Preparatory measurements for a search of charm baryon EDM at LHCb

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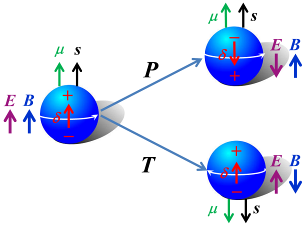
Outline

- Introduction & motivation
- Charm baryon EDM experiment proposal
  - My first year work
- Preparatory measurements at LHCb
  - My next two years work

Electric dipole moment (EDM)

- Classical definition $\boldsymbol{\delta} = \int \mathbf{r}\rho(\mathbf{r})d^3r$
- Quantum systems: $\boldsymbol{\delta}$ must be proportional to $\boldsymbol{s}$, the only vector describing the particle

$$\boldsymbol{\delta} = d\frac{\mu_B}{\hbar}\boldsymbol{s}$$

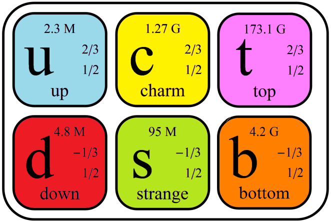


- Parity: $\mathcal{P}\boldsymbol{\delta} = -\boldsymbol{\delta}$ but $\mathcal{P}\boldsymbol{s} = +\boldsymbol{s}$
- Time reversal: $\mathcal{T}\boldsymbol{\delta} = +\boldsymbol{\delta}$ but $\mathcal{T}\boldsymbol{s} = -\boldsymbol{s}$

- An EDM violates $\mathcal{P}$ and $\mathcal{T}$, thus $\mathcal{CP}$ symmetry for CPT theorem
- The EDM, together with the magnetic dipole moment $\boldsymbol{\mu} = g\frac{\mu_B}{\hbar}\mathbf{s}$, drives the particle spin precession in electromagnetic (EM) fields

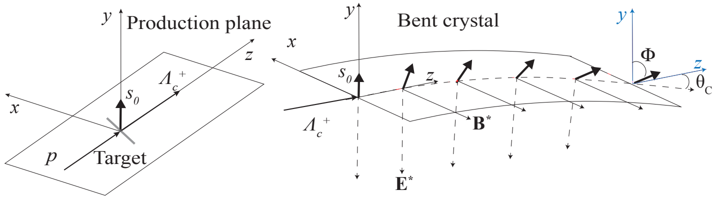
EDM as probe of new physics

- Standard model EDMs practically zero, but enhanced in many beyond the SM (BSM) physics scenarios
- BSM *CP*-violation sources needed to explain baryogenesis, the matter-antimatter asymmetry observed in our Universe
- EDMs being probed in different systems: leptons, nucleons, nuclei, atoms, and Λ baryon
- Charm baryon EDMs never measured so far; only weak indirect limits from other measurements available



Experiment concept

- Source of polarized charm baryons
- Selected from *p*-nucleus collisions, with polarization orthogonal to the p-Λ_c^+ production plane for parity symmetry in strong interactions



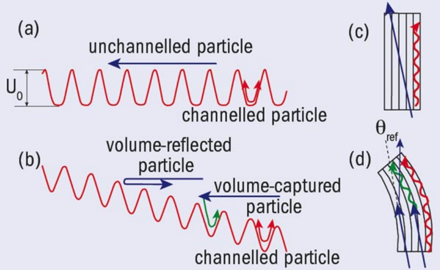
- Intense EM field enough to induce significant spin precession before the baryon decay

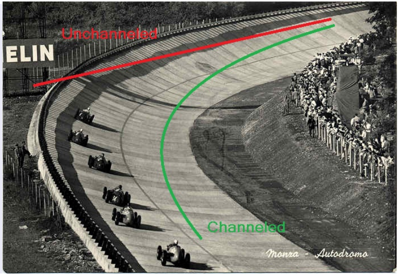
→ Exploit the interatomic electric field $\boldsymbol{E} \approx 10^{11}\, eV/m$ of a bent crystal

- Derived spin evolution equations in which EDM effects are treated as small corrections to the MDM induced precession

Particle channeling in bent crystals

- Positive particles can be trapped between crystal atomic planes, acting as potential barriers
- In bent crystals channeled particles are deflected by following planar channels
- The electric field deflecting the particle, providing the centripetal force, produce the desired spin precession



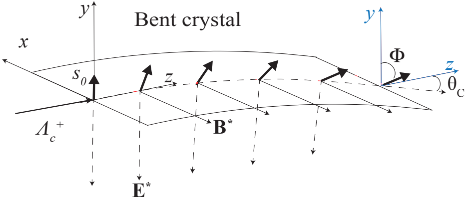


Charm baryons spin precession

- Spin after channeling along the crystal with deflection angle θ_C

$$\mathbf{s} = s_0 \left(\frac{d}{g-2}(\cos\Phi - 1), \cos\Phi, \sin\Phi \right)$$

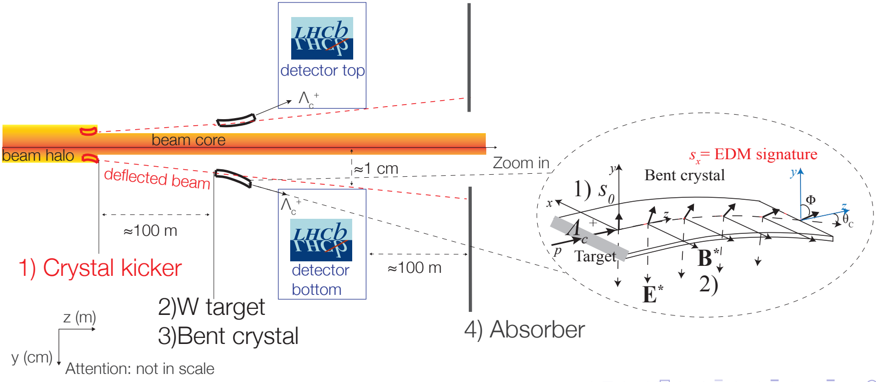
$$\Phi \approx \frac{g-2}{2}\gamma\theta_C$$



- Main MDM precession in the bending plane, the EDM producing an orthogonal spin component otherwise not present
- Spin precession proportional to $\gamma\theta_C$: need high momentum baryons and high crystal bending angle
- Measurement of the charm baryon polarization after channeling by studying the angular distribution of their decays, reconstructed with the LHCb detector

Charm baryons EDM experiment layout

- A first bent crystal is used to extract protons from the LHC beam halo
- Directed on a target attached to a second bent crystal for spin precession
- Charm baryons are deflected inside the LHCb experiment acceptance
- Non-interacting protons follow the beampipe to be absorbed after LHCb



EDM sensitivity

- Experimental layout and sensitivity estimate done for LHCb upgraded for LHC Run 3 (2020-2022)
- Precision dominated by statistics: limited by channeling probability ($\approx 10^{-3}$) and detector reconstruction efficiency ($\approx 5\%$)
- The first measurement of charm baryon (Λ_c^+, Ξ_c^+) EDMs and MDMs should be possible at 10^{-17} *e cm* order
- Value not excluded by current theoretical indirect limits, at $10^{-17} - 10^{-15}$ *e cm* level

Status of the proposal

- Selected among the new fixed-target initiatives under evaluation by the LHCb management
- Presented at the “Low-energy probes of new physics” workshop
- One published paper (Eur. Phys. J. C **77** (2017) 181) and one submitted to EPJC (arXiv:1708.08483)
- Simulation studies reported in the LHCb internal note LHCb-INT-2017-011

Preparatory measurements

- The sensitivity to the charm baryon EDM depends on some quantities which at present are poorly known
- The parameters relating the polarization to the angular distribution of charm baryon decays, in particular of the main decay channel $\Lambda_c^+ \to pK^-\pi^+$
  - For quasi two-body decays, e.g. $\Lambda_c^+ \to \Delta^{++}(\to p\pi^+)K^-$

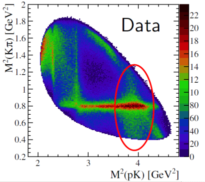
$$\frac{dN}{d\Omega'} \propto 1 + \alpha \mathbf{s} \cdot \hat{\mathbf{k}}$$

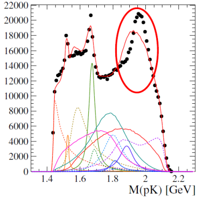
- Polarization of charm baryon produced in fixed-target collisions
- But, they can be measured at LHCb!

Charm baryon amplitude fit

- LHCb has recorded order 1M $\Lambda_c^+ \to pK^-\pi^+$ events from *pp* collisions
- This allows to perform a precise study of the decay structure by means of an amplitude fit

  - Measurement of the contribution of resonances and non-resonant components
  - Development the decay model needed for polarization measurement and useful for simulation purposes
  - Search for local *CP*-violation in the phase-space at very high precision, comparing Λ_c^+ and $\overline{\Lambda}_c^-$ decays

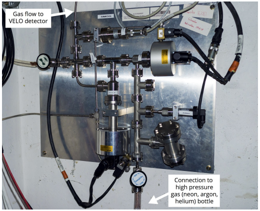


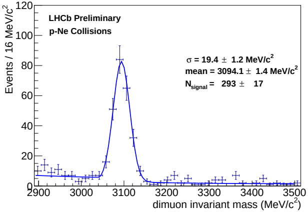


- Amplitude fit framework applicable to other baryon decays

Charm baryon polarization in fixed-target collisions

- LHCb has developed SMOG, an internal gas target for luminosity measurement
- Indeed, it is a fixed-target experiment, and LHCb has already recorded a few hundreds charm baryon decays from *p*-gas collisions
- With the next SMOG run $\times 10$ events are expected
- Using the decay model fit from *pp* collision events it is possible to measure charm baryon polarization with a few percent precision





- Baryon polarization measurements also interesting as benchmark for low-energy QCD models

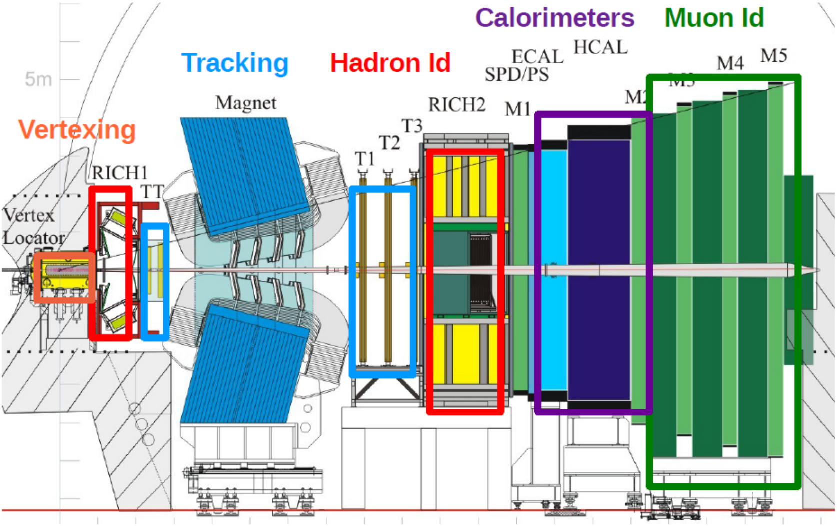
Summary

- A proposal for the first measurement of charm baryons EDM at 10^{-17} *e cm* precision
  - A new physics search complementary but not overlapping to others
  - Need installation of a fixed-target + bent crystal device in LHCb
- Preparatory measurements are needed to better understand the experiment feasibility and sensitivity
  - Amplitude fit of charm baryon decays for polarization measurement
  - Charm baryon polarization in fixed-target collisions
- Measurements already possible with current LHCb dataset

Thank you for your attention!

Backup Slides

LHCb detector



Bent crystals

- Particle deflection using bent crystal is a well understood phenomenon
  - R&D for LHC proton collimation system (UA9 collaboration)
- Measurement of Σ^+ MDM exploiting spin precession in a bent crystal performed at Fermilab (PRL **69** (1992) 3286)

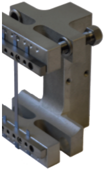
- Two materials to build bent crystal technologically available
  - Ge: Better channeling efficiency, having higher Z thus higher electric potential walls
  - Si: Technologically better understood, cheaper
- Spin precession angle proportional to the crystal bending angle
  - Need long crystals (5-10 cm) with high curvature ($\approx$ 10 mrad)

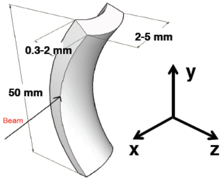
Bent crystals

- Two main production mechanisms (R&D at INFN Ferrara)

1) Anticlastic deformation

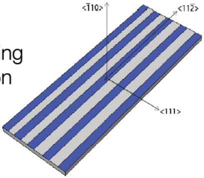
- Bending of the crystal exploits anticlastic deformation
- A mechanical bending device is needed

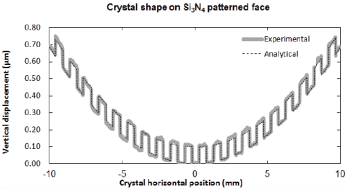




2) Self bent crystals

- Curvature generated by deposition and patterning of a thin (100 nm) silicon nitride layer





Charm baryons final polarization

- Extraction of the charm baryon polarization after channeling by studying the angular distribution of Λ_c^+, Ξ_c^+ decays to $pK^-\pi^+$ final states.
  - Possibility to study decays to narrow strong resonances, e.g. $\Lambda_c^+ \to \Delta^{++}(\to p\pi^+)K^-$, with simple two-body angular distribution

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

  - Possibility to study the full 3-body decay angular distribution via phase-space analysis, complex but allowing best precision on charm baryon polarization components
- Spin precession angle depending on Lorentz boost: angular distribution depending on γ as parameter

Charm baryons EDM sensitivity study

- Very simple study, aiming at charm baryon EDM order of magnitude
  - The details of the experiment layout are under study
  - $g-2$, initial polarization and α parameters for charm baryons very poorly known to date
  - $g-2$, initial polarization to be measured by the proposed experiment, α parameters measurable at LHCb
- Crystal parameters thus not optimized to the expected charm baryon momentum distribution
  - Considered $\gamma = 1000$ ($\approx 2\,\mathrm{TeV}$) as typical energy of channeled charm baryons
  - Considered a 10 cm long crystal bent at 10 mrad

Charm baryons EDM sensitivity study

- Frequency of (e.g.) Λ_c^+ baryons produced

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

- Proton flux on target $F \approx 5 \times 10^8/s$ according to LHC proton extraction studies using bent crystals (AFTER@LHC proposal)
- Areal density of target nucleons $\frac{N_T}{A}$ depending on target properties: chosen a 5 mm W target

- Frequency of channeled and reconstructed Λ_c^+ baryons

$$\frac{dN_{\Lambda_c^+}^{\text{reco}}}{dt} = \frac{dN_{\Lambda_c^+}}{dt} \mathcal{B}(\Lambda_c^+ \to pK^- \pi^+) \varepsilon_{TOT}$$

Charm baryons EDM sensitivity study

- Different contributions to the total efficiency $\varepsilon_{TOT} \sim 10^{-5}$

x Channeling acceptance $\sim 10^{-3}$
- Particles channeled only if aligned to the planar channel within order of μrad
- Boosted particles emitted within a cone of $1/\gamma \approx 1$ mrad

x Particle decaying before the crystal end $\approx 20/50\%$ (Λ_c^+/Ξ_c)

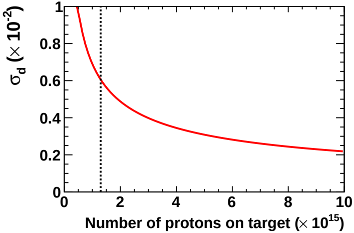
x Detector reconstruction efficiency $\approx 5\%$

Charm baryons EDM sensitivity study

- EDM uncertainty dominated by available statistics

$$\sigma_d \approx \frac{g-2}{\alpha s_0 (\cos\Phi - 1)} \frac{1}{\sqrt{N^{\text{reco}}_{\Lambda_c^+}}}$$

- Considering one month of data-taking:



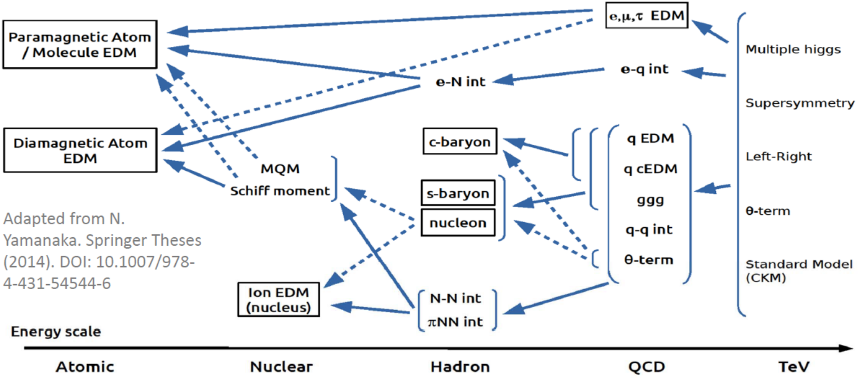
- Precision on Λ_c^+ EDM at

$$\sigma(\delta) \sim 10^{-17}\ e\ cm$$

- Precision on Ξ_c^+ EDM worse by a factor 3/2 due to lower production ratio

Complementarity of EDM searches

- EDM searches in different systems sensitive to different CPV sources, useful to disentangle the contribution of underlying CPV operators. that may have varying new physics enhancements.
- Many new physics models predict EDM enhancements for different systems



Adapted from N. Yamanaka. Springer Theses (2014). DOI: 10.1007/978-4-431-54544-6

Baryon EDM

- A baryon EDM $\delta(B)$ can arise from a collective CPV interaction of its constituting quark and gluon fields with the EM field
- Described by 5 CPV operators in an effective Lagrangian scheme:

$$
\begin{aligned}
\mathcal{L}_{\text{eff}}^{\not{P}\not{T}} = &-\frac{i}{2}\sum_{q=u,d,s,c,b}\delta_q\,\bar{q}\sigma^{\mu\nu}\gamma_5 q\,F_{\mu\nu} && \boxed{\text{qEDM}}\\
&+ i\sum_{q=u,d,s,c,b}\tilde{\delta}_q\,\bar{q}\sigma^{\mu\nu}\gamma_5 t_a q\,G^a_{\mu\nu} && \boxed{\text{qCEDM}}\\
&+ \sum_{i,j,k,l=u,d,s,c,b} C_{ijkl}\,\bar{q}_i\Gamma q_j\,\bar{q}_k\Gamma' q_l && \text{4q op.}\\
&+ \frac{d_W}{6} f_{abc}\varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\,\rho}_{\nu} && \text{gCEDM (Weinberg op.)}\\
&- \bar{\theta}\frac{g^2}{64\pi^2}\epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta} && \theta\text{-QCD term}
\end{aligned}
$$

Baryon EDM

- θ-QCD term heavily constrained by the neutron EDM limit, absent if Peccei-Quinn symmetry is assumed
- Dimension-six gCEDM and 4 quark operators suppressed at baryon energy scale $\approx 1\,\mathrm{GeV}$

$\rightarrow$ $\delta(B)$ dominated by constituent quark EDM and CEDM operators

- Structure of Λ baryon similar to the neutron, since $m(s) \ll m(\Lambda)$
- Neutron EDM limit constrains directly u, d quark EDM, less sensitive to s quark EDM
- Indirect limit from neutron EDM is $\lesssim 10^{-23}$ $e\,cm$ (PLB **291** (1992) 293), still beyond this proposal capabilities
- Of course this does not mean this measurement useless...

Charm baryon EDM

- Structure of charm baryons very different from the neutron, being $m(c) \sim m(\Lambda_c^+)$
- The dominance of the heavy charm quark suggests $\delta(B_c) \approx \delta(c)$ (e.g. PRD **56** (1997) 7273 for charm MDM calculation)
- $\delta(B_c)$ dominated by charm qEDM and qCEDM operators
- Indirect, model-dependent, weak bounds on charm baryon EDMs have been extracted from observables containing qEDM and qCEDM couplings
  - Neutron and electron EDM limits, $\sigma(e^+e^- \to c\bar{c})$, $\Gamma(Z^0 \to c\bar{c})$, $\mathcal{B}(B \to X_s\gamma)$ (e.g. JHEP **03** (2014) 061, NPB **821** (2009) 285)
- For charmed baryons $|\delta(B_c)| < 10^{-17} - 10^{15}$ $e\,cm$, challengeable by this proposal