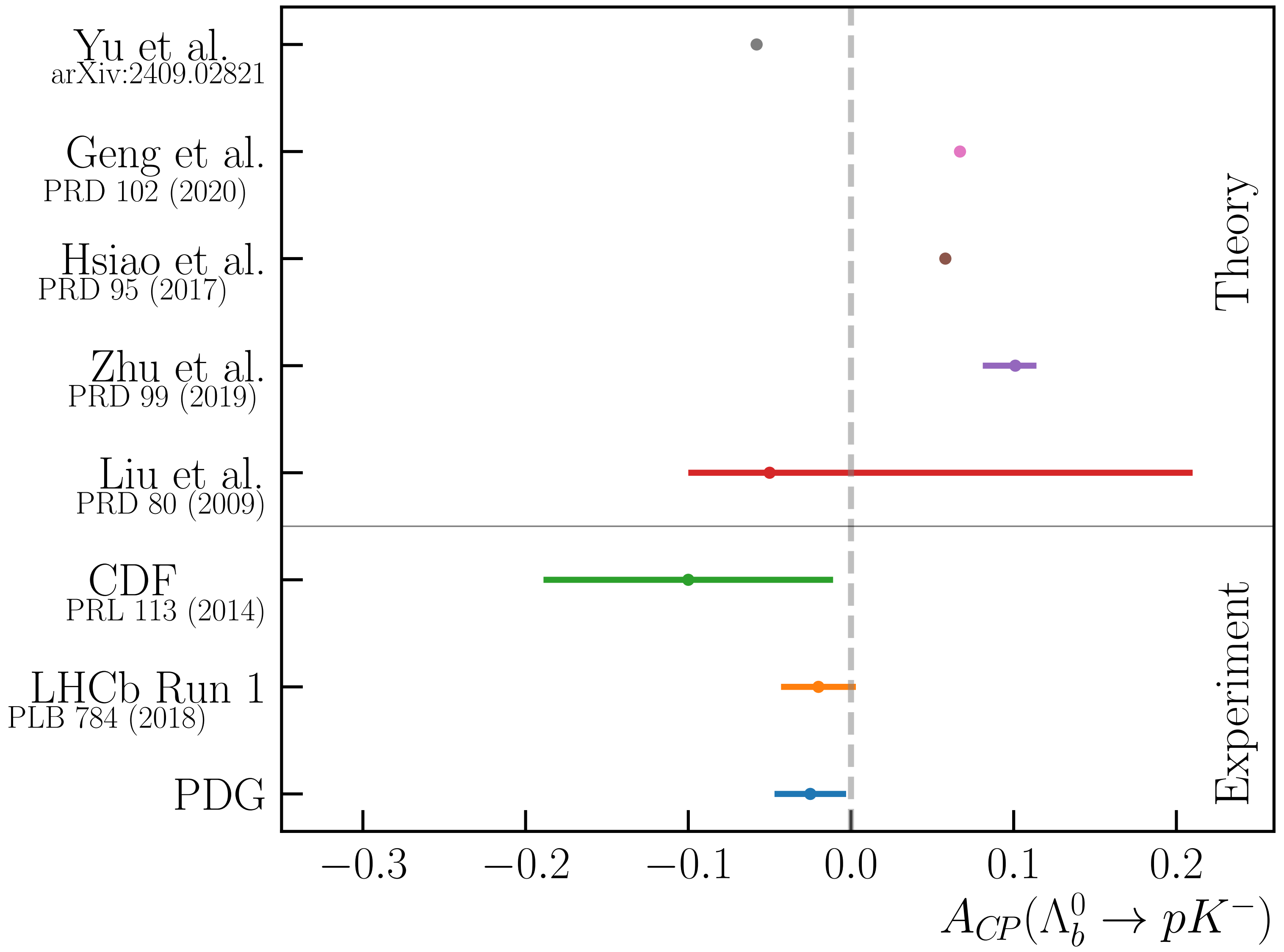


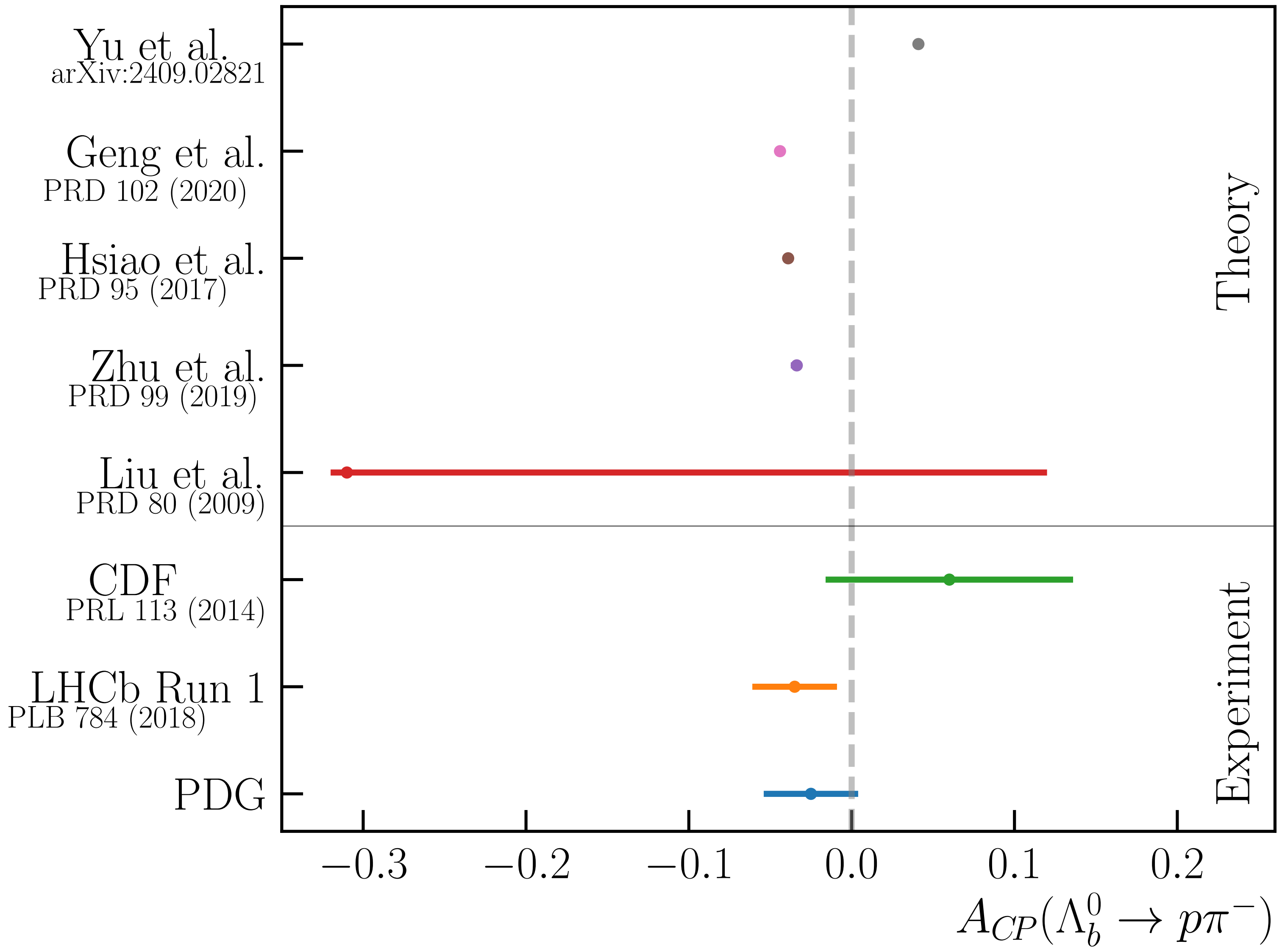
Measurement of CP asymmetries with $\Lambda_b^0 \to ph^-$ decays

- CPV in baryons still relatively unexplored
- Tree-level transition suppressed → penguin contribution to $\Lambda_b^0 \to ph^-$ could enhance CP-violating effects
- Similar diagrams to $B^0 \to K^+\pi^-$ ($A_{CP} = 8\%$) [PRD 98 (2018)]





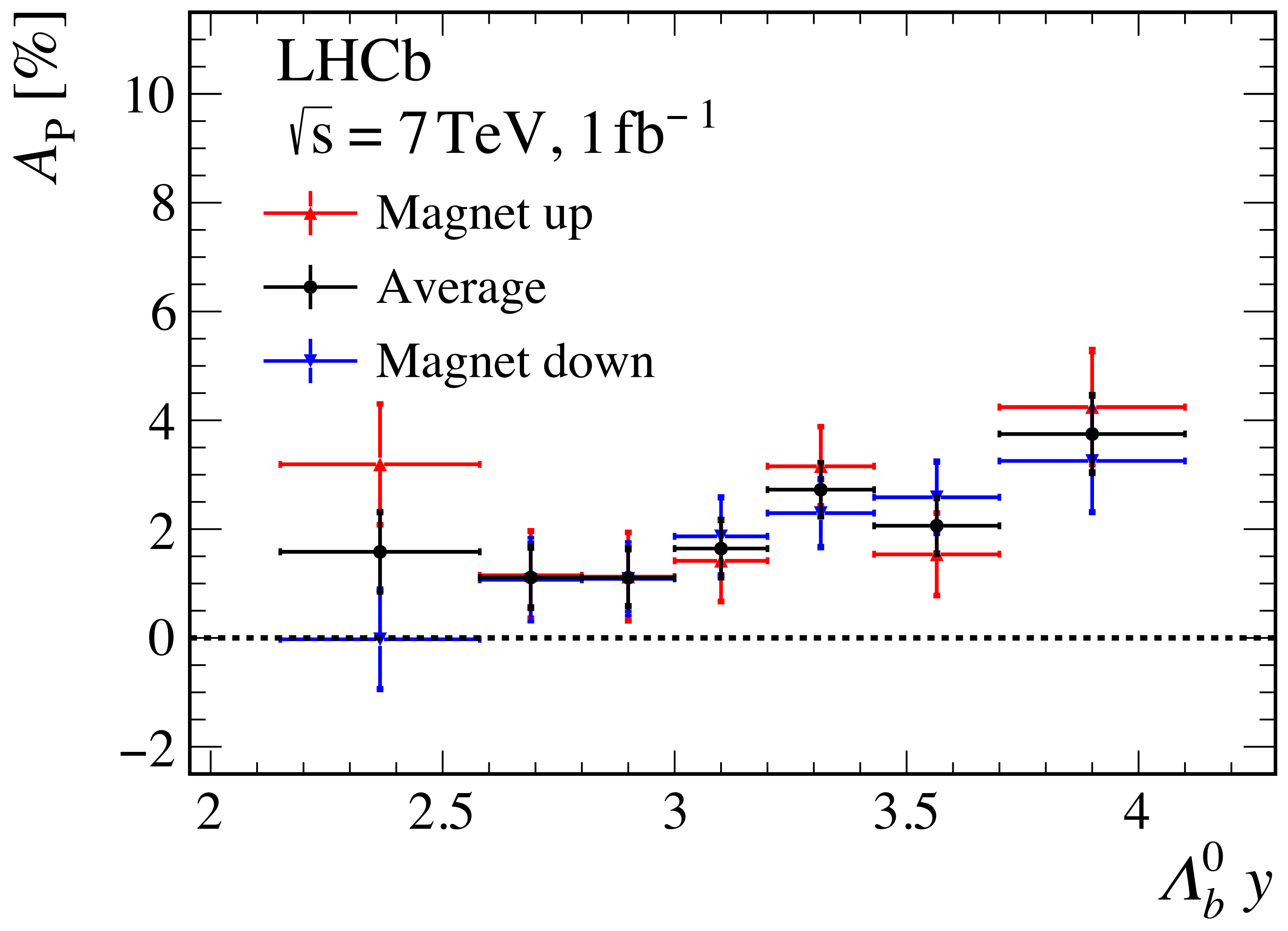


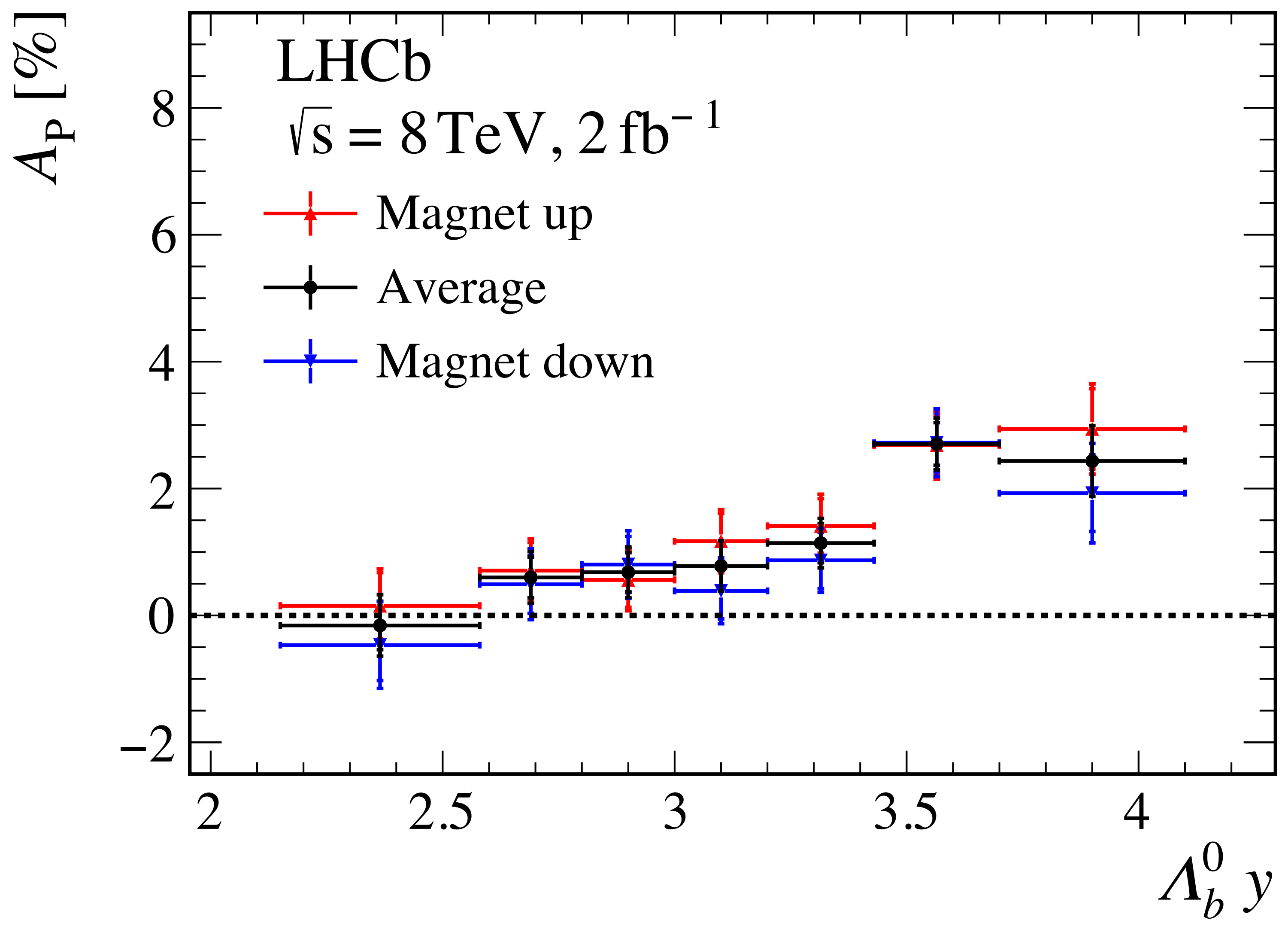


Measurement of CP asymmetries with $\Lambda_b^0 \to ph^-$ decays

[JHEP 10 (2021)]

- Update of Run 1 measurement and addition of Run 2 sample ($\mathscr{L} = 9\ \text{fb}^{-1}$)
- Run 1 precision improved thanks to $A_P(\Lambda_b^0)$ and $A_{det}(p)$ measurement
- Run 2: $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ 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 $\Lambda_b^0 \to ph^-$ decays

New!

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

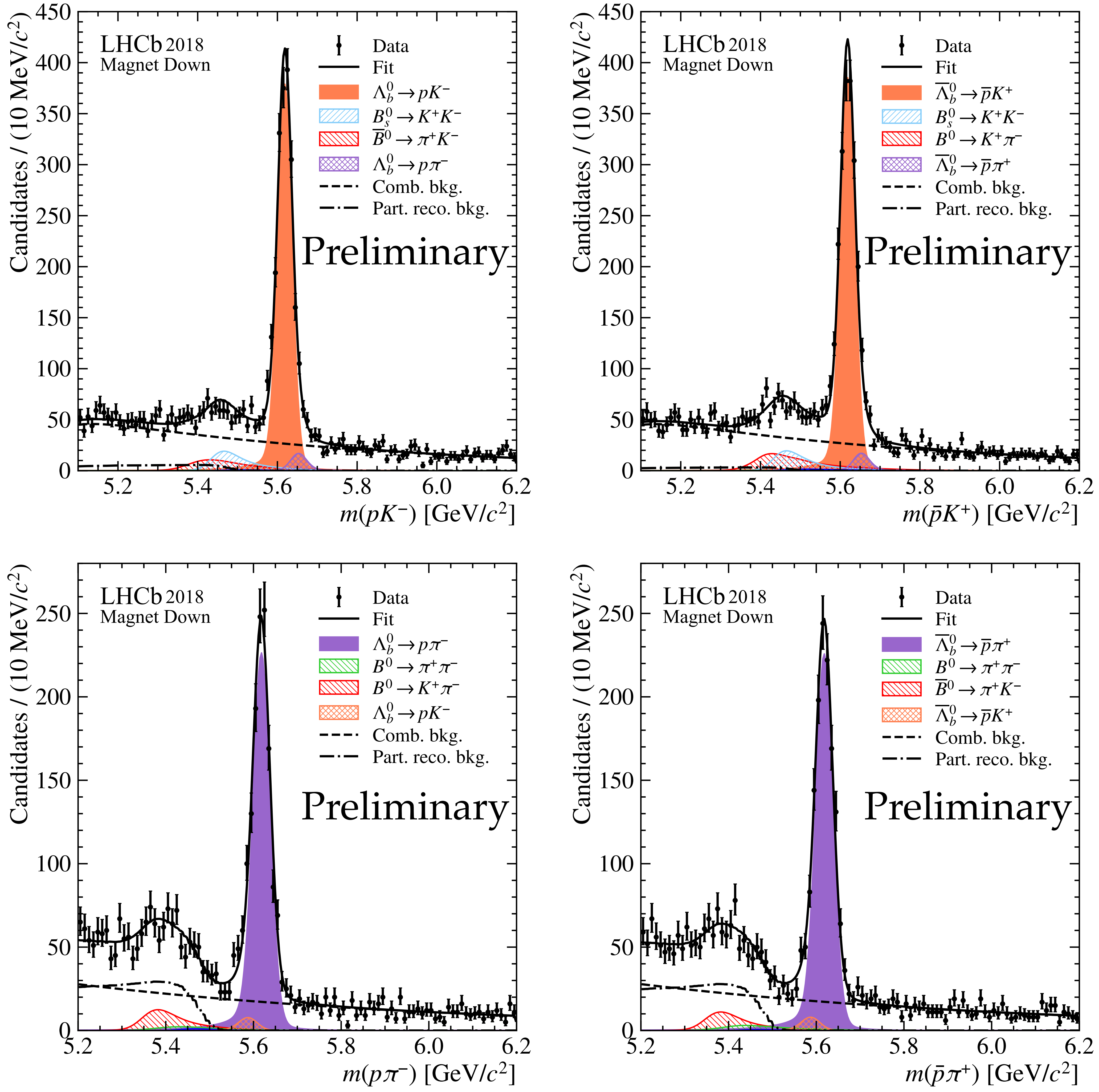
- New Run 2 measurement:

$$A_{CP}(\Lambda_b^0 \to pK^-) = (-1.39 \pm 0.75(\text{stat}) \pm 0.41(\text{syst}))\,\%$$
$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (0.42 \pm 0.93(\text{stat}) \pm 0.42(\text{syst}))\,\%$$

- Combination with updated Run 1 results:

$$A_{CP}(\Lambda_b^0 \to pK^-) = (-1.14 \pm 0.67 \pm 0.36)\,\%$$
$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (0.20 \pm 0.83 \pm 0.37)\,\%$$

- 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

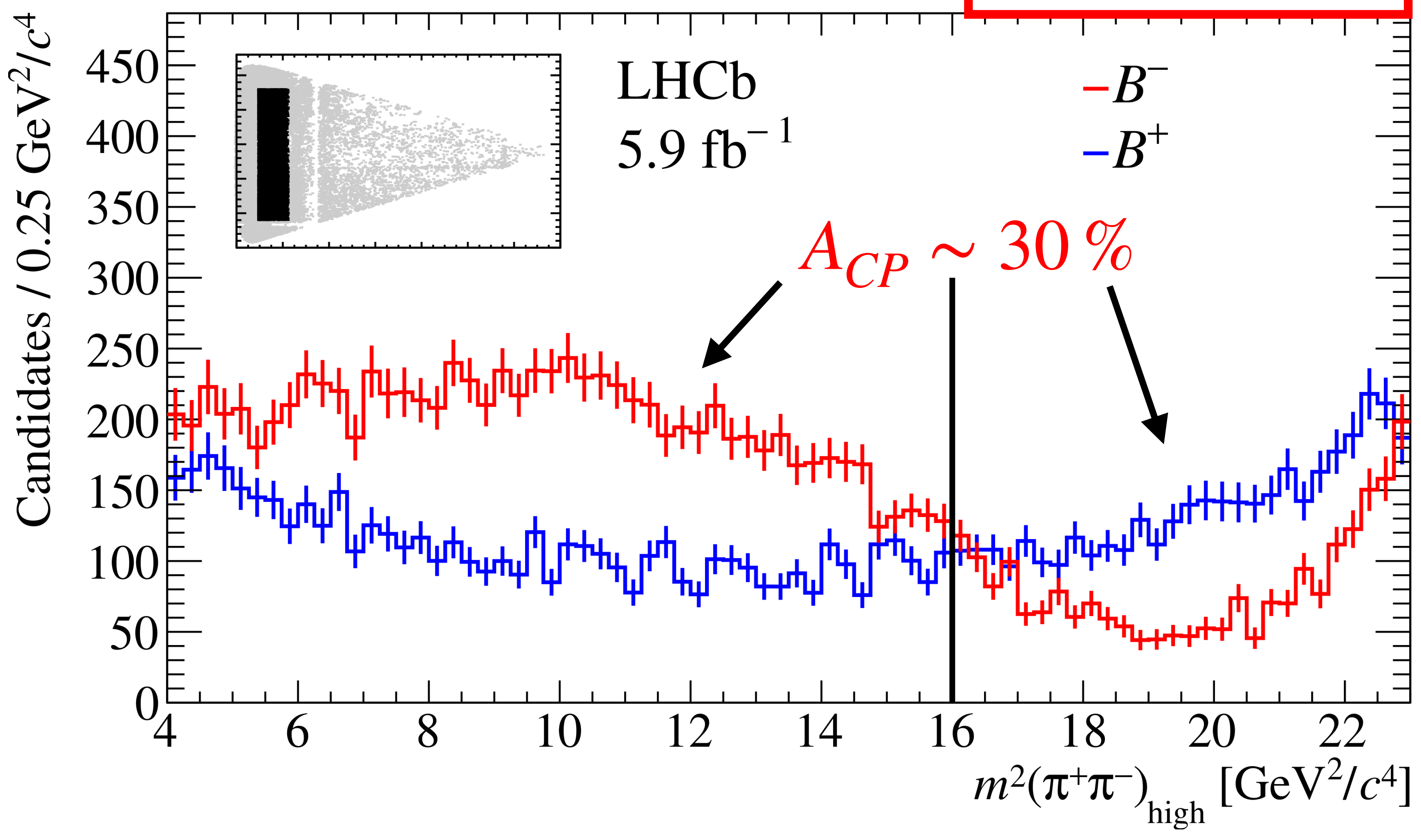
- Large *CPV* found in $\pi\pi \leftrightarrow KK$ rescattering regions of $B^\pm \to h^\pm h'^+ h''^-$ decays

- Light resonances could play a role in *CPV*?

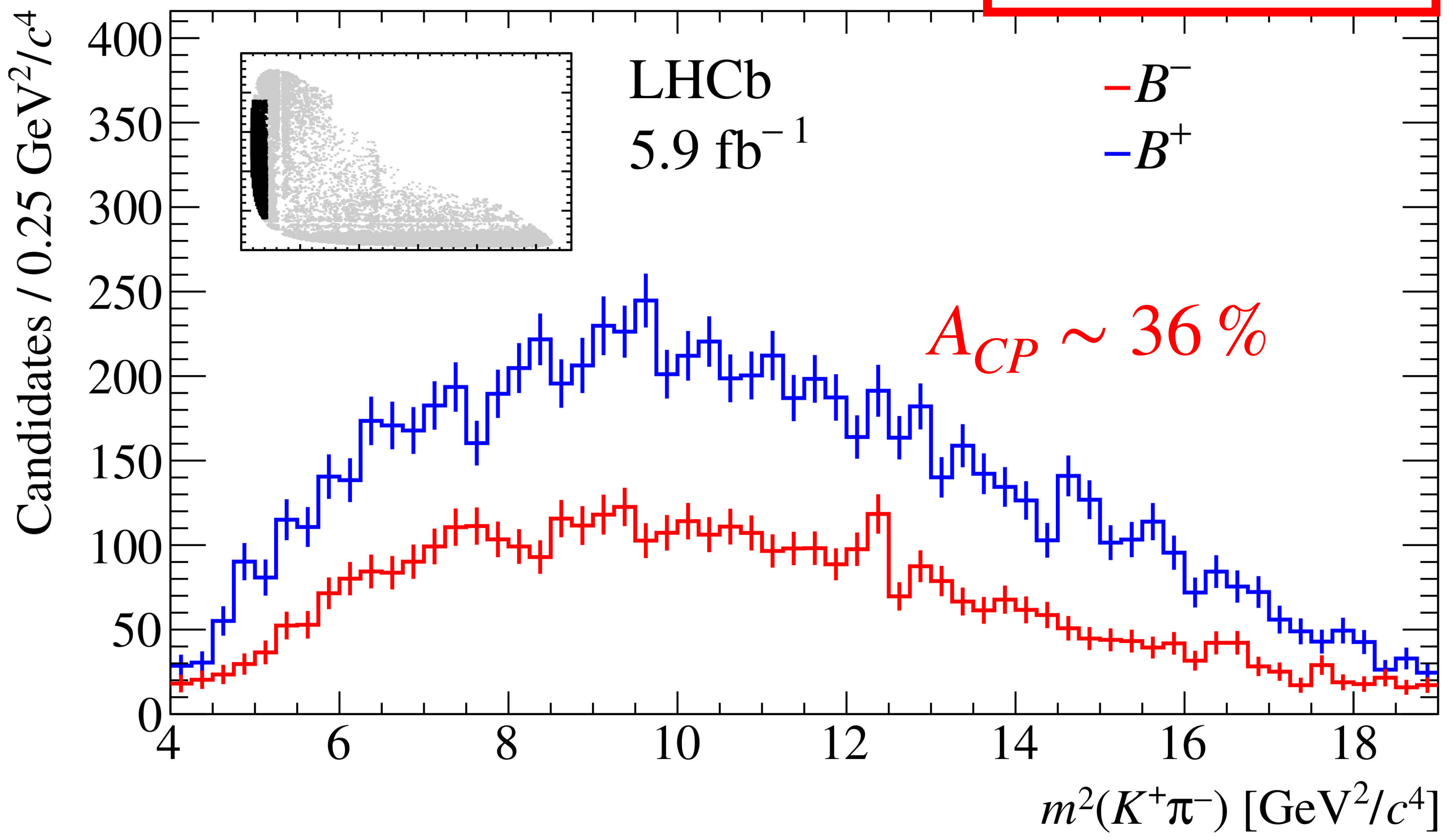
- Similar dynamics involved in $\Lambda_b^0/\Xi_b^0 \to \Lambda h^+ h'^-$ decays

- *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)]

[PRD 108 (2023)] $B^\pm \to \pi^\pm \pi^+ \pi^-$



[PRD 108 (2023)] $B^\pm \to \pi^\pm K^+ K^-$



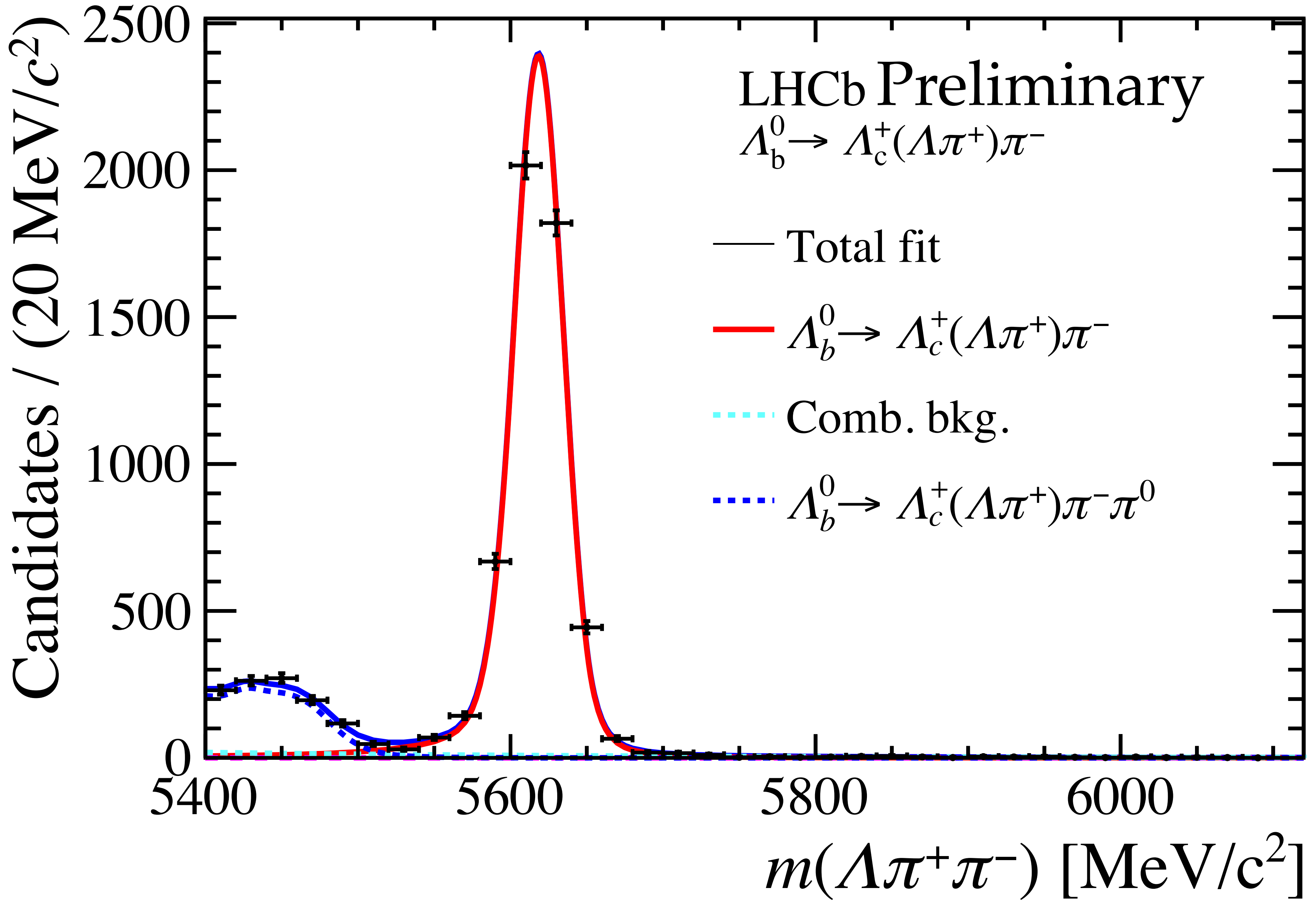
Study of Λ_b^0 and Ξ_b^0 decays to $\Lambda h^+ h^{'-}$ final states

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

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

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

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



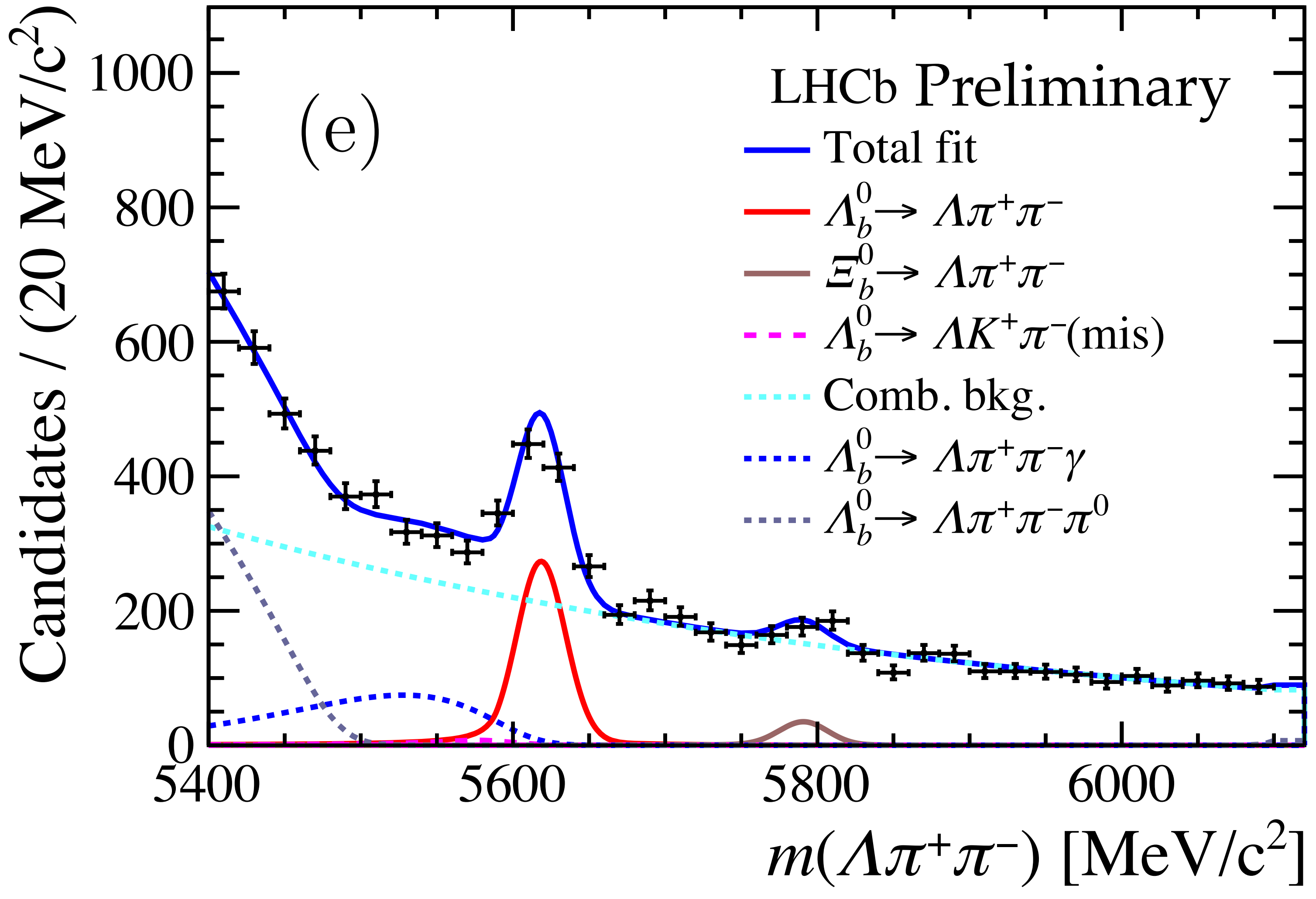
$$\frac{\mathcal{B}\left(\Lambda_b^0\left(\Xi_b^0\right) \to \Lambda h^+ h'^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+\left(\to \Lambda\pi^+\right)\pi^-\right)} = \frac{N_{\Lambda_b^0\left(\Xi_b^0\right) \to \Lambda h^+ h'^-}}{N_{\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-}} \times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

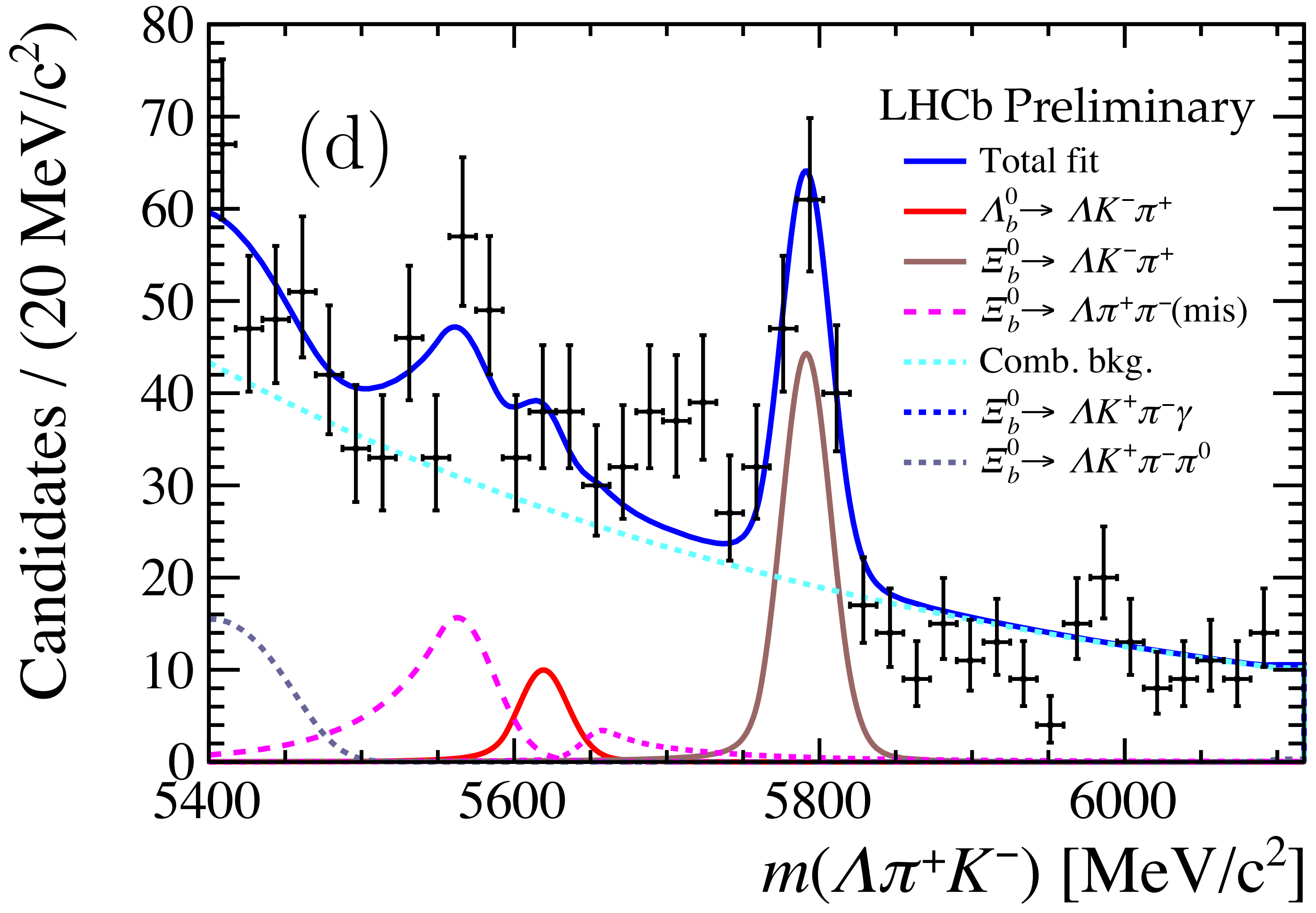
$$\Delta A_{CP}(\Lambda_b^0/\Xi_b^0 \to f) = A_{CP}(\Lambda_b^0/\Xi_b^0 \to f) - A_{CP}(\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-)$$

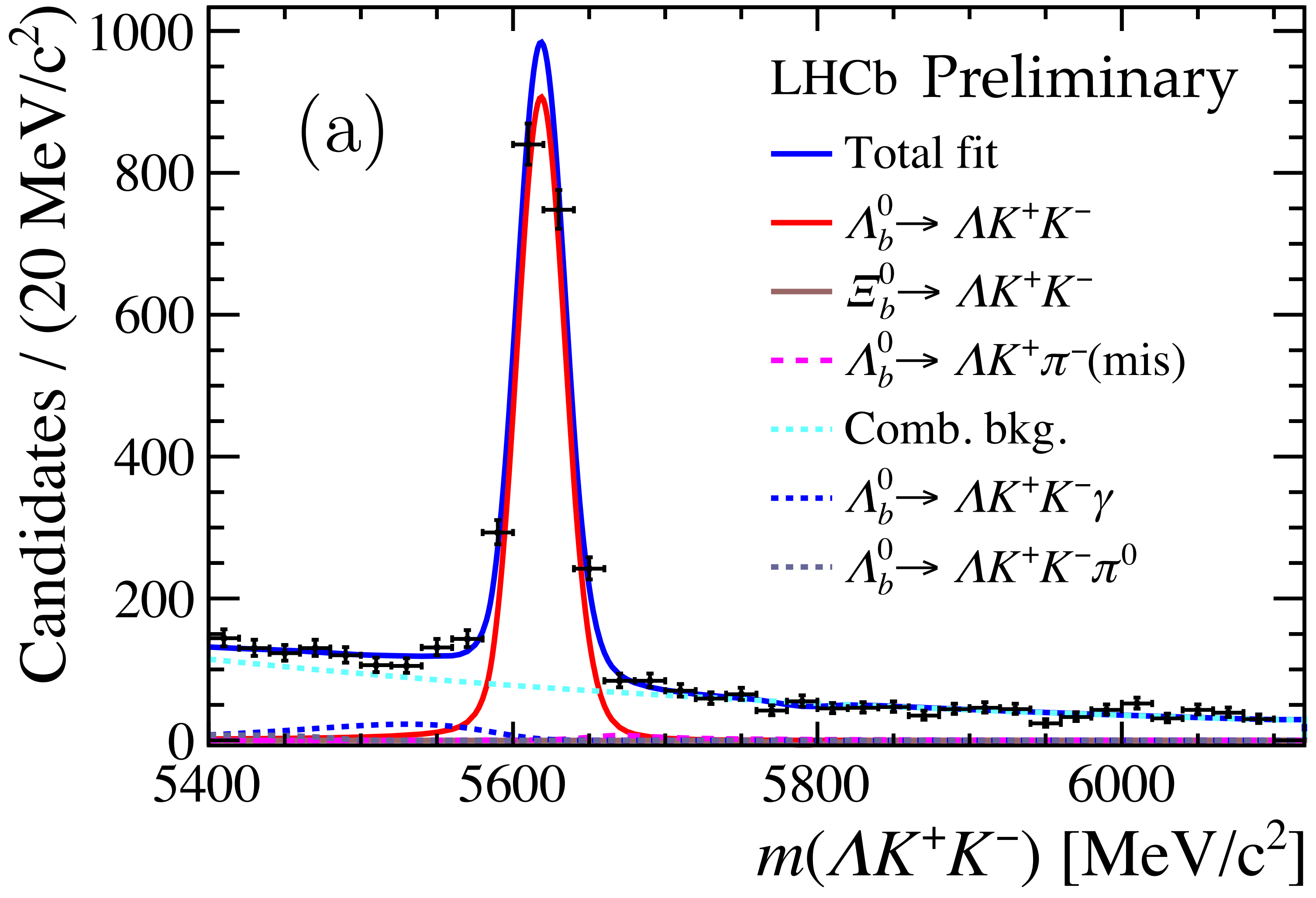
Study of Λ_b^0 and Ξ_b^0 decays to $\Lambda h^+ h'^-$ final states

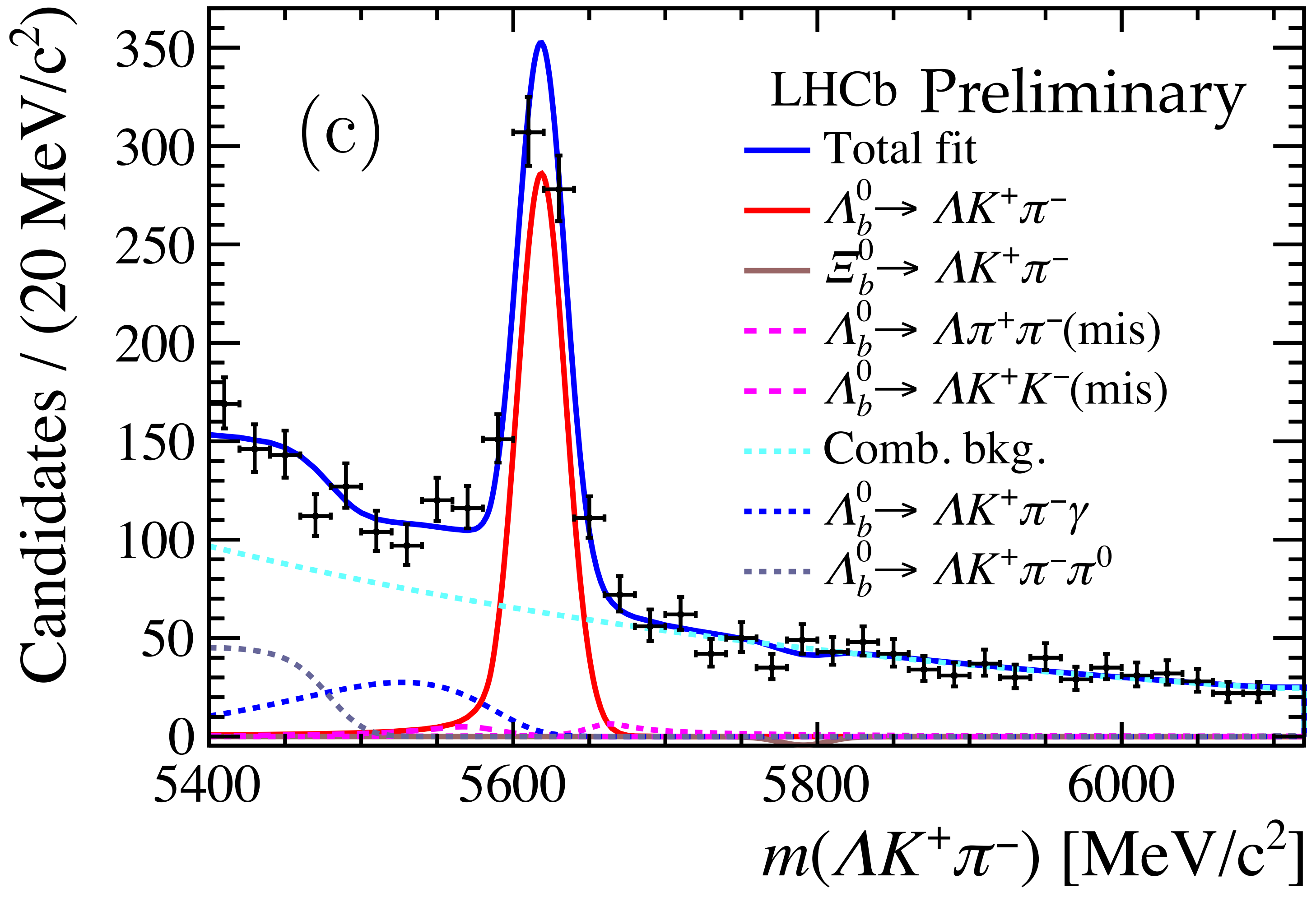
New!

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









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

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

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

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

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

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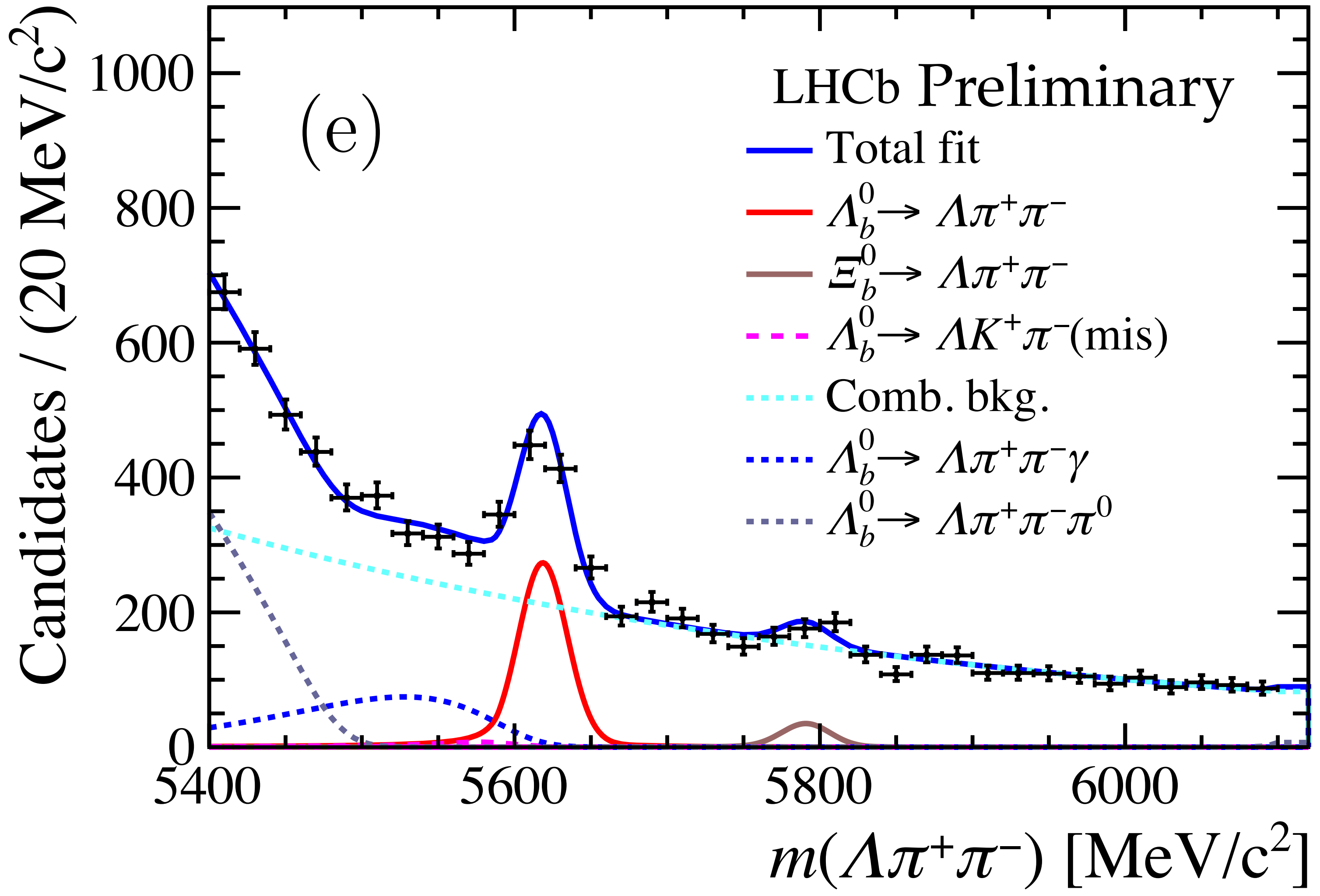

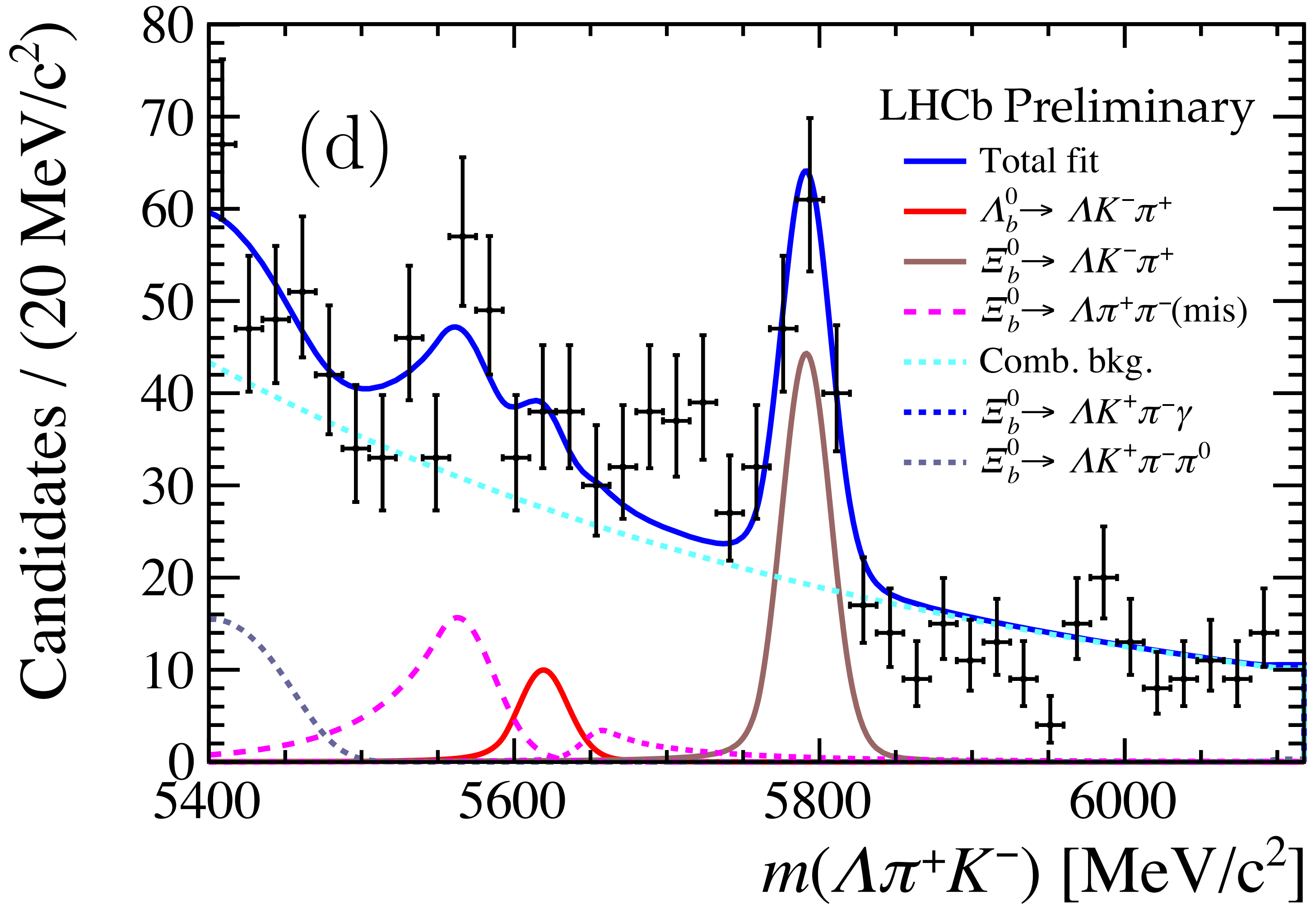

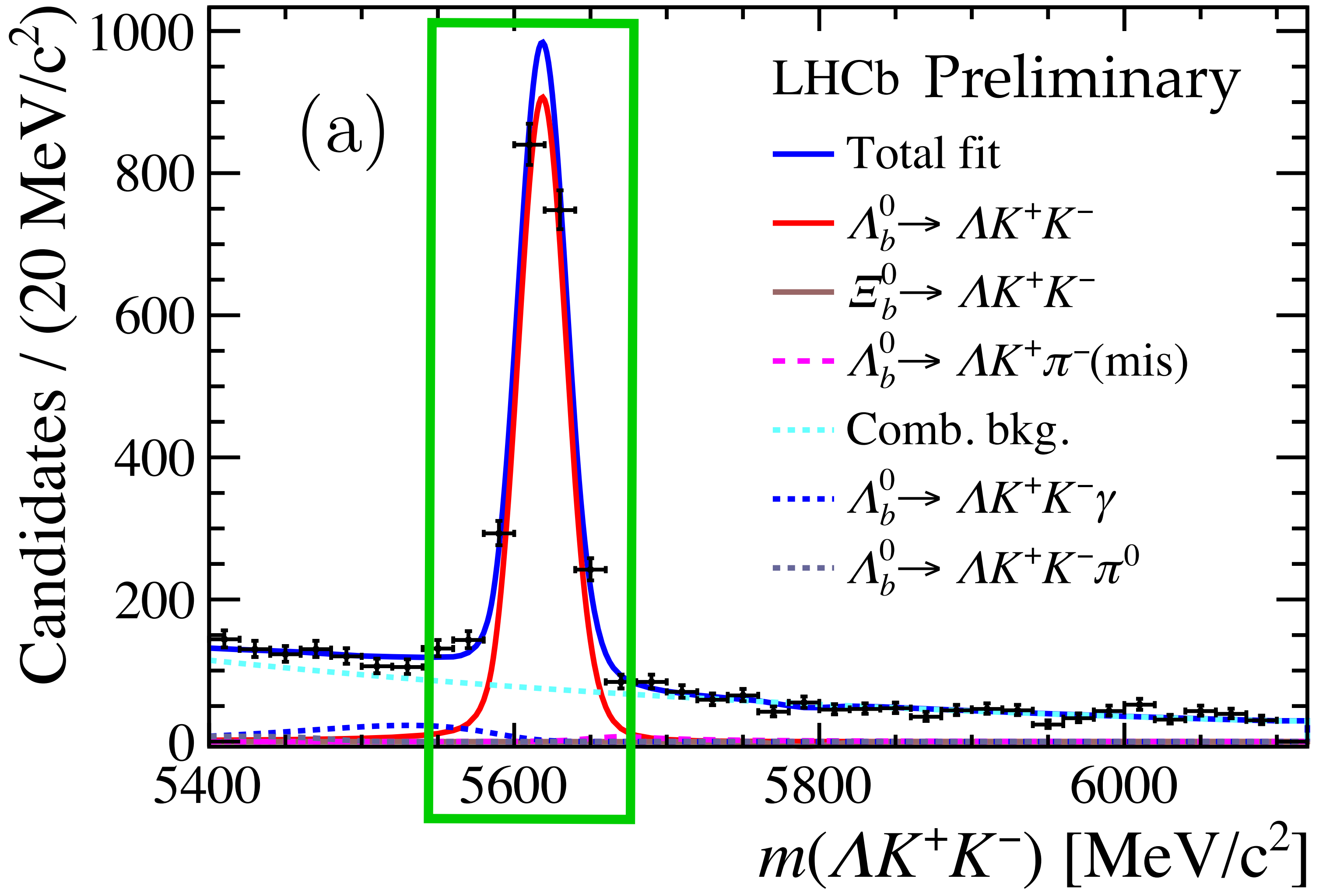

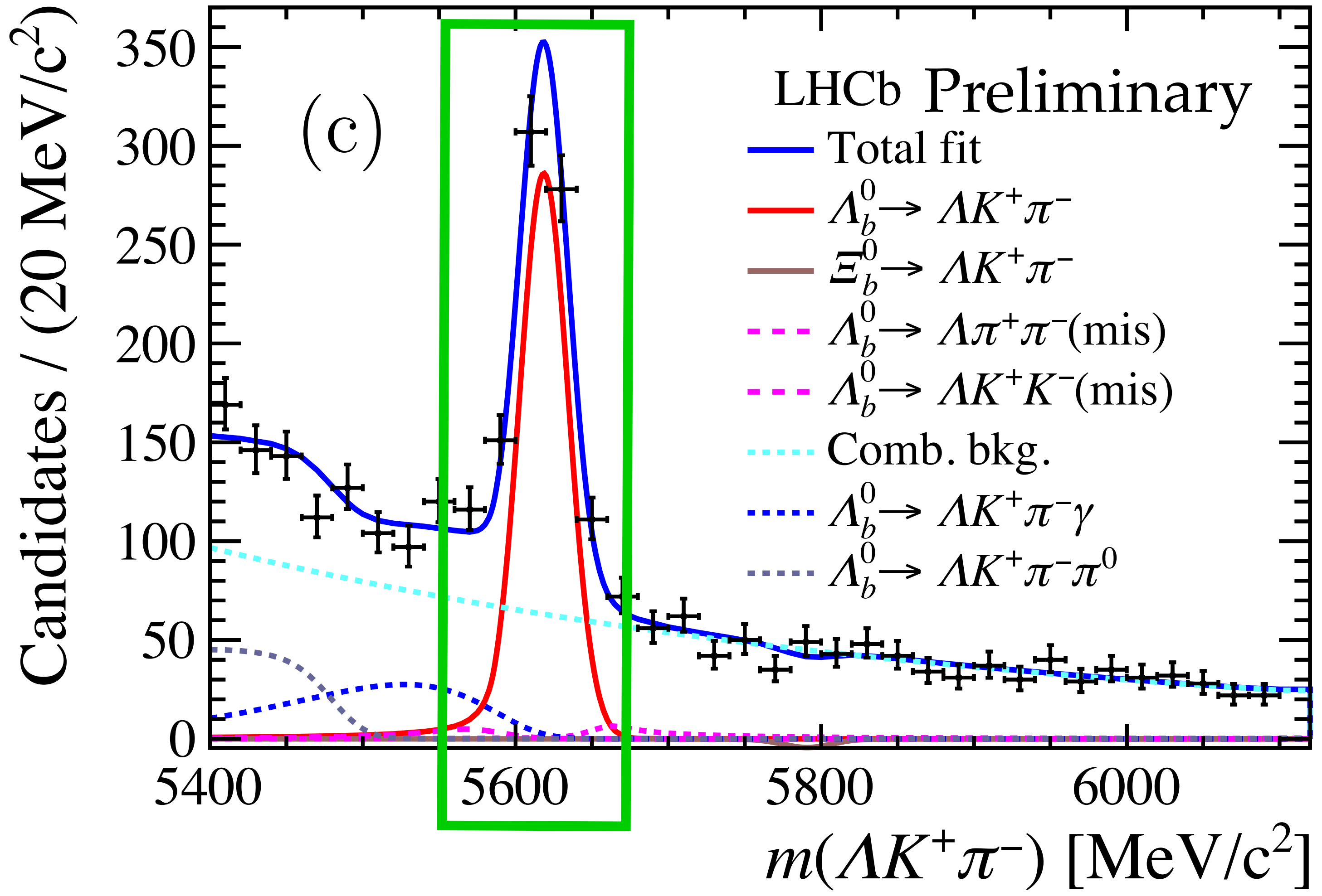

$$\mathscr{B}(\Lambda_b^0 \to \Lambda\pi^+\pi^-) = (5.3 \pm 0.4 \pm 0.5 \pm 0.5(norm)) \times 10^{-6}$$

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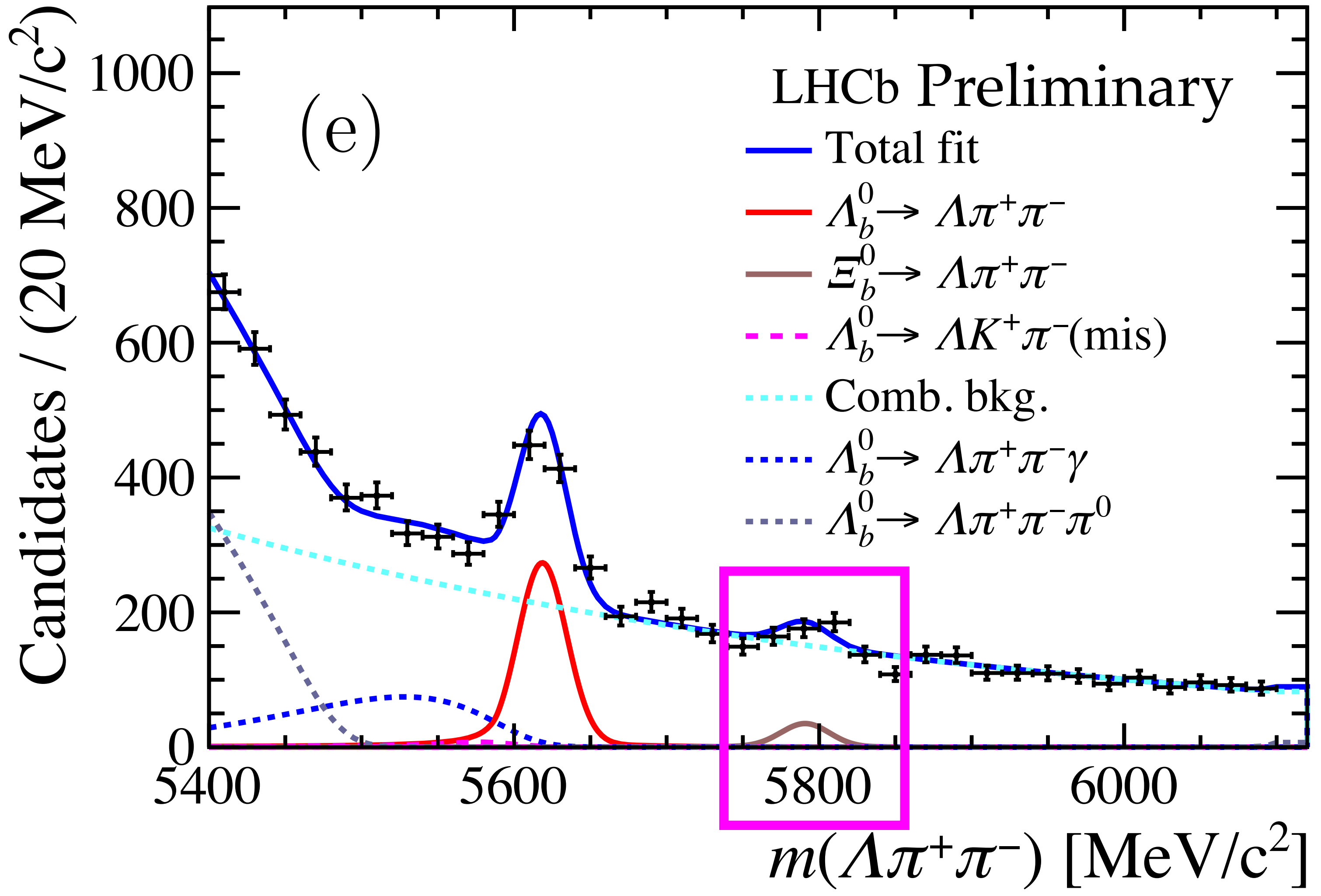

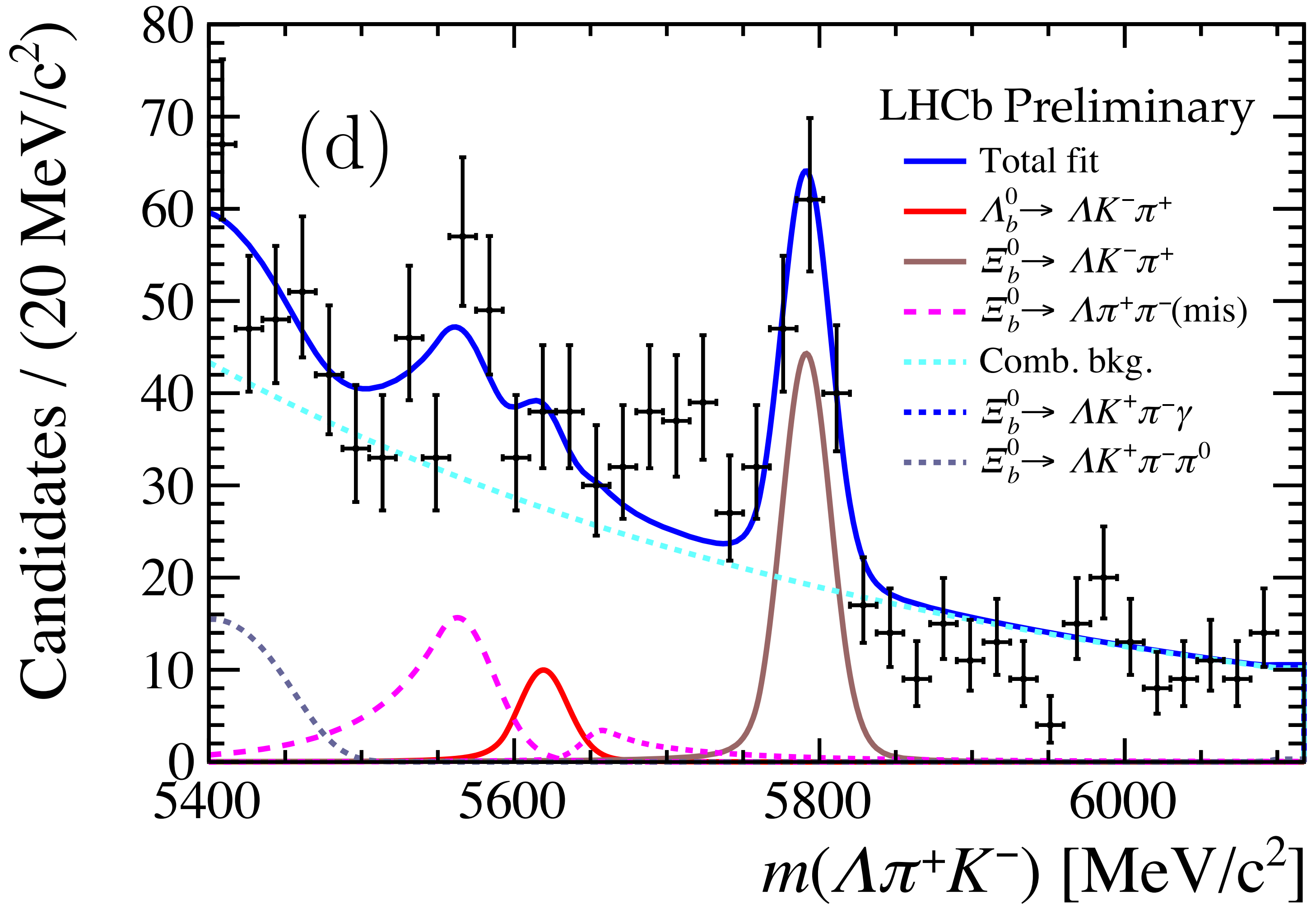

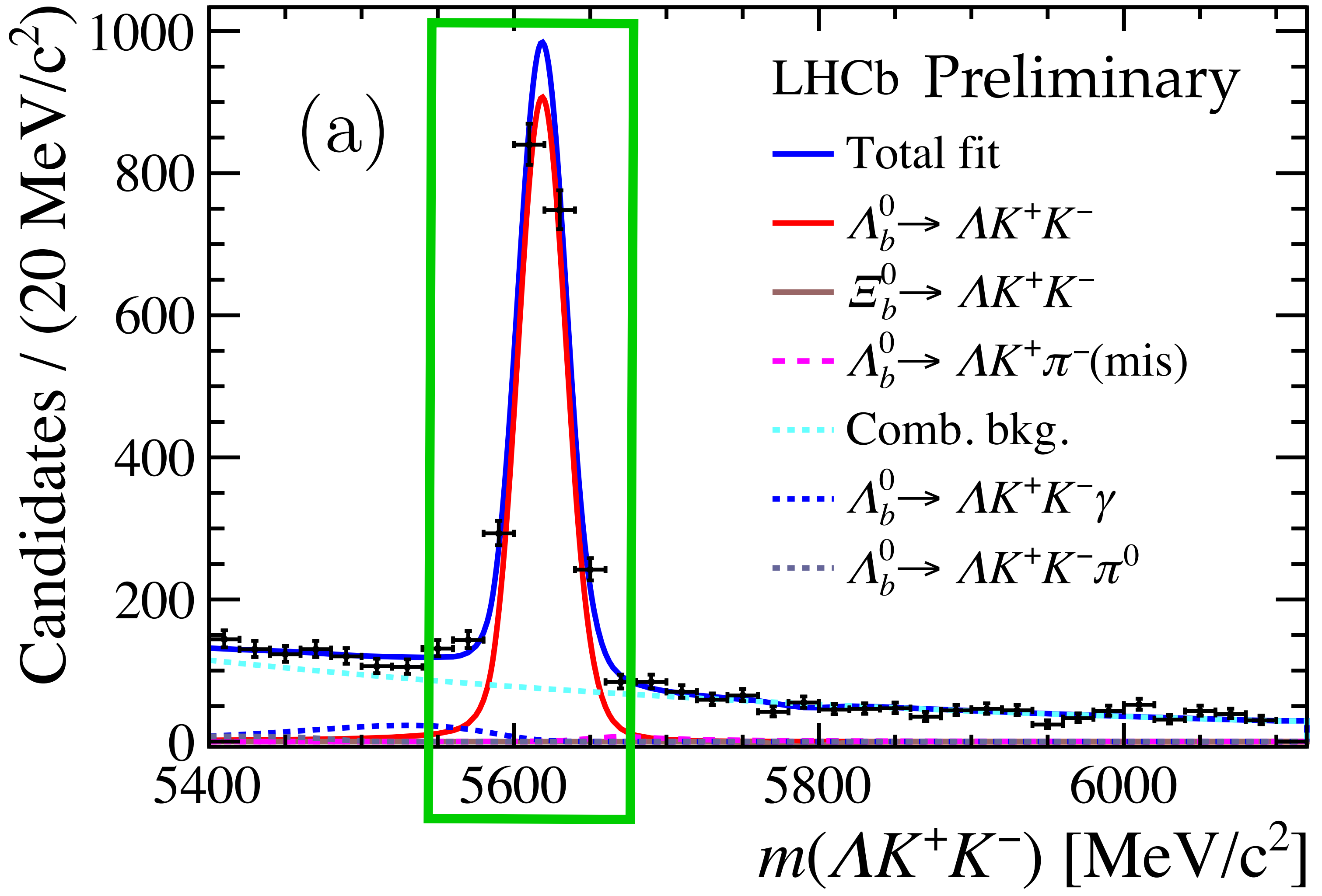

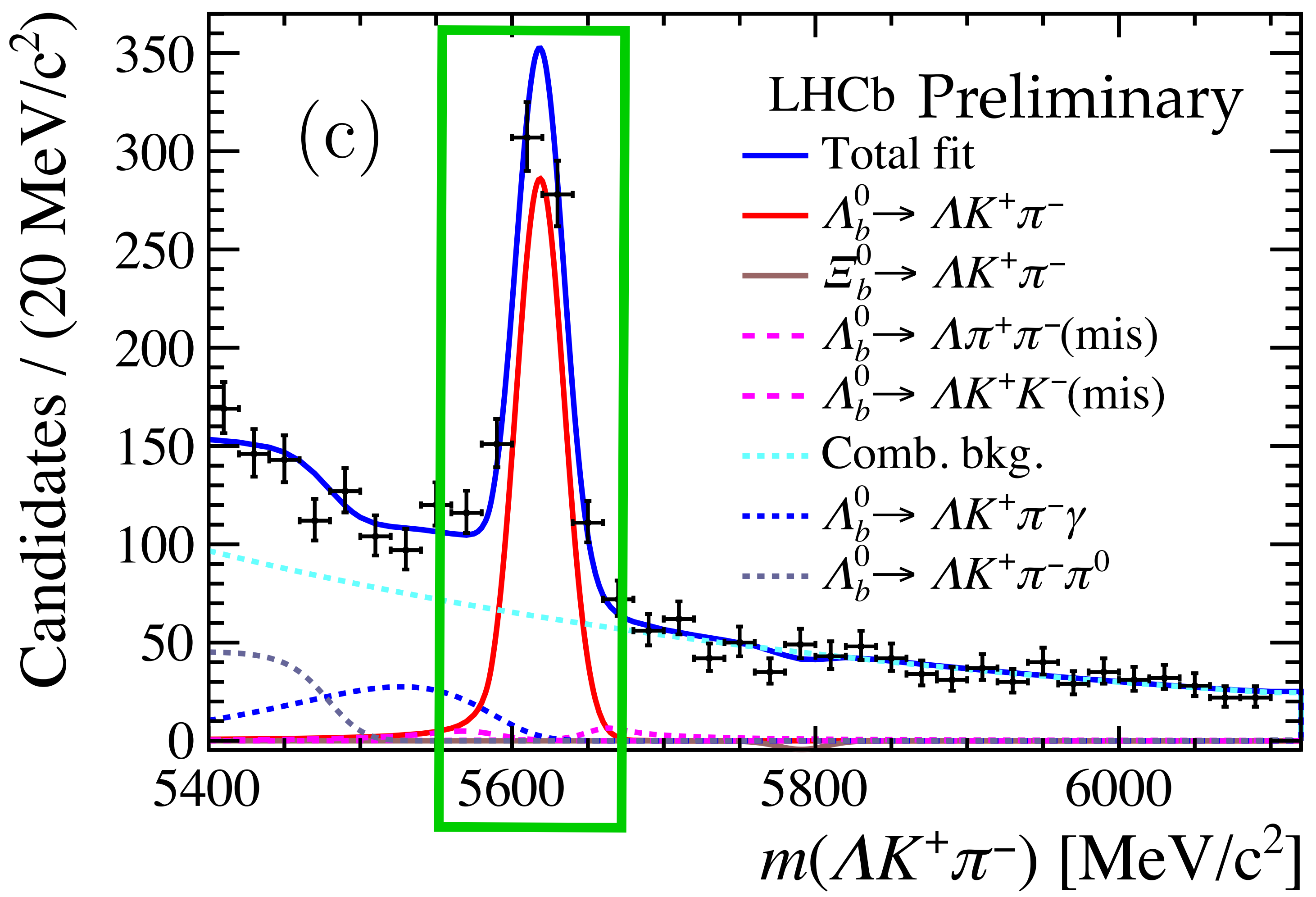

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$$\mathscr{B}(\Xi_b^0 \to \Lambda\pi^+\pi^-) = (11.0 \pm 2.6 \pm 1.4 \pm 3.8(norm)) \times 10^{-6}$$ **First evidence (4σ)**

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

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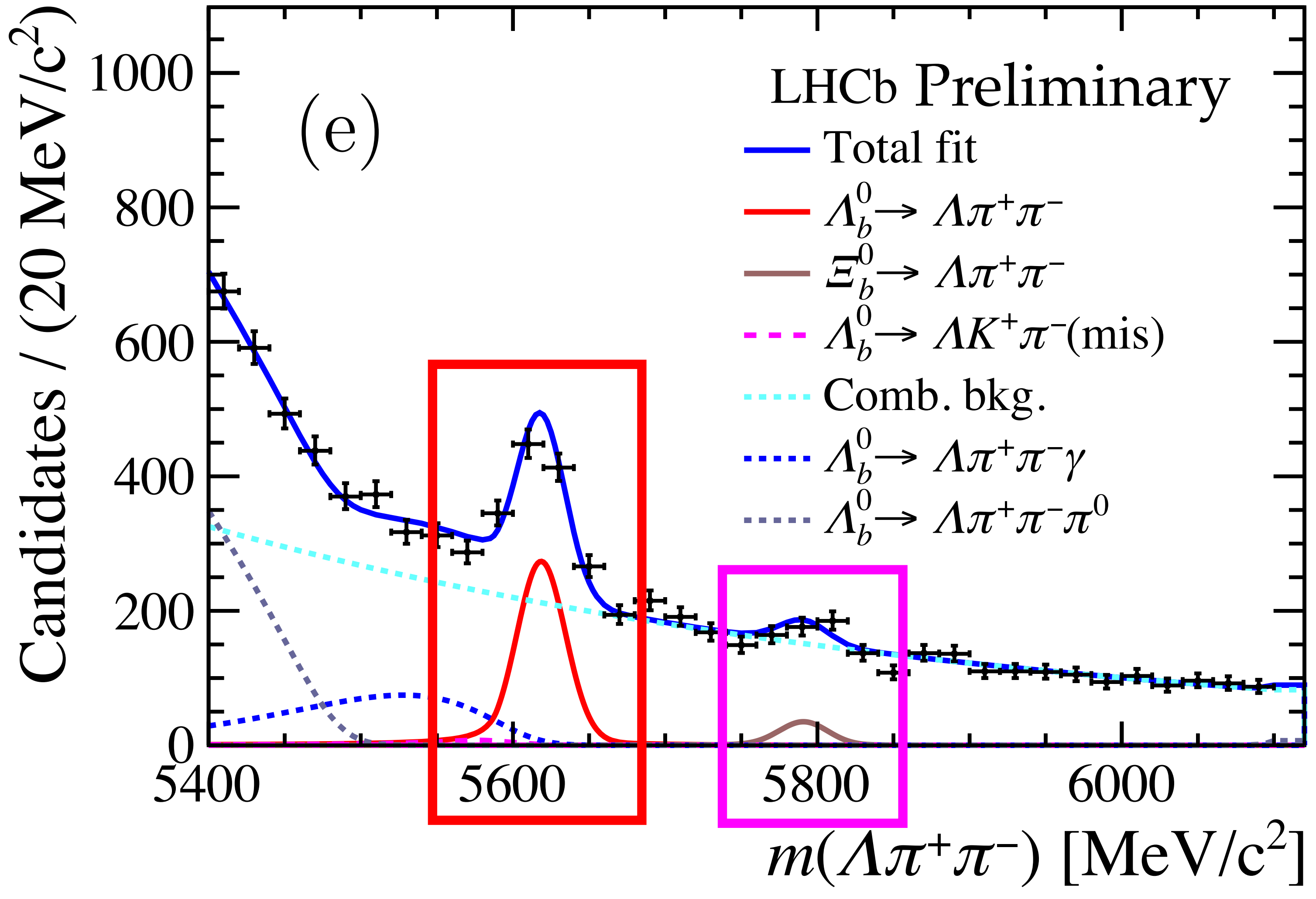

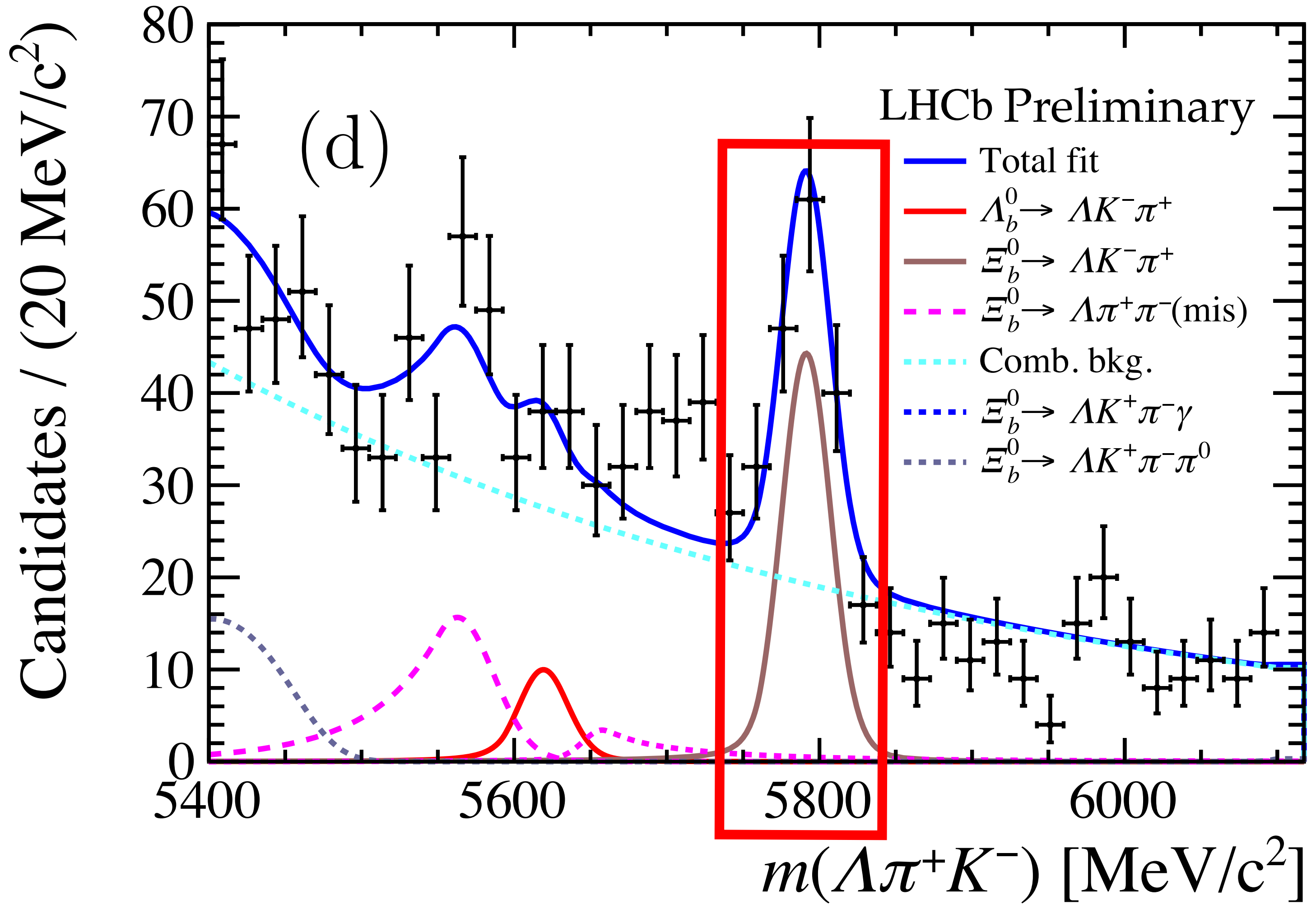

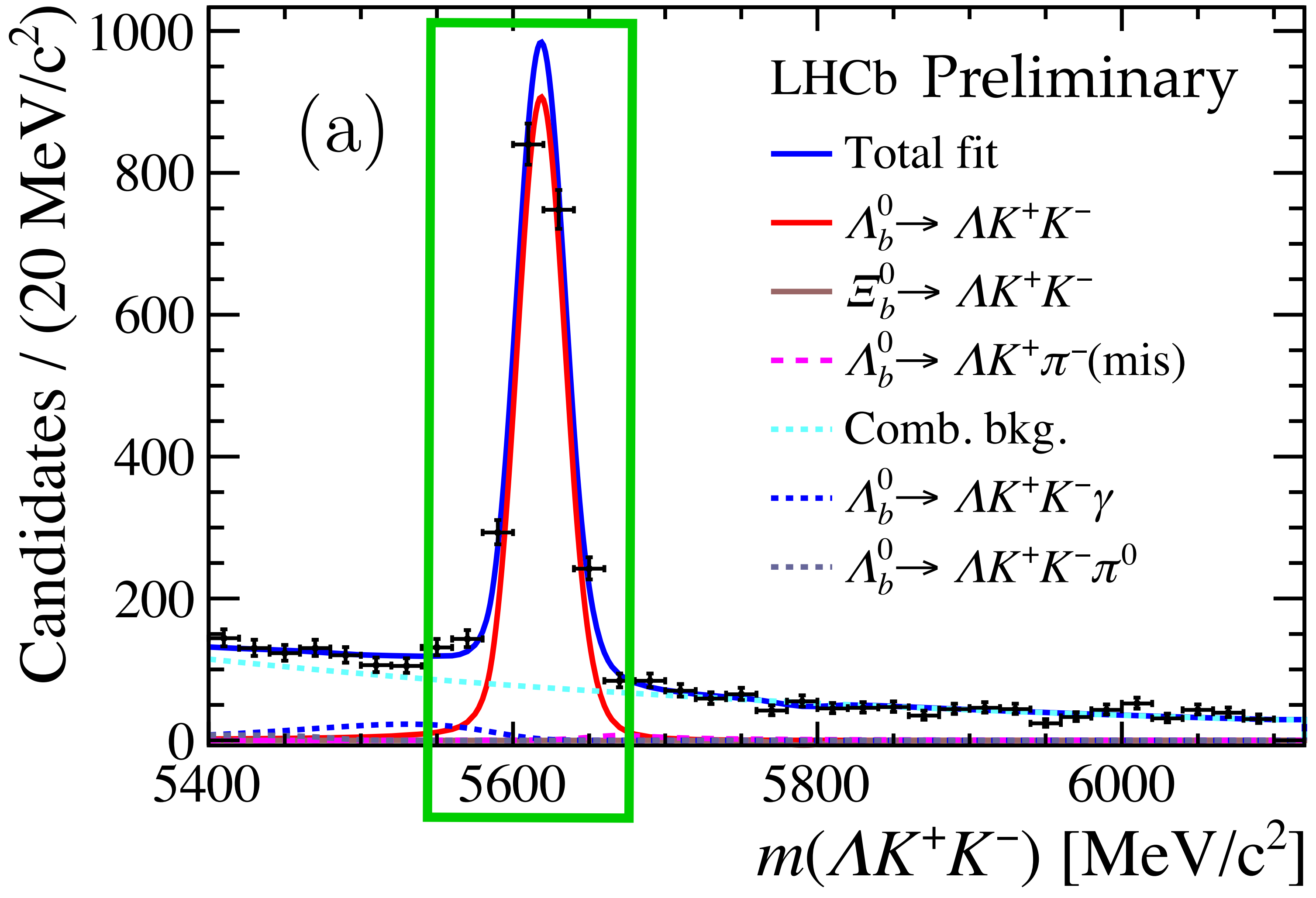

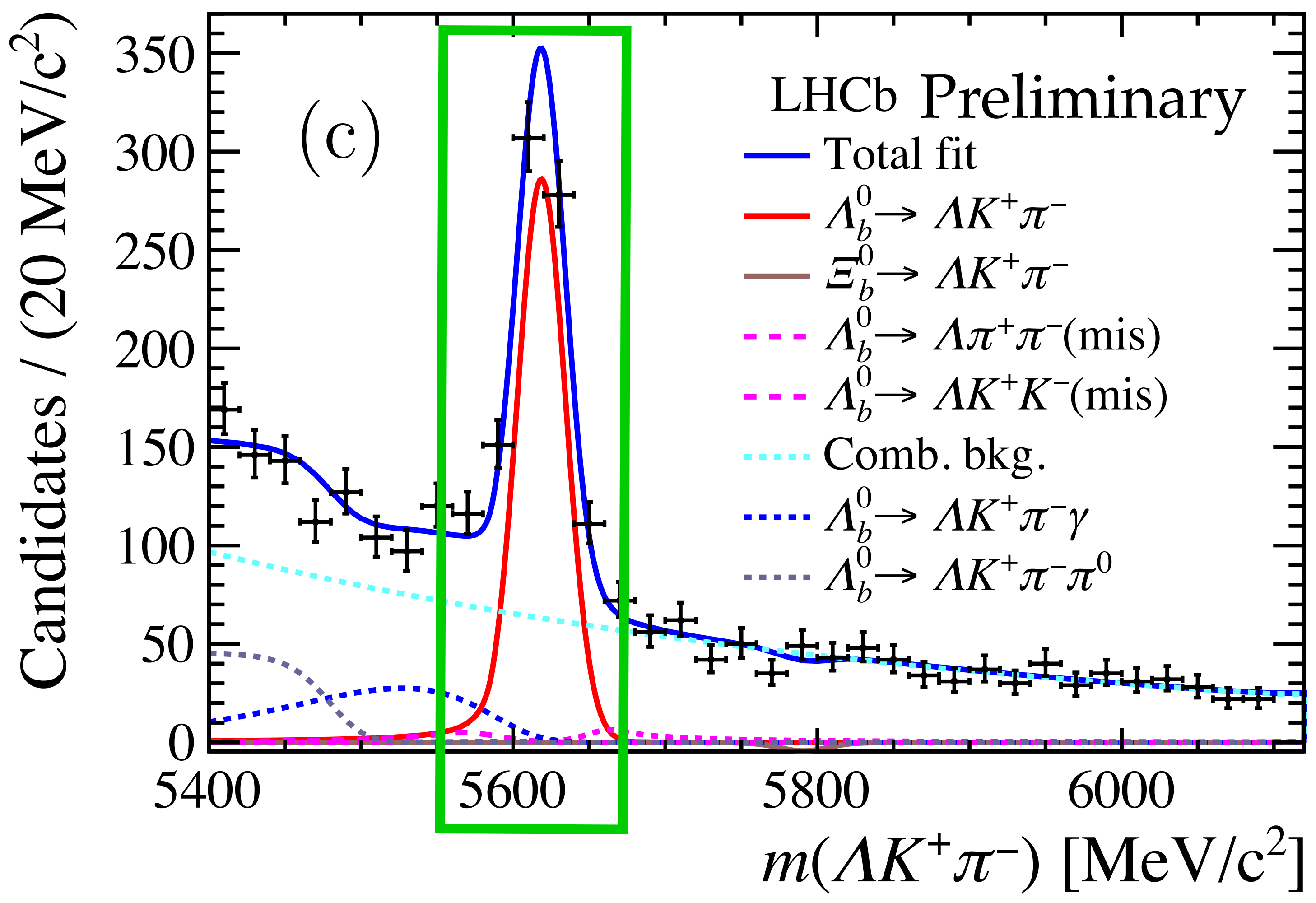

$$\mathcal{B}(\Lambda_b^0 \to \Lambda\pi^+\pi^-) = (5.3 \pm 0.4 \pm 0.5 \pm 0.5(norm)) \times 10^{-6}$$ **First observation**

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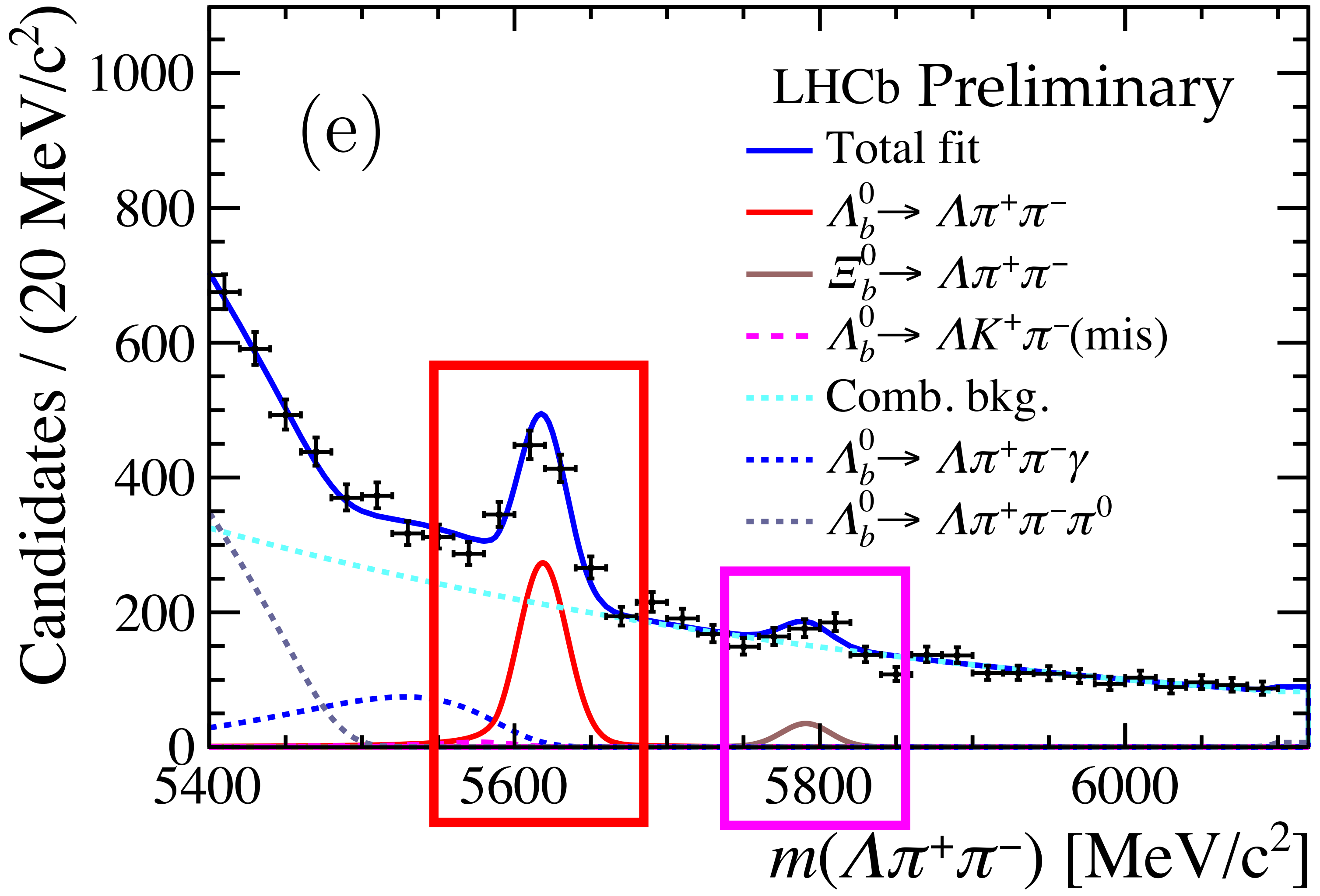

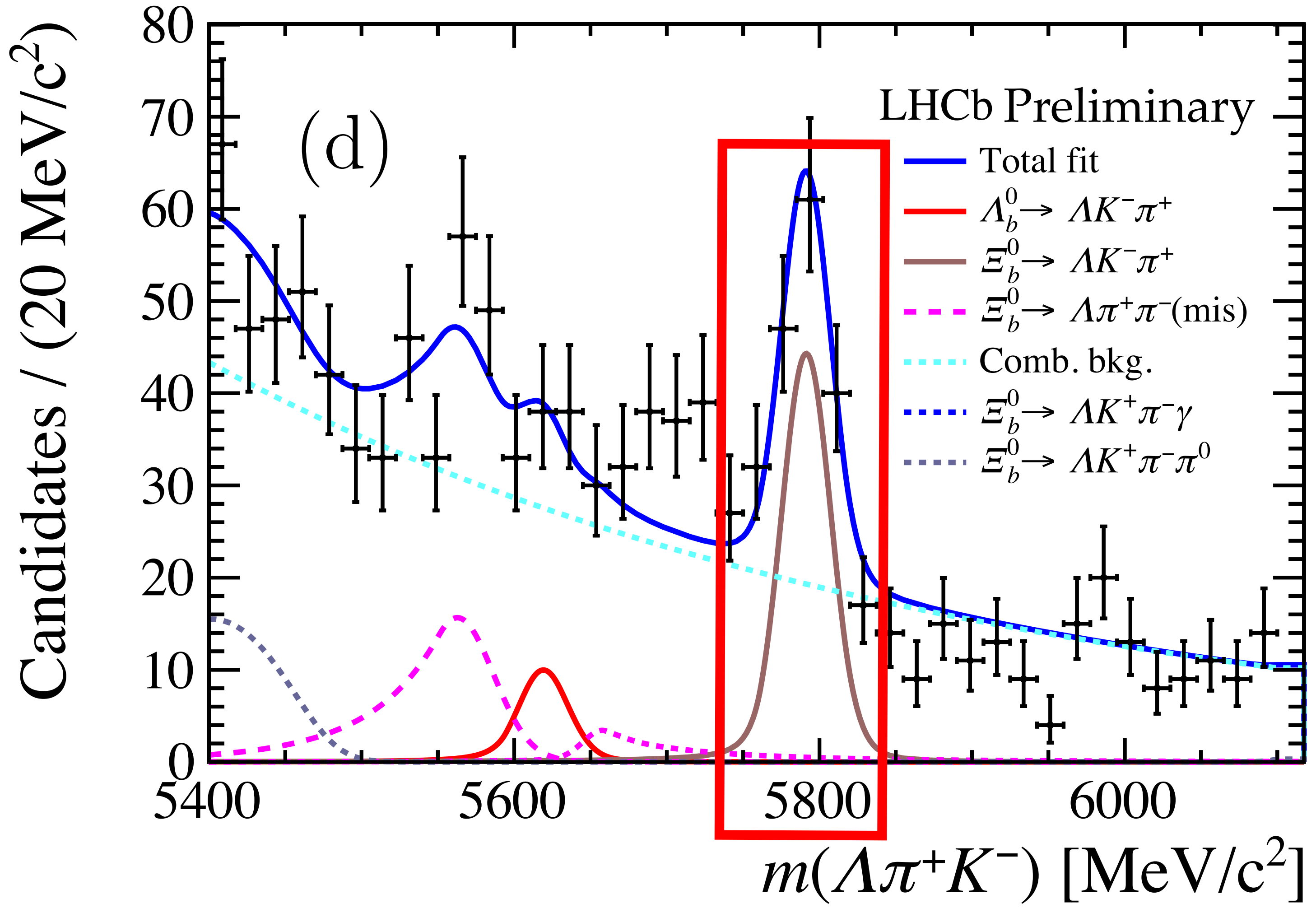

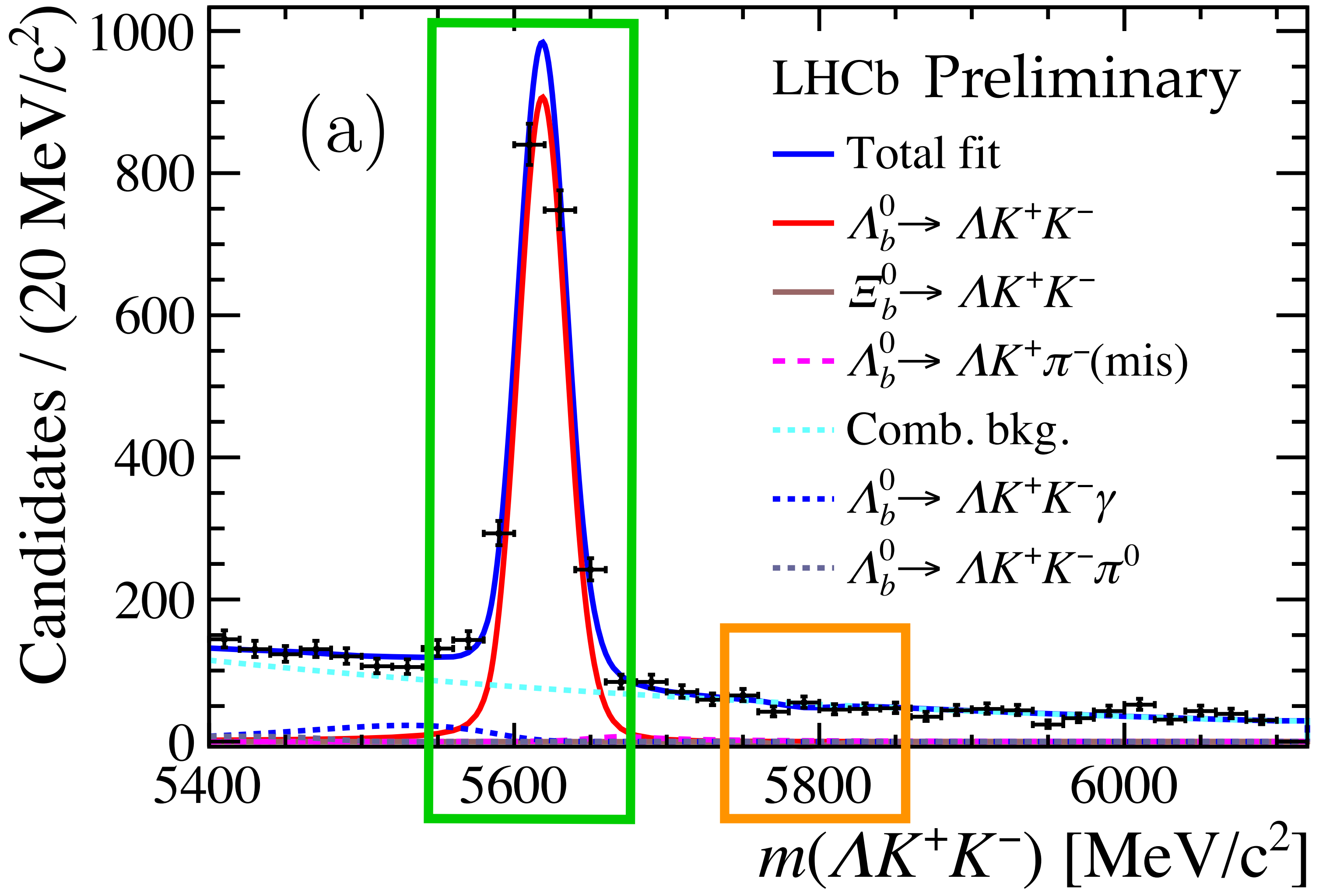

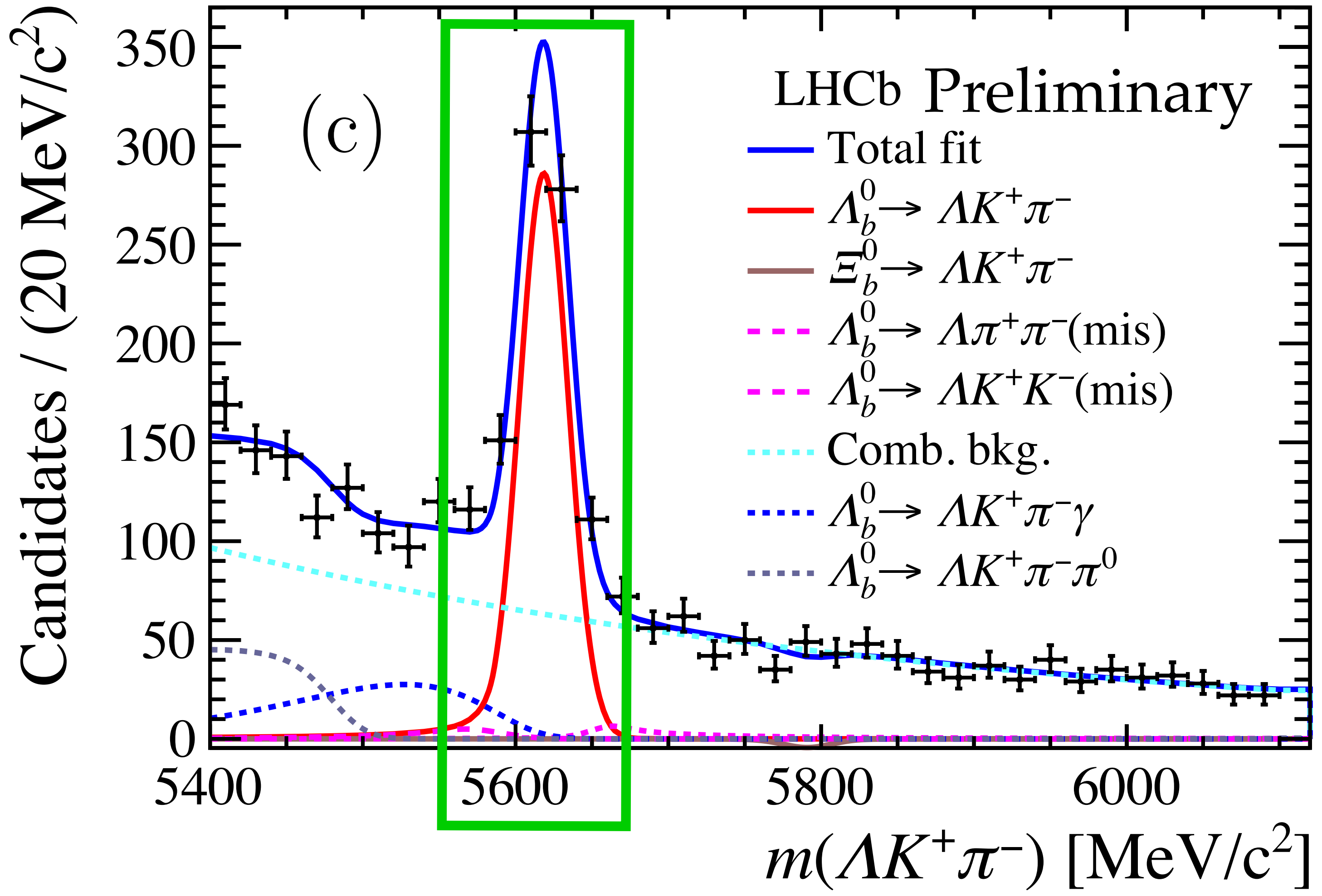

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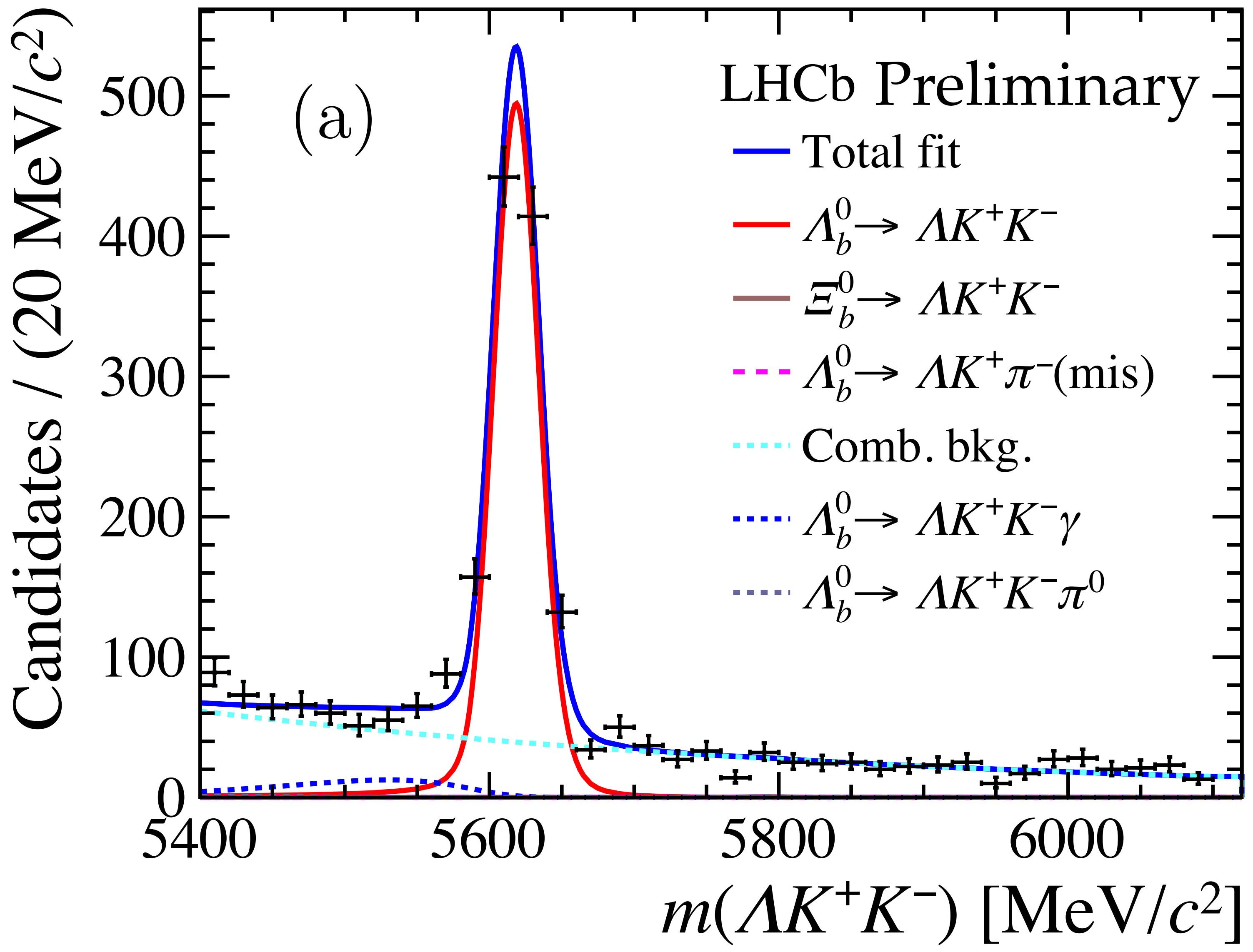
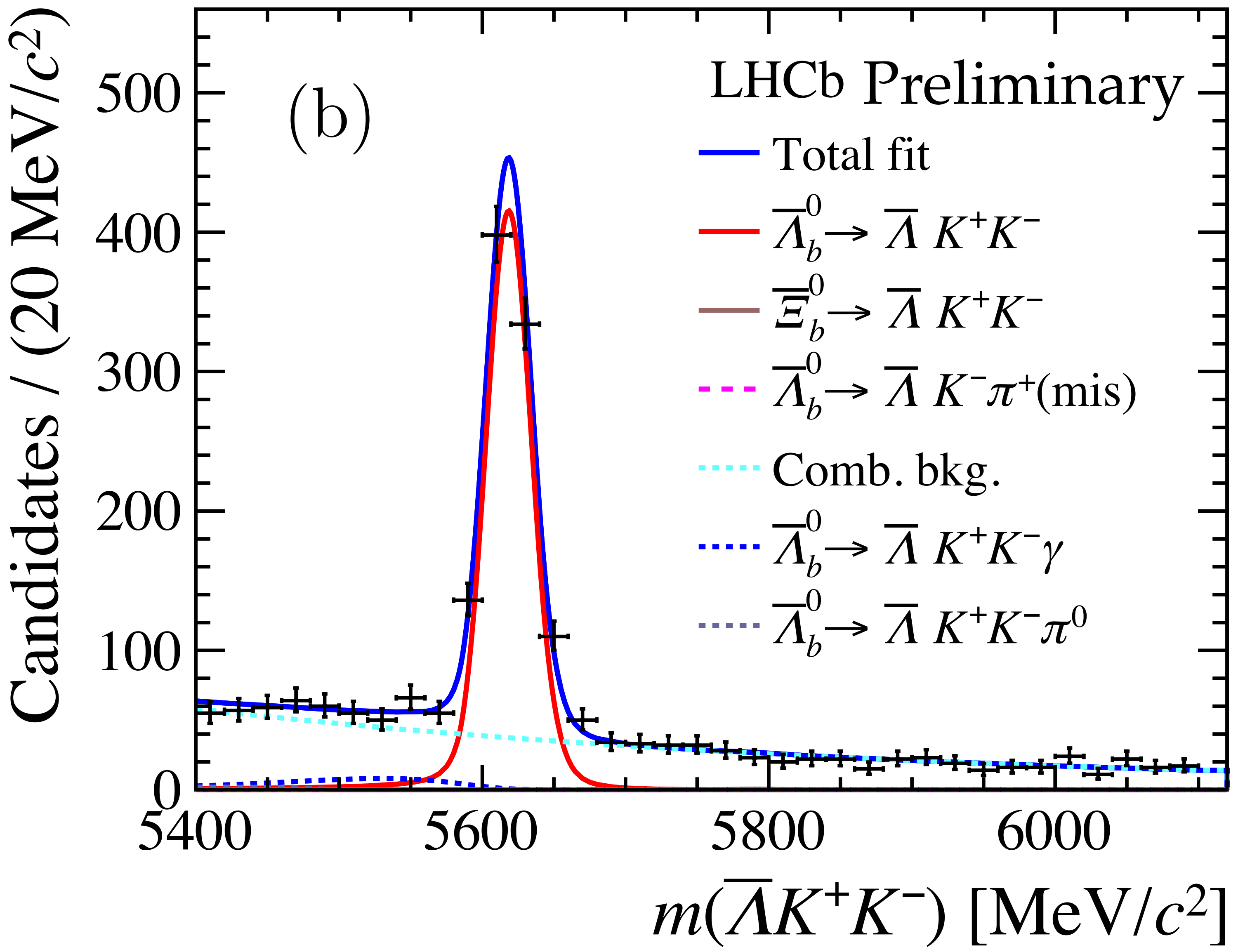
$$\mathcal{B}(\Xi_b^0 \to \Lambda K^-K^+) < 2.4 \times 10^{-6} \text{ (90\% CL)}$$ No evidence

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

New!





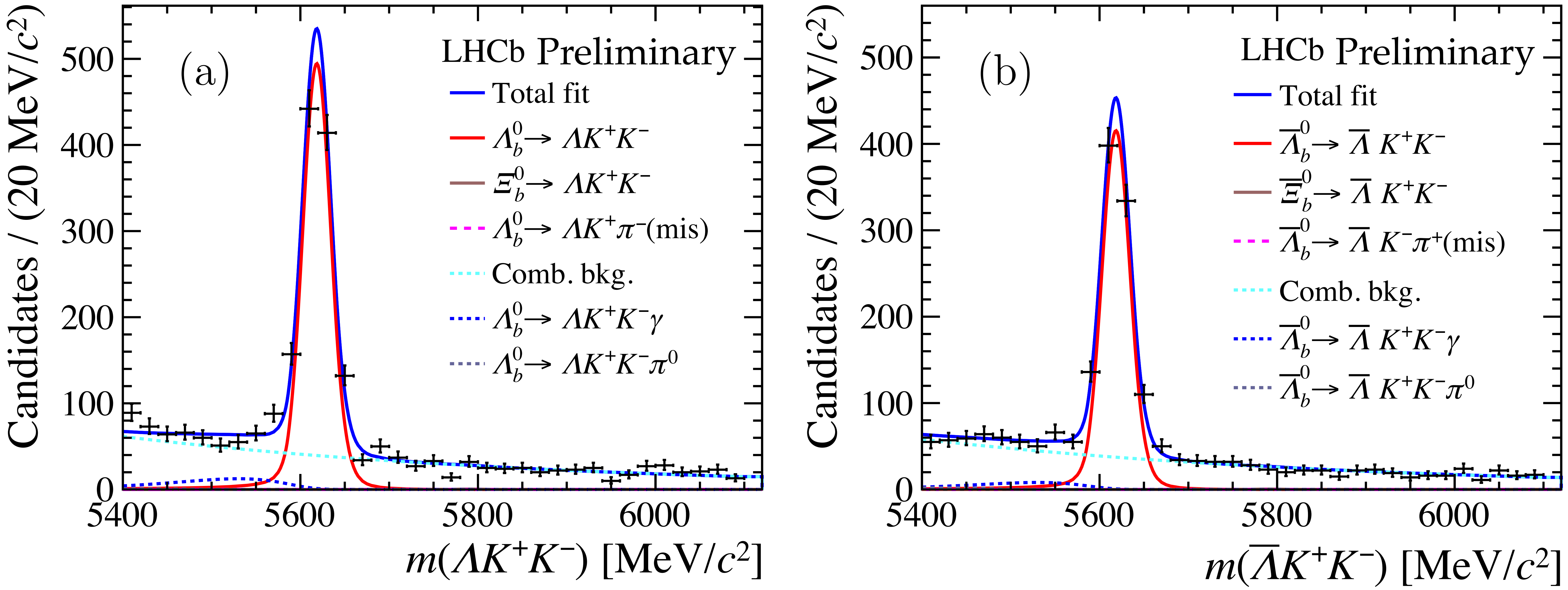
[LHCb-PAPER-2024-043], in preparation

- Run 1&2 results:

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

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:

$$\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda\pi^+\pi^-\right) = -0.013 \pm 0.053 \pm 0.018,$$
$$\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda K^+\pi^-\right) = -0.118 \pm 0.045 \pm 0.021,$$
$$\boxed{\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda K^+K^-\right) = 0.083 \pm 0.023 \pm 0.016,}$$
$$\Delta\mathcal{A}^{CP}\left(\Xi_b^0 \to \Lambda K^-\pi^+\right) = 0.27 \pm 0.12 \pm 0.05\ ,$$

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

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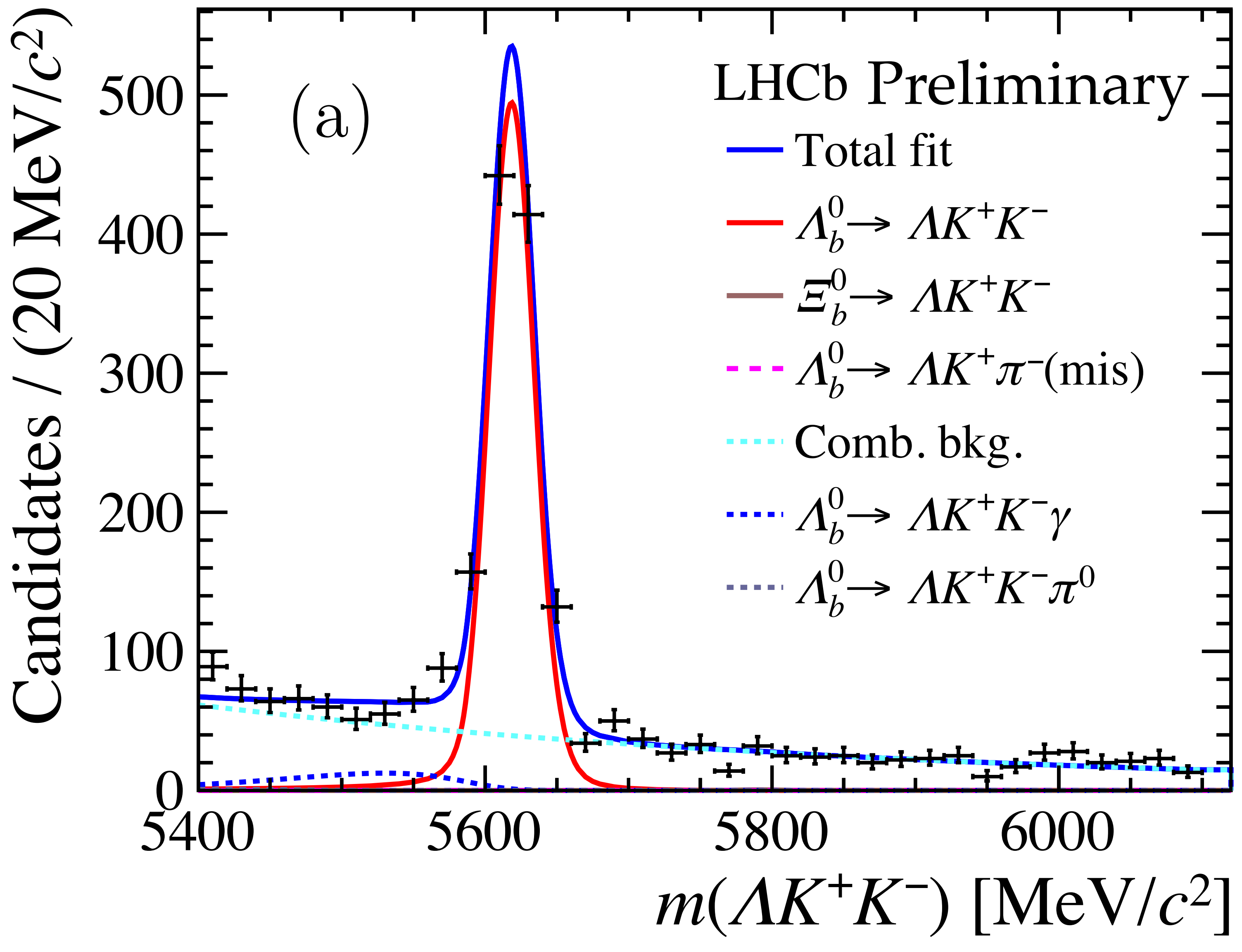

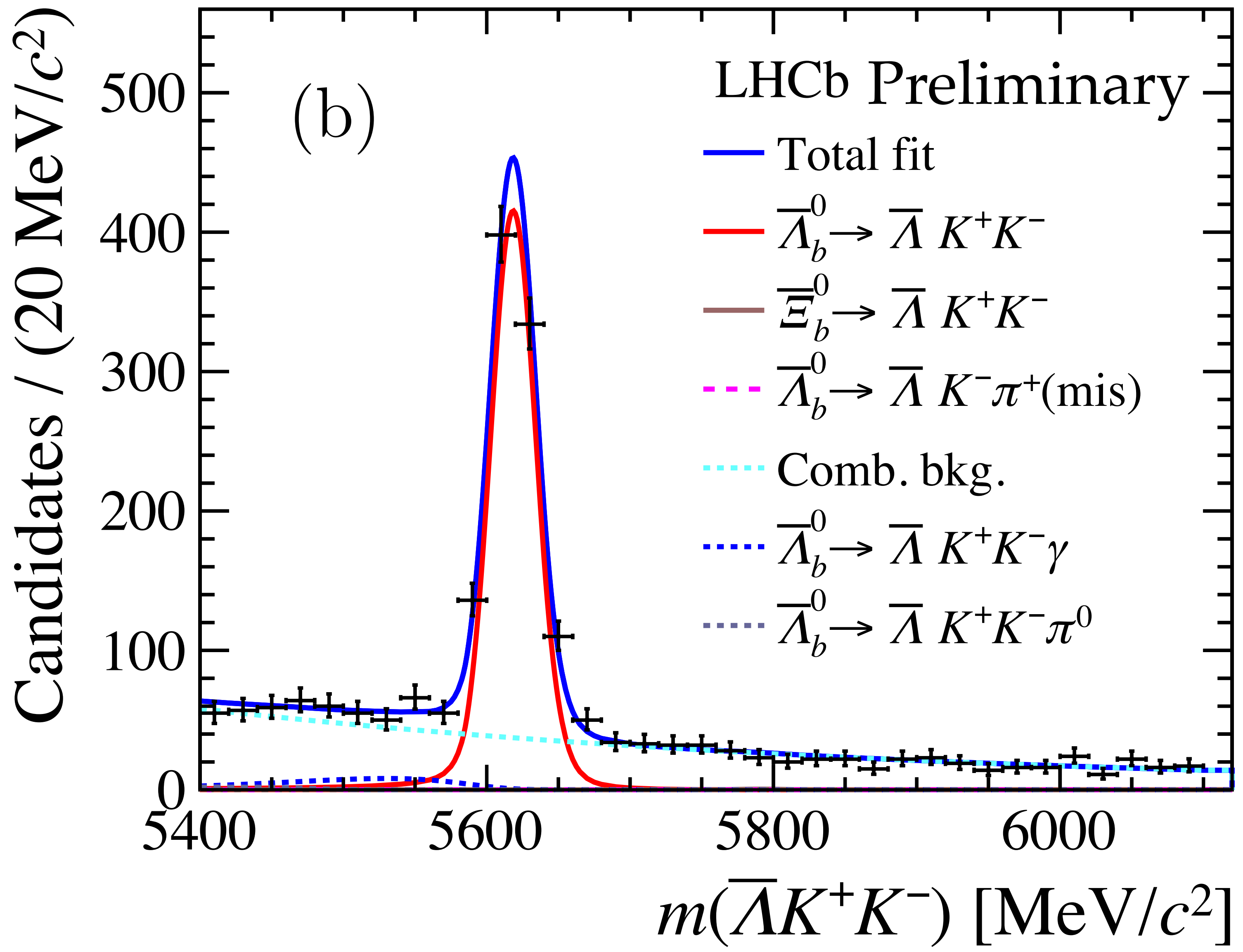

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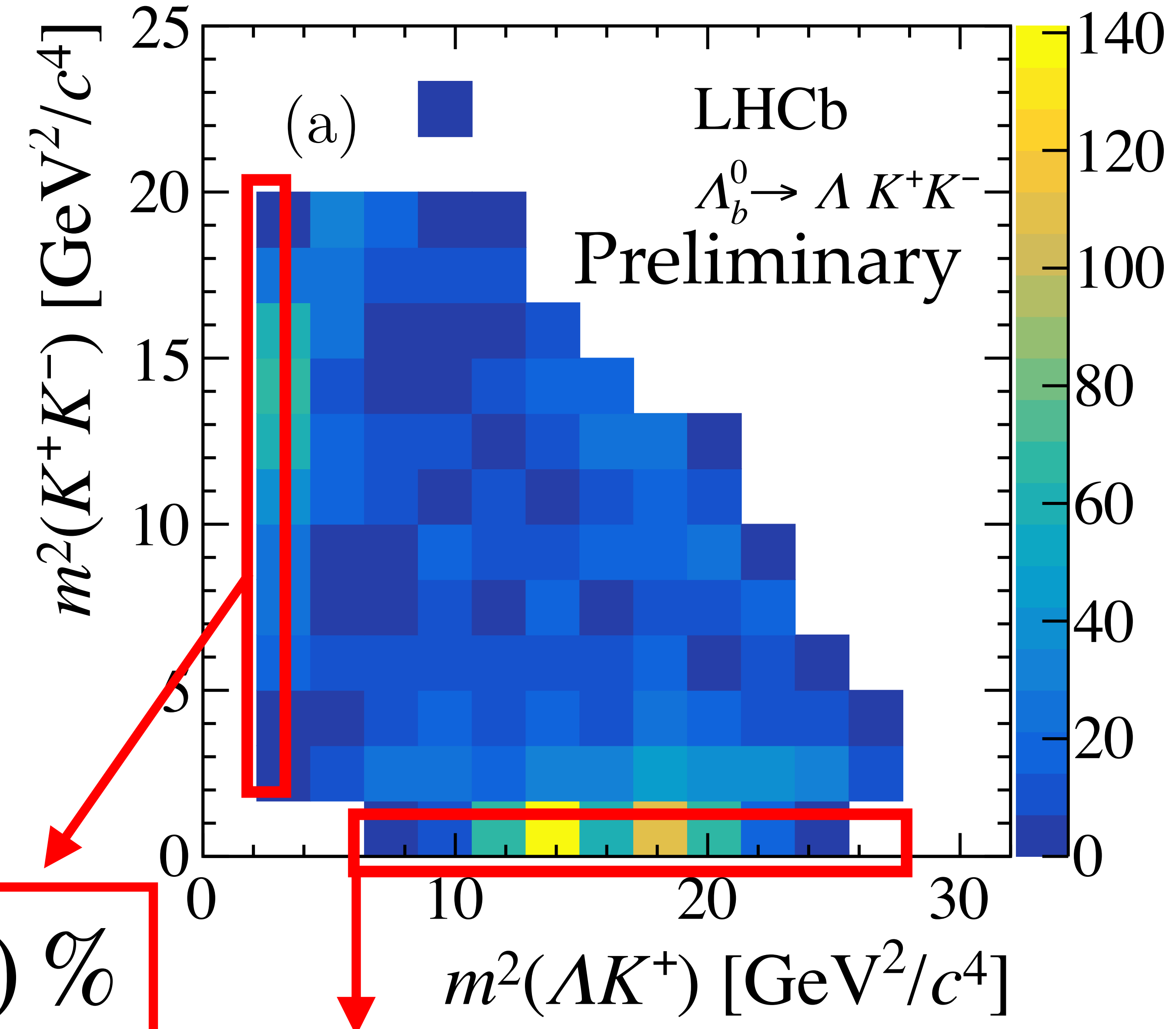
- Possible interpretation: enhancement from $N^{*+} \to \Lambda K^+$ (3.2σ) and $\phi \to K^+K^-$ resonances



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

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

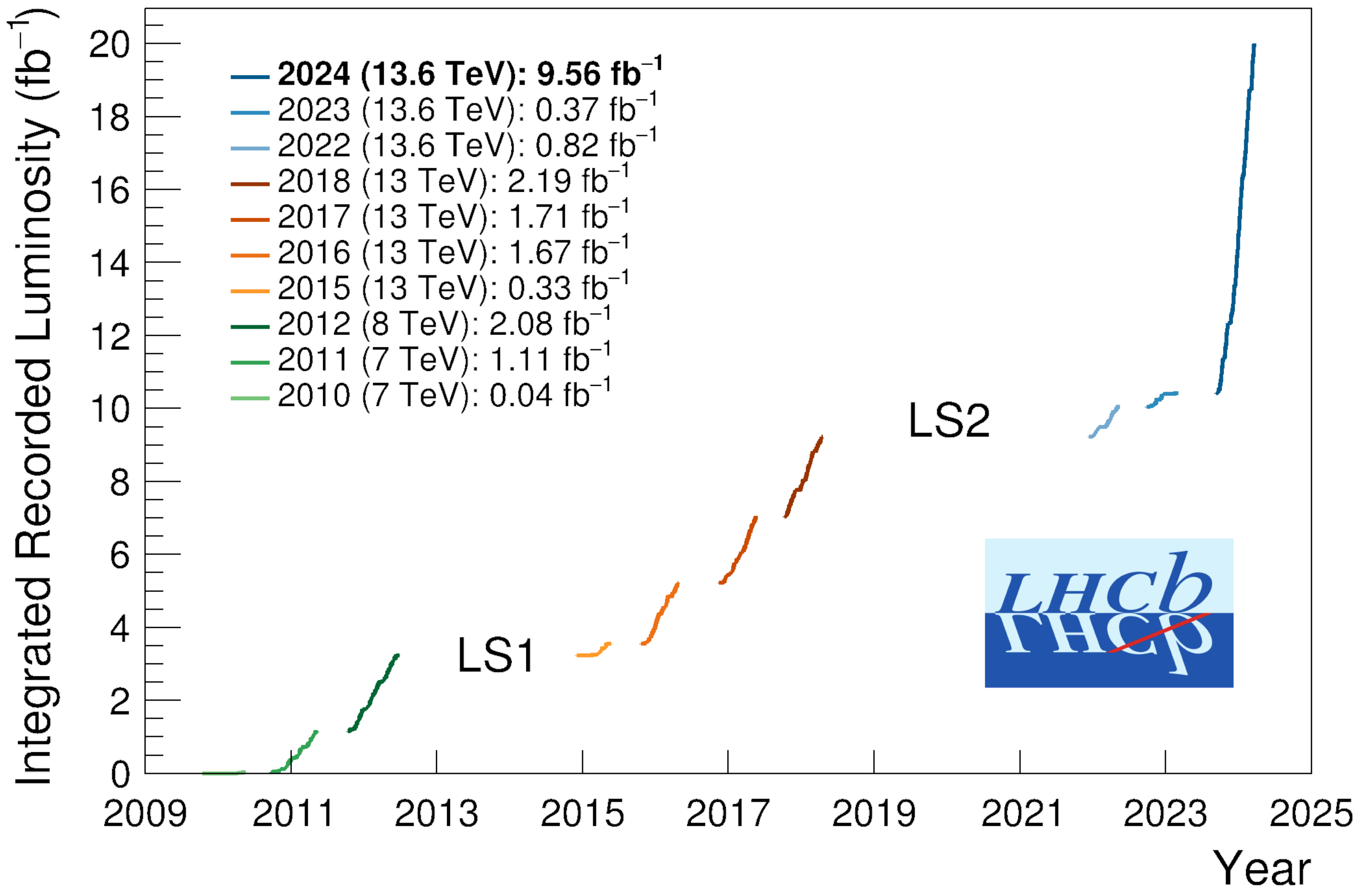
Conclusions

- LHCb is catching up with searches for baryonic CPV

- Best measurements of $A_{CP}(\Lambda_b^0 \to pK^-)$ and $A_{CP}(\Lambda_b^0 \to p\pi^-)$

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

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

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

	Run 1		Run 2	
	$\Lambda_b^0 \to pK^-$	$\Lambda_b^0 \to p\pi^-$	$\Lambda_b^0 \to pK^-$	$\Lambda_b^0 \to p\pi^-$
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

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

- Branching fractions:

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

- *CP* asymmetries

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