DIPOLE-b: direct measurement of dipole moments of short-lived particles at the LHC(b)

European Research Council
Established by the European Commission

Istituto Nazionale di Fisica Nucleare
Sezione di Milano

Website: https://web.infn.it/SELDOM/

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40th International Conference on High Energy Physics
Virtual Conference, July 28th - August 6th, 2020

MDM and EDM in Particle Physics

Fundamental particles have non-zero **magnetic dipole moments** (**MDM**), e.g. the electron, $\mu_e = -g_S \mu_B \frac{S}{\hbar}$ with the g-factor $g_s \approx 2$: excellent agreement between precision data and state-of-the-art QED predictions

Composite particles, such as hadrons, have MDM stemming from their constituents, e.g.

proton	2.793
neutron	-1.913

in units of $\mu_N = \frac{e\hbar}{2m_p}$

in qualitative agreement with a simple constituent quark model, but today more advanced QCD calculations are available

No experimental evidence of **electric dipole moment** (**EDM**) of any fundamental particles

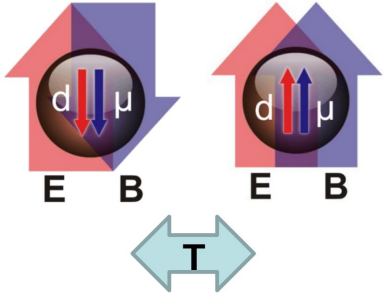
Limited experimental data for MDM/EDM of **unstable particles**, such as τ, Λ^0, Λ^0_c

BSM Physics with EDM

Permanent **EDM** → P, T and CP violation (assuming CPT)

Standard Model CP violation → very tiny EDM (e.g. for quarks < 10^{-31} e cm)

Observation of **EDM** in fundamental particles is a direct evidence of **Beyond Standard Model** (**BSM**) physics



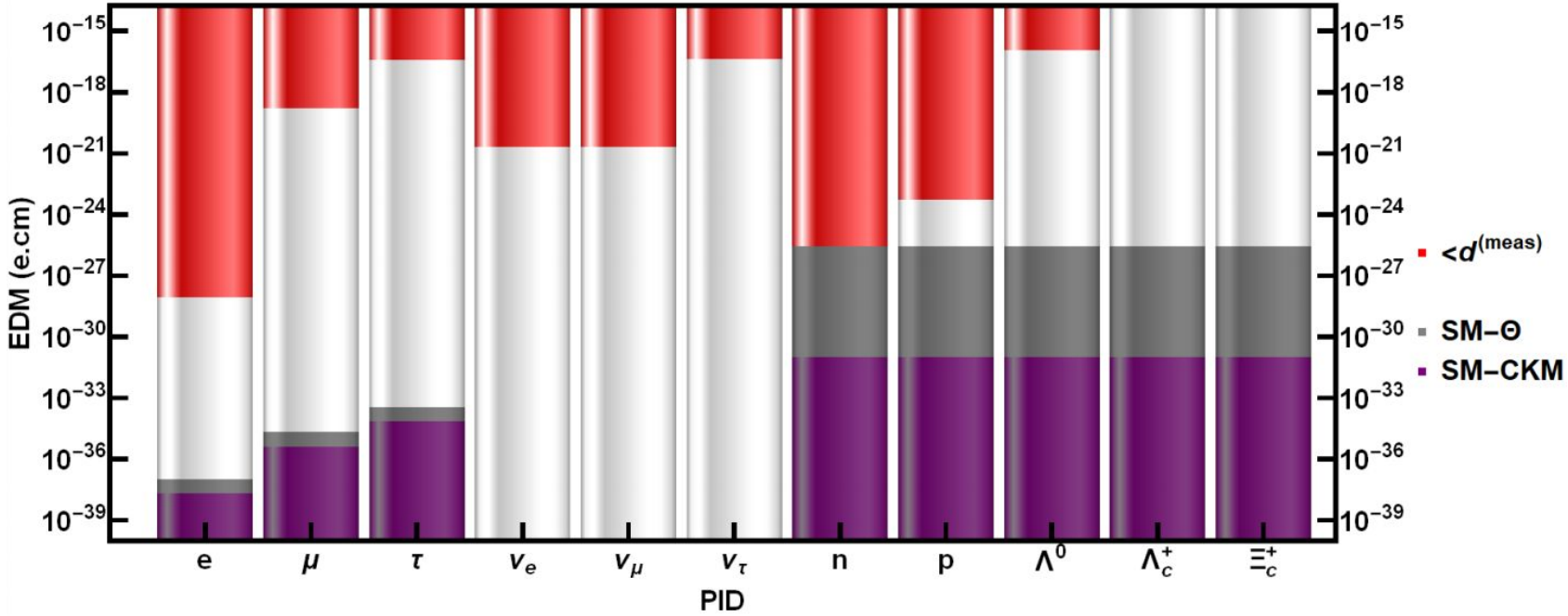
$$H_{\mathrm{M}} = -\frac{g}{2}\mu_{\mathrm{B}}\vec{\sigma}\cdot\vec{B} \qquad H_{\mathrm{E}} = -\frac{d}{2}\mu_{\mathrm{B}}\vec{\sigma}\cdot\vec{E}$$

$$\vec{\sigma} \xrightarrow{T} -\vec{\sigma}$$

$$\vec{B} \xrightarrow{T} -\vec{B} \qquad \vec{E} \xrightarrow{T} \vec{E}$$

Current EDM limits

CERN-PBC-REPORT-2018-007



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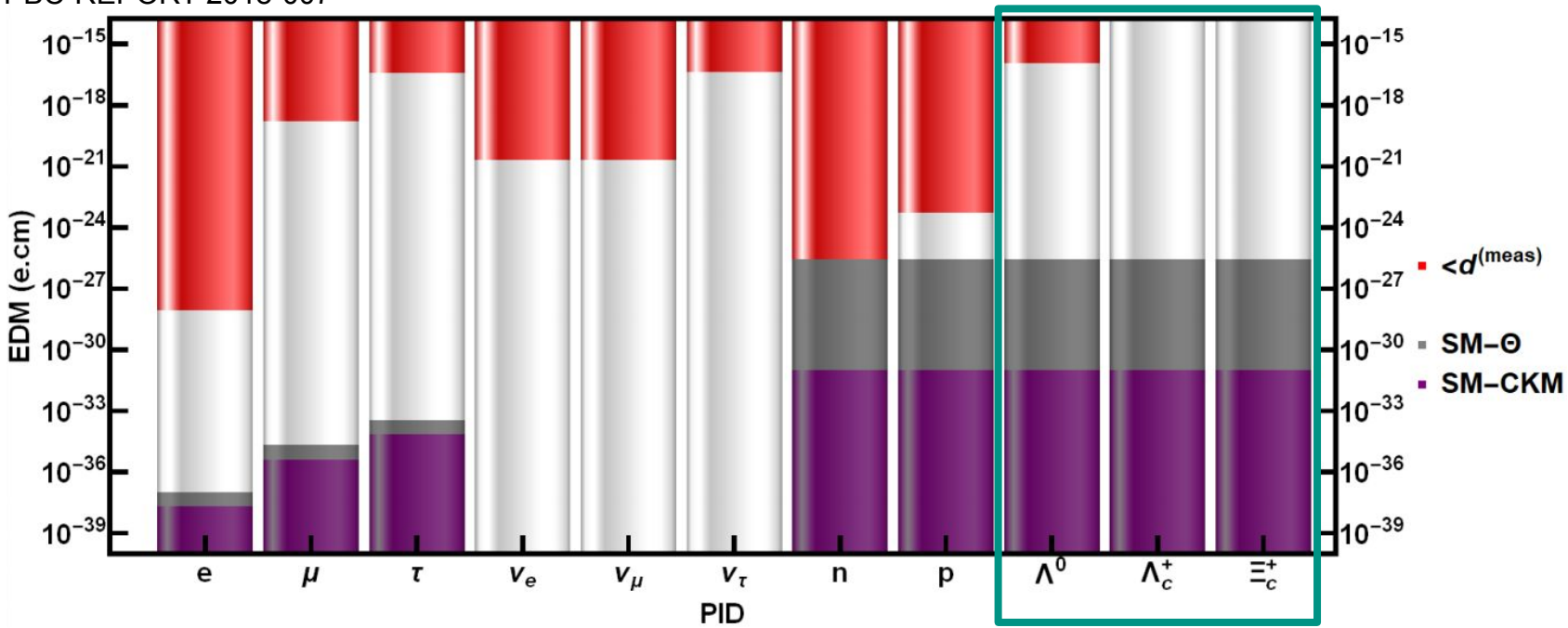


How to measure particle EDM / MDM?

- Particle EDM/MDM measured by **precession** in a strong EM field
- **Polarization required at production**
- Initial and final polarizations measured via the **angular distributions of the decay products**
- Unstable particles must travel in the EM field **long enough** to gain sufficient precession *before decay*

Λ^0

1. Production in **weak decays** of heavy baryons
2. **Longitudinal polarization** from parity violation of the weak decay
3. Precession in the **LHCb dipole magnet**
4. Reconstruction of the $\Lambda^0 \to p\pi^-$ decay in the tracking stations downstream of the magnet

Λ_c^+, Ξ_c^+

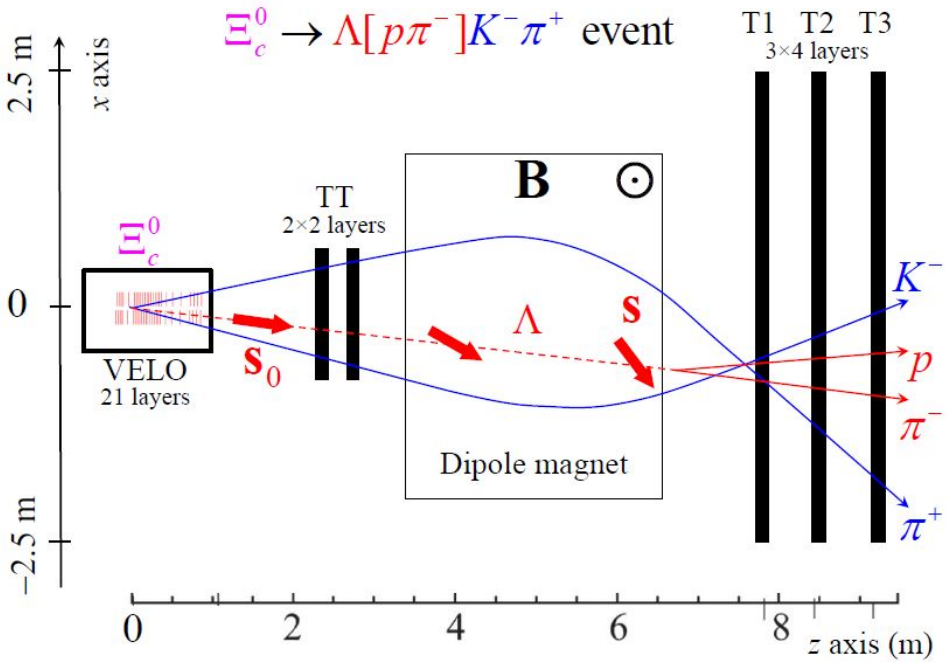
short lifetimes
$\sim 10^{-12} - 10^{-13}$ s

1. Prompt production in **fixed-target p-W** collisions
2. **Transverse polarization** (parity conserved in strong interactions)
3. Precession through **channeling** in a **bent crystal**
4. Reconstruction of the $\Lambda_c^+ \to pK^-\pi^+$ decay in LHCb

MDM/EDM of strange baryons

Measurement technique

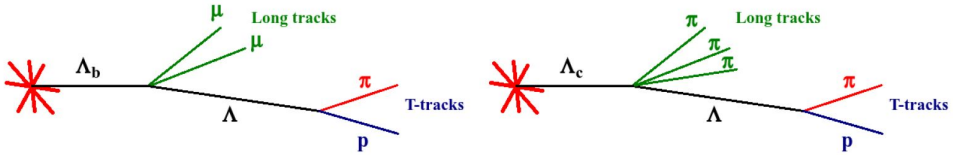
- Λ^0 from a heavy baryon decay, e.g. $\Xi_c^0 \rightarrow \Lambda^0 [\rightarrow p\pi^-] K^- \pi^+$
- Λ^0 is **polarized** longitudinally due to parity violation in weak decays
- $K^- \pi^+$ displaced vertex reconstructed with long tracks
- Λ^0 **precession** in the LHCb dipole magnet and decays between magnet and T stations
- $\Lambda^0 \rightarrow p\pi^-$ vertex reconstructed using T tracks
- **Challenge: limited momentum resolution of T tracks**



Current status

- Reconstruction of p and π^- momenta based on the presence of **leak magnetic field**
- Poor momentum resolution ~ 20% can be improved using **constraints from decay kinematics**
- Benchmark study cases

$$\Lambda_b \to \Lambda J/\psi(\to \mu\mu) \qquad \Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$$



- **Proof of principle** using **LHC Run-2** (2016-2018) data
  - Promising progress so far, with Λ^0 mass resolution ~ 15-20 MeV/c^2
  - MVA to improve signal/background discrimination and resolution (BDT, ANN)
  - Main source of background from secondary interactions
- Prepare **trigger strategy and reconstruction chain** for **LHC Run-3** (2021+)
  - LHCb will take data with a fully software-based trigger
  - Full online event reconstruction and filtering

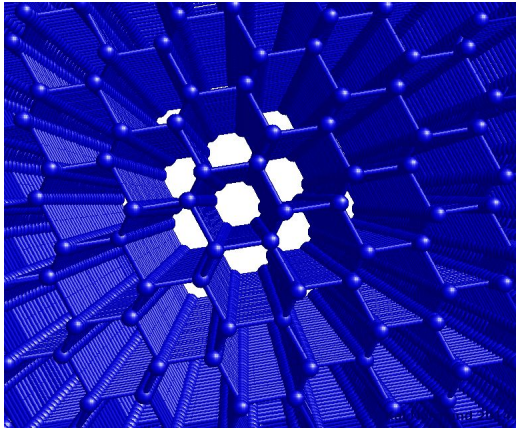
MDM/EDM of charm baryons

Particle channeling in bent crystals

Channeling: constraining the trajectory of (positively) charged particles in the planes or axis of a crystalline solid

Condition for channeling: $\theta_{in} < \theta_L = \sqrt{\frac{2U_0}{p\beta c}}$

U_0 = crystal potential well depth



Channeling through a mechanically **bent crystal** can be used to guide a particle in a **curved trajectory**

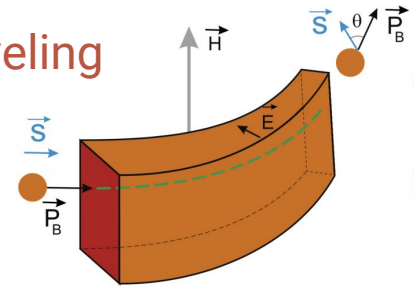
Channeling efficiency **above 80%** obtained with silicon crystals for particles with energies of 100s GeV [Phys. Rev. Lett. 101 (2008) 234801]

Channeling of 6.5 TeV protons observed at the LHC [PLB 758 (2016) 129]

Precession in a bent crystal

Spin precession of polarized particles traveling through a bent crystal theorized in 1979

[V.G. Baryshevsky, Pis'ma Zh. Tekh. Fiz. 5 (1979) 182]



It was later proposed as a technique to **measure the MDM of unstable particles**

[I.J. Kim, Nucl. Phys. B 229 (1983) 251]

In 1992 the **MDM of the Σ^+ baryon** was measured by the E761 experiment at Fermilab using a bent crystal

[D. Chen et al., Phys. Rev. Lett. 69 (1992) 3286]

E761

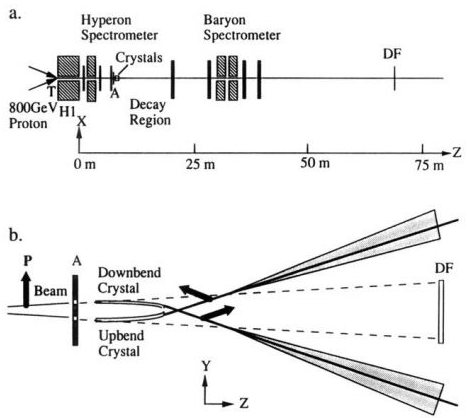
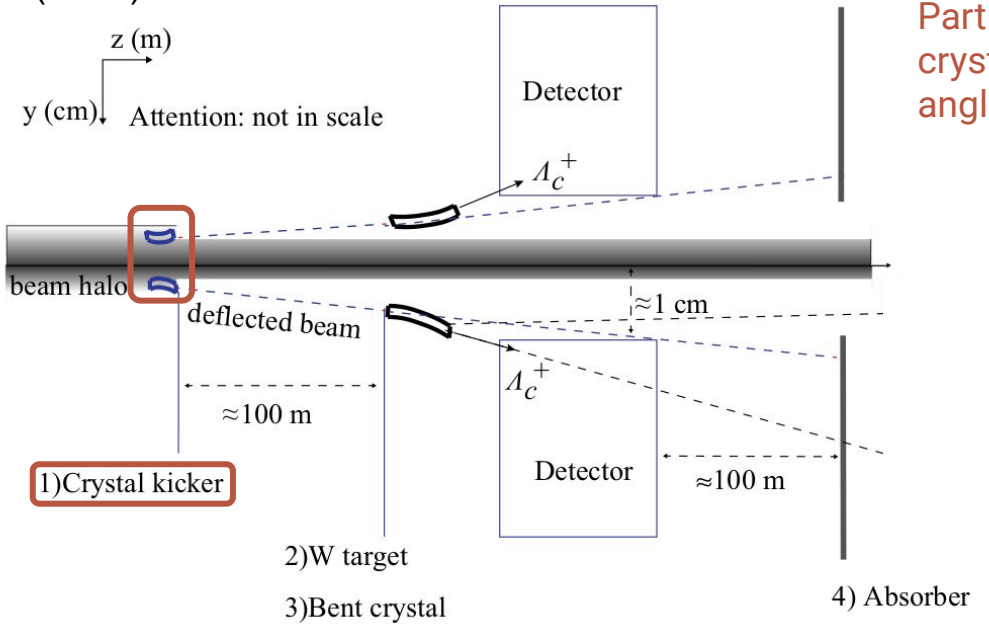


FIG. 1. (a) Plan view of the incident proton beam and spectrometer system. The horizontal scale (z) correctly illustrates the length of the apparatus, the vertical scale (x) is schematic only. (b) Elevation view of the channeling apparatus (not to scale). The arrows illustrate the spin precession in the crystals. Shaded areas depict the Σ^+ decay cone. The scintillation counters A and DF are part of the trigger and are described in the text.

DIPOLE-b experiment design

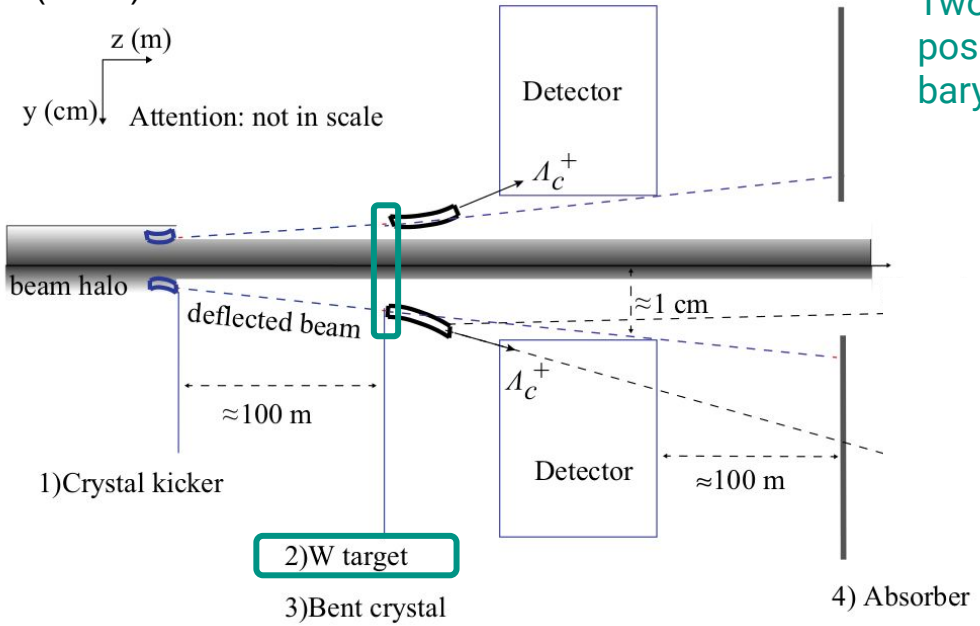
EPJC (2017) 77:828



Part of the **LHC beam halo** is **deflected** by two bent crystals (upbend and downbend) with deflection angle ~ 100 μrad

DIPOLE-b experiment design

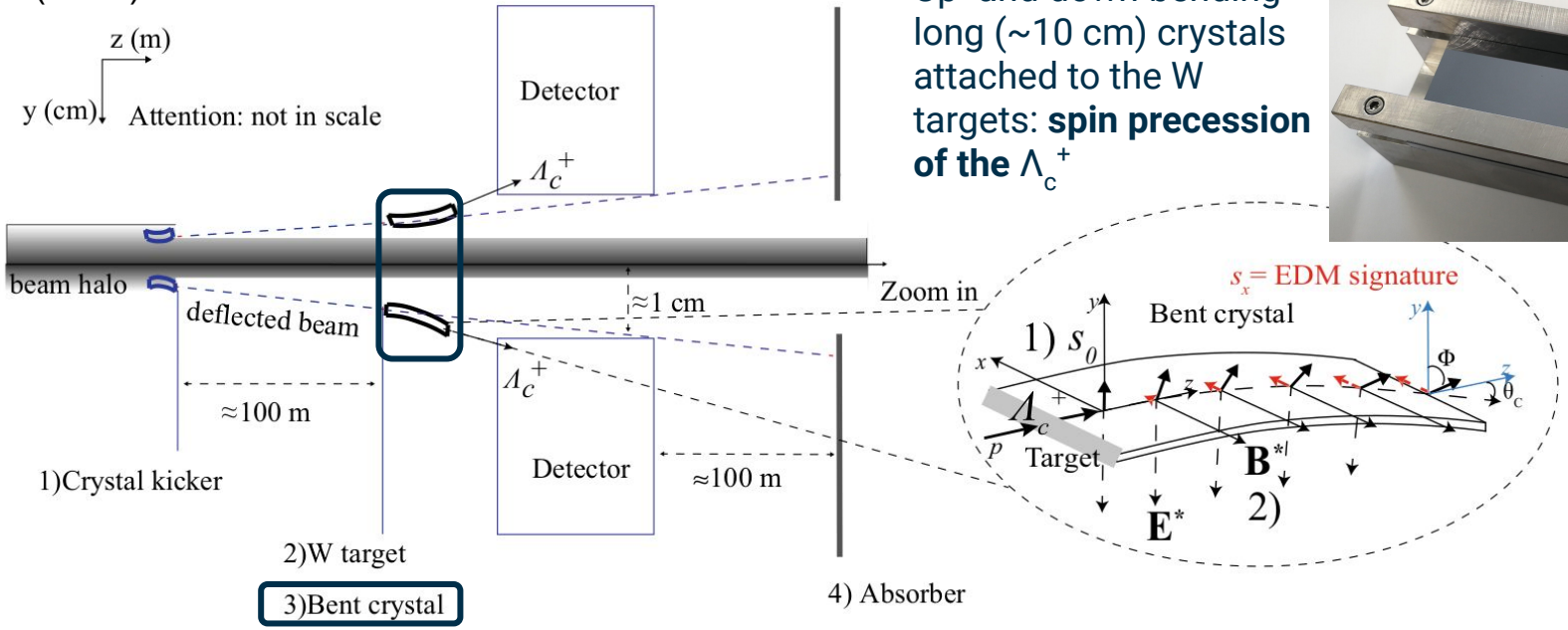
EPJC (2017) 77:828



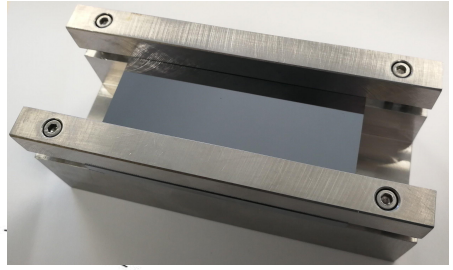
Two **tungsten targets** with thickness ~ 5 mm, positioned just in front of the LHCb VELO; Λ_c^+ baryons are produced in pW collisions

DIPOLE-b experiment design

EPJC (2017) 77:828

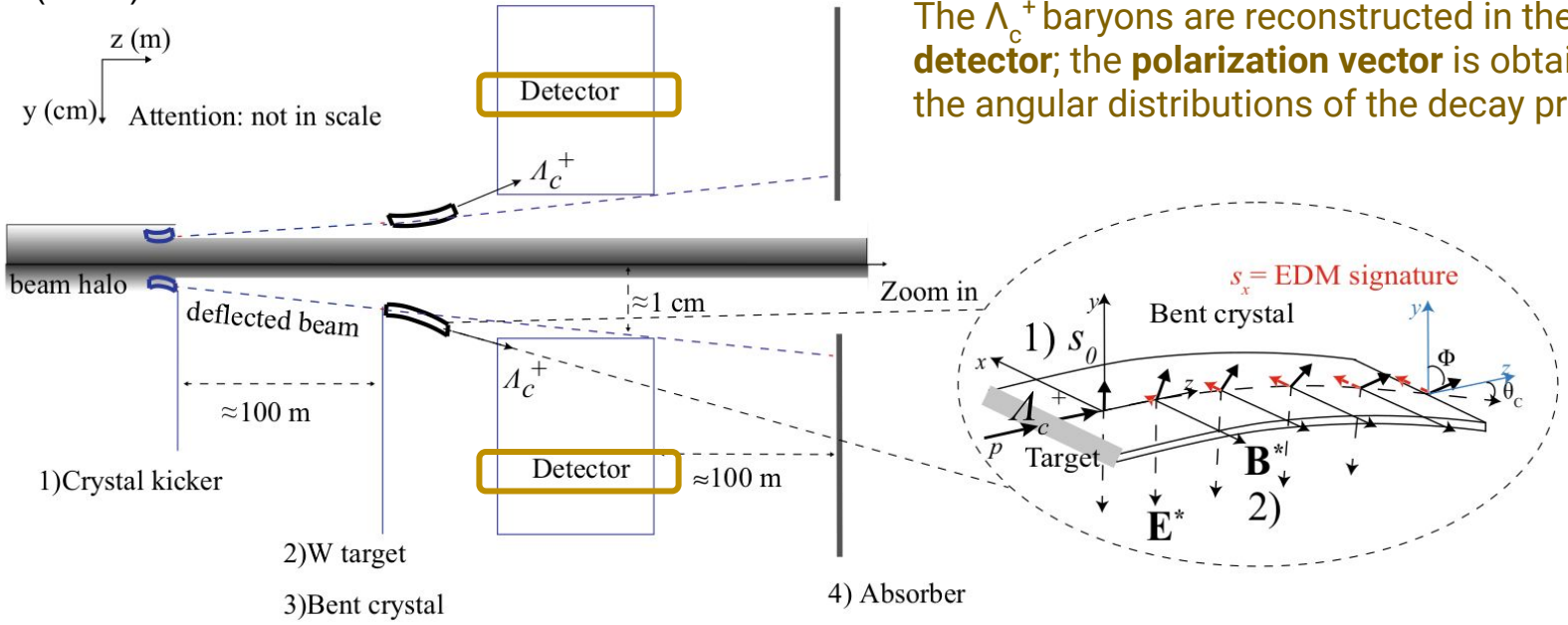


Up- and down-bending long (~10 cm) crystals attached to the W targets: **spin precession of the Λ_c^+**



DIPOLE-b experiment design

EPJC (2017) 77:828

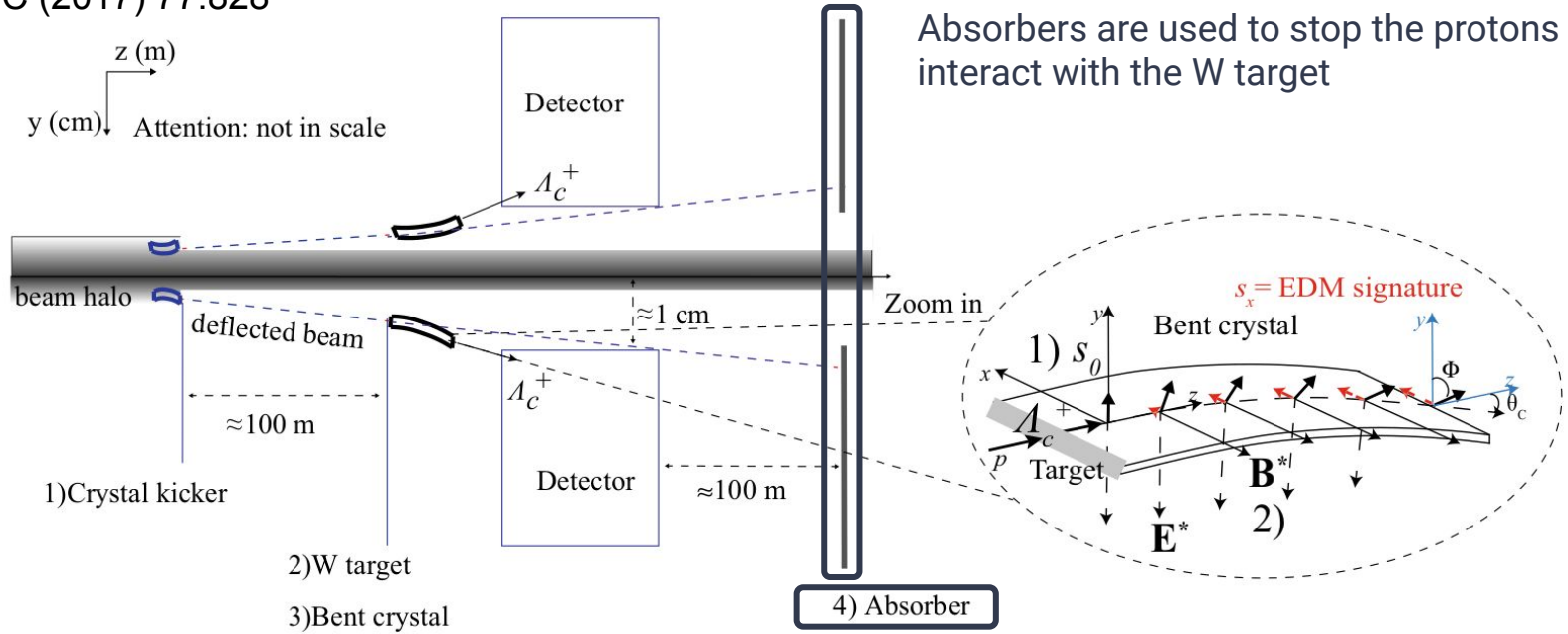


The Λ_c^+ baryons are reconstructed in the **LHCb detector**; the **polarization vector** is obtained from the angular distributions of the decay products

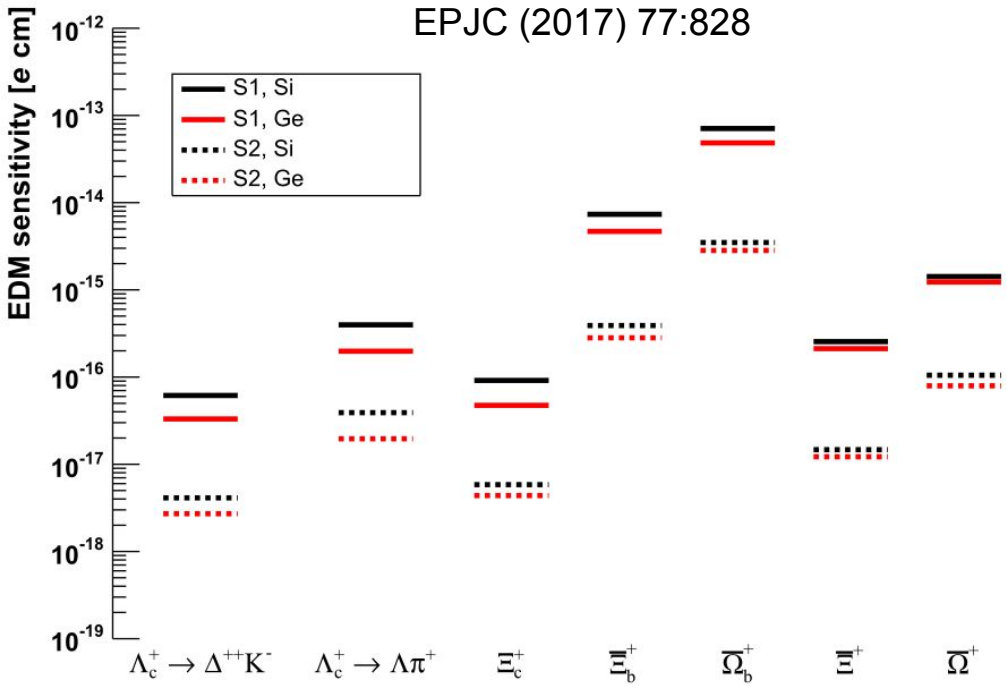
DIPOLE-b experiment design

EPJC (2017) 77:828

Absorbers are used to stop the protons that did not interact with the W target



Projected limits on EDM



S1 configuration: “parasitic” operation in LHCb using 10^{15} PoT

S2 configuration: dedicated experiment using 10^{17} PoT

PoT = protons on target
W target 5 mm thick

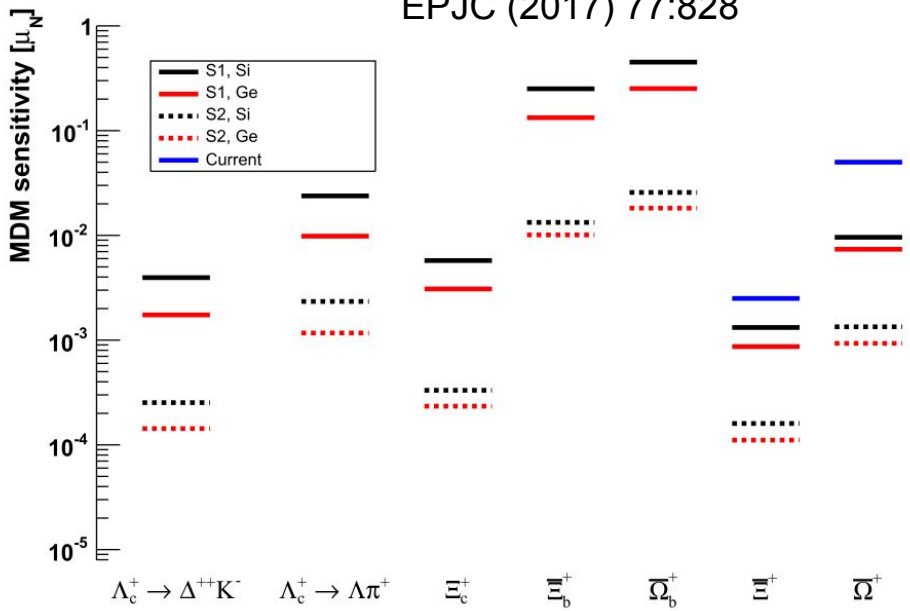
Material of the crystal

- **Silicon**
- **Germanium**

Measurements are **statistically** limited

Projected limits on MDM

EPJC (2017) 77:828



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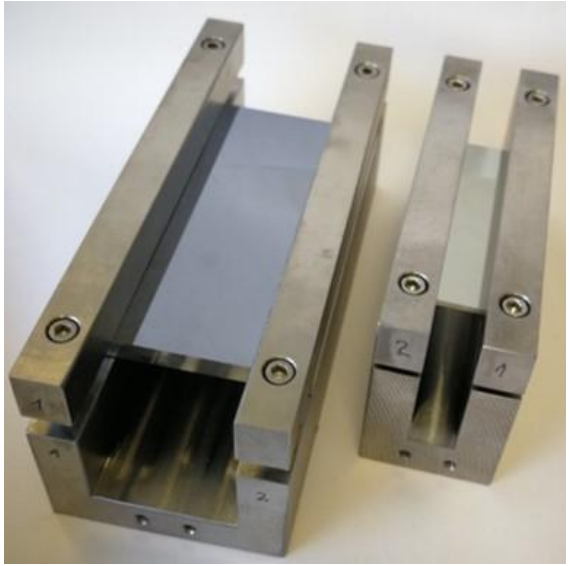
First ever measurement of Λ_c^+ MDM: QCD precision test

R&D on long bent crystals

INFN Ferrara



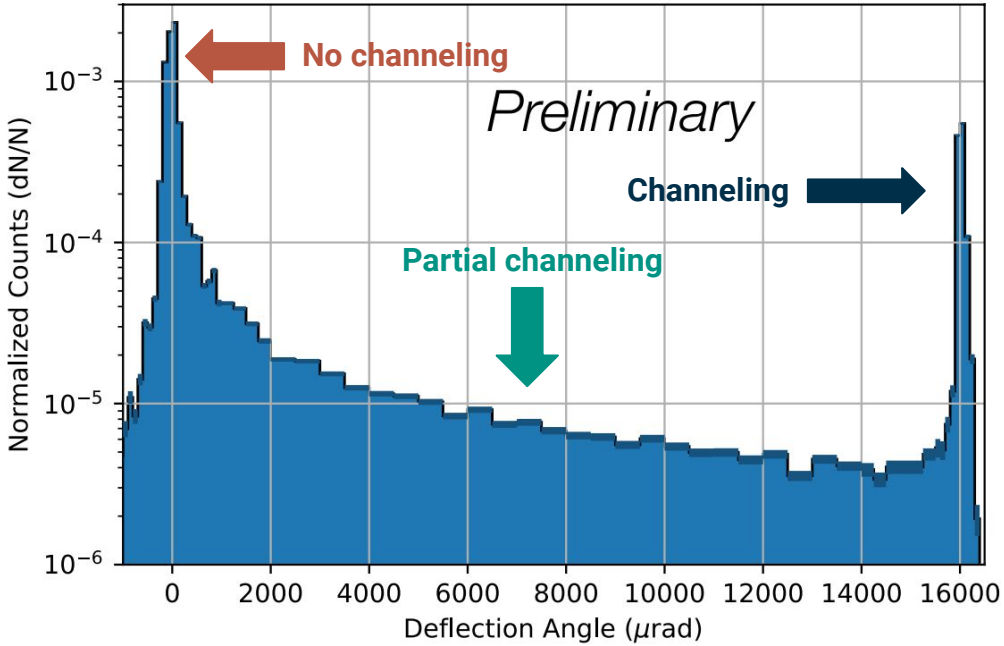
Si Ge

Two crystals were tested

Crystal	Silicon	Germanium
Deflection angle	16 mrad	14.5 mrad
Length	8 cm	5 cm
Critical angle	14.5 μrad	18.2 μrad

Critical angle = maximum incoming angle relative to the crystallographic planes that allow for channeling

Long bent crystals: preliminary results



180 GeV/c protons from CERN SPS impinging on a silicon crystal

Silicon and germanium long bent crystals developed at INFN Ferrara

Good channeling efficiency >10%

Summary

- **MDM/EDM** of unstable particles **extends the LHC physics program**
- **Unique program** of measurements at LHC using the LHCb detector

Milestones achieved

Λ^0

- reconstruction of decays beyond the magnetic region
- MVA to discriminate signal/background
- study of the background sources

Λ_c^+, Ξ_c^+

- long bent crystal prototypes
- preparatory studies in LHCb
- machine layout

Next steps

- study the helicity measurement resolution
- define and propose trigger strategy(ies) for Run-3

- Technical Design Report

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Contributions from: S. Aiola, G. Arduini, E. Bagli, L. Bandiera, S. Barsuk, O.A. Bezshyyko, L. Burmistrov, G. Cavoto, D. De Salvador, A.S. Fomin, S.P. Fomin, J.Fu, F. Galluccio, M. Garattini, M.A. Giorgi, V. Guidi, A.Yu. Korchin, I.V. Kirillin, L. Henry, Y. Ivanov, L. Massacrier, D. Marangotto, F. Martinez Vidal, V. Mascagna, J. Mazorra, A. Mazzolari, A. Merli, D. Mirarchi, S. Montesano, A. Natochii, E. Niel, M. Prest, S. Redaelli, P. Robbe, J. Ruiz Vidal, W. Scandale, N.F. Shul'ga, A. Stocchi, E. Vallazza

LHCb **FITPAN** review members: T. Eric, M. Ferro-Luzzi, G. Giacomo, R. Kurt, R. Lindner, C. Parkes, G. Passaleva, M. Pepe-Altarelli, V. Vagnoni, G. Wilkinson

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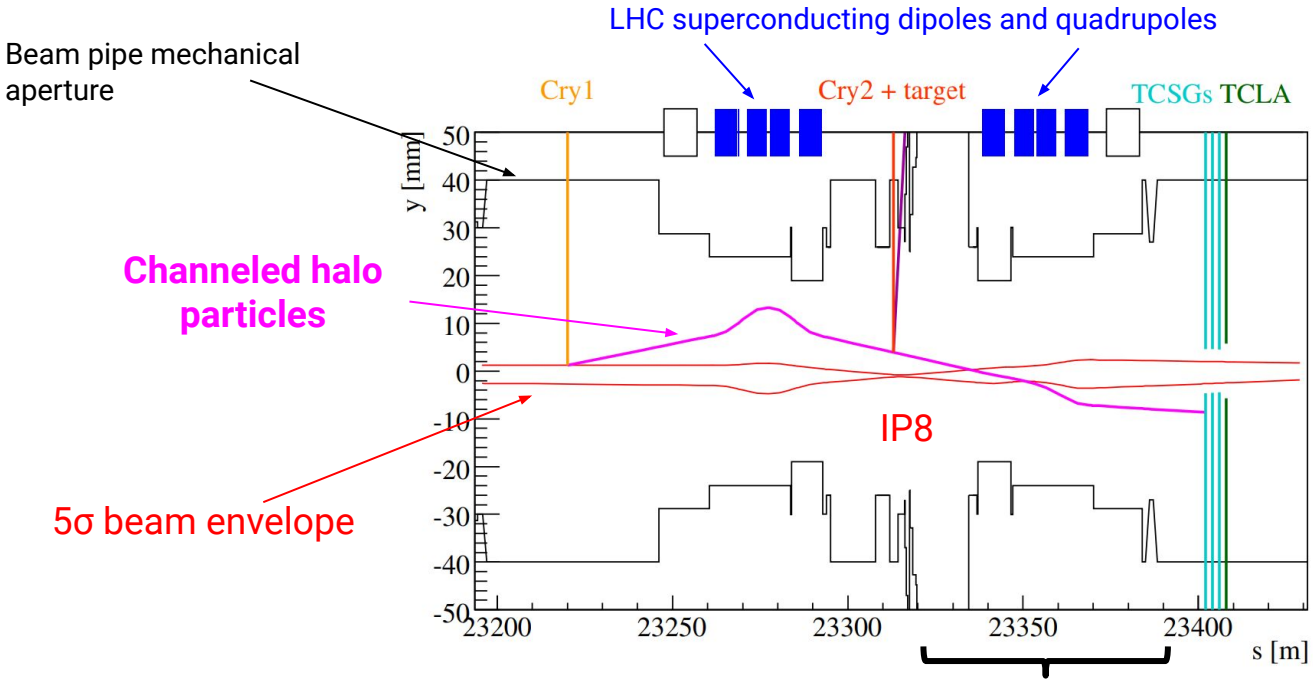
Backup

LHC machine studies

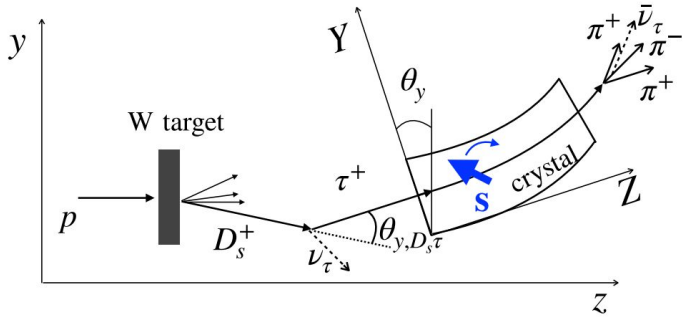


Feasible configuration for a target close to LHCb:
10^6-10^7 protons/sec

Studies for a potential **dedicated experiment** at the LHC, e.g. at IR3

D. Mirarchi, A. S. Fomin, S. Redaelli, W. Scandale
arXiv:1906.08551

Future prospects: τ MDM/EDM measurement

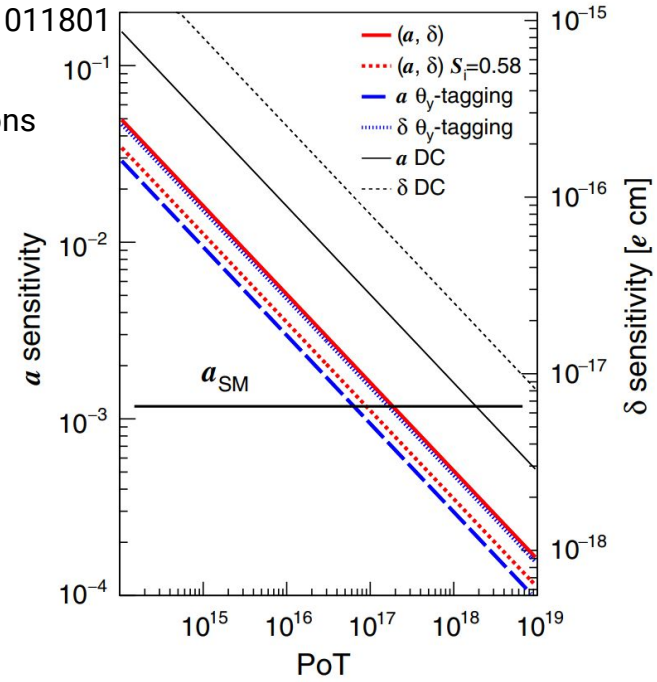


Fu, et al, PRL 123 (2019) 011801

Standard Model predictions

$$a = \frac{g-2}{2} \approx 10^{-3}$$

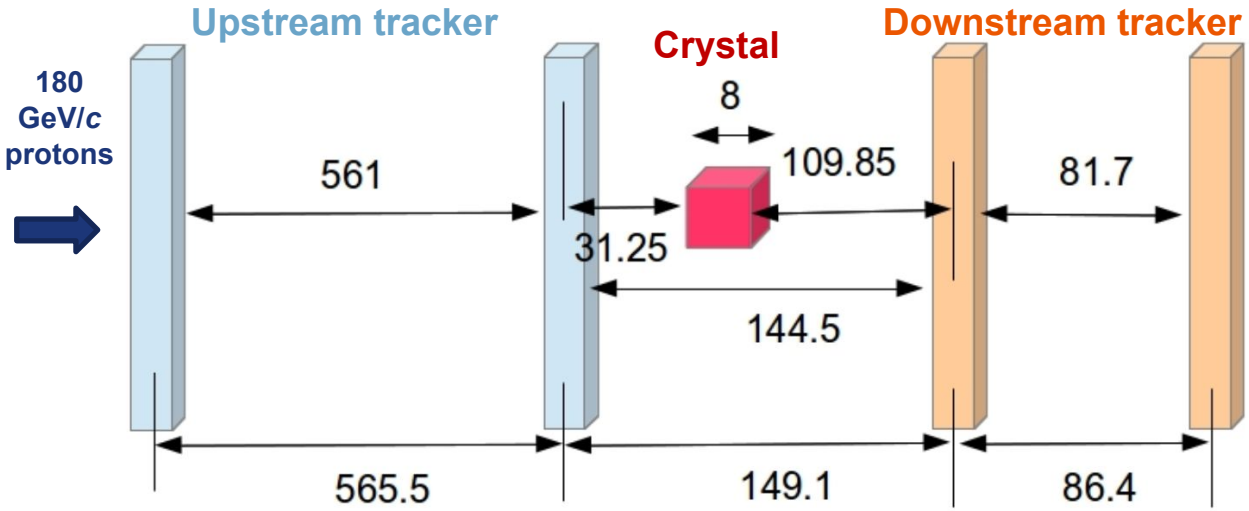
$$\delta < 10^{-44}\ e\,\mathrm{cm}$$



- Requires a future dedicated experiment to collect sufficient statistics
- Possible “proof of principle” in LHCb

See also: Fomin, et al JHEP (2019) 2019: 156.

Long bent crystals: test beam at SPS (Oct 2018)



Tracker: INFN Como
Crystals: INFN Ferrara

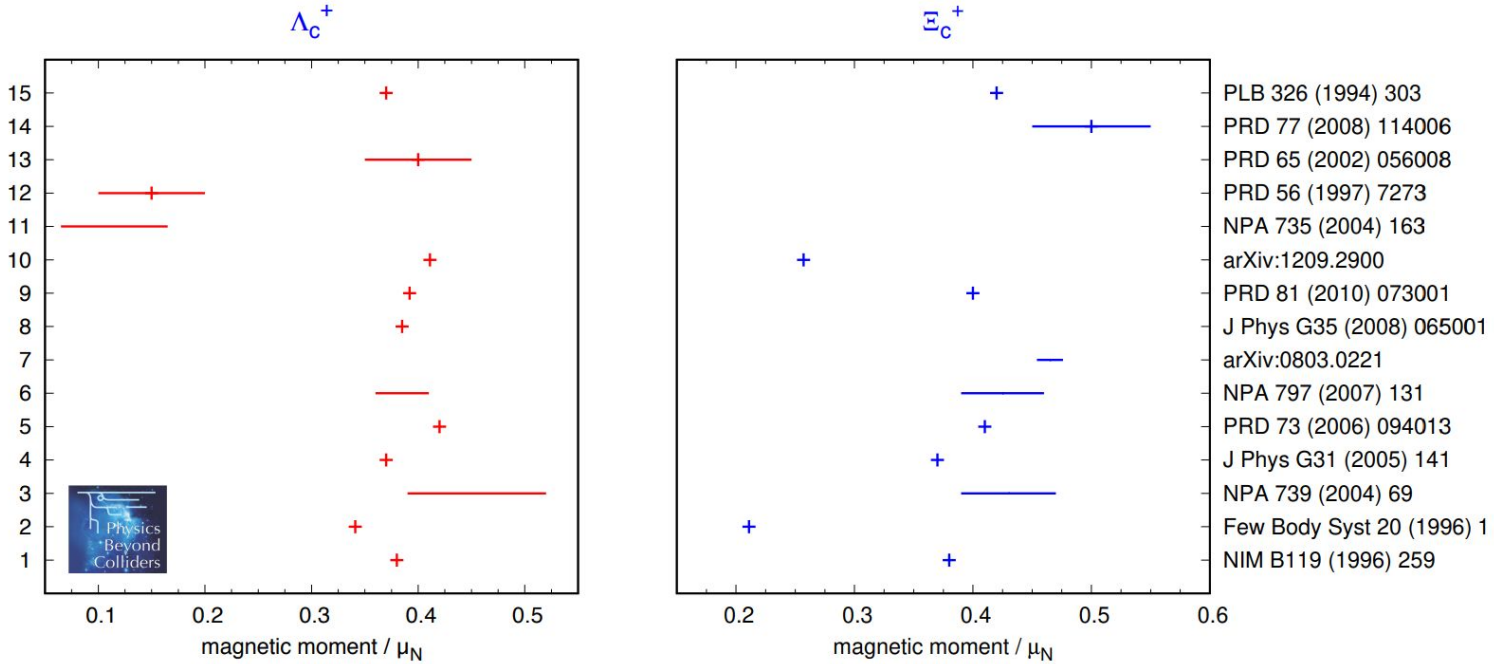
Upstream tracker:

- Double-sided silicon strip detectors, 25 μm pitch
- Resolution of the incoming particle direction ~6.5 μrad
- Resolution largely limited by **multiple scattering** in air

Downstream tracker:

- Two pairs of single-sided silicon strip detectors, 121 μm pitch
- Resolution of the outgoing particle direction ~70 μrad

Heavy baryon MDM



Many **theoretical calculations** based on QCD but **no measurement** of heavy baryon MDM!

Λ_c^+ polarization and cross section measurement

- **Amplitude analysis** of $\Lambda_c^+ \to pK^-\pi^+$ in pp collisions
- Study polarization of Λ_c^+ in fixed-target **SMOG data** (p-Ne) using the amplitude model developed for pp collisions

Resonance	J^P	BW mass (MeV)	BW width (MeV)	Existence
$\Lambda^*(1405)$	$1/2^-$	1405.1	50.5	certain
$\Lambda^*(1520)$	$3/2^-$	1515 – 1523	10 – 20	certain
$\Lambda^*(1600)$	$1/2^+$	1550 – 1700	50 – 300	very likely
$\Lambda^*(1670)$	$1/2^-$	1670	25 – 50	certain
$\Lambda^*(1690)$	$3/2^-$	1690	60	certain
$\Lambda^*(1800)$	$1/2^-$	1720 – 1850	200 – 400	very likely
$\Lambda^*(1810)$	$1/2^+$	1750 – 1850	50 – 250	very likely
$\Lambda^*(1820)$	$5/2^+$	1820	80	certain
$\Lambda^*(1830)$	$5/2^-$	1820	60 – 110	certain
$\Lambda^*(1890)$	$3/2^+$	1850 – 1910	80 – 200	certain
$\Lambda^*(2000)$	$1/2^-$	1900 – 2100	20 – 400	poor
$\Lambda^*(2020)$	$7/2^+$	1900 – 2100	20 – 400	poor
$\Delta^{++*}(1232)$	$3/2^+$	1232	120	certain
$K^*(892)$	1^-	891.76	47.3	certain
$K^*(1410)$	1^-	1421	236	certain
$K_0^*(1430)$	0^+	1375 – 1475	190 – 350	certain

Analysis on-going
D. Maranagotto (Università di Milano & INFN)
L. Henry (Università di Milano & INFN, IFIC Valencia)

References

- *On the search for the electric dipole moment of strange and charm baryons at LHC*, F. J. Botella et al, Eur.Phys.J. C77 (2017) 181
- *Electromagnetic dipole moments of charged baryons with bent crystals at the LHC*, E. Bagli et al, Eur.Phys.J. C77 (2017) 828
- *Feasibility of measuring the magnetic dipole moments of the charm baryons at the LHC using bent crystals,* A.S. Fomin , et al, JHEP 1708 (2017) 120
- *The possibility to measure the magnetic moments of short-lived particles (charm and beauty baryons) at LHC and FCC energies using the phenomenon of spin rotation in crystals*, V. G. Baryshevsky, Phys. Lett. B757 (2016) 426
- *Measurement of short living baryon magnetic moment using bent crystals at SPS and LHC*, L. Burmistrov, et al, CERN-SPSC-2016-030
- *Novel method for the direct measurement of the τ lepton dipole moments*, J. Fu, et al, Phys. Rev. Lett. 123 (2019) 011801
- *Feasibility of τ lepton electromagnetic dipole moments measurements using bent crystals at LHC*, A.S. Fomin , et al, JHEP 03 (2019) 156
- Layouts for fixed-target experiments and dipole moment measurements of short-living baryons using bent crystals at the LHC, D. Mirarchi, et al, arxiv:1906.08551

CERN reports

- *Physics Beyond Colliders: QCD Working Group Report*, A. Dainese et al, CERN-PBC-REPORT-2018-008 (p. 22-25)
- *Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report*, J. Beacham et al, CERN-PBC-REPORT-2018-007 (p. 62-65)
- *Physics case for an LHCb Upgrade II – Opportunities in flavour physics and beyond in the HL-LHC era*, LHCb Collaboration (R. Aaij et al), CERN-LHCC-2018-027 (p. 123-125)

The SELDOM Project

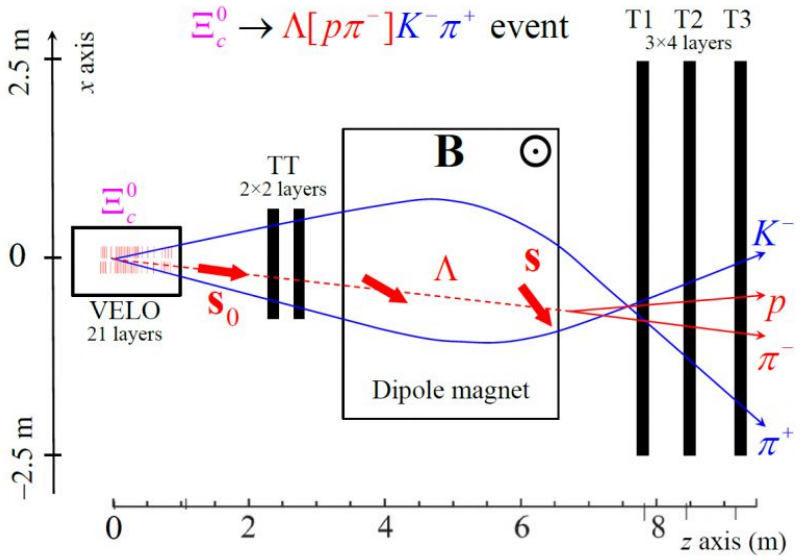
ERC Consolidator Grant

- Principal Investigator: **Nicola Neri** (Università di Milano and INFN)
- Host Institutes: INFN Milano, Università di Milano, INFN Ferrara
- ERC start date: April 2018
- ERC duration: 5 years
- Funding: 1,933,750 €
- Website: https://web.infn.it/SELDOM/
- Twitter: @SeldomTeam

European Research Council
Established by the European Commission

Λ MDM/EDM measurement

- **Λ** from heavy baryon decay, e.g. $\Xi_c^0 \rightarrow \Lambda^0 K^- \pi^+$
- **Λ** is polarized longitudinally
- $K^-\pi^+$ displaced vertex reconstructed with long tracks
- **Λ** precession in the LHCb dipole magnet and decays between magnet and T stations
- $\Lambda^0 \rightarrow p\pi^-$ vertex reconstructed using T tracks
- Challenge: must trigger on displaced vertex of $\mathbf{K^-\pi^+}$ and $\mathbf{\Lambda \rightarrow p\pi^-}$ from T tracks (SciFi in Run3+)



F.J. Botella et al, Eur. Phys. J. C (2017) 77:181