Direct measurement of short-lived particle dipole moments at the LHC

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Abstract
Magnetic and electric dipole moments of fundamental particles provide powerful probes for physics within and beyond the Standard Model. For the case of short-lived particles these have not been experimentally accessible to date due to the difficulties imposed by their short lifetimes. A unique program of direct measurements of electromagnetic dipole moments of strange and charm baryons, and ultimately beauty baryons and the tau lepton, at the LHC is proposed. Novel experimental techniques have been developed, along with feasibility studies and projected sensitivities for different luminosity scenarios.

Keywords
Snowmass 2021 report; short-lived particles; dipole moments; LHC

Measurements of magnetic and electric dipole moments of particles like the neutron, proton and electron are sensitive to physics within and beyond the Standard Model (SM), providing among the stringent constraints to theories beyond the SM [1]. The magnetic and electric dipole moments are proportional to the spin-polarization vector $\boldsymbol{s}$ of the particle, and for spin 1/2 is given by (in Gaussian units) $\boldsymbol{\mu} = g\mu_B\boldsymbol{s}/2$ and $\boldsymbol{\delta} = d\mu_B\boldsymbol{s}/2$ respectively, where $\mu_B = e\hbar/(2mc)$ is the particle magneton, with m its mass, and g and d are the gyromagnetic and gyroelectric (dimensionless) factors. Dipole moments of short-lived particles, such as charm baryons or the τ lepton, have not been measured directly to date due to the challenge imposed by their short lifetimes. A unique program of measurements of dipole moments of short-lived particles at the LHC is proposed for strange [2] and charm baryons [2–6], and ultimately for beauty baryons [5] and the τ^+ lepton [7, 8]. The upgraded LHCb detector at the LHC is particularly suited for the proposal thanks to its forward geometry and excellent performance for the reconstruction of heavy hadrons [9, 10].

For the case of strange Λ baryons, the dipole moments can be determined by measuring the spin precession of polarized particles in the magnetic field of the LHCb tracking system. Highly polarized Λ baryons, up to 90% polarization, can be obtained from weak decays of charm baryons, *e.g.* $\Lambda_c^+ \to \Lambda\pi^+$, $\Xi_c^0 \to \Lambda K^-\pi^+$ and $\Xi_c^+ \to \Lambda K^-\pi^+\pi^+$ decays, which are abundantly produced at LHCb. Sizeable spin precession, up to a maximum angle $\Phi = \frac{gD_y\mu_B}{\beta\hbar c} \approx \pi/4$, proportional to the gyromagnetic factor g and to $D_y = \int_0^\ell B_y d\ell \approx \pm 4$ T m, the integrated LHCb magnetic field along the Λ flight path, is expected. The challenge here is represented by the reconstruction of Λ baryons decaying after the LHCb dipole magnet with reduced resolution on the final particle momenta with respect to particle decaying before the magnet. Recent studies have demonstrated that Λ baryons decaying after the magnet can be reconstructed with the LHCb detector. A sensitivity on the electric dipole moment at the level of $10^{-18}\ e$ cm can be reached with a data sample corresponding to an integrated luminosity of 50 fb^{-1} after the LHCb upgrade, and a test of CPT symmetry at per mille level can be performed by measuring the magnetic dipole moment of Λ and $\overline{\Lambda}$ baryons.

For the case of charm baryons, a novel fixed-target experiment at the LHC is proposed, inspired by a previous experiment for the measurement of the spin precession of Σ^+ baryons at Fermilab [11]. The phenomenon of channeling of positively charged particles in bent crystals is exploited where the intense electromagnetic field between crystal atomic planes induces a sizeable spin precession angle

$\Phi \approx \frac{g-2}{2}\gamma\theta_C$. At the LHC, protons extracted from the beam halo with a crystal kicker can be directed on a tungsten target positioned in front of the LHCb detector, integrating about 4.3×10^{10} protons on target (PoT) in a typical 10 hour fill of the LHC operations [12]. Charm baryons are produced in fixed-target collisions at $\sqrt{s} \approx 115$ GeV with expected non negligible polarization perpendicular to the production plane [13]. A small fraction of the produced Λ_c^+ and Ξ_c^+ charm baryons are channeled in a bent crystal, positioned right after the target, and are deflected inside the LHCb detector acceptance, where they are reconstructed after the decay. The spin polarization precession induced by the crystal can be measured by an angular analysis of Λ_c^+ and Ξ_c^+ decay products with the LHCb detector. According to sensitivity studies, first measurements of Λ_c^+ and Ξ_c^+ dipole moments can be performed with 2 years of data taking with the LHCb detector using about 10^{13} PoT. Moreover, measurements of the dipole moments of the doubly strangeness Ξ^+ antibaryon, and eventually of the dipole and quadrupole moments of the Ω^+ [15, 16], would also be possible. A future dedicated experiment with much higher PoT would allow to further improve the precision [14] and give access to charged beauty antibaryons [5].

For the τ^+ lepton similar fixed-target experiments with bent crystals are proposed [7, 8]. Signal events are generated from strong production of D_s^+ mesons in fixed-target collisions and subsequent $D_s^+ \to \tau^+\nu_\tau$ weak decays. Novel methods that fully exploit the polarization properties of τ^+ leptons produced in D_s^+ decays are proposed. Those are based on τ^+ leptons emitted at relatively large angles with respect to the D_s^+ flight direction, showing enhanced polarization along the axis perpendicular to the crystal plane, and on the selection of the highest momentum candidates, since the Lorentz boost makes larger acceptance for forward- than for backward-emitted τ^+ leptons, inducing a polarization of about 10% antialigned with the crystal longitudinal axis. The τ^+ leptons can be reconstructed in the $3\pi\nu$ final state in order to exploit the experimental signature of the secondary vertex for good signal over background discrimination. A novel analysis technique based on multivariate classifiers is employed to determine the rotation of the spin-polarization vector after the bent crystal and to determine the dipole moments [8]. The SM prediction for the τ^+ magnetic dipole moment could be verified experimentally with a sample of about 10^{17} PoT, whereas at the same time a search for the τ^+ electric dipole moment at the level of $10^{-17}e$ cm or below could be performed. This would require a dedicated experiment and about 10% of the protons stored during a decade of LHC operation.

In summary, a unique program of direct measurements of dipole moments of short-lived particles at LHC is proposed that would allow to perform stringent tests of the SM. Improved measurement of strange baryons and first measurements of charm baryons would be possible with the LHCb detector with a luminosity of 50 fb^{-1} and about 10^{13} PoT, respectively. The test of SM predictions for the magnetic dipole moment of the τ^+ lepton would require a dedicated experiment with much higher protons on target, at the level of 10^{17} PoT.

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