Search for new physics via baryon EDM at LHC

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Permanent electric dipole moments (EDMs) of fundamental particles provide powerful probes for physics beyond the Standard Model. We propose to search for the EDM of strange and charm baryons at LHC, extending the ongoing experimental program on the neutron, muon, atoms, molecules and light nuclei. The EDM of strange Λ baryons, selected from weak decays of charm baryons produced in pp collisions at LHC, can be determined by studying the spin precession in the magnetic field of the detector tracking system. A test of CPT symmetry can be performed by measuring the magnetic dipole moment of Λ and $\overline{\Lambda}$ baryons. For short-lived Λ_c^+ and Ξ_c^+ baryons, to be produced in a fixed-target experiment using the 7 TeV LHC beam and channeled in a bent crystal, the spin precession is induced by the intense electromagnetic field between crystal atomic planes. The experimental layout based on the LHCb detector and the expected sensitivities in the coming years are discussed.

Keywords: Baryons (including antiparticles) - Electric and magnetic moments

1. Introduction

The magnetic dipole moment (MDM) and the electric dipole moment (EDM) are static properties of particles that determine the spin motion in an external electromagnetic field, as described by the T-BMT equation [1–3].

The EDM is the only static property of a particle that requires the violation of parity (P) and time reversal (T) symmetries and thus, relying on CPT invariance, the violation of CP symmetry. The amount of CP violation in the weak interactions of quarks is not sufficient to explain the observed imbalance between matter and antimatter in the Universe. CP-violation in strong interactions is strongly bounded by the experimental limit on the neutron EDM [4]. In the Standard Model (SM), contributions to the EDM of baryons are highly suppressed but can be largely enhanced in some of its extensions. Hence, the experimental searches for the EDM of fundamental particles provide powerful probes for physics beyond the SM.

Since EDM searches started in the fifties [5,6], there has been an intense experimental program, leading to limits on the EDM of leptons [7–9], neutron [4], heavy atoms [10], proton (indirect from ^{199}Hg) [11], and Λ baryon [12]. New experiments are ongoing and others are planned, including those based on storage rings for muon [13,14], proton and light nuclei [15–17]. Recently we proposed to improve the limit on strange baryons and extend it to charm and bottom baryons [18,19].

EDM searches of fundamental particles rely on the measurement of the spin precession angle induced by the interaction with the electromagnetic field. For unstable particles this is challenging since the precession has to take place before the decay. A solution to this problem requires large samples of high energy polarized particles traversing an intense electromagnetic field.

Here we reviewed the unique possibility to search for the EDM of the strange Λ baryon and of the charmed baryons at LHC. Using the experimental upper limit of the neutron EDM, the absolute value of the Λ EDM is predicted to be $< 4.4 \times 10^{-26}\ e\,\mathrm{cm}$[20–23], while the indirect constraints on the charm EDM are weaker, $\lesssim 4.4 \times 10^{-17}\ e\,\mathrm{cm}$[24]. Any experimental observation of an EDM would indicate a new source of CP violation from physics beyond the SM. The EDM of the long-lived Λ baryon was measured to be $< 1.5 \times 10^{-16}\ e\,\mathrm{cm}$ (95% C.L.) in a fixed-target experiment at Fermilab[12]. No experimental measurements exist for short-lived charm baryons since negligibly small spin precession would be induced by magnetic fields used in current particle detectors.

2. Experimental setup

The magnetic and electric dipole moment of a spin-1/2 particle is given (in Gaussian units) by $\boldsymbol{\mu} = g\mu_B \mathbf{s}/2$ and $\boldsymbol{\delta} = d\mu_B \mathbf{s}/2$, respectively, where $\mathbf{s}$ is the spin-polarization vector[a] and $\mu_B = e\hbar/(2mc)$ is the particle magneton, with m its mass. The g and d dimensionless factors are also referred to as the gyromagnetic and gyroelectric ratios. The experimental setup to measure the change of the spin direction in an elextromagnetic field relies on three main elements:

(i) a source of polarized particles whose direction and polarization degree are known;
(ii) an intense electromagnetic field able to induce a sizable spin precession angle during the lifetime of the particle;
(iii) the detector to measure the final polarization vector by analysing the angular distribution of the particle decays.

2.1. *Λ and $\overline{\Lambda}$ case*

Weak decays of heavy baryons (charm and beauty), mostly produced in the forward/backward directions at LHC, can induce large longitudinal polarization due to parity violation. For example, the decay of unpolarized Λ_c^+ baryons to the $\Lambda\pi^+$ final state[25], produces Λ baryons with longitudinal polarization $\approx -90\%$. Another example is the $\Lambda_b^0 \to \Lambda J/\psi$ decay where Λ baryons are produced almost 100% longitudinally polarized[26,27].

The spin-polarization vector $\mathbf{s}$ of an ensemble of Λ baryons can be analysed through the angular distribution of the $\Lambda \to p\pi^-$ decay[28,29],

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

[a]The spin-polarization vector is defined such as $\mathbf{s} = 2\langle \mathbf{S} \rangle/\hbar$, where $\mathbf{S}$ is the spin operator.

where $\alpha = 0.642 \pm 0.013$[30] is the decay asymmetry parameter. The CP invariance in the Λ decay implies $\alpha = -\overline{\alpha}$, where $\overline{\alpha}$ is the decay parameter of the charge-conjugate decay. The unit vector $\hat{\mathbf{k}} = (\sin\theta' \cos\phi', \sin\theta' \sin\phi', \cos\theta')$ indicates the momentum direction of the proton in the Λ helicity frame, with $\Omega' = (\theta', \phi')$ the corresponding solid angle. For the particular case of Λ flying along the z axis in the laboratory frame, an initial longitudinal polarization s_0, *i.e.* $\mathbf{s}_0 = (0, 0, s_0)$, and $\mathbf{B} = (0, B_y, 0)$, the solution of the T-BMT equation is[18]

$$\mathbf{s} = \begin{cases} s_x = -s_0 \sin\Phi \\ s_y = -s_0 \dfrac{d\beta}{g} \sin\Phi \\ s_z = s_0 \cos\Phi \end{cases} \tag{2}$$

where $\Phi = \frac{D_y \mu_B}{\beta\hbar c}\sqrt{d^2\beta^2 + g^2} \approx \frac{g D_y \mu_B}{\beta\hbar c}$ with $D_y \equiv D_y(l) = \int_0^l B_y dl'$ the integrated magnetic field along the Λ flight path. The polarization vector precesses in the xz plane, normal to the magnetic field, with the precession angle Φ proportional to the gyromagnetic factor of the particle. The presence of an EDM introduces a non-zero s_y component perpendicular to the precession plane of the MDM, otherwise not present. At LHCb, with a tracking dipole magnet providing an integrated field $D_y \approx \pm 4$ T m[31], the maximum precession angle for particles traversing the entire magnetic field region yields $\Phi_{\max} \approx \pm\pi/4$, and allows to achieve about 70% of the maximum s_y component. Moreover, a test of CPT symmetry can be performed by comparing the g and $-\bar{g}$ factors for Λ and $\overline{\Lambda}$ baryons, respectively, which precess in opposite directions as g and d change sign from particle to antiparticle.

2.2. *Charm baryon case*

The Λ_c^+ baryon EDM can be extracted by measuring the precession of the polarization vector of channeled particles in a bent crystal. There, a positively-charged particle channeled between atomic planes moves along a curved path under the action of the intense electric field between crystal planes. In the instantaneous rest frame of the particle the electromagnetic field causes the spin rotation. The signature of the EDM is a polarization component perpendicular to the initial baryon momentum and polarization vector, otherwise not present, similarly to the case of the Λ baryon.

The phenomenon of spin precession of positively-charged particles channeled in a bent crystal was firstly observed by the E761 collaboration that measured the MDM of the strange Σ^+ baryon[32]. The feasibility of the measurement at LHC energies offers clear advantages with respect to lower beam energies since the estimated number of channeled charm baryons is proportional to $\gamma^{3/2}$, where γ is the Lorentz factor of the particles[33].

In the limit of large boost with Lorentz factor $\gamma \gg 1$, the precession angle Φ,

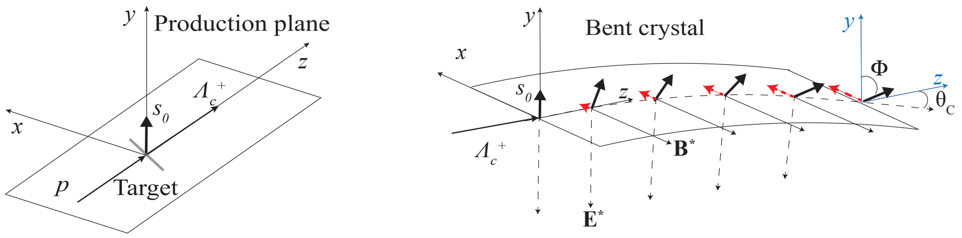

Fig. 1. (Left) Production plane of the Λ_c^+ baryon defined by the proton and the Λ_c^+ momenta. The initial polarization vector $\mathbf{s}_0$ is perpendicular to the production plane, along the y axis, due to parity conservation in strong interactions [34]. (Right) Deflection of the baryon trajectory and spin precession in the yz and xy plane induced by the MDM and the EDM, respectively. The red (dashed) arrows indicate the (magnified) s_x spin component proportional to the particle EDM. Φ is the MDM precession angle and θ_C is the crystal bending angle. $\mathbf{E}^*$ and $\mathbf{B}^*$ are the intense electromagnetic field in the particle rest frame [35,36] which induce spin precession.

shown in Fig. 1, induced by the MDM is [37]

$$\Phi \approx \frac{g-2}{2}\gamma\theta_C, \tag{3}$$

where g is the gyromagnetic factor, $\theta_C = L/\rho_0$ is the crystal bending angle, L is the circular arc of the crystal and ρ_0 the curvature radius .

In presence of a non-zero EDM, the spin precession is no longer confined to the yz plane, originating a s_x component proportional to the particle EDM represented by the red (dashed) arrows in (Right) Fig. 1. The polarization vector, after channeling through the crystal is [18]

$$\mathbf{s} \;=\; \begin{cases} s_x \approx s_0 \dfrac{d}{g-2}(\cos\Phi - 1) \\ s_y \approx s_0 \cos\Phi \\ s_z \approx s_0 \sin\Phi \end{cases}, \tag{4}$$

where Φ is given by Eq. (3). The MDM and EDM information can be extracted from the measurement of the spin polarization of channeled baryons at the exit of the crystal, via the study of the angular distribution of final state particles. For Λ_c^+ decaying to two-body final states such as $f = \Delta^{++}K^-, pK^{*0}, \Delta(1520)\pi^+$ and $\Lambda\pi^-$, the angular distribution is described by Eq. 1. A Dalitz plot analysis would provide the ultimate sensitivity to the EDM measurement.

The initial polarization s_0 would require in principle the measurement of the angular distribution for unchanneled baryons. In practice this is not required since the measurement of the three components of the final polarization vector for channeled baryons allows a simultaneous determination of g, d and s_0, up to discrete ambiguities. These can be solved exploiting the dependence of the angular distribution with the Λ_c^+ boost γ, as discussed in Ref. [19].

3. Sensitivity studies

3.1. Λ and $\overline{\Lambda}$ case

The number of Λ particles produced can be estimated as

$$N_\Lambda = 2\mathcal{L}\sigma_{q\overline{q}} f(q \to H)\mathcal{B}(H \to \Lambda X')\mathcal{B}(\Lambda \to p\pi^-)\mathcal{B}(X' \to \text{charged}), \tag{5}$$

where $\mathcal{L}$ is the total integrated luminosity, $\sigma_{q\overline{q}}$ $(q = c, b)$ are the heavy quark production cross sections from pp collisions at $\sqrt{s} = 13\,\text{TeV}$ [38–41], and f is the fragmentation fraction into the heavy baryon H [42–45]. In Table 1 the dominant production channels and the estimated yields are summarised. Only the decays where it is experimentally possible to determine the production and decay vertex of the Λ are considered. Overall, there are about 1.5×10^{11} Λ baryons per fb^{-1} produced directly from heavy baryon decays (referred hereafter as short-lived, or SL events), and 3.8×10^{11} from charm baryons decaying through an intermediate Ξ^- particle (long-lived, or LL events). The yield of Λ baryons experimentally available can then be evaluated as $N_\Lambda^{\text{reco}} = \epsilon_{\text{geo}}\epsilon_{\text{trigger}}\epsilon_{\text{reco}}N_\Lambda$, where ϵ_{geo}, $\epsilon_{\text{trigger}}$ and ϵ_{reco} are the geometric, trigger and reconstruction efficiencies of the detector system. The geometric efficiency for SL topology has been estimated to be about 16% using a Monte Carlo simulation of pp collisions at $\sqrt{s} = 13\,\text{TeV}$ and the decay of heavy hadrons.

Table 1. Dominant Λ production mechanisms from heavy baryon decays and estimated yields produced per fb^{-1} at $\sqrt{s} = 13\,\text{TeV}$, shown separately for SL and LL topologies. The Λ baryons from Ξ^- decays, produced promptly in the pp collisions, are given in terms of the unmeasured production cross section.

SL events	$N_\Lambda/\,\text{fb}^{-1}$ $(\times 10^{10})$	LL events, $\Xi^- \to \Lambda\pi^-$	$N_\Lambda/\,\text{fb}^{-1}$ $(\times 10^{10})$
$\Xi_c^0 \to \Lambda K^-\pi^+$	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]

To assess the EDM sensitivity, pseudo-experiments have been generated using a simplified detector geometry that includes an approximate LHCb magnetic field mapping[31,46]. Λ baryons decaying towards the end of the magnet provide most of the sensitivity to the EDM and MDM, since a sizeable spin precession could happen. The decay angular distribution and spin dynamics have been simulated using Eq. (1) and the general solution as a function of the Λ flight length[18], respectively. For this study the initial polarization vector $\mathbf{s}_0 = (0, 0, s_0)$, with s_0 varying between 20% and 100%, and factors $g = -1.458$[30] and $d = 0$, were used. Each generated sample was fitted using an unbinned maximum likelihood method with d, g and $\mathbf{s}_0$ as free parameters. The d-factor uncertainty scales with the number of events N_Λ^{reco}

and the initial longitudinal polarization s_0 as $\sigma_d \propto 1/(s_0\sqrt{N_\Lambda^{\rm reco}})$. The sensitivity saturates at large values of s_0, as shown in (Left) Fig. 2, and it partially relaxes the requirements on the initial polarizations. Similarly, (Right) Fig. 2 shows the expected sensitivity on the EDM as a function of the integrated luminosity, summing together SL and LL events, assuming global trigger and reconstruction efficiency $\epsilon_{\rm trigger}\epsilon_{\rm reco}$ of 1% (improved LHCb software-based trigger and tracking for the upgrade detector[47,48]) and 0.2% (current detector[31]), where the efficiency estimates are based on a educated guess. An equivalent sensitivity is obtained for the gyromagnetic factor. Therefore, with 8 fb^{-1} a sensitivity $\sigma_d \approx 1.5\times10^{-3}$ could be achieved (current detector), to be compared to the present limit, 1.7×10^{-2}[12]. With 50 fb^{-1} (upgraded detector) the sensitivity on the gyroelectric factor can reach $\approx 3\times10^{-4}$.

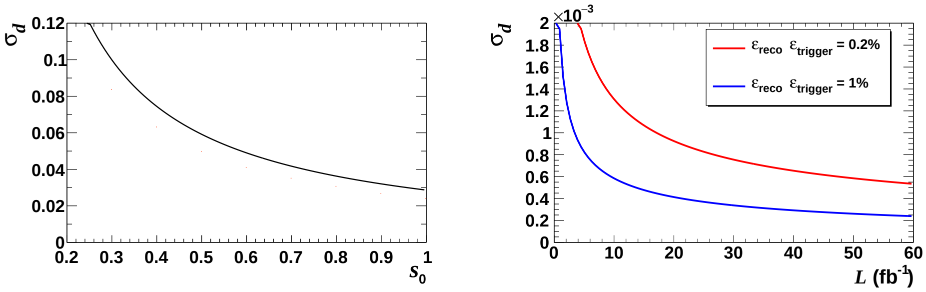

Fig. 2. (Left) Dependence of the Λ gyroelectric factor uncertainty with the initial polarization for $N_\Lambda^{\rm reco} = 10^6$ events, and (Right) as a function of the integrated luminosity assuming reconstruction efficiency of 0.2% and 1%.

3.2. *Charm baryon case*

We propose to search for charm baryon EDMs in a dedicated fixed-target experiment at the LHC to be installed in front of the LHCb detector. The target should be attached to the crystal to maximize the yield of short-lived charm baryons to be channeled. The rate of Λ_c^+ baryons produced with 7 TeV protons on a fixed target can be estimated as

$$\frac{dN_{\Lambda_c^+}}{dt} = \frac{F}{A}\sigma(pp\to\Lambda_c^+X)N_T, \tag{6}$$

where F is the proton rate, A the beam transverse area, N_T the number of target nucleons, and $\sigma(pp\to\Lambda_c^+X)$ is the cross-section for Λ_c^+ production in pp interactions at $\sqrt{s} = 114.6$ GeV center-of-mass energy. The number of target nucleons is $N_T = N_A\rho A T A_N/A_T$, where N_A is the Avogadro number, ρ (T) is the target density (thickness), and A_T (A_N) is the atomic mass (atomic mass number). For our estimates we consider a target of tungsten thick $T = 0.5$ cm with density $\rho =$

19.25 g/cm. The rate of Λ_c^+ particles channeled in the bent crystal and reconstructed in the LHCb detector is estimated as

$$\frac{dN^{\rm reco}_{\Lambda_c^+}}{dt} = \frac{dN_{\Lambda_c^+}}{dt}\mathcal{B}(\Lambda_c^+ \to f)\varepsilon_{\rm CH}\varepsilon_{\rm DF}(\Lambda_c^+)\varepsilon_{\rm det}, \tag{7}$$

where $\mathcal{B}(\Lambda_c^+ \to f)$ is the branching fraction of Λ_c^+ decaying to f, $\varepsilon_{\rm CH}$ is the efficiency of channeling Λ_c^+ inside the crystal, $\varepsilon_{\rm DF}$ (Λ_c^+) is the fraction of Λ_c^+ decaying after the crystal and $\varepsilon_{\rm det}$ is the efficiency to reconstruct the decays. A 6.5 TeV proton beam was extracted from the LHC beam halo by channeling protons in bent crystals [49]. A beam with intensity of 5×10^8 proton/s, to be directed on a fixed target, is attainable with this technique [50].

The Λ_c^+ cross section is estimated from the total charm production cross section [51], rescaled to $\sqrt{s} = 114.6\,\mathrm{GeV}$ assuming a linear dependence on $\sqrt{s}$, and Λ_c^+ fragmentation function [44] to be $\sigma_{\Lambda_c^+} \approx 18.2\,\mu\mathrm{b}$, compatible with theoretical predictions [52].

The channeling efficiency in silicon crystals, including both channeling angular acceptance and dechanneling effects, is estimated to be $\varepsilon_{\rm CH} \approx 10^{-3}$ [53], while the fraction of Λ_c^+ baryons decaying after the crystal is $\varepsilon_{\rm DF}(\Lambda_c^+) \approx 19\%$, for $\gamma = 1000$ and 10 cm crystal length. The geometrical acceptance for $\Lambda_c^+ \to pK^-\pi^+$ decaying into the LHCb detector is $\varepsilon_{\rm geo} \approx 25\%$ according to simulation studies. The LHCb software-based trigger for the upgrade detector [47] is expected to have efficiency for charm hadrons comparable to the current high level trigger [31], *i.e.* $\varepsilon_{\rm trigger} \approx 80\%$. The tracking efficiency is estimated to be 70% per track, leading to an efficiency $\varepsilon_{\rm track} \approx 34\%$ for a Λ_c^+ decay with three charged particles. The detector reconstruction efficiency, $\varepsilon_{\rm det} = \varepsilon_{\rm geo}\varepsilon_{\rm trigger}\varepsilon_{\rm track}$, is estimated to be $\varepsilon_{\rm det}(pK^-\pi^+) \approx 5.4 \times 10^{-2}$ for $\Lambda_c^+ \to pK^-\pi^+$ decays.

Few Λ_c^+ decay asymmetry parameters α_f are known. At present, they can be computed from existing $\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis results [54] yielding $\alpha_{\Delta^{++}K^-} = -0.67 \pm 0.30$ for the $\Lambda_c^+ \to \Delta^{++}K^-$ decay [18].

For the sensitivity studies we assume $s_0 = 0.6$ and $(g-2)/2 = 0.3$, according to experimental results and available theoretical predictions, respectively, quoted in Ref. [55]. The d and $g-2$ values and errors can be derived from Eq. (4). The estimate assumes negligibly small uncertainties on θ_C, γ.

Given the estimated quantities we obtain $dN^{reco}_{\Lambda_c^+}/dt \approx 5.9\times10^{-3}\ \mathrm{s}^{-1} = 21.2\ \mathrm{h}^{-1}$ for $\Lambda_c^+ \to \Delta^{++}K^-$. A data taking of 1 month will be sufficient to reach a sensitivity of $\sigma_\delta = 1.3 \times 10^{-17}$ on the Λ_c^+ EDM. Therefore, a measurement of Λ_c^+ EDM is feasible in Λ_c^+ quasi two-body decays at LHCb.

The dependence of the sensitivity to Λ_c^+ EDM and MDM as a function of the number of incident protons on the target is shown in Fig. 3. The same technique could be applied to any other heavy charged baryon, for instance containing b quark. The production rate is lower than Λ_c^+ and the estimates have been studied and discussed in Ref. [19].

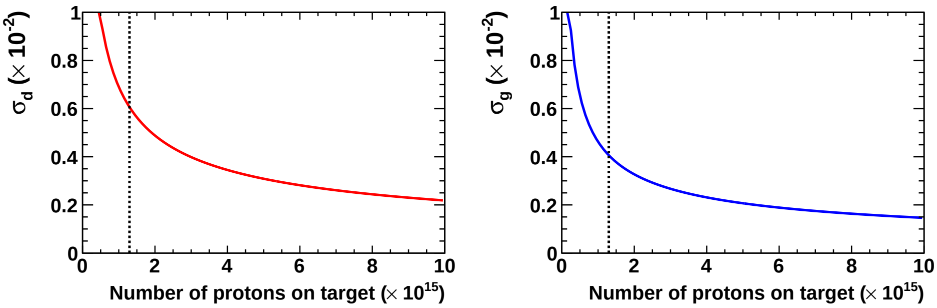

Fig. 3. Dependence of the (Left) d and (Right) g uncertainties for the Λ_c^+ baryon, reconstructed in the $\Delta^{++}K^-$ final state, with the number of protons on target. One month of data taking corresponds to 1.3×10^{15} incident protons (dashed line), according to the estimated quantities.

4. Conclusions

The unique possibility to search for the EDM of strange and charm baryons at LHC is discussed, based on the exploitation of large statistics of baryons with large Lorentz boost and polarization. The Λ strange baryons are selected from weak charm baryon decays produced in pp collisions at ≈ 14 TeV center-of-mass energy, while Λ_c^+ charm baryons are produced in a fixed-target experiment to be installed in the LHC, in front of the LHCb detector. Signal events can be reconstructed using the LHCb detector in both cases. The sensitivity to the EDM and the MDM of the strange and charm baryons arises from the study of the spin precession in intense electromagnetic fields. The long-lived Λ precesses in the magnetic field of the detector tracking system. Short-lived charm baryons are channeled in a bent crystal attached to the target and the intense electric field between atomic planes induces the spin precession. Sensitivities for the Λ EDM at the level of 1.3×10^{-18} $e\,$cm can be achieved using a data sample corresponding to an integrated luminosity of 50 fb^{-1} to be collected during the LHC Run 3. A test of *CPT* symmetry can be performed by measuring the MDM of Λ and $\overline{\Lambda}$ baryons with a precision of about 4×10^{-4} on the g factor. The EDM of the Λ_c^+ can be searched for with a sensitivity of 2.1×10^{-17} $e\,$cm in 11 days of data taking. The proposed experiment would allow about two orders of magnitude improvement in the sensitivity for the Λ EDM and the first search for the charm baryon EDM, expanding the search for new physics through the EDM of fundamental particles.

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