Electromagnetic Dipole Moments of Heavy Baryons with bent crystals at the LHC

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for E. Bagli, L. Bandiera, G. Cavoto, V. Guidi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Mazzolari, A. Merli, N. Neri

Talk based on Eur. Phys. J. C77(12):828, 2017

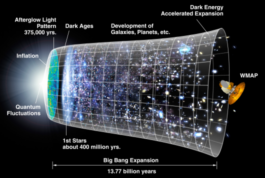
Overview

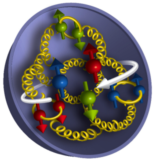
- Motivation
- Experiment Concept @ LHCb
- Sensitivity Reach
- Conclusions

Motivation

Electric Dipole Moment (EDM)

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





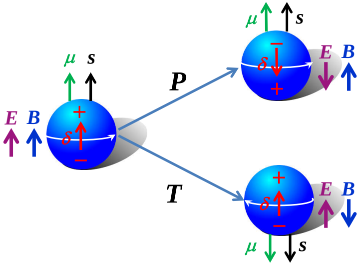
Magnetic Moment (MDM)

- Contains information on the **internal spin structure**
- Quark model yielded good phenomenological description
- Different **non-perturbative QCD** methods obtain uncompatible results for charm baryons
  $\rightarrow$ MDM provide input **fixing points**

Electric Dipole Moment (EDM)

Definition

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



Quantum systems

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

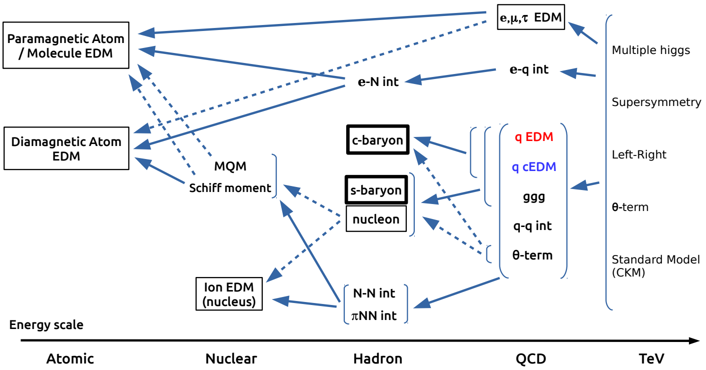
Energy of a system

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

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

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

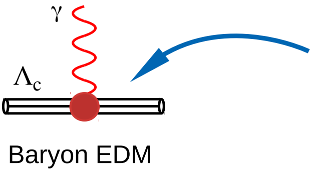
Map of the EDM Field

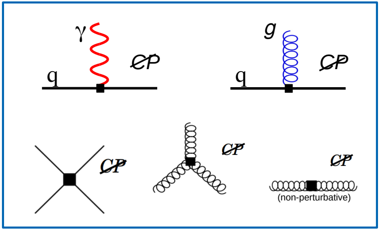


Based on N. Yamanaka. Springer Theses (2014), DOI: 10.1007/978-4-431-54544-6

- 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

Baryon EDM in non-perturbative QCD





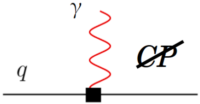
- No calculation for EDM of Λ_c^+ (or c,b-baryons) found in the literature
- Estimations (NDA) point to $d_{\Lambda_c^+} \sim d_c \pm \frac{e}{4\pi}\tilde{d}_c$
- **Theoretical uncertainties** are key to understand the constraining power of heavy baryon EDM searches
- **Non-perturbative methods**: Chiral theories, sum rules, lattice (?), ...

Sources of baryon EDM

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

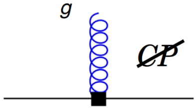
charm EDM

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



charm chromo-EDM

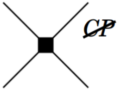
$$\delta_q \, \bar{q} i \sigma^{\mu\nu} \gamma_5 t_a q \, G^a_{\mu\nu}$$



- All other contributions are **suppressed**

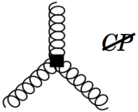
4 quark op.

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



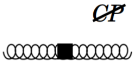
Weinberg op.

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



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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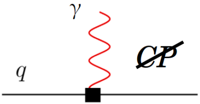

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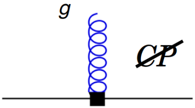

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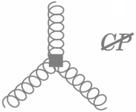

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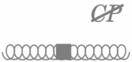

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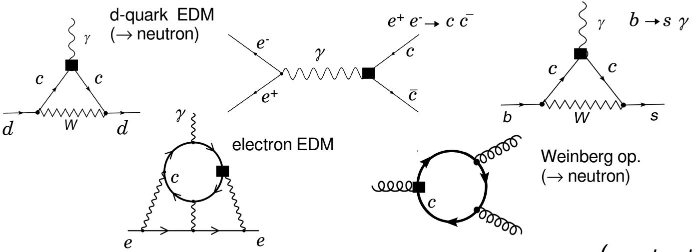
$\Longrightarrow$ These operators constitute the *CP-odd flavour diagonal Lagrangian*

Indirect limits

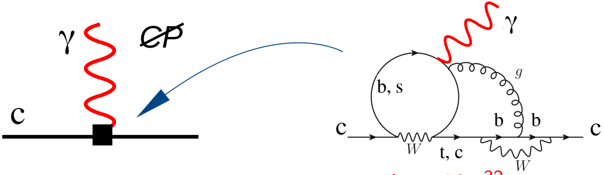
The dipole couplings of the **charm quark** are bounded indirectly by different observables using some model assumptions. These bounds, at the level of $< 10^{-15} - 10^{-17} e$cm, can be challenged with this proposal.



(*see backup*)

The indirect limits on **b quarks**, $\lesssim 10^{-14} - 10^{-16} e\mathrm{cm}$, are beyond the reach of this proposal. Ultimate sensitivity from a dedicated experiment (*see slide 19*).

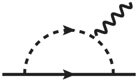
Standard Model has its leading contribution at **3-loop** level

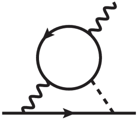


$d_c \sim 10^{-32} ecm$

negligible

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



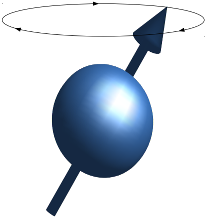


- Enhanced for heavy flavours

$d_c \sim 10^{-17} ecm$	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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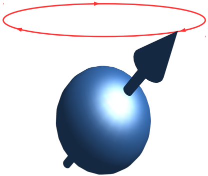

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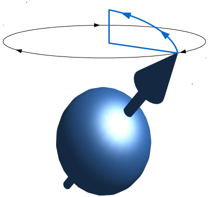


Experiment concept: Requirements

- A source of **polarized baryons**
- **Electromagnetic field** intense enough to induce precession
- A **detector** to measure the polarization

Experiment concept: Requirements

Case of **short-lived charmed baryons**

Λ_c^+

- A source of **polarized baryons**

  Strong production in a **fixed target**

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

  Interatomic electric field
  in **bent crystals**

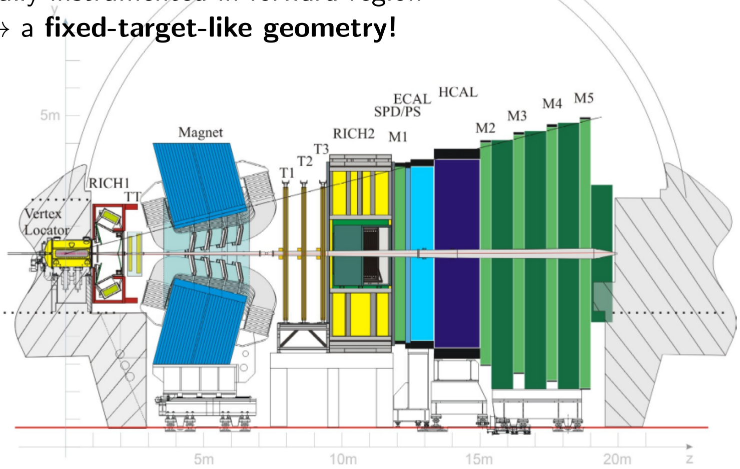
- A **detector** to measure the polarization

  Angular distribution of baryon decay
  products at **LHCb**

EPJ C77 (2017) 181

LHCb Detector

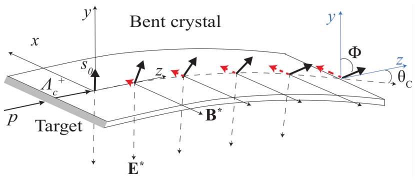
- Spectrometer for flavor physics
  Excellent particle identification. Closest tracking detectors to the LHC beam
- Fully instrumented in forward region
  $\rightarrow$ a **fixed-target-like geometry!**

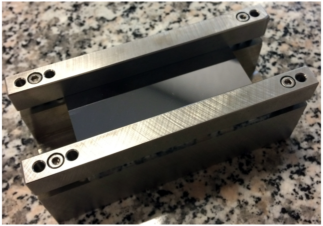


Channelling in Bent Crystals

- 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

$$\boldsymbol{s} \approx s_0 \left(\frac{d}{g-2}(\cos\Phi - 1),\ \cos\Phi,\ \sin\Phi \right) \ , \quad \Phi \approx \frac{g-2}{2}\gamma\theta_C \approx \pi$$

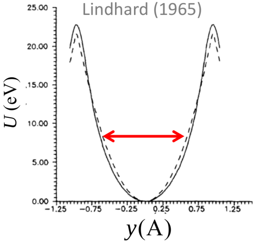


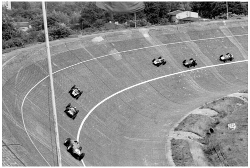


Courtesy of A.Mazzolari

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** (~ 5 m)

Proof of principle at E761

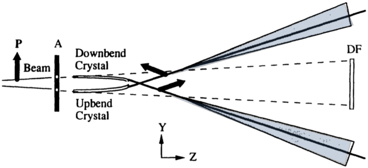
- E761 Fermilab experiment firstly observed spin precession in bent crystals and measured MDM of Σ^+

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



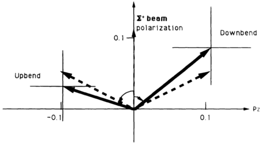
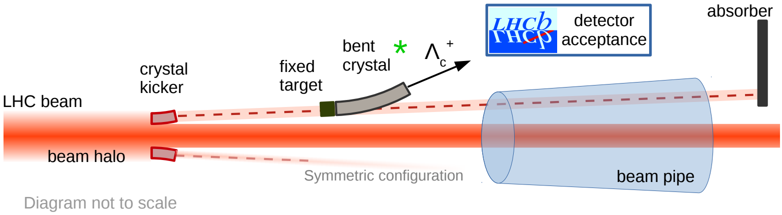


FIG. 3. Measured polarizations and uncertainties (1σ statistical errors) after spins have been precessed by the two crystals. The dashed arrows show the expected precessions.

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 $\approx$ 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 $\Lambda_c^+ \to pK^-\pi^+$

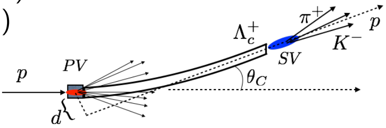
$$dN/d\Omega \propto 1 + \alpha \mathbf{s} \cdot \mathbf{k}$$

Phys. Lett. B 757 (2016) 426
CERN-SPSC-2016-030
Eur. Phys. J. C 77 (2017) 181
JHEP 1708 (2017)
Eur. Phys. J. C 77 (2017) 828

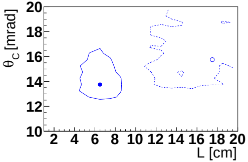
Crystal specifications

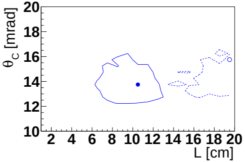
EPJ C77 (2017) 828

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



- Regions of maximum sensitivity (20 % increase)





Germanium (L=5cm, $\theta_C = 15$mrad) **Silicon** (L=7cm, $\theta_C = 14$mrad)

- Very **long crystals** needed ⇒ R&D ongoing at INFN Ferrara

Sensitivity

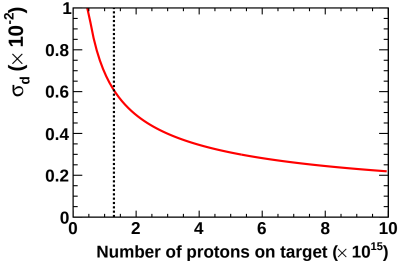
EPJ C77 (2017) 181

- The EDM uncertainty dominated by statistics,

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

$$\left[\begin{array}{l} \gamma = 1000 \text{ (E} \approx 2 \text{ TeV)} \\ L \approx 10 \text{ cm} \\ \theta_C \approx 10 \text{ mrad} \\ F = 10^8 \text{ p/s} \end{array} \right]$$

- $g-2$, 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

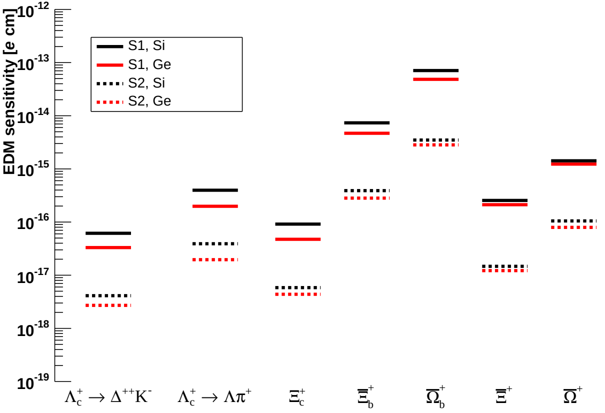


- With **few weeks** of data taking ($\approx 10^{15}$ protons on target) the **EDM** sensitivity would reach $\sigma_\delta \approx \mathbf{10^{-17} ecm}$

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

Extension to other baryons

- The same technique applies to all positive baryons with $\tau \gtrsim 10^{-13}s$ $\rightarrow$ rich physics program ahead!



S1: Configuration at the LHCb
S2: Dedicated experiment at the LHC

Material of the crystal:
$\rightarrow$ **Silicon**
$\rightarrow$ **Germanium**

Feasibility of a dedicated experiment (S2) explored in EPJ C77 (2017) 828

Conclusions

- Direct spin precession on **charm baryons**
- **First EDM search**, at $\approx 10^{-17}$ecm
  First measurement of magnetic moment, at 1% accuracy level
  - Fixed target and bent crystals in front of LHCb
- Can be extended to other positively-charged baryons such as Ω^+, Ξ^+, $\Xi_b{}^+$, ... extending the physics program. EPJ C77 (2017) 828
- 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

LHCb | CERN Physics Beyond Colliders

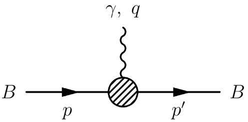
- The proposed experiment will greatly benefit from the **LHCb Upgrade**, planned for Run 3

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

Backup

Electromagnetic form factors

All electromagnetic properties parametrized in four EM form factors



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

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

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

EJP 26 (2005) 545

JHEP 12 at (2012) 097

Charm (chromo-)EDM bounds

Bound	Ref.	Measurement	Method
$\lvert d_c\rvert < 4.4 \times 10^{-17}$ $e$cm	Sala:2013osa	neutron EDM	Considers threshold contributions of d_c into d_d. Neglects all other contributions to the d_n.
$\lvert d_c\rvert < 3.4 \times 10^{-16}$ $e$cm	Sala:2013osa	BR$(B \to X_s\gamma)$	Considers contributions from d_c to the Wilson coefficient C_7.
$\lvert d_c\rvert < 3 \times 10^{-16}$ $e$cm	Grozin:2009jq	electron EDM	Extracted from d_c threshold contribution to d_e through light-by-light scattering diagrams.
$\lvert d_c\rvert < 1 \times 10^{-15}$ $e$cm	Grozin:2009jq	neutron EDM	Similar approach than ref. Sala:2013osa. Evaluates contributions in two steps: c-quark $\to$ d-quark $\to$ neutron.
$\lvert d_c\rvert < 5 \times 10^{-17}$ $e$cm	Blinov:2008mu	$e^+e^- \to c\bar{c}$	The total cross section (LEP) might be enhanced by the charm qEDM vertex $c\bar{c}\gamma$.
$\lvert d_c\rvert < 8.9 \times 10^{-17}$ $e$cm	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			
$\lvert\tilde{d}_c\rvert < 1.0 \times 10^{-22}$ $e$cm	Sala:2013osa	neutron EDM	Considers threshold contributions of d_c into the light quark EDMs $d_{u,d}$ and the Weinberg operator w
$\lvert\tilde{d}_c\rvert < 3 \times 10^{-14}$ $e$cm	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

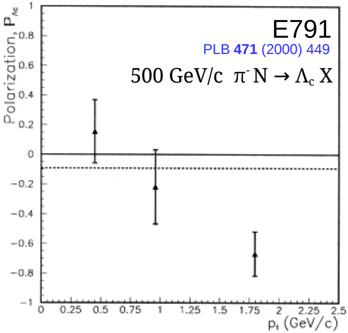
Bound	Ref.	Measurement	Method
$\vert d_b\vert < 7 \times 10^{-15}$ $e$cm	Grozin:2009jq	electron EDM	From the b-quark EDM threshold contribution to d_e through light-by-light scattering diagrams
$\vert d_b\vert < 2 \times 10^{-12}$ $e$cm	Grozin:2009jq	neutron EDM	Similar estimation but evaluating contributions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

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 ($\approx 50\%$)

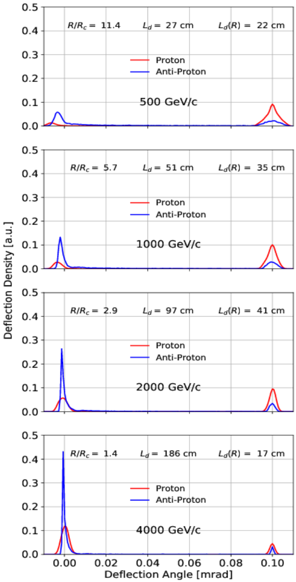
Channeling conditions. **Parametrization**

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):

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

Channeling conditions. **Full simulation**



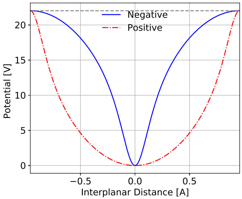
- Full simulations using GEANT4 toolkit performed in EPJ C77 (2017) 828
  - Including channeling phenomenon (deflection efficiency)
  - And **spin precession**
- Checked agreement with channeling parametrization

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

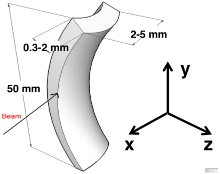
- Still, b-baryons are accesible
  - Ξ_b^- particle $\to$ lower efficiencies
  - Ξ_b^+ antiparticle $\to$ lower production rate

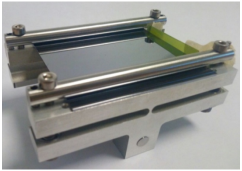


EPJ C77 (2017) 828

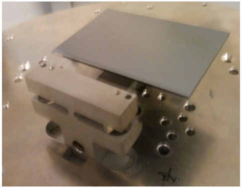
Crystal production

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





  - Self-bent crystal



A. Mazzolari, Channeling 2016