Evidence for CP violation in $\Lambda_b^0 \to \Lambda h^+ h^-$ decays at the LHCb experiment

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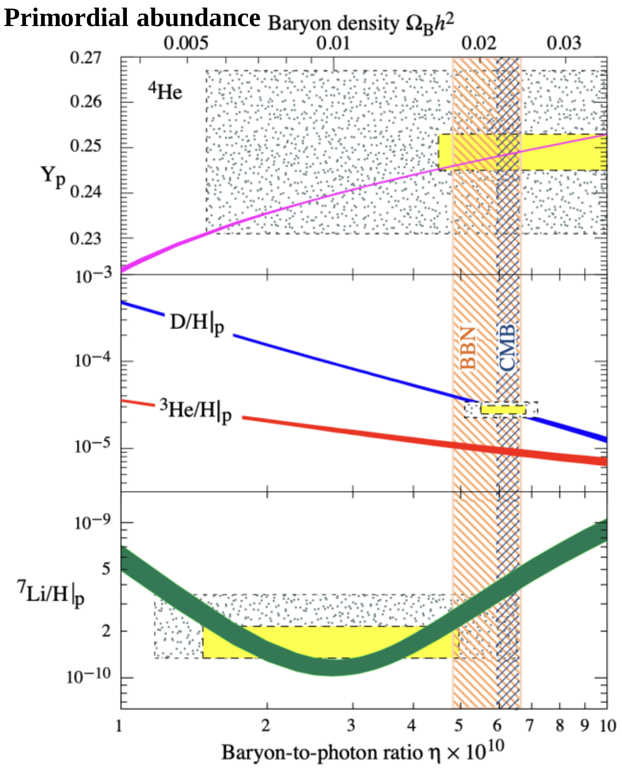
On behalf of the LHCb Collaboration

LHC Seminar, CERN, 2024/11/05

Outline of the talk

- Introduction
- New CP violation measurements from $\Lambda_b^0 \to \Lambda h^+ h'^-$ decays
- New CP violation measurements from $\Lambda_b^0 \to p h^-$ decays
- Prospects and conclusion

Matter and antimatter asymmetry



PLB667 (2008) 1

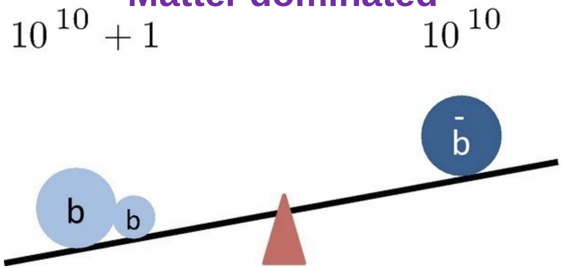
- "Visible" world dominated by matter
- Big-Bang Nucleosynthesis and Cosmic Microwave Background all indicate large matter-antimatter asymmetry in Universe:

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

- No yet fully understood:

After inflation
Matter = Antimatter

Today
Matter dominated



EW Baryogenesis

PRL 55 (1985) 1039
CKMfitter

- Sakharov conditions: CP violation need
- In SM, offered by CKM matrix

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim \frac{n_B}{n_\gamma} \sim \frac{J \times P_u \times P_d}{M^{12}}$$

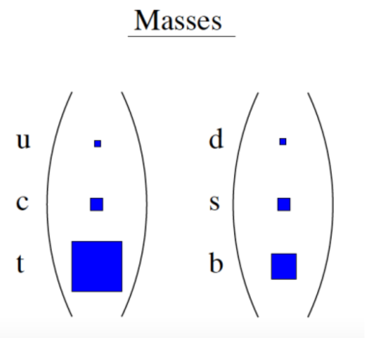
EW Scale:
M~100 GeV

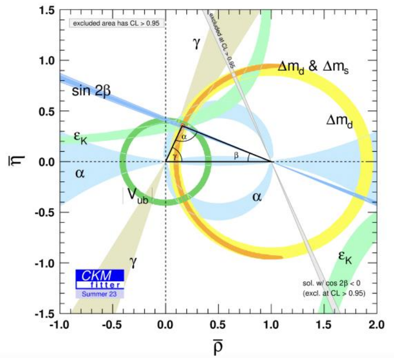
Jarlskog invariant:

$$P_u = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)$$

$$P_d = (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)$$

$$J \sim 3 \times 10^{-5}$$





Far smaller than observed matter antimatter asymmetry in Universe

Need new mechanism

$$10^{-17} \ll 10^{-10}$$

EW Baryogenesis

PRL 55 (1985) 1039
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- Sakharov conditions: CP violation need
- In SM, offered by CKM matrix

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim \frac{n_B}{n_\gamma} \sim \frac{J \times P_u \times P_d}{M^{12}}$$

EW Scale:
$M \sim 100$ GeV

$$P_u = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)$$
$$P_d = (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)$$

Jarlskog invariant:
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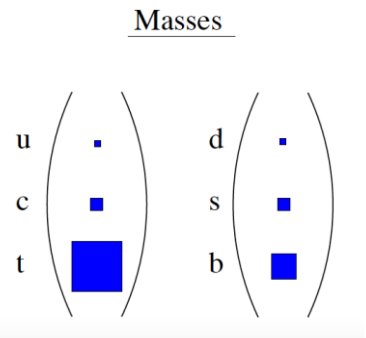
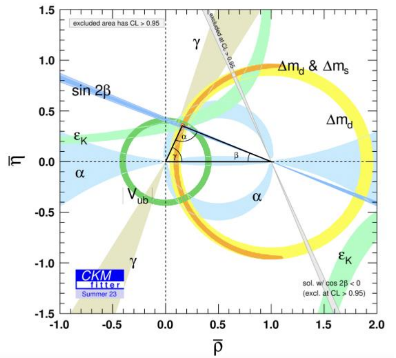




Far smaller than observed matter antimatter asymmetry in Universe

Need new mechanism

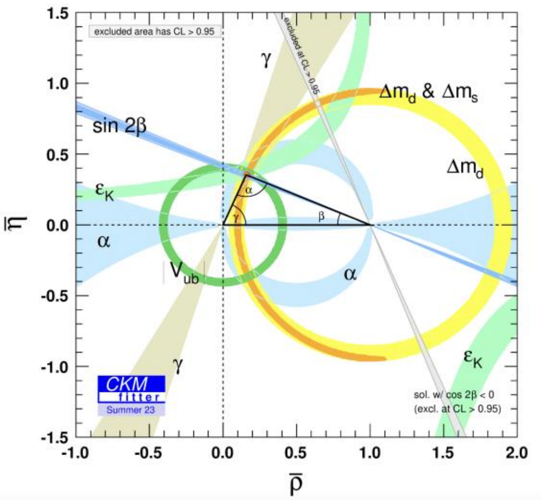
$$10^{-17} \ll 10^{-10}$$

Very rich CP violation phenomena

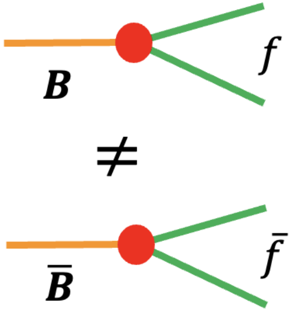
Do we understand all?

CP violation types

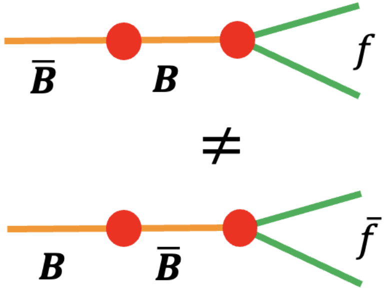
PRL124 (2020) 031801
PRD101 (2020) 012006



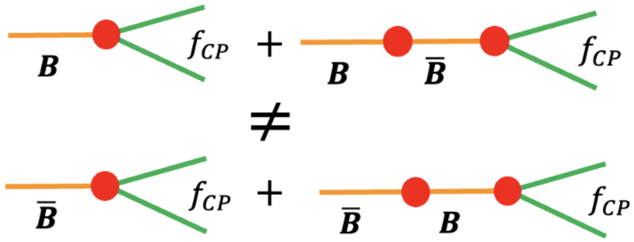
Direct CP violation



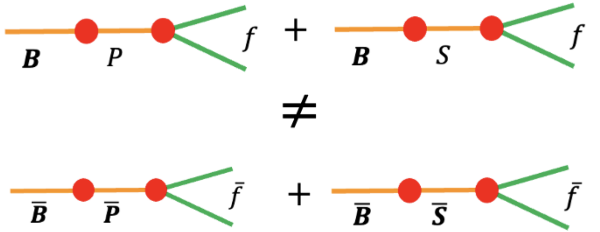
CP violation in mixing



CP violation in interference between mixing and decay



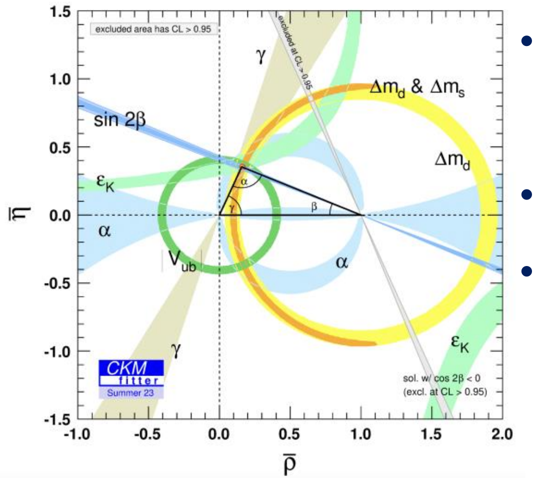
CP violation from S- and P-wave interference



We continue to discover new types of CP violation

CP violation in baryon decays not yet discovered

1964	1999	2001	2004	2012	2013	2018	2019	????
CP violation (in mixing) in neutral Kaon decays	Direct CP violation in neutral Kaon decays	CP violation in mixing and decay in B^0 decays	Direct CP violation in B^0 decays	Direct CP violation in B^+ decays	Direct CP violation in B_s^0 decays	CP violation in mixing and decay in B_s^0 decays	Direct CP violation in D^0 decays	**Direct CP violation in baryon decays**

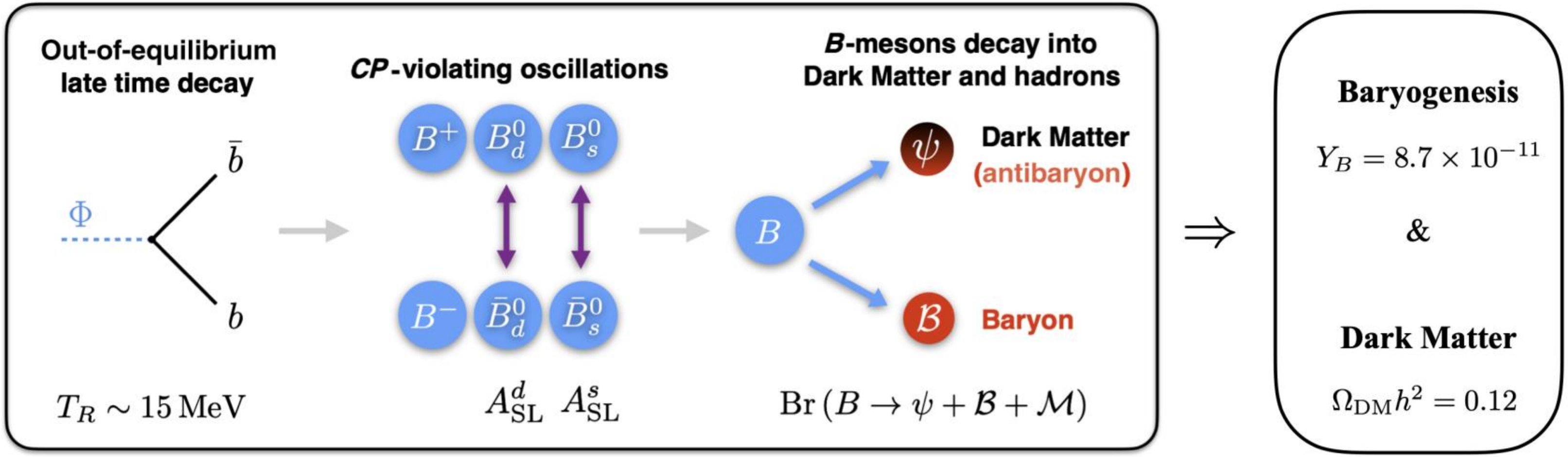


- **60 years after discovery of CP violation, strikingly, not yet found in baryon decays**
- **Will it be SM or not, we don't know**
- **Discover it not only rich our understanding, but also provide new mechanism for generating matter antimatter asymmetry**

B-mesogenesis

PRD104 (2021) 035028

- **SM CP violation phenomenon may also lead to baryogenesis**



Operates at very low temperatures

$$\Gamma(B^0_{(s)} \to \bar{B}^0_{(s)}) \neq \Gamma(\bar{B}^0_{(s)} \to B^0_{(s)})$$

$\mathrm{Br}(B \to \text{baryon} + \text{dark matter}) > 10^{-4}$

$\mathrm{Br}(\text{b baryon} \to \text{meson} + \text{dark matter}) > 10^{-4}$

CP violation in baryon decays, new possibilities?

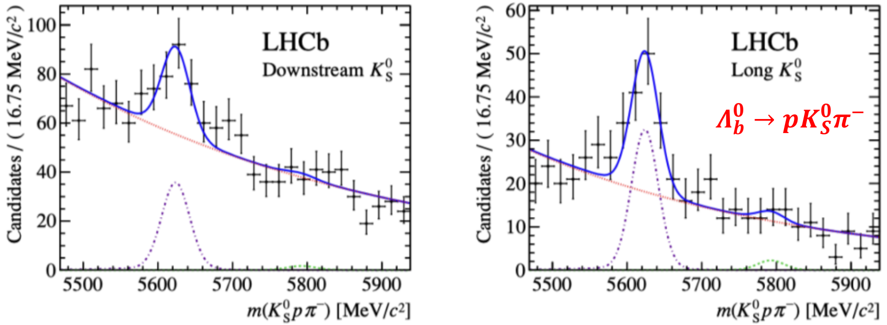
Generate matter antimatter asymmetry

Methods to search for CP violation

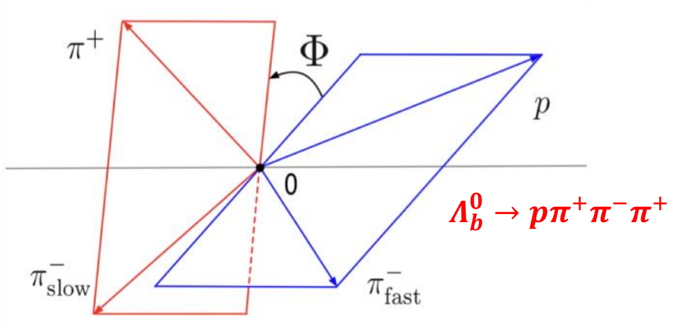
JHEP04(2014)087
PRD108(2023)L011101
PRL133 (2024) 101902
Nature Phys.13(2017)391

- **Many methods have been explored to search for CP violation in baryon decays**

Direct CP violation ($\propto \sin(\Delta\delta_{ST})\sin(\Delta\phi_{EW})$)

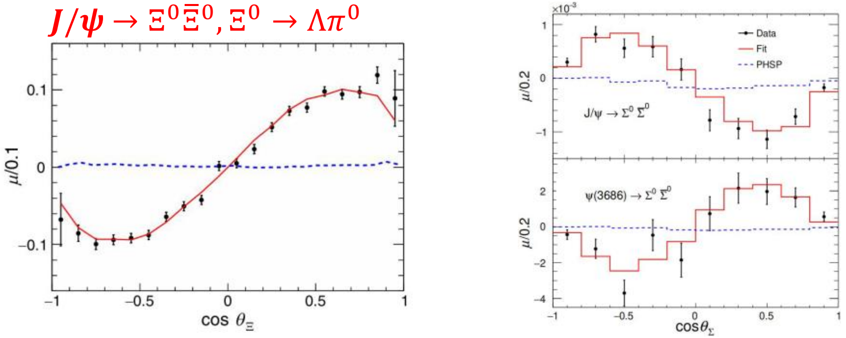


Triple-product asymmetry ($\propto \cos(\Delta\delta_{ST})\sin(\Delta\phi_{EW})$)



Decay parameters asymmetry

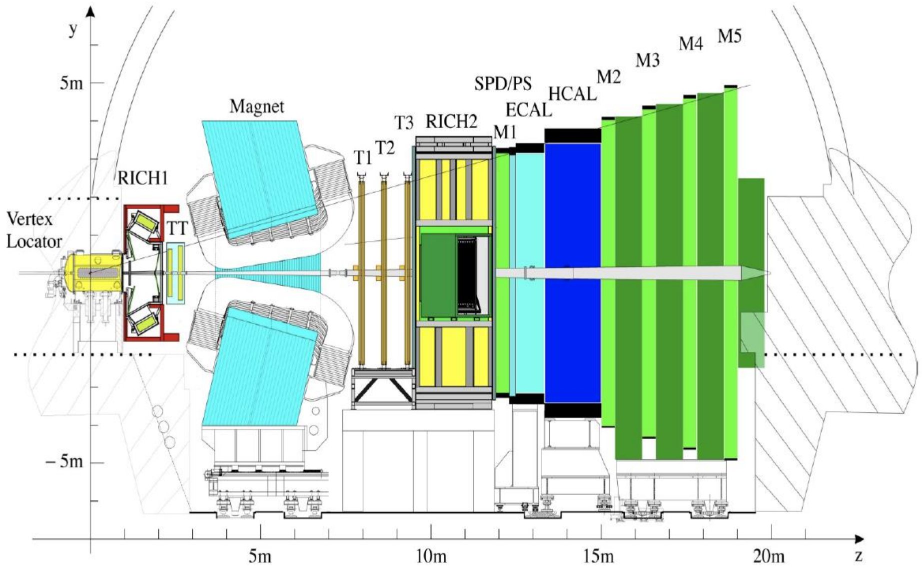
$J/\psi \to \Xi^0\bar{\Xi}^0, \Xi^0 \to \Lambda\pi^0$

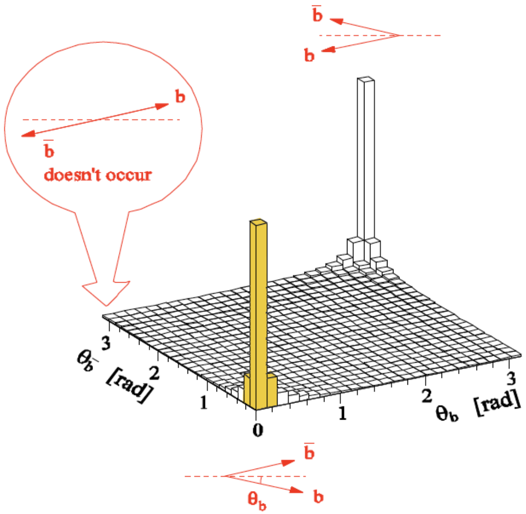


- **Important to investigate phase space dependence (amplitude analysis, binned method, energy test etc.)**
- **CPV: b baryon $\mathcal{O}(1\% - 10\%)$, c baryon $\mathcal{O}(0.1\%)$, hyperon $\mathcal{O}(0.001\% - 0.01\%)$**
- **LHCb: massive production of b baryons!**

The LHCb detector (Run 1+2)

2008 JINST 3 S08005





Excellent vertex and IP, decay time resolution:

- $\sigma(\mathrm{IP}) \approx 20\ \mu\mathrm{m}$ for high-p_T tracks
- $\sigma(\tau) \approx 45$ fs for $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^-\pi^+$ decays

Very good momentum resolution:

- $\delta p/p \approx 0.5\% - 1\%$ for $p \in (0{,}200)$ GeV
- $\sigma(m_B) \approx 24$ MeV for two-body decays

Hadron and Muon identification

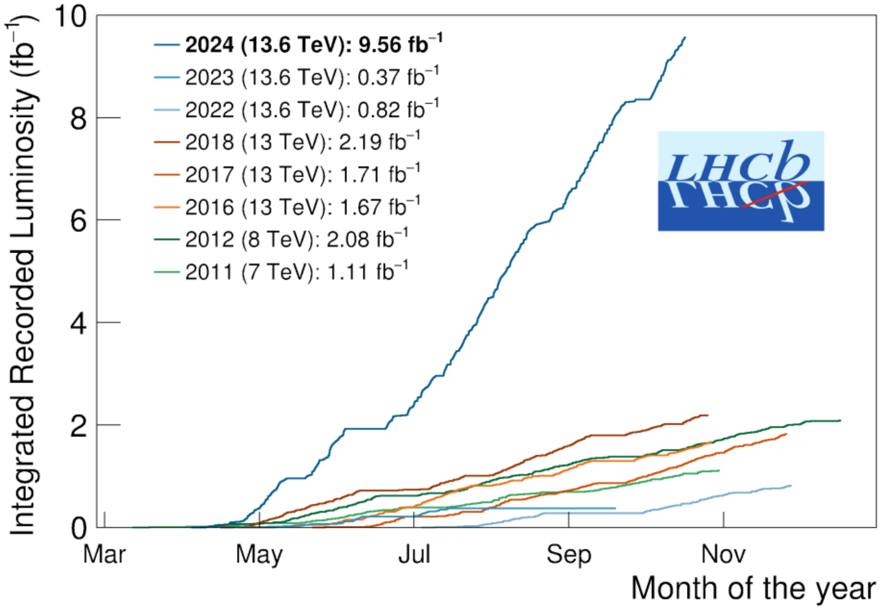
- $\epsilon_{K\to K} \approx 95\%$ for $\epsilon_{\pi\to K} \approx 5\%$ up to 100 GeV
- $\epsilon_{\mu\to\mu} \approx 97\%$ for $\epsilon_{\pi\to\mu} \approx 1-3\%$

Data good for analyses

- $> 99\%$

Designed for CP violation and heavy flavor studies

The LHCb status



- Run 1:
  - 2011 (7 TeV): 1 fb^{-1}
  - 2012 (8 TeV): 2 fb^{-1}
- Run 2:
  - 2015-2018 (13 TeV): 6 fb^{-1}
- **Run 3:**
  - **2024 alone (13.6 TeV): 9.56 fb^{-1}**

- **A new LHCb detector for Run 3 operates at $\times$ 5 higher instantaneous luminosity**
- **Similar performance, while efficiency for hadron final states increased by a factor of 2**

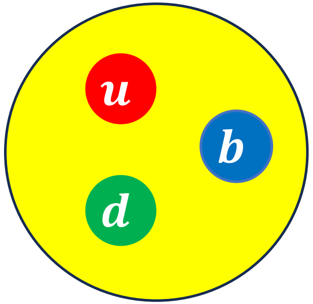
What we have from LHCb?

UPDATED!

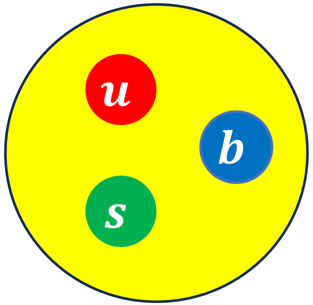
Decays	Data	Methods	Reference
$\Lambda_b^0 \to ph^-$	3 fb^{-1}	A_{CP}	PLB787 (2018) 124
$\Lambda_b^0 \to pK_S^0\pi^-$	1 fb^{-1}	A_{CP}	JHEP04 (2014) 087
$\Lambda_b^0 \to \Lambda K^+\pi^-, \Lambda K^+K^-$	3 fb^{-1}	A_{CP}	JHEP05 (2016) 081
$\Xi_b^0 \to pK^-K^-$	5 fb^{-1}	Amplitude analysis	PRD104 (2021) 052010
$\Lambda_b^0 \to J/\psi p\pi^-, J/\psi pK^-$	3 fb^{-1}	A_{CP}	JHEP07 (2014) 103
$\Lambda_b^0 \to DpK^-$, ADS	9 fb^{-1}	A_{CP}	PRD104 (2021) 112008
$\Lambda_b^0, \Xi_b^0 \to p3h$	3 fb^{-1}	A_{CP}	EPJC79 (2019) 745
$\Lambda_b^0, \Xi_b^0 \to p3h$	3 fb^{-1}	TPA	Nature Phys. 13 (2017) 391 JHEP08 (2018) 039
$\Lambda_b^0 \to p3\pi$	6.6 fb^{-1}	TPA, energy test	PRD102 (2020) 051101

Many attempts from LHCb already, we continue to explore the fundamental question

Λ_b^0



Ξ_b^0



$\mathrm{J^P} = \frac{1}{2}^+$

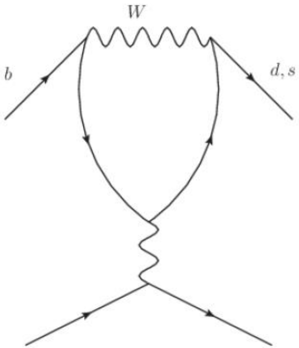
Studies of $\Lambda_b^0(\Xi_b^0) \to \Lambda h^+ h'^-$ decays

Branching fraction and A_{CP} measurments

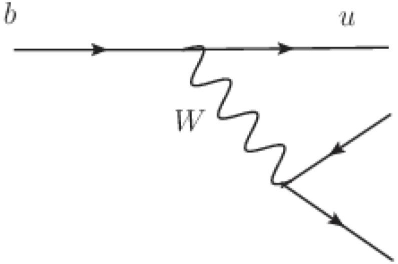
Charmless three-body *b* decays

PRL124 (2020) 031801
PRD101 (2020) 012006

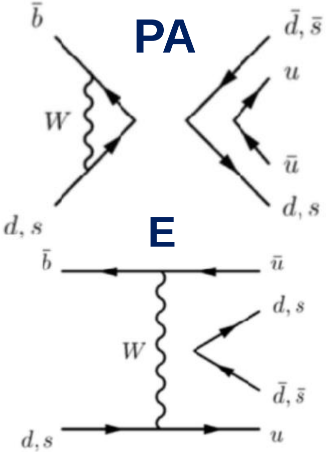
$|V_{td}|e^{i\beta}$ or $-|V_{ts}|e^{-i\beta_s}$



$|V_{ub}|e^{-i\gamma}$



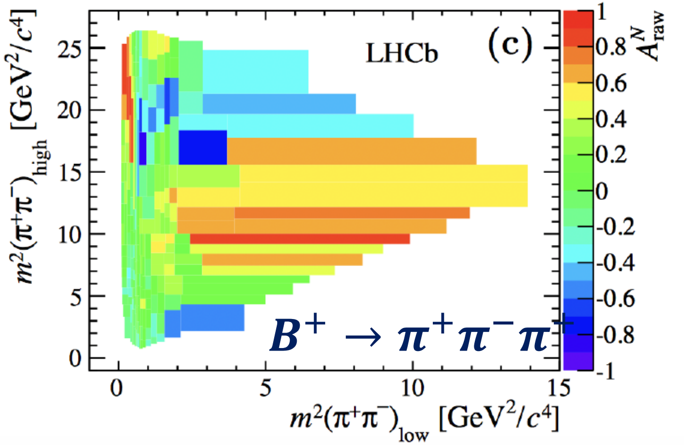
+



Similar level of amplitudes from penguin and tree diagrams and different weak phases

Can generate large CP violation

- **Charmless *b* decays, ideal to search for CP violation**
- **Multi-body *b* decays, complex CP violation pattern seen previously**
- **CP violation as large as 80%**
- **Interesting to search in $\Lambda_b^0 \to \Lambda h^+ h'^-$ decays and look into phase space**



Branching fraction measurements

LHCb-PAPER-2024-043

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

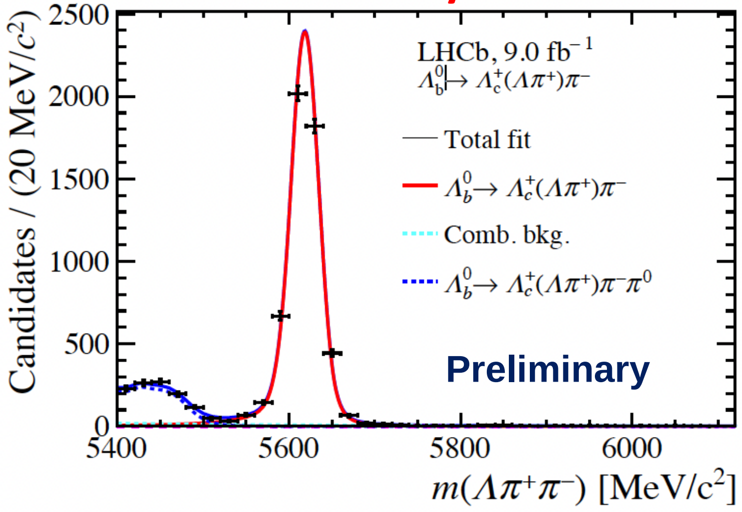
- Branching fraction (in addition to A_{CP}) offers important information to the internal dynamics
- In LHCb, we measure w.r.t. control channels (relative branching fraction)
- Control channel $\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-$ used to reduce systematic uncertainties in both branching fraction and A_{CP} measurements

Yields extraction

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

- Yields extracted from invariant mass fit:
  - Signal: two Crystal Ball function, tail parameters from simulation
  - Combinatorial background: exponential function
  - Partially reconstructed background: threshold function convolved with resolution
  - Cross-feed background: shape fixed from simulation

Control channel yield: ~5200



Efficiency and fragmentation fraction

LHCb-PAPER-2024-043
PRD99 (2019) 052006

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

- Efficiencies determined from simulation with corrections using data-driven methods
  - Particle ID, trigger, tracking : using control channels from $D^{*+}\to D^0(\to K^-\pi^+)\pi^+$ etc.
  - Dalitz plot corrections: difference on Dalitz plot distribution between data and simulation
- Fragmentation fraction $\frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}}$ $\begin{cases} (6.7\pm0.5\pm0.5\pm2.0)\times10^{-2} & \text{@ 7, 8 TeV} \\ (8.2\pm0.7\pm0.6\pm2.5)\times10^{-2} & \text{@ 13 TeV} \end{cases}$

Fragmentation fraction of Ξ_b^- used assuming Isospin symmetry

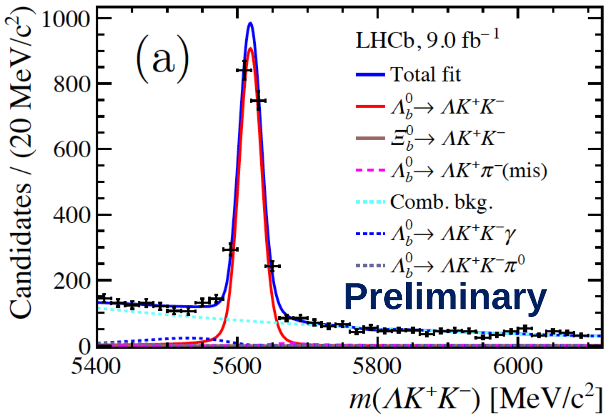
Signal channel ($\Lambda_b^0 \to \Lambda K^+ K^-$)

LHCb-PAPER-2024-043

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

Optimized using significance F.O.M.

$$N_S/(\sqrt{N_S + N_B})$$



$\Lambda K^+ K^-$

Signal yield: $N = 1920 \pm 50$

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

stat. sys. control channel

- **Predictions rather limited, only for quasi two-body processes;**
- **Mainly on $\Lambda_b^0 \to \Lambda V$ processes, e.g. $\Lambda_b^0 \to \Lambda\phi$**
  - QCDF：6.3×10^{-6} arXiv:1803.01297
  - GFA: 1.7×10^{-6} arXiv:1603.06682
  - PQCD: 6.9×10^{-6} arXiv:2210.15357
- **Amplitude analysis needed for precise test**
- **Little on other processes, like $\Lambda_b^0 \to N^{*+} K^-$**

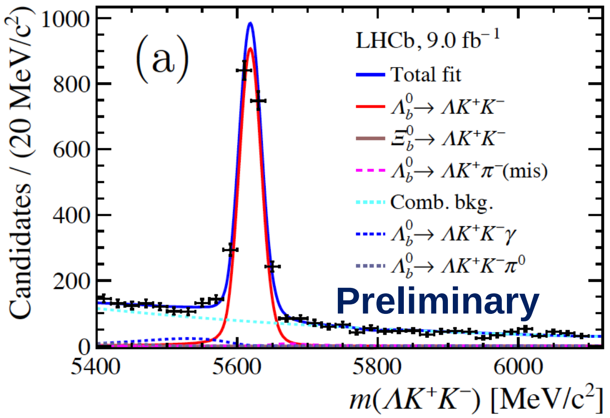
Signal channel ($\Lambda_b^0 \to \Lambda K^+\pi^-$)

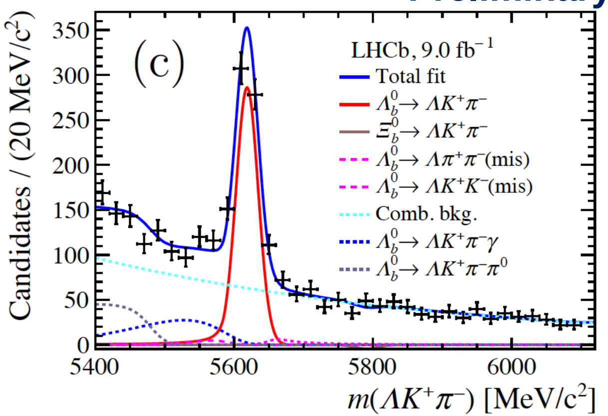
LHCb-PAPER-2024-043

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

Optimized using significance F.O.M.

$N_S/(\sqrt{N_S + N_B})$





ΛK^+K^- $\Lambda K^+\pi^-$

Signal yield: $N = 1920 \pm 50$ $N = 618 \pm 32$

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

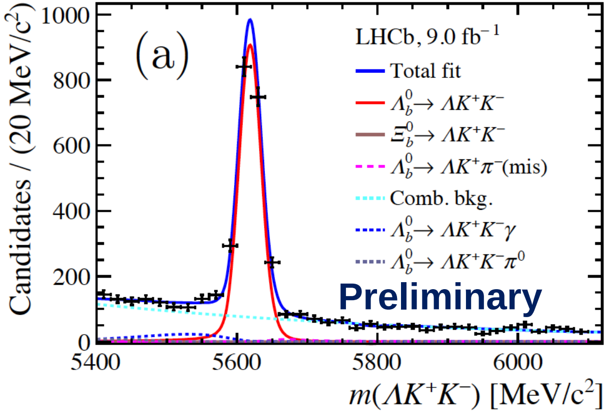
Signal channels ($\Lambda_b^0 \to \Lambda\pi^+\pi^-$)

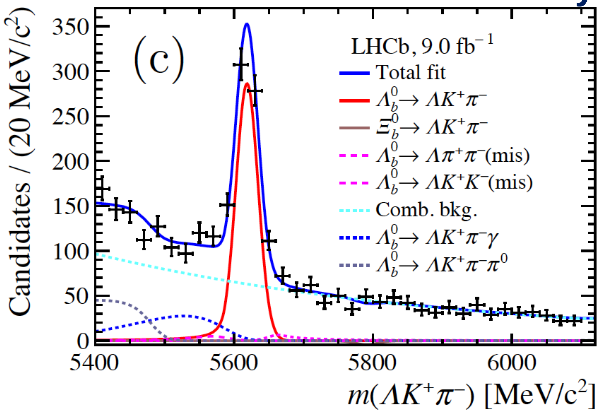
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda h^+ h'^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-)} = \frac{N_{\Lambda_b^0 \to \Lambda h^+ h'^-}}{N_{\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-}} \times \frac{\epsilon_{\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-}}{\epsilon_{\Lambda_b^0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

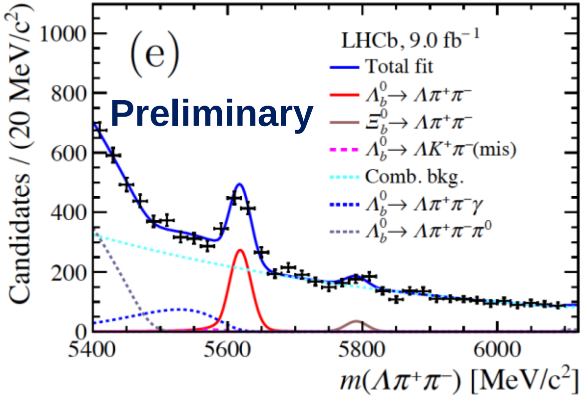
Optimized using significance F.O.M.

$$N_S/(\sqrt{N_S + N_B})$$

Preliminary







ΛK^+K^- | $\Lambda K^+\pi^-$ | $\Lambda\pi^+\pi^-$

Signal yield: $N = 1920 \pm 50$ | $N = 618 \pm 32$ | $N = 640 \pm 40$

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

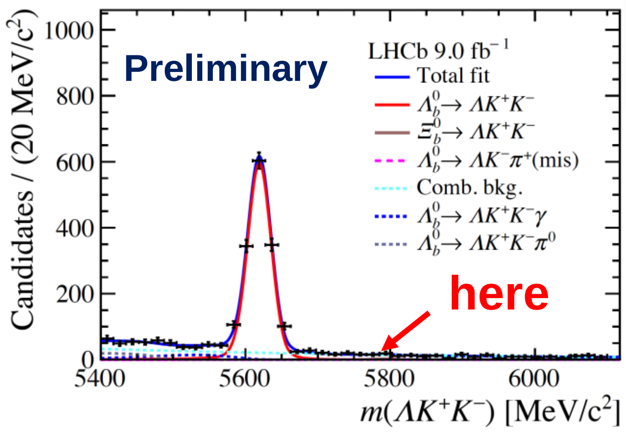
First observation

Signal channels ($\Xi_b^0 \to \Lambda K^+ K^-$)

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

Optimized using Punzi F.O.M.

$$N_S/(\sqrt{N_B} + 5/2)$$



$\Lambda K^+ K^-$

$N = 12 \pm 9$

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

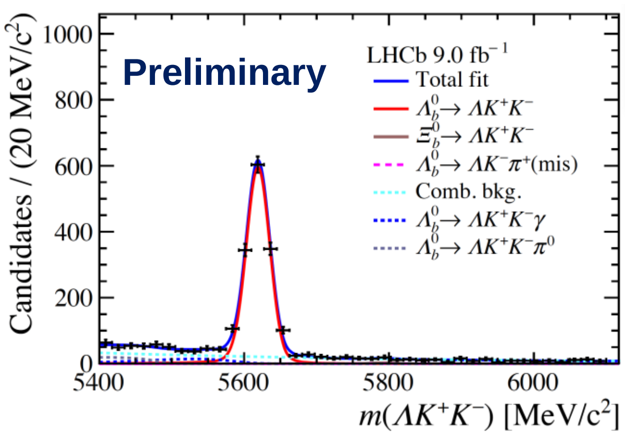
Not significant, 1.7 σ

Signal channels ($\Xi_b^0 \to \Lambda K^- \pi^-$)

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

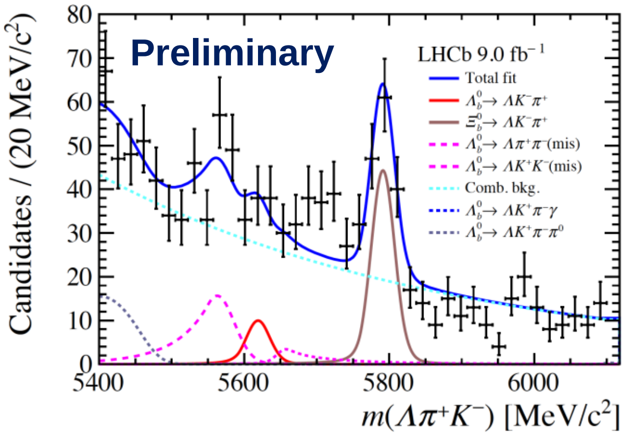
Optimized using Punzi F.O.M.

$N_S/(\sqrt{N_B} + 5/2)$



$\Lambda K^+ K^-$

$N = 12 \pm 9$



$\Lambda K^- \pi^+$

$N = 119 \pm 15$

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

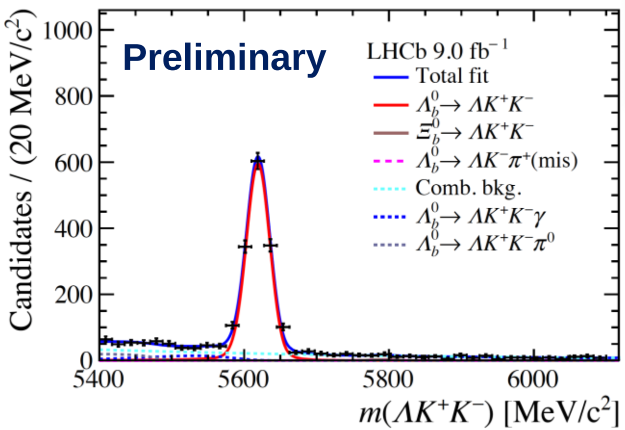
First observation

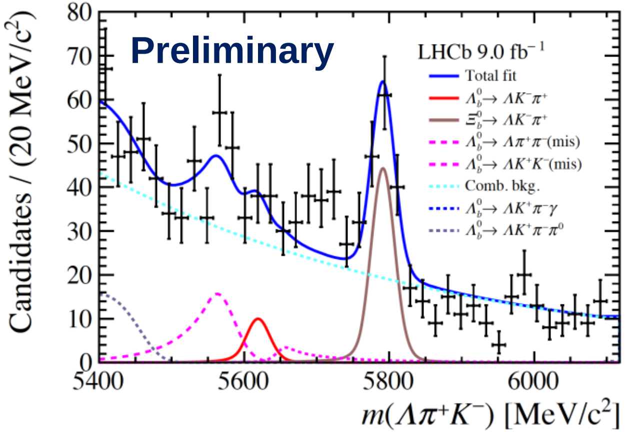
Signal channels ($\Xi_b^0 \to \Lambda\pi^+\pi^-$)

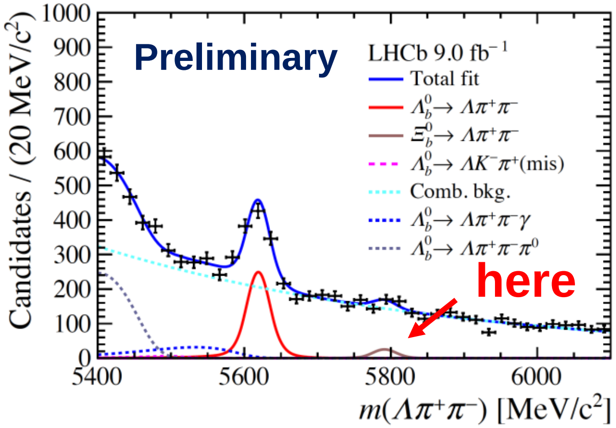
$$\frac{\mathcal{B}(\Xi_b^0 \to \Lambda h^+ h'^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-)} = \frac{N_{\Xi_b^0\to\Lambda h^+ h'^-}}{N_{\Lambda_b^0\to\Lambda_c^+(\to\Lambda\pi^+)\pi^-}} \times \frac{\epsilon_{\Lambda_b^0\to\Lambda_c^+(\to\Lambda\pi^+)\pi^-}}{\epsilon_{\Xi_b^0\to\Lambda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

Optimized using Punzi F.O.M.

$$N_S/(\sqrt{N_B} + 5/2)$$







ΛK^+K^-

$N = 12 \pm 9$

$\Lambda K^-\pi^+$

$N = 119 \pm 15$

$\Lambda\pi^+\pi^-$

$N = 56 \pm 27$

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

4σ, first evidence

Methodology of A_{CP} measurements at LHCb

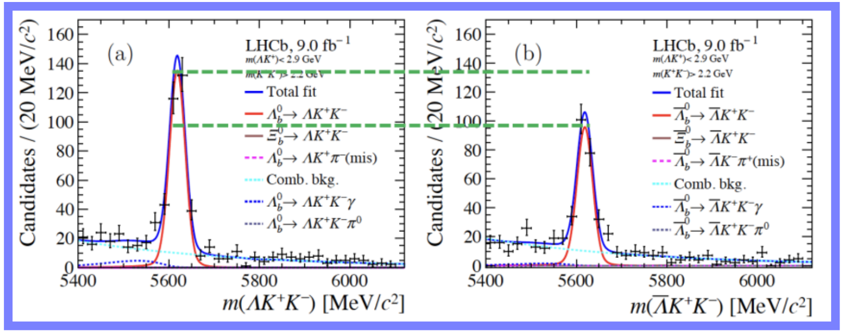
Physical quantity of interests

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

Experimental effects

$$A_{\mathrm{Raw}}^{f} = \frac{N(\Lambda_b^0 \to f) - N(\overline{\Lambda}_b^0 \to \bar{f})}{N(\Lambda_b^0 \to f) + N(\overline{\Lambda}_b^0 \to \bar{f})}$$

What we see directly from mass plots



Preliminary **See later**

Methodology of A_{CP} measurements at LHCb

Physical quantity of interests

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

$$A_{CP}^{f} = A_{\mathrm{Raw}}^{f} - A_{\mathrm{P}}^{\Lambda_b^0} - A_{\mathrm{D}}^{f}$$

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

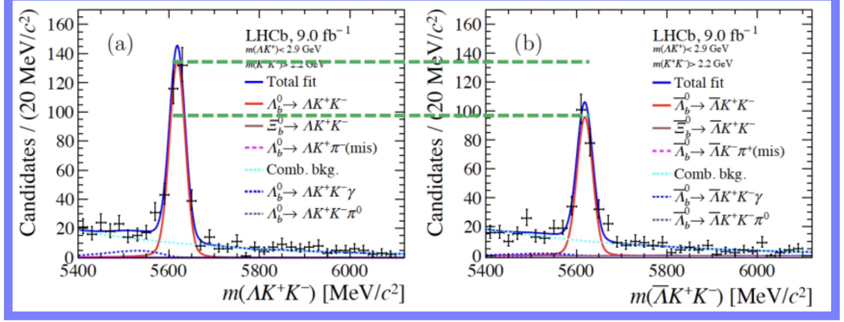
$$A_{\mathrm{D}}^{f} = \frac{\epsilon(f) - \epsilon(\bar{f})}{\epsilon(f) + \epsilon(\bar{f})}$$

Experimental effects

Production asymmetry

Detection asymmetry

$$A_{\mathrm{Raw}}^{f} = \frac{N(\Lambda_b^0 \to f) - N(\overline{\Lambda}_b^0 \to \bar{f})}{N(\Lambda_b^0 \to f) + N(\overline{\Lambda}_b^0 \to \bar{f})}$$



What we see directly from mass plots

Preliminary

See later

Control channel for A_{CP} measurements

Signal channel

$$A_{CP}^{S} = A_{\mathrm{Raw}}^{S} - A_{\mathrm{P}}^{\Lambda_b^0} - A_{\mathrm{D}}^{S}$$

Control channel

$$A_{CP}^{C} = A_{\mathrm{Raw}}^{C} - A_{\mathrm{P}}^{\Lambda_b^0} - A_{\mathrm{D}}^{C}$$

$$\Delta A_{CP} = \Delta A_{\mathrm{Raw}} - \Delta A_{\mathrm{P}}^{\Lambda_b^0} - \Delta A_{\mathrm{D}}$$

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

$A_{CP}\sim 0$

Similar topology

$\Delta A_P^{\Lambda_b^0}$: mostly canceled, small residual due to kinematic difference induced by selections

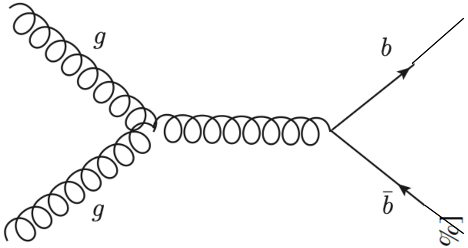
ΔA_D: mostly canceled, small residual due to kinematic difference induced by selections or particle type difference (K vs π)

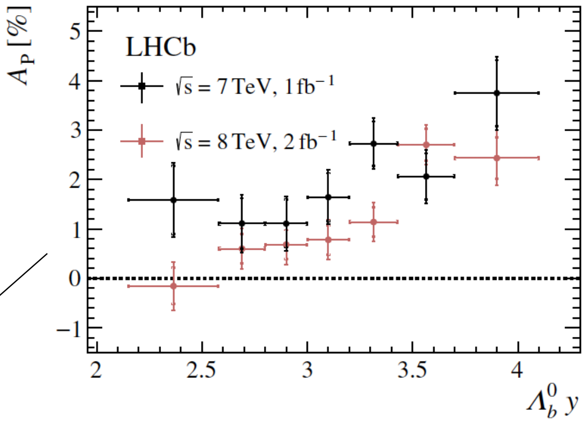
Production asymmetry

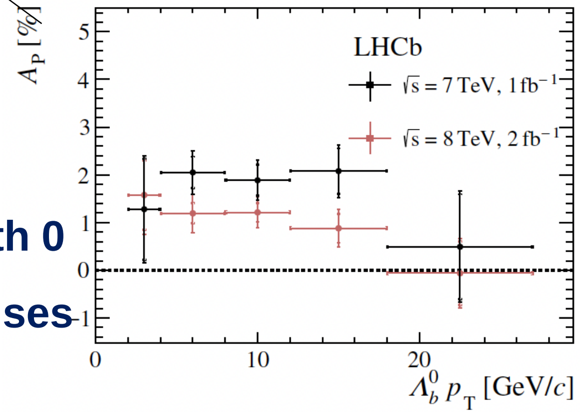
LHCb-PAPER-2021-016

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

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





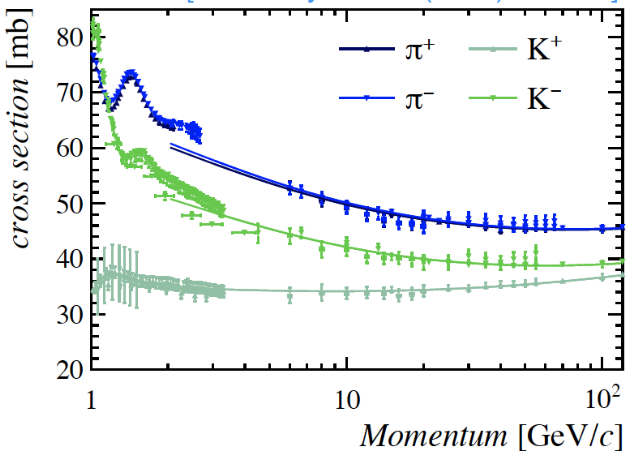


- **A_P : 1~2%, measured by LHCb as a function of y, p_T**
- **$\Delta A_P \sim 0.2\%$, with uncertainties around 0.2%: consistent with 0**
- **A_P: Only Run 1 measured, Run2 (expected to be smaller) uses Run1 measurements**

Detection asymmetry

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

[Chin. Phys. C 40 (2016) 100001]



- **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**

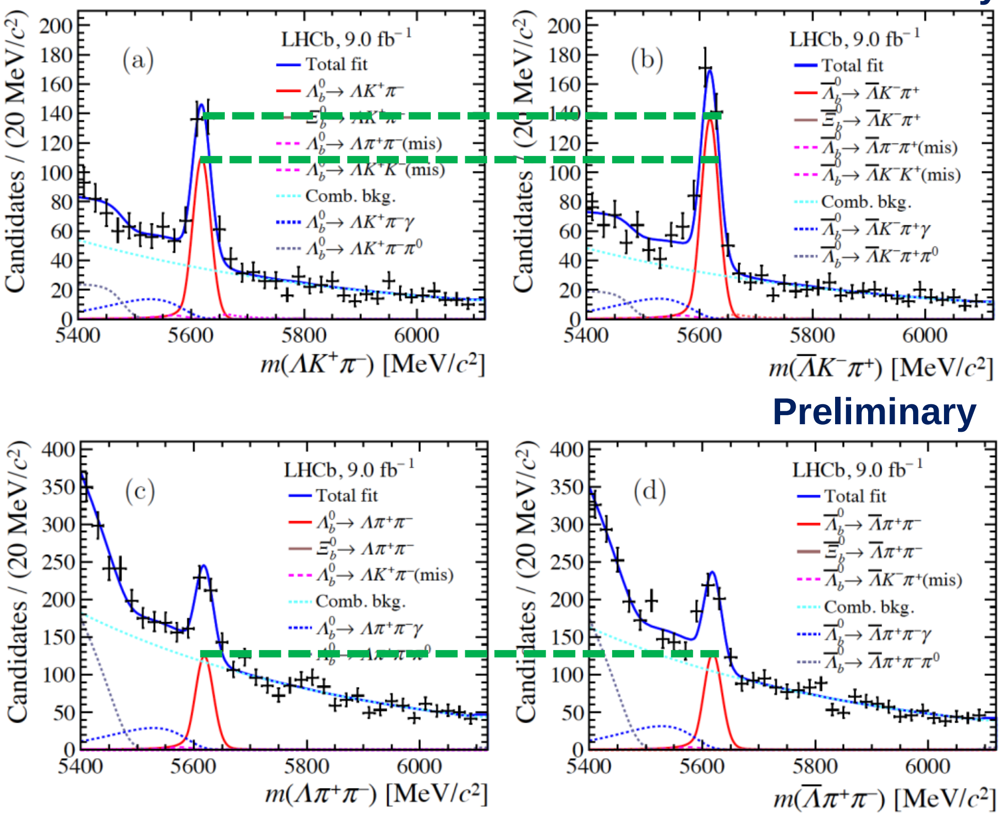
$$A_D(\pi^{\pm}) \approx 0.1\%, A_D(K^{\pm}) \approx 1\%, A_D(p/\bar{p}) \approx 1-2\%$$

→ ΔA_D: ~1%

Significantly reduced using control channel

CP violation measurements (1)

Preliminary



$\boldsymbol{\Lambda_b^0 \to \Lambda K^+\pi^-}$

$$\Delta A_{CP} = -0.118 \pm 0.045 \pm 0.021$$

Consistent with 0 within 2.4σ

$\boldsymbol{\Lambda_b^0 \to \Lambda\pi^+\pi^-}$

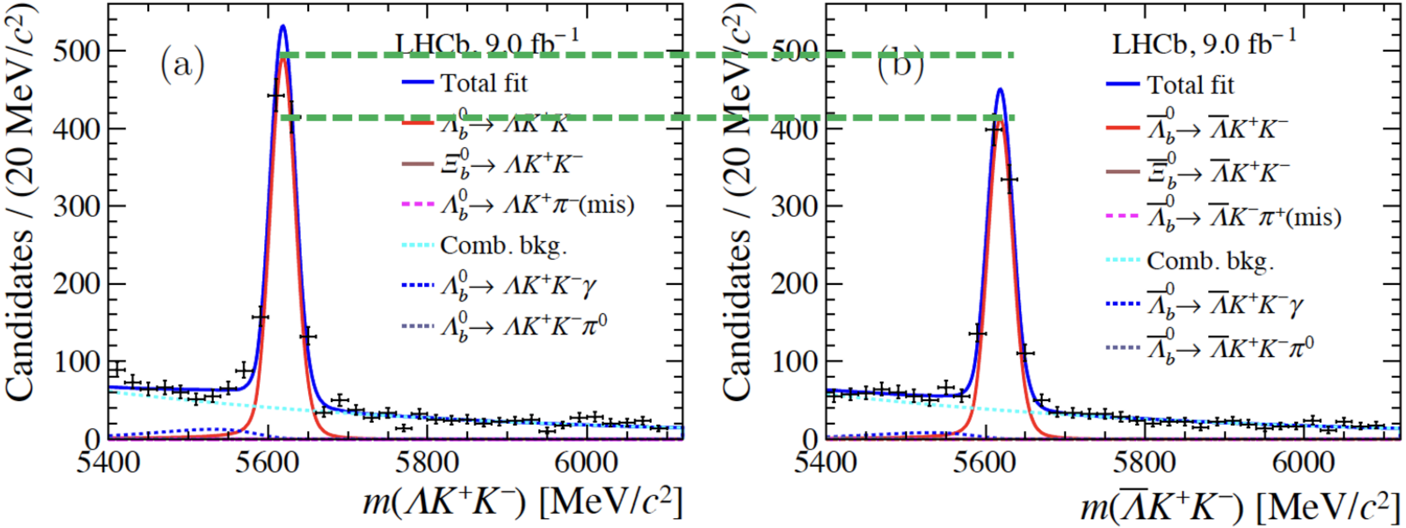
$$\Delta A_{CP} = -0.013 \pm 0.053 \pm 0.018$$

Consistent with 0

CP violation measurements (2)

LHCb-PAPER-2024-043

Preliminary



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

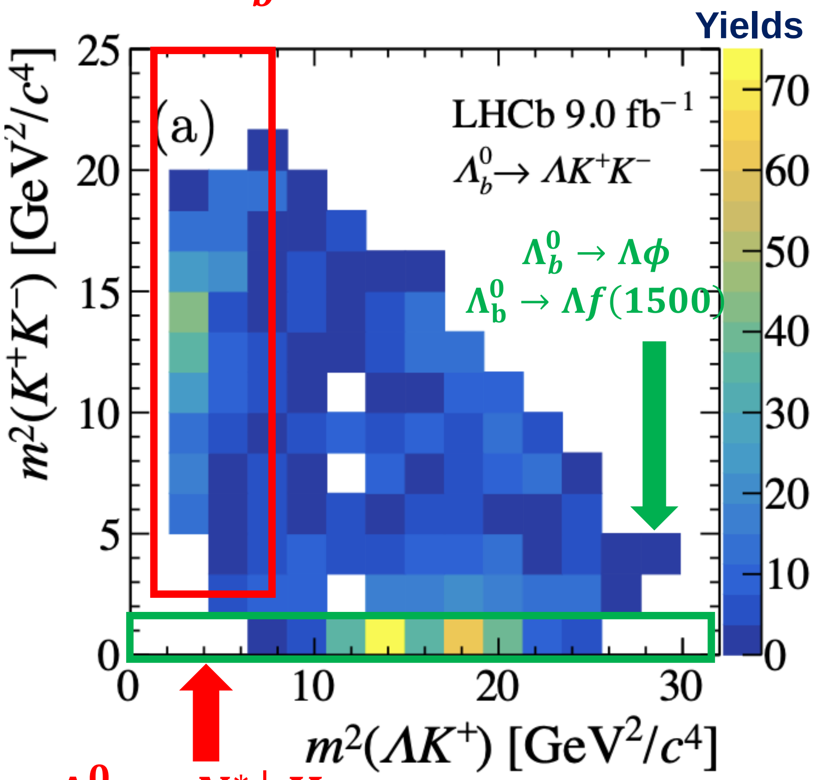
$$\Delta A_{CP} = 0.083 \pm 0.023 \pm 0.016$$

First evidence of CP violation, 3.1σ

Three body decays, need to know which resonance contributes

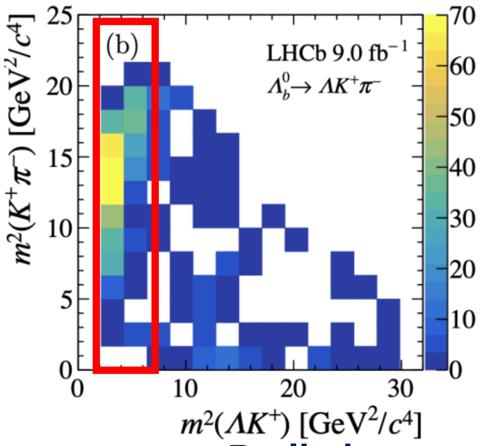
Dalitz plot distributions

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

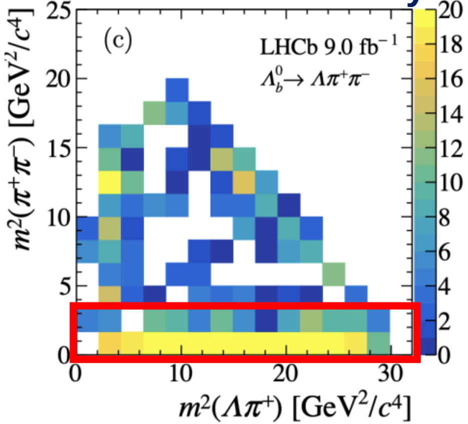


$\Lambda_b^0 \to N^{*+} K^-$

Preliminary



Preliminary



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

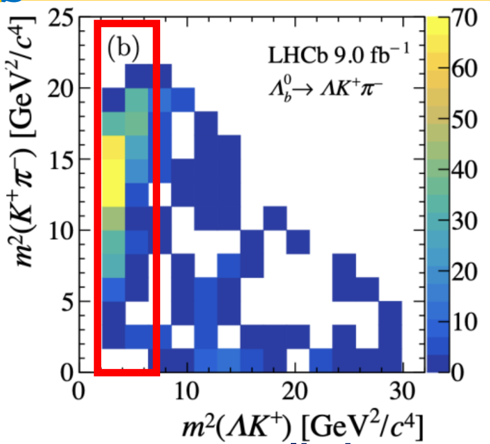
Mainly $\Lambda_b^0 \to N^{*+}\pi^-$
Small contribution
from $\Lambda_b^0 \to \Lambda K^*$

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

Mainly $\Lambda_b^0 \to \Lambda f_0(980)$,
$\Lambda_b^0 \to \Lambda f_2(1270)$

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

$\Delta A_{CP}(N^{*+}\pi^-) = -0.078 \pm 0.051 \pm 0.027$

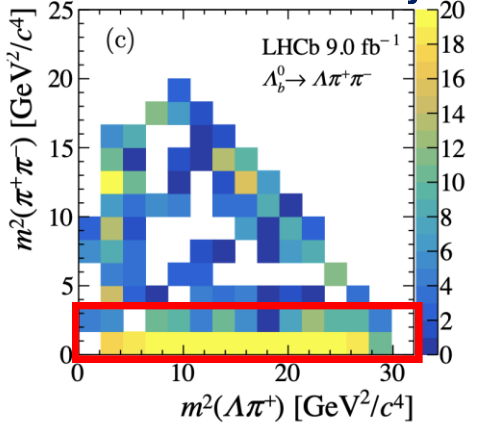


$\Lambda_b^0 \to \Lambda K^+\pi^-$

Mainly $\Lambda_b^0 \to N^{*+}\pi^-$
Small contribution from $\Lambda_b^0 \to \Lambda K^*$

No evidence of CP violation in resonant regions (quasi two-body decays)

Preliminary



$\Delta A_{CP}(\Lambda f) = 0.088 \pm 0.069 \pm 0.021$

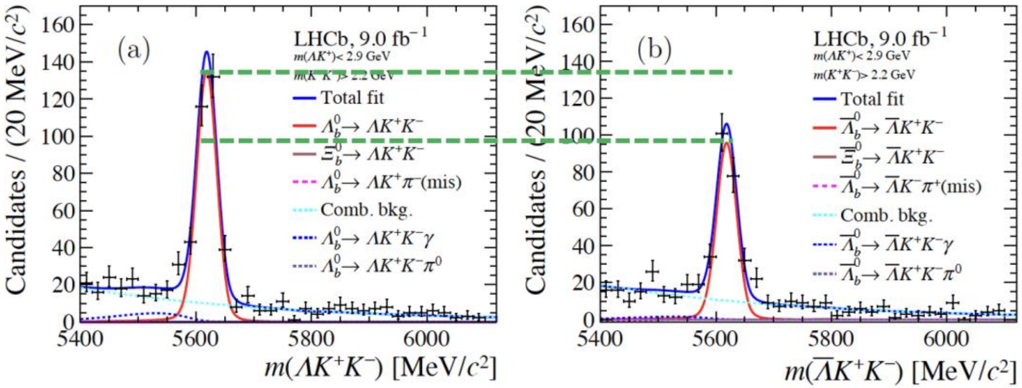
$\Lambda_b^0 \to \Lambda \pi^+\pi^-$

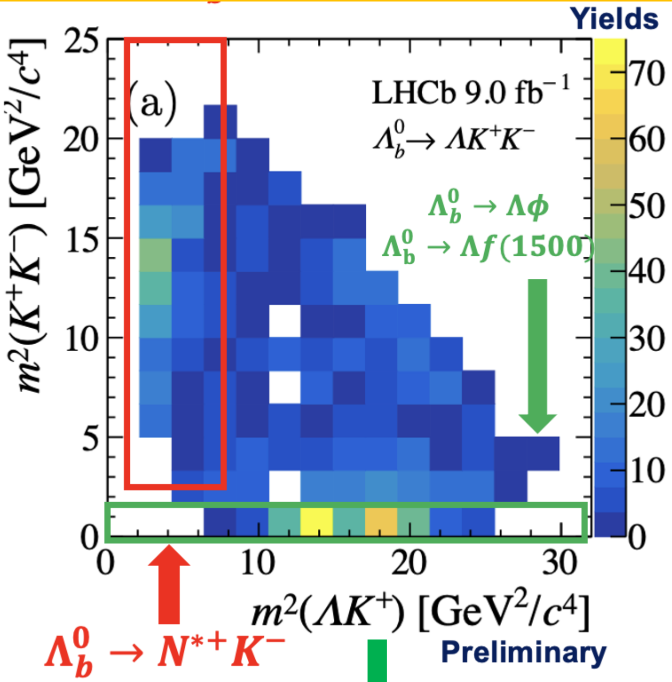
Mainly $\Lambda_b^0 \to \Lambda f_0(980)$, $\Lambda_b^0 \to \Lambda f_2(1270)$

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

LHCb-PAPER-2024-043

Preliminary





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

First evidence of CP violation in local resonant region, 3.2σ

region

$$\Delta A_{CP}(\Lambda\phi) = 0.150 \pm 0.055 \pm 0.021$$

Consistent with 0 within 2.5σ

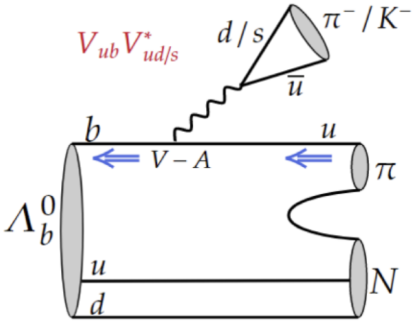
PRD107 (2023) 053009

Predicted CPV (resonant), ~1.5%

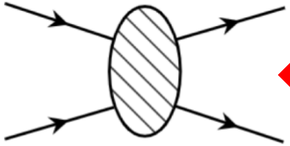
CP violation in $\Lambda_b^0 \to N^{*+} K^-$

CPC48 (2024) 101002

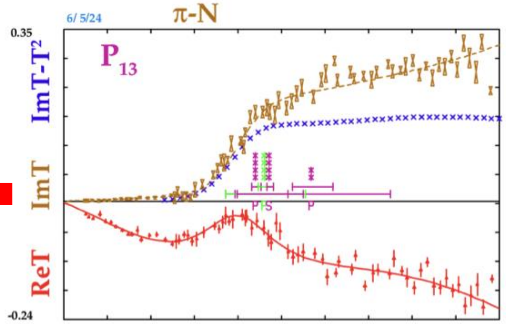
- Many N^{*+} contributions： $N(1520), N(1650), N(1680), N(1710)$ etc. difficult to untangle

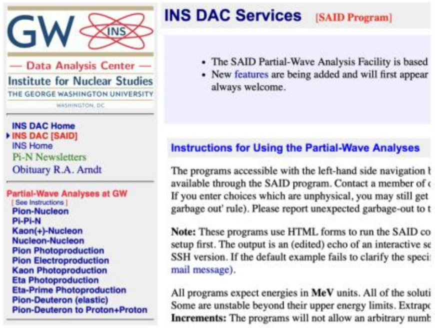


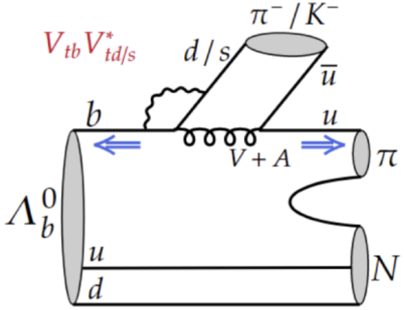
$N\pi$ scattering



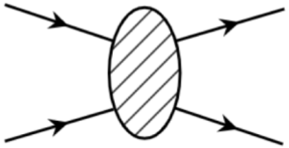
Scattering input from SAID program

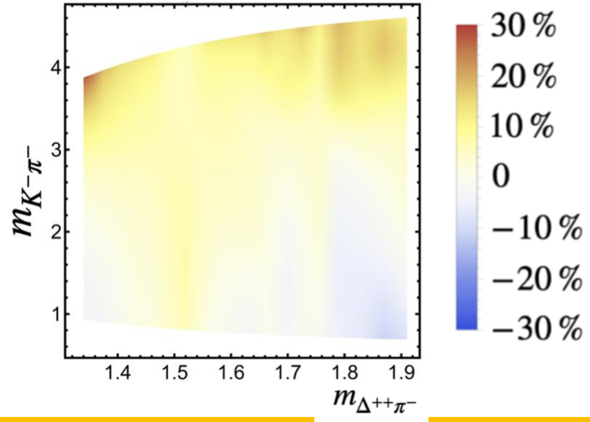






Different scattering amplitudes





CP violation as large as 20~30% expected

weak phase

strong phase

Studies of $\Lambda_b^0 \to p h^-$ decays

Analysis strategy

- Golden channel to search for CP violation in baryon decays
- Predictions ranges from few percent to as large as 30%
- Two different strategy taken for Run1 data and Run2 data

$$A_{CP}^{ph} = A_{Raw}^{ph} - A_D^p - A_D^h - A_{PID}^{ph} - A_{Tri}^{ph} - A_P$$

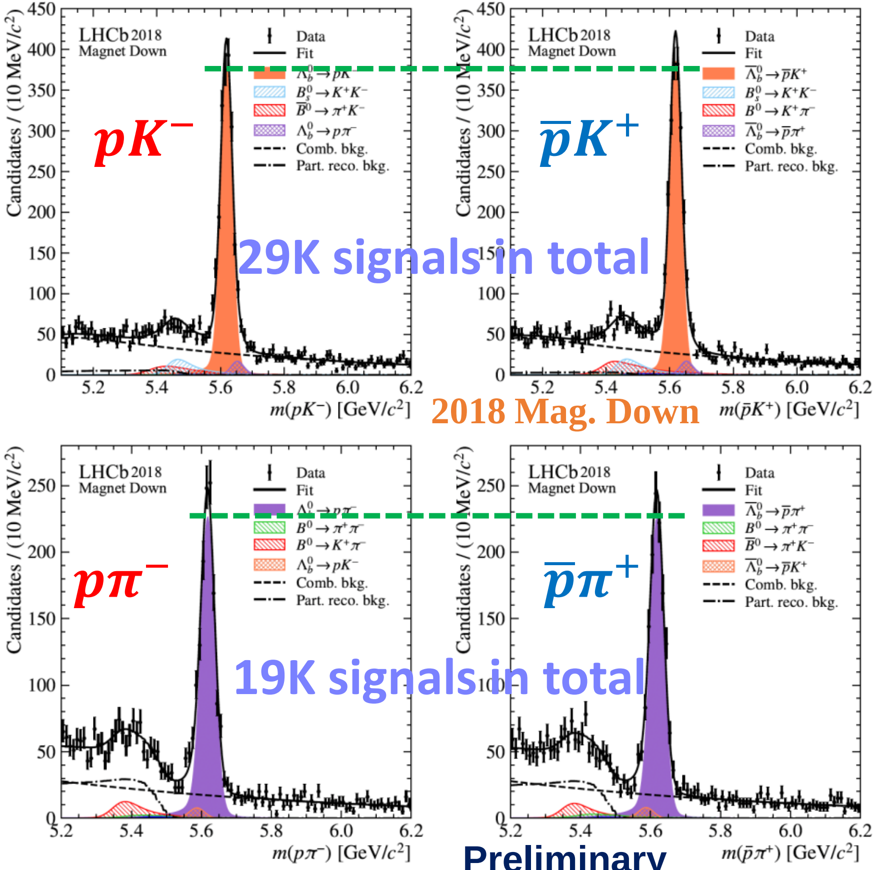
- Production and detection asymmetry all measured by calibration channels
- Used directly to obtain A_{CP}^{ph}

$$A_{CP}^{ph} = \Delta A_{Raw} - \Delta A_D^p - \Delta A_D^h - \Delta A_{\mathrm{PID}} - \Delta A_P - \Delta A_{\mathrm{Tri}} + A_{\mathrm{CP}}^{\Lambda_c^+\pi^-}$$

- $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$ used as control channel to cancel production asymmetry
- $\Delta A_P = 0$ by default by reweighting kinematic
- $A_{CP}^{\Lambda_c^+\pi^-} = 0$ in SM

Results of A_{CP} measurements

LHCb-PAPER-2024-048



Preliminary

- No clear asymmetry observed directly from invariant mass plot
- Run 1 results (updated with much smaller systematic uncertainties):

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

- Run 2 results:

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

- Combined: 9.6% correlation

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

Systematic uncertainties

	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

PID uncertainties from calibration, reduced with more data

Estimated with control sample, validated with simulation, reduced with more data

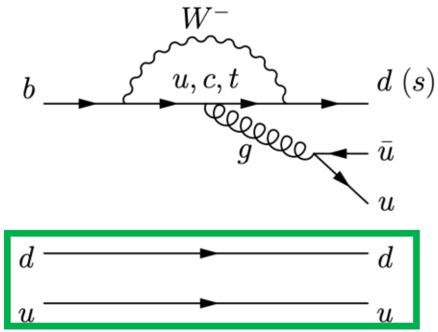
Dominant systematic uncertainty, reduced with more data

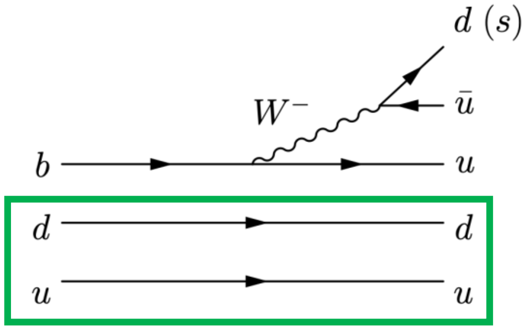
No crucial systematic uncertainties for future improvements

Why CP violation in $\Lambda_b^0 \to ph$ small?

- **Sizeable CP violation found in $B_{(s)}^0 \to h^+h'^-$ decays**
- **Many theoretical predictions also give large CP violation**

Transitions	$b \to d u \bar{u}$			$b \to s u \bar{u}$		
Decays	$B^0 \to \pi^+\pi^-$	$B_s^0 \to \pi^+K^-$	$\Lambda_b^0 \to p\pi^-$	$B^0 \to K^+\pi^-$	$B_s^0 \to K^+K^-$	$\Lambda_b^0 \to pK^-$
Direct CPV (%)	-31.4 ± 3.0	22.4 ± 1.2	0.20 ± 0.91	8.31 ± 0.31	16.2 ± 3.5	-1.14 ± 0.76





Same Feynman diagrams, only spectator quark(s) different

+

Possible additional W-exchange diagram in baryon decays

Possible explanations

- **Small strong phase difference?**

$$A = a_1 e^{i(\delta_1+\phi_1)} + a_2 e^{i(\delta_2+\phi_2)} \qquad \bar{A} = a_1 e^{i(\delta_1-\phi_1)} + a_2 e^{i(\delta_2-\phi_2)}$$

$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \propto \sin(\delta_1-\delta_2)\sin(\phi_1-\phi_2)$$

$\delta_1 - \delta_2 \sim 0?$

$$r_S = \frac{a_2^S}{a_1^S} \qquad r_P = \frac{a_2^P}{a_1^P}$$

- **Complications in baryon weak decays**

$½^+ \rightarrow ½^+ + 0^-$

S + P waves

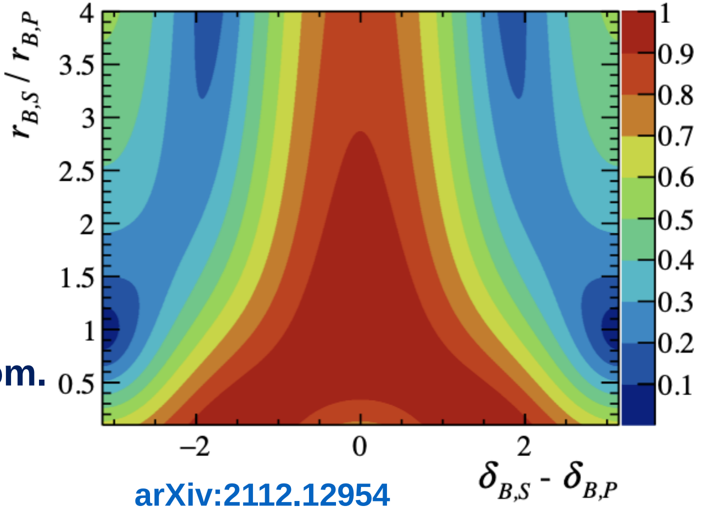
Cancellation between S, P waves

arXiv:2409.02821

	$\Lambda_b \to p\pi^-$	$\Lambda_b \to pK^-$
Br	3.3×10^{-6}	2.9×10^{-6}
A_{CP}^{dir}	4.1%	−5.8%
A_{CP}^{S}	0.15	−0.05
A_{CP}^{P}	−0.07	−0.23

General phenom.

Effective reduction on sensitivity

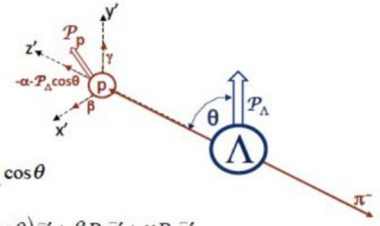


arXiv:2112.12954

Can we do more?

Phys. Rev. 108 (1959) 1645

- **More complicated, but also add more information**
- **Decay parameters, first proposed by Lee and Yang (1959) to study hyperon decays**



$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha P_\Lambda \cos\theta$$

$$P_p = \frac{(\alpha + P_\Lambda \cos\theta)\vec{z}' + \beta P_\Lambda \vec{x}' + \gamma P_\Lambda \vec{y}'}{1 + \alpha P_\Lambda \cos\theta}$$

$$\alpha_{\mp} = \pm \frac{2\Re(S^* P)}{|S|^2 + |P|^2} = \pm \frac{2|S||P|\cos(\delta \pm \phi)}{|S|^2 + |P|^2}$$

$$\beta_{\mp} = \pm \frac{2\Im(S^* P)}{|S|^2 + |P|^2} = \pm \frac{2|S||P|\sin(\delta \pm \phi)}{|S|^2 + |P|^2}$$

$$\gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2} \qquad \alpha^2 + \beta^2 + \gamma^2 = 1$$

δ: strong phase difference between S and P waves
ϕ: weak phase difference between S and P waves

- **New CP observables:**

$$A_\alpha = \frac{\alpha_+ + \alpha_-}{\alpha_+ - \alpha_-} = -\tan(\delta)\tan(\phi) \qquad R_{\beta_1} = \frac{\beta_+ + \beta_-}{\alpha_+ - \alpha_-} = \tan(\phi) \qquad R_{\beta_2} = \frac{\beta_+ - \beta_-}{\alpha_+ - \alpha_-} = -\tan(\delta)$$

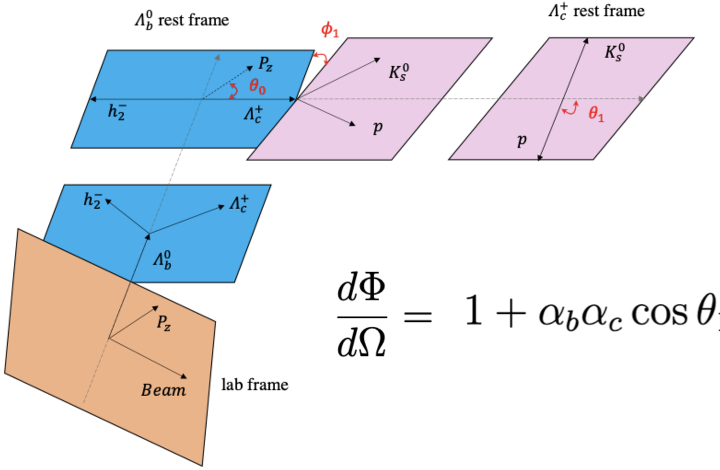
LHCb can contribute

arXiv:2409.02759

- **Several decay chains considered:**

$$\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)h^-$$

$\alpha_b: \Lambda_b^0 \to \Lambda_c^+ h^-$ $\alpha_c: \Lambda_c^+ \to pK_S^0$

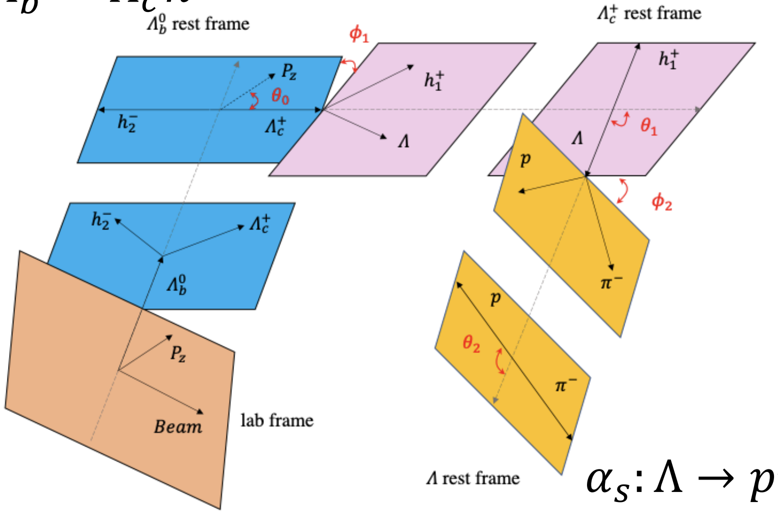


$$\frac{d\Phi}{d\Omega} = 1 + \alpha_b\alpha_c \cos\theta_1$$

$$\Lambda_b^0 \to \Lambda_c^+(\to \Lambda h^+)h^-, \Lambda \to p\pi^-$$

$$\frac{\mathrm{d}\Phi}{\mathrm{d}\Omega} \propto (1 + \alpha_b\alpha_c \cos\theta_1 + \alpha_c\alpha_s \cos\theta_2 + \alpha_b\alpha_s \cos\theta_1 \cos\theta_2 - \alpha_b\gamma_c\alpha_s \sin\theta_1 \sin\theta_2 \cos\phi_2 + \alpha_b\beta_c\alpha_s \sin\theta_1 \sin\theta_2 \sin\phi_2)$$

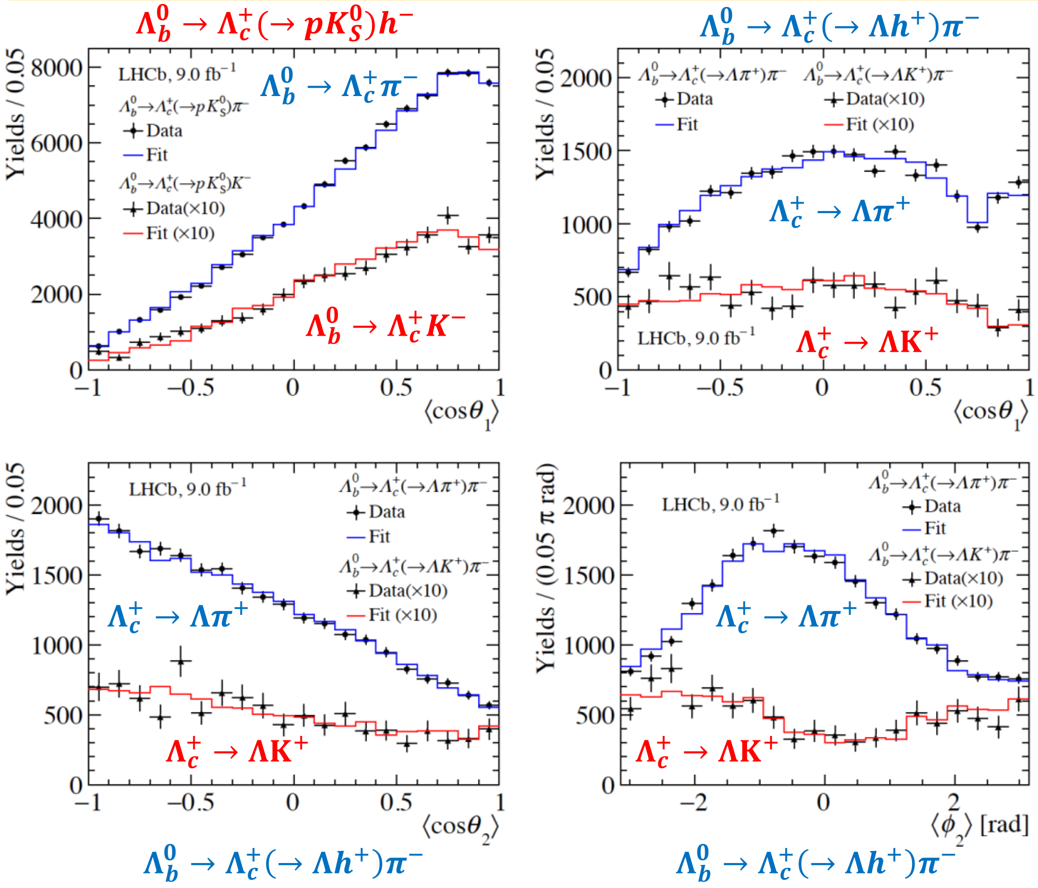
$\alpha_b: \Lambda_b^0 \to \Lambda_c^+ h^-$ $\alpha_c, \beta_c, \gamma_c: \Lambda_c^+ \to \Lambda h^+$



$\alpha_s: \Lambda \to p\pi^-$

Results of decay parameters

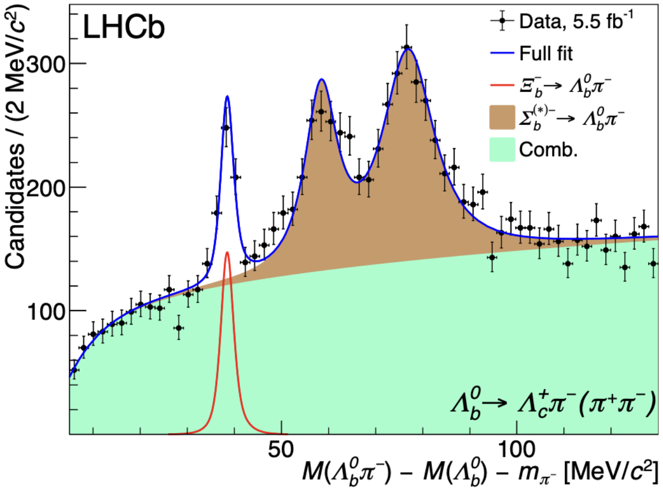
arXiv:2409.02759

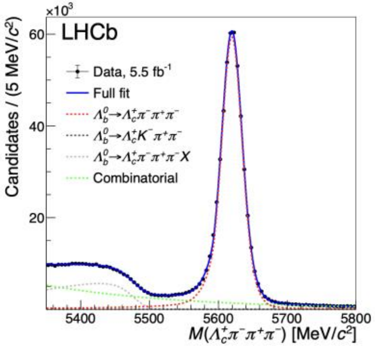


- **First determination of α in $\Lambda_b^0 \to \Lambda_c^+ h^-$ decays (precision $\sim 0.9\%$ for $\Lambda_c^+\pi^-$)**
- **Most precise determinations of $\alpha, (\beta, \gamma)$ in $\Lambda_c^+ \to pK_S^0$ (precision $\sim 1.4\%$) and $\Lambda_c^+ \to \Lambda h^+$ decays**
- **Confirmation of $\alpha(\Lambda \to p\pi^-)$ from BESIII (significantly higher than previous measurements)**
- **Results consistent with no CP violation in both A_α and R_{β_1} (precision $\sim 2\%$ for $\Lambda_c^+\pi^-$)**
- **Pave the way for other decay parameter measurements (more sensitive)**

We can understand with $\Xi_b^- \to \Lambda_b^0 \pi^-$ decay

PRD108 (2023) 072002





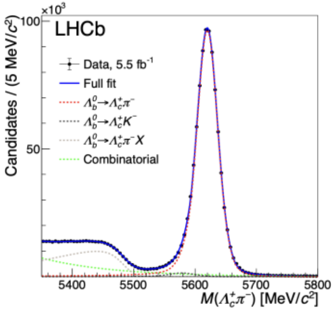
$$\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^+\pi^-\pi^+$$

$$\mathcal{B} = (47 \pm 7) \times 10^{-5}$$

$$N \sim 5 \times 10^5$$

$$N(\Lambda_c^+\pi^+\pi^-\pi^+) = 154 \pm 23$$

$$N(\Lambda_c^+\pi^-) = 126 \pm 19$$



$$\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$$

$$\mathcal{B} = (30.6 \pm 2.8) \times 10^{-5}$$

$$N \sim 9 \times 10^5$$

$$\mathcal{B}(\Xi_b^- \to \Lambda_b^0\pi^-) = (0.89 \pm 0.10 \pm 0.07 \pm 0.29)\%,$$

$O(100)$ events expected for $\Xi_b^- \to \Lambda_b^0(\to ph^-)\pi^-$ decays for α measurement adding LHCb Run3; more information on the small A_{CP} in $\Lambda_b^0 \to ph^-$

CP violation in baryon decays in near future

- **Hyperon decays: $\Lambda \to p\pi^-$ (3.2M events from BESIII)**

$$\frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+} = -(2.5 \pm 4.8) \times 10^{-3}$$

With Super τ-charm factory, sensitivity around 10^{-4}, approaching SM prediction

- **Charm decays: $\Lambda_c^+ \to p\pi^+\pi^-, pK^+K^-$ (LHCb, Run1, Λ_c^+ from b decays)**

$$A_{CP}(\Lambda_c^+ \to pK^+K^-) - A_{CP}(\Lambda_c^+ \to p\pi^+\pi^-) = 0.003 \pm 0.011$$

With prompt Λ_c^+ and Run3 data, precision less than 10^{-3}, approaching SM predictions

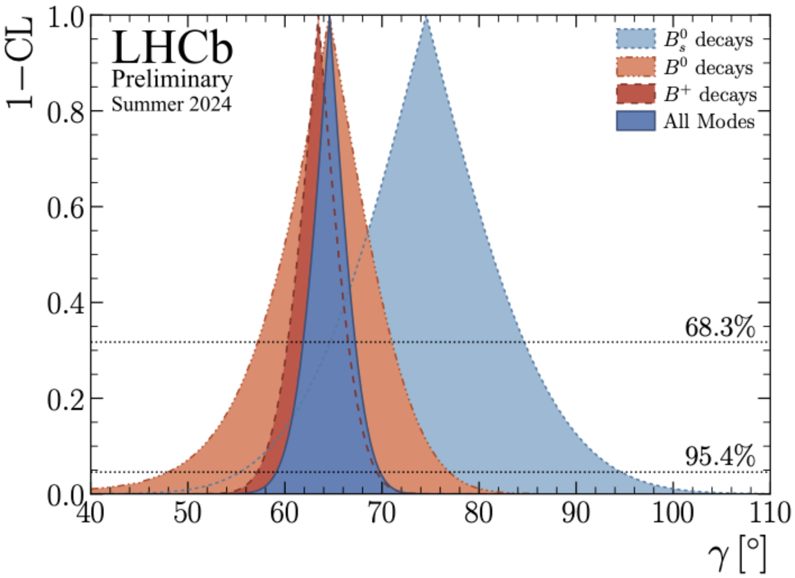
- **Beauty baryon decays:**
  - **Further explore channels with more data: $\Lambda_b^0 \to pK_S^0h^-$ (Run 1), $\Lambda_b^0 \to J/\psi ph^-$ (Run 1), $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ (Run 1 A_{CP}, Run 1+2 TPA), $\Lambda_b^0 \to pK^-\pi^+\pi^-$ (Run 1) and $\Lambda_b^0 \to p\pi^0h^-$**
  - **Especially $\Lambda_b^0 \to pK^-\pi^+\pi^-$ ($\Lambda_b^0 \to p\pi^0K^-$), which also contains resonant contributions from $\Lambda_b^0 \to N^{*+}(\to p\pi^+\pi^-)K^-$ ($\Lambda_b^0 \to N^{*+}(\to p\pi^0)K^-$)**
- **Unknown suppression factor (QCD related), luck needed to find where it hides！**

What if we find 5σ CP violation in baryon?

Next question: is it SM?

γ measurements in Λ_b^0 decays

- Measuring angle γ in Λ_b^0 decays help answering



- Angle γ measured in different *b* hadrons
  - B^+: $(63.4^{+3.2}_{-3.3})^\circ$
  - B^0: $(64.6^{+6.5}_{-7.5})^\circ$
  - B_s^0: $(75.0^{+10.0}_{-11.0})^\circ$
  - Λ_b^0: no measurements yet!!!

A non-zero γ indicates CP violation

- Provide additional way to search CP in baryon decays

- LHCb has already made a first step forward

Observation of ADS mode in $\Lambda_b^0 \to DpK$

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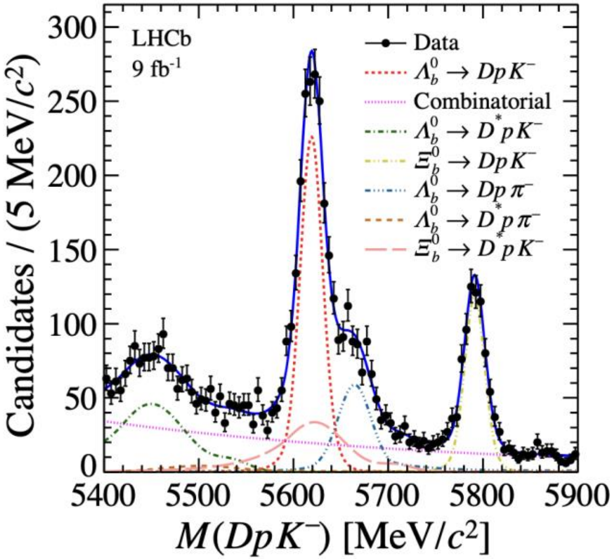
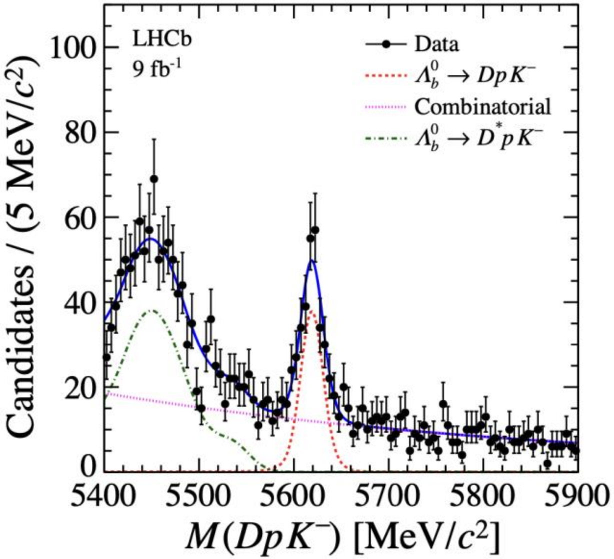


1437 ± 92

Favored: $\Lambda_b^0 \to [K^-\pi^+]pK^-$



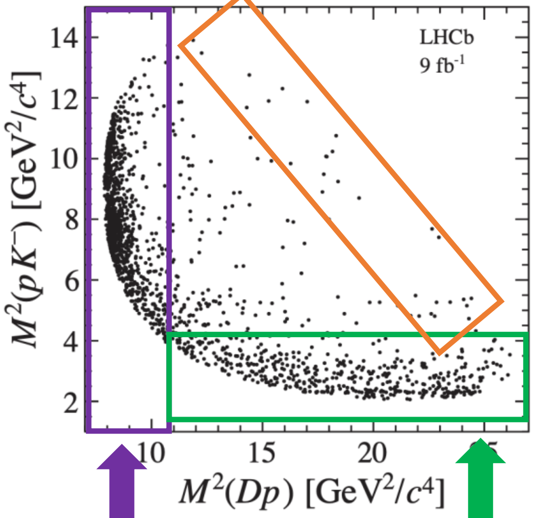
241 ± 22

Suppressed: $\Lambda_b^0 \to [K^+\pi^-]pK^-$

$b \to u$ and $b \to c$ similar level: suitable for γ measurement

D_s^{*+} ($b \to u$)

Can be used for for γ?



Λ_c^{*+} ($b \to c$)

not sensitive for γ

Λ^* ($b \to c$ + $b \to u$)

sensitive for γ

A_{CP} measurements in $\Lambda_b^0 \to DpK$

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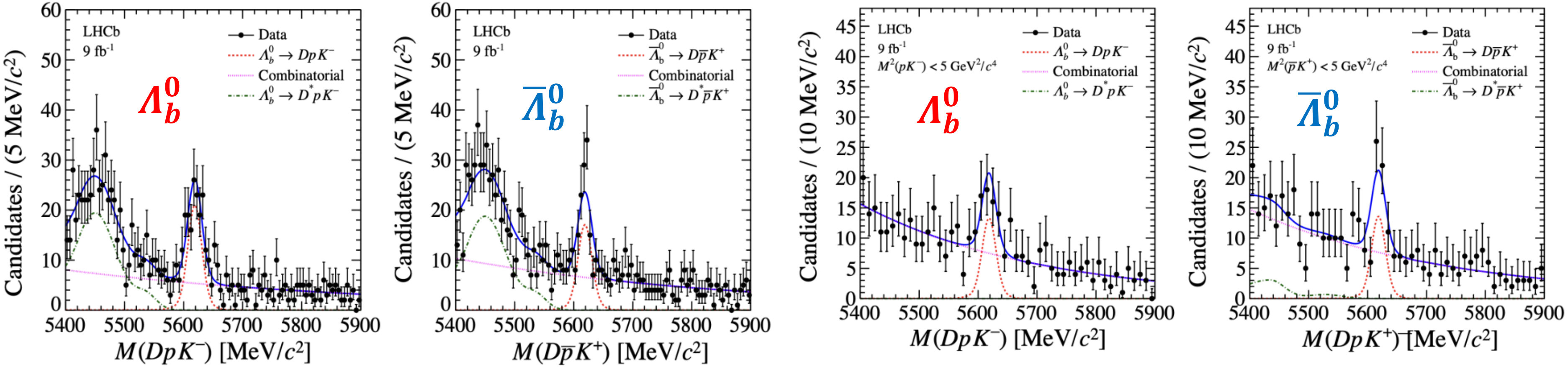
Full phase space | $M^2(pK) < 5\ \mathrm{GeV}^2$



$$R = 7.1 \pm 0.8(\text{stat})^{+0.4}_{-0.3}(\text{syst}),$$
$$A = 0.12 \pm 0.09(\text{stat})^{+0.02}_{-0.03}(\text{syst}),$$

$$R = \frac{\mathcal{B}(\Lambda_b^0 \to [K^-\pi^+]_D pK^-)}{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D pK^-)},$$

$$R = 8.6 \pm 1.5(\text{stat})^{+0.4}_{-0.3}(\text{syst}),$$
$$A = 0.01 \pm 0.16(\text{stat})^{+0.03}_{-0.02}(\text{syst}).$$

$$A = \frac{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D pK^-) - \mathcal{B}(\bar{\Lambda}_b^0 \to [K^-\pi^+]_D \bar{p}K^+)}{\mathcal{B}(\Lambda_b^0 \to [K^+\pi^-]_D pK^-) + \mathcal{B}(\bar{\Lambda}_b^0 \to [K^-\pi^+]_D \bar{p}K^+)}$$

Extracting γ complicated, more channels/data, better methods needed

Most important: more data coming

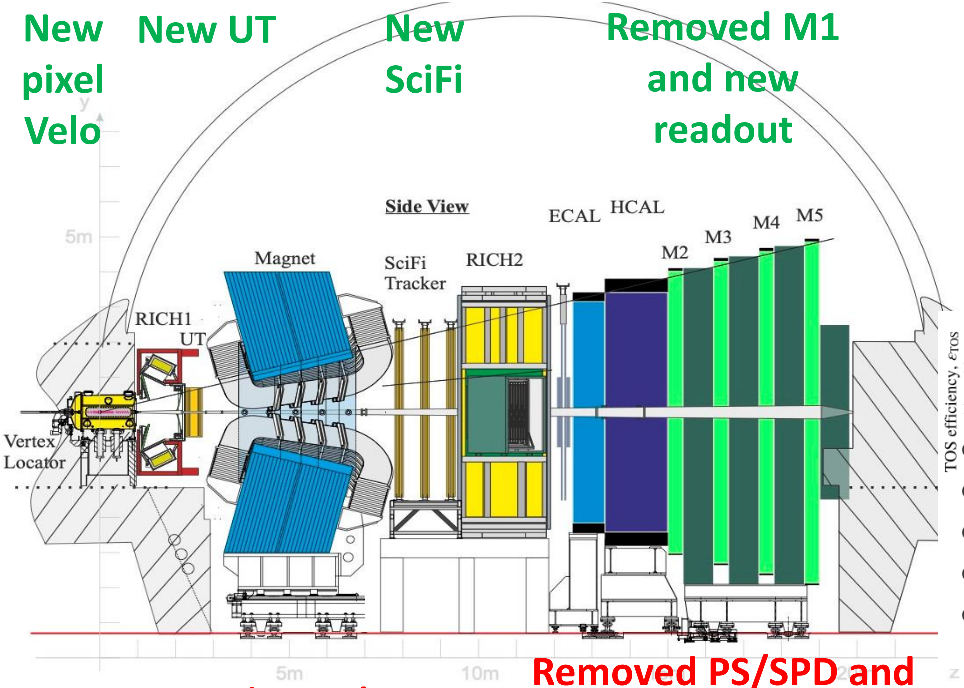
- **With our new LHCb detector, already collected more data than Run1+2**
- **More importantly, full software trigger ➜ better performance on hadronic final states**

New pixel Velo

New UT

New SciFi

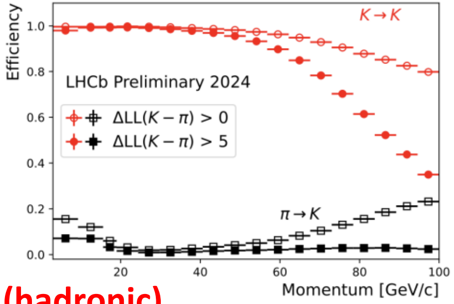
Removed M1 and new readout



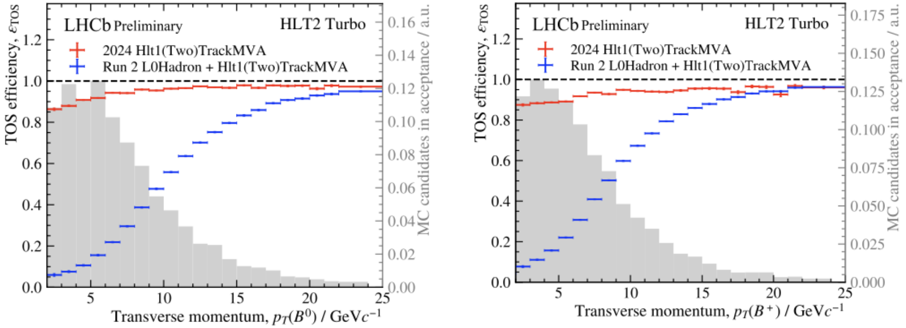
New RICH optics and PMS

Removed PS/SPD and new readout

Similar PID performance



Twice trigger efficiencies (hadronic)



$B^0 \to D^- \pi^+$

$B^+ \to \overline{D}^0 \pi^+$

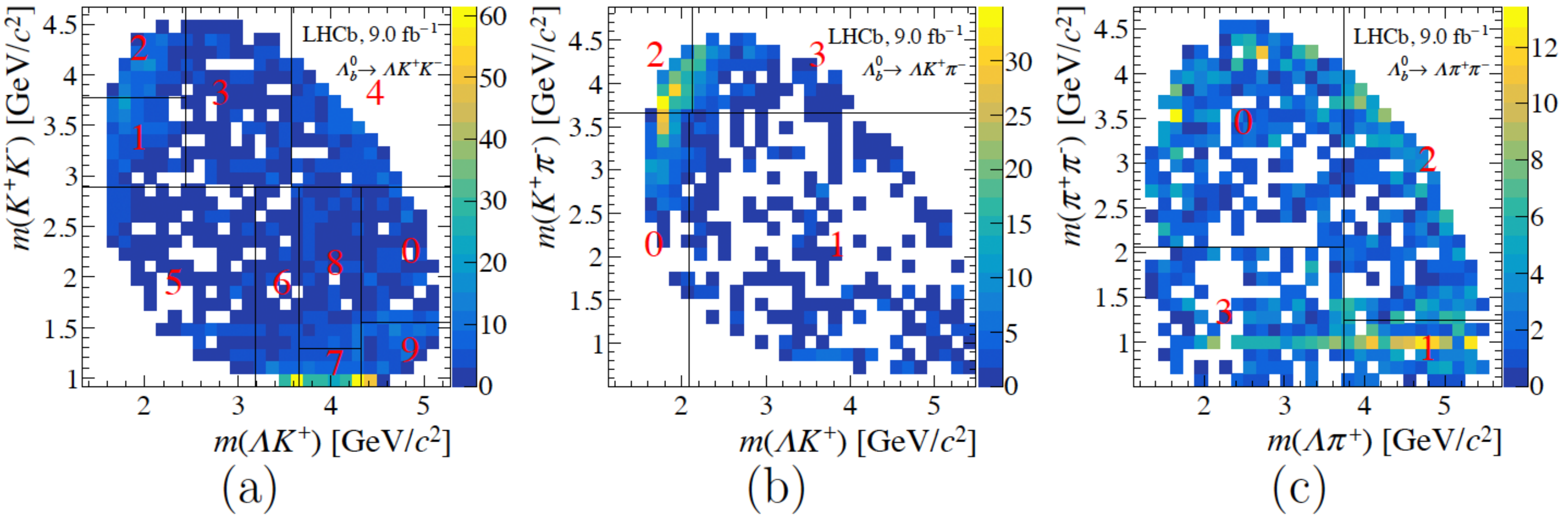
Conclusion

- CP violation crucial for understanding matter antimatter asymmetry in Universe
- However, CP violation in baryon decays not established yet
- LHCb experiments fully explore its potential on baryon CP violation
- Evidence of baryon CP violation found in $\Lambda_b^0 \to \Lambda K^+ K^-$ decays (full phase space) and in local resonant region $\Lambda_b^0 \to N^{*+} K^-$
- Precise CP violation measurements also in $\Lambda_b^0 \to p h^-$ decays, further understanding of the small A_{CP} needed
- Stay tuned for more interesting results on baryon CP violation from LHCb

Thank you for your attention!

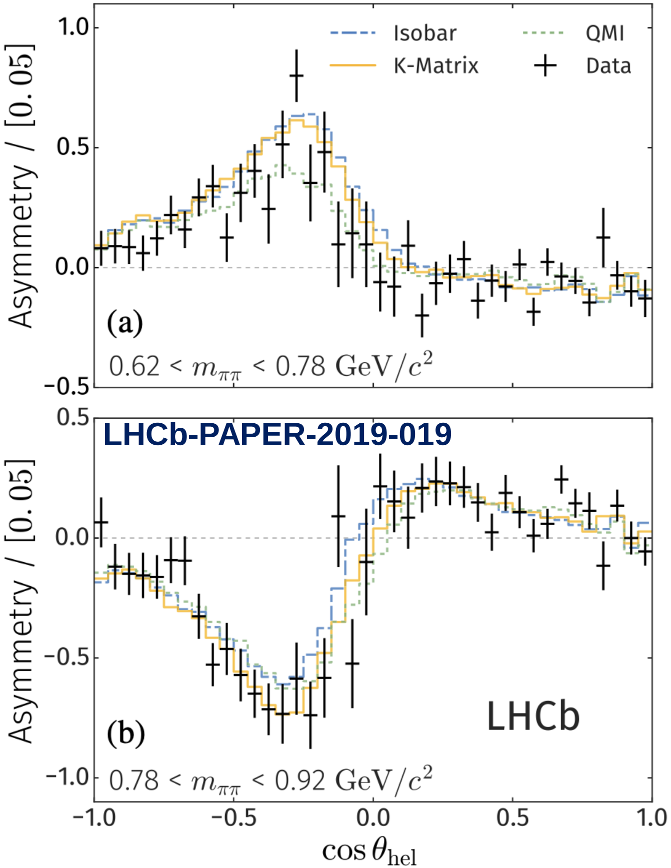
Further investigation

LHCb-PAPER-2024-043

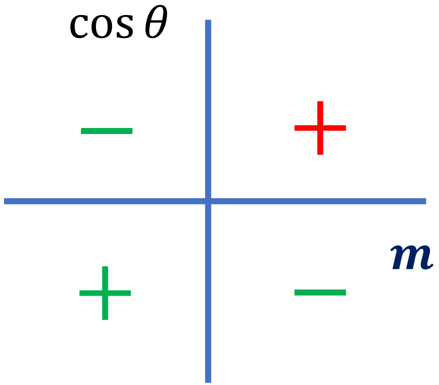


- **Less resonant dependence binning: adaptive binning approach (efficient when events are huge)**
- **Due to lack of statistics, no bin has significance more than 3σ**

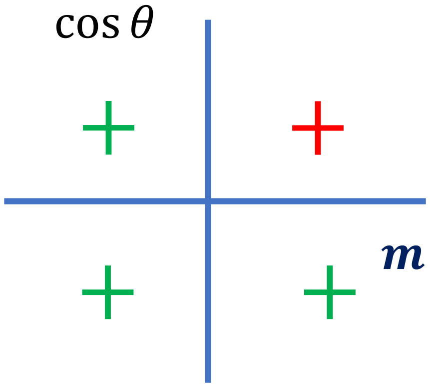
CP violation induced by different components



- **New types of CP violation found by the LHCb experiment in $B^+ \to \pi^+\pi^-\pi^+$ decays: CP violation through interference between S- and P-waves**
- **Similarly, also in b-baryon decays, affecting search of CP violation**



A_{CP} through S- and P-wave interference



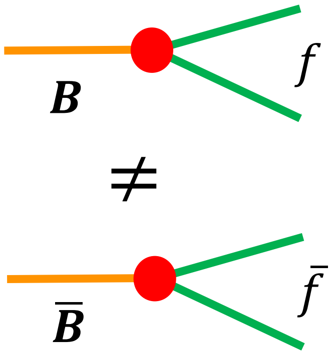
A_{CP} in one resonance

CP violation phenomena

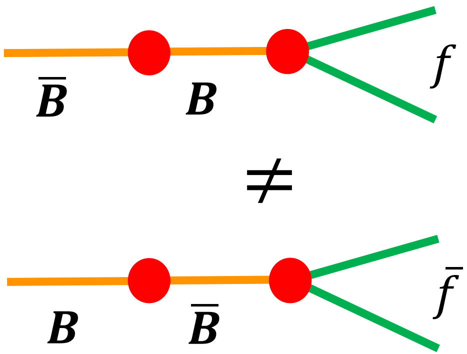
1964	1999	2001	2004	2012	2013	2019	????
CP violation (in mixing) in neutral Kaon decays	Direct CP violation in neutral Kaon decays	CP violation in mixing and decay in B^0 decays	Direct CP violation in B^0 decays	Direct CP violation in B^+ decays	Direct CP violation in B_s^0 decays	Direct CP violation in D^0 decays	Direct CP violation in baryon decays

Not only rich our understanding, but also provide new mechanism for generating matter antimatter asymmetry

Direct CP violation



CP violation in mixing



CP violation in interference between mixing and decay