Measurement of MDM/EDM of Λ baryons at LHCb

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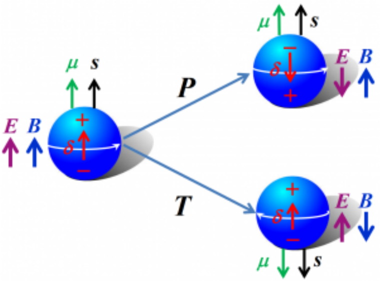
September 28, 2022

Electric and Magnetic Dipole Moments of spin-1/2 particles

$$\delta = d\mu_N \frac{\mathbf{S}}{2}, \qquad \mu = g\mu_N \frac{\mathbf{S}}{2}.$$

$\mu_N = e\hbar/(2mc)$ is the particle magneton,
d the gyroelectric factor and
g the gyromagnetic factor.



$$H = -\delta \cdot \mathbf{E} - \mu \cdot \mathbf{B} \xrightarrow{P,T} H = +\delta \cdot E - \mu \cdot B.$$

- A non-zero value of the EDM violates T and P symmetries
  $\rightarrow$ Test of CP violation.

- Also implies an upper bound on $\theta_0 \lesssim 10^{-10}$.
  $\rightarrow$ Strong CP problem.
- Measurement of the MDM of particle and anti-particle constitute a test of the CPT theorem.
- First studies on electric dipole moments date from the 50's.
  - *E. M. Purcell and N. F. Ramsey Phys. Rev. 78, 807 - 1950*
  - *J. H. Smith, E. M. Purcell, and N. F. Ramsey Phys. Rev. 108, 120 - 1957.*
- Experimental efforts have been able to put limits on the EDM of leptons, neutrons, heavy atoms and Λ baryons.
- Limit on the neutron EDM

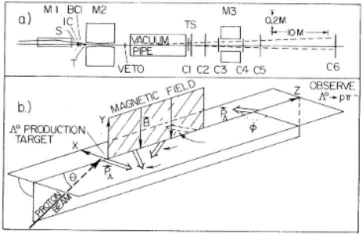
$$|d_n| < 1.8 \times 10^{-26}\, e\,\text{cm},$$

implies that for the Λ

$$|d_\Lambda| \lesssim 10^{-23}\, e\,\text{cm}.$$

[Phys. Rev. Lett. 124 - 2020]

Measurement of Λ EDM/MDM



- Fixed target p-Be experiment at Fermilab.
- Proton beam of 300 GeV.
- $\sim 3 \times 10^6$ Λ events.
- Strong Λ production with $\sim 8\%$ polarization but no $\bar{\Lambda}$ polarization.

- Measurement of the MDM of the Λ baryon.

$$\mu = (0.6138 \pm 0.04)\mu_N.$$

- Upper bound on the EDM of the Λ

$$|d_\Lambda| < 1.6 \times 10^{-16}\, e\,\text{cm}.$$

[PRD 23, 814 (1981) and PRL 41, 1348 (1978)]

Spin-polarization vector **s** of Λ can be analysed through the angular distribution of the decay $\Lambda \to p\pi^-$

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

$\alpha = 0.642 \pm 0.013$ is the decay asymmetry parameter.
Dynamics of the spin in an external magnetic field is given by the T-BMT equation.
For a Λ baryon flying with an initial longitudinal polarization $\mathbf{s}_0 = (0, 0, s_0)$ on a magnetic field $\mathbf{B} = (0, B_y, 0)$

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

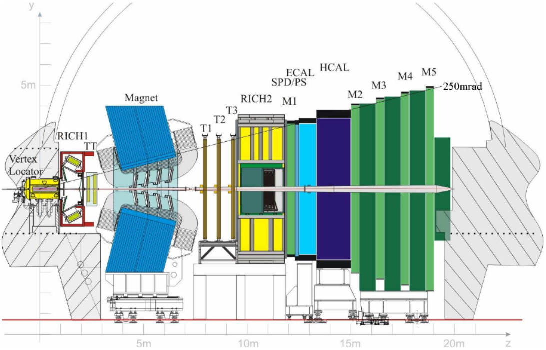
where ϕ is the precession angle.

Measurement of Λ EDM/MDM

Interaction of EDMs and MDMs with an external electromagnetic field produces a spin precession.
Three elements are necessary for the measurement of this effect

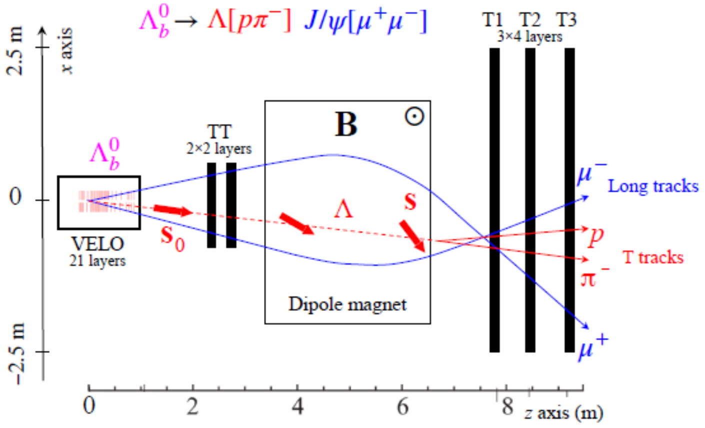
- Source of polarized particles whose direction and polarization degree are known.
- Intense electromagnetic field able to induce a sizable spin precession angle.
- A detector to measure the final polarization vector by analysing the angular distribution of the particle decays.

Measurement of Λ EDM/MDM at LHCb

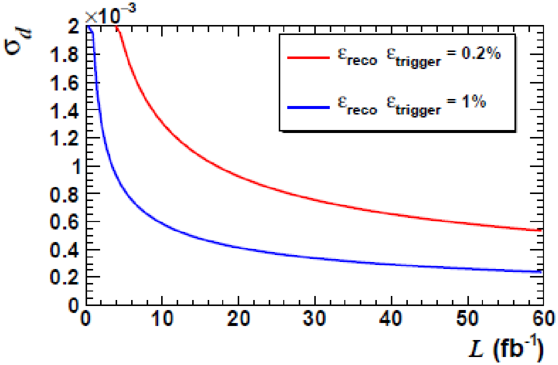


- Weak decays of heavy baryons produce a large number of highly polarized Λ baryons, e.g. $\Lambda_b \to \Lambda J/\psi$ with $\sim 100\%$ longitudinal polarization.
- Measurement using prompt Λs produced at LHC is not possible since they are not polarized.[PRD 91, (2015)]

Spin precession of Λ baryons at the LHCb magnet

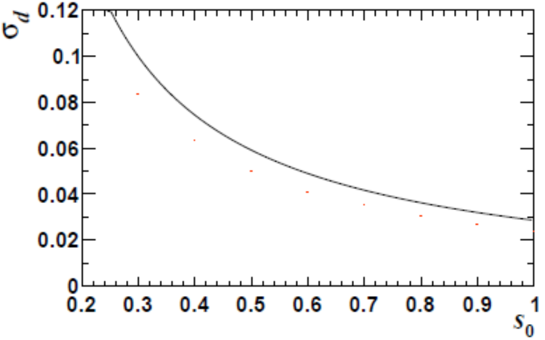


Dependence of d uncertainty with the integrated luminosity for a reconstruction efficiency of 0.2% and 1%.



At $L \sim 50\text{fb}^{-1} \rightarrow \sigma_d \approx 1.3 \times 10^{-18}\, e\,$cm.
$\rightarrow$Improved limit on the MDM of $\approx 10^{-4}\mu_N$.
[EPJC 77, 181, 2017]

Measurement of Λ EDM/MDM at LHCb



A source of initially polarized Λ is needed to achieve a higher sensitivity.
$\Lambda_b \to \Lambda J/\psi$ offers $\sim 100\%$ initial Λ polarization.
[JHEP, 2020, 110]

Channels of interest

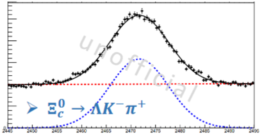
SL events	N_Λ/fb^{-1} ($\times 10^{10}$)	LL events, $\Xi^- \to \Lambda\pi^-$	N_Λ/fb^{-1} ($\times 10^{10}$)
$\Xi_c^0 \to \Lambda K^-\pi^+$	7.7	$\Xi_c^0 \to \Xi^-\pi^+\pi^+\pi^-$	23.6
$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	3.3	$\Xi_c^0 \to \Xi^-\pi^+$	7.1
$\Xi_c^+ \to \Lambda K^-\pi^+\pi^+$	2.0	$\Xi_c^+ \to \Xi^-\pi^+\pi^+$	6.1
$\Lambda_c^+ \to \Lambda\pi^+$	1.3	$\Lambda_c^+ \to \Xi^- K^+\pi^+$	0.6
$\Xi_c^0 \to \Lambda K^+K^-$ (no ϕ)	0.2	$\Xi_c^0 \to \Xi^- K^+$	0.2
$\Xi_c^0 \to \Lambda\phi(K^+K^-)$	0.1	Prompt Ξ^-	$0.13 \times \sigma_{pp\to\Xi^-}$ [μb]

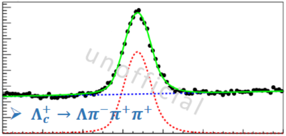
Ongoing polarization studies

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

More on this on Z. Wang talk.

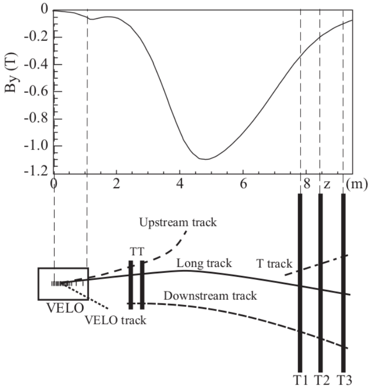
- $\Xi_0 \to \Xi^-(\to \Lambda\pi^-)\pi^-$
- $\Xi_c^+ \to \Xi^-\pi^+\pi^+$





Final Polarization using TTracks

Tracks that leave only hits after the magnet have never been used for physics analysis at LHCb.

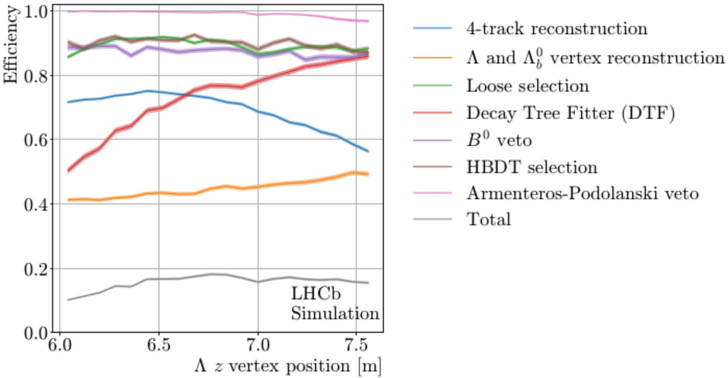


- Poor momentum resolution $\rightarrow 20 - 30\%$, for Long tracks $\sim 0.1\%$.
- Long propagation distances in the magnet region make track extrapolation more difficult.
- Low vertex reconstruction efficiencies and resolution.
- Lack of RICH2 for TTracks in Run 1 - 2 makes background distintion harder. See M. Wang talk.

Feasibility study using $\Lambda_b \rightarrow \Lambda J/\psi$ to explore the reconstruction using TTracks.

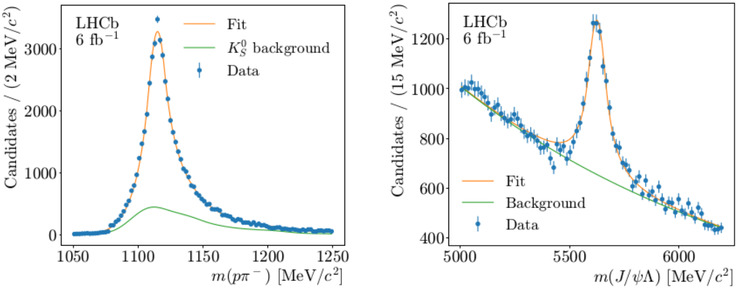
$\Lambda_b \to \Lambda J/\psi$ using TTracks

Relative efficiencies on the selection process



$\rightarrow$ Λ vertex reconstruction presents the lowest efficiency, efforts to improve it are on progress. See G. Tonani talk.

$\Lambda_b \to \Lambda J/\psi$ using TTracks

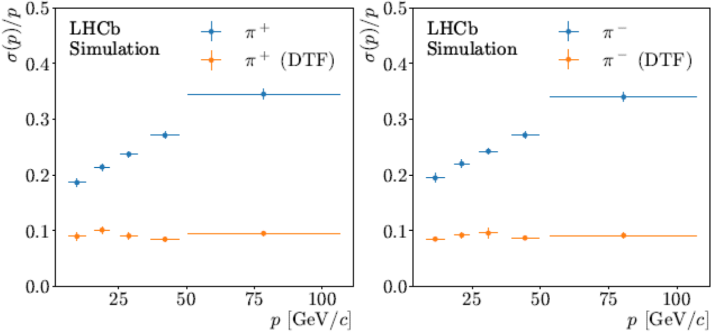


~ 6140 signal events with a core mass resolution of (7.7 ± 0.4)MeV/c^2 and (41 ± 2)MeV/c^2 for the Λ and Λ_b respectively.

- A wide physics program is being proposed for the study of the EDM and MDM of charm and strange baryons, where the LHCb will play a central role at improving the precision on the Λ.
- Prospect to improve the current bound on the Λ EDM by two orders of magnitude.
- Study of particles that decay in the magnet region for Run 1-2 is feasible, although there is still room for improvement.
- Work being done on the implementation of Trigger lines for Run 3, on the new fully software-based trigger.
- Possibility to expand the sensitivity to BSM Long-Lived Particles at LHCb.

Backup

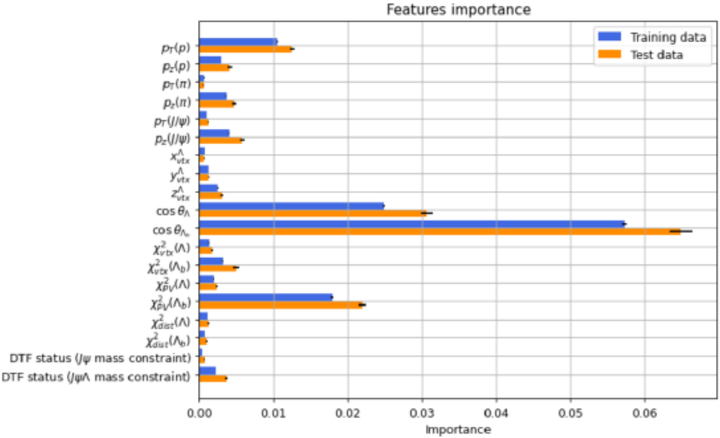
Selection


LHCb
Simulation
π^+
π^+ (DTF)
$\sigma(p)/p$
0.5
0.4
0.3
0.2
0.1
0.0
25
50
75
100
p [GeV/c]
LHCb
Simulation
π^-
π^- (DTF)
$\sigma(p)/p$
0.5
0.4
0.3
0.2
0.1
0.0
25
50
75
100
p [GeV/c]

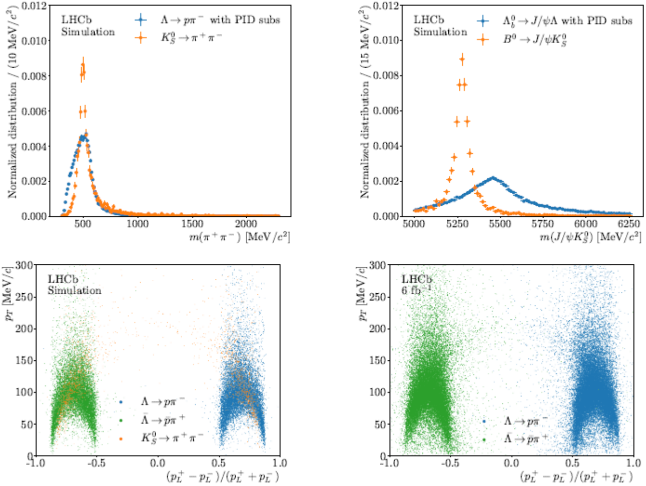
Selection

Variable	Units	Minimum	Maximum
$p\,(\pi)$	MeV/c	20 00	500 000
$p\,(p)$	MeV/c	10 000	500 000
$p_T\,(p)$	MeV/c	400	–
$m(p\pi)$	MeV/c^2	600	1 500
$z^{\Lambda}_{\mathrm{vtx}}$	mm	5 500	8 500
$\cos\xi_p\,(\Lambda)$		0.9999	–
$\chi^2_{\mathrm{IP}}\,(\Lambda)$		–	200
$\chi^2_{\mathrm{dist}}\,(\Lambda)$		–	$2\cdot 10^7$
$\chi^2_{\mathrm{vtx}}\,(\Lambda)$		–	750
$\lvert m(\mu^-\mu^+) - m(J/\psi)\rvert$	MeV/c^2	–	90
$p_T(\Lambda)$	MeV/c	450	–
$m(J/\psi\,\Lambda)$	MeV/c^2	4 700	8 500
$\lvert\cos\xi_p\,(\Lambda^0_b)\rvert$		0.99	–
$\chi^2_{\mathrm{IP}}\,(\Lambda^0_b)$		–	1 750
$\chi^2_{\mathrm{vtx}}\,(\Lambda^0_b)$		–	150

Selection


Features importance
Training data
Test data
$p_T(p)$
$p_z(p)$
$p_T(\pi)$
$p_z(\pi)$
$p_T(J/\psi)$
$p_z(J/\psi)$
x^{Λ}_{vtx}
y^{Λ}_{vtx}
z^{Λ}_{vtx}
$\cos\theta_{\Lambda}$
$\cos\theta_{\Lambda_b}$
$\chi^2_{vtx}(\Lambda)$
$\chi^2_{vtx}(\Lambda_b)$
$\chi^2_{PV}(\Lambda)$
$\chi^2_{PV}(\Lambda_b)$
$\chi^2_{dist}(\Lambda)$
$\chi^2_{dist}(\Lambda_b)$
DTF status (J/ψ mass constraint)
DTF status ($J/\psi\Lambda$ mass constraint)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
Importance

Selection


LHCb
Simulation
Λ → pπ⁻ with PID subs
K⁰_S → π⁺π⁻
Normalized distribution / (10 MeV/c²)
m(π⁺π⁻) [MeV/c²]
LHCb
Simulation
Λ⁰_b → J/ψΛ with PID subs
B⁰ → J/ψK⁰_S
Normalized distribution / (15 MeV/c²)
m(J/ψK⁰_S) [MeV/c²]
LHCb
Simulation
Λ → pπ⁻
Λ̄ → p̄π⁺
K⁰_S → π⁺π⁻
p_T [MeV/c]
(p⁺_L − p⁻_L)/(p⁺_L + p⁻_L)
LHCb
6 fb⁻¹
Λ → pπ⁻
Λ̄ → p̄π⁺
p_T [MeV/c]
(p⁺_L − p⁻_L)/(p⁺_L + p⁻_L)

TTracks reconstructibility