Baryon CPV in LHCb: status and our plans

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Outline

- **Published results from LHCb**
- **Current activities and plans from LHCb-China group**
- **Conclusion**

Introduction

- Key physics question: why more matter than anti-matter in our Universe
- Sakharov three conditions: need CPV processes during involvement of our Universe
- CPV in SM: weak phase in CKM matrix

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

N.B. Vanishes for degenerate masses

$$J = \cos(\theta_{12})\cos(\theta_{23})\cos^2(\theta_{13})\sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\sin(\delta)$$

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

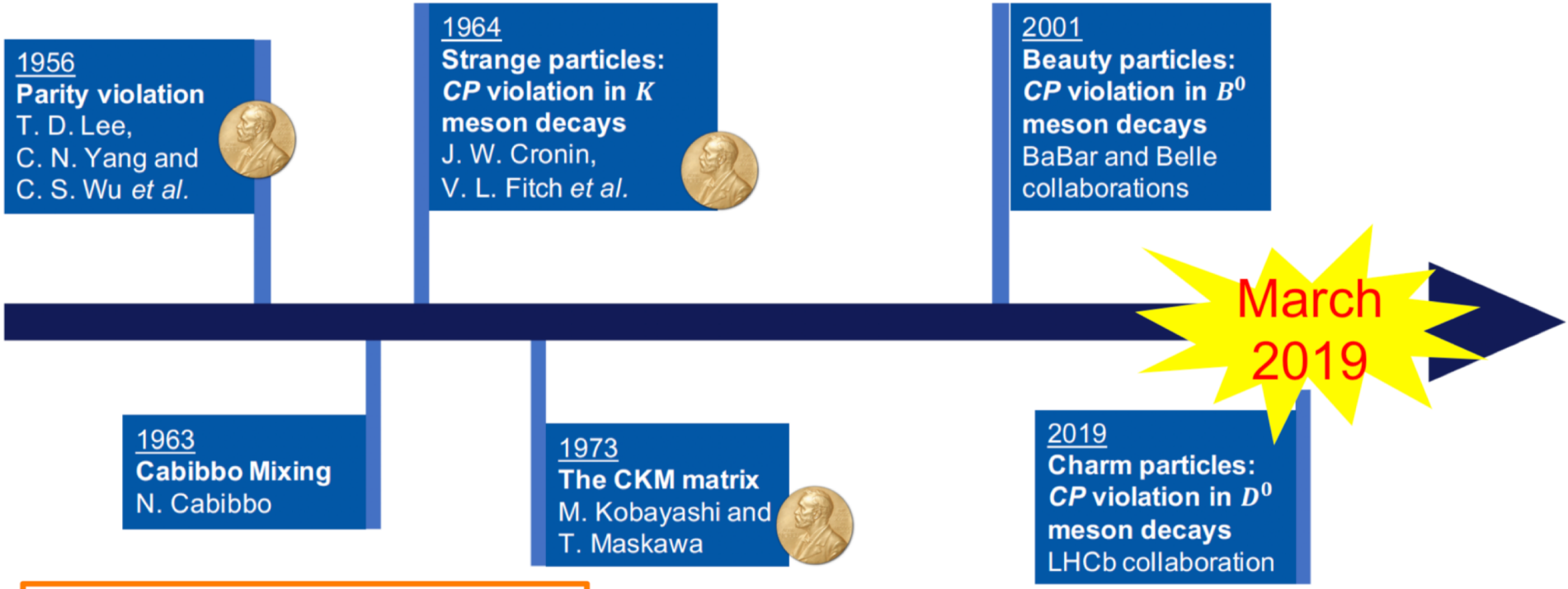
$$P_d = (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)$$

PRL 55 (1985) 1039

- J ~ 10^{-5}, M ~ 100 GeV (EW scale)
- SM predicts $\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-17}$, while observation gives 10^{-10}, orders of magnitude difference → Need to find new sources of CPV
- Find CPV in all possible places first

Observation of CPV in charm decays

LHCb-PAPER-2019-006



$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

A. Carbone, CERN seminar, March 19, 2019

CP violation in charm observed at 5.3σ

- The only place where CPV is not found is in baryon decays, closely related to baryon number asymmetry

Search for CPV in baryons before LHC

A. Merli, CERN seminar, October 22, 2019

Experiment	Decay	Measurement	
HyperCP	$\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$	$(0.0 \pm 5.1 \pm 4.4) \times 10^{-4}$	[1]
HyperCP	$\Omega^- \to \Xi^-\pi^+\pi^-$	0.12 ± 0.20	[2]
FOCUS	$\Lambda_c^+ \to \Lambda\pi^+$	$-0.07 \pm 0.19 \pm 0.12$	[3]
CLEO	$\Lambda_c^+ \to \Lambda e^+\nu_e$	$0.00 \pm 0.03 \pm 0.01 \pm 0.02$	[4]
CDF	$\Lambda_b^0 \to pK^-$	$-0.10 \pm 0.08 \pm 0.04$	[5]
CDF	$\Lambda_b^0 \to p\pi^-$	$0.06 \pm 0.07 \pm 0.03$	[5]

[1] Phys. Rev. Lett. 93 (2004) 262001
[2] Phys. Lett. B 693 (2010) 236
[3] Phys. Lett. B 634 (2006) 165
[4] Phys. Rev. Lett. 94 (2005) 191801
[5] Phys. Rev. Lett. 113 (2014) 242001

Consistent with CP symmetry

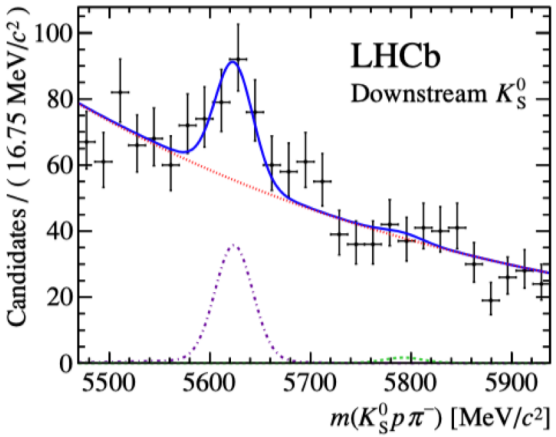
Current publications in LHCb

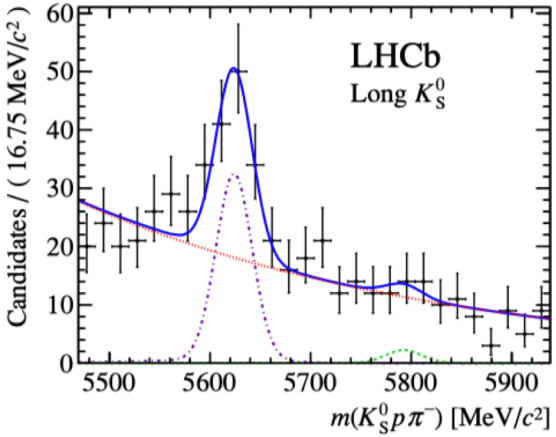
- A_{CP} measurements for $\Lambda_b \to K_S^0 p\pi^-$ (1 fb^{-1}) JHEP 04 (2014) 087
- A_{CP} measurements for $\Lambda_b \to \Lambda K^+\pi^-, \Lambda_b \to \Lambda K^+K^-$ (3 fb^{-1}) JHEP 05 (2016) 081
- A_{CP} measurements for $\Lambda_b \to p\pi^-, \Lambda_b \to pK^-$ (3 fb^{-1}) PLB 787 (2018) 124
- A_{CP} measurements for $\Lambda_b, \Xi_b \to p3h$ (3 fb^{-1}) EPJC 79 (2019) 745
- ΔA_{CP} measurements between $\Lambda_b \to J/\psi p\pi^-$ and $\Lambda_b \to J/\psi pK^-$ (3 fb^{-1}) JHEP 07 (2014) 103
- T-odd (energy test) measurements with $\Lambda_b \to p3h$ (3 or 6.6 fb^{-1}) Nature Phys. 13 (2017) 391, JHEP 39 (2018) 1808, LHCb-PAPER-2019-028

A_{CP} measurements for $\Lambda_b \to K^0_S p\pi^-$

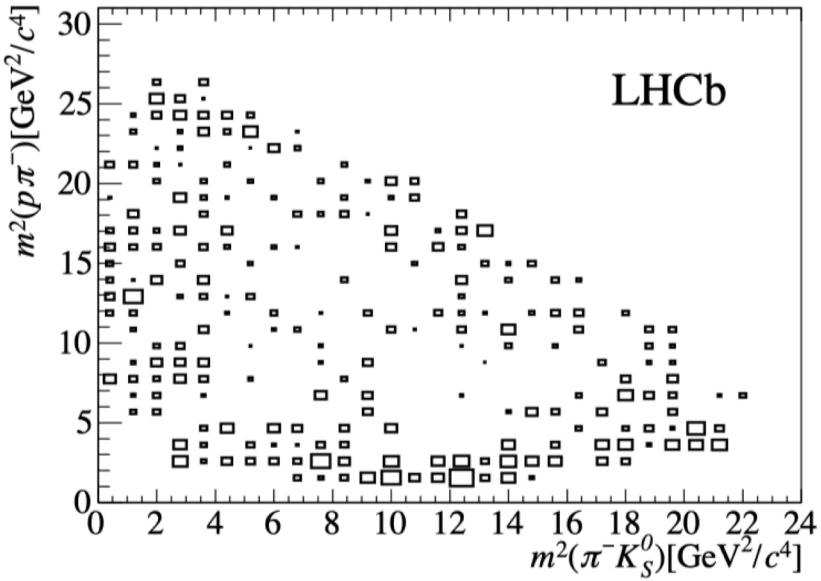
JHEP 04 (2014) 087

- Measurements performed with only 1 fb^{-1} data from 2011 (7 TeV)





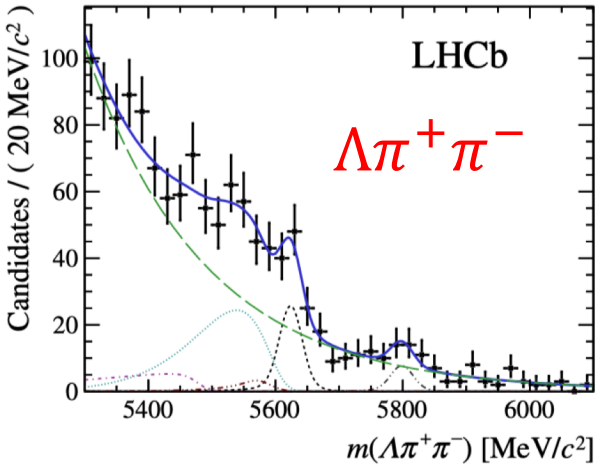
- Around 106 ± 22 DD events and 91 ± 15 LL events observed
- $A_{CP} = 0.22 \pm 0.13\,(\text{stat.}) \pm 0.03\,(\text{syst.})$
- CP violation over Dalitz plot may be interesting with more data
- 10 × more data with full Run1 + Run2

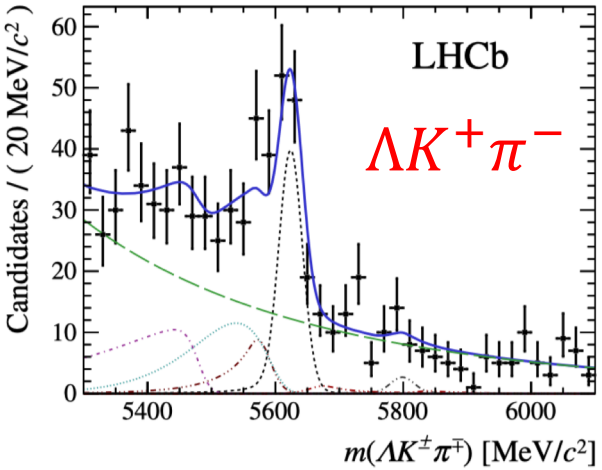


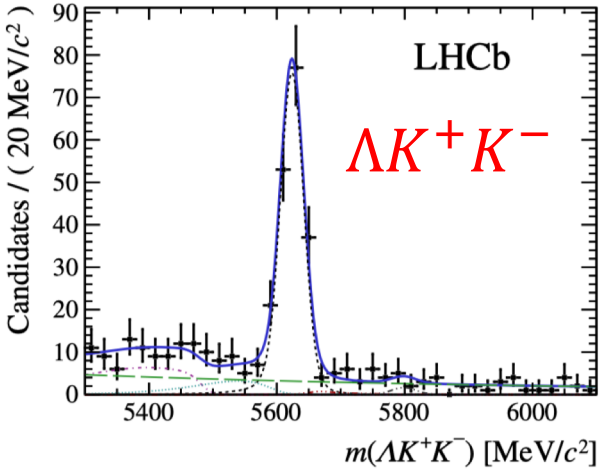
A_{CP} measurements for $\Lambda_b \to \Lambda hh$ (1)

JHEP 05 (2016) 081

- Measurements performed with 3 fb^{-1} data from Run1 (7 + 8 TeV)





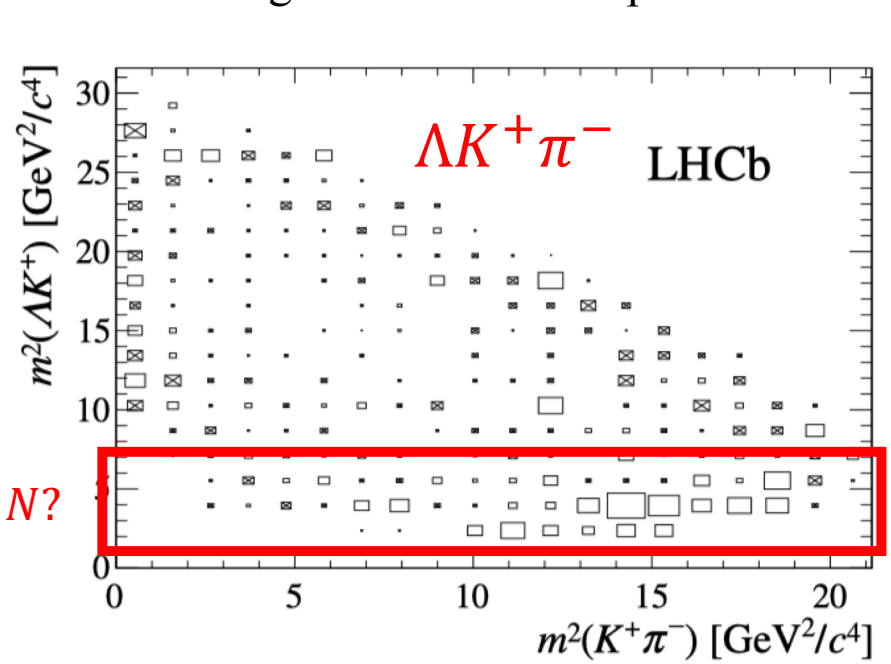


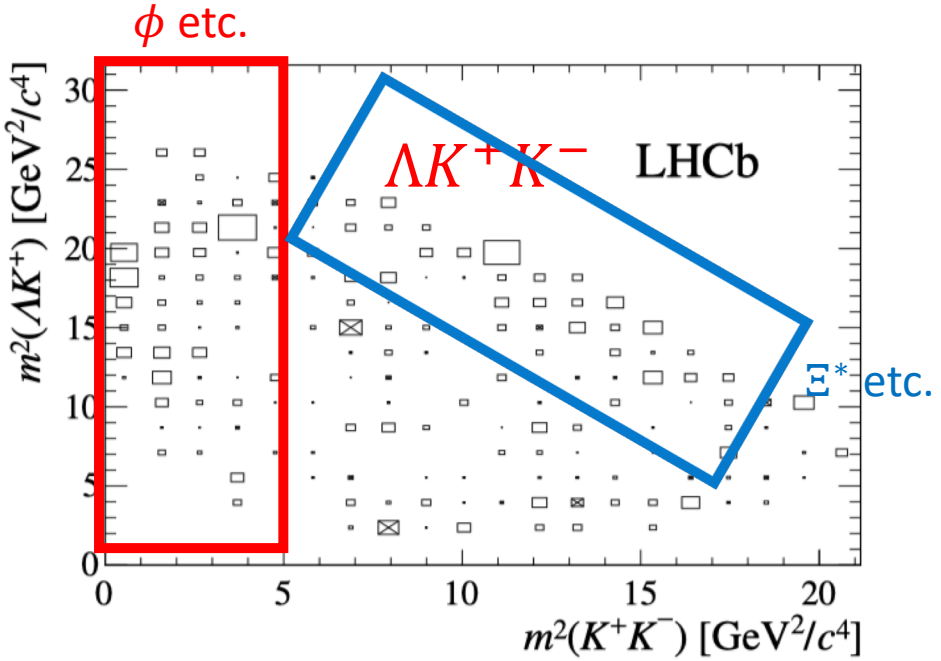
- For $\Lambda_b \to \Lambda\pi^+\pi^-$, 65 ± 14 events observed
- For $\Lambda_b \to \Lambda K^+\pi^-$, 97 ± 14 events observed
- For $\Lambda_b \to \Lambda K^+K^-$, 185 ± 15 events observed
- $A_{CP}\left(\Lambda_b^0 \to \Lambda K^+\pi^-\right) = -0.53 \pm 0.23\,(\text{stat.}) \pm 0.11\,(\text{syst.})$
- $A_{CP}\left(\Lambda_b^0 \to \Lambda K^+K^-\right) = -0.28 \pm 0.10\,(\text{stat.}) \pm 0.07\,(\text{syst.})$

A_{CP} measurements for $\Lambda_b \to \Lambda hh$ (2)

JHEP 05 (2016) 081

- Investigation over Dalitz plots are of interests



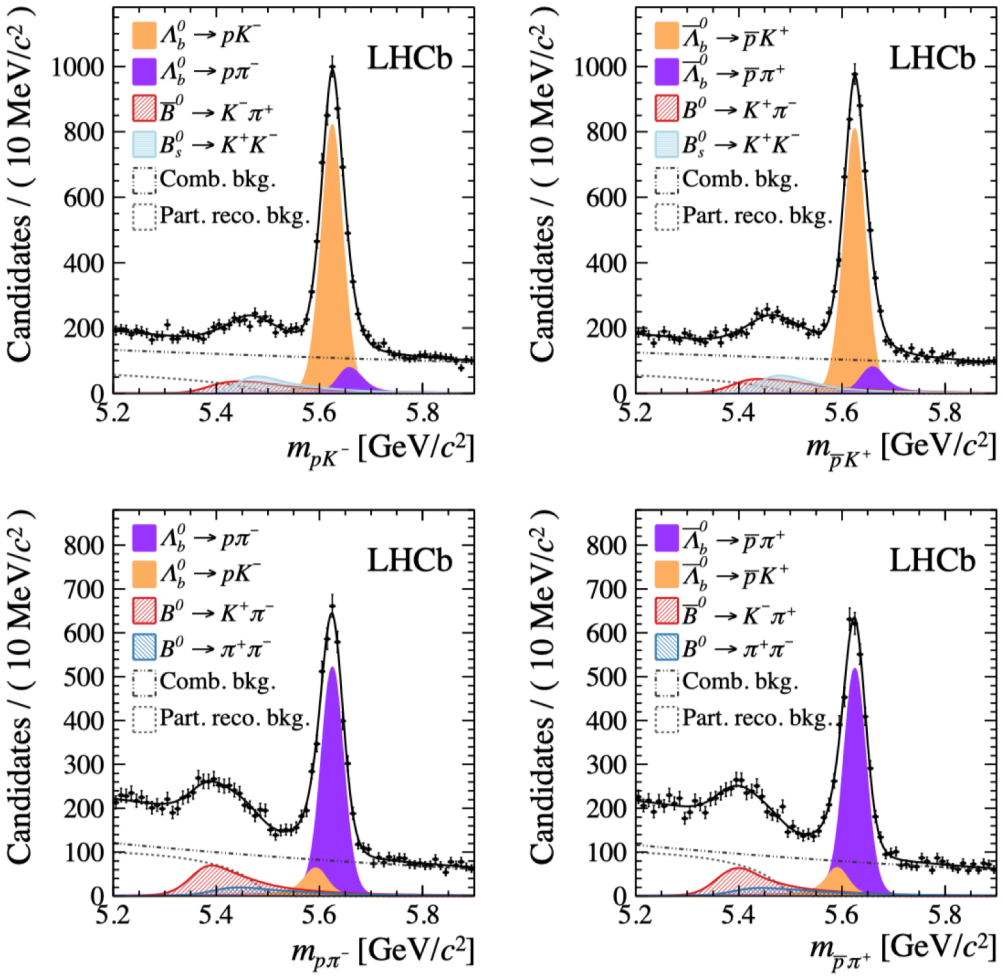


- Possible quasi-two contributions dominate over Dalitz plot

A_{CP} measurements for $\Lambda_b \to ph$

PLB 787 (2018) 124

- Measurements performed with 3 fb^{-1} data from Run1 (7 + 8 TeV)



- Around 8847 ± 125 $\Lambda_b \to pK$ and 6026 ± 105 $\Lambda_b \to p\pi$
- A_{CP} measured to be

$$A_{CP}^{pK^-} = -0.020 \pm 0.013 \pm 0.019,$$
$$A_{CP}^{p\pi^-} = -0.035 \pm 0.017 \pm 0.020,$$

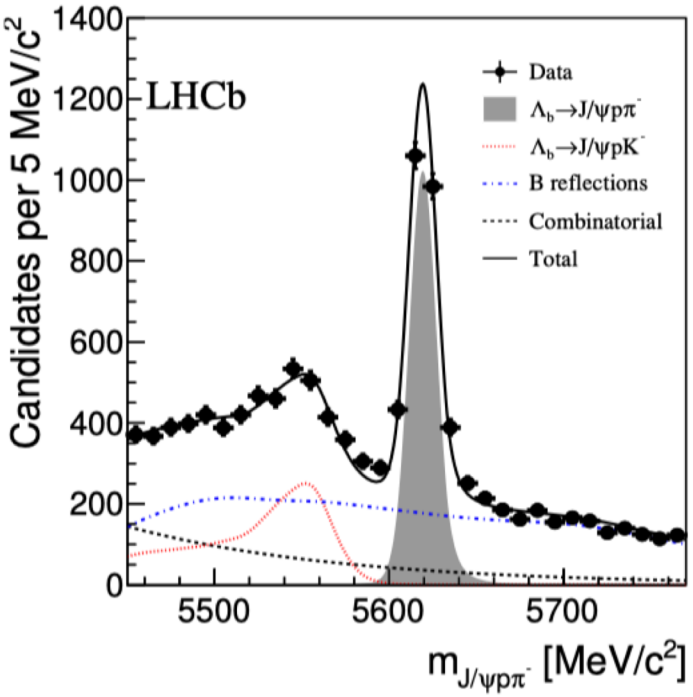
- Also ΔA_{CP} measured to be

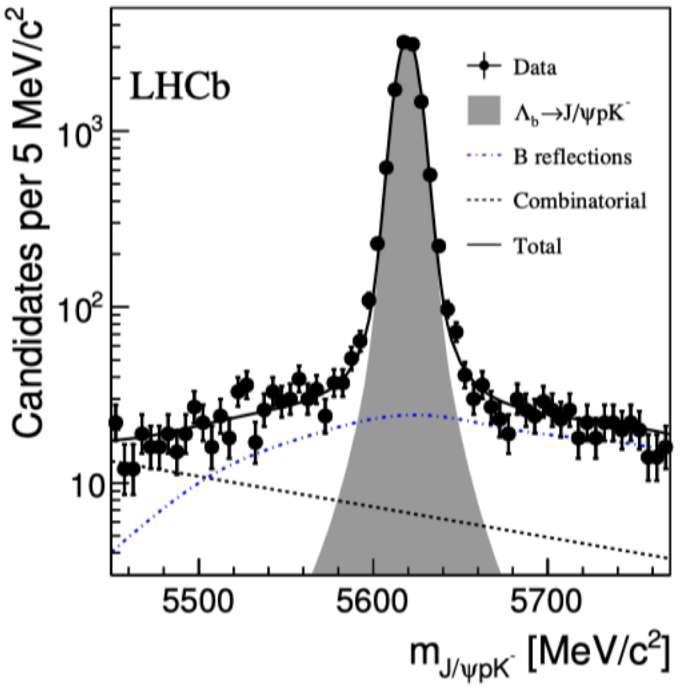
$$\Delta A_{CP} = 0.014 \pm 0.022 \pm 0.010,$$

A_{CP} measurements for $\Lambda_b \to J/\psi ph$

JHEP 07 (2014) 103

- Measurements performed with 3 fb^{-1} data from Run1 (7 + 8 TeV)





- Around $11179 \pm 109\ \Lambda_b^0 \to J/\psi pK$ and $2102 \pm 61\ \Lambda_b^0 \to J/\psi p\pi$
- $A_{CP}(\Lambda_b^0 \to J/\psi p\pi) - A_{CP}(\Lambda_b^0 \to J/\psi pK) = 0.057 \pm 0.024\ (\text{stat.}) \pm 0.012\ (\text{sys.})$

A_{CP} measurements for $\Lambda_b, \Xi_b \to p3h$

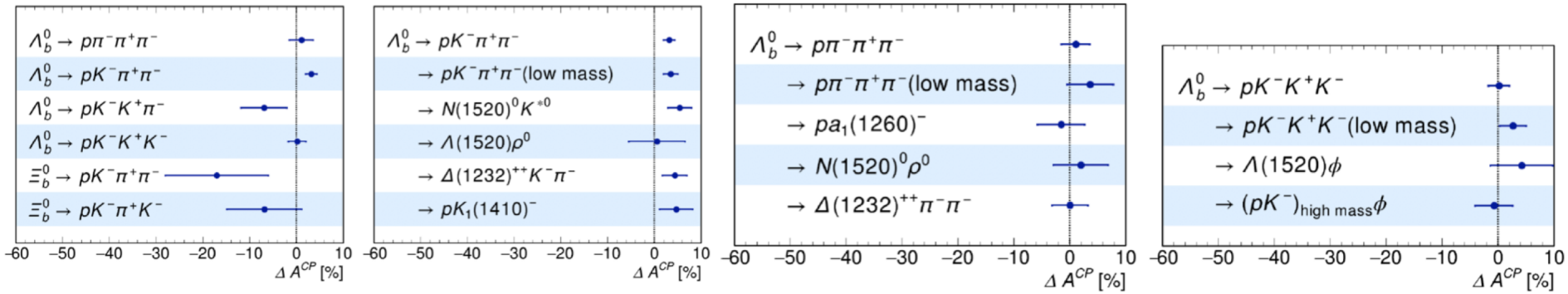
EPJC 79 (2019) 745

- Measurements performed with 3 fb^{-1} data from Run1 (7 + 8 TeV)
- Six channels studied w.r.t. control channels $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and $\Xi_b^0 \to \Xi_c^+\pi^-$, three of which further divided into specific regions of phase space :

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

$\Xi_b^0 \to pK^-\pi^+\pi^-$
$\Xi_b^0 \to pK^-\pi^+K^-$

- Results consistent with no CPV



Methods to measure A_{CP}

A_{CP} measurements

- Simple and direct measurements
- Crucial to get production asymmetry and to understand detector
- A_{CP} proportional to $\sin(\Delta\theta_{\text{strong}})\sin(\Delta\theta_{\text{weak}})$

TPA measurements

- Less efficiency sensitive and production sensitive
- CPV proportional to $\cos(\Delta\theta_{\text{strong}})\sin(\Delta\theta_{\text{weak}})$
- Only for four-body final states

Energy test measurements

- Less efficiency sensitive and production sensitive
- CPV proportional to $\cos(\Delta\theta_{\text{strong}})\sin(\Delta\theta_{\text{weak}})$ or $\sin(\Delta\theta_{\text{strong}})\sin(\Delta\theta_{\text{weak}})$ depending on configuration
- Can use TPA variables when more than three tracks

TPA measurements for $\Lambda_b \to p3h$

Nature Phys. 13 (2017) 391
JHEP 39 (2018) 1808
LHCb-PAPER-2019-028

- TPA measurements first measured on $\Lambda_b \to p3\pi$ and $\Lambda_b \to p\pi KK$ using 3 fb^{-1} data (7+8 TeV)
- Evidence of CPV found in $\Lambda_b \to p3\pi$ around 3.3 σ
- Further analysis with $\Lambda_b \to pK\pi\pi, \Xi_b \to pKK\pi$ and $\Lambda_b \to p3K$ are performed later using 3 fb^{-1} data, CPV compatible with zero
- A new updated analysis on $\Lambda_b \to p3\pi$ has been performed using 6.6 fb^{-1} data with 3.6 fb^{-1} more data from Run2 (13 TeV), 4× more than Run 1 analysis

Decay channels	Events in Run1
$\Lambda_b \to p3\pi$	6646 ± 105 (~1.6%)
$\Lambda_b \to pK\pi\pi$	19877 ± 195 (~1.0%)
$\Lambda_b \to pKK\pi$	1030 ± 56 (~5.4%)
$\Lambda_b \to p3K$	5297 ± 83 (~1.6%)
$\Xi_b \to pKK\pi$	709 ± 45 (~6.3%)

TPA measurements for $\Lambda_b \to p3\pi$ (1) LHCb-PAPER-2019-028

- Triple products defined in Λ_b rest frame

$$C_{\hat{T}} = \vec{p}_p \cdot \left(\vec{p}_{\pi^-_{fast}} \times \vec{p}_{\pi^+} \right) \propto \sin\Phi$$

$$\overline{C}_{\hat{T}} = \vec{p}_{\bar{p}} \cdot \left(\vec{p}_{\pi^+_{fast}} \times \vec{p}_{\pi^-} \right) \propto \sin\overline{\Phi}$$

- T(P)-odd asymmetries

$$A_{\hat{T}} = \frac{N_{\Lambda_b^0}(C_{\hat{T}} > 0) - N_{\Lambda_b^0}(C_{\hat{T}} < 0)}{N_{\Lambda_b^0}(C_{\hat{T}} > 0) + N_{\Lambda_b^0}(C_{\hat{T}} < 0)}$$

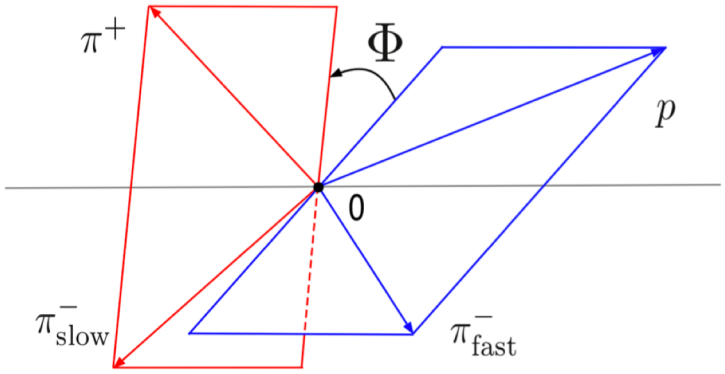
$$\overline{A}_{\hat{T}} = \frac{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} > 0) - N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} < 0)}{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} > 0) + N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} < 0)}$$

- CP and P-violating variables

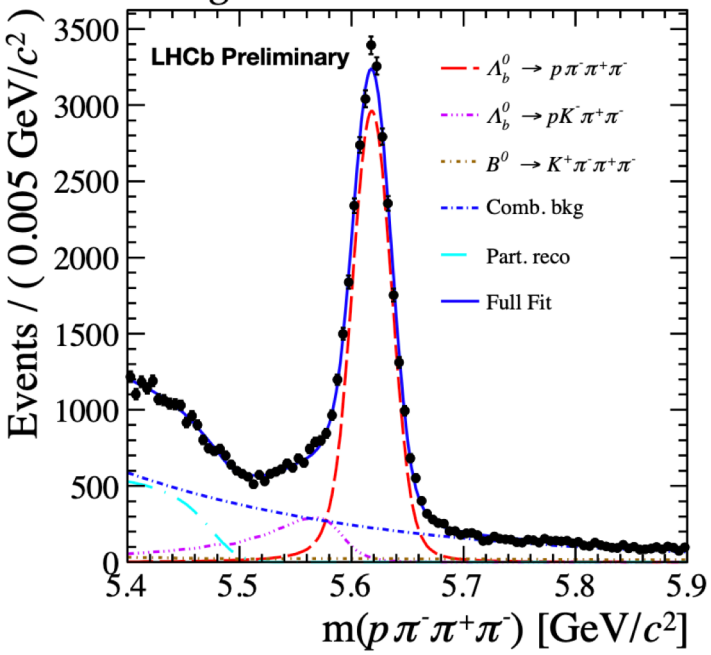
$$a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} - \overline{A}_{\hat{T}}\right) = -0.70 \pm 0.70 \pm 0.17$$

$$a_{P}^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} + \overline{A}_{\hat{T}}\right) = -3.98 \pm 0.70 \pm 0.17$$

- Investigating over PHSP may gain more

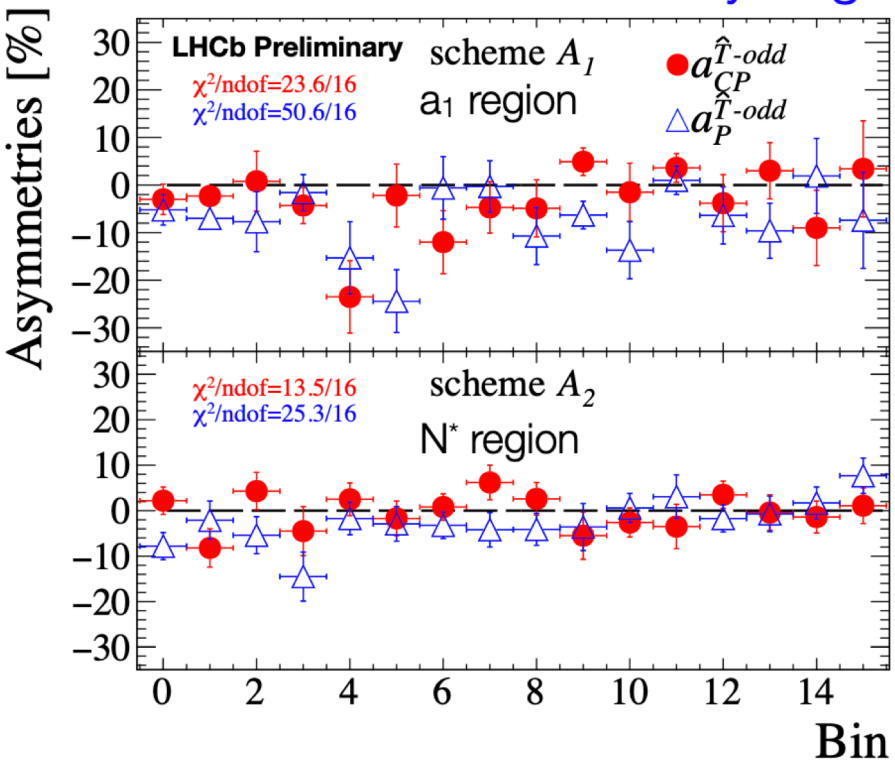


$N_{sig} = 27600 \pm 200$

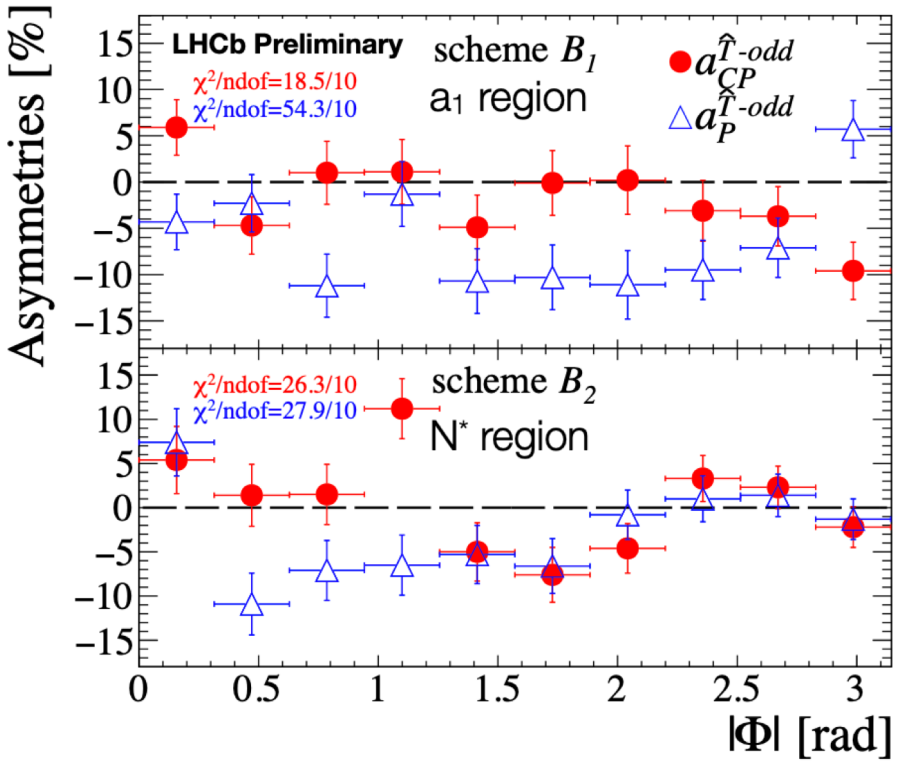


TPA measurements for $\Lambda_b \to p3\pi$ (2) LHCb-PAPER-2019-028

Scheme A: based on helicity angles



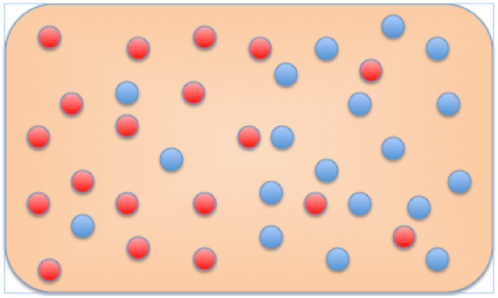
Scheme B: on Φ angle intervals



- Main contributions from $\Lambda_b \to N^{*+}\pi^-, pa_1^-$(negligible CPV)
- Two binning scheme: scheme A (helicity angle of N^{*+}), scheme B (ϕ)
- A_1, B_1 dominated by pa_1^-, while A_2, B_2 dominated by $N^{*+}\pi^-$
- CPV at the level of 2.9 σ in scheme B_2

Energy test for $\Lambda_b \to p3\pi$

LHCb-PAPER-2019-028



Test Statistic:

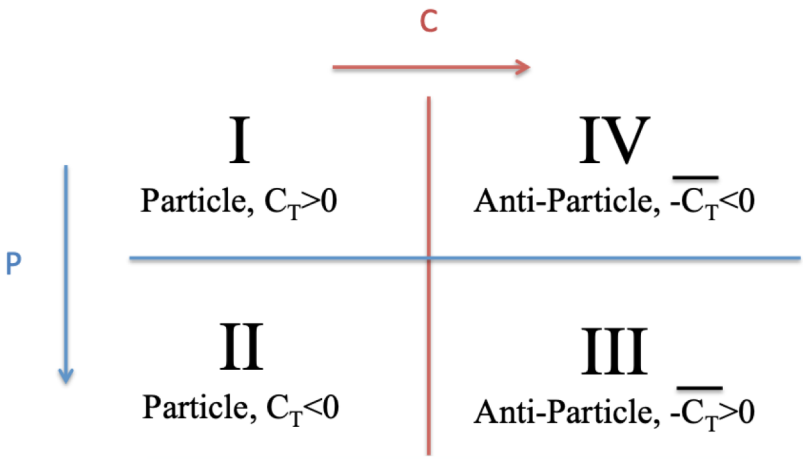
$$T = \frac{1}{n(n-1)} \sum_{i,j>1}^{n} \psi(d_{ij}) + \frac{1}{\bar{n}(\bar{n}-1)} \sum_{i,j>1}^{\bar{n}} \psi(d_{i,j}) - \frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi(d_{ij})$$

Sample A | Sample B | All sample

- $\psi(d_{ij}) = e^{-d_{ij}^2/\delta^2}$: distance function
- $n, \bar{n}$: number of particle (antiparticle) candidates
- d_{ij} : distance in phase space
- δ : parameter to optimize

- **P violation**:
  - CP-even P-odd: [I]+[III] vs [II]+[IV]
- **CP violation**:
  - CP-odd P-even test: [I+II] vs [III+IV]
  - CP-odd P-odd test: [I+IV] vs [II+III]

- Overall P-even CPV at 2.8 σ



$$C_T = \vec{p}(\pi_3) \cdot [\vec{p}(\pi_1) \times \vec{p}(\pi_2)]$$

$$CP(C_T) = -C(C_T) = -\bar{C}_T$$

What's next

Ongoing analysis by LHCb China

- A_{CP} measurements for $\Lambda_b \to K_S^0 p\pi^-$ (9 fb^{-1}) , expect 1500 signals with better background rejection;
- Can also investigate CPV in Dalitz regions
- Large CPV predicted by theorists (PRD 91 (2015) 116007)

Pipeline analyses

- A_{CP} measurements for $\Lambda_b \to \Lambda K^+\pi^-, \Lambda_b \to \Lambda K^+K^-$ (9 fb^{-1})
- A_{CP} measurements for $\Lambda_b, \Xi_b \to p3h$ (9 fb^{-1})
- A_{CP} measurements for $\Lambda_b \to K_S^0 \Lambda$ (9 fb^{-1})
- 5-6 × more signals than Run1

Further analyses

- CPV measurements in hyperon
- Cross section ~ O(1) barn, $10^{15\text{-}16}$, wise trigger needed to get them!!

Conclusion

- Search for CPV in baryon decays is important to understand matter-antimatter asymmetries in our Universe
- There are already some publications in LHCb, no CPV found yet
- The LHCb-China group is currently working on $\Lambda_b \to pK_S h$ analysis
- Will continue to investigate more channels like $\Lambda_b \to \Lambda hh, \Lambda_b \to p3h$ etc
- Suggestions from our theorist friends on more/better channels are welcomed
- How can we interpret them once CPV found in b-baryons? Are they consistent with SM? Extraction of CKM parameters?

Thank you for your attention