Multihadronic charm baryon decays with hyperons

Joan Ruiz-Vidal

Lund University

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Probing baryon weak decays - from experiment to theory
Warsaw, 6–7 March 2023

Credits

LHCb analyses of $H_c \to \Lambda\, h\,(h)\,(h)$ being developed by a broad team at

University of Valencia - IFIC
Fernando Martínez Vidal, Sergio Jaimes, Miguel Rebollo, JRV (formerly)

University of Milano - INFN
Nicola Neri, Andrea Merli, Giorgia Tonani

University of Chinese Academy of Sciences
Jinlin Fu, Chuangxin Lin, Ziyi Wang, Jian-Yu Zhang

CERN
Louis Henry

Introduction: hadronic modes with Λs

$\boldsymbol{\Xi_c^0 \to \Lambda K^- \pi^+}$	CF	$\Xi_c^0 \to \Lambda \pi^+ \pi^-$	SCS
$\boldsymbol{\Lambda_c^+ \to \Lambda \pi^+ \pi^+ \pi^-}$	CF	$\Xi_c^0 \to \Lambda \pi^- K^+$	DCS
$\boldsymbol{\Xi_c^+ \to \Lambda K^- \pi^+ \pi^+}$	CF	$\boldsymbol{\Xi_c^0 \to \Xi^- \pi^+ \pi^+ \pi^-}$	CF
$\Xi_c^0 \to \Lambda K^+ K^-$	SCS	$\boldsymbol{\Xi_c^+ \to \Xi^- \pi^+ \pi^+}$	CF
$\Lambda_c^+ \to \Lambda K^+ \pi^+ \pi^-$	SCS	$\boldsymbol{\Xi_c^0 \to \Xi^- \pi^+}$	CF
$\Lambda_c^+ \to \Lambda \pi^+$	CF	$\Lambda_c^+ \to \Xi^- K^+ \pi^+$	CF

modes with stripped Run2 data available

- Essentially unexplored both for theory and experiment
- Full of **physics opportunities**: polarimetry, spin correlations, spectroscopy in amplitude analyses, CPV, ...
- Several **analyses in progress** at LHCb. CS modes for Run3+

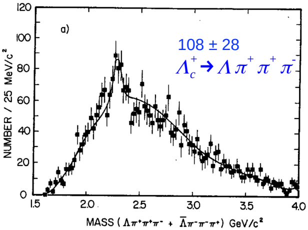
Interest originally triggered by the measurement of **electric and magnetic dipole moment** of Λs crossing the magnet (**T-tracks**). More at the end.

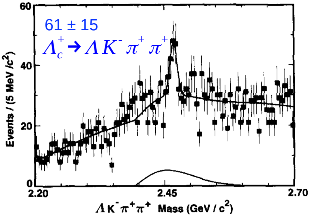
First observations in the 80s and 90s

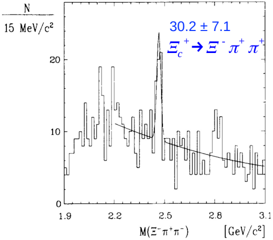
CLEO Phys.Rev.Lett. 55 (1985) 923

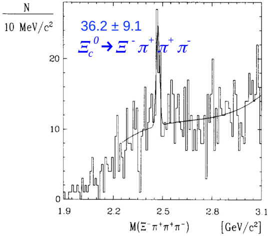
CLEO Phys.Lett.B 365 (1996) 431

ARGUS Phys.Lett.B 247 (1990) 121



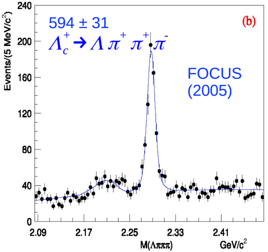


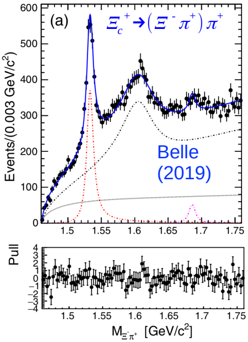




What has been done – previous measurements (II)

- Precise measurements of **branching fractions**, often wrt $\mathcal{B}(\Lambda_c^+ \to pK^- pi^+)$ or $\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)$
  FOCUS Phys.Lett.B 571 (2003) 139
  Belle Phys.Lett.B 605 (2005) 237
  BESIII Phys.Rev.Lett. 116 (2016) 5, 052001
  Belle Phys.Rev.D 103 (2021) 5, 052005
- Higher yields allow tighter selections to increase the purity: first **Dalitz analyses**
  FOCUS Phys.Lett.B 624 (2005) 22
  Belle Phys.Rev.Lett. 122, 072501 (2019)
  Belle 2211.11151
- **Angular distributions not exploited**. Only some decay-asymmetry parameters of 2-body modes
  - $\Lambda_c^+ \to \Lambda\pi^+$ (Belle 2208.08695, and many others)
  - $\Xi_c^0 \to \Xi^-\pi^+$ (Belle PRL 127 (2021) 12, 121803)
  - $\Xi_c^0 \to \Lambda\bar{K}^{*0}$ (Belle JHEP 06 (2021) 160)





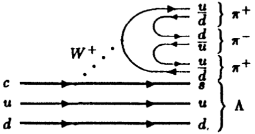
What can be done – physics opportunities (I)

Proton angular distribution

- Λ spin accessed through its self-analysing decay $\Lambda \to p\pi^-$.

$$\frac{dW}{dcos\theta_p d\phi_p} = \frac{1}{4\pi}\left[1 + \alpha_\Lambda \mathrm{P}_\Lambda \cdot \mathrm{k}\right] \qquad \frac{dW}{dcos\theta_p} = \frac{1}{2}\left[1 + \alpha_\Lambda P_{\Lambda,z}\cos\theta_p\right]$$

  - Λ polarization: $\mathrm{P}_\Lambda = (P_{\Lambda,x}, P_{\Lambda,y}, P_{\Lambda,z})$
  - proton dir. in the Λ helicity rest frame: $\mathrm{k} = (\cos\phi_p \sin\phi_p, \sin\phi_p \sin\phi_p, \cos\theta_p)$
- Charm baryon decay asymmetry α
  - Two-body decays (*e.g.* $\Lambda_c^+ \to \Lambda\pi^+$): $P_{\Lambda,z} = \alpha_{\Lambda_c^+}$
  - Multibody decays: consider effective decay asymmetry of $H_c \to \Lambda X$, dependent on the momentum transfer $q^2 = (p_{H_c} - p_\Lambda)^2$. Naive "*leading order*" diagram of $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$ as $\Lambda_c^+ \to \Lambda W^+$



(e) $\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$

PRD 43 (1991) 3599

$$P_{\Lambda,z}(q^2) = \alpha(q^2) \equiv \frac{\left(|H_{\frac{1}{2}1}|^2 + |H_{\frac{1}{2}0}|^2\right) - \left(|H_{-\frac{1}{2}-1}|^2 + |H_{-\frac{1}{2}0}|^2\right)}{\left(|H_{\frac{1}{2}1}|^2 + |H_{\frac{1}{2}0}|^2\right) + \left(|H_{-\frac{1}{2}-1}|^2 + |H_{-\frac{1}{2}0}|^2\right)}$$

where $H_{\lambda_\Lambda \lambda_W}$ are the helicity amplitudes with $\lambda_\Lambda = \pm\frac{1}{2}$ and $\lambda_W = 0, \pm 1$

What can be done – physics opportunities (II)

CP violation

- Independently of the interpretation / parametrization, different $\alpha(q^2) \neq -\overline{\alpha}(q^2)$ would signal CPV in the decay,

$$A_{CP}(q^2) = \frac{\alpha(q^2) + \overline{\alpha}(q^2)}{\alpha(q^2) - \overline{\alpha}(q^2)} \approx A_{CP,\Lambda} + A_{CP,H_c}(q^2)$$

$$A_{CP,\Lambda} = \frac{\alpha_\Lambda + \alpha_{\bar{\Lambda}}}{\alpha_\Lambda - \alpha_{\bar{\Lambda}}}\ , \quad A_{CP,H_c}(q^2) = \frac{\alpha_{H_c}(q^2) + \overline{\alpha}_{H_c}(q^2)}{\alpha_{H_c}(q^2) - \overline{\alpha}_{H_c}(q^2)}$$

- Similarly to the observation of CPV in D meson decays, difference of direct decay asymmetries between CF / SCS as

$$\Delta A_{CP} = A_{CP}(\mathrm{SCS}) - \mathrm{A}_{\mathrm{CP}}(\mathrm{CF})$$

- **T-odd triple products** in four-body modes $P \to abcd$ PLB 749 (2015) 104

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}, \quad \text{where} \quad C_T = \boldsymbol{p}_a \cdot (\boldsymbol{p}_b \times \boldsymbol{p}_c).$$

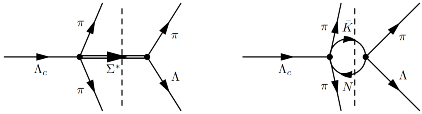
What can be done – physics opportunities (III)

Complete angular analysis

- Accounting for all angular variables, extract additional decay-asymmetry parameters and charm baryon polarization
- Test polarization transfer $H_c \to \Lambda$ induced by *missing* intermediate rest frame PRC 95 (2017) 5, 054902

Amplitude analysis and spectroscopy

- Combining all information of invariant masses + angular distribution = build full amplitude model
- Predictions of pentaquark state Σ^* as a broad $(\Lambda\pi^{\pm})$ resonance with mass $m(\Sigma^*) \approx 1380\,\mathrm{MeV}$ and $J^P = \frac{1}{2}^-$. Entangled with the known $\Sigma(1385)^{\pm}$ $(\frac{3}{2}^-)$. Angular variables crucial. nucl-th/0011071, hep-ph/0403210, 1001.0805
- Structures in $m(\Lambda\pi^{\pm})$ may also be produced from $\bar{K}N$ re-scattering 2211.11151



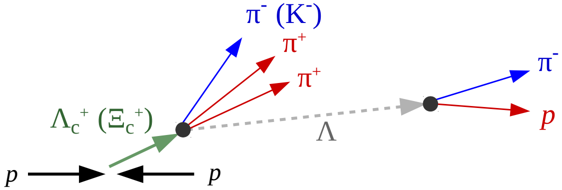
(a) (b)

What is being done (at LHCb)

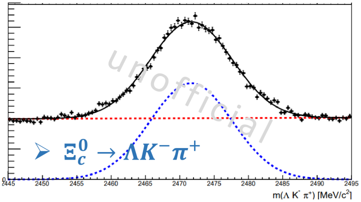
- Several of these channels being tackled by different groups at LHCb
  - $\Xi_c^0 \to \Lambda K^- \pi^+$
  - $\Lambda_c^+ \to \Lambda \pi^+ \pi^+ \pi^-$
  - $\Xi_c^0 \to \Xi^- \pi^+ \pi^+ \pi^-$
  - $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$
  - $\Xi_c^0 \to \Xi^- \pi^+$
- Steps to harvest Run2 data (stripping, trigger) started in 2017
- Challenging reconstruction

  ▷ Long-lived Λ (and Ξ^-) ▷ relatively soft $\pi^\pm, K^\pm$

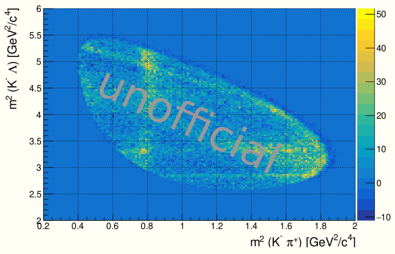
  ▷ Huge combinatorial background from *pp* collisions



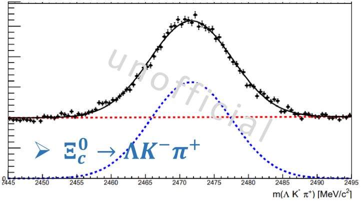
$\Xi_c^0 \to \Lambda K^- \pi^+$



- Higher yields than previous experiments. Run2 signal yield ~**120k**
- P_Λ studied in bins of phase space: (quasi-2-body; interferences; nonresonant) significant dilution / enhancements
- Very rich resonant structure: aim for a full amplitude analysis



$\Xi_c^0 \to \Lambda K^- \pi^+$



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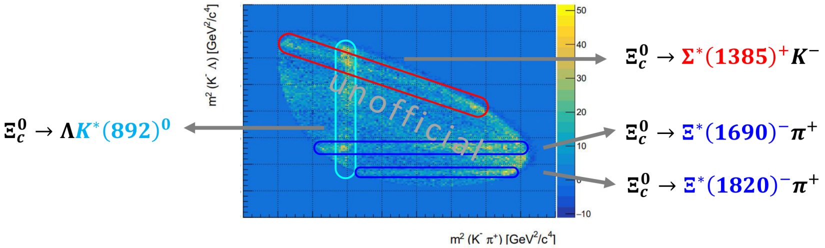
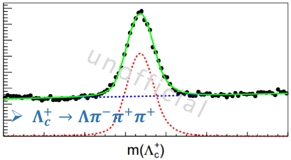
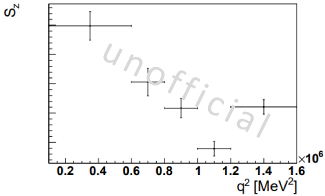
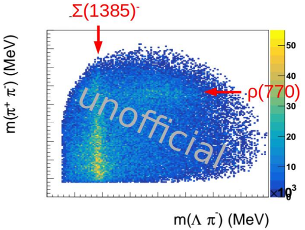


$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$



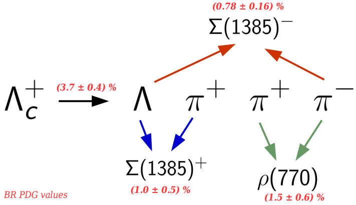




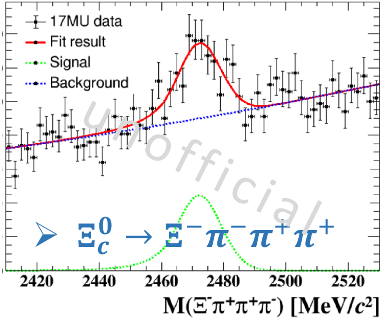
- Signal yields

Year	DD	LL	Total yield
16	49k	81k	130k
17	70k	95k	165k
18	325k	434k	759k
All	444k	610k	**1.05M**

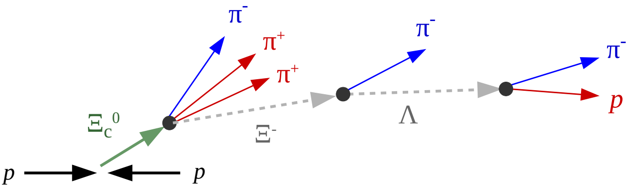
- $\boldsymbol{P}_\Lambda$ as a function of $q^2 = (p_{\Lambda_c^+} - p_\Lambda)^2$: large dependency in $P_{\Lambda,z}(q^2)$
- Rather simple dalitz plot. Large statistics allow clean search for new states and possible $\bar{K}N$ structure (see intro)
- Full angular analysis in progress. Effective decay parameters in bins of PS



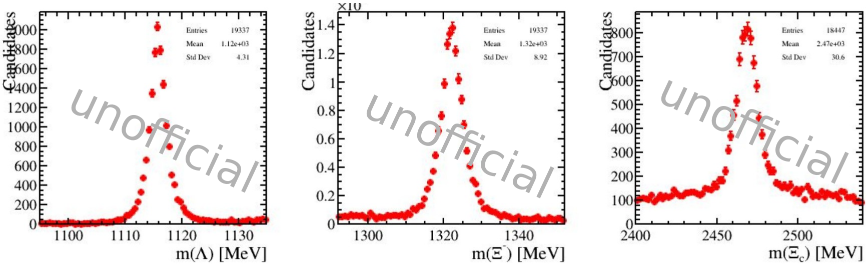
$\Xi_c^0 \to \Xi^-\pi^+\pi^+\pi^-$



- Especially difficult reconstruction. Soft pions and huge backgrounds from *pp*
- Analysis only starting
- Few events with inclusive Ξ^- Turbo. Stripping data with 2018 trigger promising



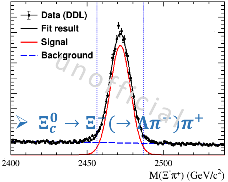
$\Xi_c^+ \to \Xi^- \pi^+ \pi^+$



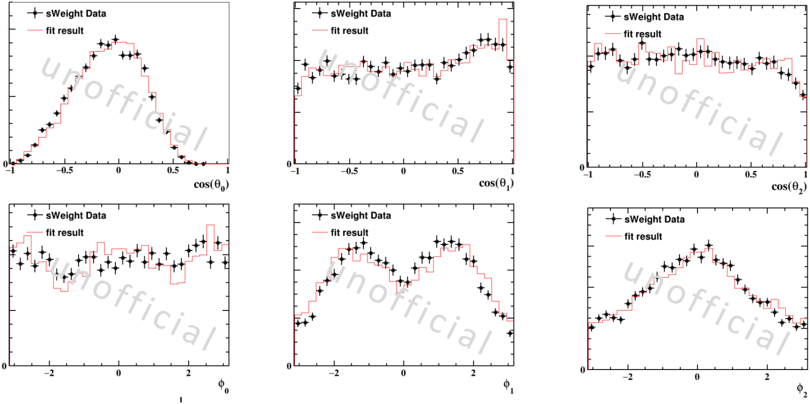
- Large signal yields especially in 2018, with dedicated trigger
- Plans for a full angular analysis in bins of phase space

Year	Signal yield
16	19k
17	32k
18	218k
Total	**270k**

$\Xi_c^0 \to \Xi^- \pi^+$



- Complete angular analysis in progress
- 2-body decay: more direct interpretation of asymmetry parameters
- Signal yield from turbo (17/18): $\sim$35k (25k DDL + 10k LLL)



Original motivation

Physics with T tracks: first results

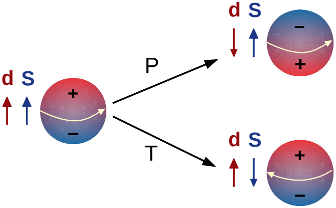
Electric dipole moment (EDM)

Classical definition

$$\boldsymbol{\delta} = \int \boldsymbol{r}\rho(\boldsymbol{r})d^3r$$

Quantum systems

$$\boldsymbol{\delta} = d\mu_N \frac{\boldsymbol{S}}{2}$$

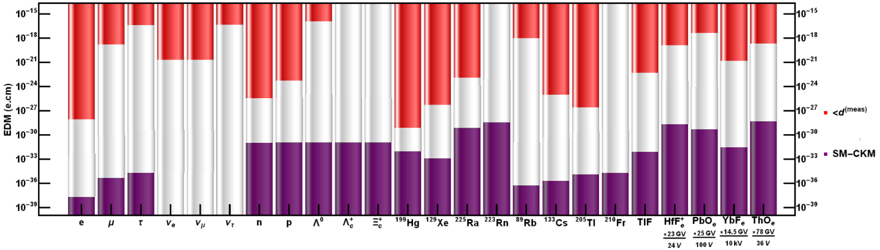


Interaction Hamiltonian

$$H = -\boldsymbol{\delta}\cdot\boldsymbol{E} \quad \xrightarrow{T} \quad +\boldsymbol{\delta}\cdot\boldsymbol{E}$$

$$\xrightarrow{P} \quad +\boldsymbol{\delta}\cdot\boldsymbol{E}$$

The EDM violates separately T and P $\Rightarrow$ **CP violation**



Adapted from P.M. Murthy 2018

Measurement at LHCb

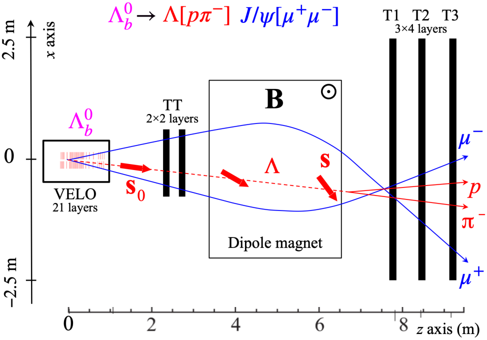
Proposed in Eur.Phys.J.C 77 (2017) 3, 181

Spin precession in external $\boldsymbol{B}$ field

$$\frac{d\boldsymbol{s}}{dt} = \boldsymbol{s} \times \boldsymbol{\Omega}\,, \quad \boldsymbol{\Omega} = \frac{\mu_N}{\hbar}\left[g\left(\boldsymbol{B} - \frac{\gamma - 1}{\gamma}(\boldsymbol{u}\cdot\boldsymbol{B})\boldsymbol{u}\right) + d\beta\boldsymbol{u}\times\boldsymbol{B}\right].$$

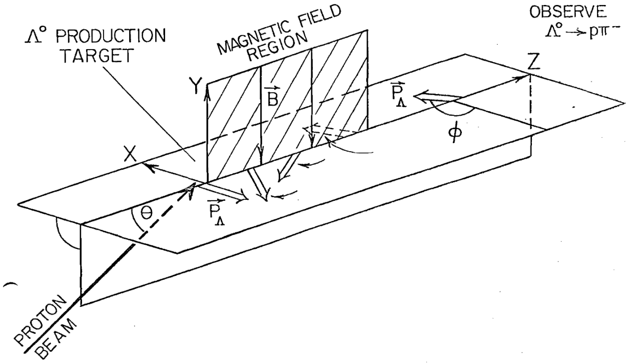
Experiment concept at LHCb

- Large initial longitudinal pol. from weak decays *e.g.* $\Lambda_b^0 \to \Lambda J/\psi$, $|\boldsymbol{s}_\Lambda| \approx 100\%$ $\Lambda_c^+ \to \Lambda\pi^+$, $|\boldsymbol{s}_\Lambda| \approx 84\%$
- Reconstruct $\Lambda \to p\pi^-$ with T tracks. Fit angular distribution
- Compare polarization before and after the magnet



State of the art

Previous experiment at Fermilab



- Proton beam on beryllium target
- 8.5% polarization
- Integrated field $\int Bd\ell =$ $10 - 15\,\mathrm{Tm}$
- $3 \cdot 10^6$ events

$\delta_\Lambda \leq 1.5 \cdot 10^{-16}$ ecm

$\mu_\Lambda = (-0.6138 \pm 0.0047)\ \mu_N$

PRD 23 (1981) 814

PRL 41 (1978) 1348

Λ production channels: selection criteria

- Weak decays
- Charged particles in the final state
- Known branching fractions
- Ignoring strong resonances

Direct Λ from baryon decays

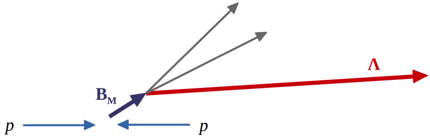
Channel	N_Λ (5 fb^{-1})
$\Xi_c^0 \to \Lambda K^- \pi^+$	3.83×10^{11}
$\Lambda_c^+ \to \Lambda \pi^+ \pi^+ \pi^-$	1.63×10^{11}
$\Xi_c^+ \to \Lambda K^- \pi^+ \pi^+$	9.78×10^{10}
$\Lambda_c^+ \to \Lambda \pi^+$	6.73×10^{10}
$\Xi_c^0 \to \Lambda K^+ K^-$	1.03×10^{10}
$\Xi_c^0 \to \Lambda \phi(K^+ K^-)$	5.95×10^{9}
Sum	**7.27** $\times 10^{11}$

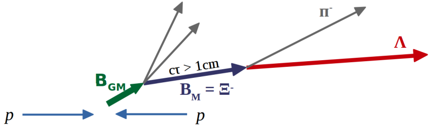
Intermediate Ξ^-

Channel		N_Λ (5 fb^{-1})
$\Xi_c^0 \to \Xi^- \pi^+ \pi^+ \pi^-$	$\Xi^- \to \Lambda \pi^-$	1.18×10^{12}
$\Xi_c^0 \to \Xi^- \pi^+$	$\Xi^- \to \Lambda \pi^-$	3.57×10^{11}
$\Xi_c^+ \to \Xi^- \pi^+ \pi^+$	$\Xi^- \to \Lambda \pi^-$	3.03×10^{11}
$\Lambda_c^+ \to \Xi^- K^+ \pi^+$	$\Xi^- \to \Lambda \pi^-$	3.20×10^{10}
$\Xi_c^0 \to \Xi^- K^+$	$\Xi^- \to \Lambda \pi^-$	1.00×10^{10}
Sum		**1.88** $\times 10^{12}$

Run II (2015-2018): $\sqrt{s} = 13\,TeV$, $\mathcal{L} = 5$ fb^{-1}

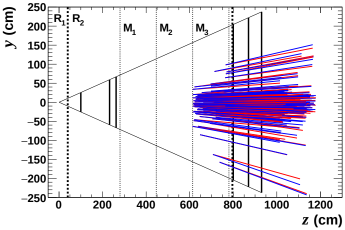
analyses ongoing

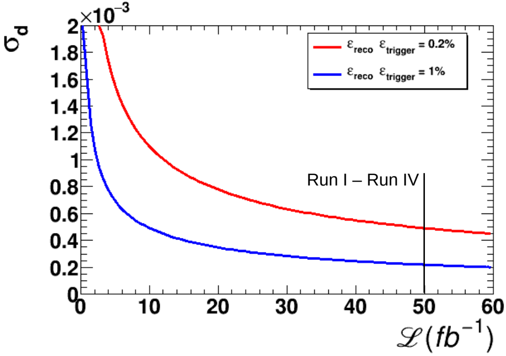




Sensitivity Reach

$$N_\Lambda^{\text{det}} = \underbrace{\varepsilon_{\text{reco}} \quad \varepsilon_{\text{trigger}}}_{0{,}2\% \; - \; 1\%} \quad \underbrace{\varepsilon_{\text{geo}}}_{\sim 10\%} \quad N_\Lambda$$





Statistical uncertainty (50 fb^{-1}):

$$\sigma(d_\Lambda) \approx 5 \times 10^{-4}$$

$$\downarrow \delta_\Lambda = 0$$

$$|\boldsymbol{\delta_\Lambda}| \lesssim 4 \times 10^{-18} \textbf{ ecm } (95\% CL)$$

Current limit: $|\delta_\Lambda| \leq 1.5 \times 10^{-16}$ ecm

Improvement of 2 orders of magnitude

Reconstruction challenges

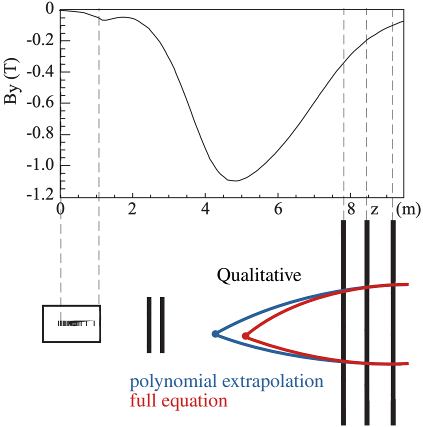
Low momentum resolution
Foremost source of challenges

Track extrapolation
Through intense and inhomogeneous magnetic field

Vertex efficiency
Bottleneck of reconstruction efficiencies

misID Λ/K_S^0
PID information not available out of the box

Crossing tracks
Bent tracks produce a fake vertices



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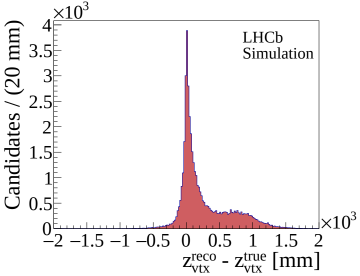
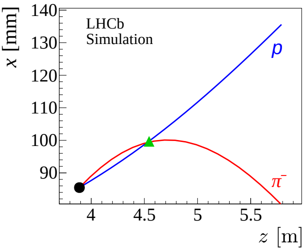
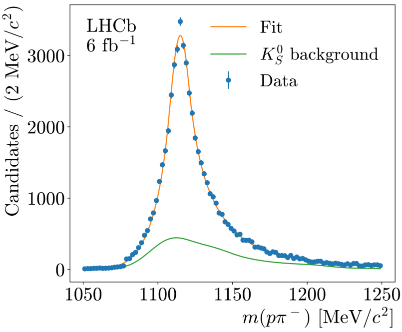




Feasibility demonstrated

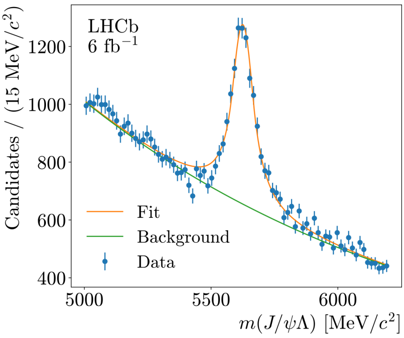
CERN-LHCb-DP-2022-001, arXiv:2211.10920

$\Lambda \to p\pi^-$



$\sigma_{m(\Lambda)} \approx 8\,\mathrm{MeV}$

$\Lambda_b^0 \to \Lambda J/\psi$



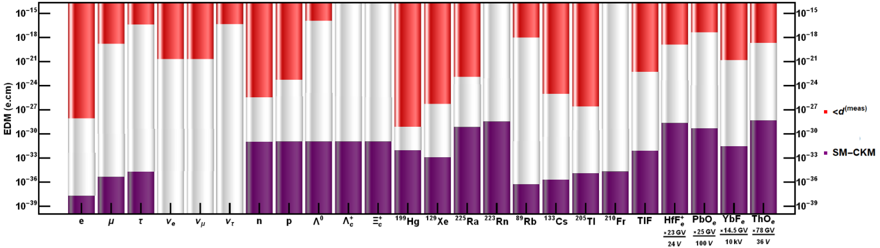
$\sigma_{m(\Lambda_b^0)} \approx 41\,\mathrm{MeV}$

Mass peaks with reconstructed and combined T tracks at LHCb

6140 $\Lambda_b^0 \to \Lambda J/\psi$ signal candidates. Run2 data

A different probe of CPV with heavy baryons:

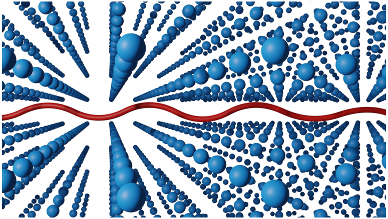
Charm baryon EDMs

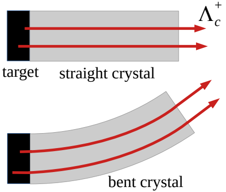


Adapted from P.M. Murthy 2018

Channelling in bent crystals

- Very short-lived Λ_c^+ ($\sim$ 5cm) $\rightarrow$ need large EM field in small space ($\sim 10^3$ T)
- **E** field between atomic planes



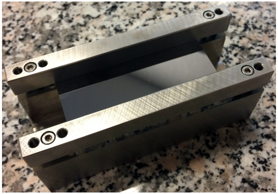


- Precession induced by the net EM field

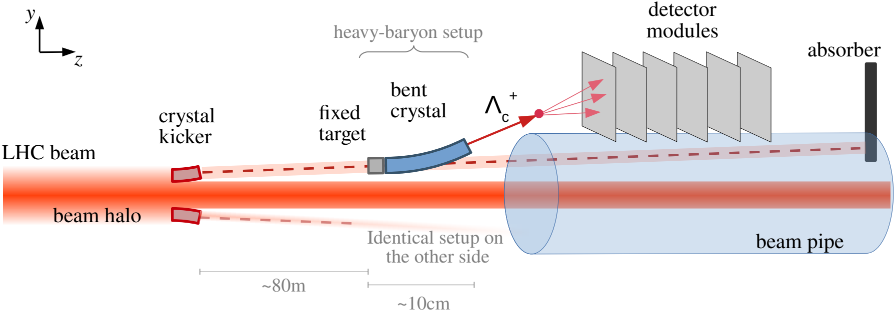
$$\boldsymbol{s} \approx s_0 \left(\frac{\color{red}{d}}{g-2}(\cos\Phi - 1), \;\; \cos\Phi, \;\; \sin\Phi \right)$$

$$\Phi \approx \frac{\color{blue}{g} - 2}{2}\gamma\theta_C \approx \pi$$

see *e.g.* EPJ C 77 (2017) 828



Layout for the LHC



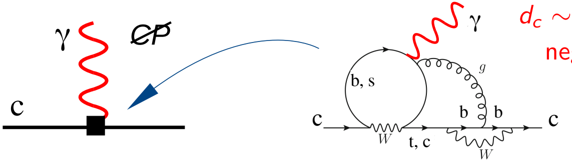
Sensitivity with two years of data taking (10^{13} PoT)

- **EDM** sensitivity $\sigma_\delta \approx 4 \cdot 10^{-16} e\mathrm{cm}$
- First measurement of Λ_c^+ (Ξ_c^+) **magnetic moment**, $\sigma_{g-2} \approx 2 \times 10^{-2}$

PRD 103 (2021) 7, 072003

Charm EDM in BSM theories

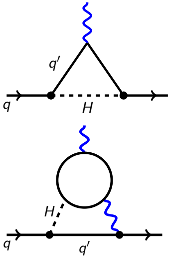
Standard Model has its leading contribution at **3-loop** level



$d_c \sim 10^{-32}$ecm
negligible

Beyond SM contributions at **1,2 loops**

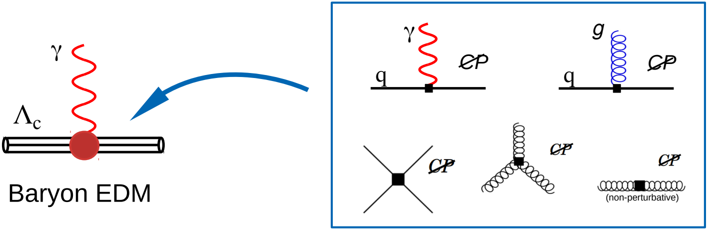
$d_c \sim 10^{-17}$ecm	EPJ C77 (2017), no.2 102	**BLMSSM**
$d_c \sim 10^{-17}$ecm	PRD 67 (2003) 036006	**MSSM**
$d_c \sim 10^{-19}$ecm	arXiv:hep-ph/0412360	**MSSM**
$d_c \sim 10^{-20}$ecm	PRD 95 (2017) 035041	**Colour-octet scalars**
$d_c \sim 10^{-21}$ecm	JHEP 1901 (2019) 069	**Scalar leptoquarks**
...	...	



Indirect bounds on charm EDM

$d_c < 1.5 \times 10^{-21}$ ecm PRD 101, 115010 (2020)

Baryon EDM in non-perturbative QCD



- Scarce theory literature on the EDM of Λ_c^+ (or c,b-baryons) (Ünal, Meißner, JHEP 01 (2021) 115; de Vries, Hanhart, Severt, Ünal, Meißner, PRD 105 (2022) 5, 055026)
- Estimations (NDA) point to $d_{\Lambda_c^+} \sim d_c \pm \frac{e}{4\pi}\tilde{d}_c$
- **Theoretical uncertainties** are key to understand the constraining power of heavy baryon EDM searches

Conclusion

- LHCb has the largest sample ever of charm decays
- **Angular information** opens possibilities for many potential observables: polarization, decay asymmetries, CPV, T-odd spin correlations, spectroscopy of new states, ..
- Many **measurements on the way** for multihadronic modes with Λs
  - $\Xi_c^0 \to \Xi^- \pi^+ \pi^+ \pi^-$
  - $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$
  - $\Xi_c^0 \to \Xi^- \pi^+$
  - $\Lambda_c^+ \to \Lambda \pi^+ \pi^+ \pi^-$
  - $\Xi_c^0 \to \Lambda K^- \pi^+$
- Lack of theory predictions. Challenging calculations with fully hadronic multibody modes