Experimental proposal for MDM/EDM of strange baryons in LHCb

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on behalf of the SELDOM Collaboration

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Introduction

- Electromagnetic dipole moments are static properties of particles

EDM: $\overrightarrow{\delta} = d\mu_B \vec{s}/2$

MDM: $\overrightarrow{\mu} = g\mu_B \vec{s}/2$

Gaussian units

$\mu_B = e\hbar/(2mc)$

- EDM violates P and T, thus violates CP. EDM searches are sensitive to new physics

- MDM measurement of particle and anti-particle allows to test CPT

How to access EDM/MDM

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- **Spin precession** induced by interaction of its EDM and MDM with external EM field

T-BMT equation:

$$\frac{d\mathbf{s}}{dt} = \mathbf{s} \times \mathbf{\Omega}$$

$$\mathbf{\Omega} = \mathbf{\Omega}_{\mathrm{MDM}} + \mathbf{\Omega}_{\mathrm{EDM}} + \mathbf{\Omega}_{\mathrm{TH}}$$

$$\mathbf{\Omega}_{\mathrm{MDM}} = \boxed{\frac{g\mu_B}{\hbar}} \left(\mathbf{B} - \frac{\gamma}{\gamma+1} (\boldsymbol{\beta} \cdot \mathbf{B}) \boldsymbol{\beta} - \boldsymbol{\beta} \times \mathbf{E} \right)$$

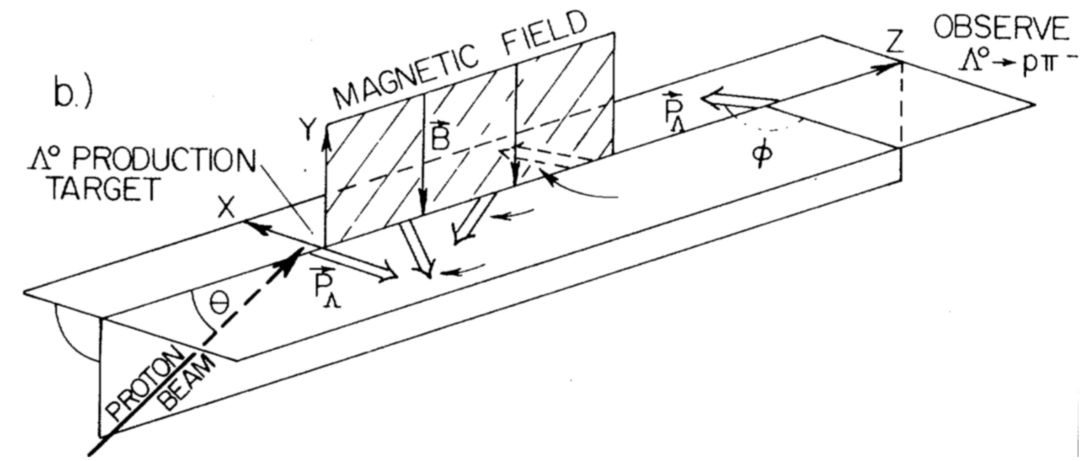
$$\Omega_{\mathrm{EDM}} = \boxed{\frac{d\mu_B}{\hbar}} \left(\mathbf{E} - \frac{\gamma}{\gamma+1} (\boldsymbol{\beta} \cdot \mathbf{E}) \boldsymbol{\beta} - \boldsymbol{\beta} \times \mathbf{B} \right)$$

$$\mathbf{\Omega}_{\mathrm{TH}} = \frac{\gamma^2}{\gamma+1} \boldsymbol{\beta} \times \frac{d\boldsymbol{\beta}}{dt} = \frac{q}{mc} \left[\left(\frac{1}{\gamma} - 1 \right) \mathbf{B} + \frac{\gamma}{\gamma+1} (\boldsymbol{\beta} \cdot \mathbf{B}) \boldsymbol{\beta} - \left(\frac{1}{\gamma+1} - 1 \right) \boldsymbol{\beta} \times \mathbf{E} \right]$$

- Known polarised sample, intense E and B inducing sizeable precision angle

Experimental status

- Last direct measurement in 70's,80's from E761@Fermilab
  - ✓ Fixed target experiment with 300GeV proton beam on Be
  - ✓ Reconstructed 3x10^6 $\Lambda \to p\pi^-$decays
  - ✓ Small transverse polarisation ~8%
  - ✓ Magnet: 5m,±15Tm
  - ✓ Momentum direction fixed to be perpendicular to $\vec{B}$



d_Λ< 1.5 x 10^{-16} e cm @95% C.L. Phys. Rev. D23 (1981) 814

μ_Λ=(–0.613±0.004) μ_N Phys. Rev. Lett. 41 (1978) 1348

  - ✓ No measurement for $\overline{\Lambda}$, hence no CPT test via MDM

- Prediction using experimental upper limit of neutron EDM

d_Λ< 4.4 x 10^{-26} e cm @95% C.L.

plenty of scopy to improve direct measurement

JHEP 12 (2012) 097
PLB291 (1992) 293
Nucl. Phys. B367(1991) 313
Phys.Rev.D61 (2000) 114017

Advantages in LHCb

- Single arm forward detector, optimised for c and b hadron physics with large pseudorapidity ($2<\eta<5$)

  Perfect tracking, vertex determination, particle identification

- Production
  - ✓ from weak decays of c and b baryons
  - ✓ compatible Λ and $\overline{\Lambda}$

- Large initial longitudinal polarisation

- Magnet
  - ✓ a tracking dipole magnet providing $D_y \approx \pm 4$ Tm over 10 meters
  - ✓ allow sizeable Λ spin precession

Challenges in LHCb

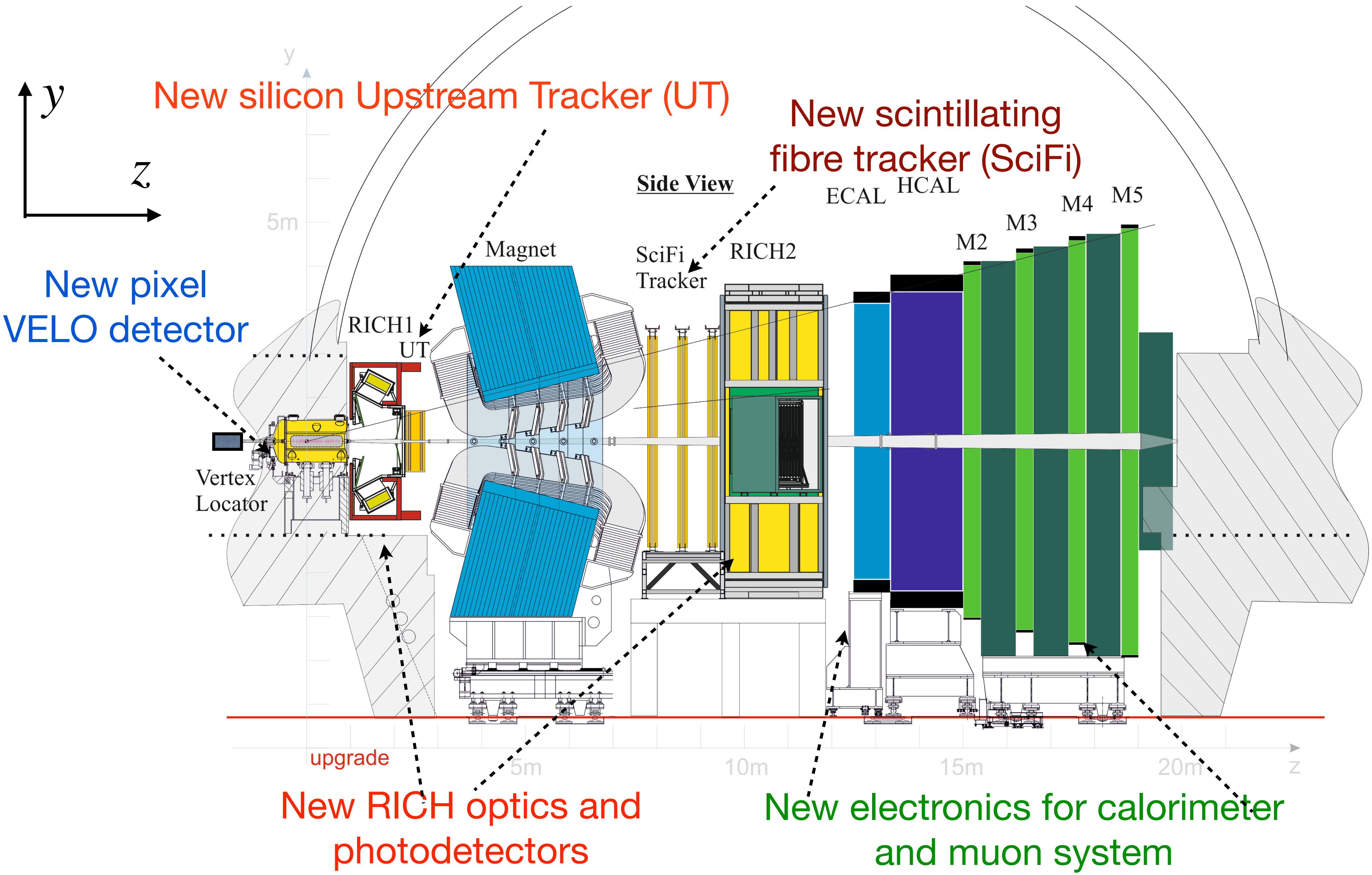
- Significant backgrounds and limited resolution on measurement of Λ momentum and decay point

- LHCb Upgrade for Run3 (2021~2023):
  - ✓ $2 \times 10^{33} cm^{-2} s^{-1}$(14TeV) 5 times than Run2 (13TeV), 50fb^{-1} end Run3
  - ✓ Only software trigger
  - ✓ 40 MHz readout
  - ✓ Real-time alignment and calibration
  - ✓ Offline quality reconstruction at the online level

- Details of trigger and reconstructions, see talks from Salvatore and Louis

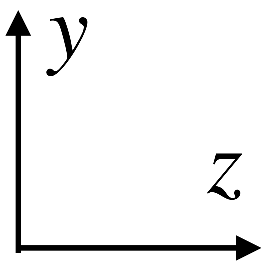
LHCb upgraded detector

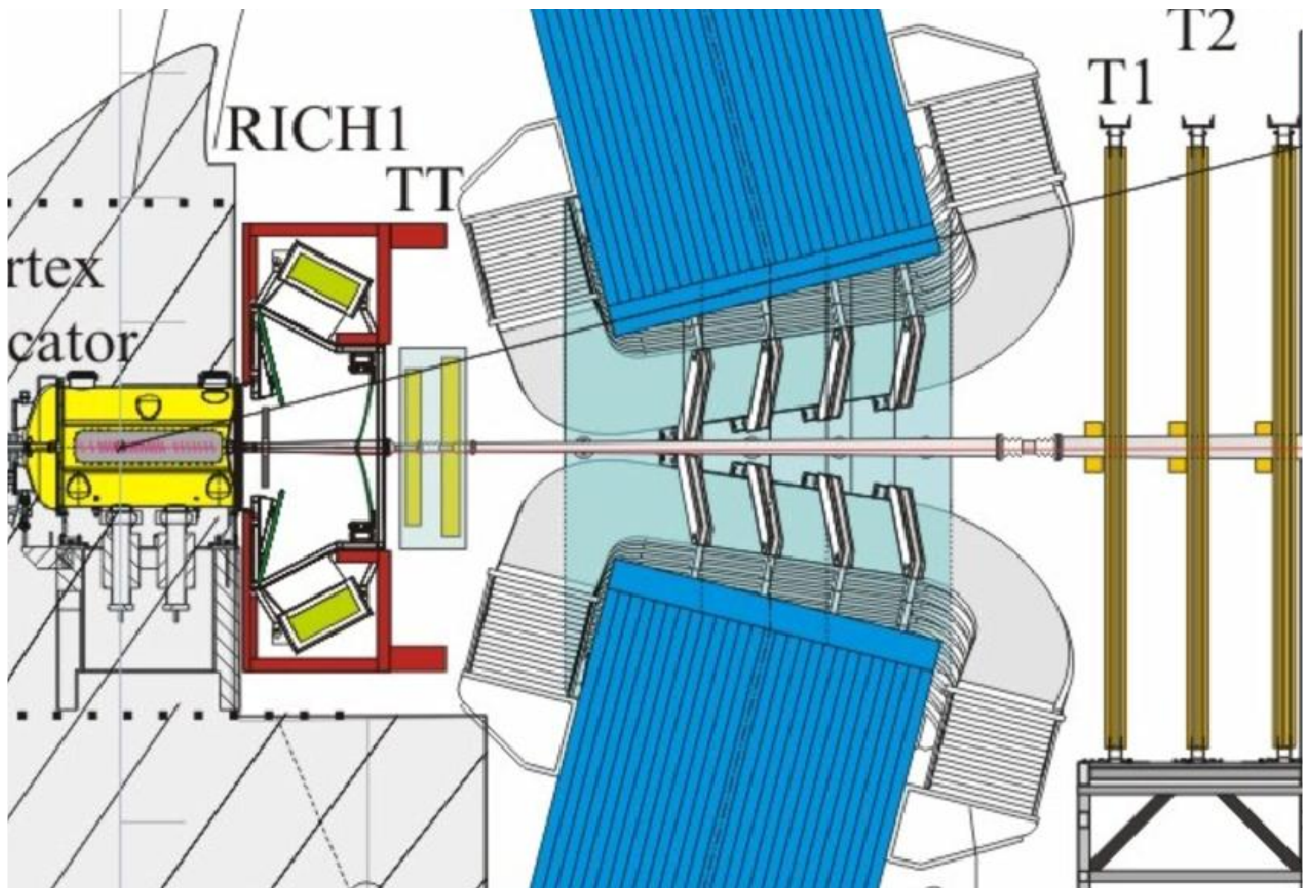
Detectors for Run3



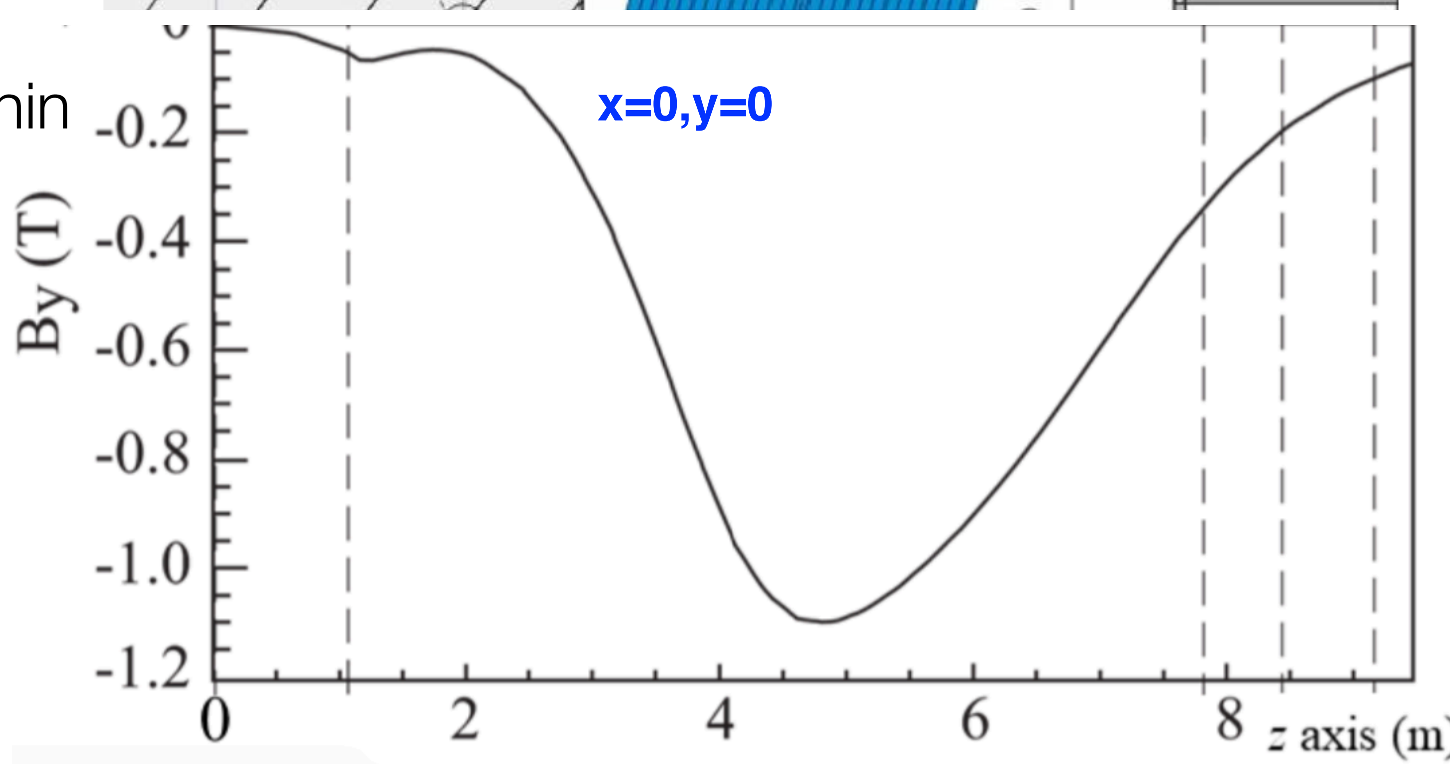
LHCb Magnet

LHCb-INT-2015-034

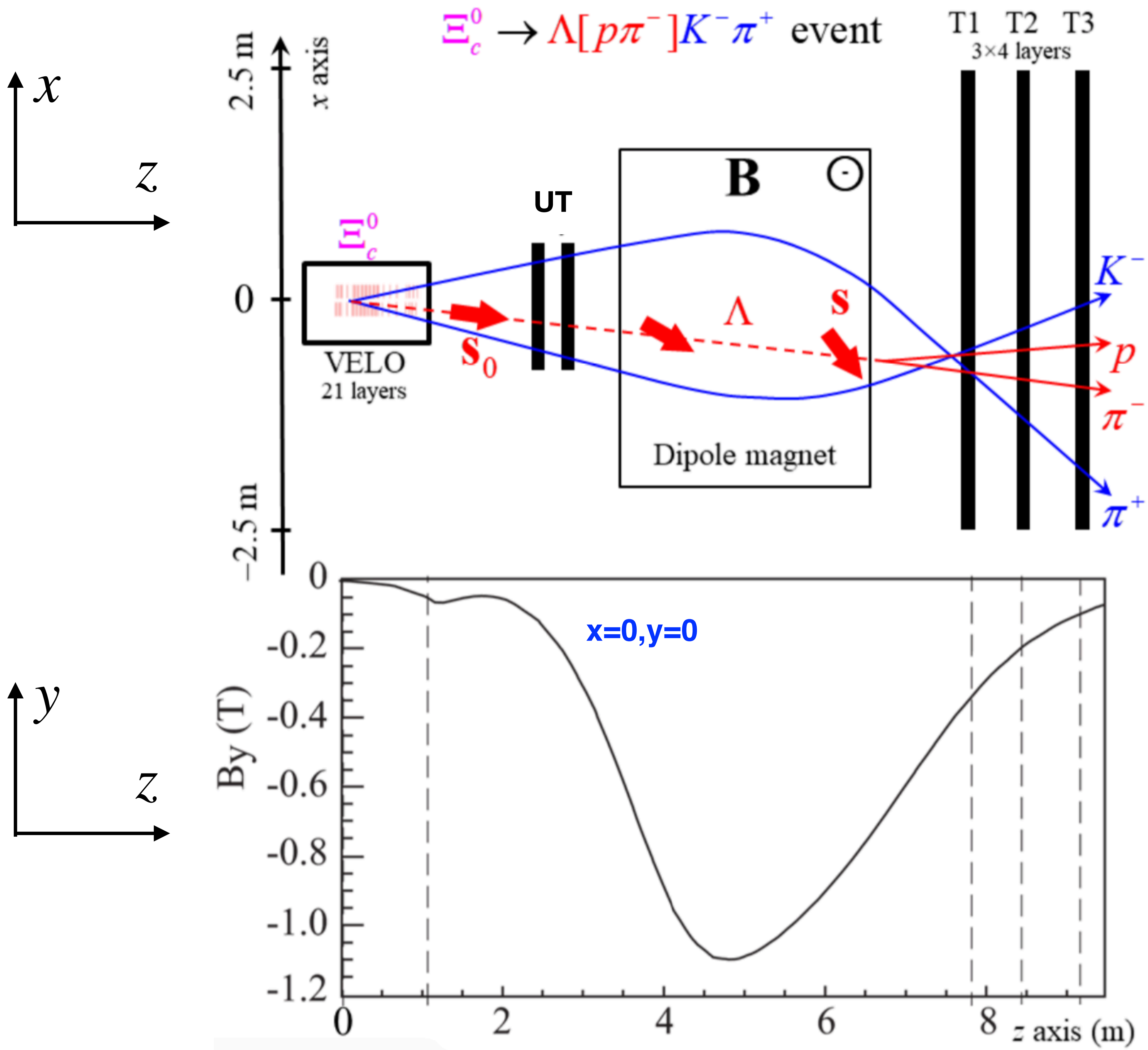




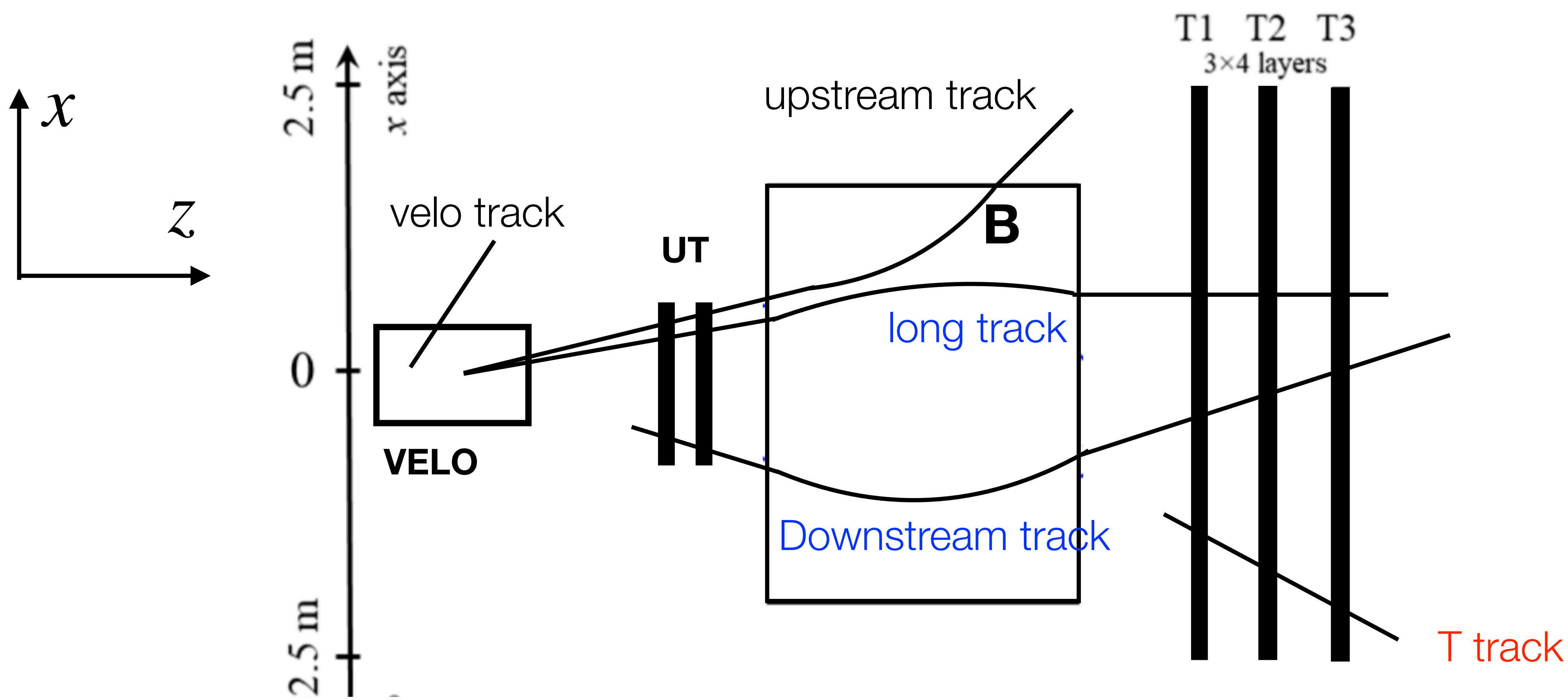
- Acceptance:
  hor. ±300 mrad
  vert. ±250 mrad
- Measured B field values stable within σ=±0.07gauss
- $\int B dl = 4\text{Tm}$



Λ procession in LHCb



LHCb charged tracks



- Long track: reconstructed in VELO and T-stations. Perfect reconstruction
- Downstream track: UT + T-stations. Good reconstruction
- T track: T-stations. Worse reconstructed, not used in physics analysis yet. Need to improve. (details see Salvatore's talk)

Long + Downstream tracks to measure polarisation before Magnet

T tracks to measure polarisation after Magnet

T–BMT for Λ in LHCb

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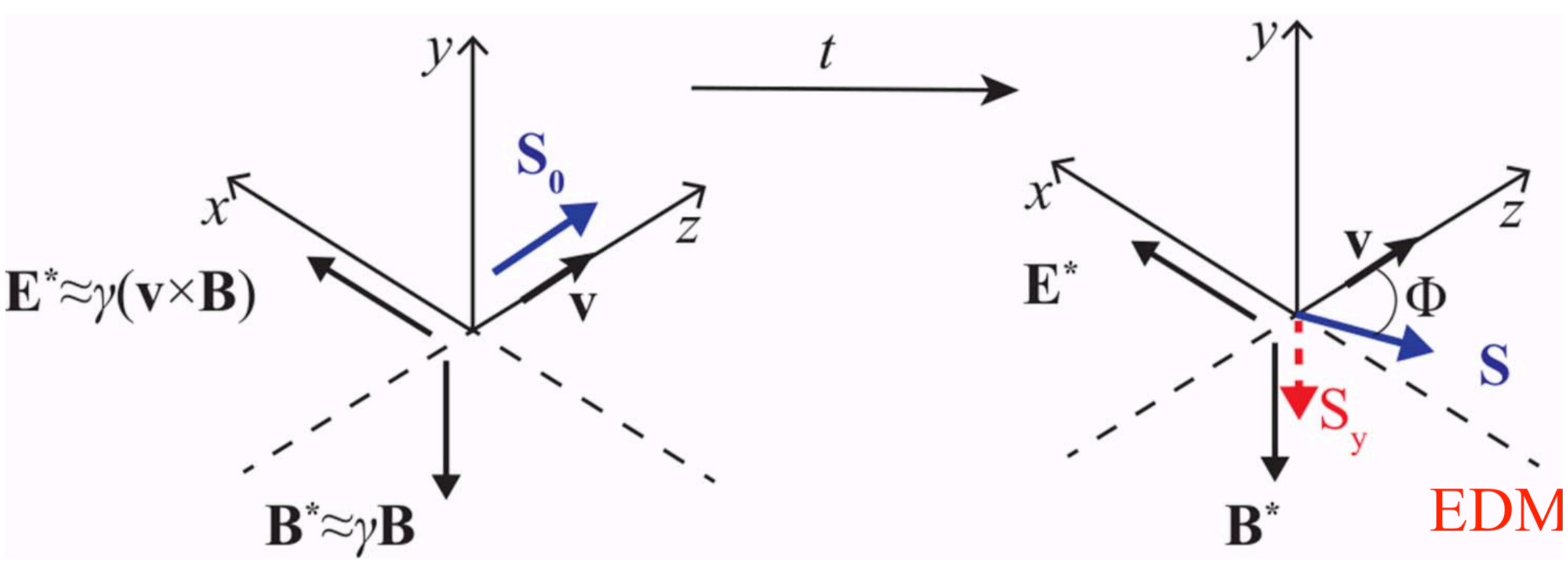
- Negligible field gradient effects, $\mathbf{B} = (0, B_y, 0)$, E=0, q=0
- **Specific case**: Λ and heavy baryon flying along z axis in lab system

$$\mathbf{s}_0 = (0, 0, s_0)$$



$$\mathbf{s} = \begin{cases} s_x = -s_0 \sin \Phi \\ s_y = -s_0 \dfrac{d\beta}{g} \sin \Phi \\ s_z = s_0 \cos \Phi \end{cases}$$

$$\Phi = \frac{D_y \mu_B}{\beta \hbar c} \sqrt{d^2 \beta^2 + g^2} \approx \frac{g D_y \mu_B}{\beta \hbar c} \approx \pm \pi/4$$

$$D_y \equiv D_y(l) = \int_0^l B_y dl' \approx 4 \text{ Tm}$$

- Main precession (MDM) in xz plane
- Non zero s_y indicates EDM
- Sizeable spin precession achieved

Initial Λ polarisation in LHCb

- Λ directly produced from *pp* collisions via strong interactions:
  - ✓ Initial transversal polarisation perpendicular to production plane, $\vec{p}_{beam} \times \vec{p}_{\Lambda}$
  - ✓ polarisation increase with Pt_{Λ}
  - ◉ not within LHCb angular acceptance
- Λ produced from heavy baryon weak decays:
  - ✓ large longitudinal polarisation: ~90% in $\Lambda_c^+ \to \Lambda\pi^+$
  - ✓ polarisation measured via analysis angular distribution of $\Lambda \to p\pi^-$ decay

Source and production of Λ

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- Consider c baryon decays and charged final particles
- At least one particle from heavy baryon decay vertex

$$N_\Lambda = 2\mathcal{L}\sigma_{q\bar{q}} f(q \to H)\mathcal{B}(H \to \Lambda X')$$
$$\times \mathcal{B}(\Lambda \to p\pi^-)\mathcal{B}(X' \to \text{charged})$$

$\sigma_{q\bar{q}}$: c,b cross section pp@14TeV

$f(q \to H)$:fragmentation fraction into heavy baryon

short-lived (SL) 1.5×10^{11}

SL events	N_Λ/fb^{-1} $(\times 10^{10})$
$\Xi_c^0 \to \Lambda K^- \pi^+$	7.7
$\Lambda_c^+ \to \Lambda \pi^+ \pi^+ \pi^-$	3.3
$\Xi_c^+ \to \Lambda K^- \pi^+ \pi^+$	2.0
$\Lambda_c^+ \to \Lambda \pi^+$	1.3
$\Xi_c^0 \to \Lambda K^+ K^-$ (no ϕ)	0.2
$\Xi_c^0 \to \Lambda \phi (K^+ K^-)$	0.1

long-lived (LL) 3.8×10^{11}

LL events, $\Xi^- \to \Lambda \pi^-$	N_Λ/fb^{-1} $(\times 10^{10})$
$\Xi_c^0 \to \Xi^- \pi^+ \pi^+ \pi^-$	23.6
$\Xi_c^0 \to \Xi^- \pi^+$	7.1
$\Xi_c^+ \to \Xi^- \pi^+ \pi^+$	6.1
$\Lambda_c^+ \to \Xi^- K^+ \pi^+$	0.6
$\Xi_c^0 \to \Xi^- K^+$	0.2
Prompt Ξ^-	$0.13 \times \sigma_{pp \to \Xi^-}$ [μb]

Geometry efficiency

Experimental yield: $N_{\Lambda}^{\text{reco}} = \epsilon_{\text{geo}}\epsilon_{\text{trigger}}\epsilon_{\text{reco}}N_{\Lambda}$

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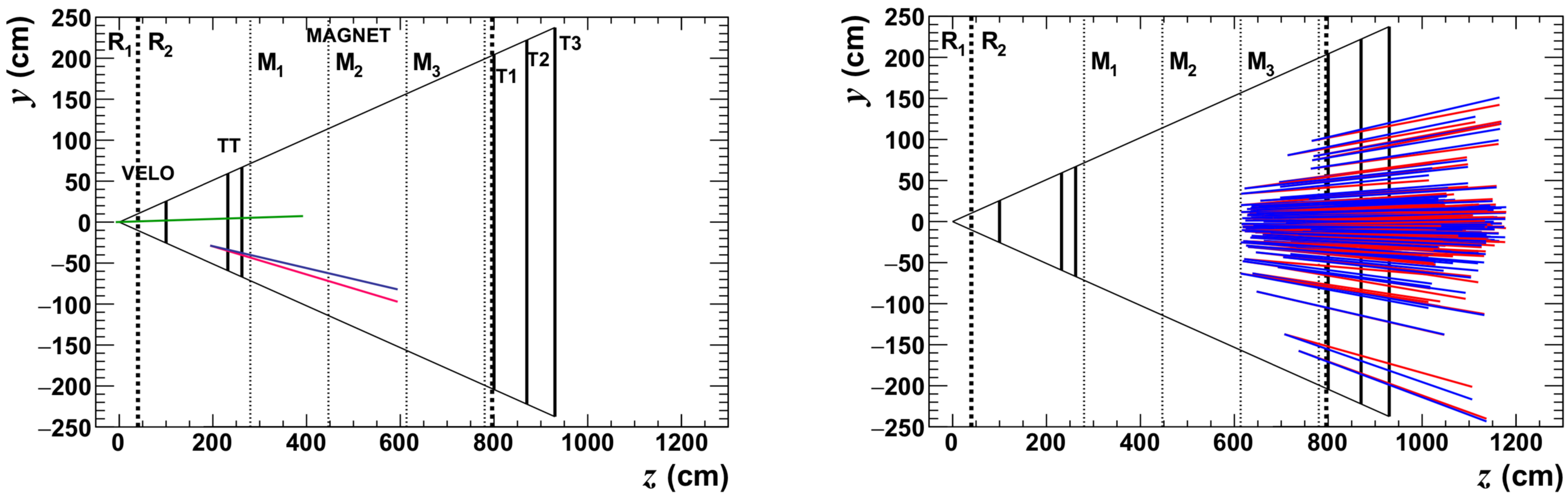
Geometry eff. for SL topology estimated from simulation



Region Λ decay vertex z position (cm)	R_1 [0–40	R_2 [40–800]	M_1 [280–450]	M_2 [450–610]	M_3 [610–780]
$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	4.7	10.5	1.3	0.7	0.3
$\Xi_c^0 \to \Lambda K^-\pi^+$ (in %)	5.2	12.2	1.7	1.0	0.6
$\Xi_c^+ \to \Lambda K^-\pi^+\pi^+$	5.3	11.9	1.6	0.9	0.4

R1: measure initial polarisation

R2: measure polarisation as decay length in $\vec{B}$

M3: most sensitivity to MDM/EDM

Sensitivity

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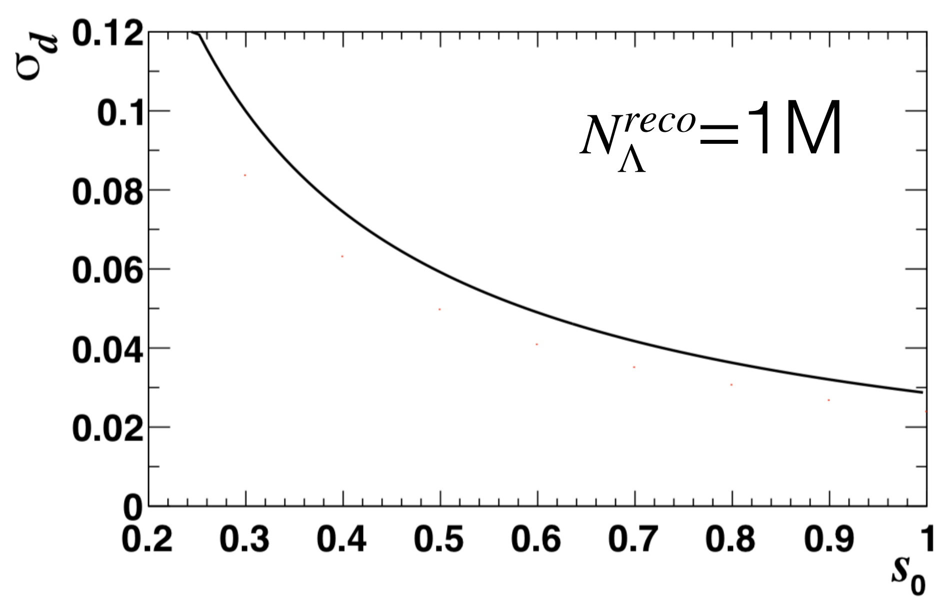
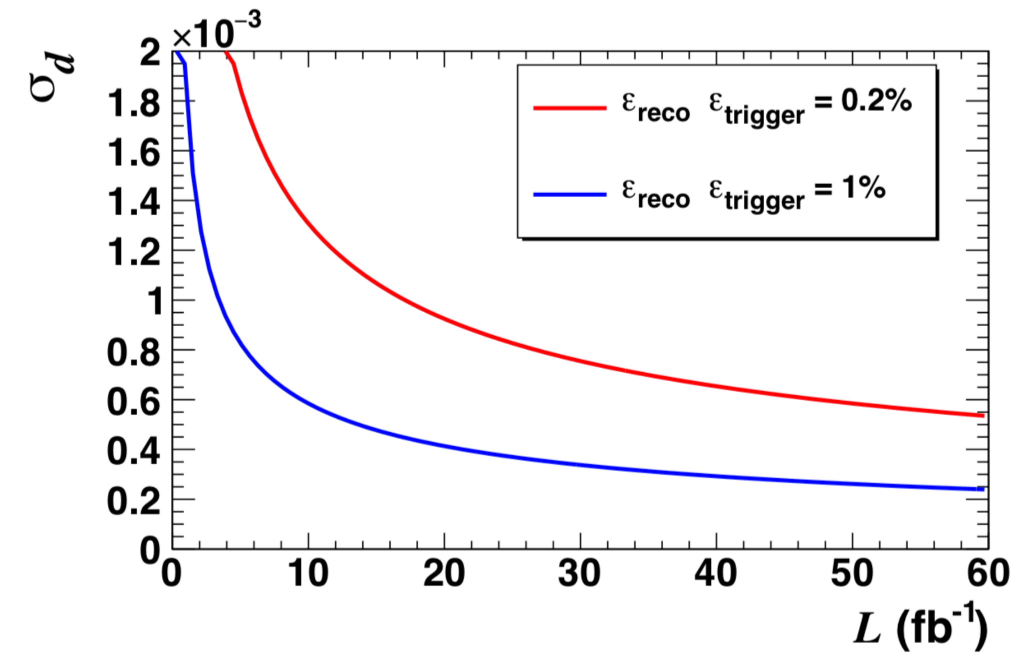
- Pseudo-experiments using simplified detector geometry
- d-factor uncertainty: $\sigma_d \propto 1/(s_0\sqrt{N_\Lambda^{\rm reco}})$



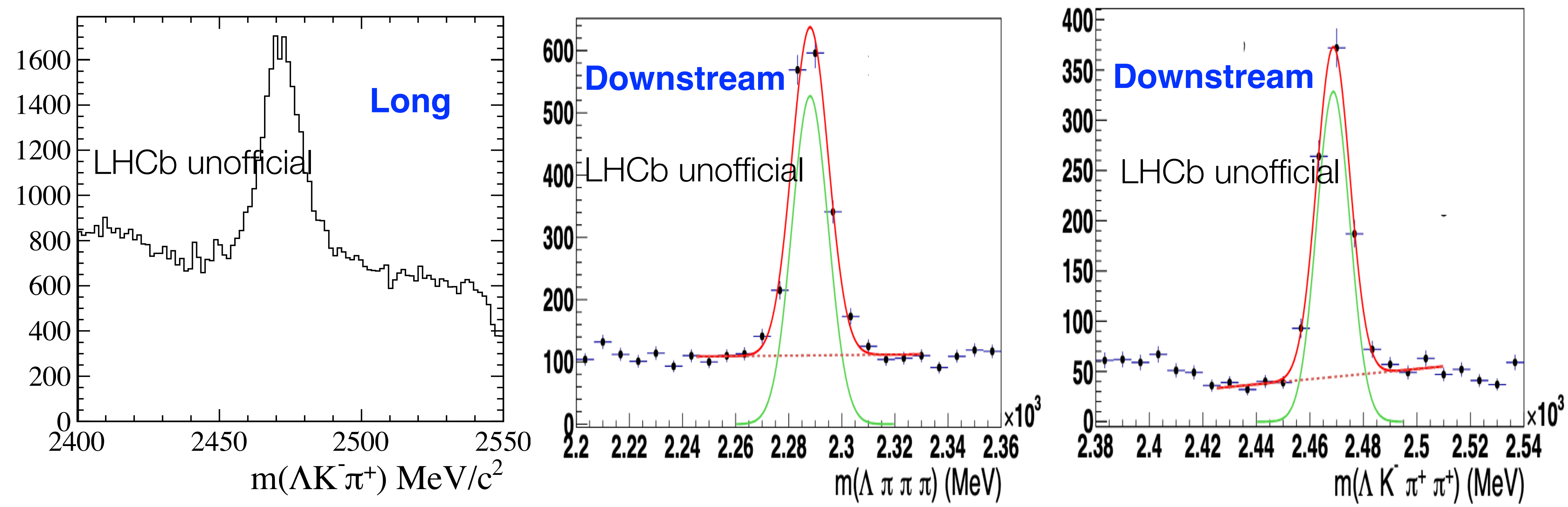


- With 50 fb^{-1} (end Run3) :
  - ✓ $\sigma_d \approx 3\times 10^{-4}$, $\delta(\Lambda) \lesssim 1.3\times 10^{-18}$ e cm, 2 orders of magnitude improve
  - ✓ First $\overline{\Lambda}$ MDM measurement at similar precision
  - ✓ First CPT test via Λ MDM at 10^{-3} level

Polarisation measurement before magnet

- Program starting with Run 2 (6 fb^{-1})
- Λ reconstructed using long and downstream tracks
- $\Xi_c^0 \to \Lambda h^{\pm} h^{\mp}$, $\Lambda_c^+, \Xi_c^+ \to \Lambda h^{\pm} h^{\pm} h^{\mp}$

small fraction of data, not optimal selection



- Still in tuning

Summary

- Proposed Λ EDM/MDM measurements in LHCb

- With 50 fb^{-1} in LHCb, expect 100 improvement of EDM, first $\overline{\Lambda}$ MDM measurement with similar precision as EDM ~10^{-4}, and first CPT test via MDM at 10^{-3} level

- Measurement of polarisation before Magnet starting from Run2 data

- Hard work needed to improve Λ reconstructions: trigger, T-track reconstruction…

Probability Distribution Function

- spin-polarisation can be analysed through angular distribution of $\Lambda \to p\pi^-$

$$\frac{dN}{d\Omega'} \propto 1 + \alpha \mathbf{s} \cdot \hat{\mathbf{k}} \,,$$

  - Angular distribution
    $\rightarrow$ extract initial polarization $\boldsymbol{s}_0$ (**LL, DD** events)

$$PDF(\theta', \phi', \boldsymbol{H}, \beta) = \frac{1}{4\pi}\left[1 + \alpha_\Lambda s_z \cos\theta' + \alpha_\Lambda (s_x \cos\phi' + s_y \sin\phi') \sin\theta'\right]$$

  - Combining with spin precession (**TT** events)
    - Adding equations of spin motion subjected to EM field
      (solved analytically by assuming an average B field along the Λ path, $\boldsymbol{H} \approx \overline{\boldsymbol{B}} l$)

$$\boldsymbol{s} \equiv \boldsymbol{s}(\boldsymbol{H}, \beta) = (\boldsymbol{s}_0 \cdot \boldsymbol{\omega}')\boldsymbol{\omega}' + [\boldsymbol{s}_0 - (\boldsymbol{s}_0 \cdot \boldsymbol{\omega}')\,\boldsymbol{\omega}'] \cos\Omega' + (\boldsymbol{s}_0 \times \boldsymbol{\omega}') \sin\Omega' \,,$$

$$\Omega' = |\boldsymbol{\Omega}'| \,, \quad \boldsymbol{\omega}' = \boldsymbol{\Omega}'/\Omega' \,,$$

and

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

$\rightarrow$ PDF with 5 parameters $\{d, g, \boldsymbol{s}_0\}$ and 8 variables $\{\theta', \phi', \boldsymbol{H}, \beta\}$