第七届“重味物理与量子色动力学”研讨会 南京师范大学

Baryon CPV in $\Lambda_b^0 \to \Lambda h^+ h'^-$ decays at LHCb

LHCb合作组

主导工作者：钱文斌[1]、谢跃红[2]、许傲[3]、虞晨煦[4]、张艳席[4] 、朱展文[1]等

报告人：万关越

1. UCAS
2. CCNU
3. INFN
4. PKU

Outline

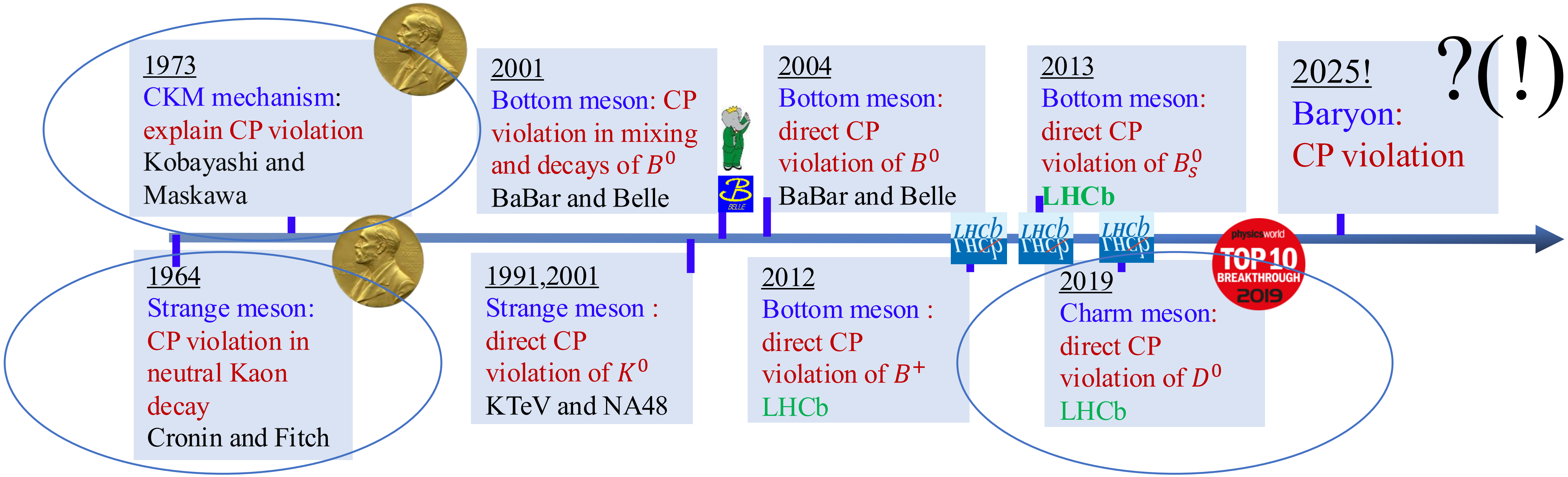
- Introduction
- Event selection
- CP violation
- Results and prospect

Introduction

CP violation

https://arxiv.org/abs/1204.4186
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.55.1039

- Within SM: observation of **baryon CPV** still awaiting…… **until 2025!**
- Sakharov conditions: CP violation required to explain matter-antimatter asymmetry
- Astrophysics reveals asymmetry **beyond explanation of SM** $(\eta = (\mathrm{n_B} - \mathrm{n_{\bar{B}}})/n_\gamma \sim 10^{-10}$



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CP violation

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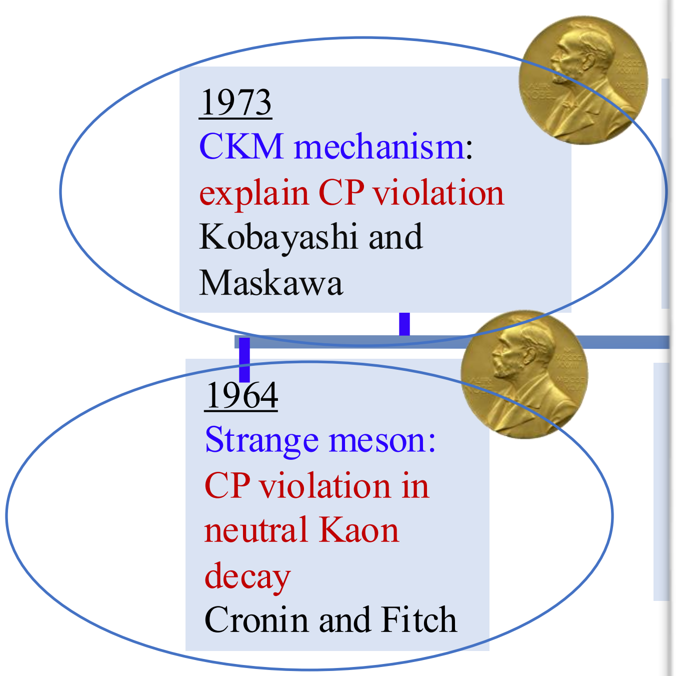
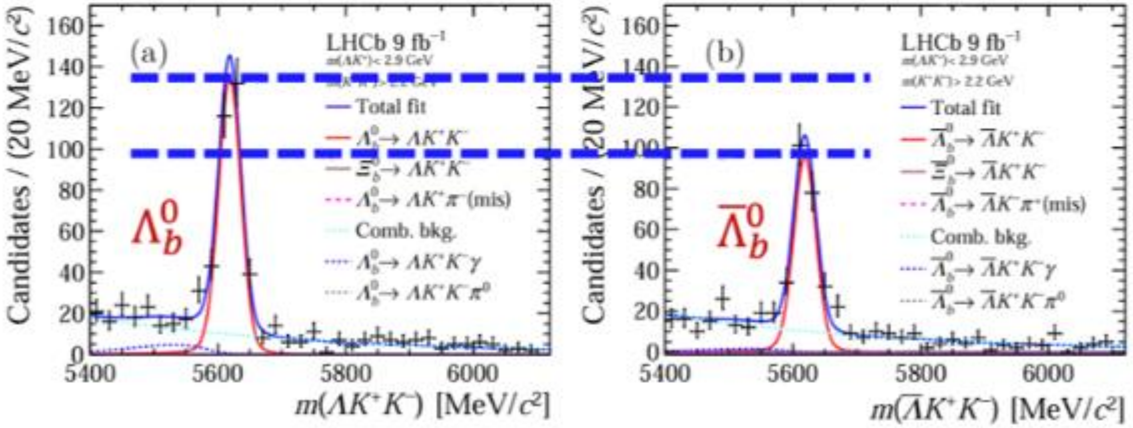


$$\Delta A^{CP}(\Lambda_b^0 \to \Lambda\pi^+\pi^-) = -0.013 \pm 0.053 \pm 0.018,$$
$$\Delta A^{CP}(\Lambda_b^0 \to \Lambda K^+\pi^-) = -0.118 \pm 0.045 \pm 0.021,$$
$$\Delta A^{CP}(\Lambda_b^0 \to \Lambda K^+K^-) = 0.083 \pm 0.023 \pm 0.016,$$
$$\Delta A^{CP}(\Xi_b^0 \to \Lambda K^-\pi^+) = 0.27 \pm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

3.1σ, evidence for CPV in baryons

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



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CP violation

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- Astrophysics reveals asymmetry **beyond explanation of SM** ($\eta = (n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$)

1973 CKM mechanism:

2001 Bottom meson: CP

2004 Bottom meson:

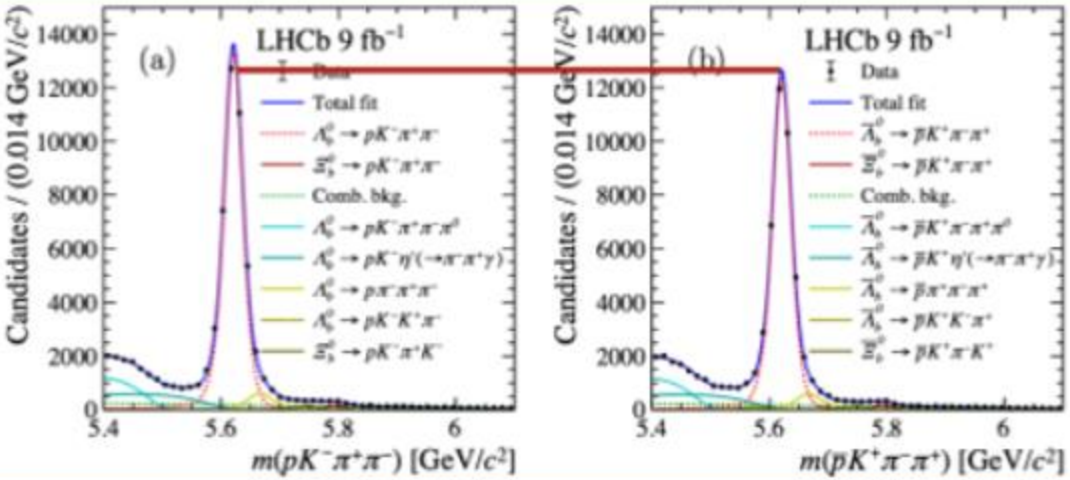
2013 Bottom meson:

2025! ?(!)

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

$$\mathcal{A}_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$$

5.2σ



Motivation

$$A_{CP}^{pK^-} = (-1.1 \pm 0.7 \pm 0.4)\%,$$
$$A_{CP}^{p\pi^-} = (\ \ 0.2 \pm 0.8 \pm 0.4)\%,$$

- **No observation** in $\Lambda_b^0 \to ph$ two-body decays
- **Three (or more) body** decays may provide more insight:
  - Phase-space dependent **strong-phase** & **resonant contributions**
- **LHCb has explored**:
  - $\Lambda_b \to J/\psi ph$ direct CPV, 3fb^{-1}
  - $\Xi_b \to pK^-K^-$ amplitude analysis, 5fb^{-1}
  - $\Lambda_b \to pD^0K^-$ direct CPV, 9fb^{-1}
  - $\Lambda_b \to \Lambda_c(\to \Lambda h^+)h^-$ decay parameters, 9fb^{-1}
  - ...

Predictions

<table><tr><td>

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

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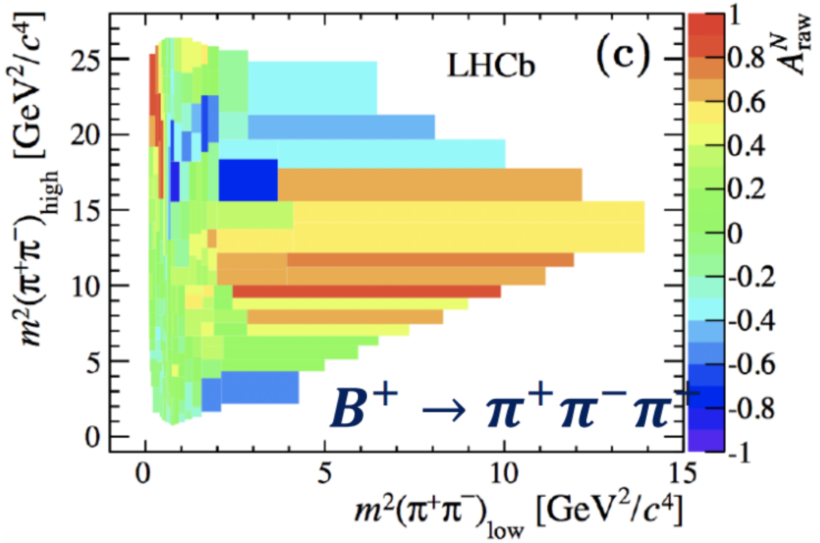
- This work: CPV in $\Lambda_b^0/\Xi_b^0 \to \Lambda h^+h'^-$ channels

- b meson decays: $B^+ \to h^+h^+h^-$



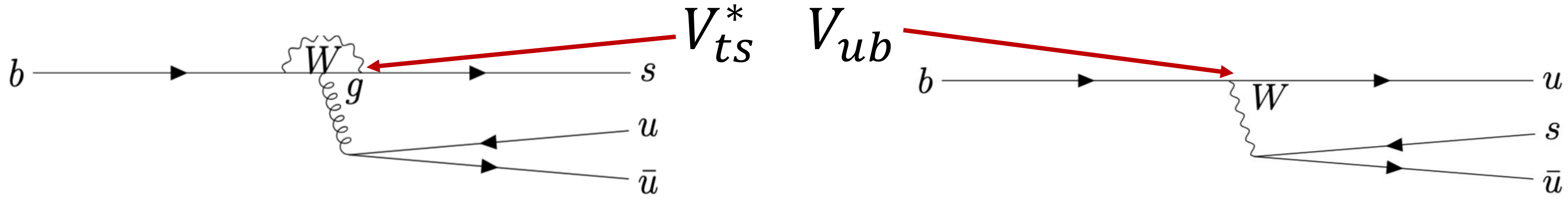
$A_{CP} \sim 4\%$

- b baryon decays: $\Lambda_b^0 \to \Lambda h^+h'^-$

$\Lambda_b^0 \to \Lambda V$ decay chains, $A_{CP} \sim 0 - 4\%$
[PRD.107.053009, EPJC.76.399, PRD95.093001, PRD99.054020]

$N^{*+}\pi^-$ scattering, $A_{CP} \sim -4\%{\sim}10\%$
[CPC.48.101001]

Both dominated by $b \to su\bar{u}$ process, CP violation exists theoretically

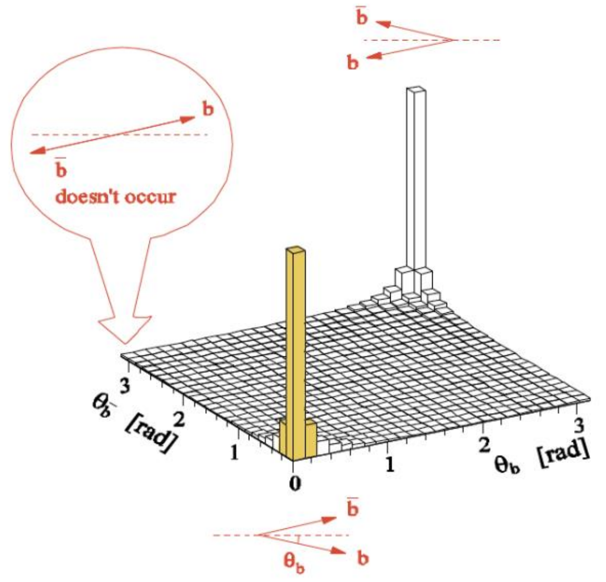


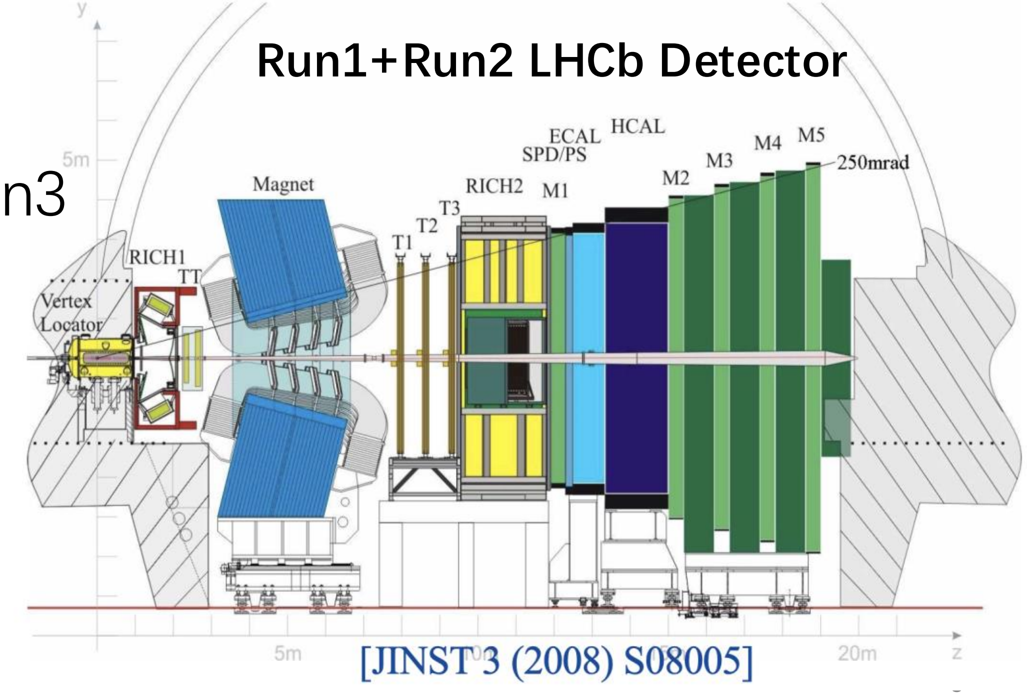
LHCb detector

- LHCb detector is designed for heavy flavour events
  - **VELO Detector:** excellent position & time resolution
  - **PID System:** hadron & muon identification
  - **Tracking System:** track resolution
  - **Trigger System:** high efficiency, high signal rate

  - Has collected 9 fb^{-1} with Run1 + 2
    - Expecting even more events (~5 times) in Run3
    - Efficiency also increased

The LHCb detector has world-leading precision in bottom hadron CPV measurements .

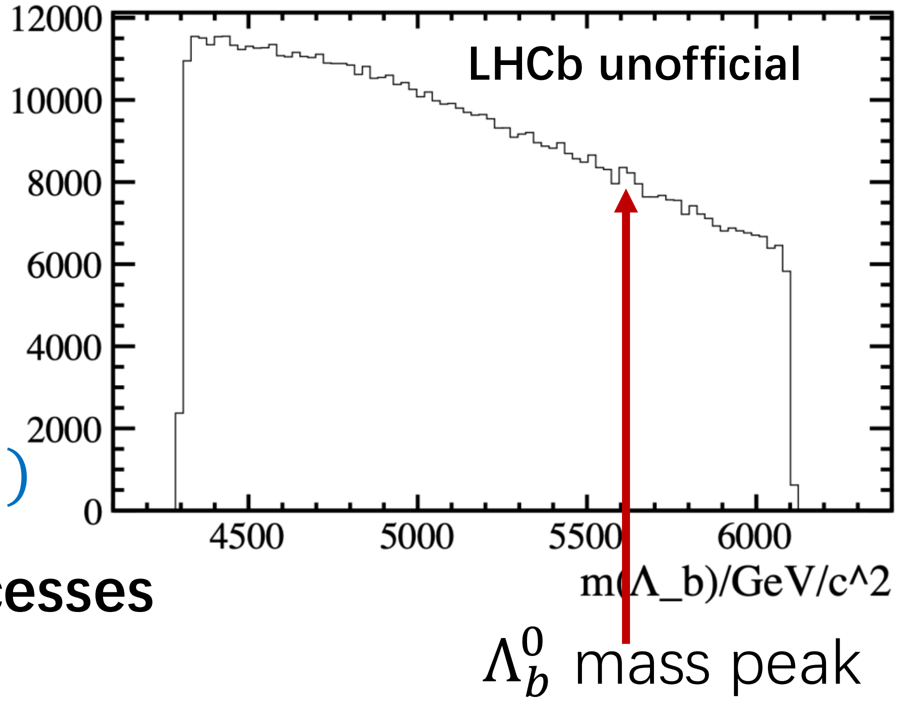




Experimental method

Signal extraction

- Events collected with LHCb trigger system is **"dirty",** when we need ***N***
- A set of **selection procedures** to suppress backgrounds, which mainly come from:
  1. Randomly combined tracks (majority)
  2. Physical backgrounds:
     a. decays through charm states $(D^0, J/\psi, \chi_{c0} \ldots)$
     b. partial reconstruction or mis-identified **processes**



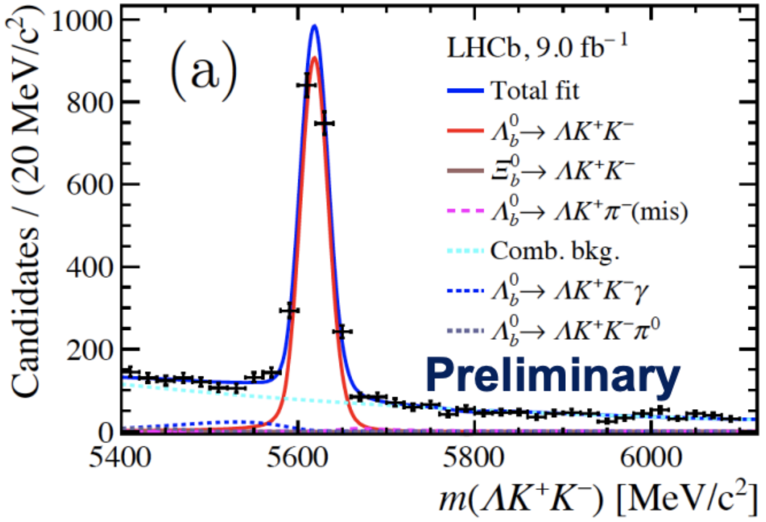
Event selections

$\Lambda_b^0/\Xi_b^0 \to \Lambda K^+K^-$
$\Lambda_b^0/\Xi_b^0 \to \Lambda\pi^+\pi^-$
$\Lambda_b^0 \to \Lambda K^+\pi^-$
$\Xi_b^0 \to \Lambda K^-\pi^+$
all measured

➢ Dedicated selection procedures:

1. **Mass vetoes:** remove mass regions near **physical peaks**
2. **MVA selection:** **machine-learning** based BDT classifier
   - Utilizing kinematic and topological information
   - Trained with simulated sample, optimized with $N_S/\sqrt{N_S + N_B}$
3. **PID requirements**
4. **Mass fits** are performed:
   - Describe remained backgrounds
   - Signal component

$\Lambda_b \to \Lambda KK$ signal yield: $N = 1920 \pm 50$

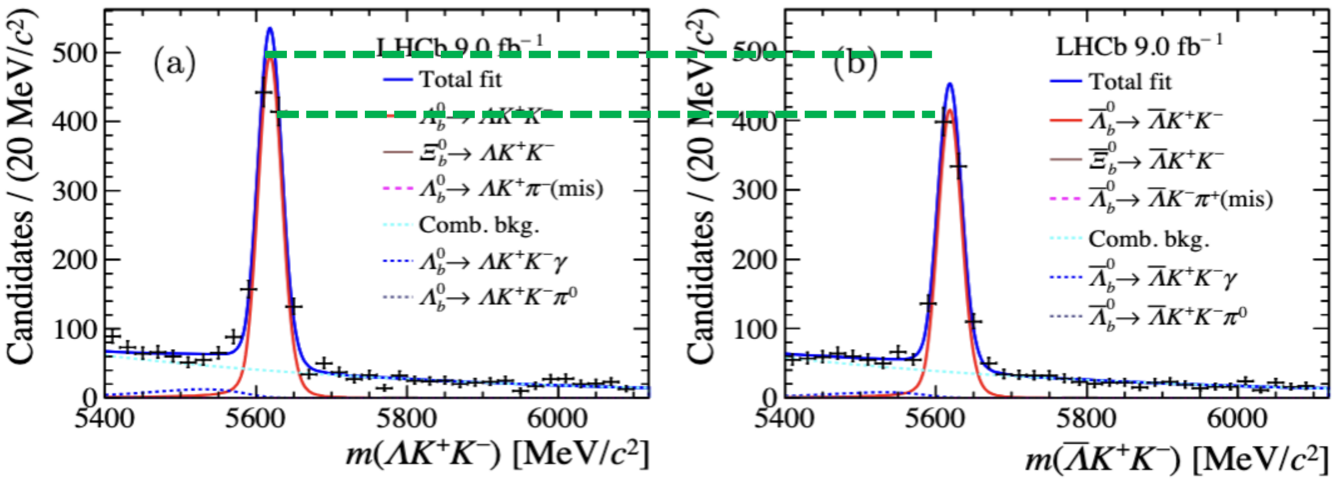


CPV observable

$$A_{CP}^{\mathrm{phy}} \equiv \frac{\Gamma(\Lambda_b \to f) - \Gamma(\bar{\Lambda}_b \to \bar{f})}{\Gamma(\Lambda_b \to f) + \Gamma(\bar{\Lambda}_b \to \bar{f})} \Rightarrow \frac{N(\Lambda_b \to f) - N(\bar{\Lambda}_b \to \bar{f})}{N(\Lambda_b \to f) + N(\bar{\Lambda}_b \to \bar{f})} \equiv A_{CP}^{\mathrm{raw}}$$

Event selection → Signal extraction

signal (DCB function)
combine background (exponential function)
partially reconstructed background
cross-feed background (DCB function)



A_{CP} measurements

Corrections

$$A_{CP}^{\mathrm{Phy}} = +A_{CP}^{\mathrm{Raw}} \cdot - A_{\mathrm{prod}} \cdot - A_{\mathrm{det}} \cdot$$

$$\sigma_{sys} \approx (\sim 0.1\%) \quad 1.8\% \quad 1.5\% \approx 2.4\%$$

$A_{CP}^{\mathrm{Phy}} = \frac{\Gamma(\Lambda_b \to f) - \Gamma(\bar{\Lambda}_b \to \bar{f})}{\Gamma(\Lambda_b \to f) + \Gamma(\bar{\Lambda}_b \to \bar{f})}$, Physical CP asymmetry

$A_{prod} = \frac{\sigma_P(\Lambda_b^0) - \sigma_P(\bar{\Lambda}_b^0)}{\sigma_P(\Lambda_b^0) + \sigma_P(\bar{\Lambda}_b^0)}$, Production asymmetry

[arxiv:1807.06544]

$A_{exp} = \frac{\epsilon_{exp}(f) - \epsilon_{exp}(\bar{f})}{\epsilon_{exp}(f) + \epsilon_{exp}(\bar{f})}$, Experimental efficiency asymmetry

[arxiv:1807.06544]

ΔA_{CP} measurements

similar topology

- $\Delta A_{CP}^{\text{Phy}} = A_{\text{Signal}}(\Lambda_b^0 \to \Lambda h^+ h'^-) - A_{\text{Control}}(\Lambda_b^0 \to \Lambda_c^+(\Lambda\pi^+)\pi^-)$

$$= \Delta A_{CP}^{\text{Raw}} \left(\equiv A_{\text{Signal}}^{\text{Raw}} - A_{\text{Control}}^{\text{Raw}}\right) - \Delta A_{\text{prod.}} - \Delta A_{\text{exp.}}$$

- **No CPV** in control mode $\Lambda_b^0 \to \Lambda_c^+(\Lambda\pi^+)\pi^-$:

$$\Delta A_{CP}^{\text{Phy}} \equiv A_{CP,\text{Signal}}^{\text{Phy}}$$

- $\Delta A_{\text{prod.}}, \Delta A_{\text{exp.}}$ helps to **reduce systematic uncertainties**

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

Results and conclusion

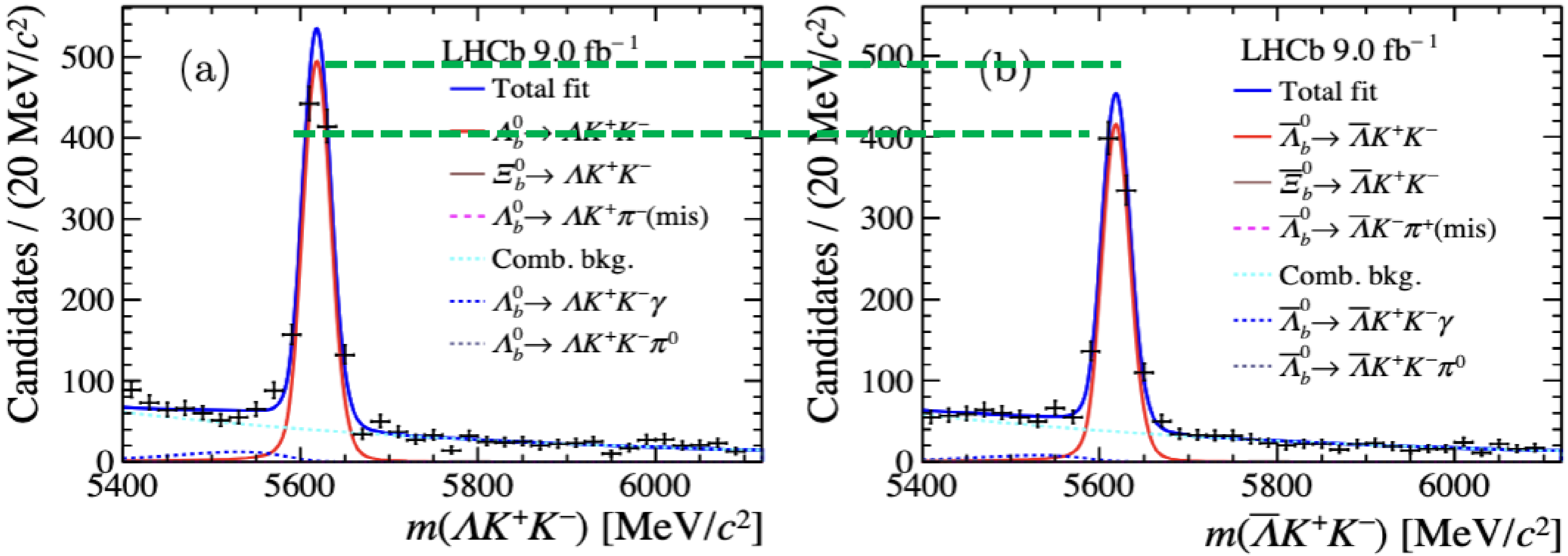
Global ΔA_{CP} measurements

$$\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda\pi^+\pi^-\right) = -0.013 \pm 0.053 \pm 0.018,$$ Significance: 0.3σ

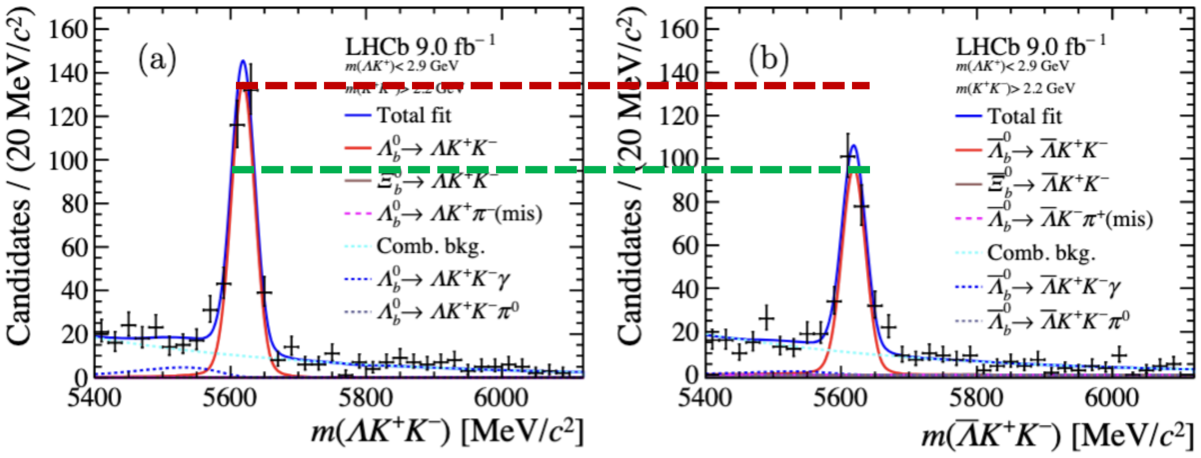
$$\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda K^+\pi^-\right) = -0.118 \pm 0.045 \pm 0.021,$$ Significance: 2.2σ

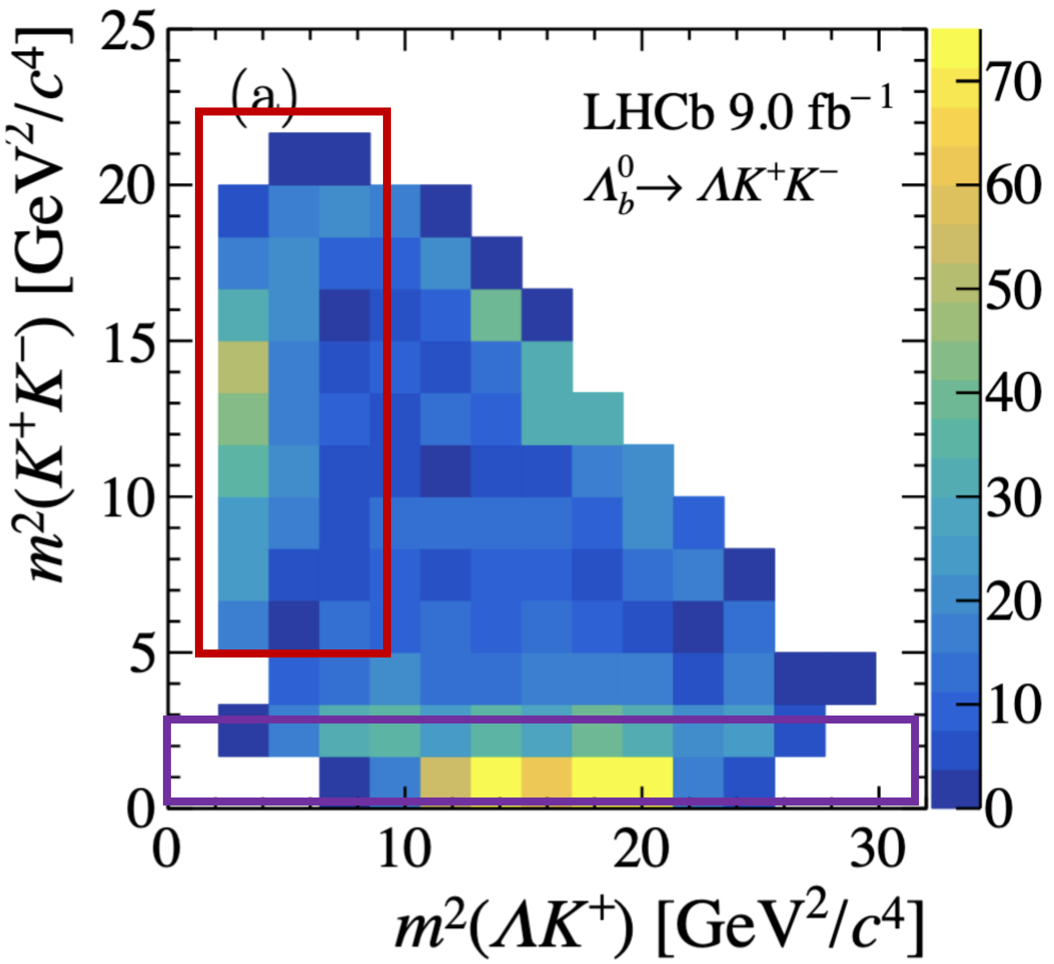
$$\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda K^+K^-\right) = 0.083 \pm 0.023 \pm 0.016$$ Significance: 3.1σ

- **First evidence for CP violation in $\Lambda_b^0 \to \Lambda K^+K^-$ decays until publishment**



Source of CP asymmetries





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

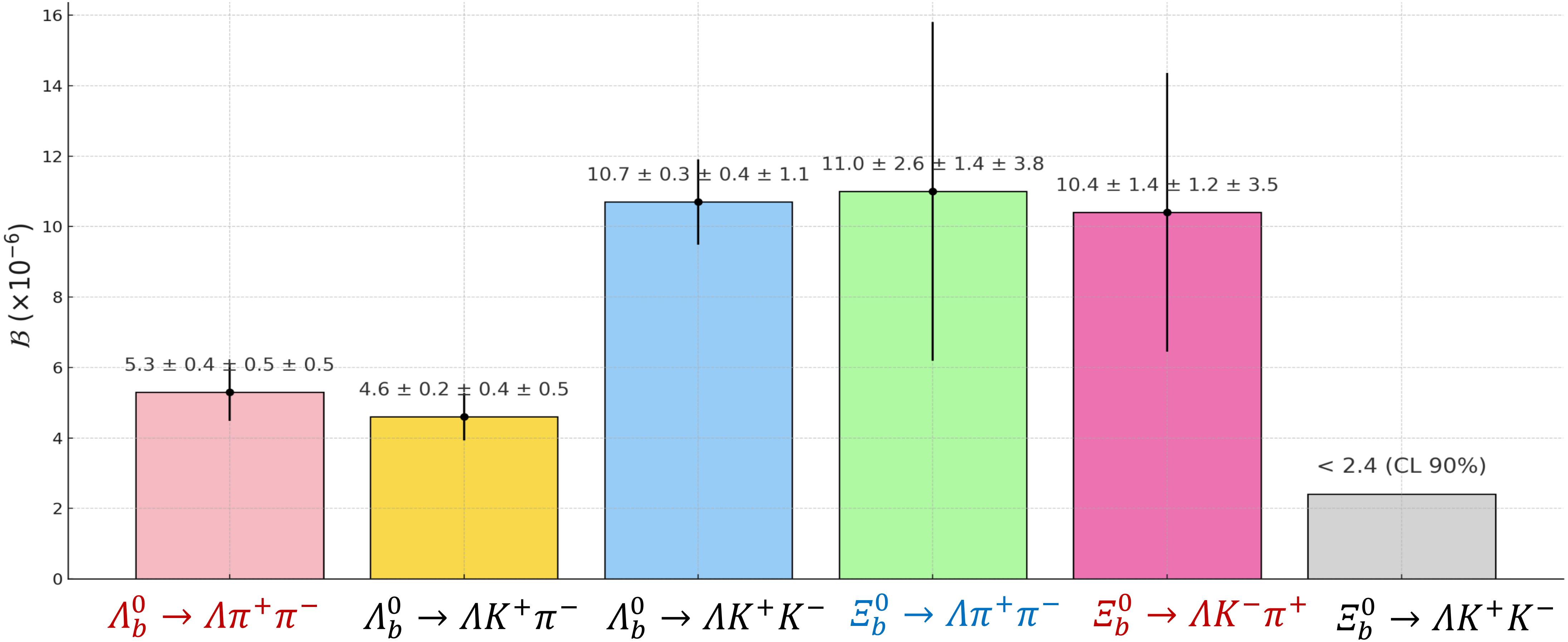
$\Delta\mathcal{A}_{CP} = 0.165 \pm 0.048 \pm 0.017$ (3.2σ)

Main source

$\Lambda_b^0 \to \Lambda\phi/f(1500)(\to K^+K^-)$ region

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

Results for Branching Fractions



First observation

First evidence

First observation of Ξ_b^0 charmless three body decays

Conclusion

- First evidence for CP violation in $\Lambda_b^0 \to \Lambda K^+ K^-$ decay mode,

  which mainly origins in the N^{*+} region.

- First observation for charmless three body Ξ_b^0 decay

$\Xi_b^0 \to \Lambda \pi^+ K^-$ and First observation of $\Lambda_b^0 \to \Lambda \pi^+ \pi^-$ decay mode.

- One solid step towards establishment of CP violation in baryons

Outlook: Stories ahead

CERN-EP-2025-031
LHCb-PAPER-2024-054
March 21, 2025

arXiv:2503.16954v1 [hep-ex] 21 Mar 2025

Observation of charge-parity symmetry breaking in baryon decays

LHCb collaboration†

Abstract

The Standard Model of particle physics, the theory of particles and interactions at the smallest scale, predicts that matter and antimatter interact differently due to violation of the combined symmetry of charge conjugation (C) and parity (P). Charge conjugation transforms particles into their antimatter particles, while the parity transformation inverts spatial coordinates. This prediction applies to both mesons, which consist of a quark and an antiquark, and baryons, which are composed of three quarks. However, despite having been discovered in various meson decays, CP violation has yet to be observed in baryons, the type of matter that makes up the observable Universe. This article reports a study of the decay of the beauty baryon Λ_b^0 to the $pK^-\pi^+\pi^-$ final state and its CP-conjugated process, using data collected by the LHCb (Large Hadron Collider beauty) experiment at CERN. The results reveal significant asymmetries between the decay rates of the Λ_b^0 baryon and its CP-conjugated antibaryon, marking the first observation of CP violation in baryon decays, thus demonstrating the different behaviour of baryons and antibaryons. In the Standard Model, CP violation arises from the Cabibbo–Kobayashi–Maskawa mechanism, while new forces or particles beyond the Standard Model could provide additional contributions. This discovery opens a new path to search for physics beyond the Standard Model.

Submitted to Nature

First observation baryon CP violation in $\Lambda_b^0 \to pK\pi^+\pi^-$

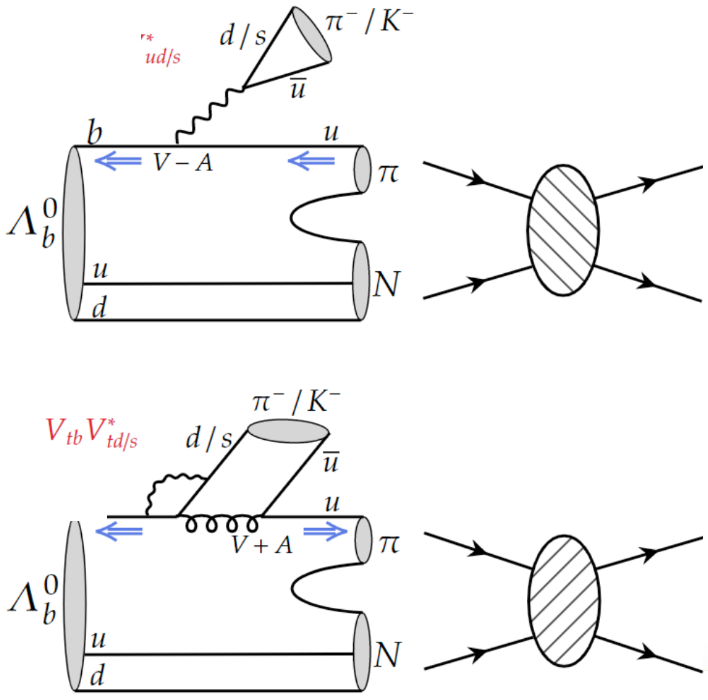
What's coming next?

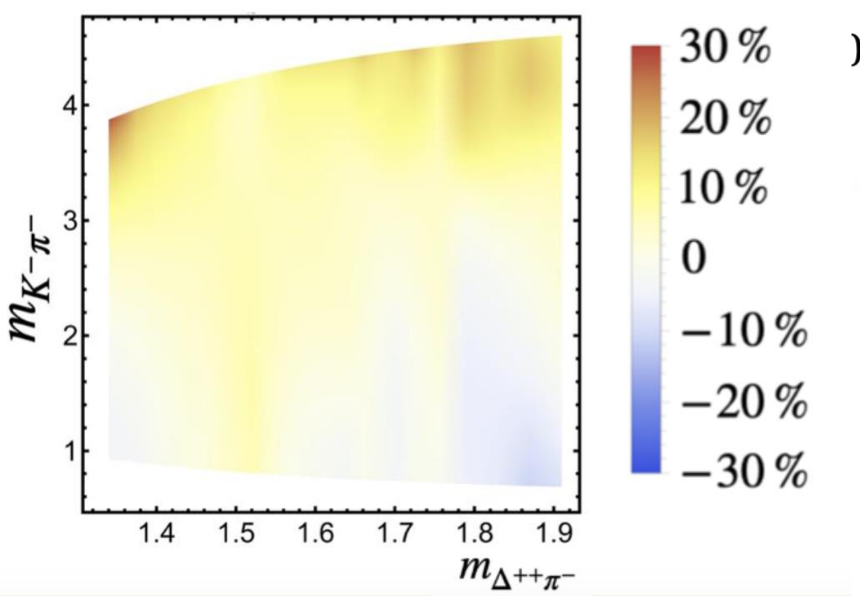
- More data with Run3/4/5…
- New questions will be raised

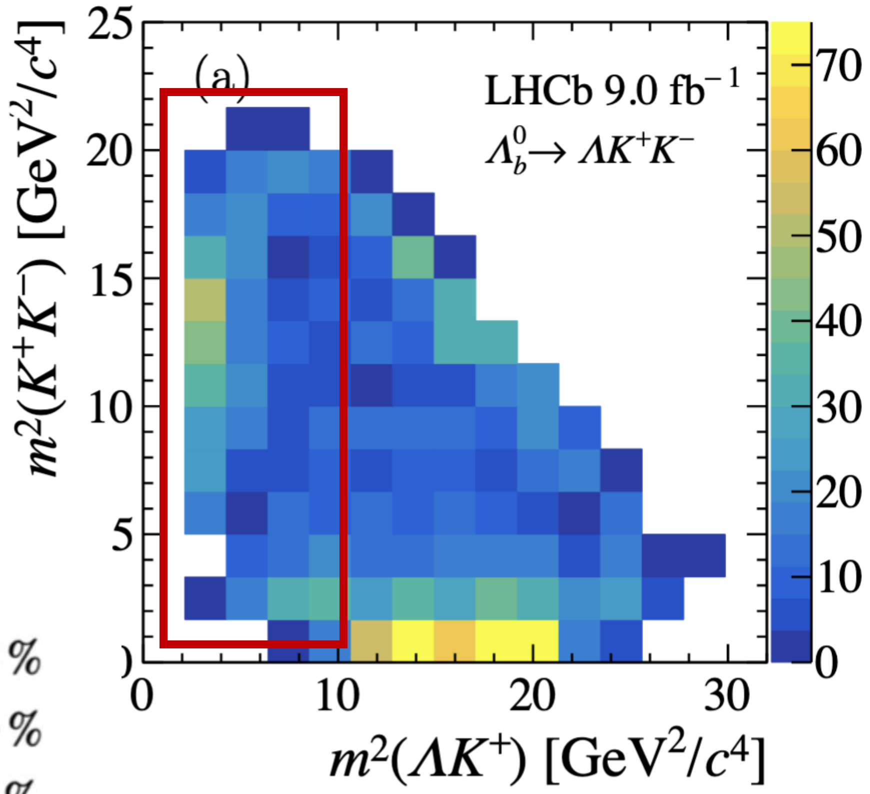
Discussion

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

$\Delta\mathcal{A}_{CP} = 0.165 \pm 0.048 \pm 0.017$ (3.2σ)







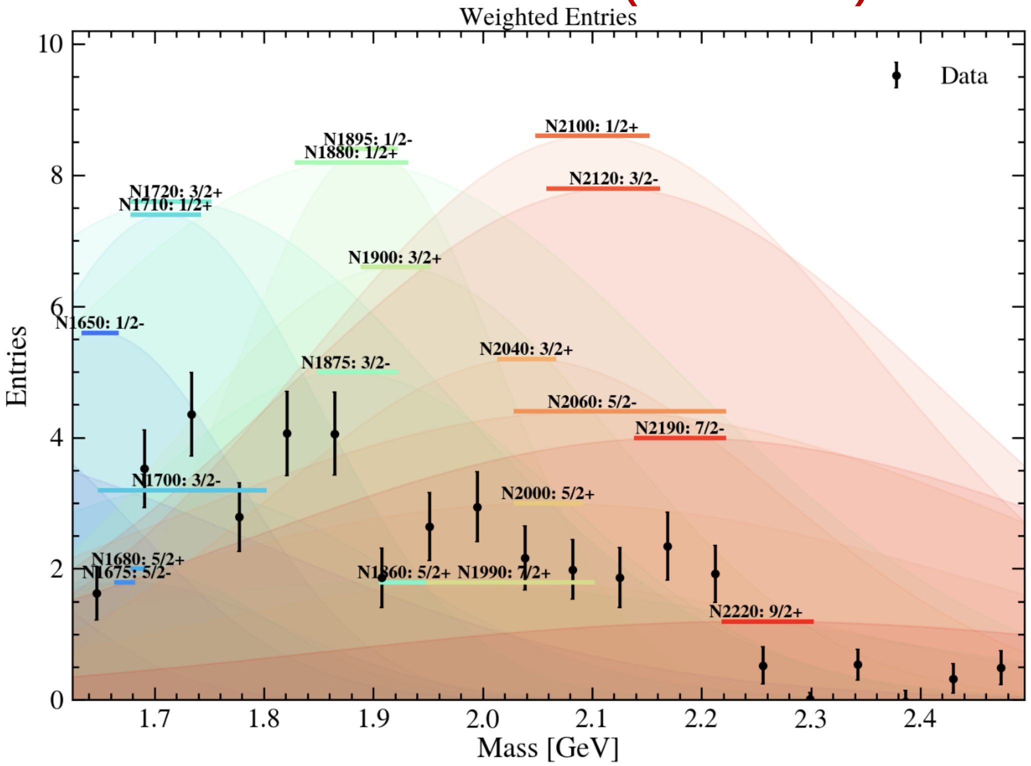
CP violation ~10% expected in specific phase space.

[CPC.48.101001]

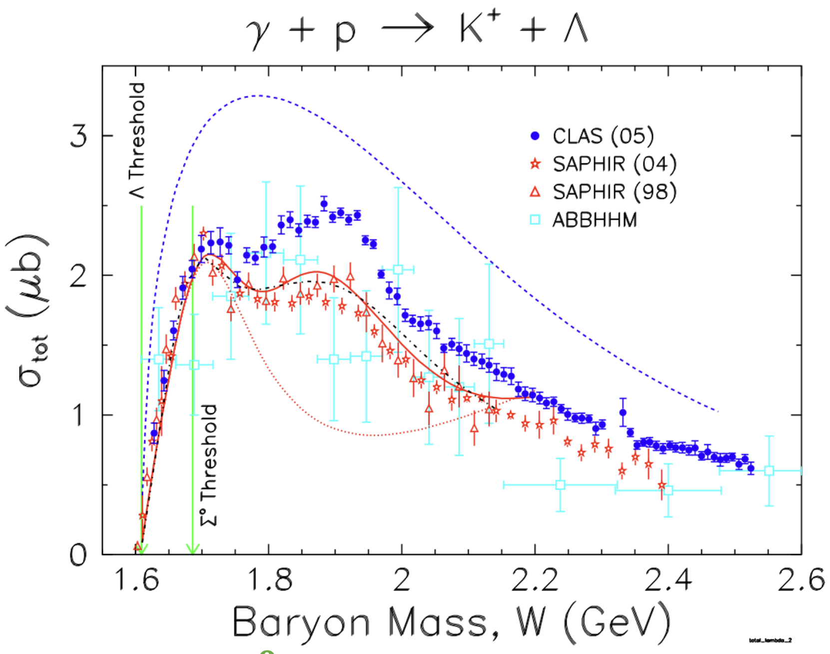
Discussion

- Pinning down CPV sources in $\Lambda_b \to N^*(\to \Lambda K^+)K^-$
  - ➢ Amplitude analysis
- Entangled N^{*+} contributions: **scattering data**?

Mass & width illustrations (from PDG)



$\gamma p \to \Lambda K^+$ scattering process



$\pi^- p \to \Lambda K^0$ scattering process

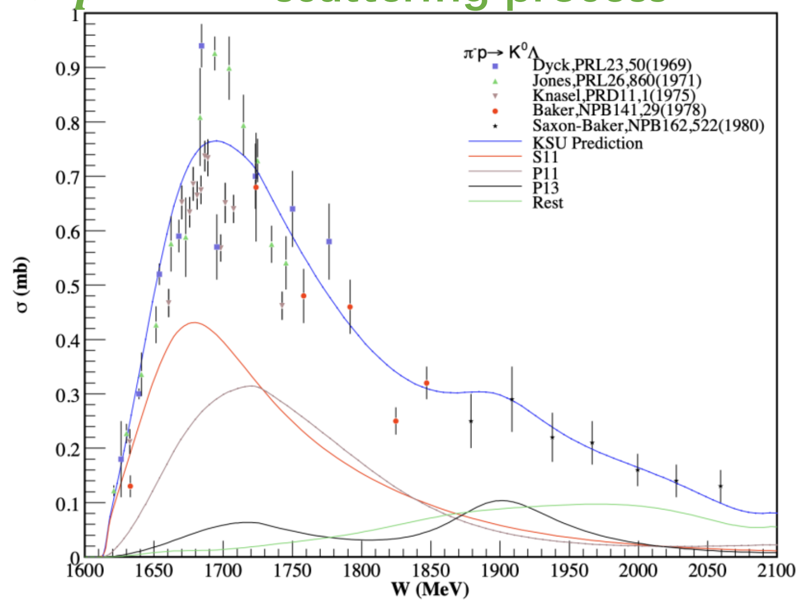
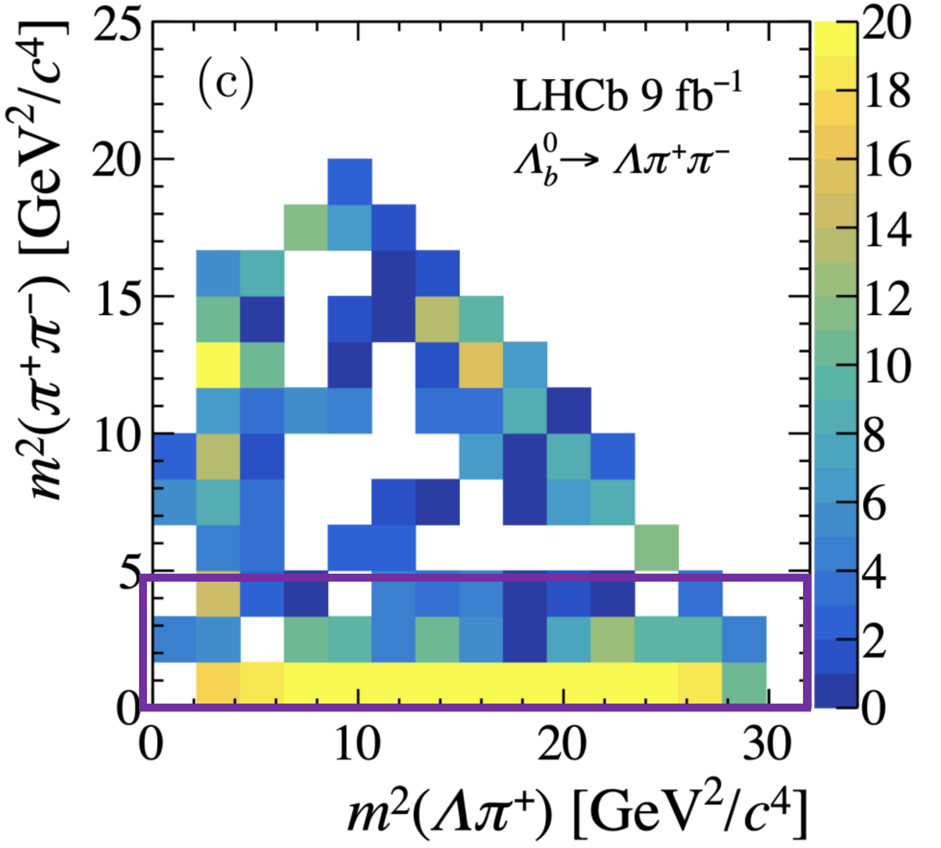


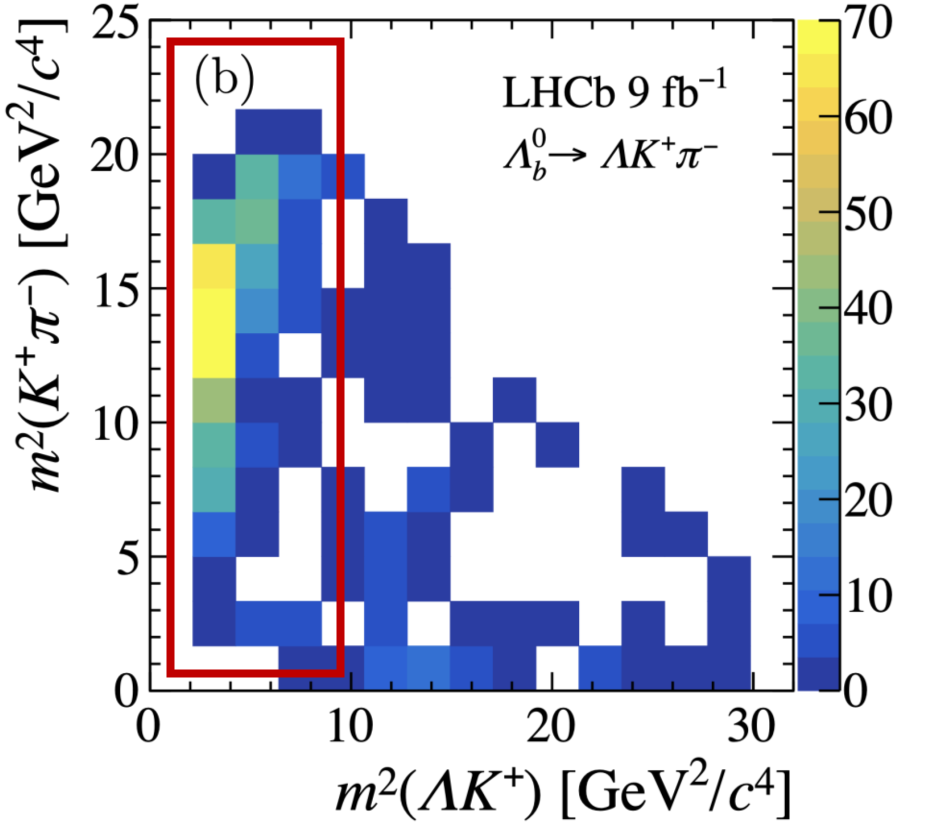
FIG. 5. Predictions of integrated cross sections of $\pi^- p \to \eta n$ and $\pi^- p \to K^0\Lambda$.

Thanks for your attention!

Back up

Source of CP asymmetries (Continue)





$\Lambda_b^0 \to \Lambda f_2/f_0(\to \pi^+\pi^-)$ region

$\Delta\mathcal{A}_{CP} = 0.088 \pm 0.069 \pm 0.021 (1.2\sigma)$

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

$\Delta\mathcal{A}_{CP} = -0.078 \pm 0.051 \pm 0.027\ (1.4\sigma)$

Small contribution from $\Lambda_b^0 \to \Lambda K^*$

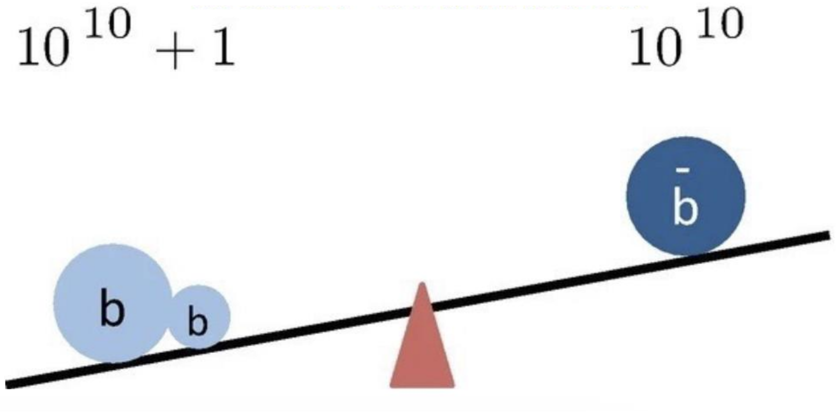
Matter and antimatter asymmetries

- Visible world dominated by matter
- Cosmic Microwave Background indicate large matter-antimatter asymmetry in universe

$$\eta = \frac{n_B}{n_\gamma} \sim 10^{-10}$$

After inflation
Matter = antimatter

Today
Matter dominated



Sakharov conditions: CP violation required

Motivations (Experimental)

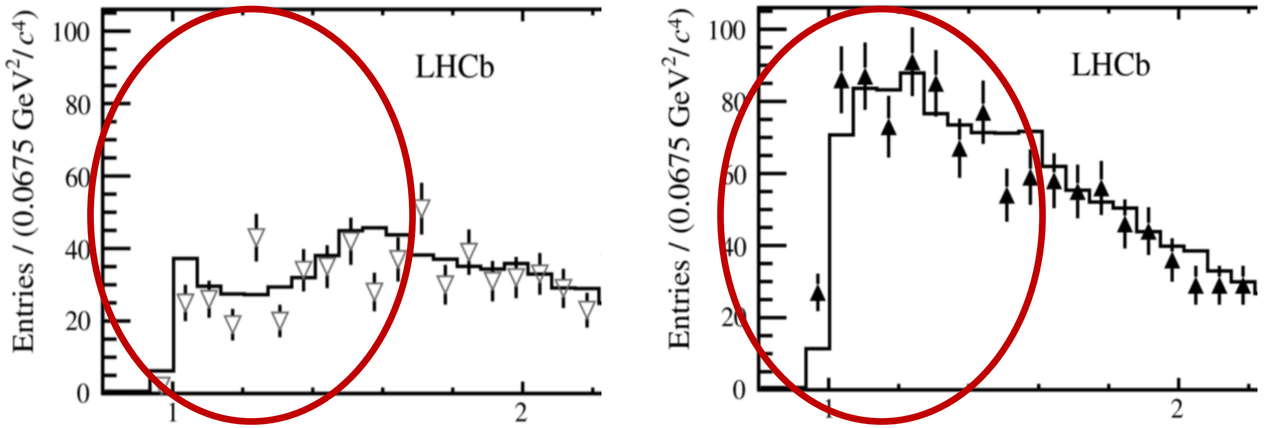
$\Lambda_b^0 \to \Lambda K^+ K^-$
$\Lambda_b^0 \to \Lambda K^+ \pi^-$
$\Lambda_b^0 \to \Lambda \pi^+ \pi^-$

CP asymmetries in charmless b baryon decays

b meson decays: $B^+ \to h^+ h^+ h^-$

Significant CP asymmetries observed in localized bins

[LHCb, PRL 123.231802]



b baryon decays: $\Lambda_b^0 \to \Lambda h^+ h'^-$

?

Great opportunity for CPV in baryon decays

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 (200 events per bin)

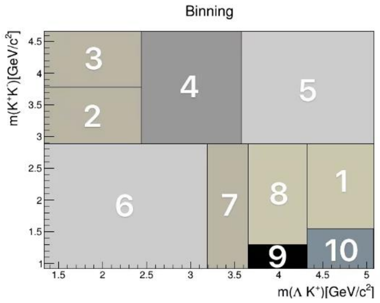
$\Lambda_b^0 \to \Lambda K^+ K^-$ 10 :

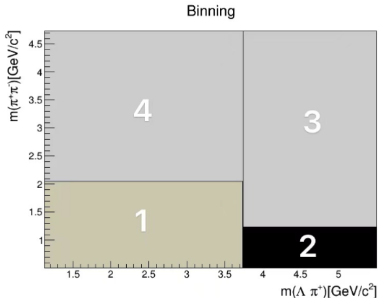
$\Lambda_b^0 \to \Lambda K^+ \pi^-$ 4 :

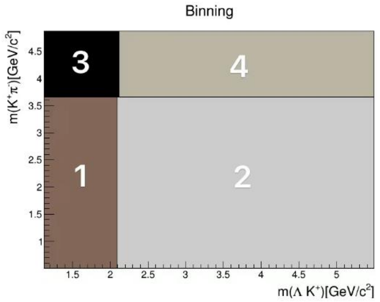
$\Lambda_b^0 \to \Lambda \pi^+ \pi^-$ 4 :

only measures in three Λ_b^0 decays

Demonstration of Binning Scheme







A_{CP} results in adaptive binning scheme

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

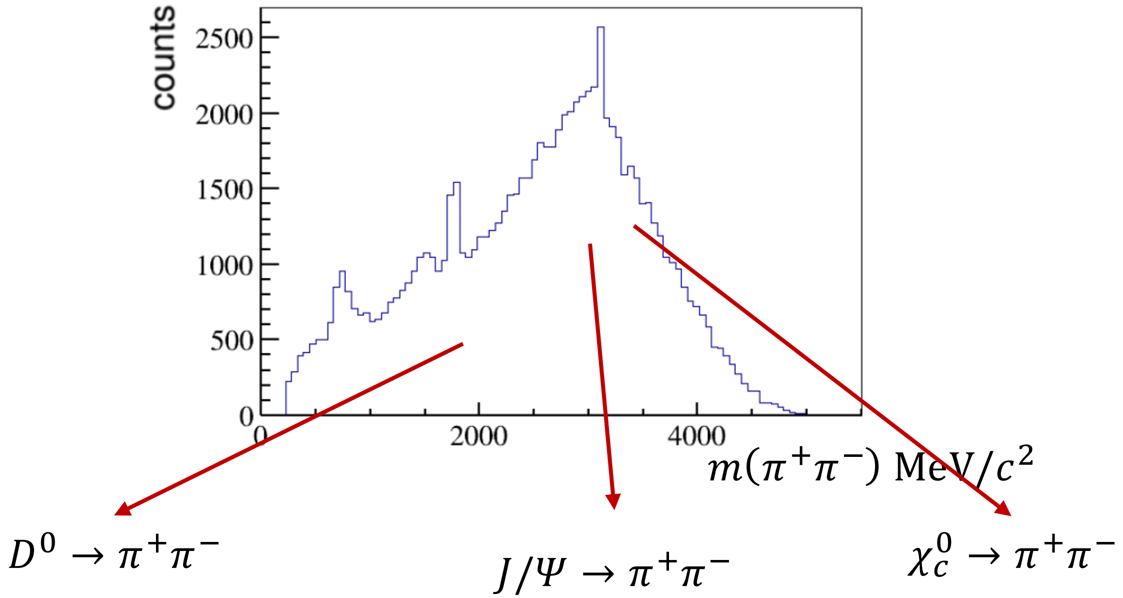
No significant CP asymmetries observed

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 $\Lambda_b^0 \to \Lambda\pi^+\pi^-$ before mass veto



Signal extraction

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

Λ_b^0 decays ~ 1000 events
Ξ_b^0 decays ~ 100 events

Yields and significance:
(using Wilks' theorem)

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

Efficiencies

Total efficiency is calculated with:

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

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: sweight of data

Production asymmetry

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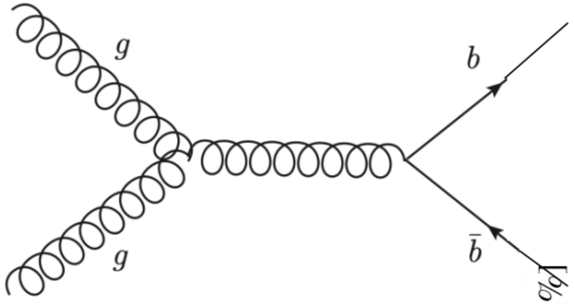
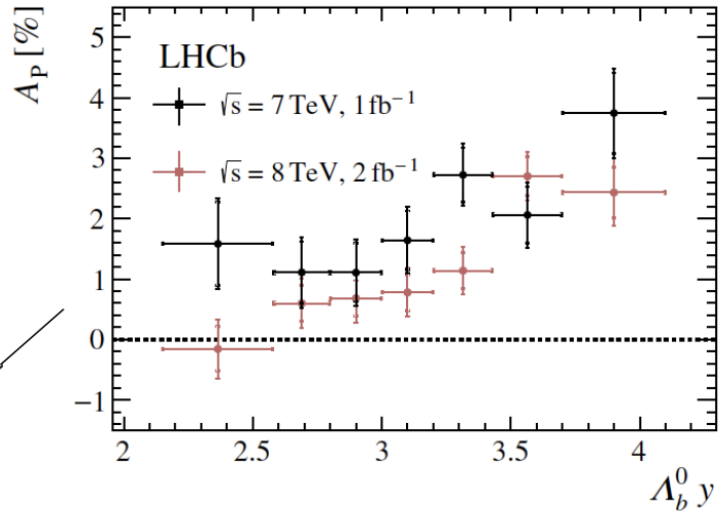
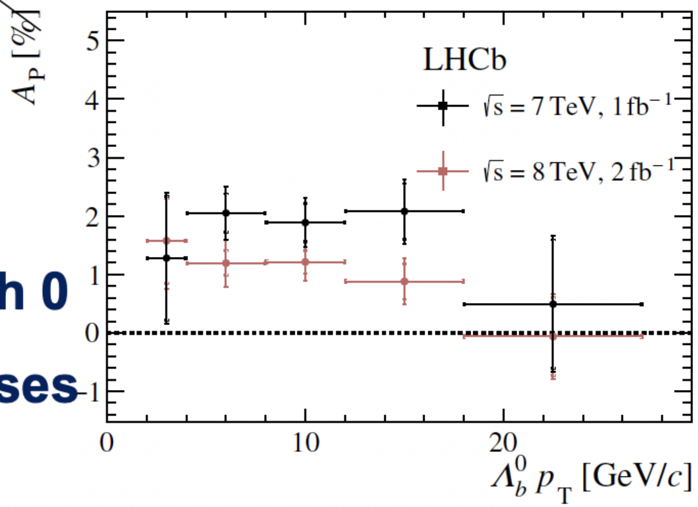
$$A_{\mathrm{P}}^{\Lambda_b^0} = \frac{\sigma(pp \to \Lambda_b^0) - \sigma(pp \to \overline{\Lambda}_b^0)}{\sigma(pp \to \Lambda_b^0) + \sigma(pp \to \overline{\Lambda}_b^0)}$$

- **Production asymmetry of $b\overline{b}$, dominated by gg fusion**
- **Hadronization asymmetry of Λ_b^0 and $\overline{\Lambda}_b^0$ in pp collisions**







- **A_P : 1~2% , measured by LHCb as a function of y, p_T**
- **$\Delta A_P \sim 0.2\%$, with uncertainties around 0.2%: consistent with 0**
- **A_P: Only Run 1 measured, Run2 (expected to be smaller) uses Run1 measurements**

Detection asymmetry

$$A_D^f = \frac{\epsilon(f) - \epsilon(\bar{f})}{\epsilon(f) + \epsilon(\bar{f})}$$

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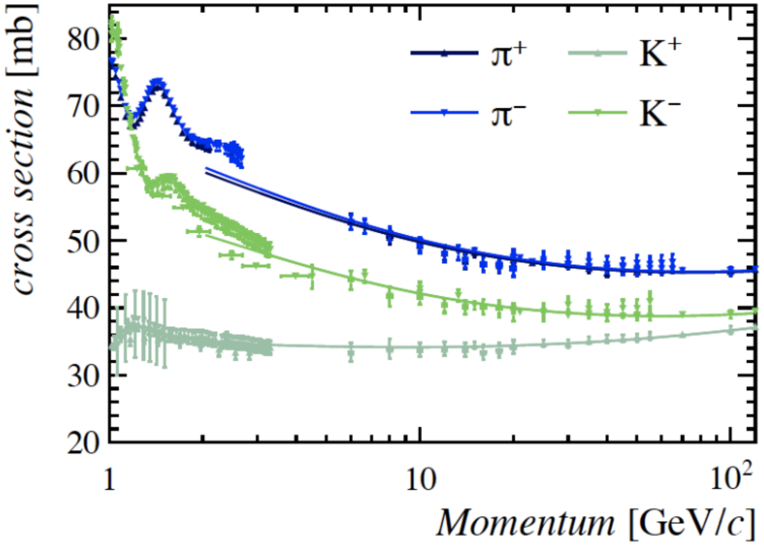


- **Matter, antimatter interact with detector (made by matter) differently**
- f: **different combinations of** p, K, π **etc.**
- **Including effects from reconstruction of particles, PID, trigger effects;** $A_D^h = A_{Rec}^h + A_{Tri}^h + A_{PID}^h, h = K, \pi, p$

- **Obtained using data-driven method with calibration channels**

$A_D(\pi^{\pm}) \approx 0.1\%, A_D(K^{\pm}) \approx 1\%, A_D(p/\overline{p}) \approx 1 - 2\%$ → ΔA_D: ~1%

Significantly reduced using control channel

CPV observable

$$A_{CP}^{\mathrm{phy}} \equiv \frac{\Gamma(\Lambda_b \to f) - \Gamma(\bar{\Lambda}_b \to \bar{f})}{\Gamma(\Lambda_b \to f) + \Gamma(\bar{\Lambda}_b \to \bar{f})} \Rightarrow \frac{N(\Lambda_b \to f) - N(\bar{\Lambda}_b \to \bar{f})}{N(\Lambda_b \to f) + N(\bar{\Lambda}_b \to \bar{f})} \equiv A_{CP}^{\mathrm{raw}}$$

Experimental effects

$$A_{\mathrm{P}}^{\Lambda_b^0} = \frac{\sigma(\Lambda_b^0) - \sigma(\bar{\Lambda}_b^0)}{\sigma(\Lambda_b^0) + \sigma(\bar{\Lambda}_b^0)}$$

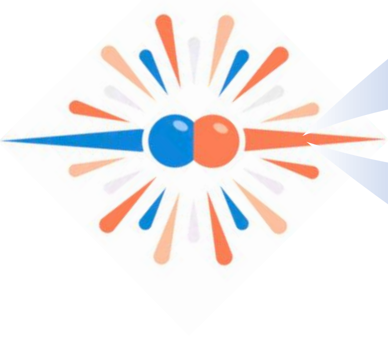
Production asymmetry

$$A_{\mathrm{D}}^{f} = \frac{\epsilon(f) - \epsilon(\bar{f})}{\epsilon(f) + \epsilon(\bar{f})}$$

Detection asymmetry

Measurements of A_{CP}

p-p collision



Λ_b^0 production: N^+_{prod} × Λ_b^0decay → $\Lambda h^+ h'^-$: Γ^+/Γ_{tot} × Detection $\Lambda h^+ h'^-$: ϵ^+_{exp} = N^+_{sig} (Λ_b^0)

$\bar{\Lambda}_b^0$ production: N^-_{prod} × $\bar{\Lambda}_b^0$decay → $\Lambda h^+ h'^-$: $\Gamma^-/\bar{\Gamma}_{tot}$ × Detection $\Lambda h^+ h'^-$: ϵ^-_{exp} = N^-_{sig} ($\bar{\Lambda}_b^0$)

$$A_{prod} = \frac{N^+_{prod} - N^-_{prod}}{N^+_{prod} + N^-_{prod}} \qquad A_{CP} = \frac{\Gamma^+/\Gamma_{tot} - \Gamma^-/\bar{\Gamma}_{tot}}{\Gamma^+/\Gamma_{tot} + \Gamma^-/\bar{\Gamma}_{tot}} \qquad A_{exp} = \frac{\epsilon^+_{exp} - \epsilon^-_{exp}}{\epsilon^+_{exp} + \epsilon^-_{exp}} \qquad A_{sig} = \frac{N^+_{sig} - N^-_{sig}}{N^+_{sig} + N^-_{sig}}$$

$$A_{prod} + A_{CP} + A_{exp} \approx A_{raw}$$

$$A_{CP} = +A_{sig}. \quad - A_{prod}. \quad - A_{exp}.$$

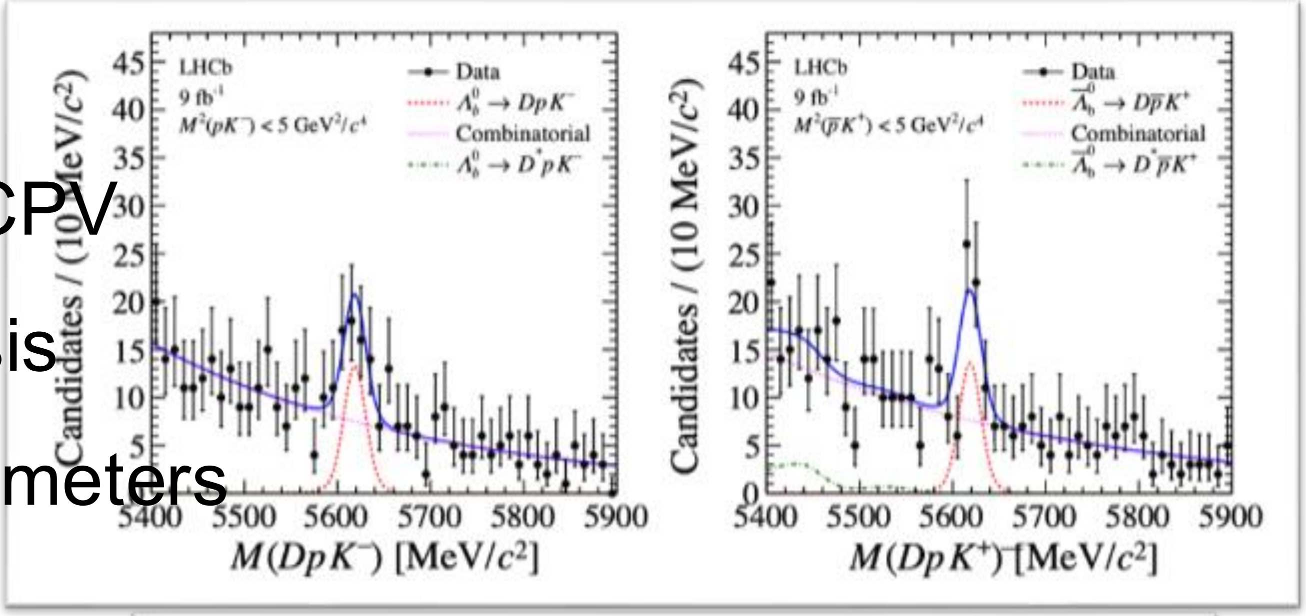
$$\sigma_{sys} \approx \quad (\sim 0.1\%) \quad 1.8\% \quad 1.5\% \approx \quad 2.4\%$$

Larger/close to statistical uncertainties

Motivation

$$A_{CP}^{pK^-} = (-1.1 \pm 0.7 \pm 0.4)\%,$$
$$A_{CP}^{p\pi^-} = (\ \ 0.2 \pm 0.8 \pm 0.4)\%,$$

- **No observation** in Λ_b^0 two-body decays
- **Three (or more) body** decays may provide more insight:
  - Phase-space dependent **strong-phase** & **resonant contributions**
- **LHCb has explored**:
  - $\Lambda_b \to pD^0K^-, pK_S^0\pi^-$ ... direct CPV
  - $\Xi_b \to pK^-K^-$ amplitude analysis
  - $\Lambda_b \to \Lambda_c(\to \Lambda h^+)h^-$ decay parameters



$$A = 0.12 \pm 0.09(\mathrm{stat})^{+0.02}_{-0.03}(\mathrm{syst}).$$

Motivation

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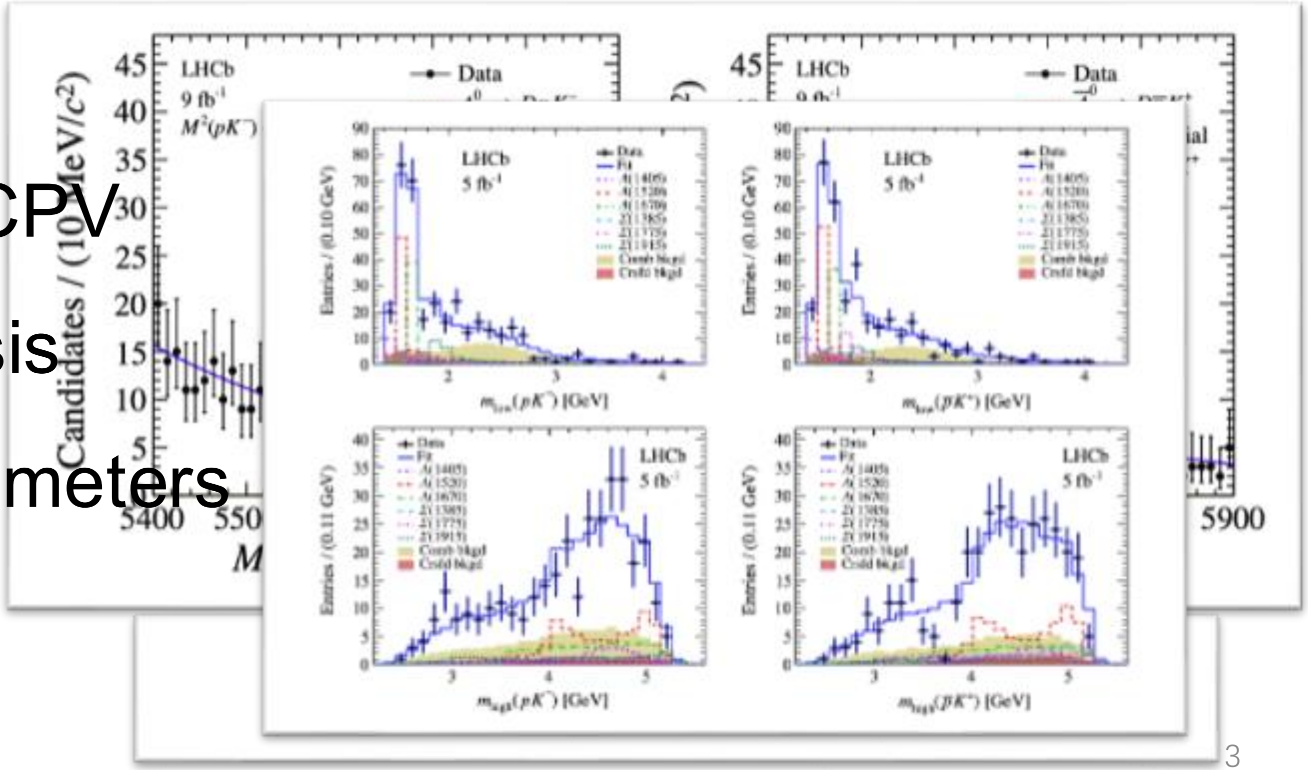

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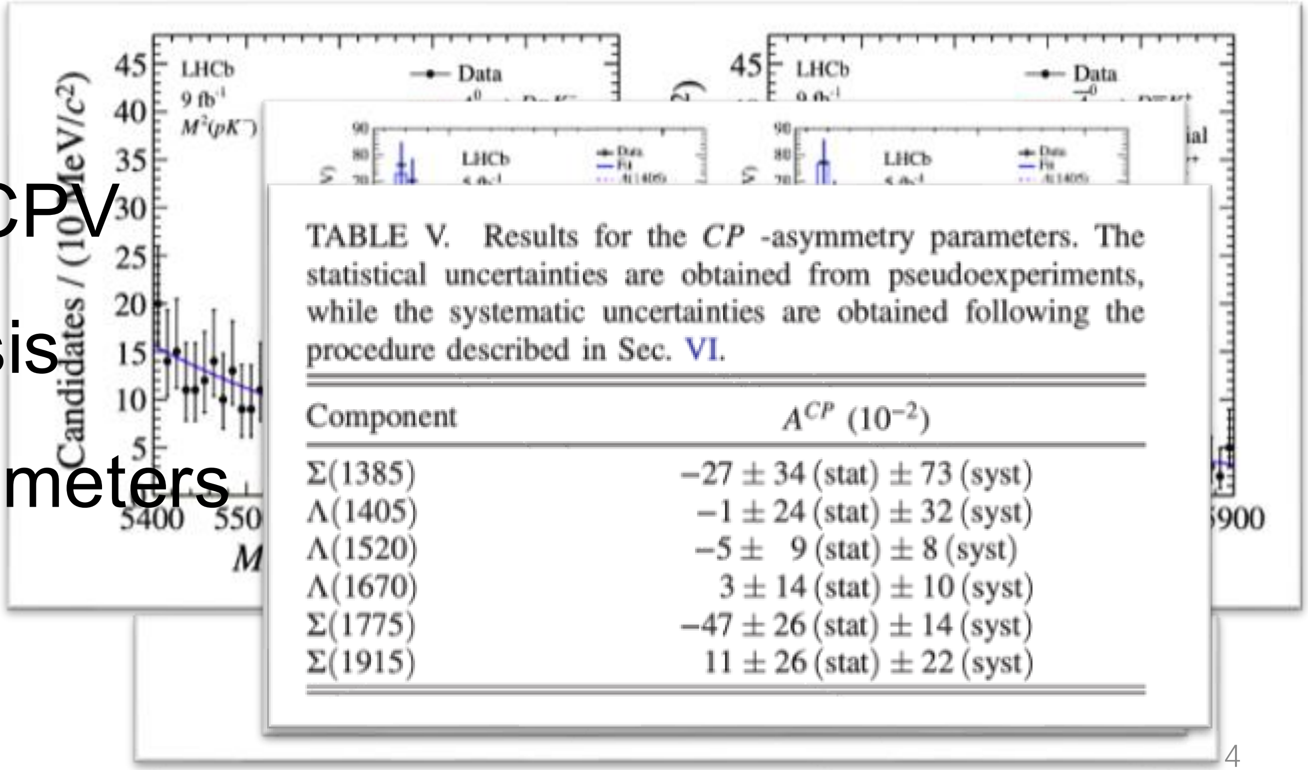

TABLE V. Results for the CP -asymmetry parameters. The statistical uncertainties are obtained from pseudoexperiments, while the systematic uncertainties are obtained following the procedure described in Sec. VI.

Component	A^{CP} (10^{-2})
Σ(1385)	-27 ± 34 (stat) ± 73 (syst)
Λ(1405)	-1 ± 24 (stat) ± 32 (syst)
Λ(1520)	-5 ± 9 (stat) ± 8 (syst)
Λ(1670)	3 ± 14 (stat) ± 10 (syst)
Σ(1775)	-47 ± 26 (stat) ± 14 (syst)
Σ(1915)	11 ± 26 (stat) ± 22 (syst)

Motivation

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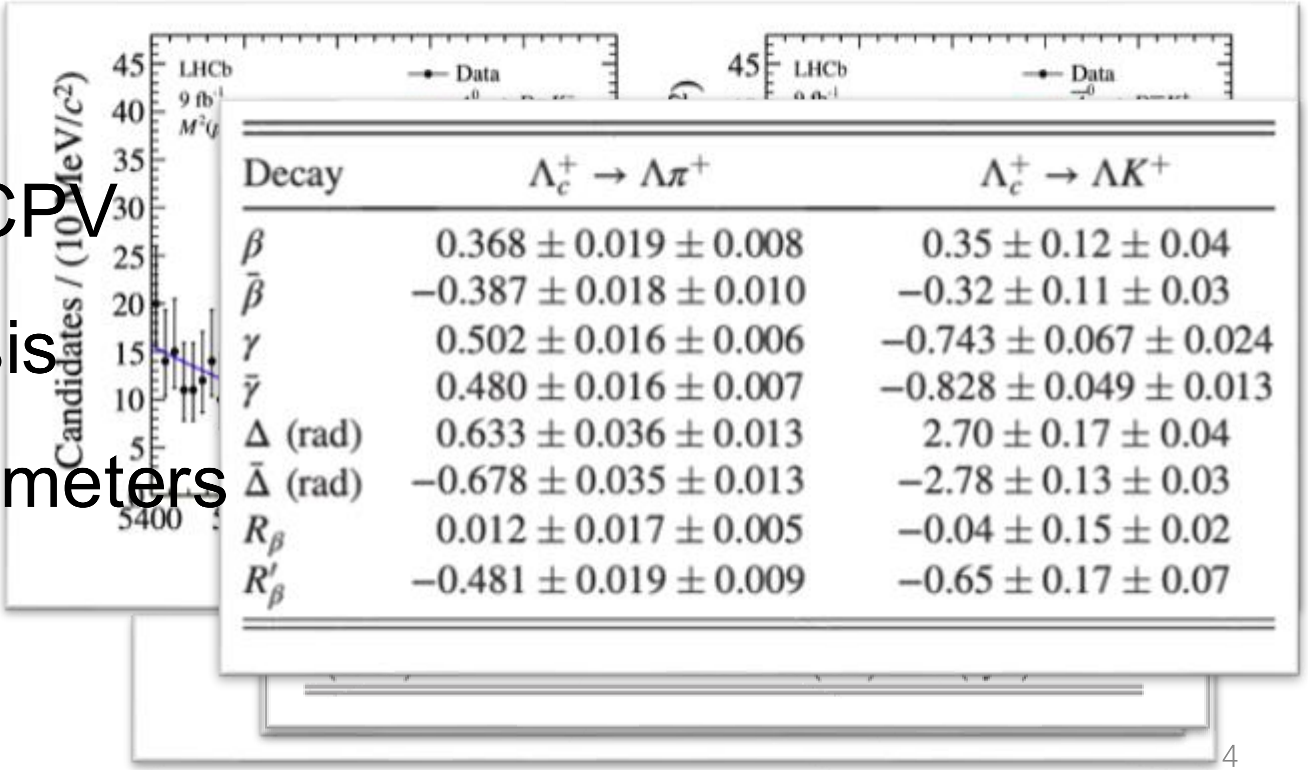

Decay	$\Lambda_c^+ \to \Lambda\pi^+$	$\Lambda_c^+ \to \Lambda K^+$
β	$0.368 \pm 0.019 \pm 0.008$	$0.35 \pm 0.12 \pm 0.04$
$\bar{\beta}$	$-0.387 \pm 0.018 \pm 0.010$	$-0.32 \pm 0.11 \pm 0.03$
γ	$0.502 \pm 0.016 \pm 0.006$	$-0.743 \pm 0.067 \pm 0.024$
$\bar{\gamma}$	$0.480 \pm 0.016 \pm 0.007$	$-0.828 \pm 0.049 \pm 0.013$
Δ (rad)	$0.633 \pm 0.036 \pm 0.013$	$2.70 \pm 0.17 \pm 0.04$
$\bar{\Delta}$ (rad)	$-0.678 \pm 0.035 \pm 0.013$	$-2.78 \pm 0.13 \pm 0.03$
R_β	$0.012 \pm 0.017 \pm 0.005$	$-0.04 \pm 0.15 \pm 0.02$
R'_β	$-0.481 \pm 0.019 \pm 0.009$	$-0.65 \pm 0.17 \pm 0.07$