Hyperons* at LHCb

* Hyperons are baryons with at least one strange quark

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Annual meeting of the German LHCb groups and affiliated theory community, Bochum

Outline

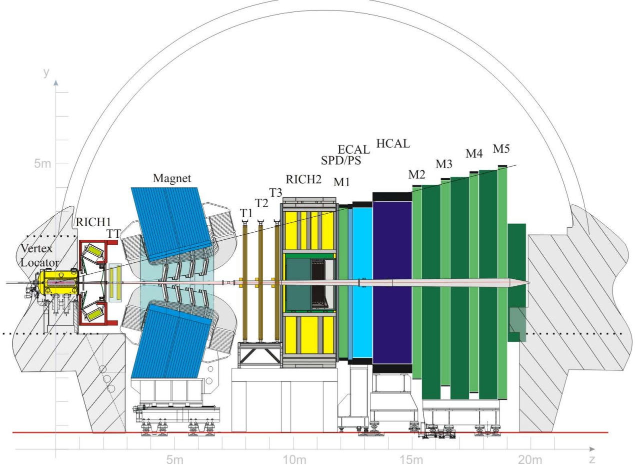
- LHCb overview
- Reconstruction and Trigger
- Hyperon reconstruction
- Hyperons for spectroscopy
- Outlook

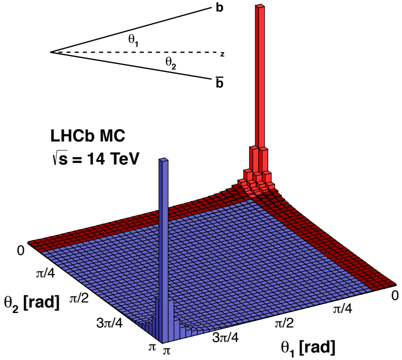
Objective

My goal is to give a feeling for LHCb's reach in physics hyperons with a focus on spectroscopy; showing advantages and limitations of the LHCb detector and its upgrades.

LHCb in Run 1 & 2 (2011-18)

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





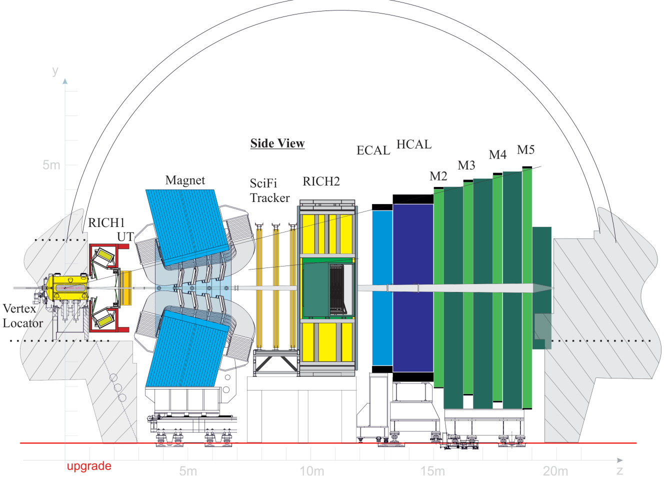
- General purpose detector with forward geometry
  + ions, fixed target, MOeDAL, CodexB ...

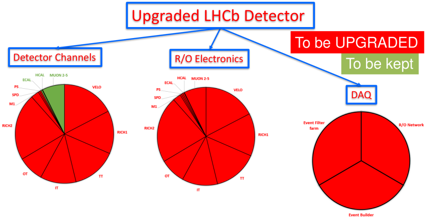
+ VELO close to interaction region moveable!
+ Excellent hadron PID
+ Flexible software trigger (CPUs)

Disadvantages for hyperons:

– Reconstruction of neutrals
– Hardware trigger (30 ⟶ 1 MHz)

[JINST 19 P05065]





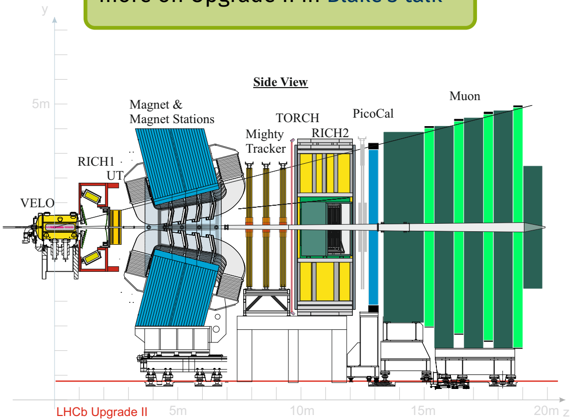
Same as before? Not quite...

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

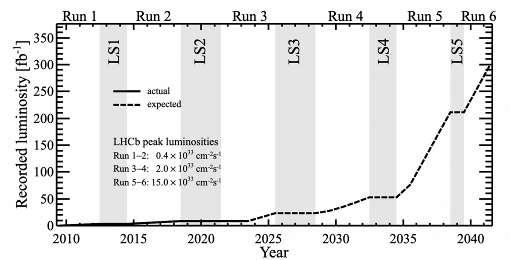
- Average visible interactions $\sim 1 \longrightarrow \sim 5$
- VELO strip $\longrightarrow$ pixels; 5 $\longrightarrow$ 3.5 mm to beam
- Heterogeneous software trigger

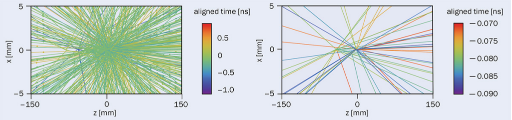
LHCb Upgrade II – Run 5 & 6 (2036-41)

more on Upgrade II in Blake's talk



[1808.08865 [hep-ex]]

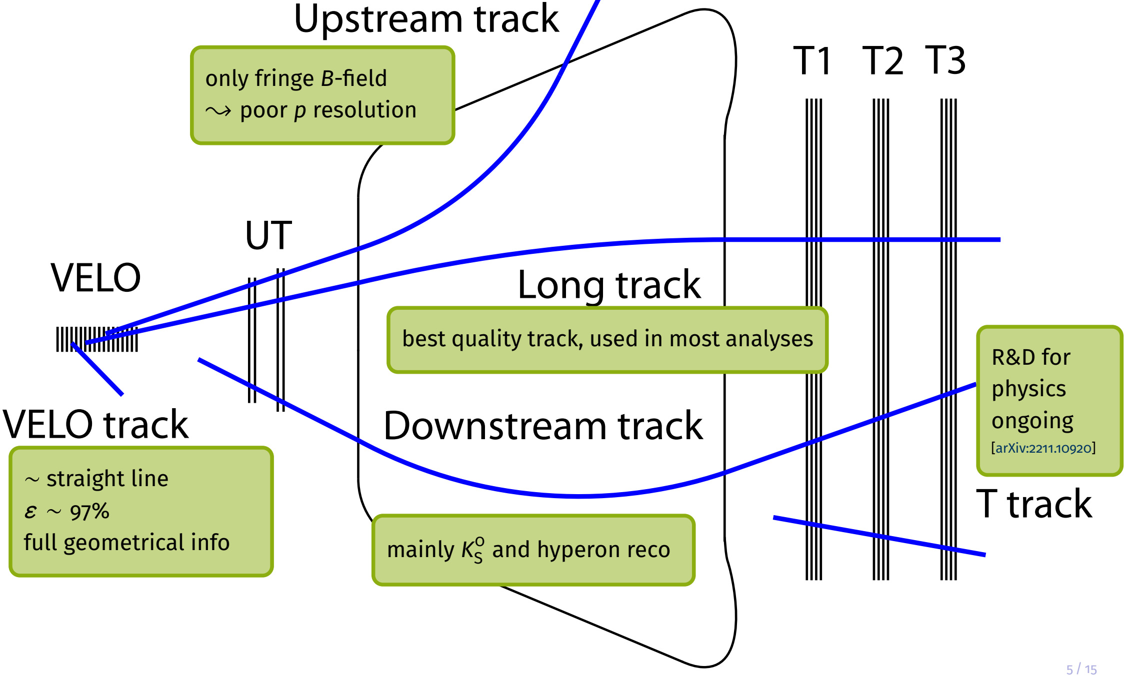




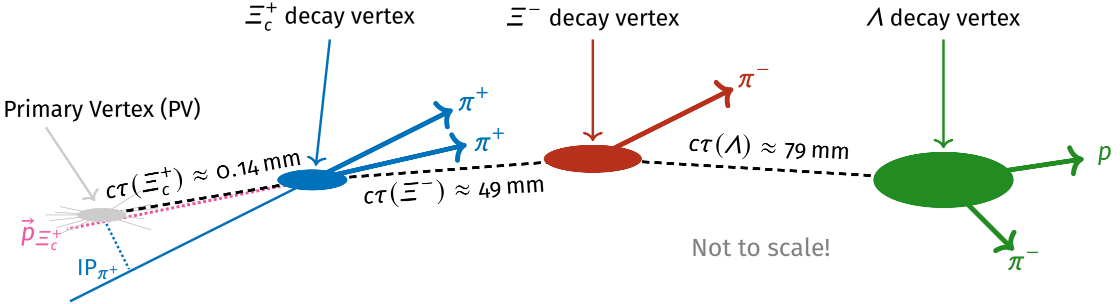
- Timing (VELO, RICH, TORCH, PicoCal)
- Pixel in UT, inner part of Mighty Tracker
- Low p track reco in Magnet Stations

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

Reconstruction: track types



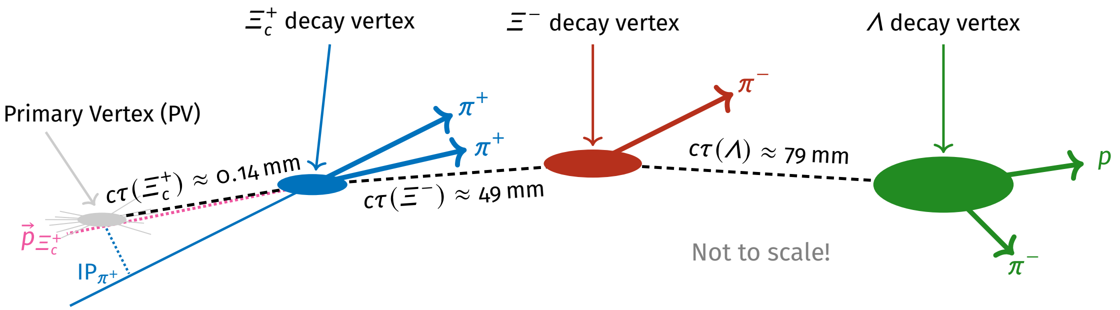
Reconstruction: (dis-)advantages

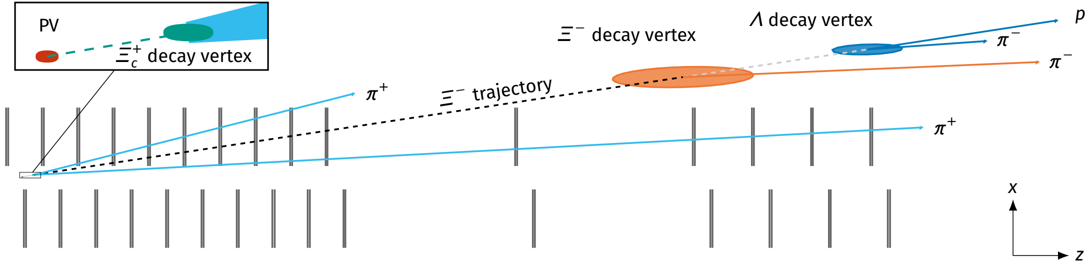


- Muons are easiest to reconstruct and select, followed by **charged (stable) hadrons ($\boldsymbol{p}$, $\boldsymbol{K}$, $\boldsymbol{\pi}$)**
  Low momentum hadrons, like π from Λ and Ξ^-, as well as downstream tracks suffer from lower $\varepsilon_{\mathrm{reco}}$
- Photons, $\boldsymbol{\pi^0}$, η, ...are difficult due to ECAL granularity; electrons OK, but poor $\delta p/p$ (due to γ_{Brem})
- **Neutron** and 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 (FD, DLS)
- b hadron lifetimes ideal: decay in VELO, good separation from PV
  c hadron lifetimes shorter $\rightsquigarrow$ lower $\varepsilon_{\mathrm{selection}}$ (especially baryons); Most hyperons decay downstream of VELO or even UT
- Kinematics and hadron PID further improve signal purity

bold: decay products of hyperon weak decays

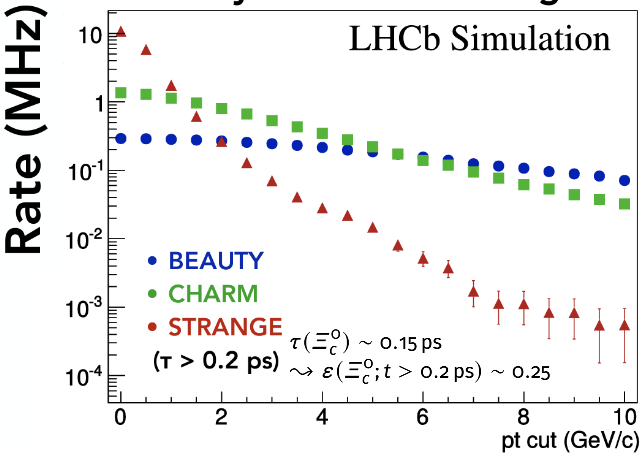
Reconstruction: topologies





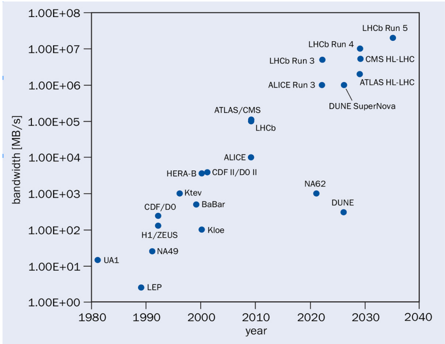
[LHCB-TDR-016]

Partially reconstructed signals



$\tau(\Xi_c^0) \sim 0.15\,\mathrm{ps}$

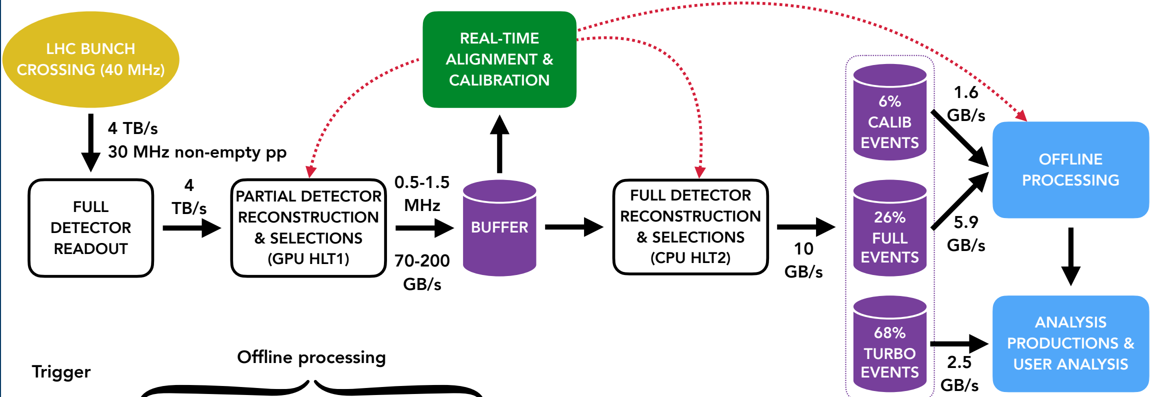
$\rightsquigarrow \varepsilon(\Xi_c^0; t > 0.2\,\mathrm{ps}) \sim 0.25$

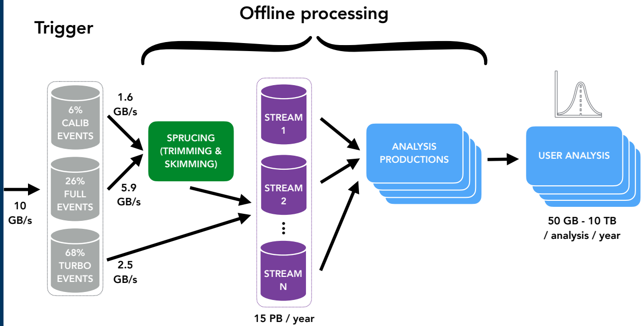


- Charm signal rate is $\mathcal{O}$ **MHz** in the LHCb acceptance
- We can only store ~ **50 kHz** in total if we store the raw event
- Need **fast, efficient** and **precise** reconstruction in a **flexible** trigger

More on the trigger in Alessandro's and Florian's talks

Dataflow (Upgrade I)

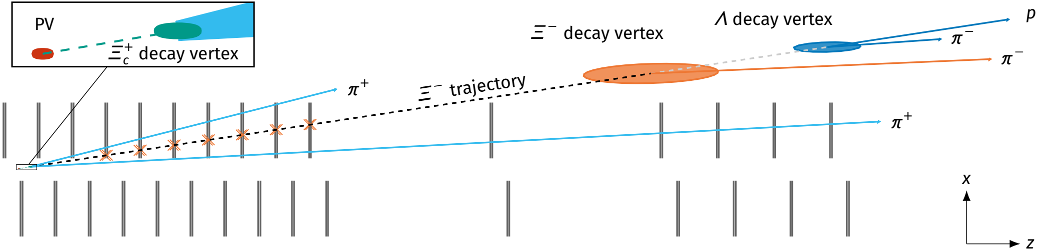


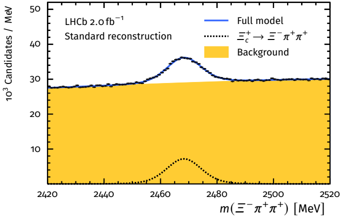


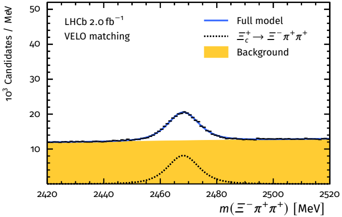
HLT1 limited by **rate and throughput**,
HLT2 by **bandwidth**, and
Sprucing by **disk/tape storage capacity**;
$\sim$ 50 HLT1 selection algorithms (lines)
$\sim$ 2.5k HLT2-, $\sim$ 1k Spruce lines
mainly from analysts

Hyperon reconstruction

- Hyperons have huge rates; How can they be triggered efficiently given the constraints?
- **New:** Reconstruct charged hyperon from downstream tracks and match it 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.
  - Studied performance with 2018 $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ data and simulation

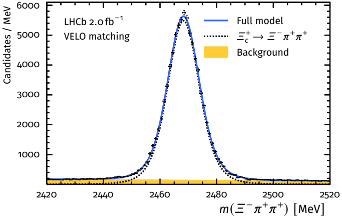


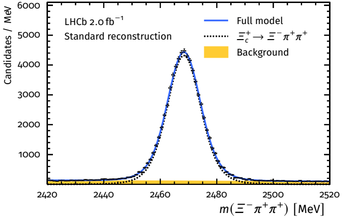




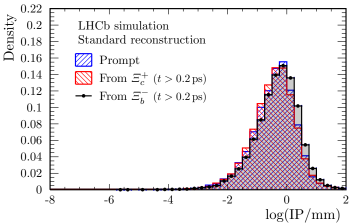
- Typical online selection
- Matching efficiency compatible with 100% ($\gtrsim$ 96% in simulation)
- Purity improved from 12% to 26%

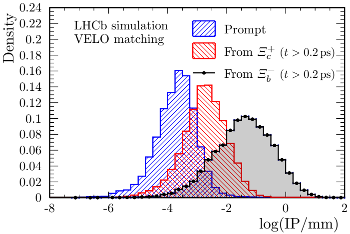
[EPJC 84, 761]





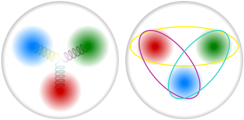
Gain 21% signal with VELO matching from typical ML-based offline selection at fixed purity of 95%



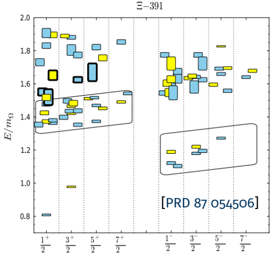


IP resolution with VELO matching such that prompt and secondary Ξ^- are distinguishable: IP > 20 µm removes ~ half of the prompt Ξ^- while retaining ~ 93 % of Ξ^- from Ξ_c^+ and 98 % of Ξ^- from Ξ_b^-

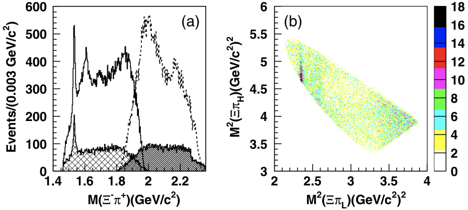
- Improved IP resolution ⇒ **inclusive Ξ^- and Ω^- HLT2 lines including raw data for Run 3**
  - In Run 2: Equivalent downstream *Turbo* lines kept 1 in 20 events due to bandwidth constraints
- Also measured improvements on mass resolution in $\Xi^- \pi^+$ subsystem, and signal-to-noise ratio as function of pileup



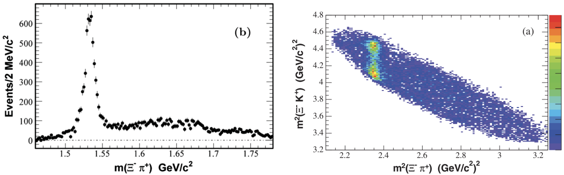
- Why should we do light hadron spectroscopy at LHCb?
  - Absence of light exotic (QCD) states? Many candidates, *e.g.* $\Lambda(1405)$
  - Tool and benchmark for theory in non-perturbative regime *e.g.* [EPJC 74, 2981]
  - Great potential to study light spectrum in particular $S=-2$ and $S=-3$ baryons where data is scarce
- Focus on Ξ^* in the $\Xi^-\pi^+$ system
  - P-wave excitations elusive: $\Xi(1620)$ and $\Xi(1690)$ candidates for $\frac{1}{2}^-$ states, but $\gtrsim$ 100 MeV lighter than quark model predictions
  - $\Xi(1620)$ and $\Xi(1690)$ close to $\Lambda\bar{K}$ and $\Sigma\bar{K}$ thresholds $\rightsquigarrow$ molecular component?
  - Strong production dependence of $\Xi^-\pi^+$ spectrum $\rightsquigarrow$ describe $\Lambda_c^+\to\Xi^-\pi^+K^+$ and $\Xi_c^+\to\Xi^-\pi^+\pi^+$ simultaneously?



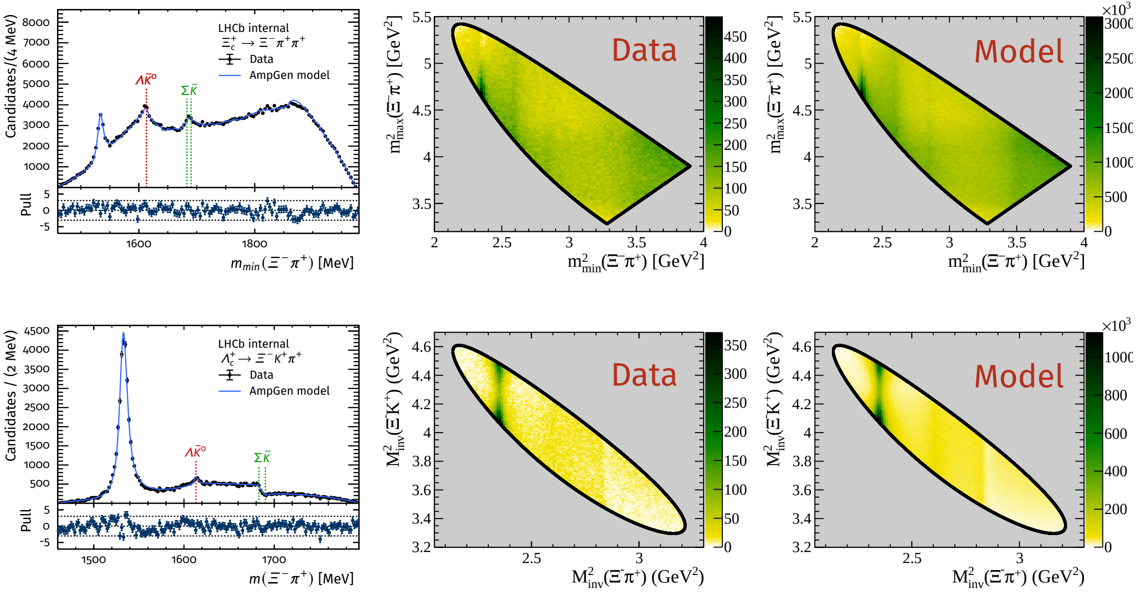
Belle $\Xi_c^+\to\Xi^-\pi^+\pi^+$ [PRL 122 072501]



BaBar $\Lambda_c^+\to\Xi^-\pi^+K^+$ [PRD 78 034008]



Yes, we can!


LHCb internal
$\Xi_c^+ \to \Xi^- \pi^+ \pi^+$
Data
AmpGen model
$\Lambda \bar{K}^0$
$\Sigma \bar{K}$
Candidates/(4 MeV)
Pull
$m_{min}(\Xi^- \pi^+)$ [MeV]
Data
Model
$m^2_{max}(\Xi^- \pi^+)$ [GeV^2]
$m^2_{min}(\Xi^- \pi^+)$ [GeV^2]
LHCb internal
$\Lambda_c^+ \to \Xi^- K^+ \pi^+$
Data
AmpGen model
$\Lambda \bar{K}^0$
$\Sigma \bar{K}$
Candidates / (2 MeV)
Pull
$m(\Xi^- \pi^+)$ [MeV]
Data
Model
$M^2_{inv}(\Xi^- K^+)$ (GeV^2)
$M^2_{inv}(\Xi^- \pi^+)$ (GeV^2)

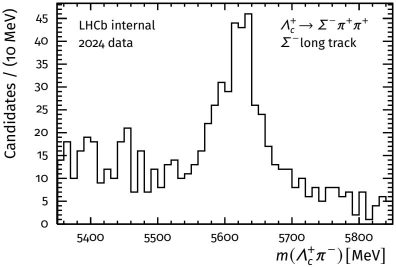
- Using K matrix model and helicity formalism.
  Cross check with covariant tensors, and including the Ξ^- and Λ decays
- Need poles in $1/2^-$ K matrix close to $\Lambda\bar{K}$ and $\Sigma\bar{K}$ thresholds
  - Measuring their positions and residues is one of the main goals
- Model building, efficiency correction and fitting is hard work.
  Still, it's one of the easiest systems to study:
  - No resonances in the crossing channels that would hamper model building
  - Only few thresholds to consider
  - Resonances narrow enough to not overlap
- Not much sensitivity to $3/2^-$ and $5/2^-$ states $\rightsquigarrow$ need $\Lambda\bar{K}$, $\Sigma\bar{K}$ or $\Xi(1530)\pi$ channels

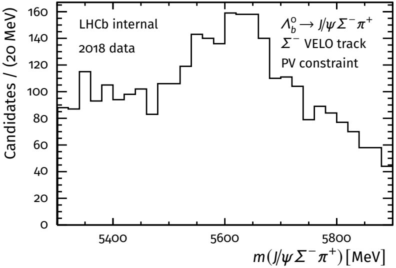
$\Rightarrow$ Need to be able to efficiently reconstruct Σ^+ ($\rightarrow p\pi^0/n\pi^+ \sim 50/50$) and $\Sigma^- \rightarrow n\pi^-$!

  - Not only for spectroscopy isospin partners of P_{cs}, but also searches for CPV in charm:
    U spin symmetry cancels hadronic effects, but $p \leftrightarrow \Sigma^+$ and $\Xi^- \leftrightarrow \Sigma^-$ [PRD 99 033005]

Σ reconstruction: First steps (Bonus)

- Proof of principle for two methods
  1. Σ^- $c\tau \approx 4.4\,\text{cm}$ as long track.
     Survival probability $\sim 2-3\%$
     beyond T stations in LHCb acceptance.Not much hope for Σ^+ as $c\tau \approx 2.5\,\text{cm}$
  2. Σ as VELO track.
     Infer momentum from PV constraint of $\Lambda_b^0 \to J/\psi \Sigma \pi$
- 1. can be used to develop (RICH) PID for Σ
- 2. can be extended in various ways
  - Use upstream tracks (in combination with RICH ID)
  - Use downstream decay products. Advantage $\Sigma^+ \to p\pi^0$: proton ID, ECAL info and kinematics Armenteros-Podolanski
  - Search for kink topologies in the VELO
    Should work better for $\Sigma \to n\pi$
  - Combine upstream and T tracks?
    Can HCAL info for neutrons improve reconstruction? ...





- Feasibility studies need to be selective and fast to write Run 3 trigger selections
  which need to be fast, discriminating selections; store the information needed to improve method offline

Summary

LHCb has a unique potential for physics with hyperons due to large production cross-sections and high instantaneous luminosity.

On the other hand, this also means that we can't afford to store every event; and we need to be flexible in what part of the event we save!

Much work has been invested to select and reconstruct decays with hyperons, and we are in an excellent position to make a significant impact on light hadron spectroscopy and other topics with Run 3 data.

We can improve by developing new methods to reconstruct hyperons with which we can explore decay modes which are currently not accessible at LHCb or elsewhere.

Support material

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

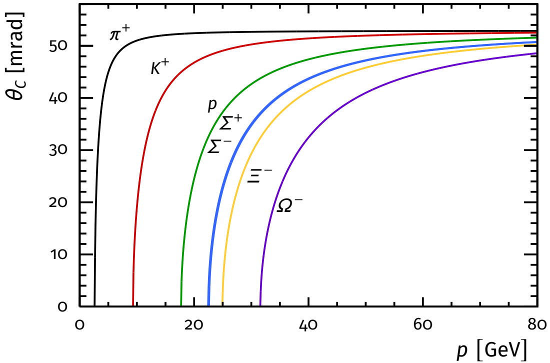
- Spectroscopy of light hadrons from c decays $\rightsquigarrow$ non-perturbative QCD
- Need better models and coupled channel analyses

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?

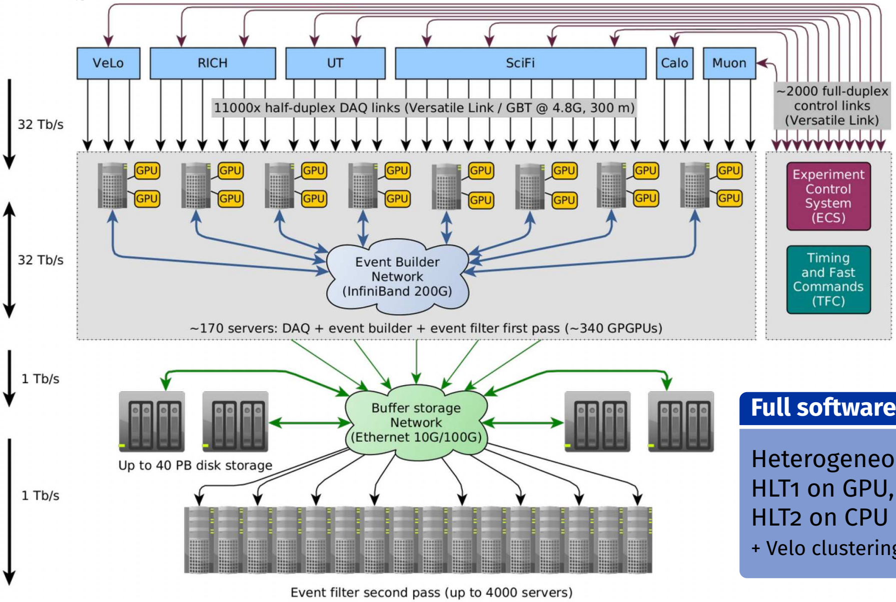
- Strange physics with VELO matching:
  - VELO matching allows to close kinematics for decays like $\Xi^- \to \Lambda\mu^-\overline{\nu}_\mu$
  - Improve $\Sigma^+ \to p\mu^-\mu^+$ double stats relative to [PRL 120, 221803]; K^+ mass with $K^+ \to \pi^+\pi^+\pi^-$
- Feasible to reconstruct Σ^+ and Σ^- from c or b?
- For decays in VELO: "kink" reconstruction; also: add hits to downstream decay products $\rightsquigarrow$ improve K_S^0 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 $\Lambda_b^0 \to J/\psi\Sigma^-\pi^+$,
  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.



- $\Xi^-\pi^+$ and Ξ^-K^+ S waves modelled by `GenericKmatrix` lineshape (à la PDG).
  - P vector approach derived from unitarity relations of the S matrix to build production amplitudes:
    $F_k = \sum_{\text{channels j}} (1 - i\rho K)^{-1}_{jk} P_k$ with P vector P, phase-space ρ, K matrix K
  - $K_{jk} = \sum_{\text{poles }\alpha} \frac{g_{\alpha j} g_{\alpha k}}{m_\alpha^2 - s} + \psi_{jk}\mathcal{B}(s)$ in channels j, k, where $g_{\alpha j}$ is the K matrix coupling of pole α to channel j, m_α is the K matrix mass of pole α,
    ψ_{jk} is bkg matrix and $\mathcal{B}(s)$ a smooth function in Mandelstam s (here $\mathcal{B}(s) = \frac{1 + s_0}{s + s_0}$ with parameter s_0). Couplings and bkg terms real $\Longleftarrow$ CP is conserved
  - The P vector is given by $P_k = \sum_{\text{poles }\alpha} \frac{\beta_\alpha g_{\alpha k}}{m_\alpha^2 - s} + \phi_k \mathcal{B}(s)$ with $\beta_\alpha = \sum_{\text{channels q}} a_q g_{\alpha q}$,
    $\phi_k = \sum_q a_q \psi_{qk}$ where a_q are real coefficients and the couplings, bkg matrix and m are the same as in the K matrix
- $\Xi^-\pi^+$ K matrix contains $\Xi\pi$, $\Lambda\bar{K}$, $\Sigma\bar{K}$ and $\Xi\eta$ channels and 2 poles or more.
  - Isospin channels taken into account, couplings shared.
- Ξ^-K^+ isoscalar K matrix contains Ξ^-K^+ and $\Lambda\eta'$ channels.
- Ensure analyticity of K matrix with Chew-Mandelstam phase-space.

LHCb's solution (Upgrade I)

[LHCb-DP-2021-003]

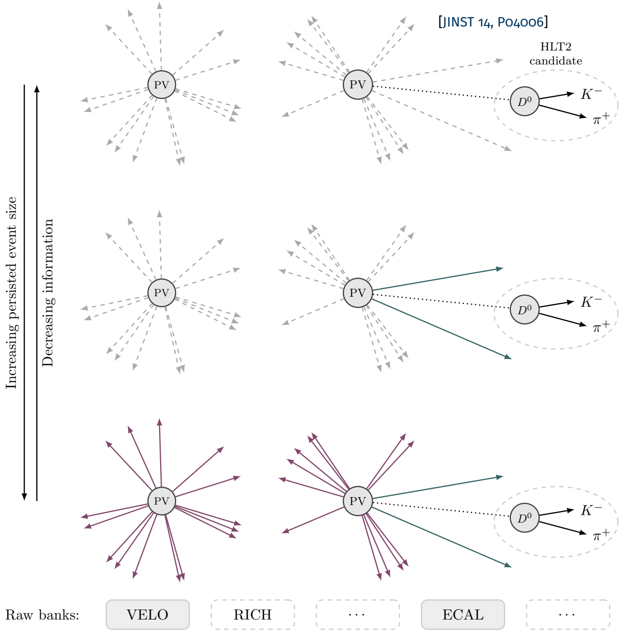


Full software trigger

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

- 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 $\rightsquigarrow$ 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 $\rightsquigarrow$ more signal offline!

[JINST 14, P04006]



Particle	Lifetime [ps]	Decay	$\mathcal{B}$ [%]	"reconstructability"
π^0	10^{-4}	$\gamma\gamma$	99	**(*)
K^0_S	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^0_S 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.