LHCb perspectives for charm baryon decays

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Baryon weak decays, Warsaw

Disclaimer / Outline

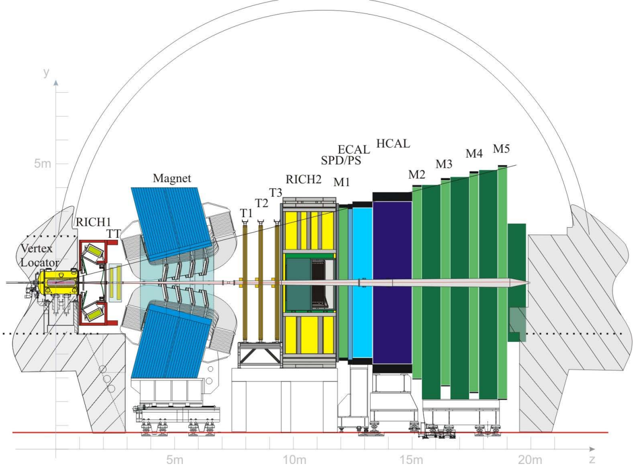
Disclaimer

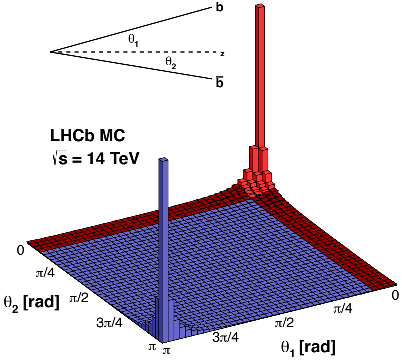
My goal is to give a feeling for LHCb's reach in physics with charm baryons, showing advantages and limitations of the past, the current (Upgrade I) and potential future (Upgrade II) detectors.

- LHCb overview and timeline
- Reconstruction and Trigger
- News on hyperon reconstruction
- Charm baryon prospects
- Selected measurements

LHCb in Run 1 and 2

[JINST 3 S08005] [IJMPA 30 07, 1530022]





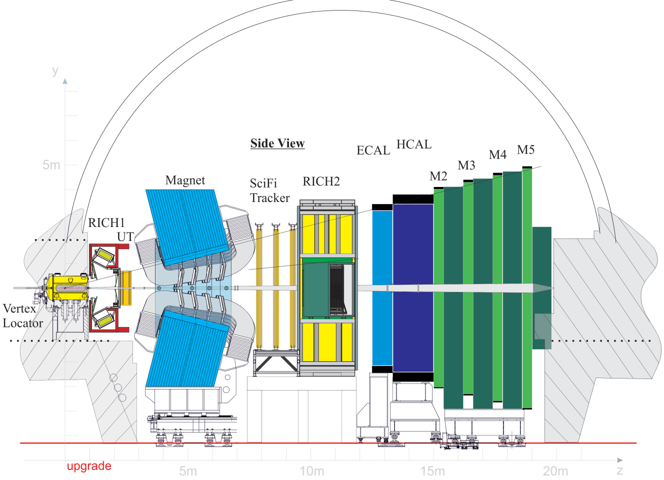
- General purpose detector with forward geometry
  + ions, fixed target, MOeDAL, CodexB ...

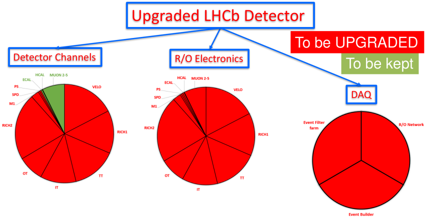
+ VELO close to interaction region moveable!
+ Excellent hadron PID
+ Flexible software trigger (CPUs)

– Reconstruction of neutrals

(–) Hardware trigger

[2305.10515 [hep-ex]]





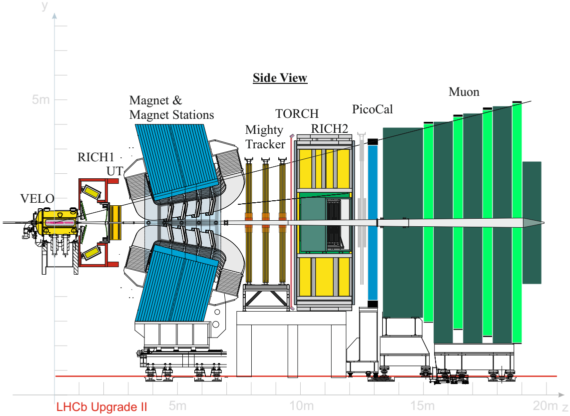
Same as before? Not quite...

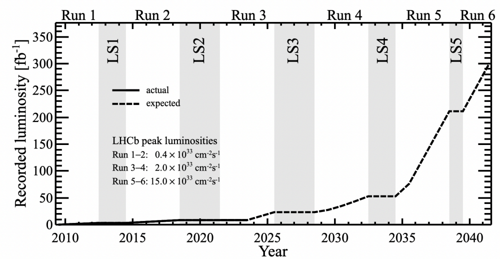
- New tracking detectors
- New RICH photo-detectors
- Detector readout @30 MHz

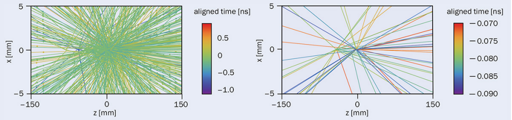
- Average visible interactions $\sim 1 \longrightarrow \sim 5$
- VELO strip $\longrightarrow$ pixels; 5 $\longrightarrow$ 3.5 mm to beam
- Heterogeneous software trigger

LHCb in Run 5 and 6 (Upgrade II)

[1808.08865 [hep-ex]]



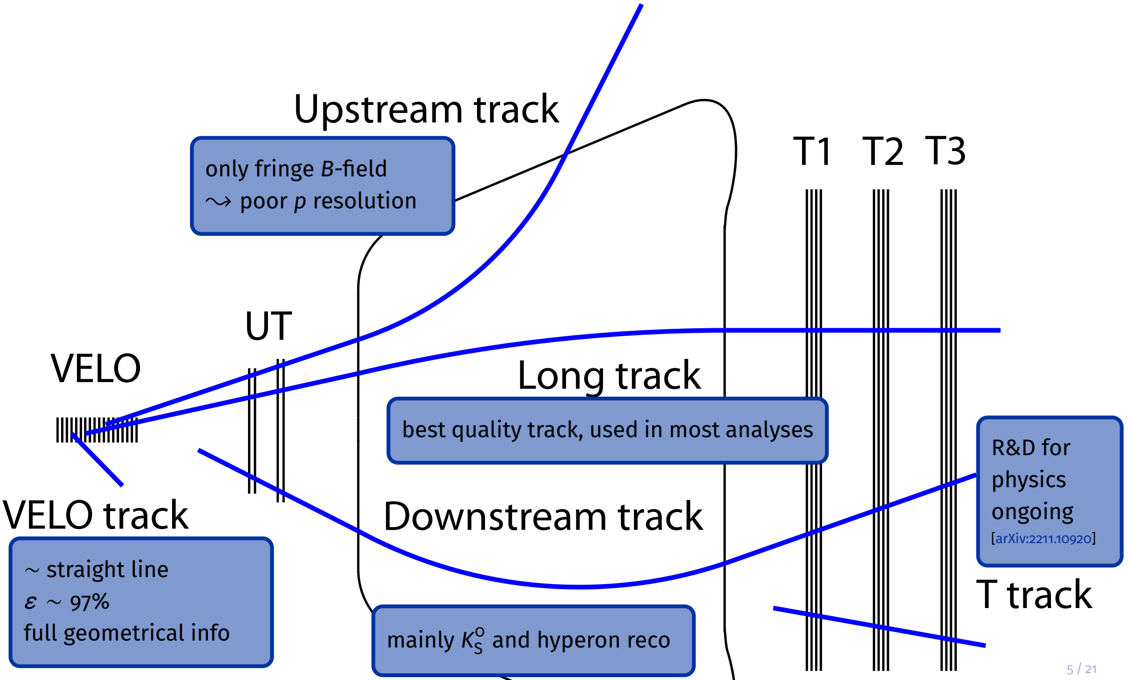




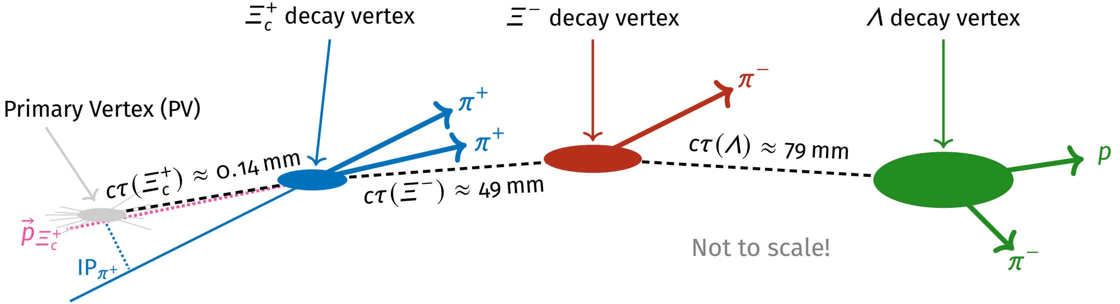
- Timing (VELO, RICH, TORCH, PicoCal)
- Pixel in UT, inner part of Mighty Tracker
- Low p track reco in Magnet Stations

- Average visible interactions $\sim$ 50
- Full GPU software trigger(s)? Co-processors?
- Currently under review

Reconstruction: track types

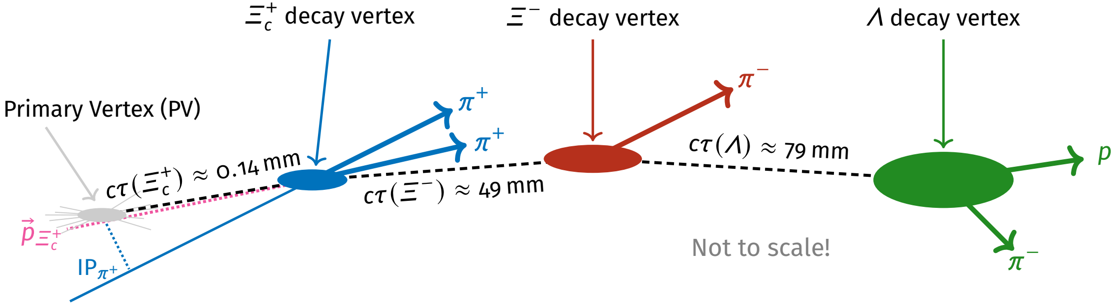


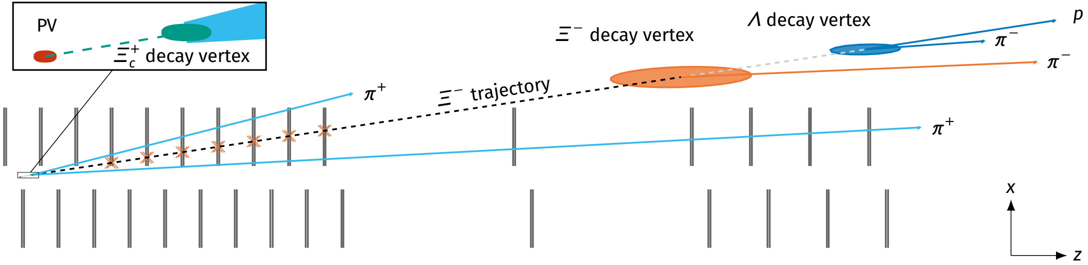
Reconstruction: (dis-)advantages



- Muons are easiest to reconstruct and select, followed by charged (stable) hadrons (p, K, π)
- Photons (π^0, η) are difficult due to ECAL granularity; electrons OK, but poor $\delta p/p$ (due to γ_{Brem})
- Neutrons, K_L^0 reconstruction is hopeless
- Most discrimination against backgrounds from geometrical information, driven by VELO tracking
- E.g. Impact parameter (IP or χ^2_{IP}), displacement of secondary vertices from PV
- b hadron lifetimes ideal: decay in VELO, good separation from PV
- Kinematics and hadron PID further improve signal purity

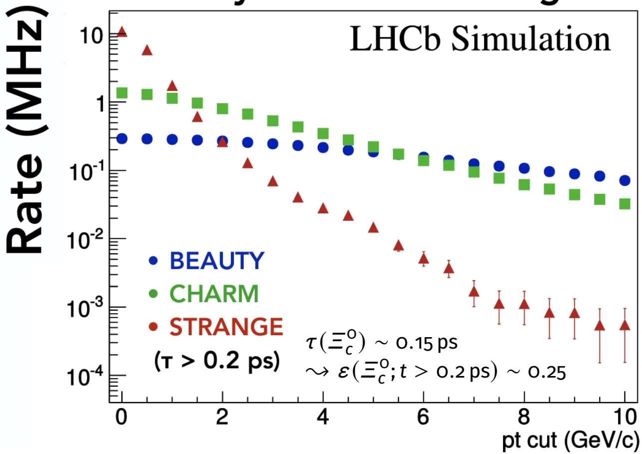
Reconstruction: topologies

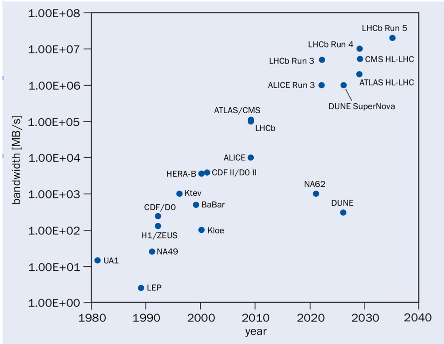




[LHCB-TDR-016]

Partially reconstructed signals

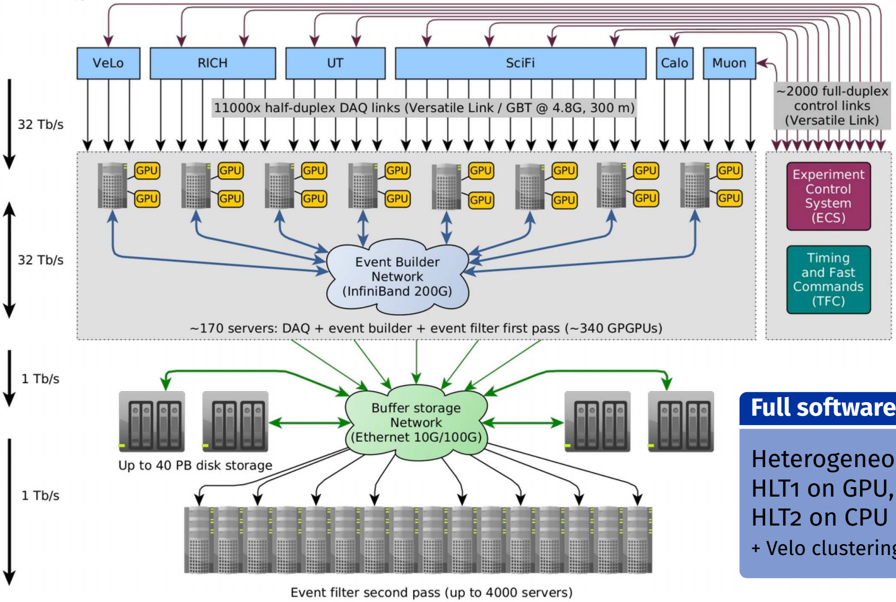




- Charm signal rate is $\mathcal{O}$ **MHz** in the LHCb acceptance
- We can only store ∼ **50 kHz** in total if we store the raw event
- Need **fast, efficient** and **precise** reconstruction in a **flexible** trigger

LHCb's solution (Upgrade I)

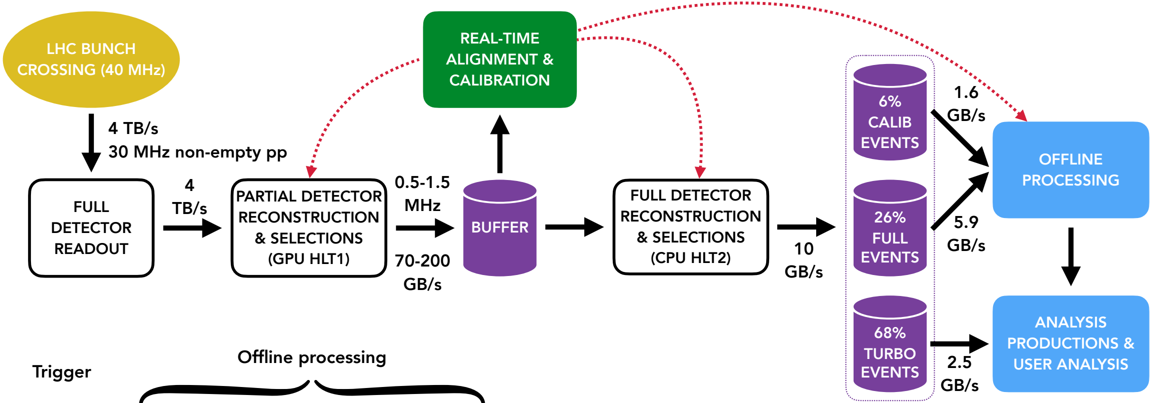
[LHCb-DP-2021-003]

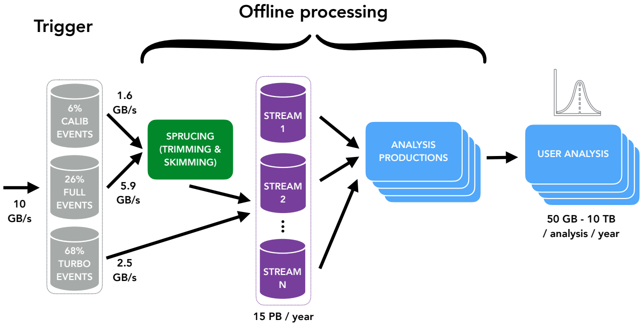


Full software trigger

Heterogeneous architecture
HLT1 on GPU,
HLT2 on CPU
+ Velo clustering on FPGA

Dataflow (Upgrade I)

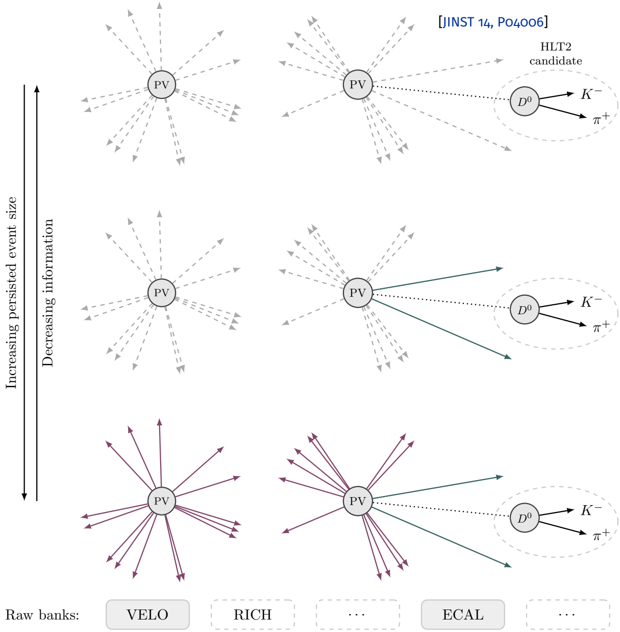




HLT1 limited by rate and throughput
HLT2 and Spruce limited by bandwidth
∼ 50 HLT1 selection algorithms (lines)
∼ 2.5k HLT2-, ∼ 1k Spruce lines
mainly from analysts

- The majority of lines persists only the reconstructed objects that define a signal candidate ("TURBO" dominated by charm physics)
- Objects written to tape/disk , including encoded data from the detectors ("raw banks") are configurable for each line individually
- **Inclusive** lines select signals partially, and persist further objects ⇝ build decays that involve the partial signal offline *e.g.* detached $J/\psi \to \mu^+\mu^-$ for b decays
- **Exclusive** lines select the full decay of interest online
- TURBO reduces event size by order of magnitude w.r.t. raw event ⇝ more signal offline!

[JINST 14, P04006]



Particle	Lifetime [ps]	Decay	$\mathcal{B}$ [%]	"reconstructability"
π^0	10^{-4}	$\gamma\gamma$	99	**(*)
K_S^0	90	$\pi^+\pi^-$	69	****
Λ	260	$p\pi^-$	64	***(*)
Σ^-	150	$n\pi^-$	100	(*)
Σ^0	10^{-7}	$\Lambda\gamma$	100	*(*)
Σ^+	80	$p\pi^0$	52	*(*)
Ξ^0	200	$\Lambda\pi^0$	100	*
Ξ^-	170	$\Lambda\pi^-$	100	***
Ω^-	80	ΛK^-	68	***
D^0	0.41	$K^-\pi^+$	4	****(*)
D^+	1.0	$K^-\pi^+\pi^+$	9.4	****(*)
Λ_c^+	0.2	$pK^-\pi^+$	6.3	****
D_s^+	0.5	$K^-K^+\pi^+$	5.4	****(*)
Ξ_c^0	0.15	$pK^-K^-\pi^+$	0.5	***(*)
Ξ_c^+	0.45	$pK^-\pi^+$	0.6	****
Ω_c^0	0.27	$pK^-K^-\pi^+$	?	***(*)
J/ψ	10^{-10}	$\mu^+\mu^-$	6	*****
B^0	1.52	$D^+\pi^-$	0.25	****(*)
B^+	1.63	$J/\psi K^+$	0.1	*****
Λ_b^0	1.47	$\Lambda_c^+\pi^-$	0.5	****(*)

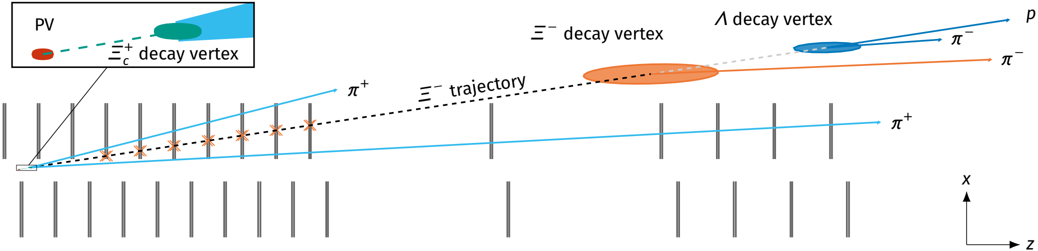
Biased selection and round numbers. "reconstructability" can be understood as a measure for efficiency and purity of a typical trigger selection.

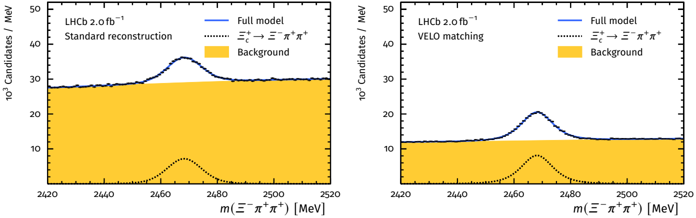
Most K_S^0 and Λ decays happen downstream of VELO. Their decay products are reconstructed as downstream tracks, with drawbacks in resolution and efficiency. The same applies to other long lived hyperons.

Short lifetimes of charm hadrons lower selection efficiencies significantly.
Golden modes of Ξ_c^+, Ω_c^0 are Cabibbo suppressed.

[LHCb-DP-2023-004 (in preparation)]

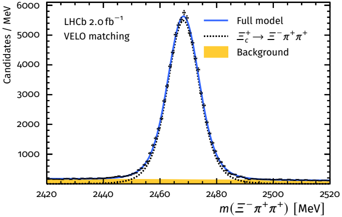
- Reconstruct charged hyperon from downstream tracks and match its trajectory to VELO track
  - RapidSim: $\sim 70\,\%$ of Ξ^- from $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ decay downstream of VELO $z > 600$ mm, $\rho > 32$ mm.
  - Study performance with 2018 $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ data and simulation

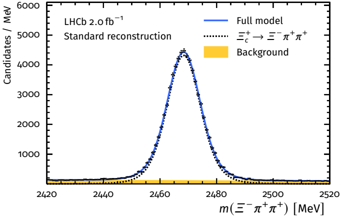




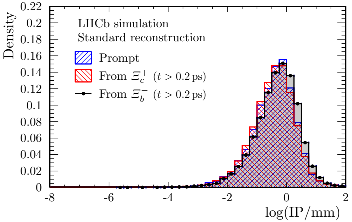
- Typical online selection
- Matching efficiency compatible with 100% ($\gtrsim$ 96% in simulation)
- Purity improved from 12% to 26%

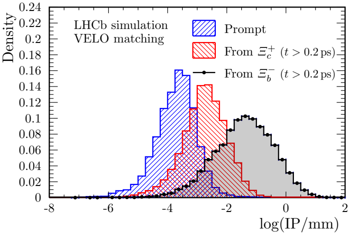
[LHCb-DP-2023-004 (in preparation)]





Gain 21% signal with VELO matching from typical ML-based offline selection, fixing purity to 95%

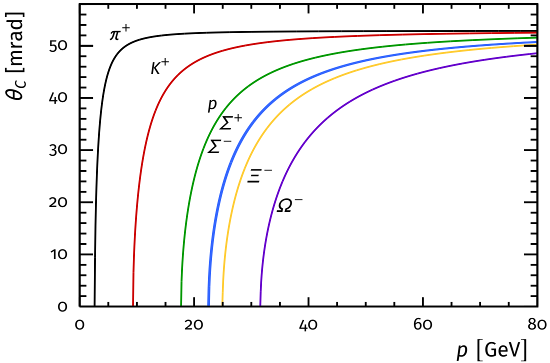




IP resolution with VELO matching such that prompt and secondary Ξ^- are distinguishable: requiring IP> 20 µm removes roughly half of the prompt Ξ^- while retaining more than 93 % of Ξ^- from Ξ_c^+ and 98 % of Ξ^- from Ξ_b^-

- Improved IP resolution allowed to write inclusive Ξ^- and Ω^- HLT2 lines
  - In Run 2: Equivalent lines only kept 1 in 20 triggered events due to bandwidth constraints
- Also measured improvements on mass resolution in $\Xi^-\pi^+$ subsystem, and signal-to-noise ratio as function of pileup

- Strange physics with VELO matching:
  - VELO matching allows to close kinematics for decays like $\Xi^- \to \Lambda\mu^-\overline{\nu}_\mu$
  - Improve $\Sigma^+ \to p\mu^-\mu^+$ double stats relative to [PRL 120, 221803]; K^+ mass with $K^+ \to \pi^+\pi^+\pi^-$
- Feasible to reconstruct Σ^+ and Σ^- from c or b?
- For decays in VELO: "kink" reconstruction; also: add hits to downstream decay products $\rightsquigarrow$ improve K^0_S and Λ reconstruction
- Use T tracks *e.g.* Λ from T tracks matched to a Ξ^- VELO track
- Use upstream tracks $\rightsquigarrow$ hyperons in RICH1
  $\sim$ 25% of Ξ^- decay downstream of TT/UT
- Hyperons can decay after SciFi; RapidSim:
  2.8 % of Σ^- from $\Lambda^0_b \to J/\psi\Sigma^-\pi^+$,
  2.7 % of Ξ^- from $\Xi^+_c \to \Xi^-\pi^+\pi^+$.
- Downstream tracking available in HLT1 now:
  VELO matching would become main method to reconstruct charged hyperons if VELO matching is implemented in HLT1.



Fundamental parameters

- Branching fractions and lifetimes
- Decay asymmetry parameters
- New decay modes
- New excited and/or multi charm baryons

Polarization

- In direct production $\rightsquigarrow$ anchor points for QCD [JHEP 11 (2015) 067][EPJC 69, 657]
- In decay chain $\rightsquigarrow$ use as polarimeter [JHEP 12 (2019) 148]
- Spin precession $\rightsquigarrow$ magnetic/electric dipole moments [PRD 103, 072003]

Spectroscopy

- Spectroscopy of light hadrons from c decays $\rightsquigarrow$ non-perturbative QCD
- Need better models and coupled channel analyses

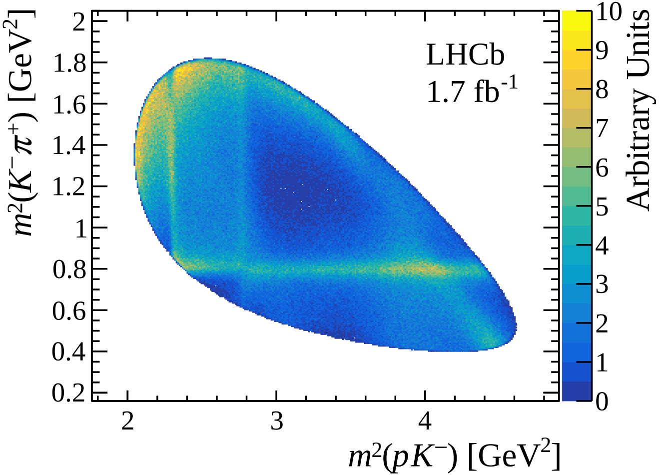
CPV

- SM: CKM complex phase, QCD θ-term
- Baryons more difficult than mesons
- ΔA_{CP}-like observables [1206.4554] [PRD 99, 033005] [EPJC 79, 429]
- SCS decays or time-dependent CPV in CF and DCS modes via neutral kaons [JHEP 03 (2018) 066]

- The four main topics are deeply connected. Polarization and CPV measurements are sensitive to physics beyond the standard model. However: They cannot be fundamentally understood without proper decomposition of the contributing amplitudes (involves Fundamental parameters and Spectroscopy)
- LHCb collects samples of charm baryon decays that are unique in statistics and fidelity
  - Unrivalled for many modes, but struggling with others see "Selections"; discuss concrete prospects during the workshop?

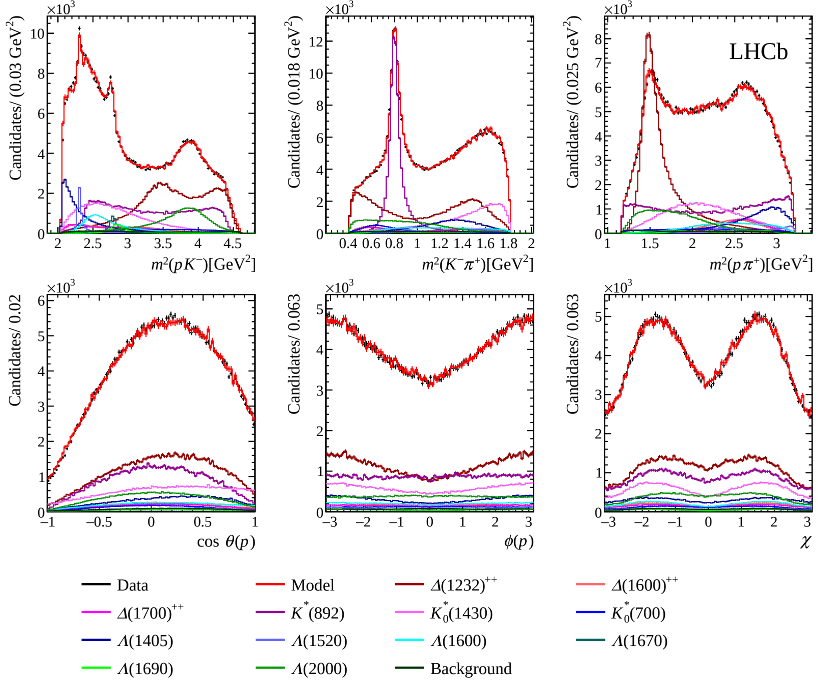
[PRD 108, 012023]

- Goal: Measure polarization vector in $\Lambda_c^+ \to pK^-\pi^+$ from semileptonic b decays, including sensitivity to polarization $S = |\alpha|/\sqrt{3}$ with decay asymmetry parameter
$$\alpha = \frac{|\mathcal{H}_{1/2,0}|^2 - |\mathcal{H}_{-1/2,0}|^2}{|\mathcal{H}_{1/2,0}|^2 + |\mathcal{H}_{-1/2,0}|^2}$$ for each resonance
- Amplitude model of $\Lambda_c^+ \to pK^-\pi^+$, parameters of $\Lambda(2000)$ byproduct
- 2016 data reduced to 400k events ($\sim 30\%$), $f_{\text{bkg}} = 1.69\%$
- Amplitude model: 6 excited Λ, 3 Δ^{++} and 3 K^{*0} resonances; $\Lambda(1405)$ as Flatté, $K_0^*(700)$ and $K_0^*(1430)$ as simplified Bugg



$\Lambda_c^+ \to pK^-\pi^+$ from SLb AmAn

[PRD 108, 012023]



[PRD 108, 012023]

Resonance	α	Stat. Unc.	Model Unc.	Syst. Unc.
Model $\sqrt{3}S$	0.662	0.005	0.010	0.007
$K^*(892)^0$ $\sqrt{3}S$	0.873	0.010	0.023	0.003
$\Lambda(1405)$	-0.58	0.05	0.28	0.01
$\Lambda(1520)$	-0.925	0.025	0.084	0.005
$\Lambda(1600)$	-0.20	0.06	0.50	0.03
$\Lambda(1670)$	-0.817	0.042	0.073	0.006
$\Lambda(1690)$	-0.958	0.020	0.027	0.006
$\Lambda(2000)$	0.57	0.03	0.19	0.01
$\Delta(1232)^{++}$	-0.548	0.014	0.036	0.004
$\Delta(1600)^{++}$	0.50	0.05	0.17	0.01
$\Delta(1700)^{++}$	-0.216	0.036	0.075	0.011
$K_0^*(700)^0$	0.06	0.66	0.24	0.23
$K_0^*(1430)^0$	-0.34	0.03	0.14	0.01

- Measurement dominated by model systematics
- Large Λ_c^+ polarization found: good polarimeter mode
- Mass and width of $\Lambda(2000)$ found to be $1988 \pm 2 \pm 21$ MeV and $179 \pm 4 \pm 16$ MeV

[JHEP 07 (2023) 228]

- Take transition amplitudes from AmAn [PRD 108, 012023] and apply Dalitz plot decomposition [PRD 101, 034033]

  $T_{\nu_0,\{\lambda\}} = \sum_{\nu} D^{1/2*}_{\nu_0,\nu}(\phi,\theta,\chi) A_{\nu,\{\lambda\}}(\kappa)$ with spin projection ν, the combined index for final state helicities $\{\lambda\}$, Wigner D matrices, Euler angles in Z-Y-Z convention (ϕ,θ,χ), transition amplitude in the aligned configuration A, and kinematic variables $\kappa (= (m^2(K^-\pi^+), m^2(pK^-)))$

- Relation to matrix element: $|\mathcal{M}|^2 = \sum_{\nu_0,\nu_0',\{\lambda\}} \Re_{\nu_0',\nu_0} T^*_{\nu_0',\{\lambda\}} T_{\nu_0,\{\lambda\}}$ with spin density matrix $\Re_{\nu_0',\nu_0} = 1 + \vec{P}\cdot\vec{\sigma}^P_{\nu_0',\nu_0}$, polarization vector $\vec{P}$ and the Pauli matrices $\vec{\sigma}^P_{\nu_0',\nu_0}$

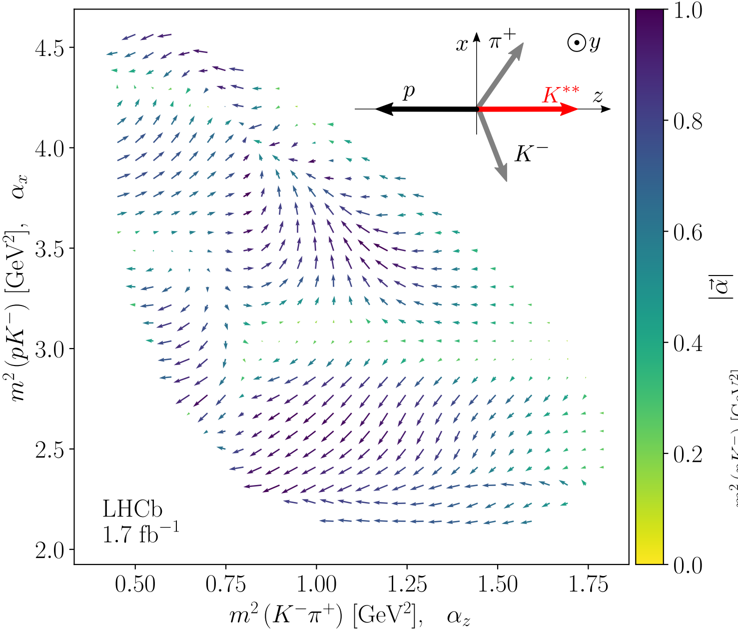
- After some algebra: $|\mathcal{M}(\phi,\theta,\chi,\kappa)|^2 = I_0(\kappa)\left(1 + \sum_{i,j} P_i R_{ij}(\phi,\theta,\chi)\alpha_j(\kappa)\right)$, with total differential decay rate $I_0(\kappa)$ and $I_0 = \sum_{\nu,\{\lambda\}} |A_{\nu,\{\lambda\}}|^2$, and the aligned polarimeter vector

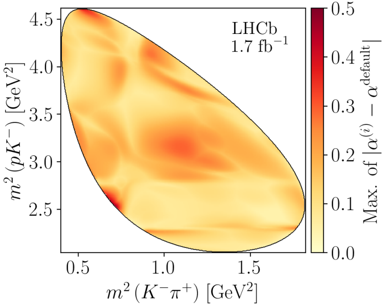
  $\vec{\alpha}(\kappa) = \sum_{\nu',\nu,\{\lambda\}} A^*_{\nu',\{\lambda\}} \vec{\sigma}_{\nu',\nu} A_{\nu,\{\lambda\}} \,/\, I_0(\kappa)$

- The polarimeter vector is a model-agnostic representation for polarisation dependence of the decay rate.

- Code available in zendoo repository

$\Lambda_c^+ \to pK^-\pi^+$ polarimetry





Summary

LHCb has a unique potential due to large production cross-sections and high instantaneous luminosity.
Because of that, we can't afford to store every event to disk; we need to be smart in what we save!
New methods of reconstruction can open up new possibilities.
Many decays are not analyzed yet, and input from/collaboration with theory is very welcome! Searches for physics beyond the standard model will require "bread and butter" inputs from spectroscopy, measurements of lifetime, branching fractions and decay asymmetry parameters.