



華中師範大學
CENTRAL CHINA NORMAL UNIVERSITY



中国科学院大学
University of Chinese Academy of Sciences



北京大学
PEKING UNIVERSITY

Branching fraction and CPV measurements for $\Lambda_b^0/\Xi_b^0 \rightarrow \Lambda h^+ h'^-$ decays

Chenxu Yu

Peking University

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Introduction

- CP violation is required to explain the matter and antimatter asymmetry in our cosmos
- No CP violation observed in baryon decays till now

~ searches in **bottom, charm baryons & hyperons**

Charm baryons:

- $A_{\text{CP}}(\Lambda_c^+ \rightarrow pK^+K^-) - A_{\text{CP}}(\Lambda_c^+ \rightarrow p\pi^+\pi^-)$
 $= 0.003 \pm 0.011$ [[LHCb](#)]
- $A_{\text{CP}}(\Lambda_c^+ \rightarrow \Lambda K^+) = 0.021 \pm 0.026$ [[Belle](#)]

Hyperon:

- $A_{\text{CP}}(\Lambda \rightarrow p\pi^-) = -0.0025 \pm 0.0048$ [[BESIII](#)]

Bottom baryons:

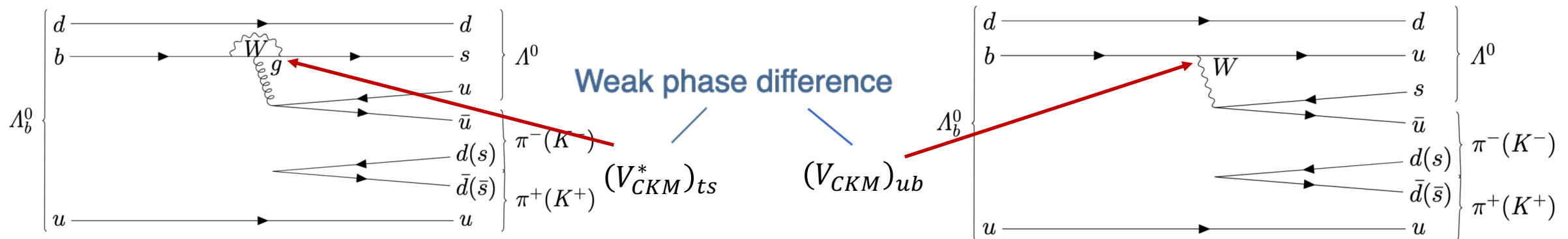
- $A_{\text{CP}}(\Lambda_b^0 \rightarrow pK^-) = -0.020 \pm 0.023$ [[LHCb Run1](#)], $A_{\text{CP}}(\Lambda_b^0 \rightarrow pK^-) = -0.0114 \pm 0.0076$ [LHCb Pre.]
- $A_{\text{CP}}(\Lambda_b^0 \rightarrow p\pi^-) = -0.035 \pm 0.024$ [[LHCb Run1](#)], $A_{\text{CP}}(\Lambda_b^0 \rightarrow p\pi^-) = 0.0020 \pm 0.0091$ [LHCb Pre.]
- $A_{\text{CP}}(\Lambda_b^0 \rightarrow pK_S^0\pi^-) = 0.22 \pm 0.13$ [[LHCb](#)]
- $\Delta A_{\text{CP}}(\Lambda_b^0 \rightarrow J/\Psi p\pi^-/K^-) = 0.057 \pm 0.027$ [[LHCb](#)]
- $A_{\text{CP}}(\Lambda_b^0 \rightarrow phh'h'')$ [[LHCb, see details in back up](#)]

Introduction (cont.)

CPV may exist in $\Lambda_b^0 / \Xi_b^0 \rightarrow \Lambda h^+ h'^-$ decays:

- Large CPV at the level of 10% observed in $B \rightarrow hh'h''$ decays experimentally [\[LHCb\]](#)
 - Theoretical predictions on the $\Lambda_b^0 / \Xi_b^0 \rightarrow \Lambda h^+ h'^-$ CPV and BF CPV: 1% ~ 4% [\[Link\]](#)
BF: 10^{-6}
- Aiming for **CPV** & **BF** in $\Lambda_b^0 / \Xi_b^0 \rightarrow \Lambda hh'$ decays

Feynman diagram contributing to the $\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$



Weak phase difference: CKM matrix
Strong phase difference: hadronic effects

} → CPV may exist

Analysis overview

Signal channels:

- Λ_b^0 decays: $\Lambda_b^0 \rightarrow \Lambda K^+ K^-$, $\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-$, $\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$, $\Lambda_b^0 \rightarrow \Lambda \pi^+ K^-$
- Ξ_b^0 decays: $\Xi_b^0 \rightarrow \Lambda K^+ K^-$, $\Xi_b^0 \rightarrow \Lambda K^+ \pi^-$, $\Xi_b^0 \rightarrow \Lambda \pi^+ \pi^-$, $\Xi_b^0 \rightarrow \Lambda \pi^+ K^-$

Blue: BF & CPV,
Blue: BF only,
Red: not measured

Reference channel:

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

- Similar kinematics & large statistics

Run1+2 analysis

- 9fb^{-1} data
- Measurement of BF and CPV of $\Lambda_b^0 / \Xi_b^0 \rightarrow \Lambda h^+ h'^-$

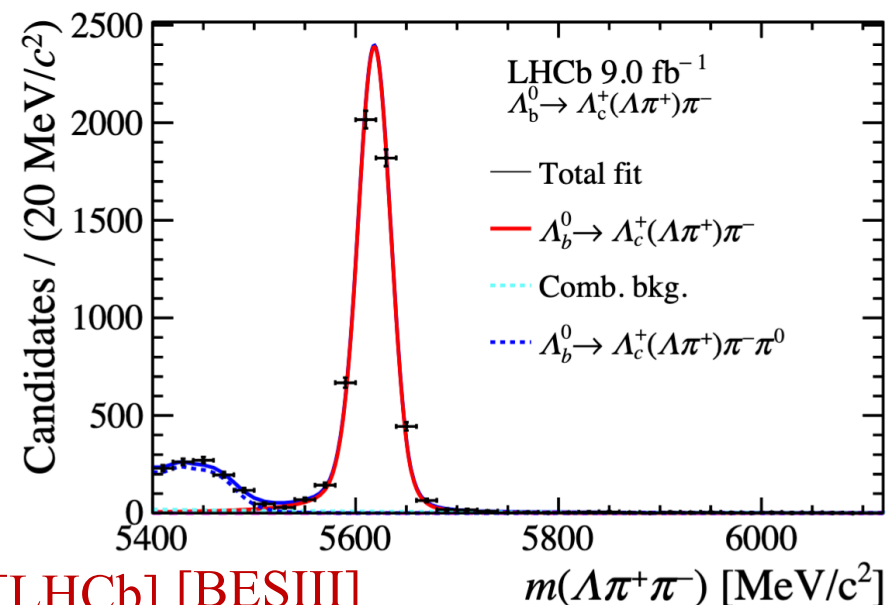
Measurements of Branching Fractions

Absolute branching fractions of signal channels are calculated according to :

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

Branching fraction (in addition to A_{CP}) offers important information to the internal dynamics

In LHCb, we measure w.r.t. **control channels** (relative branching fraction) to reduce systematic uncertainties.



Absolute branching fractions of control channel [LHCb] [BESIII]

$$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+(\Lambda\pi^+)\pi^-) = (6.0 \pm 0.6) \times 10^{-5}$$

Signal extraction

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

Fit model: Simultaneous fit applied

Signal Model

- Sum of two Crystal Ball functions
- Mean and width shared among all decays

Mis-ID background

- Sum of two Crystal Ball functions

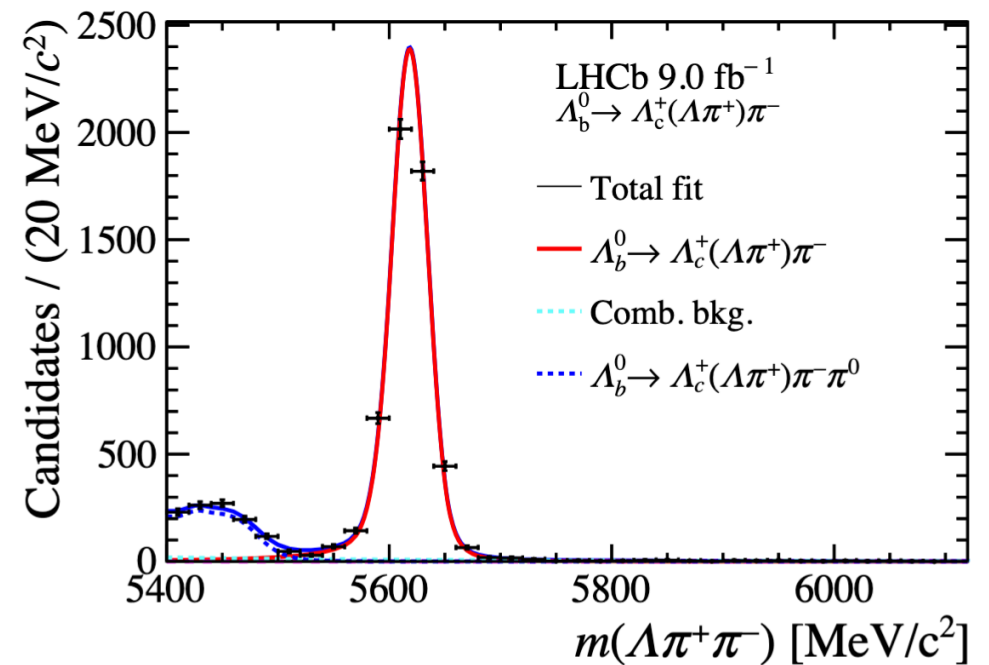
Partially reconstructed background

- Argus convolved gaussian

Combinatorial background

- Parameters shared among all decays

~ 5200 signals

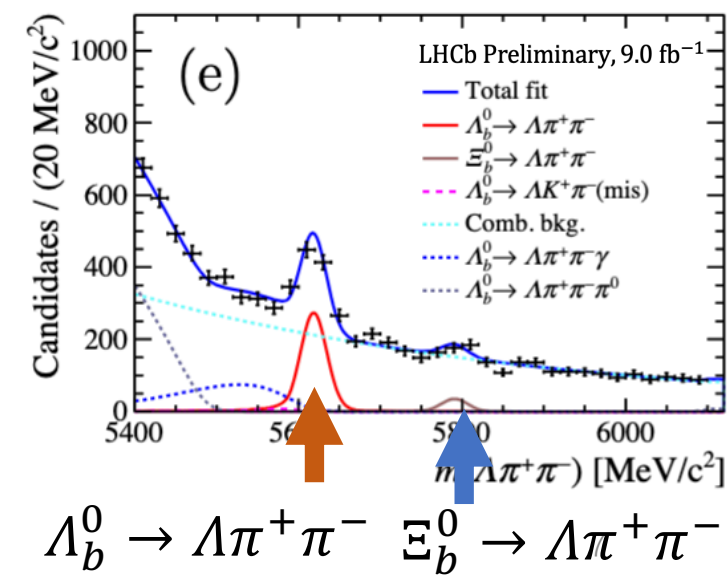
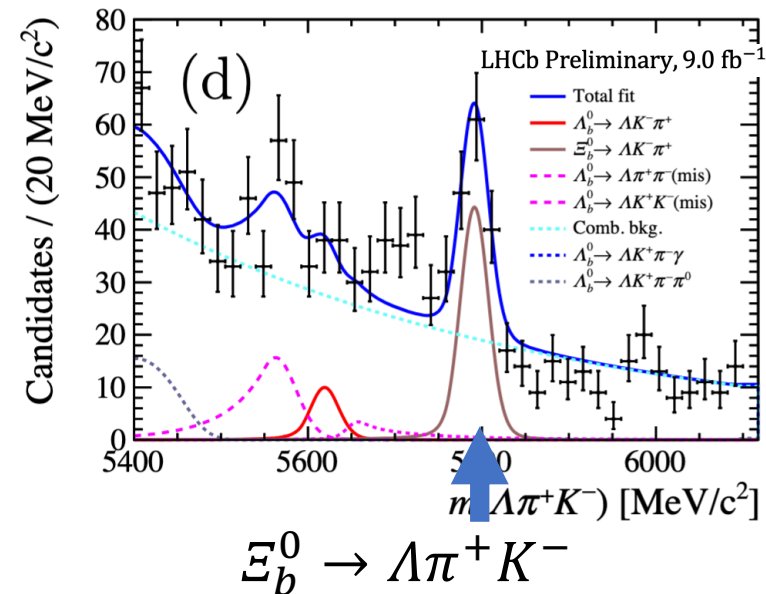
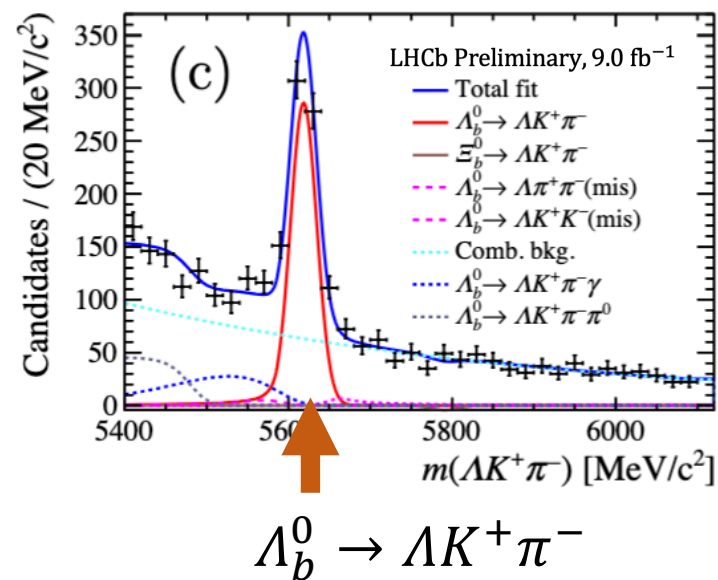
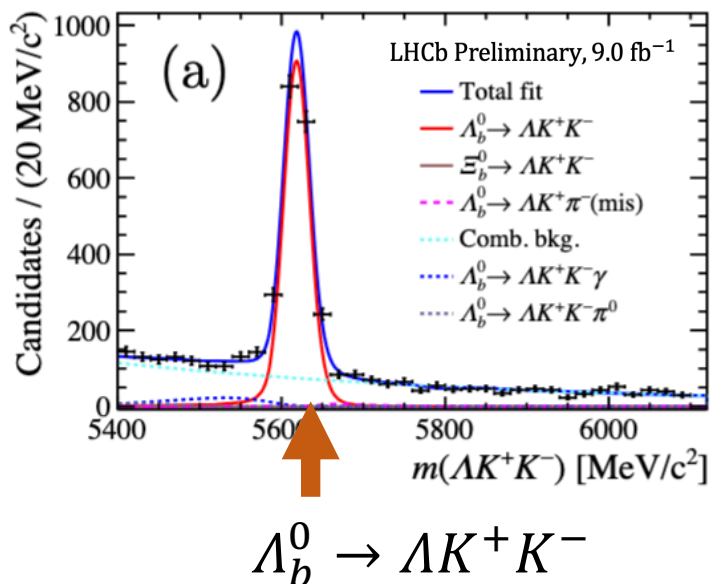


Fit results

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

Signal channels:

- Λ_b^0 decays: $\Lambda_b^0 \rightarrow \Lambda K^+ K^-$, $\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-$, $\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$, $\Lambda_b^0 \rightarrow \Lambda \pi^+ K^-$
- Ξ_b^0 decays: $\Xi_b^0 \rightarrow \Lambda K^+ K^-$, $\Xi_b^0 \rightarrow \Lambda K^+ \pi^-$, $\Xi_b^0 \rightarrow \Lambda \pi^+ \pi^-$, $\Xi_b^0 \rightarrow \Lambda \pi^+ K^-$



Measurements of Branching Fractions

Absolute branching fractions of signal channels are calculated according to :

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

Efficiencies determined from simulation with corrections using data-driven methods

- Particle ID, trigger, tracking : using control channels from $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$..
- Dalitz plot corrections: difference on Dalitz plot distribution between data and simulation

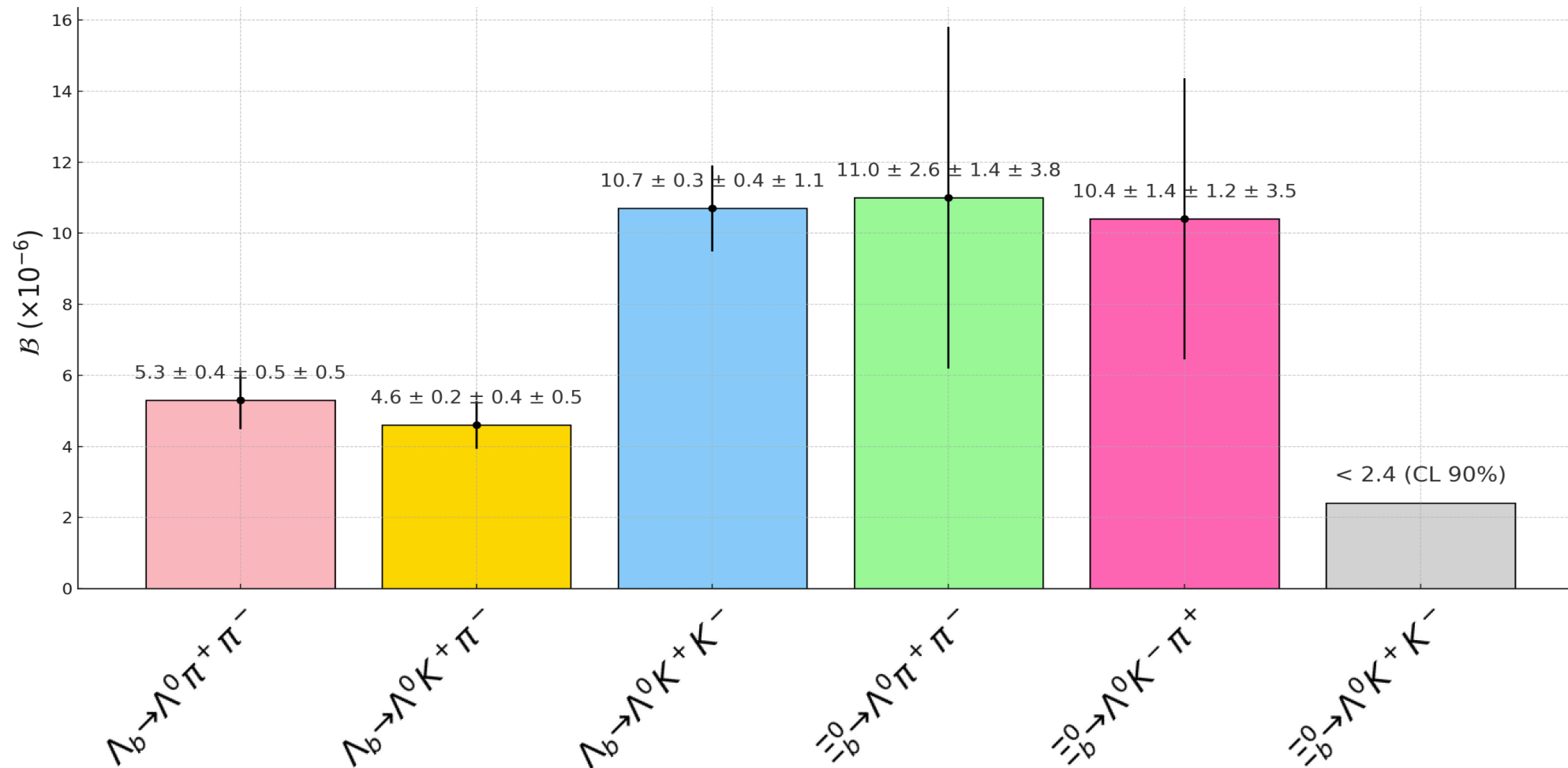
Fragmentation fraction

[LHCb]

$$\frac{f_{\Xi_b}}{f_{\Lambda_b}} = \begin{cases} (6.7 \pm 0.5 \pm 0.5 \pm 2.0) \times 10^{-2}, & 7,8 \text{ TeV} \\ (8.2 \pm 0.7 \pm 0.6 \pm 2.5) \times 10^{-2}, & 13 \text{ TeV} \end{cases}$$

Results for Branching Fractions

Results of absolute branching fractions:

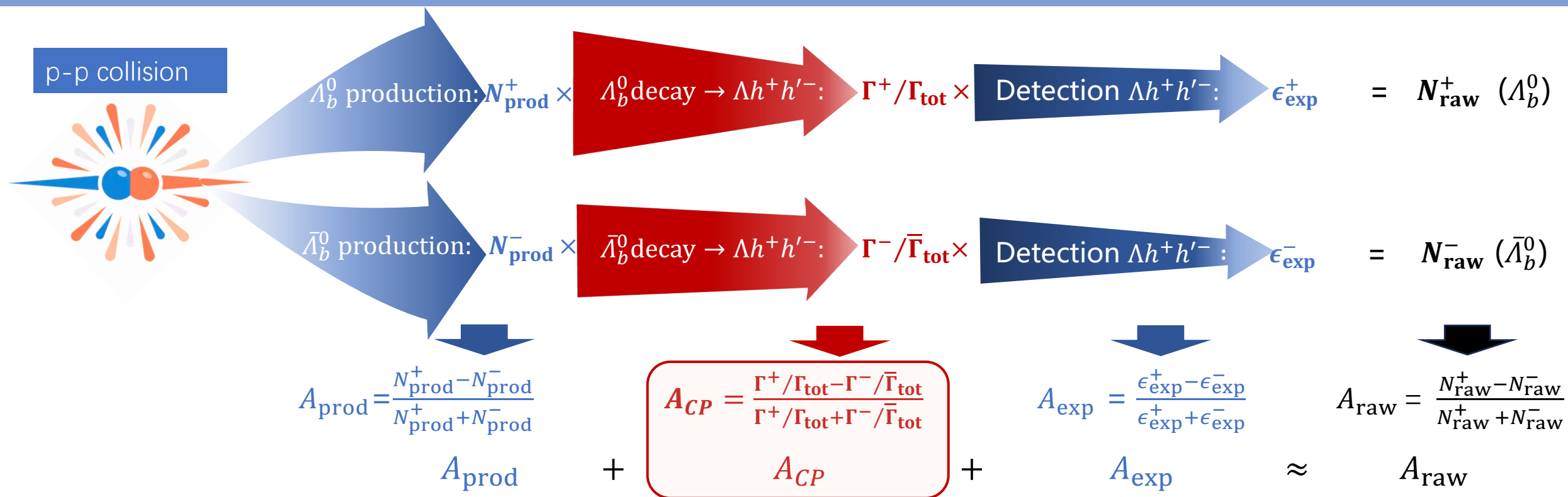


First **observation**

First **evidence**

First **observation**

Methodology for A_{CP} measurement



- Procedure :

1. Extract signal yields N_{raw}^+ , N_{raw}^-

→ Raw asymmetry A_{raw}

2. Corrections on A_{prod} , A_{exp}

→ $A_{CP} \approx A_{\text{raw}} - A_{\text{prod}} - A_{\text{exp}}$

ΔA_{CP} measurement: reduce systematics

To reduce systematic uncertainties, A_{CP} is measured according to:

$$\Delta A_{CP} = A_{CP}(signal) - A_{CP}(control)$$

Same mother particle &
similar daughter particle



Correction terms
greatly cancelled.

$$= \underbrace{A_{\text{raw}}(signal) - A_{\text{raw}}(control)}_{\text{Raw results}} - \underbrace{\Delta A_{\text{exp}} - \Delta A_{\text{P}}}_{\text{Corrections}}$$

Raw results

Corrections

- $A_{CP}(control) = 0$ within the precision of our analysis.
- $A_{\text{P}}, A_{\text{exp}}$: measured by LHCb as a function of y, P_T ,
at the level of 1%.
- $\Delta A_{\text{P}}, \Delta A_{\text{exp}}$: mostly cancelled, small residual due to the
differences between signal channel and control channel.
Both ΔA_{P} and ΔA_{exp} are consistent with 0

Channel	ΔA_{P} (%)	ΔA_{exp} (%)
$\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$	0.1 ± 0.1	0.1 ± 0.9
$\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-$	0.2 ± 0.2	1.4 ± 1.0
$\Lambda_b^0 \rightarrow \Lambda K^+ K^-$	-0.2 ± 0.2	0.0 ± 0.9
$\Xi_b^0 \rightarrow \Lambda K^- \pi^+$	-5.2 ± 4.0	0.3 ± 1.6

Global A_{CP} results

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

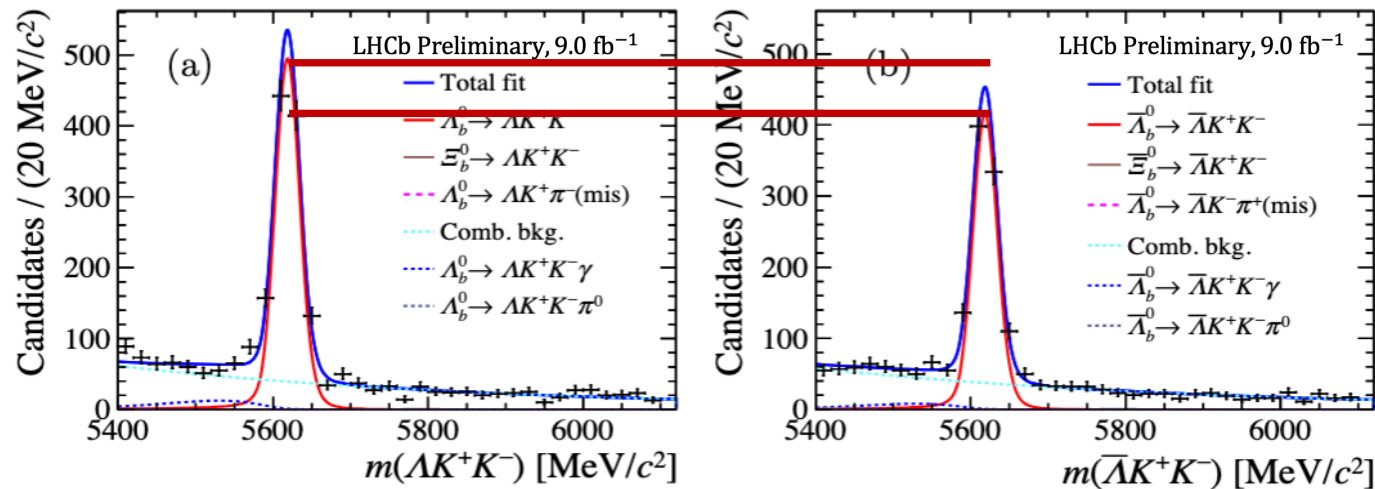
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \rightarrow \Lambda K^+\pi^-) = -0.118 \pm 0.045 \pm 0.021,$$

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

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \rightarrow \Lambda K^+K^-) = 0.083 \pm 0.023 \pm 0.016 \quad \text{Significance: } 3.1\sigma$$

Evidence of CPV observed in $\Lambda_b^0 \rightarrow \Lambda K^+K^-$

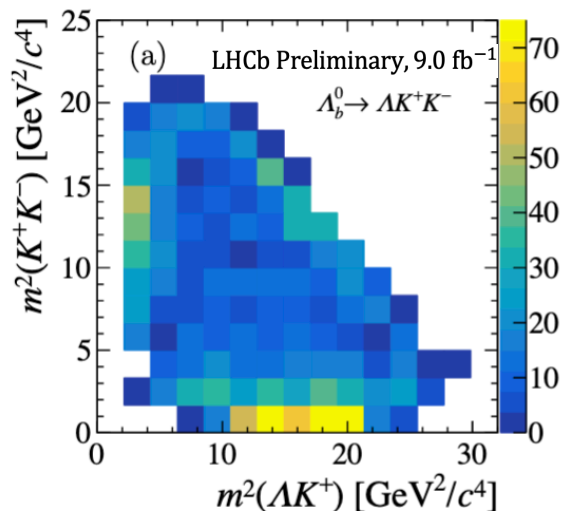
Fit results for $\Lambda_b^0 \rightarrow \Lambda K^+K^-$



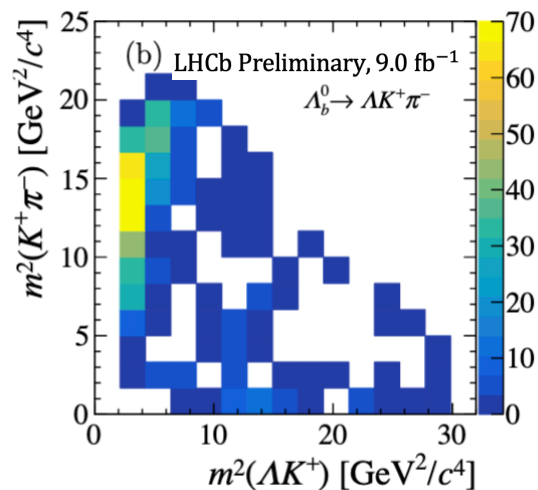
Further explore the CPV of localize regions

Looking into Dalitz plot

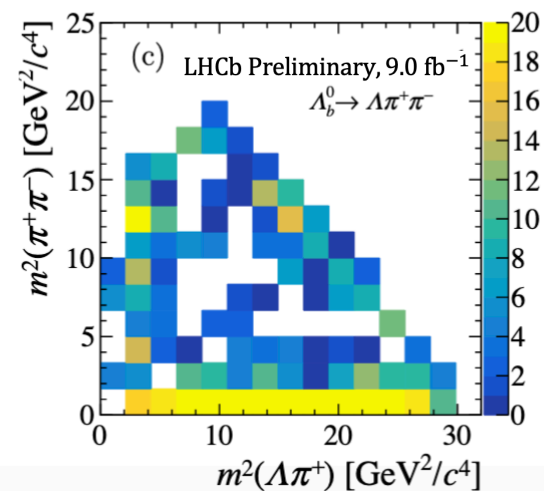
$$\Lambda_b^0 \rightarrow \Lambda K^+ K^-$$



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



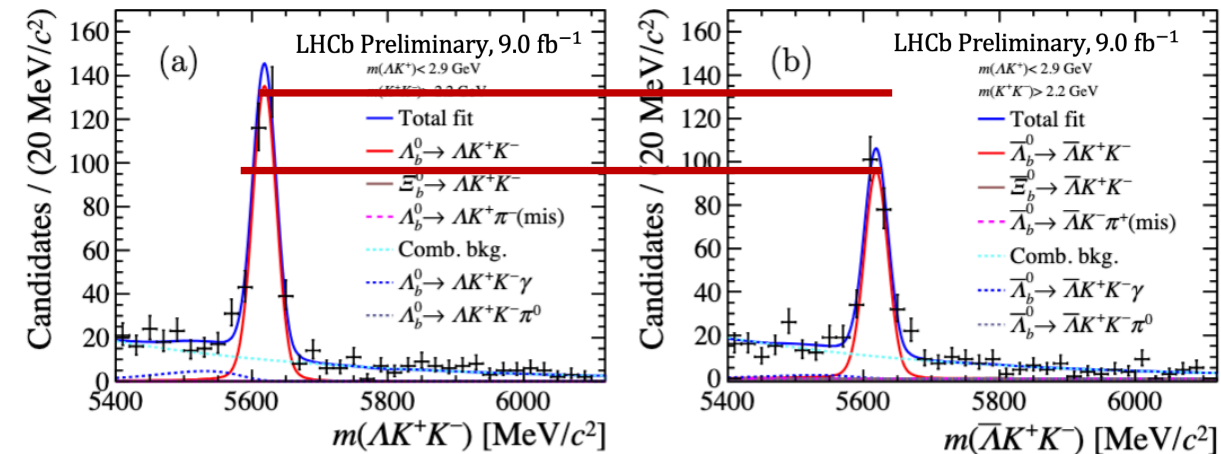
$$\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$$



Local resonant states & CP asymmetries

Channel	$m(h^+ h'^-)$	$m(\Lambda h^+)$	$\Delta \mathcal{A}^{CP}$
$\Lambda_b^0 \rightarrow \Lambda \phi (\rightarrow K^+ K^-)$	$< 1.10 \text{ GeV}/c^2$	—	$0.150 \pm 0.055 \pm 0.021$
$\Lambda_b^0 \rightarrow N^{*+} (\rightarrow \Lambda K^+) K^-$	$> 2.20 \text{ GeV}/c^2$	$< 2.90 \text{ GeV}/c^2$	$0.165 \pm 0.048 \pm 0.017$
$\Lambda_b^0 \rightarrow N^{*+} (\rightarrow \Lambda K^+) \pi^-$	—	$< 2.30 \text{ GeV}/c^2$	$-0.078 \pm 0.051 \pm 0.027$
$\Lambda_b^0 \rightarrow \Lambda f (\rightarrow \pi^+ \pi^-)$	$< 1.70 \text{ GeV}/c^2$	—	$0.088 \pm 0.069 \pm 0.021$

Looking into Dalitz plot ($\Lambda_b^0 \rightarrow \Lambda K^+ K^-$)



$\Lambda_b^0 \rightarrow N^{*+} (\rightarrow \Lambda K^+) K^-$ region

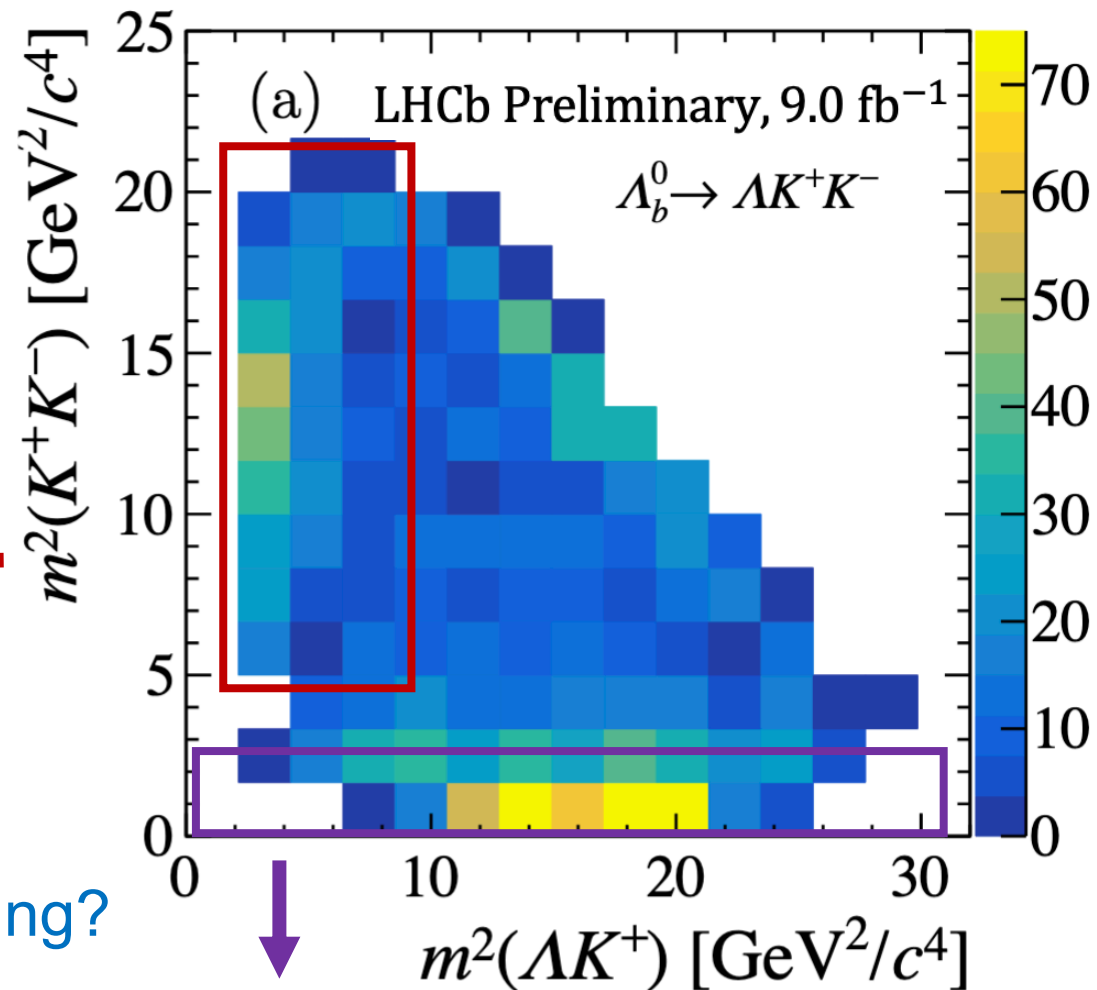
$$\Delta\mathcal{A}_{\text{CP}} = 0.165 \pm 0.048 \pm 0.017$$

Evidence of CP violation in local resonant region, 3.2 σ

Expected from model using $N - \pi$ rescattering?

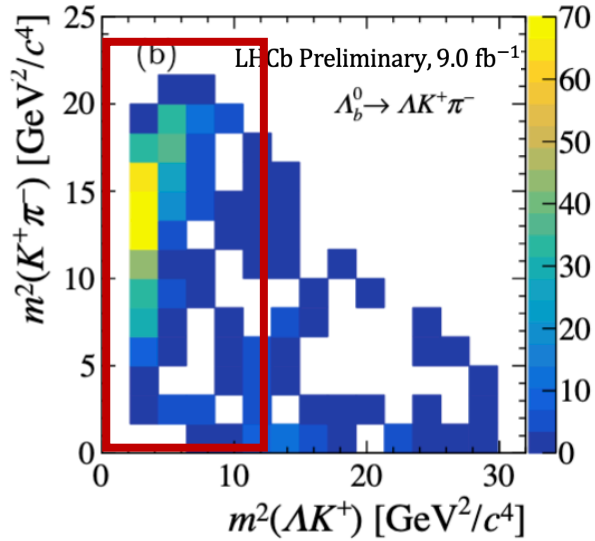
[CPC48 \(2024\) 101002](#)

$\Lambda\phi/f(1500)$



$$\Delta\mathcal{A}_{\text{CP}} = 0.150 \pm 0.055 \pm 0.021 (2.5\sigma)$$

Looking into Dalitz plot ($\Lambda_b^0 \rightarrow \Lambda h^+ \pi^-$)



Region N^{*+}

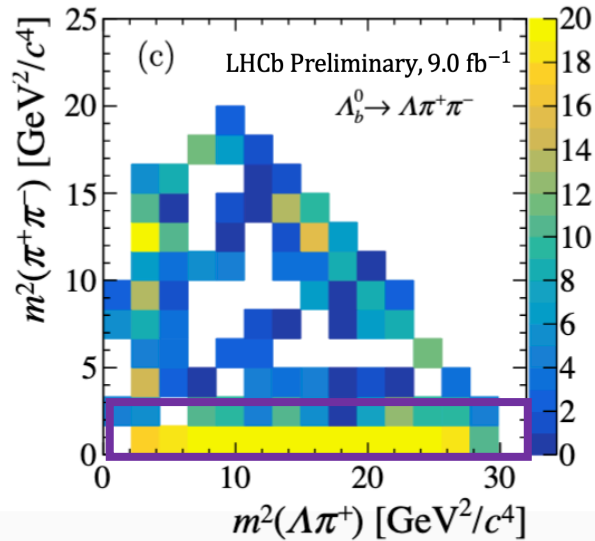
$$\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-$$

$$\text{Mainly } \Lambda_b^0 \rightarrow N^{*+} \pi^-$$

$$\text{Small contribution from } \Lambda_b^0 \rightarrow \Lambda K^*$$

$$A_{\text{CP}} = -0.078 \pm 0.051 \pm 0.027 \quad (1.2 \sigma)$$

Consistent with null CP hypothesis



Region ϕ/f

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

$$\text{Mainly } \Lambda_b^0 \rightarrow \Lambda f_0(980), \Lambda_b^0 \rightarrow \Lambda f_2(1270)$$

$$A_{\text{CP}} = 0.088 \pm 0.069 \pm 0.021 \quad (1.4 \sigma)$$

Consistent with null CP hypothesis

A_{CP} in adaptive binning scheme

2D adaptive binning on Dalitz plot ($m(h^+h^-)$ vs. $m(\Lambda h^+)$) based on signal numbers

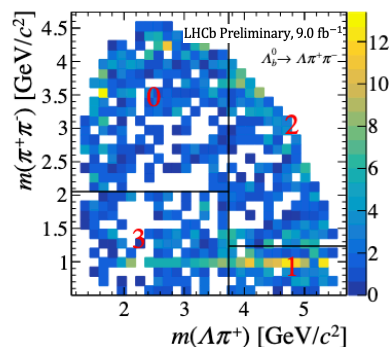
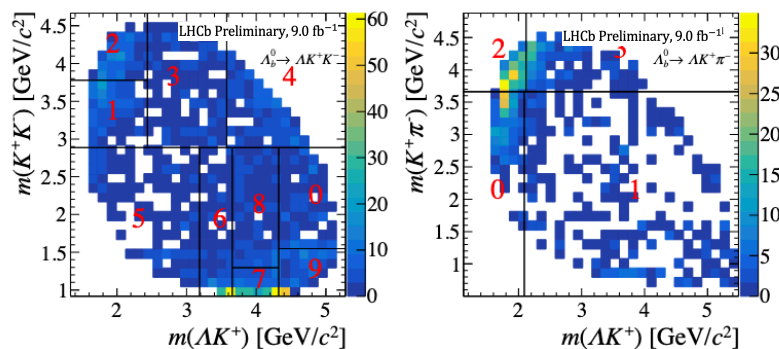
Number of bins (about 200 events per bin)

$$\Lambda_b^0 \rightarrow \Lambda K^+ K^- : 10$$

$$\Lambda_b^0 \rightarrow \Lambda K^+ \pi^- : 4$$

only measure
three Λ_b^0 decays

$$\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^- : 4$$



A_{CP} results in adaptive binning scheme

Channel	Bin	A_{CP}
$\Lambda_b^0 \rightarrow \Lambda K^+ K^-$	0	$0.017 \pm 0.092 \pm 0.025$
$\Lambda_b^0 \rightarrow \Lambda K^+ K^-$	1	$0.188 \pm 0.075 \pm 0.023$
$\Lambda_b^0 \rightarrow \Lambda K^+ K^-$	2	$0.062 \pm 0.077 \pm 0.022$
$\Lambda_b^0 \rightarrow \Lambda K^+ K^-$	3	$0.064 \pm 0.093 \pm 0.024$
$\Lambda_b^0 \rightarrow \Lambda K^+ K^-$	4	$0.088 \pm 0.077 \pm 0.022$
$\Lambda_b^0 \rightarrow \Lambda K^+ K^-$	5	$0.061 \pm 0.089 \pm 0.024$
$\Lambda_b^0 \rightarrow \Lambda K^+ K^-$	6	$0.066 \pm 0.088 \pm 0.024$
$\Lambda_b^0 \rightarrow \Lambda K^+ K^-$	7	$0.168 \pm 0.070 \pm 0.021$
$\Lambda_b^0 \rightarrow \Lambda K^+ K^-$	8	$-0.002 \pm 0.080 \pm 0.023$
$\Lambda_b^0 \rightarrow \Lambda K^+ K^-$	9	$0.025 \pm 0.074 \pm 0.022$
$\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-$	0	$-0.153 \pm 0.079 \pm 0.027$
$\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-$	1	$-0.284 \pm 0.188 \pm 0.041$
$\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-$	2	$-0.006 \pm 0.062 \pm 0.028$
$\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-$	3	$-0.264 \pm 0.125 \pm 0.030$
$\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$	0	$-0.483 \pm 0.200 \pm 0.043$
$\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$	1	$0.147 \pm 0.092 \pm 0.026$
$\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$	2	$0.058 \pm 0.114 \pm 0.028$
$\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$	3	$0.067 \pm 0.111 \pm 0.028$

No significant
local variations of
 A_{CP} observed.

Conclusion

- Measurements of **BF** & **CPV** for $\Lambda_b^0 / \Xi_b^0 \rightarrow \Lambda h^+ h'^-$ channels
 - First observation of $\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$ and $\Xi_b^0 \rightarrow \Lambda \pi^+ K^-$ channels
 - First evidence for $\Xi_b^0 \rightarrow \Lambda \pi^+ \pi^-$
 - **Evidence for A_{CP}** observed in $\Lambda_b^0 \rightarrow \Lambda K^+ K^-$ channel for the first time, both from the global A_{CP} and in local N^{*+} region.
- A solid step towards establishment of CP violation in baryon decays.

Thanks for listening!

Back up

CPV asymmetry links

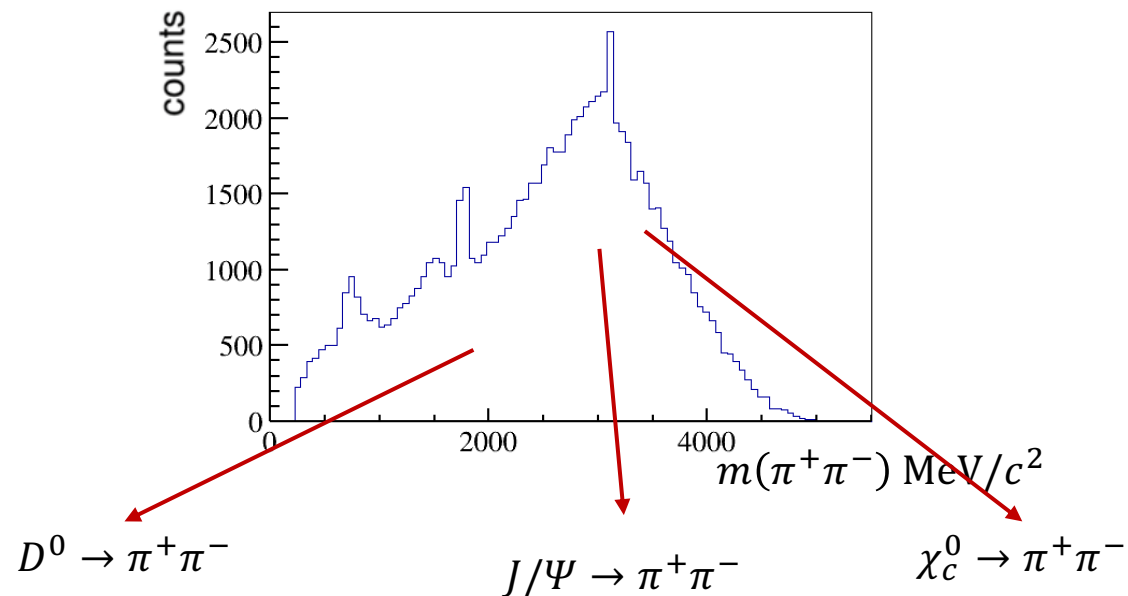
- [\[LHCb\]](#) : Observation of the suppressed $\Lambda^0_b \rightarrow D p K^-$ decay with $D \rightarrow K^+ \pi^-$ and measurement of its CP asymmetry
- [\[LHCb\]](#) : Measurement of matter-antimatter differences in beauty baryon decays
- [\[LHCb\]](#) : Search for CP violation using triple product asymmetries in $\Lambda^0_b \rightarrow p K^- \pi^+ \pi^-$, $\Lambda^0_b \rightarrow p K^- K^+ K^-$, and $\Xi^0_b \rightarrow p K^- K^- \pi^+$ decays
- [\[LHCb\]](#) : Measurement of CP asymmetries in charmless four-body Λ^0_b and Ξ^0_b decays
- [\[LHCb\]](#) : LHCb collaboration, R. Aaij et al., Search for CP violation and observation of P violation in $\Lambda^0_b \rightarrow p \pi^- \pi^+ \pi^-$ decays

Selection: Preselection and mass vetoes

Mass vetoes

- Narrow resonances: K_S^0 , D^0 , Λ_c^+ , Ξ_c^+ , J/ψ and χ_c^0 ← Add veto cuts on states

$m(\pi^+\pi^-)$ of $\Lambda_b^0 \rightarrow \Lambda\pi^+\pi^-$ before mass veto



Selection: BDT & PID selection

Boosted Decision Tree (BDT)

- Training sample:

Signal:

MC sample of $\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$

Background:

Sideband of $\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$ data
[5800, 6100] MeV/c²

- Applied to all $\Lambda h^+ h'^-$ channels
- Optimize BDT and PID cuts simultaneously

- Training variables:
kinematics, vertex, LL DD separate ...

All channels are optimized independently

- Significance F.o.M = $\frac{N_{sig}}{\sqrt{N_{sig} + N_{bkg}}}$ for Λ_b^0 decays
- Punzi F.o.M = $\frac{N_{sig}}{2.5 + \sqrt{N_{bkg}}}$ for Ξ_b^0 decays

Fit model: Simultaneous fit applied

Signal Model

- Sum of two Crystal Ball functions
- Parameters extracted from MC (except mean and width)
- Mean and width shared among all decays

Mis-ID background

- Sum of two Crystal Ball functions
- Parameters extracted from MC
- Ratio of Signal and mis-ID fixed

Partially reconstructed background

- Argus convolved gaussian
- Parameters extracted from MC

Combinatorial background

- Parameters shared among all decays



Fit results (cont.)

Λ_b^0 decays ~ 1000 events

Ξ_b^0 decays ~ 100 events

Yields and significance:

(using Wilks' theorem)

Channel	Yield	Significance
$\Lambda_b^0 \rightarrow \Lambda \pi^+ \pi^-$	$(6.4 \pm 0.4) \times 10^2$	$> 10\sigma$, first obs.
$\Lambda_b^0 \rightarrow \Lambda K^+ \pi^-$	$(6.18 \pm 0.32) \times 10^2$	$> 10\sigma$
$\Lambda_b^0 \rightarrow \Lambda K^+ K^-$	$(1.92 \pm 0.05) \times 10^3$	$> 10\sigma$
$\Xi_b^0 \rightarrow \Lambda \pi^+ \pi^-$	$(5.6 \pm 2.7) \times 10^1$	first evidence
$\Xi_b^0 \rightarrow \Lambda \pi^+ K^-$	$(1.19 \pm 0.15) \times 10^2$	first obs.
$\Xi_b^0 \rightarrow \Lambda K^+ K^-$	$(1.2 \pm 0.9) \times 10^1$	

Total efficiency is calculated with:

$$\epsilon_{Total} = \epsilon_{acceptance} \times \epsilon_{stripping/reconstruction} \times \epsilon_{trigger} \times \epsilon_{offline-selection} \times \epsilon_{PID}$$

Efficiency measurements: Based on simulation samples

- corrections on Λ_b^0 p_T , η (y) variables
- PID efficiency:
further simulated with recalibrated MC
(Data-driven)
- Efficiency evaluated in bins of Dalitz plot,
perform per-event efficiency corrections

$$\bar{\epsilon} = \frac{\sum_i \omega_i}{\sum_i \omega_i / \epsilon_i},$$

ω_i : weight of data