Measurement of Direct *CP* Violation in $\Lambda_b^0 \to ph^-$ Decays at LHCb (Run 1+2)

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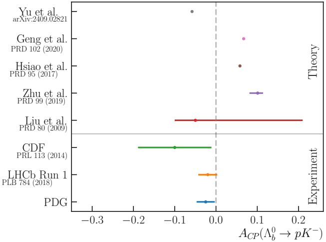
CP Violation (CPV) in $\Lambda_b^0 \to ph^-$

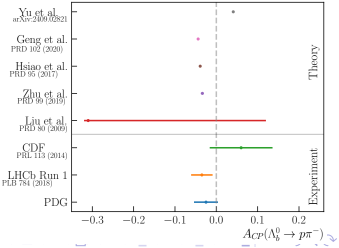
- The b quark is an excellent laboratory for searches of CPV due to its large mass and long lifetime (recent 3σ evidence for CPV in Λ_b^0 decays at LHCb[a]!)
- Two-body b-hadron decays to charmless final states ($H_b \to h^+ h'^-$; $h = \pi, K, p$) ideal channels for CPV searches
- For what concerns the Λ_b^0 baryon the $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ are viable candidates due to CPV already observed in $B^0 \to K^+\pi^-$ (+New Physics may appear in penguin loops! )
- World averages dominated by LHCb Run 1

$$A_{CP}(\Lambda_b^0 \to pK^-) = (-2.5 \pm 2.2)\%$$
$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (-2.5 \pm 2.9)\%$$

[a] https://indico.cern.ch/event/1441582/

Theoretical and experimental status





General Strategy

CPV observable A_{CP} not directly accessible

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

A_{CP} can be related to the observed countings in the detector accounting for experimental asymmetry effects (A_i)

$$A_{raw}(\Lambda_b^0 \to f) = \frac{N(\Lambda_b^0 \to f) - N(\overline{\Lambda}_b^0 \to \overline{f})}{N(\Lambda_b^0 \to f) + N(\overline{\Lambda}_b^0 \to \overline{f})} \simeq A_{CP} + \sum_i A_i \qquad (1)$$

Consistency check: all quantities measured in subsamples (year/LHCb magnet polarity) $\to$ check for flat behaviour of A_{CP}

Dataset and Selection

$H_b \to h^+ h'^-$ dataset known to contain

- Signal events $H_b \to h^+ h'^-$
- Cross-feed backgrounds
  - tackle with PID selection and efficiencies
- Partially-reconstructed multi-body b-decays
  - not too problematic thanks to excellent LHCb invariant mass resolution
- Combinatorial background
  - tackle with BDT selection

Analysis performed on events surviving dedicated $H_b \to h^+ h'^-$ trigger line

Raw Asymmetry Estimation

- Toy experiments used to determine optimal[1] BDT+PID cuts (Run 2) Run 1 data: used old requirements
- Perform simultaneous invariant-mass fit to the 8 possible $h^+h'^-$ spectra[2] with the optimal requirements
  - Signal yields in one spectrum become cross-feed in the other spectra (using PID efficiencies)
  - PID efficiencies estimated with high statistics and high purity calibration samples [1] (+kinematic reweight to translate to $H_b \to h^+h'^-$ case)

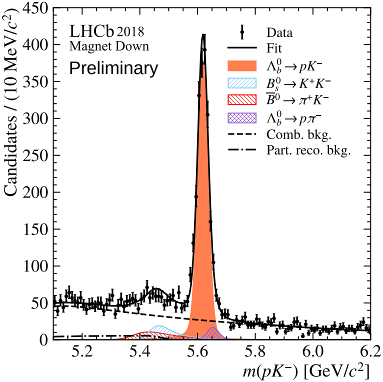
  $\to A_{raw}$ extraction and statistical uncertainty

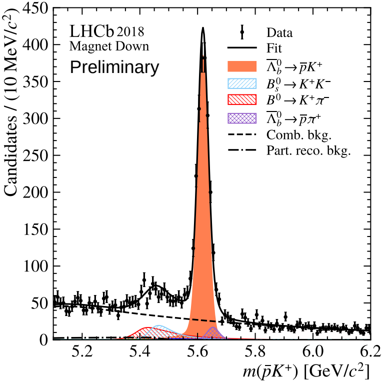
Systematic uncertainties related to the fit model estimated by fitting components with alternative models

[1] Choose selection that predicts the smallest statistical uncertainty

[2] $pK^-, \overline{p}K^+, p\pi^-, \overline{p}\pi^+, K^+\pi^-, K^-\pi^+, K^+K^-, \pi^+\pi^-$

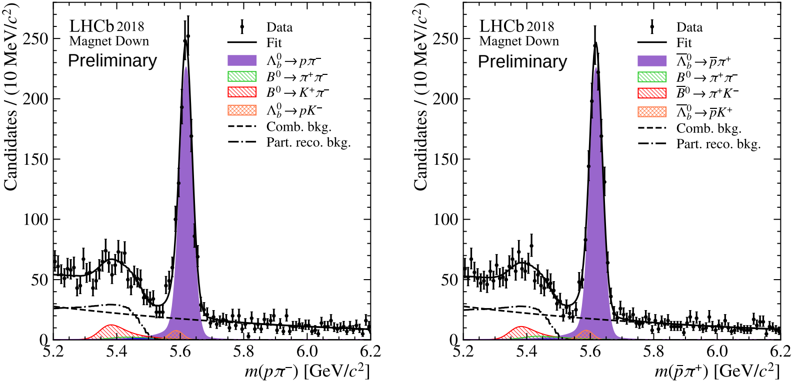
Invariant mass fit for $\Lambda_b^0 \to pK^-$





Raw Asymmetry - $\Lambda_b^0 \to p\pi^-$

Invariant mass fit for $\Lambda_b^0 \to p\pi^-$



Experimental Asymmetries

Once A_{raw} are found, need to correct for all the experimental effects
Experimental asymmetries $\rightarrow$ Determined with data driven techniques

Different strategy depending on the Run

- Run 1: New LHCb measurements of Λ_b^0 production asym. $A_P(\Lambda_b^0)$ and p detection asym. $A_D(p)$ assumed as external inputs [2]

  $$A_{CP}(ph^-) \simeq A_{raw} - A_P(\Lambda_b^0) - A_D(p) - A_D(h) - A_{PID}(ph^-) - A_{trig}(ph^-)$$

- Run 2: No external $A_P(\Lambda_b)$, $A_D(p)$ are available
  $\rightarrow$ consider $A_{raw}(\Lambda_b^0 \rightarrow ph^-) - A_{raw}(\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-)$ to subtract
  $A_P(\Lambda_b^0) - A_P(\Lambda_b \rightarrow \Lambda_c^+\pi^-)$
  kinematics was reweighted for better cancellation
  $\rightarrow$ Same $A_D(p)$ as Run 1 (no detector change, verified with $A_D(h)$)

Particle IDentification asymmetries A_{PID} studied with standard LHCb calibration samples [1]

p from $\Lambda \to pK^-$ (do not cover well full $H_b \to h^+h'^-$ kinematics)

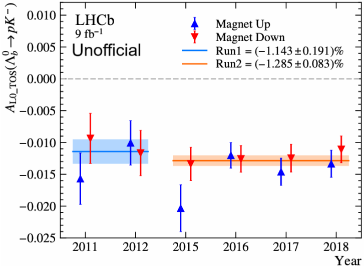
π/K from $D^{\star+} \to (D^0 \to K^-\pi^+)\pi^+$

New strategy: fiducial cuts (remove 30% of the $H_b \to h^+h'^-$ statistics BUT reduce PID systematics)

Trigger Asymmetries A_{trig}

Major improvements compared to previous analysis

Exploit semileptonic $(\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu\nu X$ for p, $B^0 \to (D^0 \to K^+\pi^-)\mu\nu X$ for π/K) and $B^+ \to J/\psi\, K^+$ decays



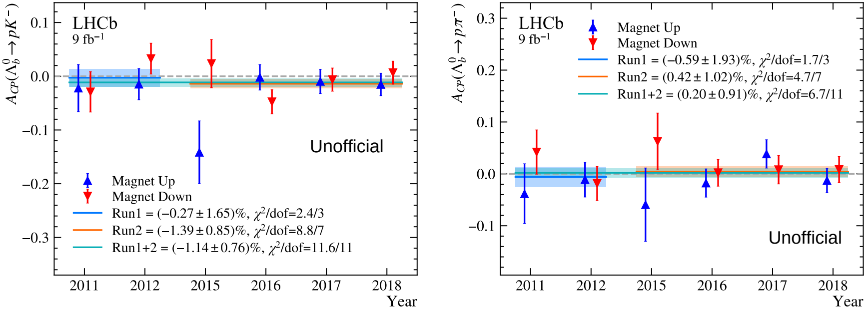
Combination of Results and Correlations

Several corrections were used multiple times, introducing correlations among different year/magnet subsamples.

Tables containing the re-used information are re-generated 1000 times (gaussianly, μ=central value used in the analysis,σ=associated uncertainty), then A_{CP} values are measured and correlations among subsamples are extracted.

Finally, once the correlations are known, the variances matrices V can be written and a final value of the asymmetry is derived (according to [3]).

A_{CP} by Subsample



Good consistency among subsamples

Results

Combined Run 1+2 results

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

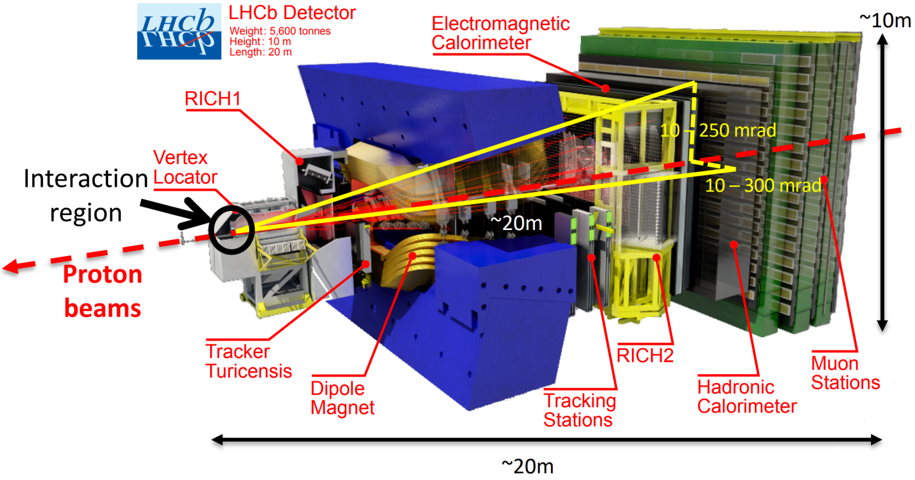
- No evidence of CPV
- Now result is statistically limited!
- Previous Run 1 result superseded
- Improved previous world averages by factor 3

Results presented at Implications of LHCb measurements workshop
https://indico.cern.ch/event/1423686/contributions/6139351/

Stay tuned for `LHCb-PAPER-2024-048`

Back-up

LHCb Detector - Run I/II



LHCb Performance Figures

Optimal for b physics

- $2 < \eta < 5$
- $\frac{\delta p}{p} \leq 1\%$
- Excellent PID
  - RICH
    $\varepsilon_{PID}(K \to K) \approx 95\%$
    $\varepsilon_{PID}(\pi \to K) < 10\%$
  - MUON
    $\varepsilon_{PID}(\mu \to \mu) \geq 95\%$
    $\varepsilon_{PID}(h \to \mu) < 5\%$
  - ECAL resolution
    $\frac{\sigma}{E} = \frac{10\%}{\sqrt{E}} \oplus 1\%$

$\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$ control sample gets rid of the necessity of the Λ_b^0 production asymmetry term $(A_P(\Lambda_b^0))$[3]

$$\begin{aligned} A_{CP}(ph^-) \simeq & + A_{raw}(ph^-) - A_D(p|\Lambda_b^0 \to ph^-) - A_D(h^-|\Lambda_b^0 \to ph^-) + \\ & - A_{PID}(ph^-) - A_{trig}(ph^-) - A_{raw}(\Lambda_b^0 \to \Lambda_c^+\pi^-) + \\ & + A_D(p|\Lambda_b^0 \to \Lambda_c^+\pi^-) + A_D(\pi^-|\Lambda_b^0 \to \Lambda_c^+\pi^-) + \\ & + A_D(K^-|\Lambda_c^+ \to pK^-\pi^+) + A_D(\pi^+|\Lambda_c^+ \to pK^-\pi^+) + \\ & + A_{PID}(\Lambda_b^0 \to \Lambda_c^+\pi^-) + A_{trig}(\Lambda_b^0 \to \Lambda_c^+\pi^-) = \\ = & \Delta A_{raw} - \Delta A_D^p - \Delta A_D^h - \Delta A_{PID} - \Delta A_{trig} + (-\Delta A_P + A_{CP}^{\Lambda_c^+\pi^-}) \end{aligned}$$

[3] After correcting for (p_T, η) distributions
$A_P(\Lambda_b^0)$ depends on (p_T, η)

Table: Triggering (HLT2) and stripping requirements for $B \to h^+ h'^-$ events during LHCb Run2.

Variable	Requirement
Track p_T	$> 1\,\mathrm{GeV}/c$
Track χ^2_{IP}	> 16
Track χ^2/ndf	< 4
Track `GhostProb`	< 3
$m_{\pi^+\pi^-}$	$\in$ 4.8-6.2 GeV/c^2
$p_T^+ + p_T^-$	$> 4.5\,\mathrm{GeV}/c$
$\chi^2_{\mathrm{DOCA}}/\mathrm{ndf}$	< 9
$\mathrm{DIRA}(H_b)$	> 0.99
$\chi^2_{\mathrm{IP}}(H_b)$	< 9
$\chi^2_{\mathrm{FD}}(H_b)$	> 100

Optimisation Cuts

Variable		Explored Values	Selection
BDT	$>$	$0 \to 0.4$ (step-size: 0.04)	$\Lambda_b^0 \to ph^-$
$\Delta \log \mathcal{L}_{p\pi}(p)$	$>$	$1, 3, 5, 7, 9, 11, 13$	
$\Delta \log \mathcal{L}_{pK}(p)$	$>$	$1, 3, 5, 7, 9$	
$\Delta \log \mathcal{L}_{K\pi}(K)$	$>$	$1, 3, 5, 7$	$\Lambda_b^0 \to pK^-$
$\Delta \log \mathcal{L}_{Kp}(K)$	$>$	$-\Delta \log \mathcal{L}_{pK}(p) \to -1$ (step-size: 2)	
$\Delta \log \mathcal{L}_{K\pi}(K)$	$<$	$-7, -5 - 3, -1$	$\Lambda_b^0 \to p\pi^-$
$\Delta \log \mathcal{L}_{Kp}(K)$	$<$	$1 \to \Delta \log \mathcal{L}_{p\pi}(p)$ (step-size: 2)	

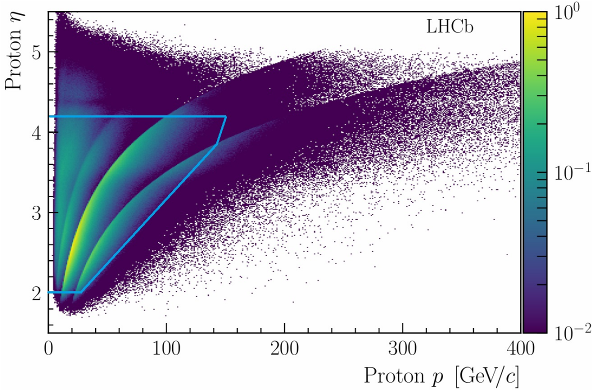


Figure: LHCb Run 2 proton calibration samples (from [1]) with the fiducial cuts (cyan) added for this analysis. 30% of the $H_b \to h^+ h'^-$ statistics is lost BUT low systematic due to highly populated calibration sample.

Fit Model

- Signal: Gaussians with Johnson tails. Ratios obtained from fit to simulated events (alternative model: crystal balls)
- Cross-feed: simulated signal events with invariant mass calculated in the wrong final state hypothesis, then templates are built with KDE [4] + correction for PID cuts (assign weight to each event $w_i = \varepsilon_{h^+} \cdot \varepsilon_{h^-}(p_i^{\pm}, \eta_i^{\pm})$) (alternate model: no PID weights)
- Multi-body b-decays: ph^- spectra from templates simulated with RapidSim [5]. Other channels with ARGUS functions (alternate model: ph^- also done with ARGUS)
- Combinatorial: exponential + term to account for trigger cuts effects (alternative model: second order Čebyšëv polynomials)

Trigger Asymmetries

- 3 levels (L0 (hardware), HLT1, HLT2)
- TIS and TOS (Trigger Independent/On Signal)

Trigger Independent of Signal (TIS) $\rightarrow$ another beauty triggers the event
$B^+ \rightarrow J/\psi K^+$, asymmetry as a function of p_T (reweight to Λ_b^0 p_T)
Unbias the sample from TIS decision $\rightarrow$ require it also fired TOS

$$\varepsilon^{\pm}_{\text{TIS}} = \frac{N(\text{TIS\&\&TOS}, B^{\pm})}{N(\text{TIS\&\&TOS}, B^{\pm}) + N(!\text{TIS\&\&TOS}, B^{\pm})}$$

$$A_{\text{TIS}} = \frac{\varepsilon^{-}_{\text{TIS}} - \varepsilon^{+}_{\text{TIS}}}{\varepsilon^{-}_{\text{TIS}} + \varepsilon^{+}_{\text{TIS}}}$$

Final L0 TIS asymmetry very small (<0.25%)

Trigger Asymmetries (II)

TOS requires both L0 and HLT1 evaluation

- Protons from $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu\nu X$
- Pions/Kaons from $B^0 \to (D^0 \to K^+\pi^-)\mu\nu X$
  Events randomly split to decorrelate π and K corrections

Procedure similar between L0 and HLT1

- Compute efficiency map as function of E_T and HCAL regions
  $\varepsilon_h^{\pm}(E_T) = \frac{N(\text{L0Hadron\_TOS}(h^{\pm})\&\text{L0Muon\_TOS}(\mu);E_T)}{N(\text{L0Muon\_TOS}(\mu);E_T)}$
- Convert to $\Lambda_b^0 \to ph^-$ via
  $\varepsilon_{\Lambda_b^0(\overline{\Lambda}_b^0)} = 1 - (1 - \varepsilon_p^{+(-)})(1 - \varepsilon_h^{-(+)})$
  $A_{\Lambda_b^0\, i} = \frac{\varepsilon_{\Lambda_b^0} - \varepsilon_{\overline{\Lambda}_b^0}}{\varepsilon_{\Lambda_b^0} + \varepsilon_{\overline{\Lambda}_b^0}}$
- Integrate over all $A_{\Lambda_b^0}$ bins

- π
  - Run 1: partially reconstructed $D^{*+} \to (D^0 \to K^-\pi^+\pi^-\pi^+)\pi^+$ (ε=N(full event)/N(missed a pion))
  - Run 2: $K_S^0 \to \pi^+\pi^-$ from $D^0 \to K_S^0\pi^+\pi^-$ (ε=N($\pi^\pm$ VELO track matched to long trang)/N($\pi^\pm$ VELO track))
- K
  - find detection asymmetry $A_D(K^-\pi^+)$ with the use of $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K_S^0\pi^+$, $A_D(K^-) = A_D(K^-\pi^+) - A_D(\pi^+)$

Systematics

	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 trigger	0.20	0.21	0.10	0.10
HLT 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
Systematic	0.57	0.53	0.41	0.42
Statistical	1.55	1.86	0.75	0.93
Total uncertainty	1.65	1.93	0.85	1.02

Results Combination

$$V = V_{stat} + V_{syst}$$

$$V_{stat} = \begin{pmatrix} (\sigma^{1U}_{stat})^2 & & 0 \\ & \ddots & \\ 0 & & (\sigma^{8D}_{stat})^2 \end{pmatrix}$$

$$V_{syst} = \begin{pmatrix} (\sigma^{1U}_{syst})^2 & \cdots & \rho_{1U,8D}\sigma^{1U}_{syst}\sigma^{8D}_{syst} \\ \vdots & \ddots & \vdots \\ \rho_{1U,8D}\sigma^{1U}_{syst}\sigma^{8D}_{syst} & \cdots & (\sigma^{8D}_{syst})^2 \end{pmatrix}$$

Correlated data, averaged using the prescription in [3]

$$A_{CP} = (\sum_i \sum_j (V^{-1})_{ij})^{-1} (\sum_i \sum_j (V^{-1})_{ij} A_{CP\,j})$$

$$\sigma^2(A_{CP}) = (\sum_i \sum_j (V^{-1})_{ij})^{-1}$$

Results

Run 1

$$A_{CP}(\Lambda_b^0 \to pK^-) = (-0.27 \pm 1.55 \pm 0.57)\%$$
$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (-0.59 \pm 1.86 \pm 0.53)\%$$

Run 2

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

[1] LHCb Collaboration, "Selection and processing of calibration samples to measure the particle identification performance of the LHCb experiment in Run 2," *EPJ Techniques and Instrumentation*, vol. 6, no. 1, p. 1, 2019. [Online]. Available: https://doi.org/10.1140/epjti/s40485-019-0050-z

[2] ——, "Observation of a Λ_b^0-$\overline{\Lambda}_b{}^0$ production asymmetry in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV," *Journal of High Energy Physics*, vol. 2021, no. 10, Oct. 2021. [Online]. Available: http://dx.doi.org/10.1007/JHEP10(2021)060

[3] M. Schmelling, "Averaging correlated data," *Physica Scripta*, vol. 51, no. 6, p. 676, 1995.

[4] K. S. Cranmer, "Kernel estimation in high-energy physics," *Comput. Phys. Commun.*, vol. 136, pp. 198–207, 2001.

[5] G. A. Cowan, D. C. Craik, and M. D. Needham, "RapidSim: an application for the fast simulation of heavy-quark hadron decays," *Comput. Phys. Commun.*, vol. 214, pp. 239–246, 2017.