CP violation in *b* baryon decays at LHCb

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Introduction

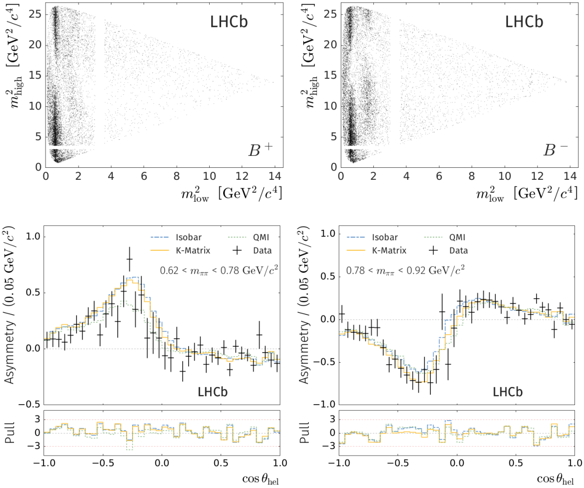
CP violation is an important phenomenon in the Standard Model, and could help find New Physics.

- Interference of at least two amplitudes, with nonzero weak and strong phases.
- Will only consider *direct* CPV here, $\Gamma(f) \neq \Gamma(\bar{f})$
- Tree-only processes (typically, beauty $\to$ charm transitions):
  - Dominated by SM, universal weak phase γ
  - Theoretically clean measurements due to factorisation of b and c decay amplitudes
  - (see talk by Philippe d'Argent)
- Processes with loops (typically, beauty $\to$ charmless):
  - Could be affected by NP
  - Hard-to-evaluate hadronic contributions

CPV in B meson decays

CPV is *very* significant in many B meson decays (charmed and charmless).

E.g. $B^{\pm} \to \pi^{\pm}\pi^{-}\pi^{+}$ decays: [PRL 124 (2020) 031801]



$\mathcal{O}(1)$ asymmetry in parts of the phase space

Similarly, CPV should manifest itself in b baryon decays, but no reliable signal so far.

- 4-body decays of Λ_b^0 (fully charged)
- 3-body baryonic decays:
  - Λ_b^0 decays with one neutral particle (K_S^0, Λ^0, π^0) $\Rightarrow$ low efficiency at LHCb
  - Fully-charged 3-body decays of Ξ_b^- $\Rightarrow$ lower pp fragmentation fraction

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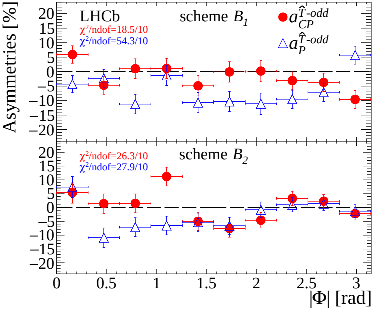
[PRD 102 (2020) 051101]

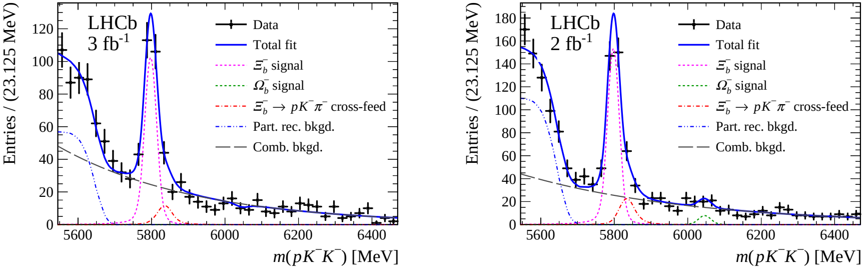
- Non-planar decays,
  $C = \vec{p}_p \cdot [\vec{p}_{\pi^-_{\rm fast}} \times \vec{p}_{\pi^+}] \neq 0$
- 4 categories of events:
  $C < 0$ and $C > 0$, Λ_b^0 and $\overline{\Lambda}_b^0$.
- CP-violating and P-violating asymmetries in bins of phase space.



$> 5\sigma$ observation of P violation, $2-3\sigma$ hint on CP violation

$\Xi_b^- \to pK^-K^-$ is among the most promising charmless CPV modes

$b \to s$ penguin transition.

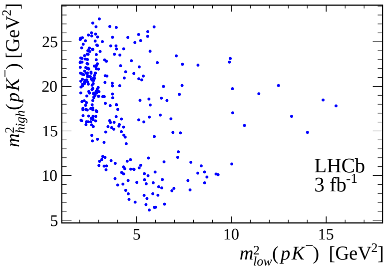


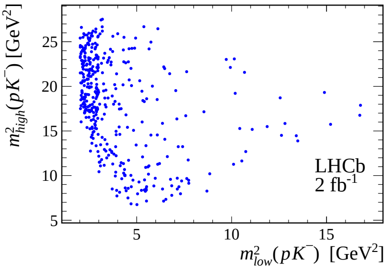
Parameter	Run 1	Run 2
$\Xi_b^- \to pK^-K^-$ yield	193 ± 21	297 ± 23
$\Omega_b^- \to pK^-K^-$ yield	-4 ± 6	15 ± 9
Partially reconstructed background yield	231 ± 34	442 ± 36
Combinatorial background yield	721 ± 50	775 ± 51

[arXiv:2104.15074]

$\Xi_b^- \to pK^-K^-$ Dalitz plot

- Assume Ξ_b^- unpolarised, no sensitivity to proton polarisation:
  $\Rightarrow$ only 2 Dalitz plot variables.
- Identical kaons: folded Dalitz plot, amplitude must be symmetric wrt. kaon exchange.
- $\Lambda^* \to pK^-$ and $\Sigma^* \to pK^-$ resonances.





[arXiv:2104.15074]

$\Xi_b^- \to pK^-K^-$: amplitude model

The need to symmetrise amplitude leads to a subtle problem:

- "Conventional" helicity formalism: $\Xi_b \to R_1 K_1^-$, $R_1 \to pK_2^-$.
  Proton helicity is in R_1 rest frame.
- Adding 2nd chain, $\Xi_b \to R_2 K_2^-$, $R_2 \to pK_1^-$.
  Need to align p helicities in two chains. $\Rightarrow$ amplitude not symmetric by construction.

Making amplitude expressly symmetric by defining p helicity in K^-K^- rest frame.

- 3rd Wigner rotation applied to both decay chains.

$$A^Q_{R,M_{\Xi_b},\lambda_p}(m^2_{\text{low}}, m^2_{\text{high}}) = T^Q_{R,M_{\Xi_b},\lambda_p}(m^2_{\text{low}}, m^2_{\text{high}}) + (-1)^{M_{\Xi_b}+\lambda_p} T^Q_{R,M_{\Xi_b},\lambda_p}(m^2_{\text{high}}, m^2_{\text{low}})$$

$$T^Q_{R,M_{\Xi_b},\lambda_p}(m^2_{\text{low}}, m^2_{\text{high}}) = \sum_{\lambda_R,\lambda'_p} \Big(d^{J_{\Xi_b}}_{M_{\Xi_b},\lambda_R}(\theta_R) d^{J_R}_{\lambda_R,\lambda'_p}(\theta_p) d^{J_p}_{\lambda'_p,\lambda_p}(\zeta) \times \eta_{\lambda'_p}(-1)^{\lambda'_p-\lambda_p} h^Q_{R,\lambda_R} R(m^2_{\text{low}}) \Big)$$

M. Mikhasenko et al. (JPAC) "Dalitz-plot decomposition for three-body decays" [PRD 101, 034033 (2020)] [Talk by Elisabeth Niel]

$\Xi_b^- \to pK^-K^-$: amplitude model

Name	J^P	Mass (MeV)	Width (MeV)	Main decay channels
		****		
$\Lambda(1405)$	$\frac{1}{2}^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	$\Sigma\pi$
$\Lambda(1520)$	$\frac{3}{2}^-$	1518 to 1520	15 to 17	$N\overline{K}$, $\Sigma\pi$
$\Lambda(1670)$	$\frac{1}{2}^-$	1660 to 1680	25 to 50	$N\overline{K}$, $\Sigma\pi$, $\Lambda\eta$
$\Lambda(1690)$	$\frac{3}{2}^-$	1685 to 1695	50 to 70	$N\overline{K}$, $\Sigma\pi$, $\Lambda\pi\pi$, $\Sigma\pi\pi$
$\Lambda(1820)$	$\frac{5}{2}^+$	1815 to 1825	70 to 90	$N\overline{K}$
$\Lambda(1830)$	$\frac{5}{2}^-$	1810 to 1830	60 to 110	$\Sigma\pi$
$\Lambda(1890)$	$\frac{3}{2}^+$	1850 to 1910	60 to 200	$N\overline{K}$
$\Sigma(1385)$	$\frac{3}{2}^+$	1383.7 ± 1	36 ± 5	$\Lambda\pi, \Sigma\pi$
$\Sigma(1670)$	$\frac{3}{2}^-$	1665 to 1685	40 to 80	$\Sigma\pi$
$\Sigma(1775)$	$\frac{5}{2}^-$	1770 to 1780	105 to 135	$N\overline{K}$, $\Lambda^{(*)}\pi$
$\Sigma(1915)$	$\frac{5}{2}^+$	1900 to 1935	80 to 160	not clear
		***		
$\Lambda(1600)$	$\frac{1}{2}^+$	1560 to 1700	50 to 250	$N\overline{K}$, $\Sigma\pi$
$\Lambda(1800)$	$\frac{1}{2}^-$	1720 to 1850	200 to 400	$N\overline{K}^{(*)}$, $\Sigma\pi$, $\Lambda\eta$
$\Lambda(1810)$	$\frac{1}{2}^+$	1750 to 1850	50 to 250	$N\overline{K}^{(*)}$, $\Sigma\pi$, $\Lambda\eta$, ΞK
$\Lambda(2110)$	$\frac{5}{2}^+$	2090 to 2140	150 to 250	$N\overline{K}^{(*)}$, $\Sigma\pi$, $\Lambda\Omega$
$\Sigma(1660)$	$\frac{1}{2}^-$	1630 to 1690	40 to 200	$N\overline{K}$, $\Sigma\pi$, $\Lambda\pi$
$\Sigma(1750)$	$\frac{1}{2}^-$	1730 to 1800	60 to 160	$N\overline{K}$, $\Sigma\pi$, $\Lambda\pi$, $\Sigma\eta$
$\Sigma(1940)$	$\frac{3}{2}^-$	1900 to 1950	150 to 300	$N\overline{K}$, $\Sigma\pi$, $\Lambda\pi$
$\Sigma(2250)$	$?^?$	2210 to 2280	60 to 150	$N\overline{K}$, $\Sigma\pi$, $\Lambda\pi$

- $\Lambda(1520)$ as a reference amplitude
- Adding resonances one-by-one, by maximising $\Delta(-2\log\mathcal{L})$
- Baseline model: $\Sigma(1385)$, $\Lambda(1405)$, $\Lambda(1520)$, $\Lambda(1670)$, $\Sigma(1775)$, $\Sigma(1915)$.

CPV in $\Xi_b^- \to pK^-K^-$: observables

Each resonance has two couplings, $\lambda_R = \pm 1/2$:

$$h^Q_{R,\lambda_R} = (x_{R,\lambda_R} + Q\,\delta x_{R,\lambda_R}) + i\,(y_{R,\lambda_R} + Q\,\delta y_{R,\lambda_R})$$

Without Ξ_b^- polarisation, not enough information to determine both unambiguously.

- Ξ_b^- polarisation was not measured before, but Λ_b^0 polarisation is consistent with zero [JHEP 2020, 110 (2020)]
- Use measured Λ_b^0 value for a systematic check

Observable parameters (all averaged over polarisations):

Fit fractions: $\mathcal{F}_i = \dfrac{\int_\Omega (d\Gamma_i^+/d\Omega + d\Gamma_i^-/d\Omega)d\Omega}{\int_\Omega (d\Gamma^+/d\Omega + d\Gamma^-/d\Omega)d\Omega}$ with $\dfrac{d\Gamma_i^Q}{d\Omega} = \dfrac{1}{(8\pi m_{\Xi_b})^3} \sum_{M_{\Xi_b},\lambda_p} \left| A^Q_{i,M_{\Xi_b},\lambda_p}(\Omega)\right|^2$

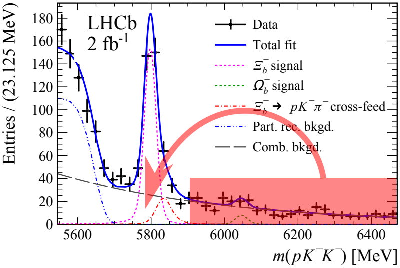
Interference fit fractions: $\mathcal{I}_{ij} = \dfrac{\int_\Omega (d\Gamma_{ij}^+/d\Omega + d\Gamma_{ij}^-/d\Omega)d\Omega}{\int_\Omega (d\Gamma^+/d\Omega + d\Gamma^-/d\Omega)d\Omega}$

CP asymmetries: $A_i^{CP} = \dfrac{\int_\Omega (d\Gamma_i^+/d\Omega - d\Gamma_i^-/d\Omega)d\Omega}{\int_\Omega (d\Gamma_i^+/d\Omega + d\Gamma_i^-/d\Omega)d\Omega}$

$\Xi_b^- \to pK^-K^-$: technical details

- Symmetrised baryonic 3-body decay: amplitude fitter written from scratch, using TensorFlow as a computational backend. (see Abhijit Mathad's talk)
- TensorFlow is a machine learning framework, so can use some ML tricks "for free".

- Background distribution estimated from Ξ_b^- mass upper sideband.
- Account for variations of density as a function of $M(\Xi_b^-)$
- ANN to estimate 3D density ($M(\Xi_b^-)$ + DP), extrapolate into signal $M(\Xi_b^-)$ region.



[arXiv:2104.15074]

More details on density estimation with ML techniques:

"Efficient description of experimental effects in amplitude analyses", A. Mathad, D. O'Hanlon, A.P., R. Rabadan, [2021 JINST 16 P06016]

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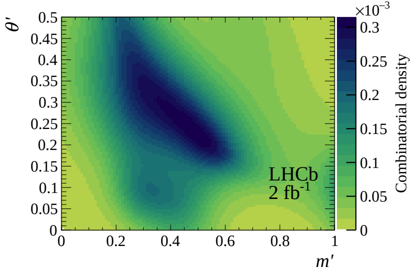

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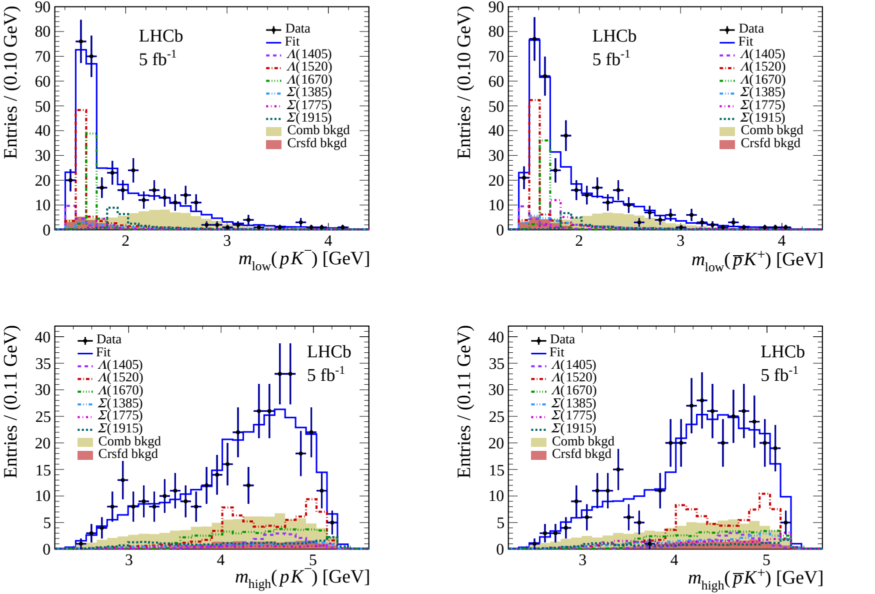
$\Xi_b^- \to pK^-K^-$: amplitude fit results



[arXiv:2104.15074]

$\Xi_b^- \to pK^-K^-$: amplitude fit results

Fit and interference fractions:

Component	$\Sigma(1385)$	$\Lambda(1405)$	$\Lambda(1520)$	$\Lambda(1670)$	$\Sigma(1775)$	$\Sigma(1915)$
$\Sigma(1385)$	$11.4 \pm 4.9 \pm 7.6$					
$\Lambda(1405)$	$-1.3 \pm 0.8 \pm 2.0$	$8.1 \pm 2.7 \pm 3.0$				
$\Lambda(1520)$	$3.4 \pm 1.6 \pm 4.2$	$0.1 \pm 0.5 \pm 0.8$	$33.0 \pm 4.1 \pm 3.6$			
$\Lambda(1670)$	$-0.1 \pm 0.6 \pm 1.0$	$3.0 \pm 1.8 \pm 2.4$	$-0.1 \pm 0.4 \pm 0.8$	$19.5 \pm 3.2 \pm 5.6$		
$\Sigma(1775)$	$0.1 \pm 0.3 \pm 0.4$	$-0.7 \pm 0.5 \pm 1.2$	$1.1 \pm 1.0 \pm 1.9$	$-0.3 \pm 0.2 \pm 0.3$	$9.7 \pm 3.5 \pm 4.1$	
$\Sigma(1915)$	$0.6 \pm 0.6 \pm 1.3$	$0.3 \pm 0.3 \pm 0.8$	$0.1 \pm 0.1 \pm 0.2$	$-0.1 \pm 0.2 \pm 0.5$	$1.0 \pm 0.5 \pm 1.3$	$11.3 \pm 3.7 \pm 9.2$

CP asymmetries:

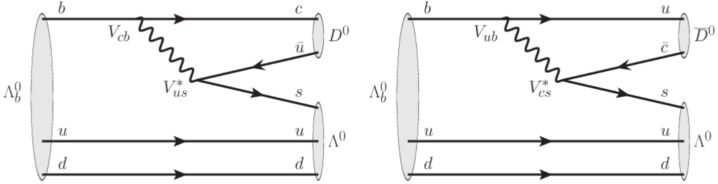
Component	A^{CP} (10^{-2})
$\Sigma(1385)$	-27 ± 34 (stat) ± 73 (syst)
$\Lambda(1405)$	-1 ± 24 (stat) ± 32 (syst)
$\Lambda(1520)$	-5 ± 9 (stat) ± 8 (syst)
$\Lambda(1670)$	3 ± 14 (stat) ± 10 (syst)
$\Sigma(1775)$	-47 ± 26 (stat) ± 14 (syst)
$\Sigma(1915)$	11 ± 26 (stat) ± 22 (syst)

No evidence of CP asymmetry, but uncertainties are large.
Systematics is dominated by resonant composition, expect to improve with larger stats. [arXiv:2104.15074]

$\Lambda_b^0 \to DpK^-$ decays New!

Charmed b decays are sensitive to CKM phase γ
through the interference of amplitudes with $D^0 \to f$ and $\overline{D}^0 \to f$
(see talk by Philippe d'Argent)

In the case of Λ_b^0:



$\Lambda_b^0 \to D\Lambda^0_{\to p\pi^-}$ mode affected by low efficiency to reconstruct long-lived Λ^0.

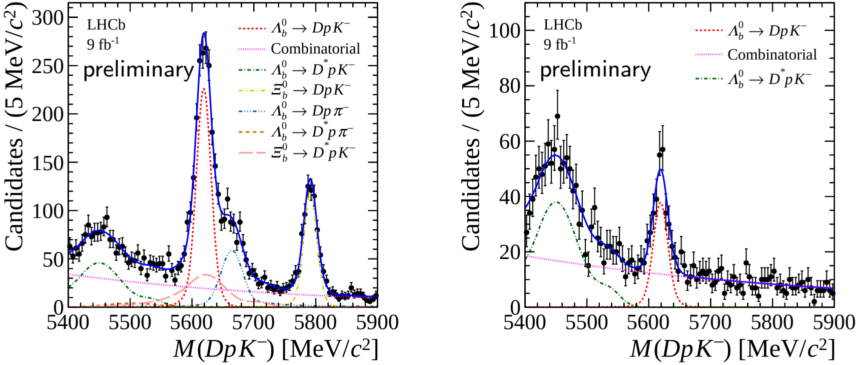
Trying with excited, strongly decaying $\Lambda^{*0} \to pK^-$ instead

- Favoured $\Lambda_b^0 \to DpK^-$ with $D \to K^-\pi^+$ is observed in Run 1 [PRD 89, 032001 (2014)]
- Now:
  - Search for suppressed mode $\Lambda_b^0 \to DpK^-$ with $D \to K^+\pi^-$ with enhanced $b \to c$ and $b \to u$ interference term
  - Measure CP asymmetry

$\Lambda_b^0 \to DpK^-$ decays

New!

Signal with full Run 1+Run 2 LHCb data sample



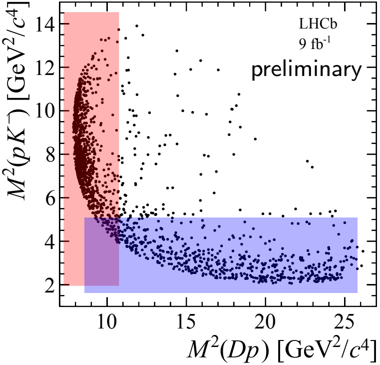
First observation of the suppressed mode!

- Yields: 1437 ± 92 (favoured), 241 ± 22 (suppressed)
- Favoured-to-suppressed $\mathcal{B}$ ratio $R = 7.1 \pm 0.8(\mathrm{stat})^{+0.4}_{-0.3}(\mathrm{syst})$

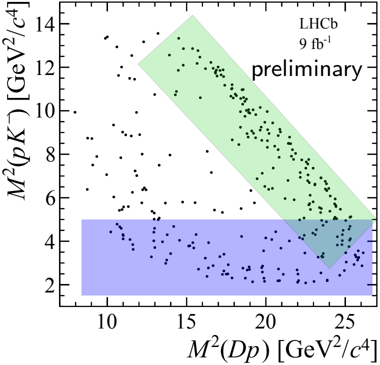
[arXiv:2109.02621]

$\Lambda_b^0 \to DpK^-$ decay amplitude

Favoured:
$\Lambda_c^{*+} \to D^0 p$ and $\Lambda^{*0} \to pK^-$



Suppressed
$D_s^{*-} \to \bar{D}^0 K^-$ and $\Lambda^{*0} \to pK^-$



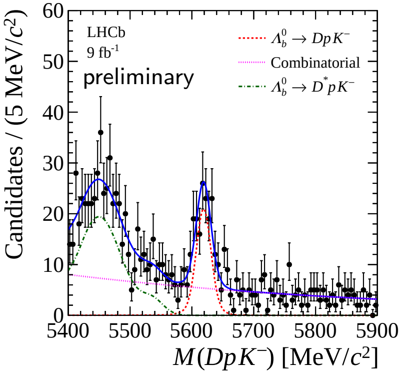
$\Lambda_b^0 \to \Lambda_c^{*+} K^-$ ($b \to c$) and $\Lambda_b^0 \to D_s^{*-} p$ ($b \to u$) amplitudes are flavour-specific

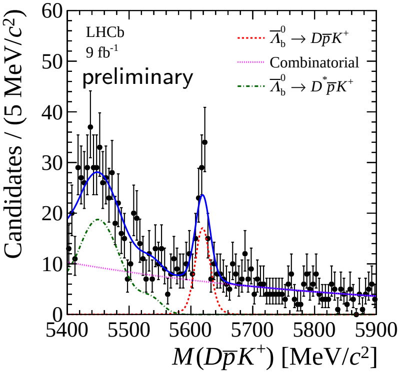
Taking only $\Lambda_b^0 \to D\Lambda^{*0}$ ($M^2(pK^-) < 5\,\mathrm{GeV}^2/c^4$) should enhance CPV term

[arXiv:2109.02621]

CPV in $\Lambda_b^0 \to DpK^-$

CP asymmetry in the full phase space



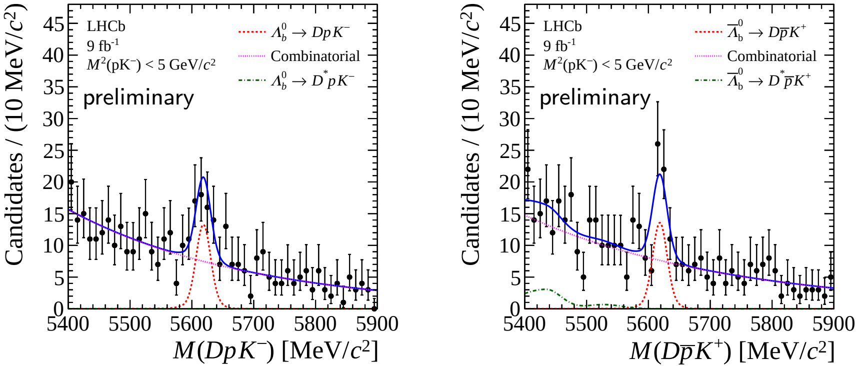


$$R = 7.1 \pm 0.8\,(\text{stat.})^{+0.4}_{-0.3}\,(\text{syst.}),$$
$$A = 0.12 \pm 0.09\,(\text{stat.})^{+0.02}_{-0.03}\,(\text{syst.}),$$

[arXiv:2109.02621]

CPV in $\Lambda_b^0 \to DpK^-$

CP asymmetry in the $\Lambda^{*0} \to pK^-$ region $(M^2(pK^-) < 5\,\mathrm{GeV}^2/c^4)$



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

[arXiv:2109.02621]

CPV in $\Lambda_b^0 \to DpK^-$: what's next?

Even provided that we measure nonzero CP asymmetry in $\Lambda_b^0 \to DpK^-$, can we extract γ?

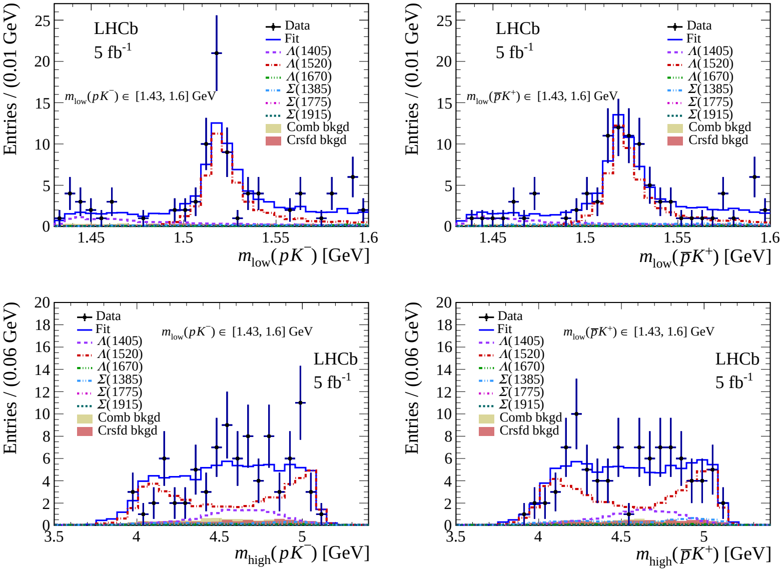
- B meson case: γ can be resolved from several D decay modes (e.g. $D \to K\pi$, $D \to KK$) due to factorisation of b and c decay amplitudes
  - Each has associated (unknown) strong phase, but (number of constraints) $>$ (number of free parameters)
- Λ_b^0 decays are more complex because of overlapping helicity states
  - Each Λ^{*0} helicity has, in general, its own strong phase
- $\Lambda_b^0 \to D\Lambda^0$ case with weak $\Lambda^0 \to p\pi^-$ decay:
  - Can measure Λ^0 polarisation and resolve γ
  - See e.g. [Giri, Mohanta, Khanna, PRD 65 (2002) 073029]
- $\Lambda_b^0 \to D\Lambda^{*0}$ is different because $\Lambda^{*0} \to pK^-$ is strong (P-conserving)
  - Can we still resolve γ without Λ_b^0 polarisation?
  - Does multitude of Λ^{*0} amplitudes make things better or worse?

Conclusion

- Unlike in B mesons, CP violation in B baryons is not yet established.
- Low pp fragmentation fraction $\Rightarrow$ lower statistics
- Ambiguities due to overlapping helicity states (esp. for unpolarised initial state).
  - Possible to select a polarisation-enhanced subsample of events? (*e.g.* events with correlated b baryon pairs)
  - Inclusive ML-based *polarisation tagger* (à la flavour tagging)?
- The work has started though:
  - 2-body decay asymmetries in Λ_b^0 decays
  - Model-independent analyses of 4-body Λ_b^0 decays
    - Observation of P-parity violation, hints on CPV
  - Model-dependent amplitude analysis allowing for CPV: $\Xi_b^- \to pK^-K^-$
    - **First analysis of heavy baryon allowing for CPV**, no evidence of CPV yet
  - New: search for CPV in suppressed $\Lambda_b^0 \to DpK^-$ decays
    - Potentially sensitive to γ, first observation of the suppressed mode

Backup

$\Xi_b^- \to pK^-K^-$: slices



[arXiv:2104.15074]

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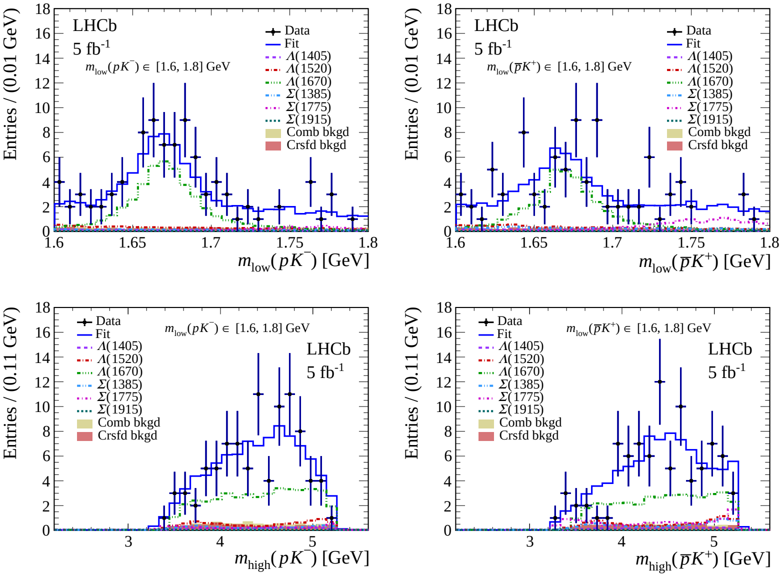

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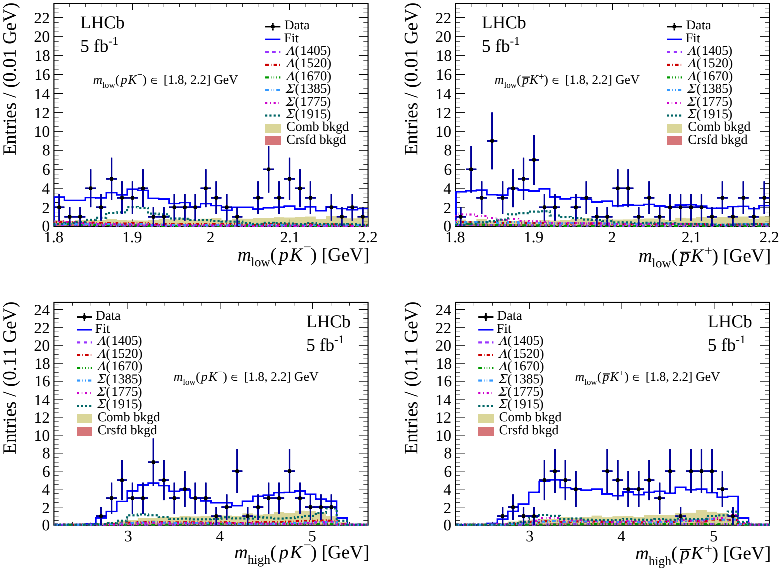

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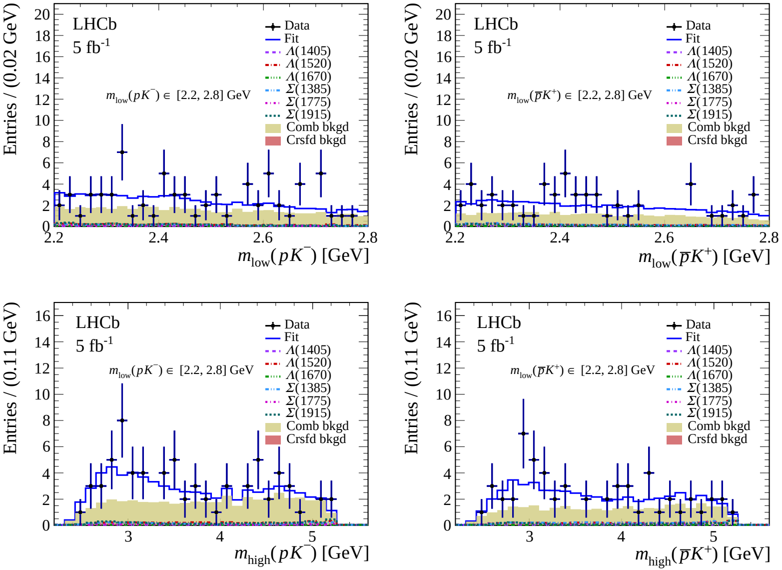

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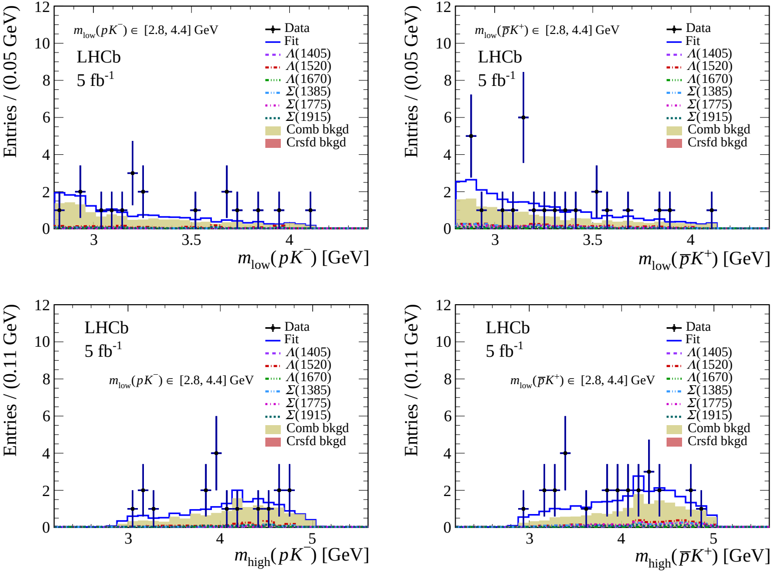

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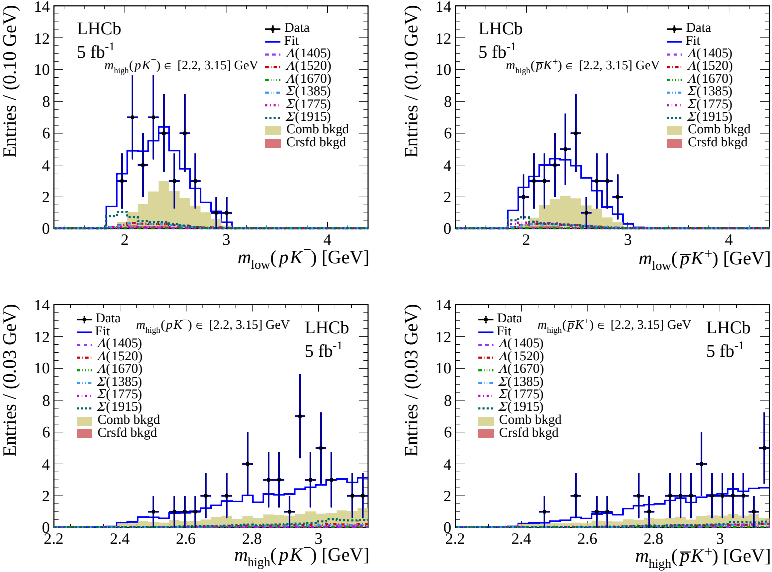

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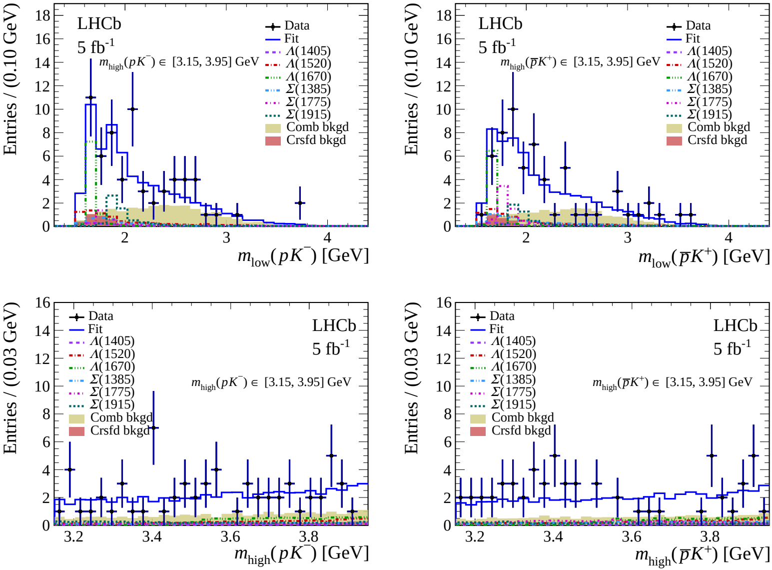

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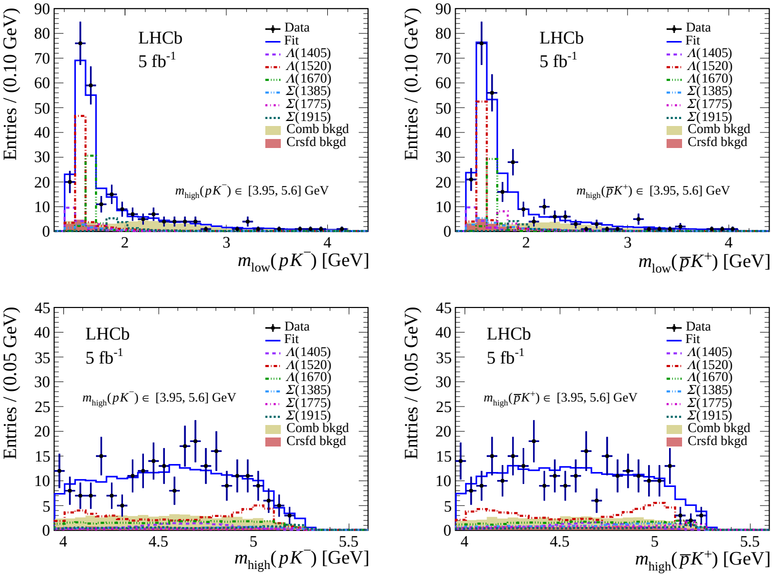

[arXiv:2104.15074]

Component	Parameter	Mass fits	Bkg shapes	Bkg asym	Eff	Prod asym	Polarisation	RBW params	Lineshapes	Alt fit model	Total
$\Sigma(1385)$	A^{CP}	3.3	20.6	4.4	8.2	6.9	15.0	7.0	12.6	65.5	72.7
	$\mathcal{F}$	1.4	3.1	0.5	0.7	0.2	1.0	5.0	0.6	4.4	7.6
$\Lambda(1405)$	A^{CP}	2.4	9.6	2.7	5.1	5.1	5.5	5.1	19.5	20.6	31.9
	$\mathcal{F}$	0.3	1.4	0.3	0.8	<0.1	0.3	0.3	2.3	0.9	3.0
$\Lambda(1520)$	A^{CP}	0.3	0.9	0.6	2.9	4.3	5.0	0.7	1.2	1.3	7.6
	$\mathcal{F}$	1.1	1.8	<0.1	1.3	<0.1	0.6	1.8	0.6	1.7	3.6
$\Lambda(1670)$	A^{CP}	1.8	4.2	1.4	2.9	4.4	3.3	3.7	4.9	1.6	10.1
	$\mathcal{F}$	0.8	2.3	0.1	0.7	0.1	0.6	1.4	1.8	4.4	5.6
$\Sigma(1775)$	A^{CP}	2.5	7.8	1.7	3.1	3.4	7.0	3.8	4.7	3.7	13.8
	$\mathcal{F}$	0.5	1.5	0.1	0.4	0.2	0.2	1.0	0.9	3.5	4.1
$\Sigma(1915)$	A^{CP}	2.5	6.7	5.0	6.4	4.8	5.2	10.5	2.1	13.9	21.8
	$\mathcal{F}$	0.2	2.3	0.1	1.3	0.2	0.2	2.2	1.5	8.4	9.2
$\Lambda(1405), \Lambda(1520)$	$\mathcal{I}$	0.2	0.6	0.1	0.1	<0.1	0.1	0.2	0.2	0.4	0.8
$\Lambda(1405), \Lambda(1670)$	$\mathcal{I}$	0.3	0.9	0.1	0.5	<0.1	<0.1	1.2	1.6	0.9	2.4
$\Lambda(1405), \Sigma(1385)$	$\mathcal{I}$	0.2	0.4	0.1	0.2	<0.1	0.1	0.5	0.7	1.8	2.0
$\Lambda(1405), \Sigma(1775)$	$\mathcal{I}$	<0.1	0.3	<0.1	0.1	<0.1	0.1	0.4	0.3	1.1	1.2
$\Lambda(1405), \Sigma(1915)$	$\mathcal{I}$	0.1	0.4	<0.1	0.1	<0.1	<0.1	0.1	0.3	0.6	0.8
$\Lambda(1520), \Lambda(1670)$	$\mathcal{I}$	0.1	0.2	<0.1	<0.1	<0.1	<0.1	0.2	0.1	0.8	0.8
$\Lambda(1520), \Sigma(1385)$	$\mathcal{I}$	0.7	0.9	0.2	0.2	0.2	0.1	1.6	0.9	3.6	4.2
$\Lambda(1520), \Sigma(1775)$	$\mathcal{I}$	0.3	0.6	0.1	0.1	0.1	0.2	0.5	0.5	1.6	1.9
$\Lambda(1520), \Sigma(1915)$	$\mathcal{I}$	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	0.1	0.2
$\Lambda(1670), \Sigma(1385)$	$\mathcal{I}$	0.2	0.3	0.1	0.1	<0.1	<0.1	0.4	0.6	0.6	1.0
$\Lambda(1670), \Sigma(1775)$	$\mathcal{I}$	0.1	0.1	<0.1	<0.1	<0.1	<0.1	0.1	0.1	0.2	0.3
$\Lambda(1670), \Sigma(1915)$	$\mathcal{I}$	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	0.3	0.1	0.4	0.5
$\Sigma(1385), \Sigma(1775)$	$\mathcal{I}$	0.1	0.3	<0.1	<0.1	<0.1	<0.1	0.2	0.1	0.2	0.4
$\Sigma(1385), \Sigma(1915)$	$\mathcal{I}$	0.2	0.6	<0.1	0.2	<0.1	0.1	0.6	0.2	1.0	1.3
$\Sigma(1775), \Sigma(1915)$	$\mathcal{I}$	0.1	0.4	<0.1	0.1	<0.1	0.1	0.7	0.2	1.0	1.3

[arXiv:2104.15074]

$\Lambda_b^0 \to DpK^-$: systematic uncertainties

	R	A
Statistical uncertainty	± 0.79	± 0.088
Systematic uncertainties		
fit model	$^{+0.37}_{-0.15}$	$^{+0.000}_{-0.011}$
efficiency corrections	$^{+0.21}_{-0.24}$	$^{+0.010}_{-0.008}$
PID efficiency	$^{+0.08}_{-0.16}$	$^{+0.001}_{-0.002}$
L0 trigger efficiency	± 0.03	± 0.001
charmless background	± 0.08	
double misID background	± 0.005	
single misID background	± 0.001	
Λ_b^0 production asymmetry		± 0.015
p detection asymmetry		± 0.015
$\pi^\pm$ detection asymmetry		± 0.005
Total systematic uncertainty	$^{+0.43}_{-0.33}$	$^{+0.024}_{-0.026}$

[arXiv:2109.02621]