Search for New Physics via Baryon EDM at LHC

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Proposal by LHCb groups of **IFIC-Valencia** and **INFN-Milano**

Talk based on

F.J. Botella et al. , Eur. Phys. J., C77(3):181, 2017.

E. Bagli et al. , arXiv:1708.08483

Overview

- Motivation
- Experiment Concept @ LHCb
- Sensitivity Reach
- Conclusions

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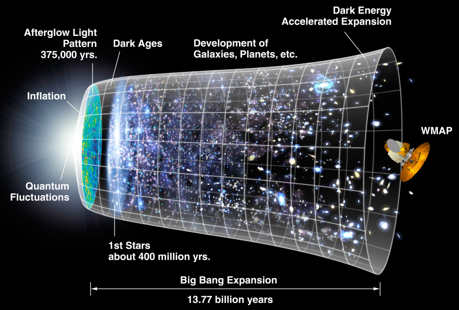
double offer

Long-lived	Short-lived
Λ	Λ_c^+, Ξ_c^+

Motivation – Why EDMs?

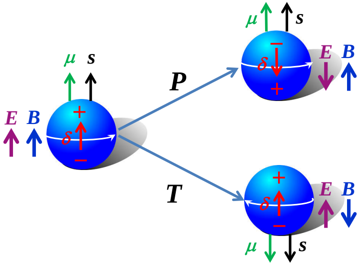


- Matter–antimatter asymmetry
- Sakharov conditions ⊃ Charge (C) and Charge Parity (CP) violation
- Sources of CP Violation (CPV): SM (not enough) and BSM
- A golden observable for new CPV sources:
  Electric Dipole Moment (EDM)

Electric Dipole Moment (EDM)

Definition

$$\boldsymbol{\delta} = \int \mathbf{r}\rho(\mathbf{r})d^3r$$



Quantum systems

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

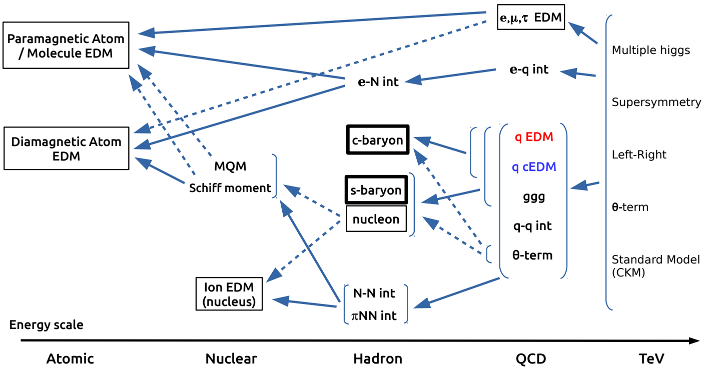
Energy of a system

$$H = -\boldsymbol{\delta}\cdot\mathbf{E} - \boldsymbol{\mu}\cdot\mathbf{B} \quad \xrightarrow{T} \quad +\boldsymbol{\delta}\cdot\mathbf{E} - \boldsymbol{\mu}\cdot\mathbf{B}$$

$$\xrightarrow{P} \quad +\boldsymbol{\delta}\cdot\mathbf{E} - \boldsymbol{\mu}\cdot\mathbf{B}$$

The EDM violates T and P $\Rightarrow$ **CP violation**

Map of the EDM Field



Based on N. Yamanaka. Springer Theses (2014), DOI: 10.1007/978-4-431-54544-6

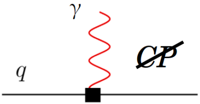
- EDM field: interplay atomic ↔ nuclear ↔ high energy physics
- The SM predicts negligible flavor-diagonal CPV
- Any signal → **clear sign of new physics**
- Current limits strongly constrain speculative models of CPV

Sources of baryon EDM

- The measurement of the Λ_c^+ EDM is **directly sensitive** to

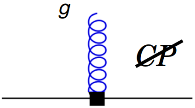
charm EDM

$$\delta_q \, \bar{q} i \sigma^{\mu\nu} \gamma_5 q \, F_{\mu\nu}$$



charm chromo-EDM

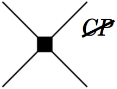
$$\delta_q \, \bar{q} i \sigma^{\mu\nu} \gamma_5 t_a q \, G^a_{\mu\nu}$$



- All other contributions are **suppressed**

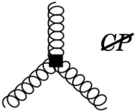
4 quark op.

$$C_{ijkl} \, \bar{q}_i \Gamma q_j \, \bar{q}_k \Gamma' q_l$$



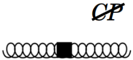
Weinberg op.

$$\frac{d_W}{6} f_{abc} \varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\,\rho}_{\nu}$$



θ-QCD

$$-\bar{\theta} \frac{g^2}{64\pi^2} \epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}$$



(non-perturbative)

$\Longrightarrow$ These operators constitute the *CP-odd flavour diagonal Lagrangian*

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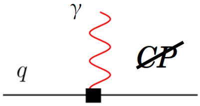

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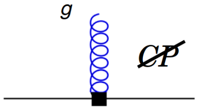

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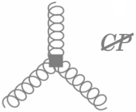

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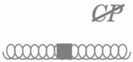
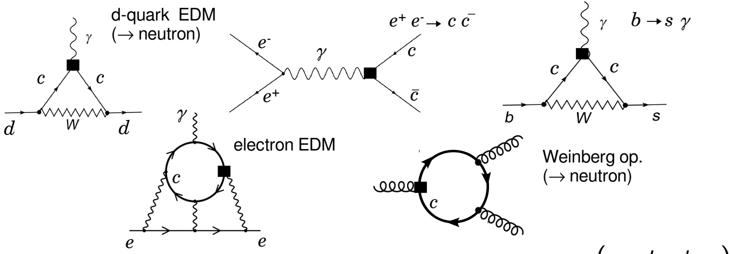


(non-perturbative)

$\Longrightarrow$ These operators constitute the *CP-odd flavour diagonal Lagrangian*

Indirect limits

The dipole couplings of the **charm quark** are bounded indirectly by different observables using some model assumptions. These bounds, at the level of $< 10^{-15} - 10^{-17}$ecm, can be challenged with this proposal.



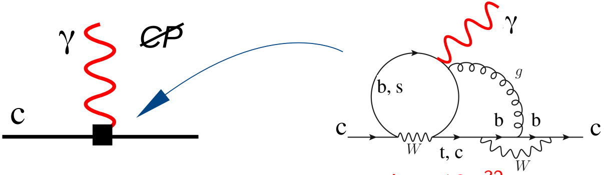
(*see backup*)

The indirect limits on the **s-baryons** from the neutron EDM, $\lesssim 10^{-23} e\mathrm{cm}$, are beyond the reach of this proposal. Phys. Rev. D23 (1981) 814

- Only direct measurement, $|\delta_\Lambda| \leq 1.5 \times 10^{-16}$ ecm, can be improved.

Potential to constrain BSM theories

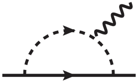
Standard Model has its leading contribution at **3-loop** level

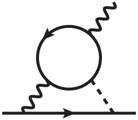


$d_c \sim 10^{-32}$ecm

negligible

Beyond SM contributions at **1,2 loops**



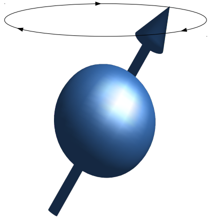


- Enhanced for heavy flavours

$d_c \sim 10^{-17}$ecm	S.-M. Zhao et al.	EPJ C77 (2017), no.2 102
$d_c \sim 10^{-17}$ecm	Z. Z. Aydin et al.	PR D67 (2003) 036006
$d_c \sim 10^{-19}$ecm	X.-J. Bi et al.	arXiv:hep-ph/0412360
...	...	...

How to access EDMs ?

- **Spin precession:**
  In the presence of an electromagnetic field, the spin-polarization rotates due to the magnetic moment. A change on the orthogonal direction signals the presence of an electric dipole moment.



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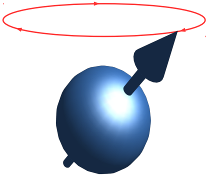

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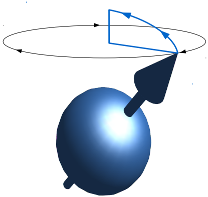


Experiment concept: Requirements

- A source of **polarized baryons**

- **Electromagnetic field** intense enough to induce precession

- A **detector** to reconstruct the baryon decay products

Experiment concept: Requirements

long-lived Λ baryon	**short-lived charmed baryons**
$\Downarrow$	$\Downarrow$

- A source of **polarized baryons**

Weak decays of charm baryons e.g. $pp \to \Xi_c^0 \to \Lambda K^- \pi^+$	Strong production in a fixed target

- **Electromagnetic field** intense enough to induce precession

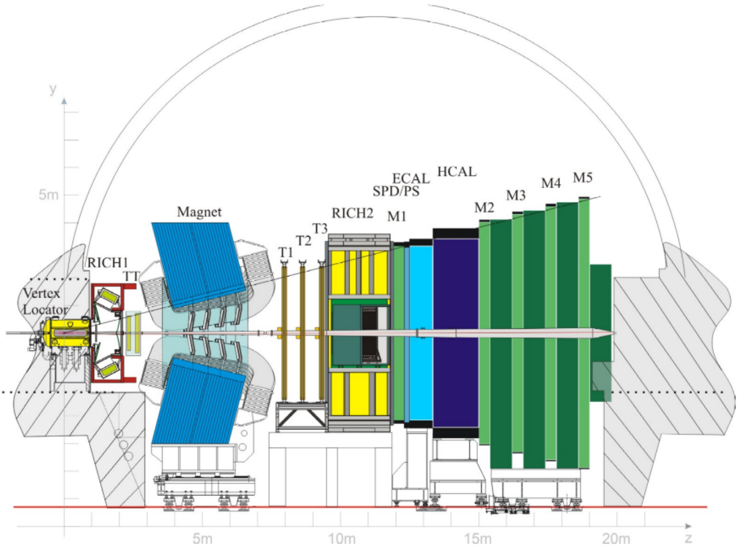
LHCb dipole magnet	Interatomic electric field in bent crystals

- A **detector** to reconstruct the baryon decay products

LHCb	LHCb

EPJ C77 (2017) 181

LHCb Detector



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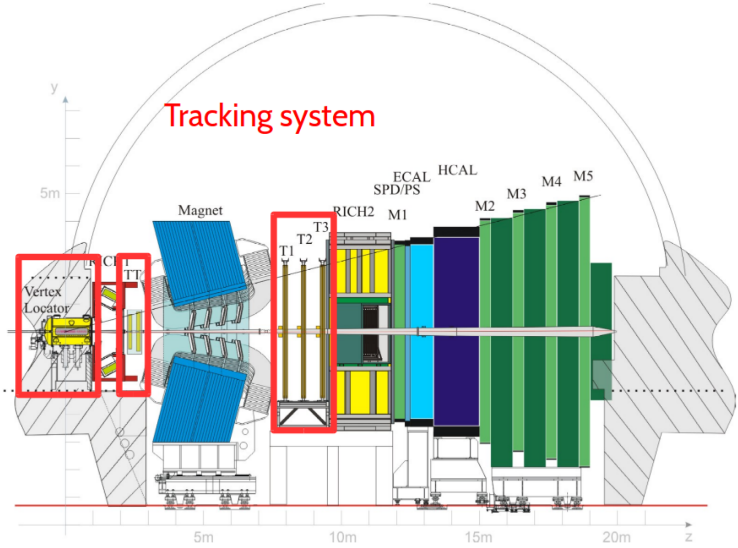
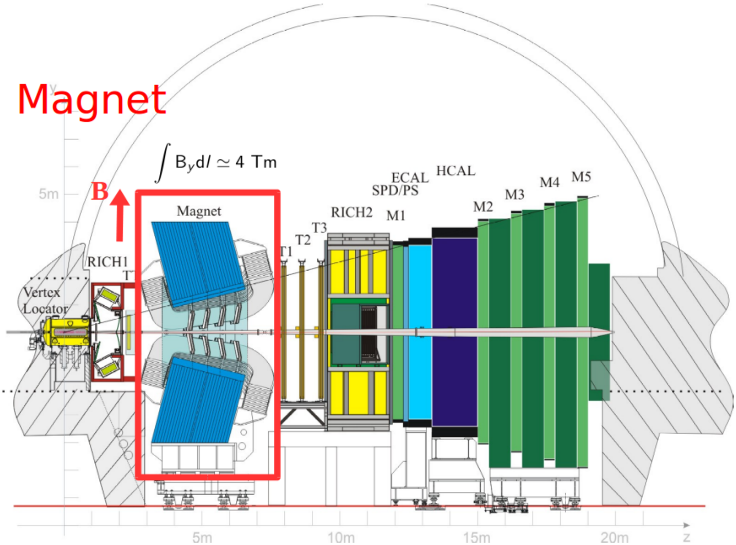
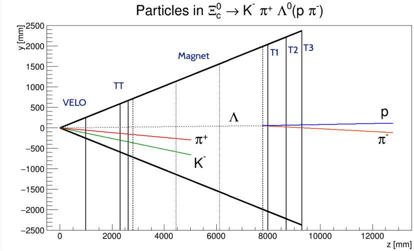


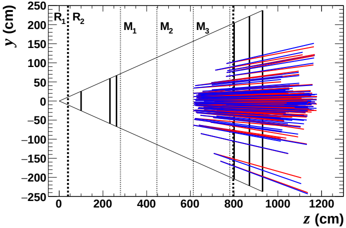
LHCb Detector



Λ Baryon

- Polarized Λ baryons from weak decays of charmed baryons. Large longitudinal polarization $\mathbf{s_0} = \mathbf{90}\%$
- The Λ travels through the magnetic field, designed for track reconstruction purposes
- The single-arm **LHCb spectrometer** at LHC, most suitable detector

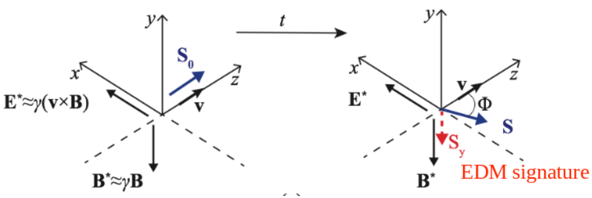




$$\text{e.g. } \Xi_c^0 \to \Lambda K^- \pi^+$$

Λ Baryon: Spin precession

- A fraction of the Λ baryons reach the the dipole magnet
- The Λ e.m. moments interact with the magnetic field
  → Spin precession
  - MDM ⇒ Main precession
  - EDM ⇔ build-up of an s_y component



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

$$\Phi \approx \frac{g\mu_N \int B_y \mathrm{d}l}{\hbar\beta c} \approx \frac{\pi}{4}$$

and $\int B_y \mathrm{d}l \approx 4$ Tm

- Measurement of polarization: $\Lambda \to p\pi^-$ angular analysis

Λ Baryon: EDM Sensitivity

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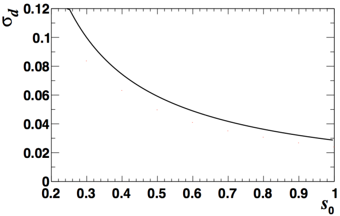
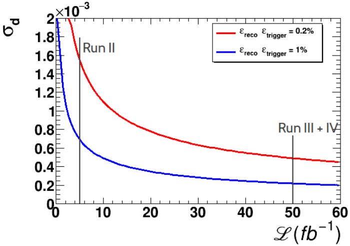
- Uncertainties $\propto 1/(s_0\sqrt{N})$, s_0 = initial Λ polarization
- Sensitivity reach to EDM at LHCb (50fb^{-1}):
  Improvement of two orders of magnitude

$$|\boldsymbol{\delta_\Lambda}| \lesssim \mathbf{2 \times 10^{-18}}\ \textbf{ecm}\ (95\% CL)$$





- Similar sensitivity for MDM: Test of CPT symmetry at per-mille level

Current bound:

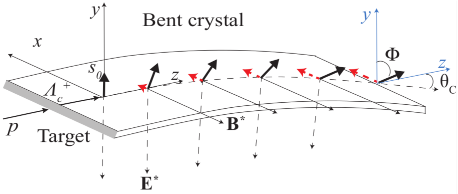
$|\delta_\Lambda| \leq 1.5 \times 10^{-16}$ ecm — Phys. Rev. D23 (1981) 814

$\boldsymbol{\mu}_\Lambda = (0.613 \pm 0.004)\mu_N$ — Phys. Rev. Lett. 41 (1978) 1348

Charmed Baryons: Channelling in Bent Crystals

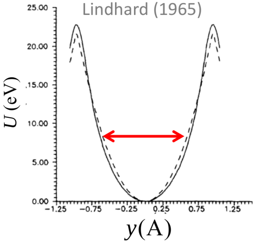
- Very short-lived $\rightarrow$ Need large EM field of $\sim 10^3$ T
- Electric field between atomic planes of a bent crystal
- Precession induced by the net EM field

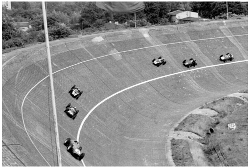
$$\Phi \approx \frac{g-2}{2}\gamma\theta_C \approx \pi$$



Charmed Baryons: Channelling in Bent Crystals

- Potential well between crystallographic planes
- Incident **positively-charged** particles can be **trapped** if their *transverse energy* is small
  $\Rightarrow$ **Small incident angle** w.r.t the crystal planes (few μrad)





- To induce a net EM field, the crystal must be bent
- The **E** field must compensate the centrifugal force which increases with the *momentum*
  $\Rightarrow$ The energy determines a **critical radius** ($\sim$ 10 cm)

Charmed Baryons: Proof of principle at E761

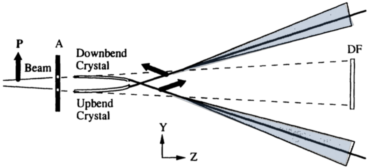
- E761 Fermilab experiment firstly observed spin precession in bent crystals and measured MDM of Σ^+

  Phys. Rev. Lett 69 (1992) 3286

- 350 GeV/c Σ^+ produced from 800 GeV/c proton beam on a Cu target
- Used up- and down-bend silicon crystals $L = 4.5cm$, $\theta_C = 1.6mrad$ to induce opposite spin precession

VOLUME 69, NUMBER 23 PHYSICAL REVIEW LETTERS 7 DECEMBER 1992

First Observation of Magnetic Moment Precession of Channeled Particles in Bent Crystals



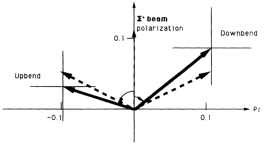
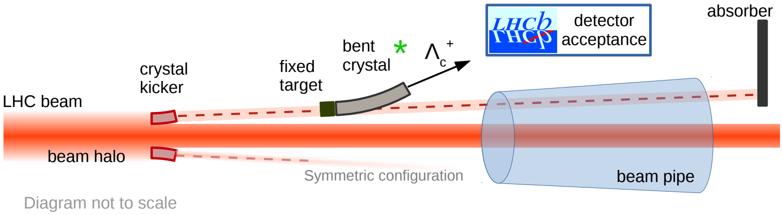


FIG. 3. Measured polarizations and uncertainties (1σ statistical errors) after spins have been precessed by the two crystals. The dashed arrows show the expected precessions.

Charmed Baryons: Experimental Setup



- How to *put* polarized Λ_c^+ inside the crystal
  - Fixed-target + bent crystal in LHCb beam pipe
  - Incident beam: 7 TeV protons extracted from LHC beam halo using bent crystals ≈ 100m upstream of the target
  - Feasibility proven by UA9 collaboration Physics Letters B 758 (2016) 129
  - Initial **transversal polarization** $\mathbf{s_0} \approx$ **50%**
- How to measure the spin precession
  - Angular distribution of the decay $\Lambda_c^+ \to pK^-\pi^+$

$$dN/d\Omega \propto 1 + \alpha \mathbf{s} \cdot \mathbf{k}$$

Charmed Baryons: Sensitivity

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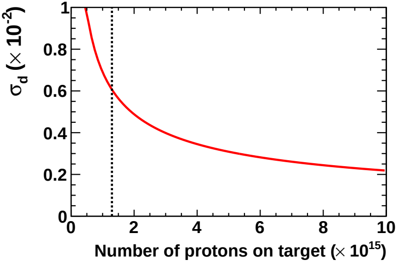
- The EDM uncertainty dominated by statistics,

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

$$\begin{bmatrix} \gamma = 1000 \text{ (E} \approx 2 \text{ TeV)} \\ L \approx 10 \text{ cm} \\ \theta_C \approx 10 \text{ mrad} \\ F = 10^8 \text{ p/s} \end{bmatrix}$$

- $g-2$, α and $\mathbf{s_0}$ for c-baryons poorly known
  - $g-2$, $\mathbf{s_0}$ to be measured by proposed experiment
  - α measurable by LHCb



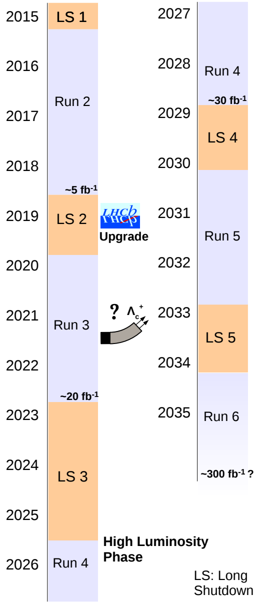
- With **few weeks** of data taking ($\approx 10^{15}$ protons on target) the **EDM** sensitivity would reach $\sigma_\delta \approx \mathbf{10^{-17} ecm}$

- The Λ_c^+ **magnetic moment** can be measured, for the first time, with $\sigma_{g-2} \approx 4 \times 10^{-3}$

Conclusions

- Proposed $\Lambda/\overline{\Lambda}$ baryon **EDM search** at $10^{-18}e$cm level (by end LHC Run 3)
  - Two orders of magnitude improvement for Λ
  - First measurement of $\overline{\Lambda}$ magnetic moment + **CPT test** at 10^{-3} level
  - Feasible with current LHCb layout
- **First EDM search** for **charm baryons**
  - Fixed target and bent crystals in front of LHCb
  - More interesting and more challenging experiment
- Can be extended to other positively-charged baryons such as Ω^+, Ξ^+, ${\Xi_b}^+$, ... arXiv:1708.08483
- Complementary to other EDM searches in different systems

Prospects



- Accurate studies for installation of device are currently under evaluation within the **LHCb Collaboration**
- Proposal included in the **Physics Beyond Colliders** study group
- Both Λ and charmed baryon EDM experiments will greatly benefit from the **LHCb Upgrade**, planned for Run 3

http://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-schedule-update.pdf

Backup

Channels for Λ baryon EDM

Channels for production of Λ baryons

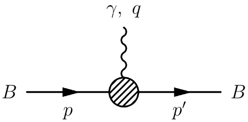
- Weak decays
- Only charged particles to define origin and end vertices

short-lived	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
$\Xi_c^0 \to \Lambda K^+ K^-$	0.2
$\Xi_c^0 \to \Lambda \phi(K^+ K^-)$	0.1

long-lived		N_Λ /fb^{-1}($\times 10^{10}$)
$\Xi_c^0 \to \Xi^- \pi^+ \pi^+ \pi^-$	$\Xi^- \to \Lambda \pi^-$	23.6
$\Xi_c^0 \to \Xi^- \pi^+$	$\Xi^- \to \Lambda \pi^-$	7.
$\Xi_c^+ \to \Xi^- \pi^+ \pi^+$	$\Xi^- \to \Lambda \pi^-$	6.1
$\Lambda_c^+ \to \Xi^- K^+ \pi^+$	$\Xi^- \to \Lambda \pi^-$	0.6
$\Xi_c^0 \to \Xi^- K^+$	$\Xi^- \to \Lambda \pi^-$	0.2
Prompt Ξ^-		0.13 $\times \sigma_{pp \to \Xi^-}$ [μb]

Electromagnetic form factors

All electromagnetic properties parametrized in four EM form factors



$$= \langle B(p')|J^{\nu}_{\mathrm{em}}|B(p)\rangle$$

$$= \bar{u}(p')\left\{\gamma^{\nu}F_1\left(q^2\right) - \frac{i\,F_2\left(q^2\right)}{2m_B}\sigma^{\mu\nu}q_{\mu} - \frac{\mathbf{F_3}\left(\mathbf{q^2}\right)}{2m_B}\sigma^{\mu\nu}q_{\mu}\gamma_5 + i\left(\gamma^{\nu}q^2\gamma_5 - 2m_B q^{\nu}\gamma_5\right)F_A\left(q^2\right)\right\}u(p)$$

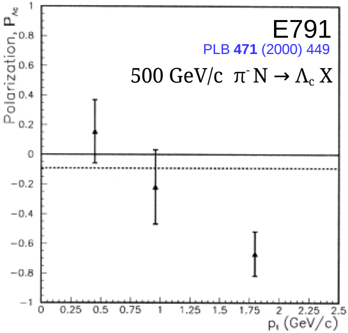
Charge	Magnetic Moment	**Electric Dipole Moment**, $\not{P}$ $\not{T}$	Anapole Moment, $\not{P}$
$F_1(0) = Q$	$\frac{1}{2m_B}[F_1(0) + F_2(0)] = \mu$	$\frac{1}{2m}\mathbf{F_3(0)} = \delta$	$F_A(0) = Q$

EJP 26 (2005) 545

JHEP 12 at (2012) 097

Charmed Baryons: initial polarization

- Strong production of Λ_c^+ in fixed target: $p - N$ collision with $\sqrt{s} = 115$ GeV/c from 7 TeV p
- Polarization orthogonal to the $p - \Lambda_c^+$ production plane (parity conservation)
- Increases with Λ_c^+ transverse momentum $p_T(\Lambda_c^+)$



- E791 measured sizeable polarization for $p_T > 1$ GeV/c ($\approx 50\%$)

Charm (chromo-)EDM bounds

Bound	Ref.	Measurement	Method
$\|d_c\| < 4.4 \times 10^{-17}$ ecm	Sala:2013osa	neutron EDM	Considers threshold contributions of d_c into d_d. Neglects all other contributions to the d_n.
$\|d_c\| < 3.4 \times 10^{-16}$ ecm	Sala:2013osa	$\mathrm{BR}(B \to X_s\gamma)$	Considers contributions from d_c to the Wilson coefficient C_7.
$\|d_c\| < 3 \times 10^{-16}$ ecm	Grozin:2009jq	electron EDM	Extracted from d_c threshold contribution to d_e through light-by-light scattering diagrams.
$\|d_c\| < 1 \times 10^{-15}$ ecm	Grozin:2009jq	neutron EDM	Similar approach than ref. Sala:2013osa. Evaluates contributions in two steps: c-quark $\to$ d-quark $\to$ neutron.
$\|d_c\| < 5 \times 10^{-17}$ ecm	Blinov:2008mu	$e^+e^- \to c\bar{c}$	The total cross section (LEP) might be enhanced by the charm qEDM vertex $c\bar{c}\gamma$.
$\|d_c\| < 8.9 \times 10^{-17}$ ecm	Escribano:1993xr	$\Gamma(Z \to c\bar{c})$	Measurement at the Z peak (LEP). Uses model dependent relationships to weight contributions from d_c and d_c^w.
		charm chromo-EDM	
$\|\tilde{d}_c\| < 1.0 \times 10^{-22}$ ecm	Sala:2013osa	neutron EDM	Considers threshold contributions of d_c into the light quark EDMs $d_{u,d}$ and the Weinberg operator w
$\|\tilde{d}_c\| < 3 \times 10^{-14}$ ecm	Kuang:2012wp	$\psi' \to J/\psi\pi^+\pi^-$	The $\tilde{d}_c$ contributes to the static potential betwen c and $\bar{c}$ both in ψ' and J/ψ. It also affects the dynamical transition amplitudes

Ordered by year of publication

References can be found by copying the abbreviations in inspire-hep

Bottom (chromo-)EDM bounds

Bound	Ref.	Measurement	Method
$\|d_b\| < 7 \times 10^{-15}$ ecm	Grozin:2009jq	electron EDM	From the b-quark EDM threshold contribution to d_e through light-by-light scattering diagrams
$\|d_b\| < 2 \times 10^{-12}$ ecm	Grozin:2009jq	neutron EDM	Similar estimation but evaluating contributions in two steps: b-quark $\to$ up-quark $\to$ neutron
$\|d_b\| < 2 \times 10^{-17}$ ecm	Blinov:2008mu	$e^+e^- \to b\bar{b}$	The total cross section (LEP) might be enhanced by the charm qEDM vertex $b\bar{b}\gamma$.
$\|d_b\| < 1.22 \times 10^{-13}$ ecm	CorderoCid:2007uc	neutron EDM	Similar estimation than Grozin:2009jq. But neglects longitudinal component in the W propagator, thus missing emerging divergences.
$\|d_b\| < 8.9 \times 10^{-17}$ ecm	Escribano:1993xr	$\Gamma(Z \to b\bar{b})$	Measurement at the Z peak (LEP). Uses model dependent relationships to weight contributions from d_b and d_b^w.
bottom chromo-EDM			
$\|\tilde{d}_b\| \lesssim 1.1 \times 10^{-21}$ cm	Konig:2014iqa	neutron EDM	Numerical result based on the the contribution of the beauty CEDM into the Weinberg operator derived in Chang:1990jv

Ordered by year of publication

References can be found by copying the abbreviations in inspire-hep

Channeling conditions. Parametrization

A SIGNAL event (completely channeled particle) requires

- Entrance to the crystal: Lindhard angle: $\theta < \theta_L \equiv \sqrt{\frac{2U_0}{p}}$
- Critical radius: $R > R_c \equiv \frac{pc}{U'(x_c)}$
- Exit the crystal: $z_{orig.} + c\tau\gamma\beta > L$
- Dechanneling probability (event-by-event):

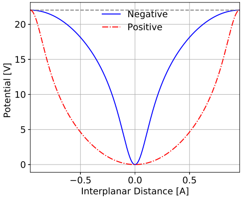
$$\varepsilon_{dechan} = (1 - \frac{R_c}{R})^2 \exp\left(-\frac{\theta_c}{\theta_D \frac{R_c}{R}(1 - \frac{R_c}{R})^2}\right)$$

Negative baryons (e.g. Ξ_b^-)

- Crystal channeling
  - Around a plane of positive atoms (planar channeling)
  - Around a string of positive atoms (axial channeling)

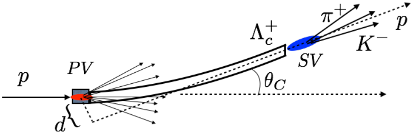
- Lower efficiencies in long crystals (wrt. positive baryons)
  - Collision with nuclei
  - Non-harmonic potential

- Still, b-baryons are accesible
  - Ξ_b^- particle $\rightarrow$ lower efficiencies
  - Ξ_b^+ antiparticle $\rightarrow$ lower production rate



arXiv:1708.08483

Characteristics of the crystal

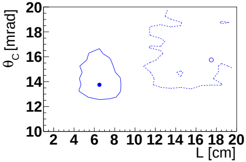


arXiv:1708.08483

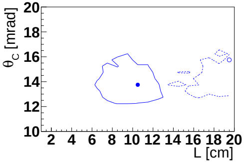
- Optimization of the crystal includes
  - Λ_c^+ from fixed target (Pythia & EvtGen)
  - Channeling efficiency (parametrization)
  - Fits to spin precession (Toy MC)
  - Sensitivities

$\Rightarrow$ Regions of maximum sensitivity (20 % increase)

Germanium crystal

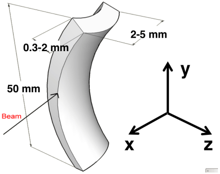


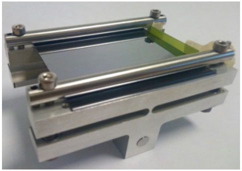
Silicon crystal



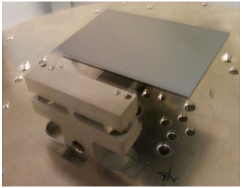
Crystal production

- R&D ongoing at INFN Ferrara. Two methods to bent the crystal
  - Anticlastic deformation





  - Self-bent crystal



A. Mazzolari, Channeling 2016