EDM and MDM measurements of heavy baryons and τ leptons

Salvatore Aiola
INFN Sezione di Milano

European Research Council
Established by the European Commission

Istituto Nazionale di Fisica Nucleare
Sezione di Milano

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

Twitter: @SeldomTeam

Contributions from:
S. A., G. Arduini, E. Bagli, L. Bandiera, S. Barsuk, O.A. Bezshyyko, L. Burmistrov, G. Cavoto, D. De Salvador, L.S. Esposito, M. Ferro-Luzzi, 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, A. Mazzolari, A. Merli, D. Mirarchi, S. Montesano, A. Natochii, N. Neri, E. Niel, M. Prest, S. Redaelli, P. Robbe, M. Romagnoni, R. Rossi, J. Ruiz Vidal, W. Scandale, N.F. Shul'ga, A. Sytov, A. Stocchi, E. Vallazza

Physics Beyond Colliders Working Group Meeting
CERN, 5-6 November 2019

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

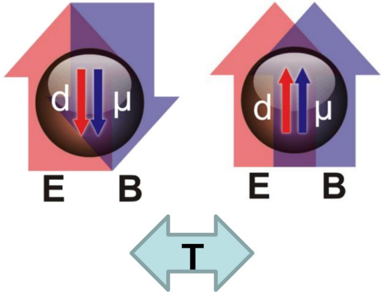
Limited experimental data for MDM/EDM of **unstable particles**, such as τ, Λ_c^+

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

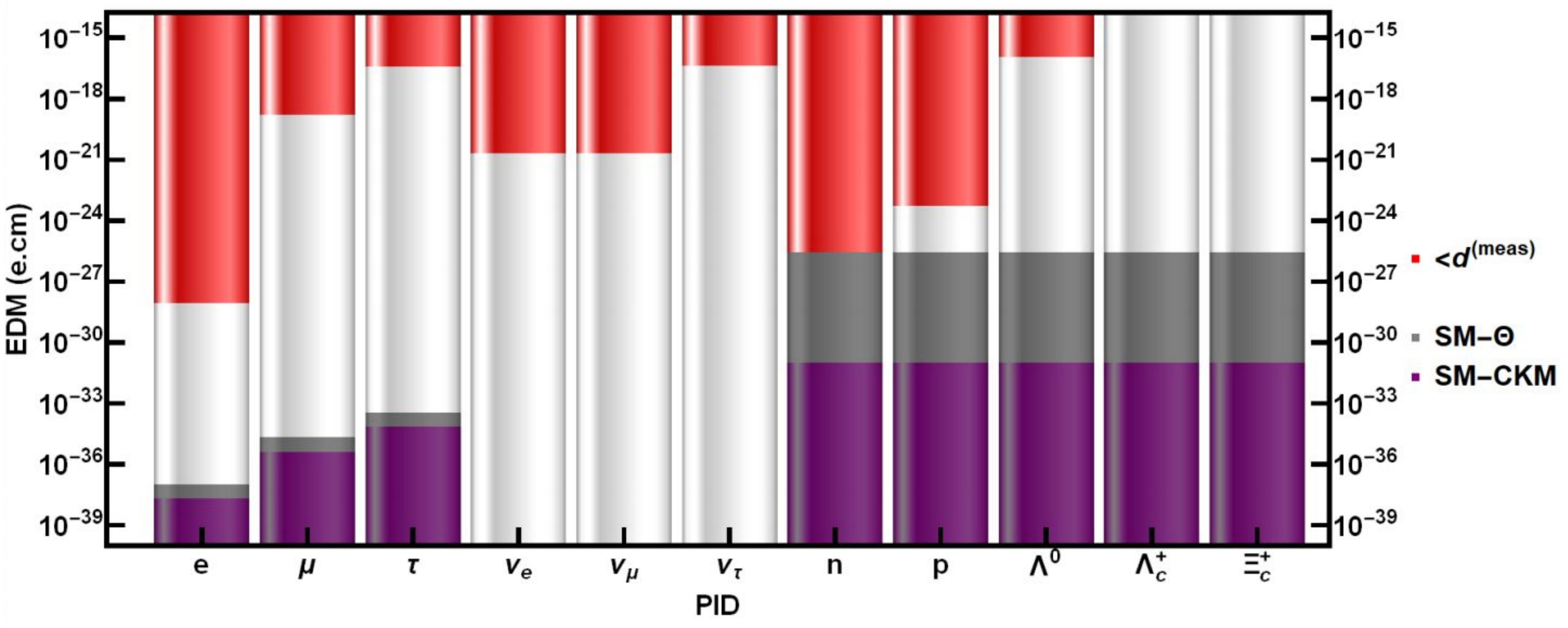


$$H_{\mathrm{M}} = -\frac{g}{2}\mu_{\mathrm{B}}\vec{\sigma}\cdot\vec{B} \qquad H_{\mathrm{E}} = -\frac{d}{2}\mu_{\mathrm{B}}\vec{\sigma}\cdot\vec{E}$$

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

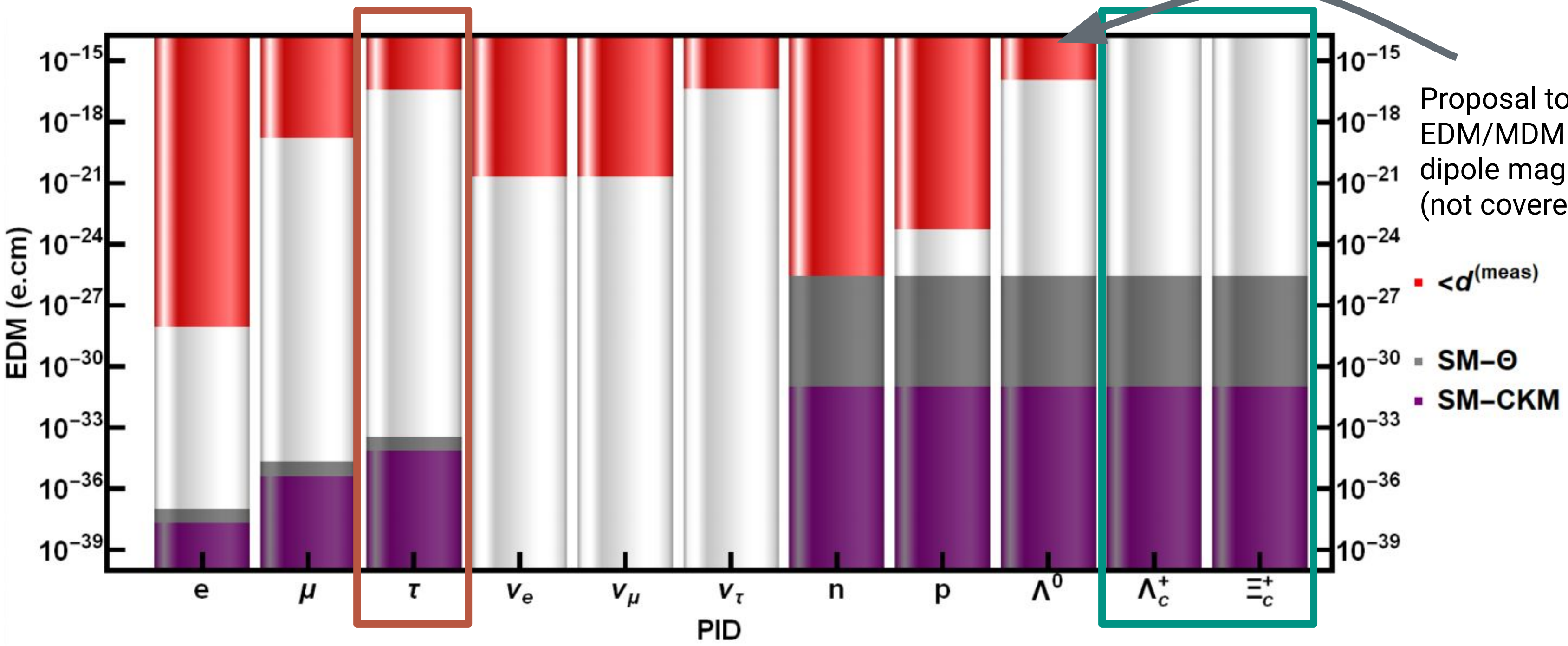
$$\vec{B} \xrightarrow{T} -\vec{B} \qquad \vec{E} \xrightarrow{T} \vec{E}$$

Current EDM limits



CERN-PBC-REPORT-2018-007 (BSM WG)

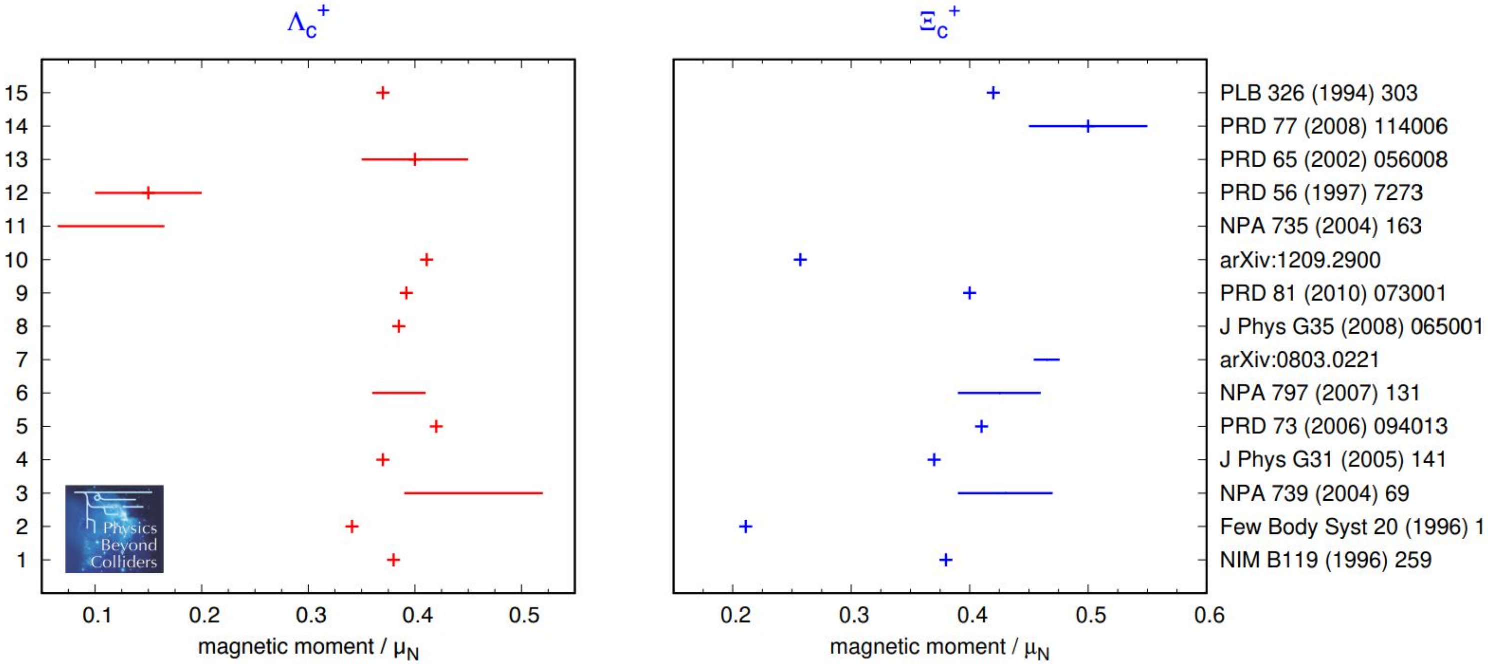
Current EDM limits



Proposal to probe Λ^0 EDM/MDM using LHCb dipole magnet
(not covered in this talk)

CERN-PBC-REPORT-2018-007 (BSM WG)

Heavy baryon MDM



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

CERN-PBC-REPORT-2018-008 (QCD WG)

Experiment concept: requirements

heavy baryons (Λ_c^+, Ξ_c^+) and τ^+ lepton

short lifetimes
~10^{-12} –10^{-13} s

1. Source of **polarized particles**
   - Prompt Λ_c^+ production in **fixed-target** collisions (transverse polarization)
   - Weak decays of charm mesons $\mathbf{D_s^+ \rightarrow \tau^+\nu_\tau}$ (longitudinal polarization)
2. Strong **electromagnetic field** to induce **precession**
   - Interatomic electric field in **bent crystals**
3. **Detector** to measure initial and final **polarizations** via angular distributions
   - Reconstruction of the $\Lambda_c^+ \rightarrow pK^-\pi^+$ decay in **LHCb**
   - Reconstruction of the $\tau^+ \rightarrow \pi^+\pi^-\pi^+\nu$ decay in a **future dedicated experiment**

E. Bagli et al, Eur.Phys.J. C77 (2017) 828
D. Mirarchi, et al, arxiv:1906.08551
A.S. Fomin, et al, JHEP 1708 (2017) 120

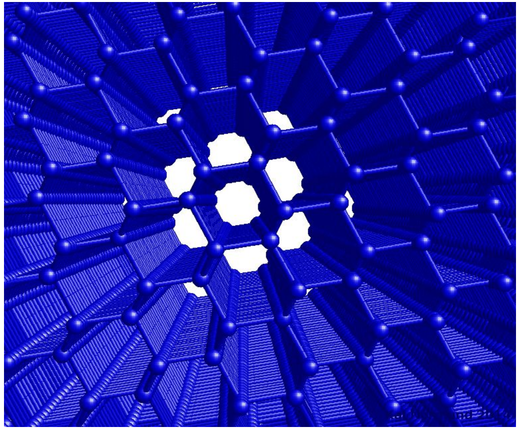
J. Fu, et al, Phys. Rev. Lett. 123 (2019) 011801
A.S. Fomin , et al, JHEP 03 (2019) 156

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**

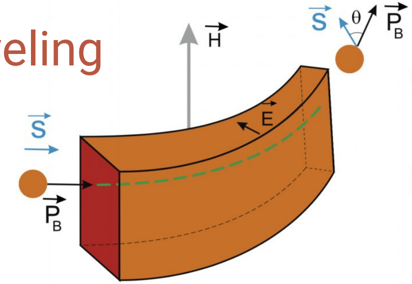
Channeling efficiency **above 80% of several hundred GeV particles** obtained with silicon crystals [Phys. Rev. Lett. 101 (2008) 234801]

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

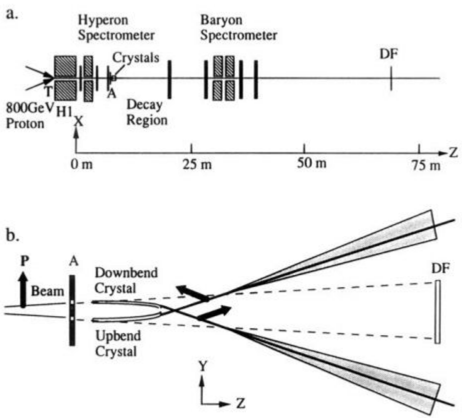


FIG. 1. (a) Plan view of the incident proton beam and spectrometer system. The horizontal scale (z) correctly illustrates the length of the apparatus, the vertical scale (x) is schematic only. (b) Elevation view of the channeling apparatus (not to scale). The arrows illustrate the spin precession in 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.

Workshop on EDM/MDM of unstable particles

Milan, 3-4 October 2019

~ 30 participants

Topics discussed

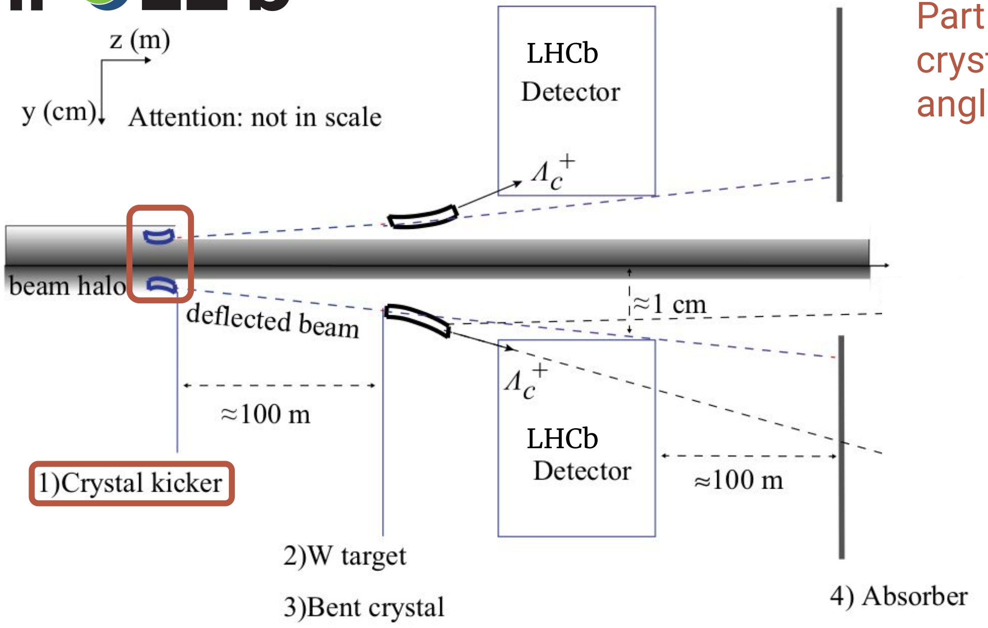
- State-of-the-art **Standard Model calculations** on EDM/MDM
- R&D efforts, particularly **bent crystal production and testing**
- Experimental techniques, decay amplitude analyses
- LHC machine layout

MDM/EDM of heavy baryons

Current status of the experimental proposal

DIPOLE-b experiment design

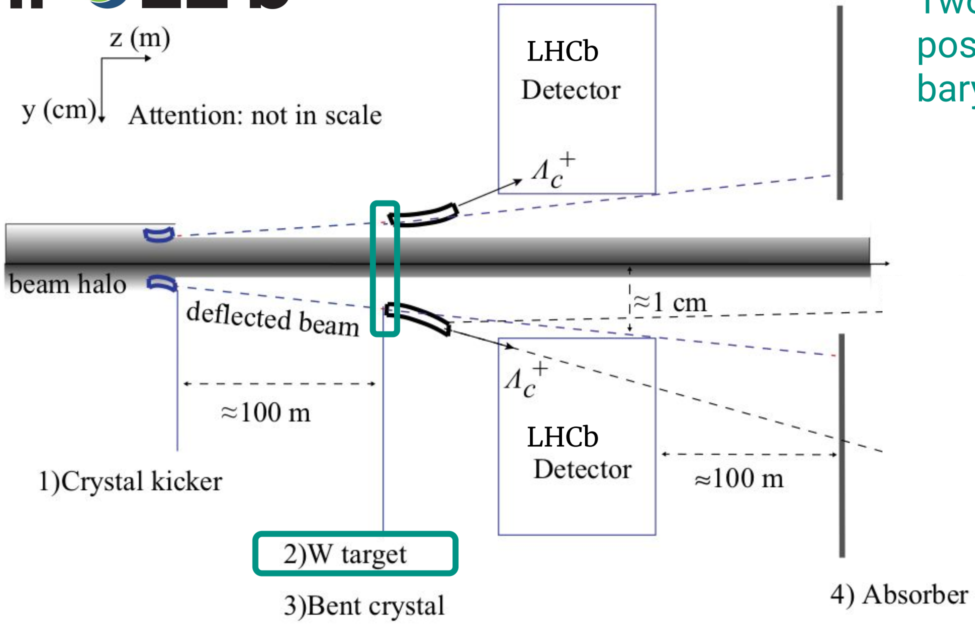
DIrect **P**robe **O**f short-**L**ived particle **E**lectromagnetic dipole moments at LHC**b**



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

DIPOLE-b experiment design

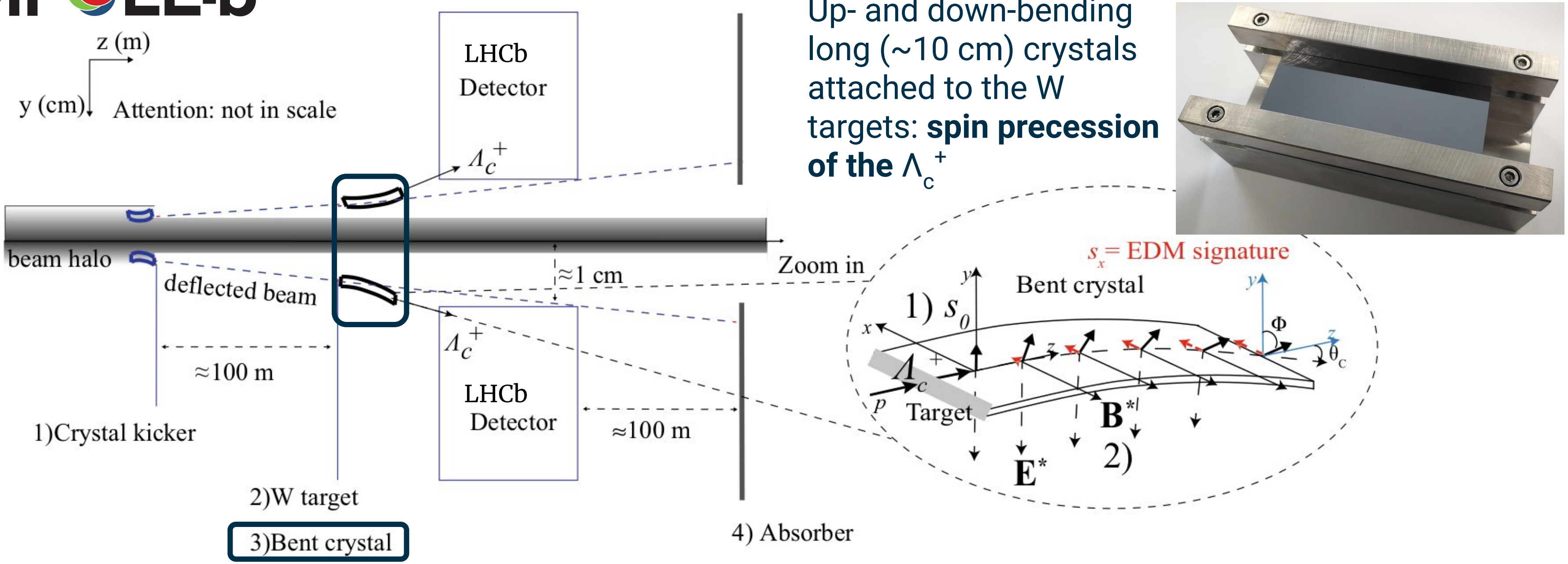
DIrect **P**robe **O**f short-**L**ived particle **E**lectromagnetic dipole moments at LHC**b**



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

DIrect **P**robe **O**f short-**L**ived particle **E**lectromagnetic dipole moments at LHC**b**

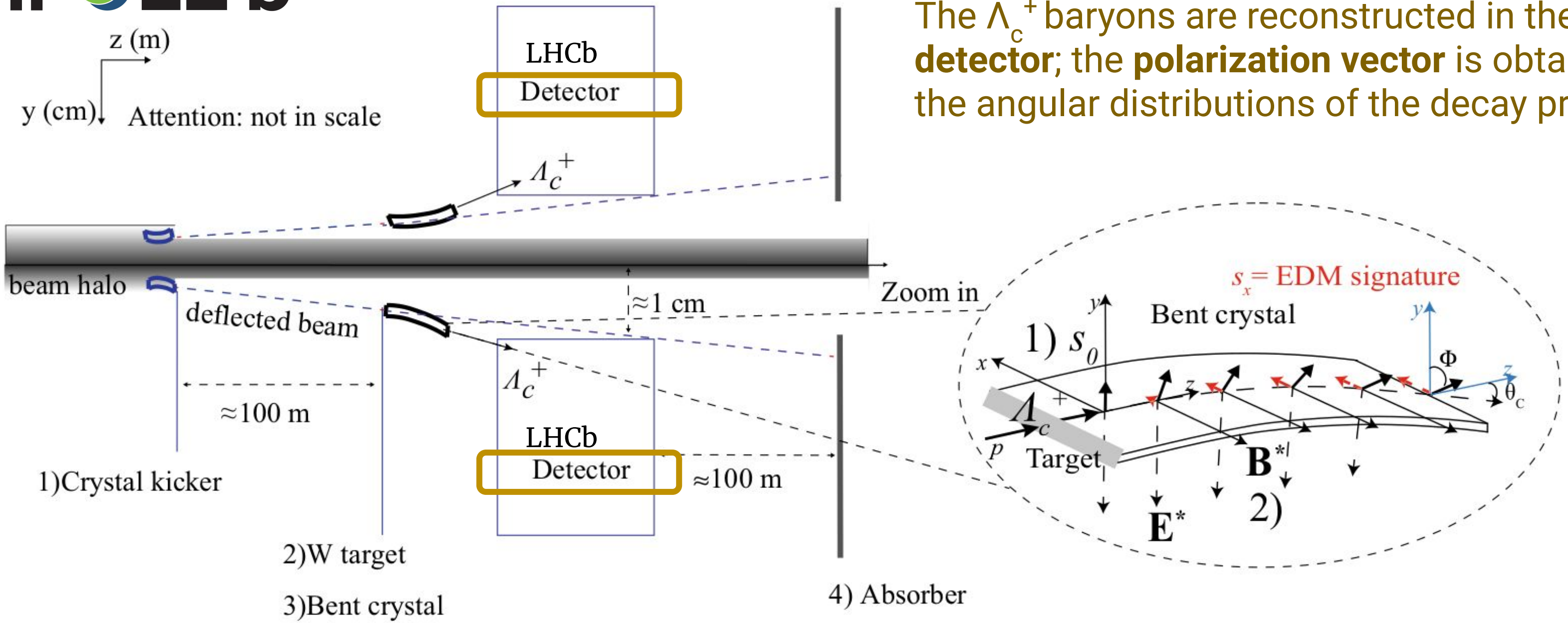


Up- and down-bending long (~10 cm) crystals attached to the W targets: **spin precession of the Λ_c^+**

EPJC (2017) 77:828

DIPOLE-b experiment design

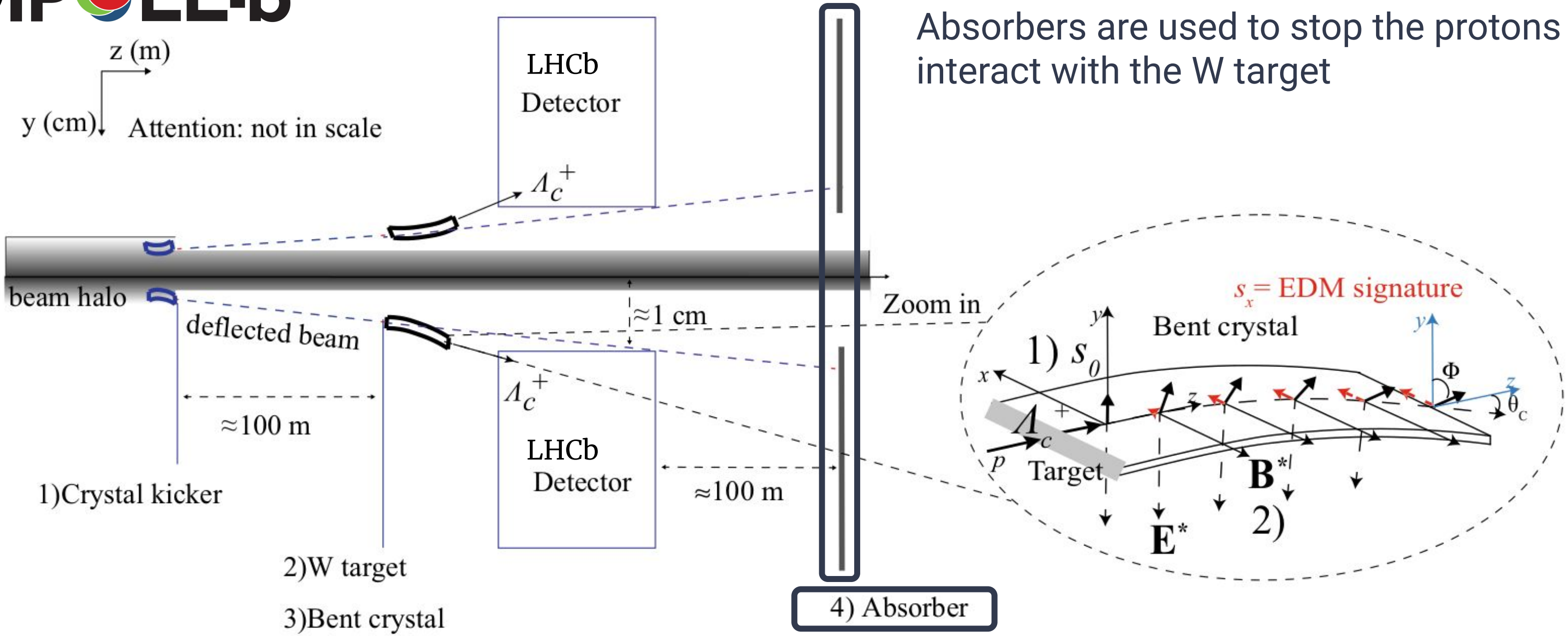
DIPOLE-b **DI**rect **P**robe **O**f short-**L**ived particle **E**lectromagnetic dipole moments at LHC**b**



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

DIrect **P**robe **O**f short-**L**ived particle **E**lectromagnetic dipole moments at LHC**b**



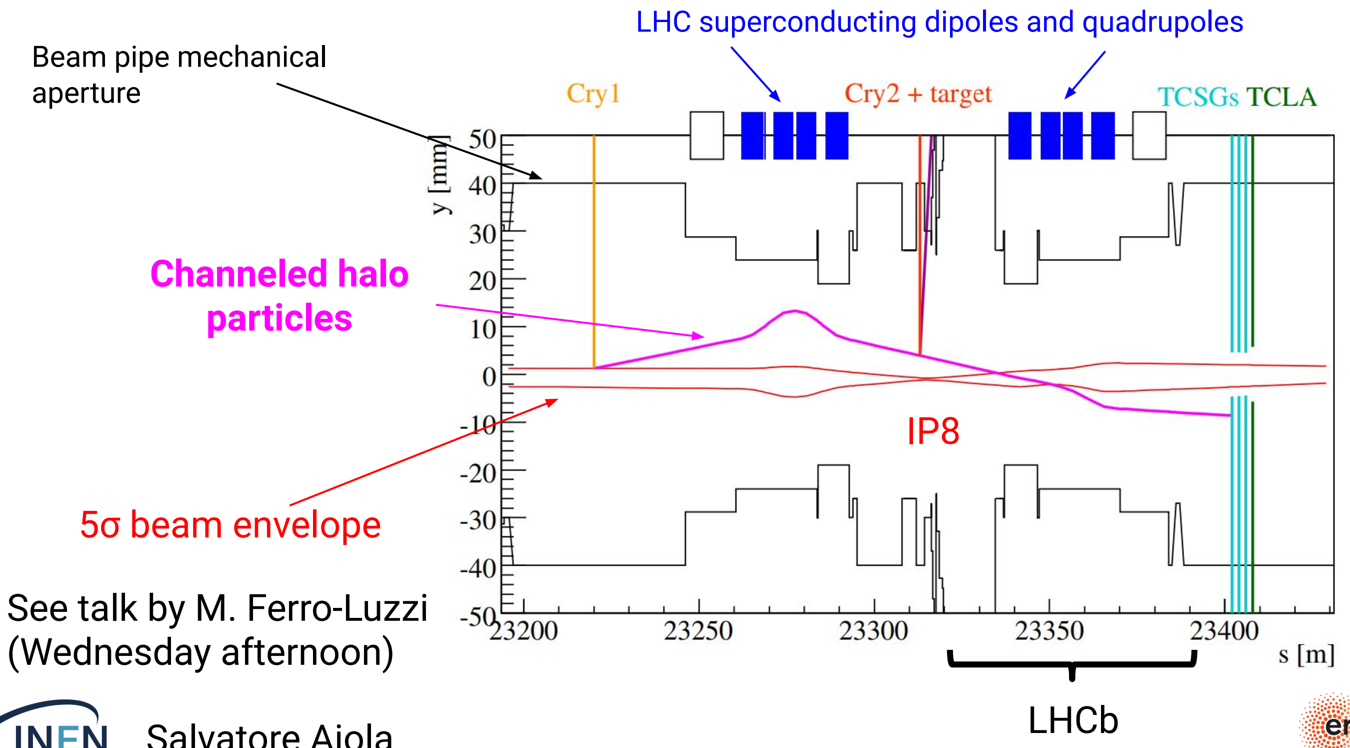
Absorbers are used to stop the protons that did not interact with the W target

LHCb FITPAN review requests (May 2018)

The proposal of the heavy baryon EDM/MDM measurement with bent crystal was reviewed by an LHCb dedicated panel (FITPAN) in May 2018

- ➔ The panel considered the proposal **well motivated** and a **valuable** extension of the LHCb physics program and encouraged to continue the R&D on the project
- ➔ In particular 3 requests were made
  1. feasibility of **operations in the LHC**
  2. demonstration of the operation of **large bending angle crystals** in a test beam
  3. updated proposals for the **model of data taking**

Request #1: feasibility of operations in the LHC

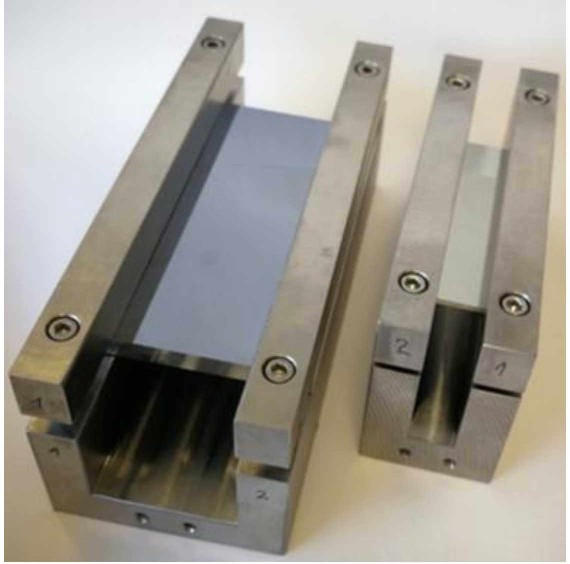


Feasible configuration for a target close to LHCb: 10^6 protons/sec

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

See talk by M. Ferro-Luzzi (Wednesday afternoon)

Request #2: large angle crystals in a test beam



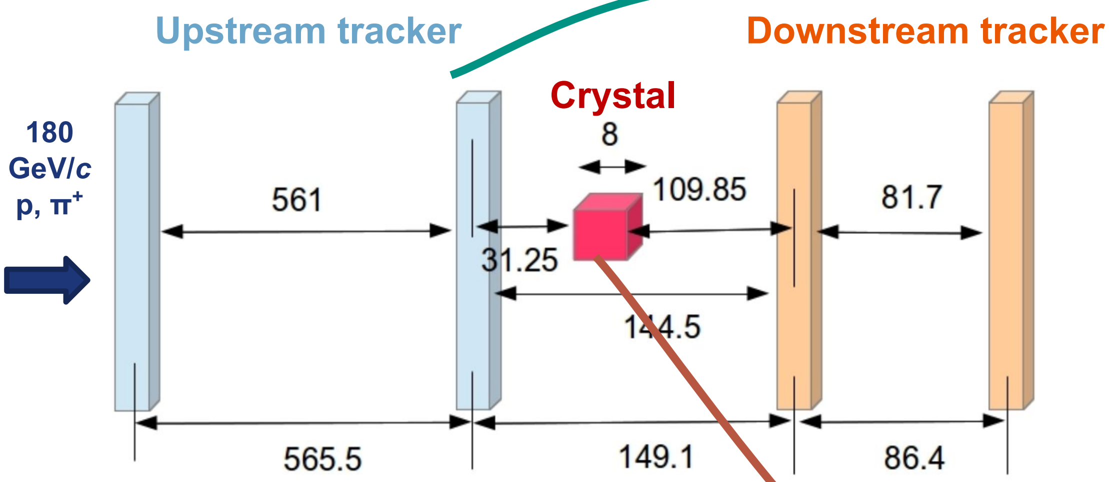
Si Ge

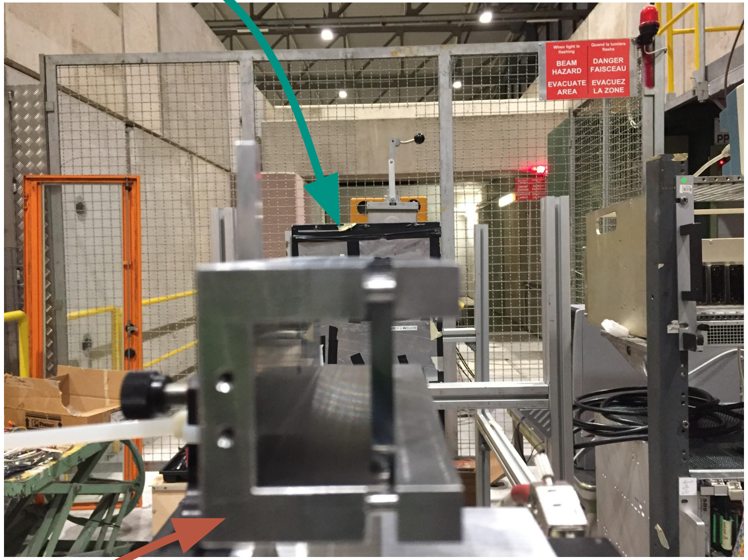
Two crystals were tested

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

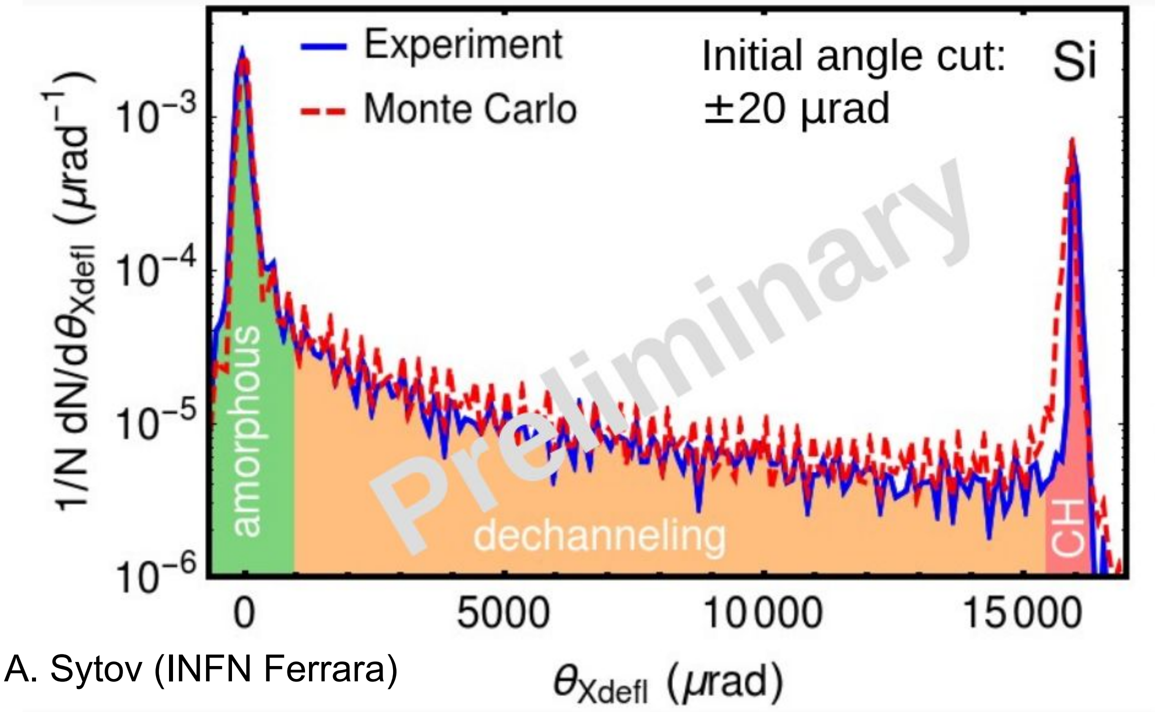
Long bent crystals: test beam at SPS (Oct 2018)





Tracker: INFN Como
Crystals: INFN Ferrara

Long bent crystals: preliminary results



A. Sytov (INFN Ferrara)

Deflection efficiency (silicon)
11±2%

Germanium crystal slightly better (~13%)

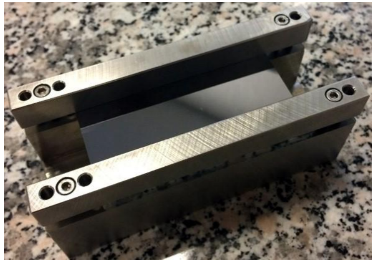
The crystal performance fits the DIPOLE-b requirements

Preliminary results from UA9 (May 2018)

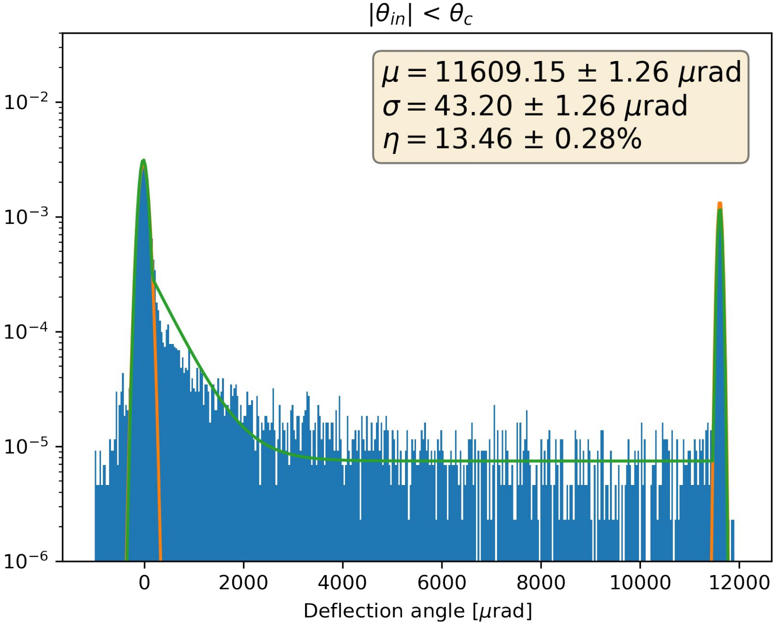
Critical Error Analysis

<u>Global fit</u>
Channeling gaussian μ_{CH}= 11609.53 µrad and σ_{CH} = 42.17 µrad
Dechanneling Length L_d= 3.445557 mm
Amorphous gaussian μ_{AM} = -17.23 µrad and σ_{AM} = 82.19 µrad

CH Efficiency = 13.5%



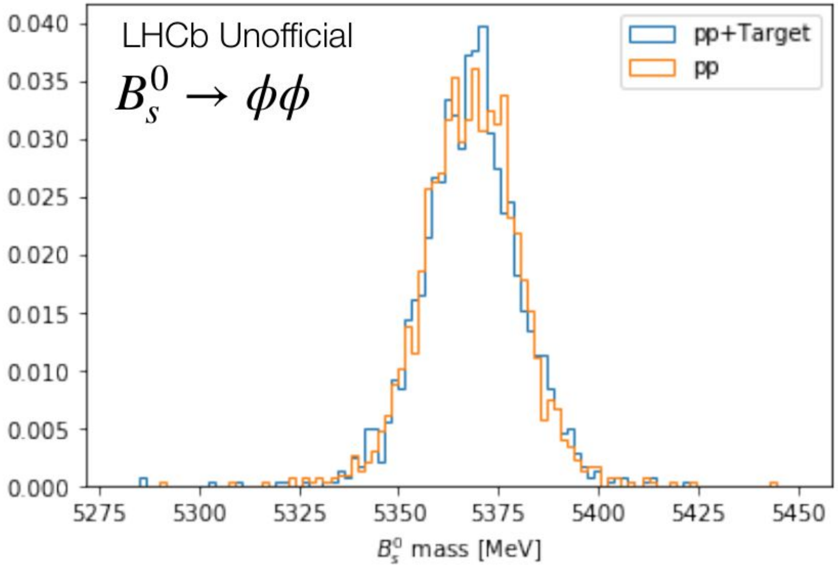
Crystal by INFN Ferrara
Silicon
Deflection angle: 12 mrad



R. Rossi (CERN), 16th meeting of PBC-FT, 21st June 2019
https://indico.cern.ch/event/828573/

Request #3: model of data taking

➔ **Synergetic operation** with pp data taking seems feasible (preliminary)



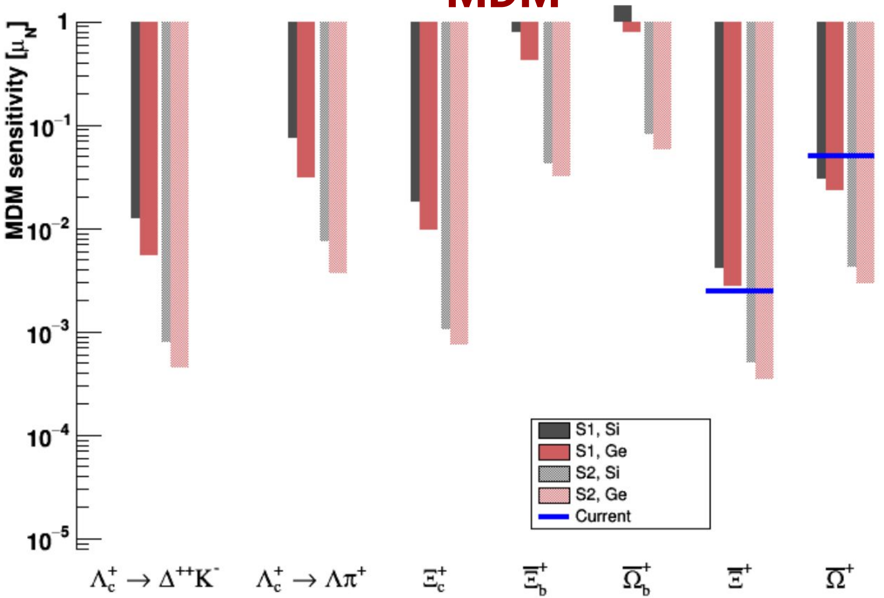
★ **No additional background or resolution degradation** for selected benchmark channels in a full LHCb simulation for a proton flux up to 10^9 p/s

★ Need to assess Impact on **reconstruction efficiency**

★ Optimize **target thickness**

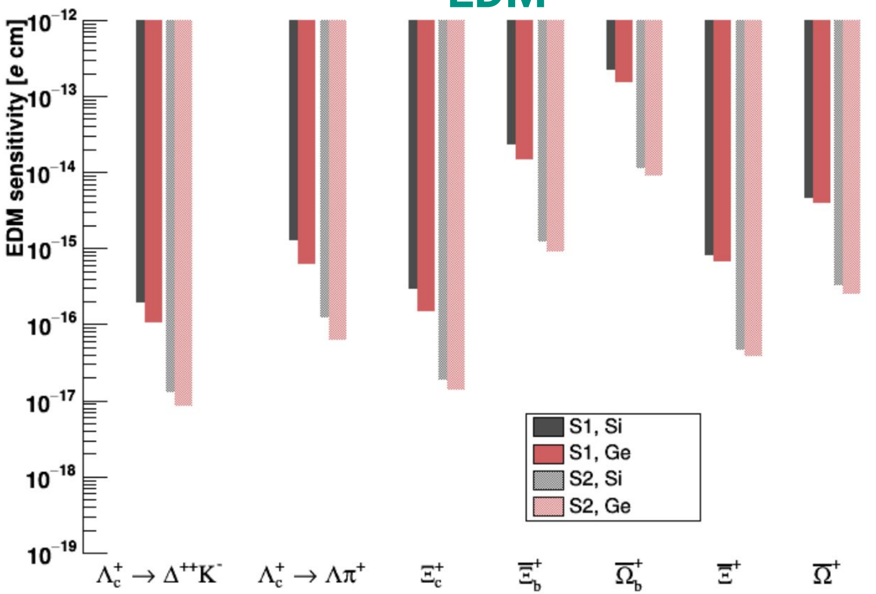
Updated sensitivities

2.5 cm W at 10^6 p/s, 5 y (4×10^6 s in a year)



First direct measurement for a heavy baryon

➔ constraints for QCD models



Establish experimental method (first EDM search with bent crystals)

➔ future dedicated run/experiment

τ lepton

Proposals for a future dedicated experiment

τ lepton anomalous magnetic moment

- Measured with **astonishing precision for the electron**
  - Most precise determination of the electromagnetic coupling constant α
  - $(g_e - 2) / 2 = 0.00115965218091(26)$
- **μ**: experimental value in **tension** with theoretical prediction at 3.5σ
  - Several dedicated experiments, e.g. μUonE @ CERN, E989 @ Fermilab and E34 @ JPARC
- **Never measured for τ**, only modest bounds from DELPHI
  - $-0.052 < (g_\tau - 2) / 2 < 0.013$
- Standard Model prediction: $(g_\tau - 2) / 2 \sim 10^{-3}$
- **New Physics effects enhanced by mass factor** $m_\tau / m_e \sim 3500$, $m_\tau / m_\mu \sim 17$

τ lepton electric dipole moment

In the Standard Model the leading contribution is at **4-loop level**: very tiny EDM

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

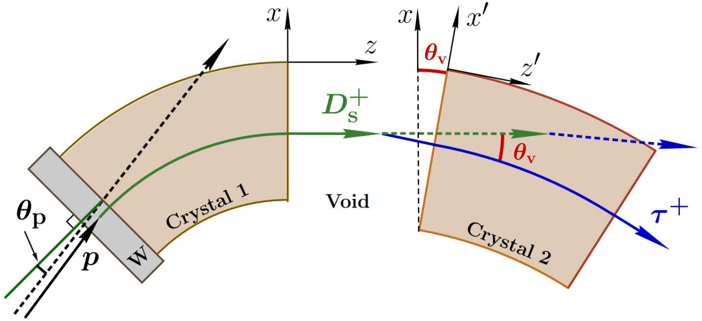
Compare with current (indirect) experimental limits on τ EDM:

$\delta_\tau < 4.5 \times 10^{-17}$ e cm	Phys.Lett. B551 (2003) 16	BELLE ($e^+e^- \to \tau^+\tau^-$)
$\delta_\tau < 5 \times 10^{-17}$ e cm	Nuc.Phys.B 821 (2009) 285	electron and neutron EDM
$\delta_\tau < 3 \times 10^{-17}$ e cm	Nucl.Phys.Proc.S. 189 (2009) 257	LEP ($e^+e^- \to \tau^+\tau^-$)

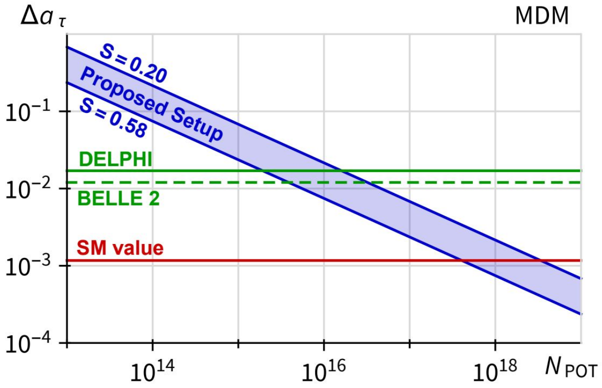
- ➔ Many orders of magnitude to go…
- ➔ Uncharted space for **new physics search**
- ➔ Many **Beyond Standard Model predictions** (just) below ~ 10^{-17} e cm

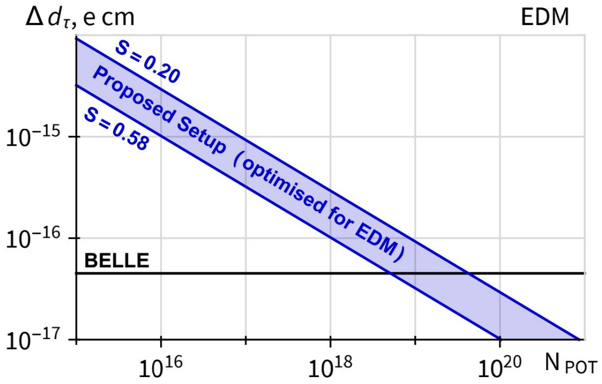
JHEP 1901 (2019) 069
J.Phys. G40 (2013) 035001
Mod.Phys.Lett. A25 (2010) 703
….

Proposal #1: double crystal



- D_s^+ □ $\tau^+\nu_\tau$ **vastly dominates** τ production in hadronic collisions
- For best sensitivity, the **directions of D_s^+ and τ^+** should be known with **high precision**

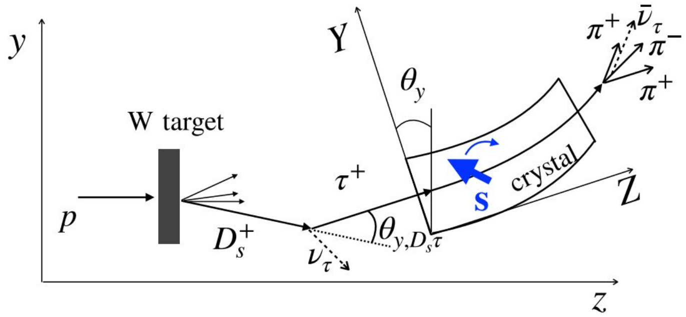


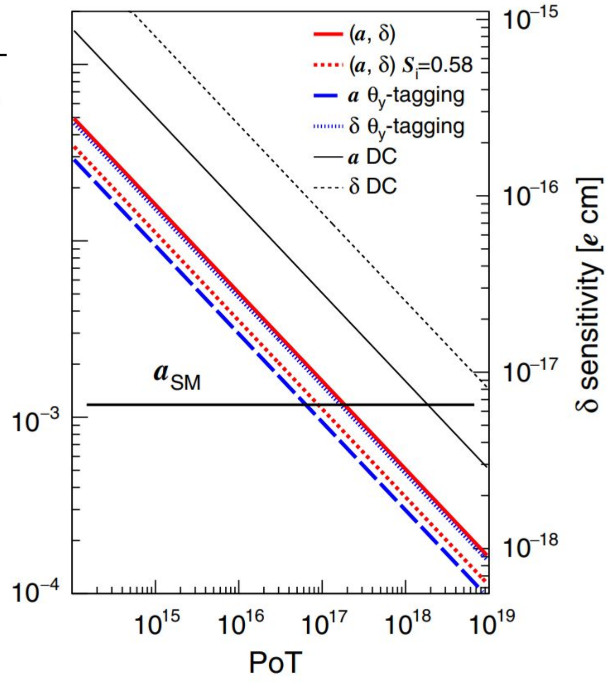


➔ Exploit the collimation provided by a **double bent crystal setup**

Fomin, et al, JHEP 03 (2019) 156

Proposal #2: single crystal





- τ$^+$ polarization well defined in the **D_s^+ rest frame**
- **Not accessible experimentally** because of the missing energy (2ν)
- Exploit **kinematic constraints** to enrich polarization
- **Multivariate classifier**
- Can reach sensitivities comparable to the double-crystal setup

➔ SM MDM prediction with ~ 10^{17} PoT
➔ Requires a **future dedicated experiment** to collect sufficient statistics
➔ Proof-of-principle in LHCb?
➔ Dedicated experiment at SPS BDF?
  - ◆ Need ~ x10^3 PoT vs. LHC

Fu, et al, PRL 123 (2019) 011801

Summary

First measurement of MDM/EDM of heavy baryons and proposal for τ lepton, also mentioned in the **European Strategy for Particle Physics 2020**:

http://cds.cern.ch/record/2691414

Heavy baryons (DIPOLE-b @ LHCb)

✓ Long bent **crystal prototypes**, **LHC machine layout**, LHCb preparatory studies

✓ Next steps: **letter of intent**, technical design report

✓ **FITPAN review on Nov 21st**

✓ Possible installation during Run-3 in a EYTS

τ lepton (future dedicated experiment, proof-of-principle in DIPOLE-b)

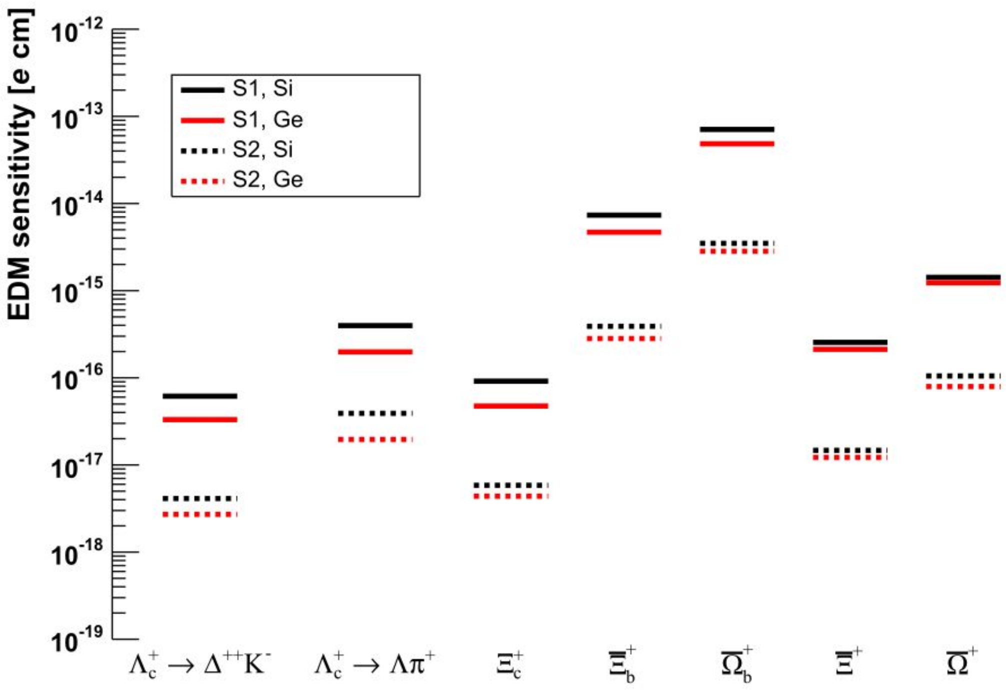
- Growing interest from the scientific community
- Two proposed, complementary experimental setups, join efforts

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

Backup

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

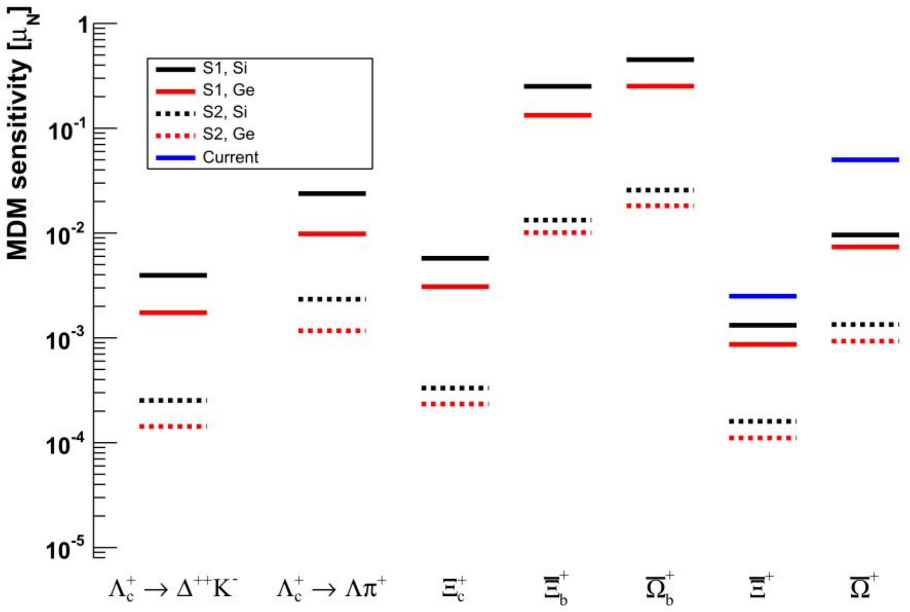
Material of the crystal

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

Measurements are **statistically** limited

EPJC (2017) 77:828

Projected limits on MDM



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**

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

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)

Λ_c^+ polarization and cross section measurement

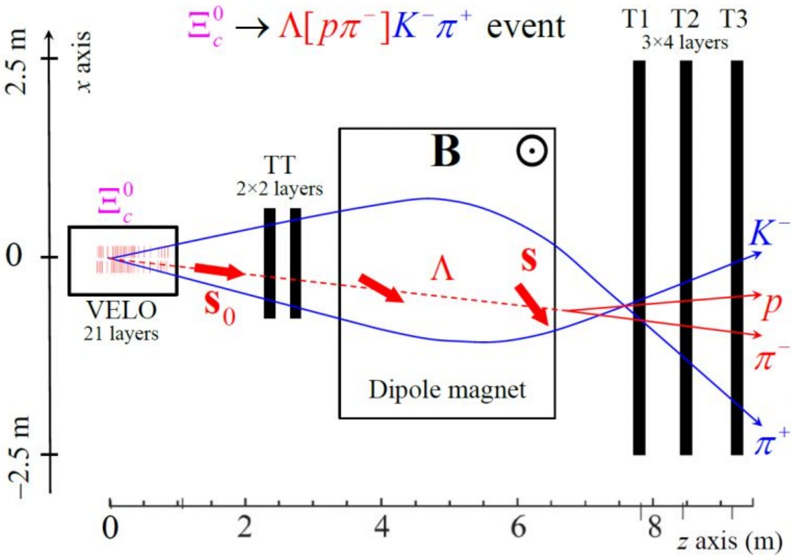
- **Amplitude analysis** of $\Lambda_c^+ \rightarrow pK^-\pi^+$ in pp collisions
- Study polarization of Λ_c^+ in fixed-target **SMOG data** (p-Ne) using the amplitude model developed for pp collisions

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),
L. Henry (IFIC Valencia)

Λ MDM/EDM measurement

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



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