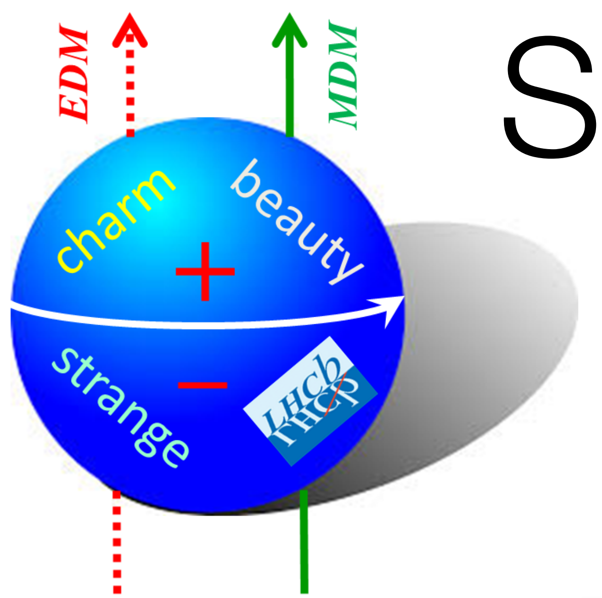


SELDOM: search for electric dipole moment at LHC

Nicola Neri
INFN Sezione di Milano

European Research Council
Established by the European Commission

Channeling 2018
Ischia, 23-28 September 2018

Talk mostly based on EPJC 77:828, 2017

in collaboration with E. Bagli, L. Bandiera, G. Cavoto, V. Guidi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Mazzolari, A. Merli, J. Ruiz Vidal

Outline

- EDM as a probe for new physics
- Experimental method
- Detector simulation studies
- EDM/MDM sensitivity studies
- Summary

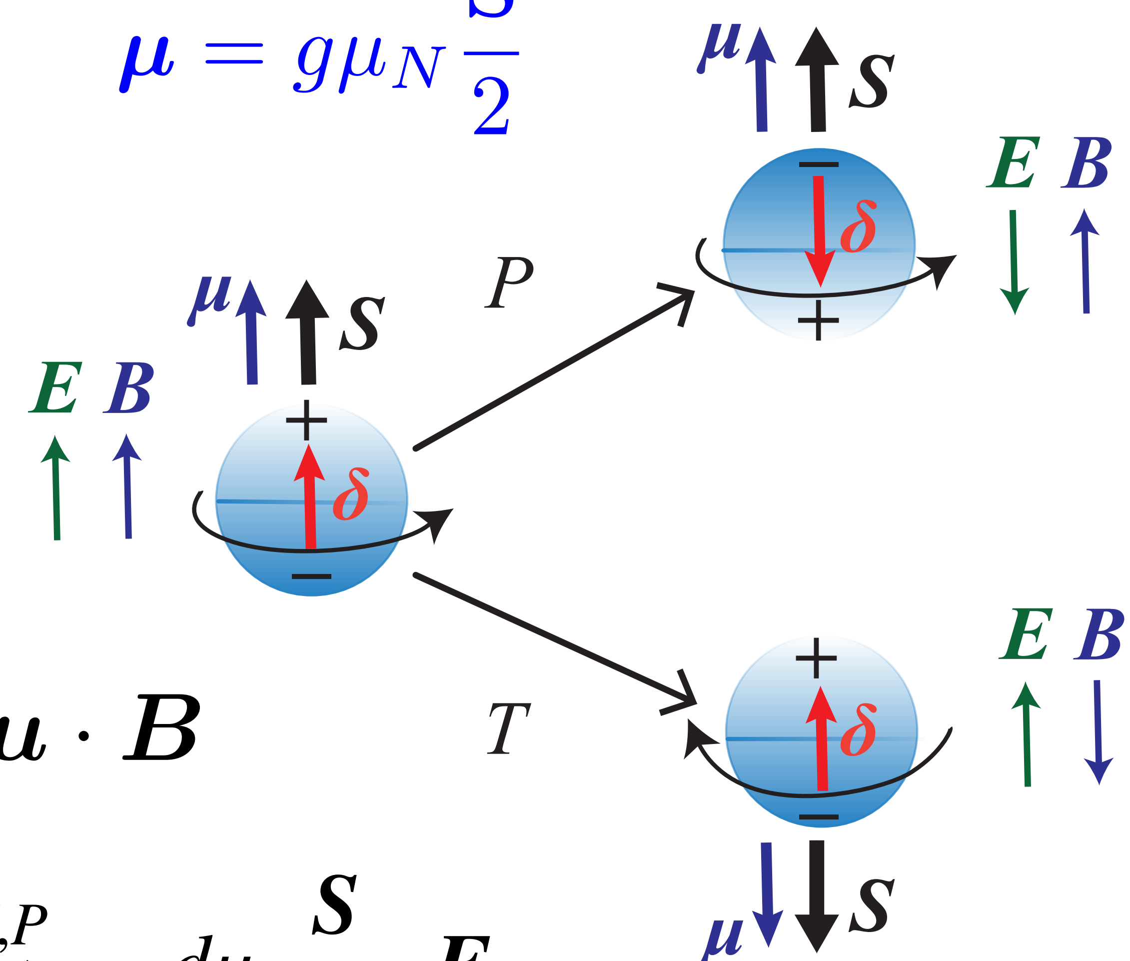
Electromagnetic dipole moments

- Classic systems $\boldsymbol{\delta} = \int \mathbf{r}\rho(\mathbf{r})d^3r$ $\quad \boldsymbol{\mu} = \int \mathbf{r} \times \boldsymbol{j}(\mathbf{r})d^3r$

- Quantum systems $\boldsymbol{\delta} = d\mu_N \frac{\mathbf{S}}{2}$ $\quad \boldsymbol{\mu} = g\mu_N \frac{\mathbf{S}}{2}$

δ= electric dipole moment (EDM)

μ= magnetic dipole moment (MDM)



- Hamiltonian $H = -\boldsymbol{\delta} \cdot \boldsymbol{E} - \boldsymbol{\mu} \cdot \boldsymbol{B}$

Time reversal, Parity: $d\mu_N \frac{\boldsymbol{S}}{2} \cdot \boldsymbol{E} \xrightarrow{T,P} - d\mu_N \frac{\boldsymbol{S}}{2} \cdot \boldsymbol{E}$

The EDM violates *T* and *P* and via *CPT* theorem, violates *CP*

Matter-antimatter asymmetry and CP violation

CP violation (CPV) is a necessary condition for baryogenesis (Sakharov, 1967)

CPV in weak interactions via CKM mechanism in the SM is too small to explain the absence of antimatter in the Universe

$$\eta = \frac{n_B - n_{\bar{B}}}{\gamma} \sim 6 \times 10^{-10}$$ (WMAP)

CPV in strong interactions allowed in SM. Stringent experimental limit from neutron EDM → "strong CP problem"

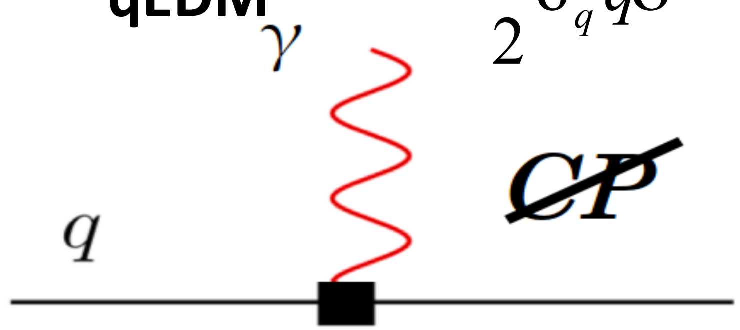
$$|\delta_n| \leq 2.9 \times 10^{-26} e \text{ cm (90\% C.L.)} \Rightarrow \theta \lesssim 10^{-10}$$ Phys.Rev.Lett.97:131801,2006

New sources of CPV are expected to exist

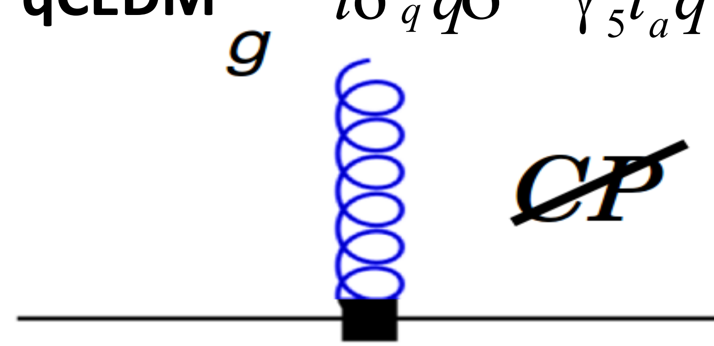
EDM a possible solution for baryogenesis

- EDM of fundamental particles from the structure of quarks and gluons, and processes with photon and flavour-diagonal coupling
- A measurement of a heavy baryon EDM is **directly sensitive** to:

qEDM $-\frac{i}{2}\delta_q \bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu}$

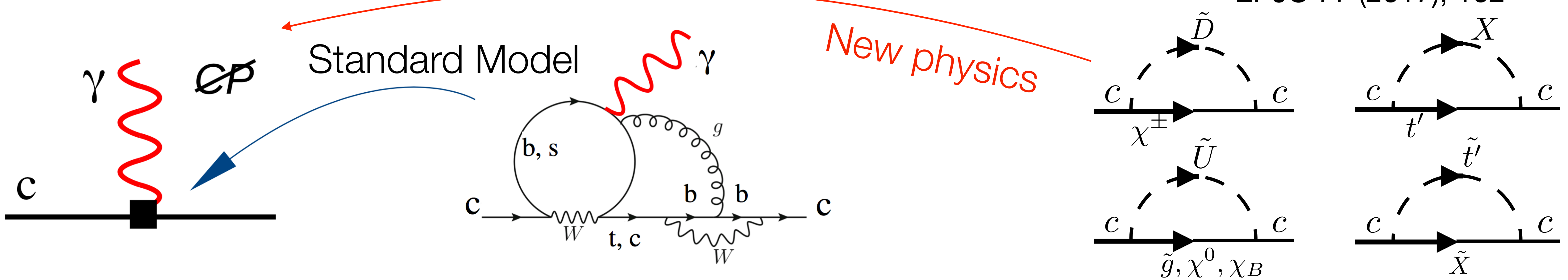


qCEDM $i\tilde{\delta}_q \bar{q}\sigma^{\mu\nu}\gamma_5 t_a q G^a_{\mu\nu}$



Charm EDM in Standard Model ~10^{-32} e cm   Charm EDM with new physics ~$5\cdot10^{-17}$ e cm

EPJC 77 (2017), 102



- EDM observation = clear signature of **new physics**

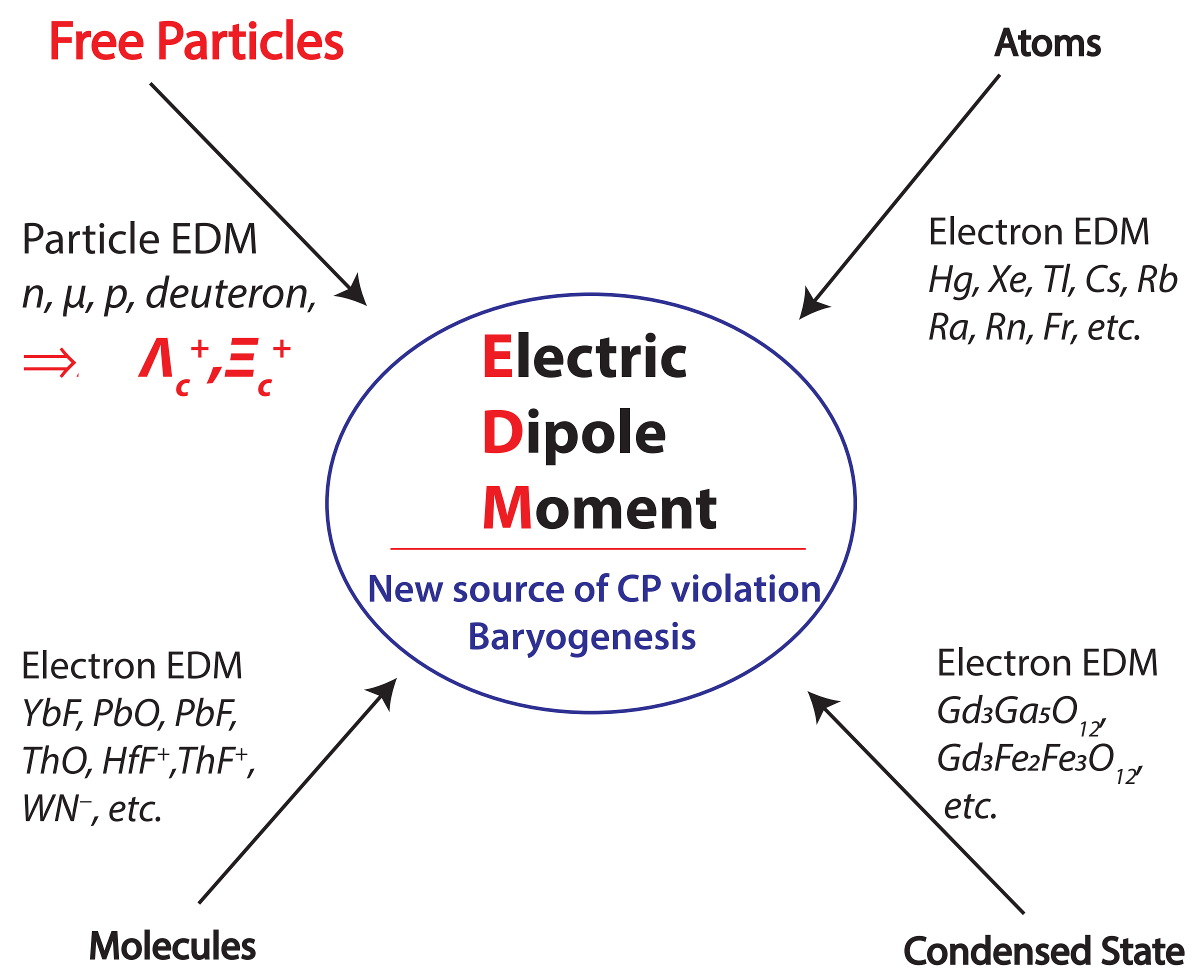
Current limits on EDM

- Intense EDM program is ongoing worldwide and new experiments are planned

- Possibility to contribute at LHCb searching for the first time Λ_c^+, Ξ_c^+ charm baryon EDM

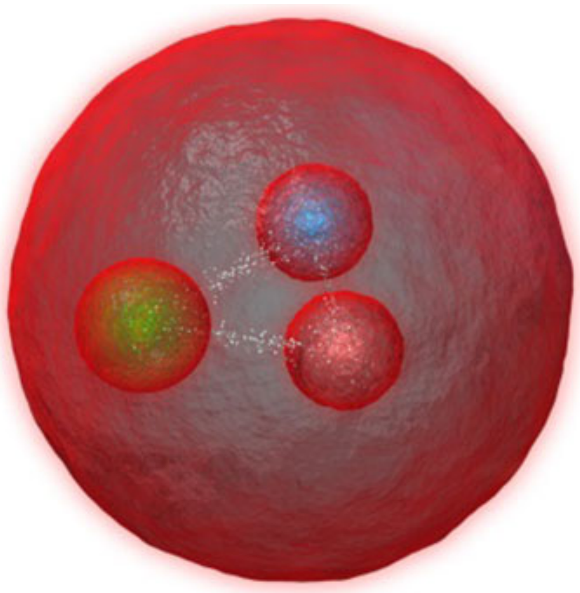
Particle	Limit/Measurement [e cm]	SM limit [factor to go]
e	$<1.05 \times 10^{-27}$	10^{11}
μ	$<1.8 \times 10^{-19}$	10^{8}
τ	$(-2.2 < d_\tau < 4.5) \times 10^{-17}$	10^{7}
n	$<2.9 \times 10^{-26}$	10^{4}
p	$<0.54 \times 10^{-23}$	10^{6}
Λ^0	$(-3.0 \pm 7.4) \times 10^{-17}$	10^{11}
$\nu_{e,\mu}$	$<2 \times 10^{-21}$	
ν_τ	$<5.2 \times 10^{-17}$	
Hg-atom	$<3.1 \times 10^{-29}$	$\leq 10^{4}$

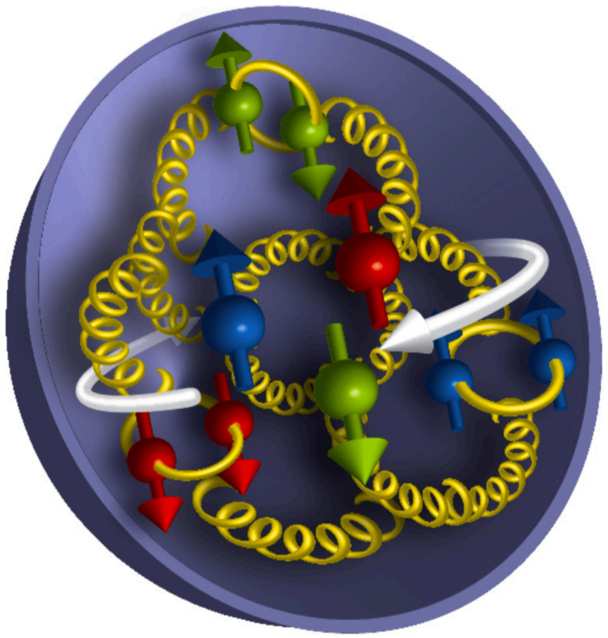
Ann. Phys. (Berlin) 525, No. 8–9 (2013)



Physics motivations for MDM

- Experimental anchor points for test of low-energy QCD models, related to **non-perturbative QCD** dynamics
- Test of **quark substructure**
- Measurement of MDM of particles and antiparticles would allow a **test of CPT symmetry**

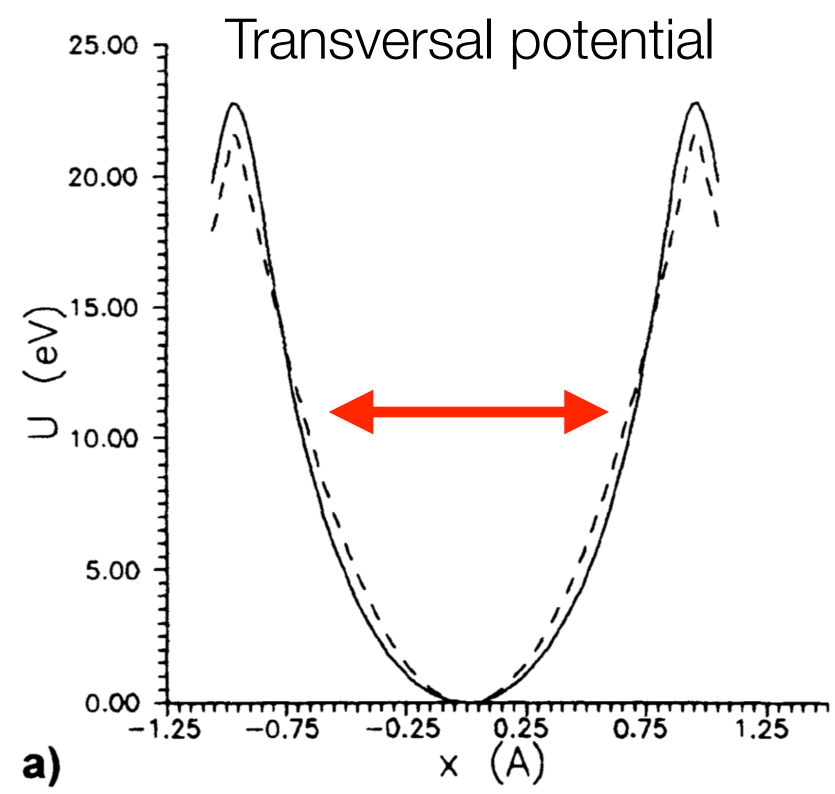


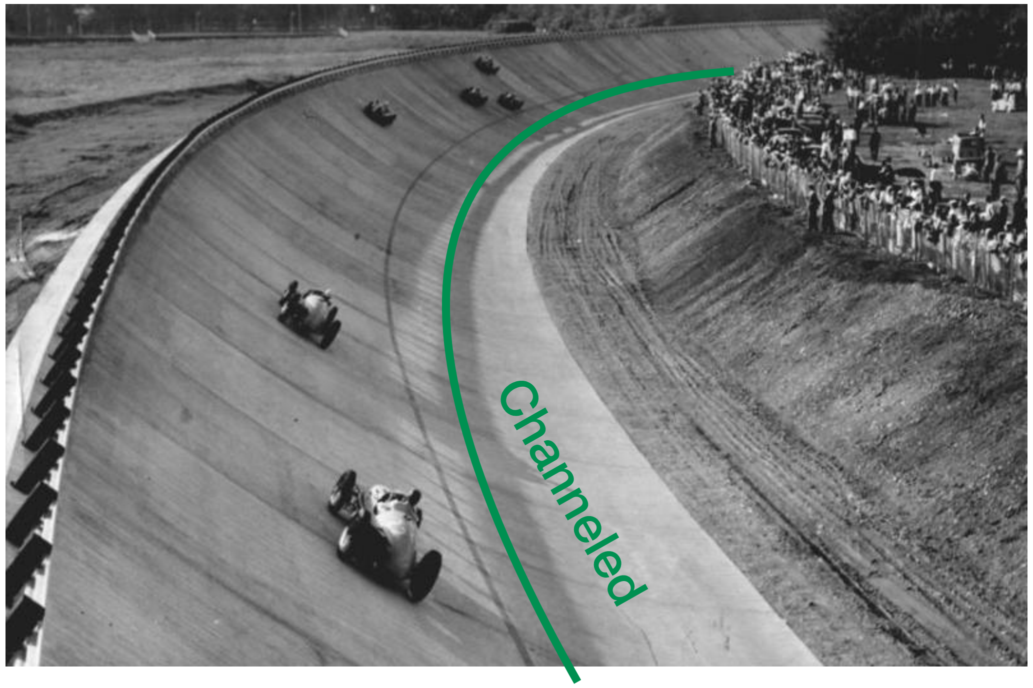


Experimental method

Channeling in bent crystals

- Potential well between crystal planes
- Incident positive charge particle can be trapped if parallel to crystal plane (within few μrad)
- Well understood phenomenon (Lindhard 1965).
- Bent crystals used to:
  - steer high-energy particle beams
  - induce spin precession





Spin precession in bent crystals

- Firstly predicted by **Baryshevsky** (1979)

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

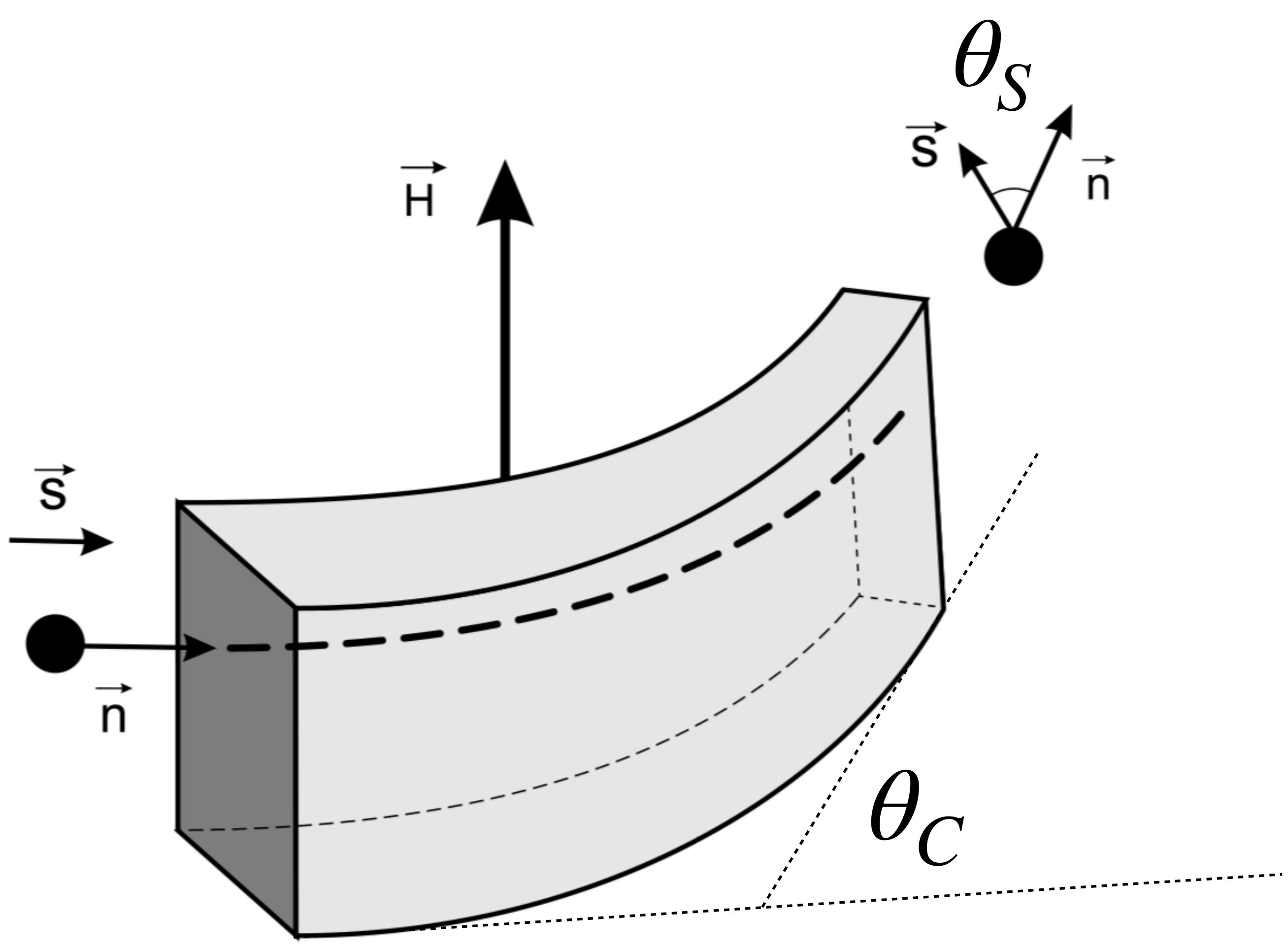


Fig. 1. Spin rotation in a bent crystal.

- Determine particle gyromagnetic factor from BMT equation

V.L. Lyuboshits, Sov. J. Nucl. Phys. 31 (1980) 509.

$$\theta_S = \frac{g-2}{2}\gamma\theta_C$$

θ_S = spin rotation angle

θ_C = crystal bending angle

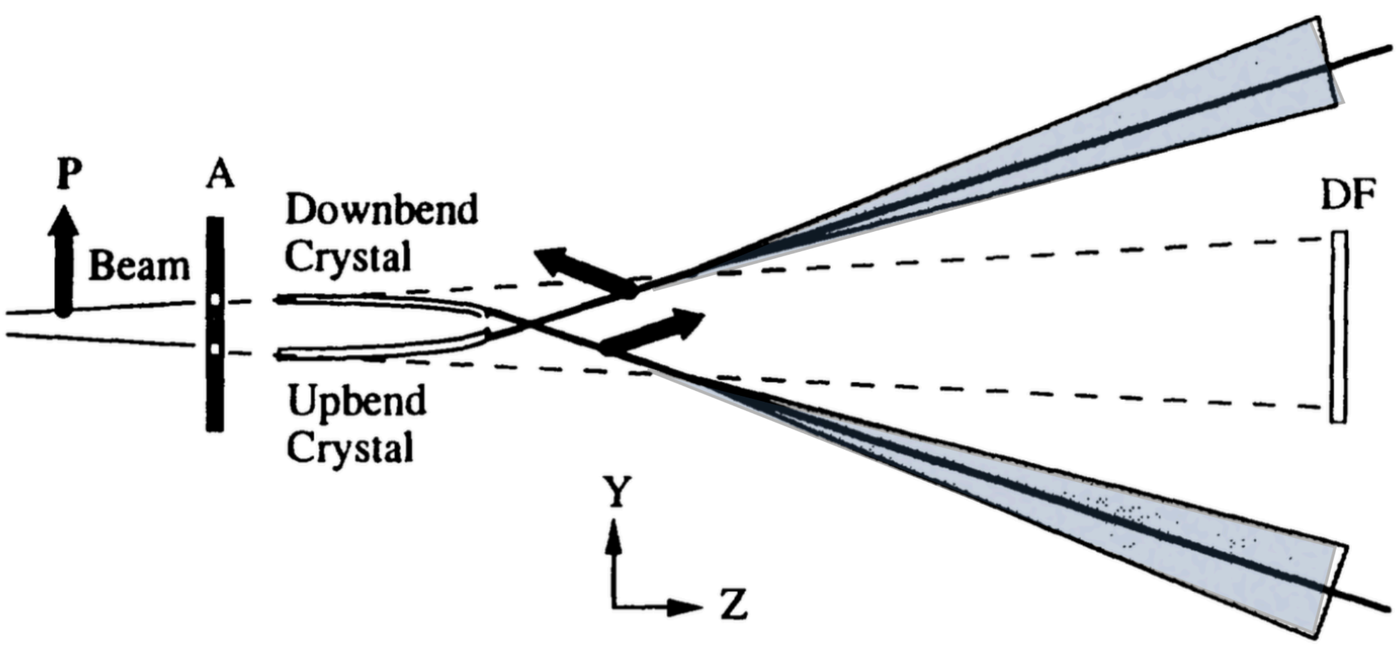
g = gyromagnetic factor

γ = Lorentz boost

Proof of principle in E761

- E761 Fermilab experiment firstly observed **spin precession** in bent crystals and measured MDM of Σ^+
- **350 GeV/c Σ^+** produced from interaction of 800 GeV/c proton beam on Cu target
- Used **upbent** and **downbent** silicon **crystals** L=4.5cm, θ_C=1.6 mrad for opposite spin precession, reduced systematics

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



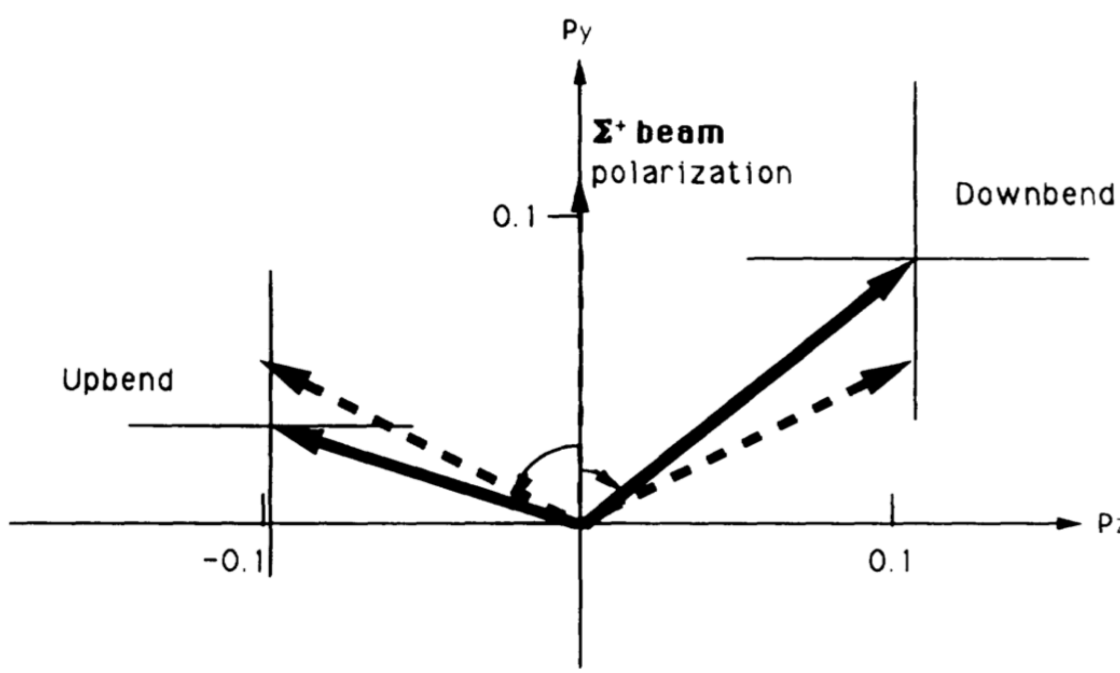


FIG. 3. Measured polarizations and uncertainties (1σ statistical errors) after spins have been processed by the two crystals. The dashed arrows show the expected precessions.

MDM of short-lived baryons

- **Charm baryon MDM** with bent crystals firstly studied in:
  - I. J. Kim, Nucl. Phys B 229 (1983) 251-268
  - V. V. Baublis et al., NIMB 90 (1994) 112-118
  - V. M. Samsonov, NIMB 119 (1996) 271-279
- Recently revisited for LHC energies:
  - V. M. Baryshevsky, PLB 757 (2016) 426–429, NIMB 402, 5 (2017)
  - L. Burmistrov et al., Tech. Rep. CERN-SPSC-2016-030 (2016)
  - O. A. Bezshyyko et al., JHEP 8, 107 (2017)

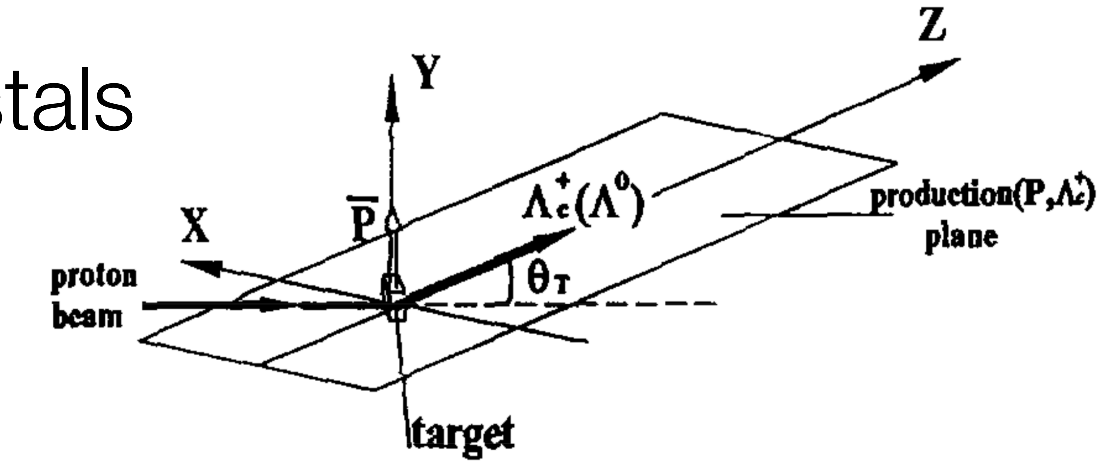


Fig. 3. Schematic diagram of the Λ_c^+ (Λ^0) polarization production.

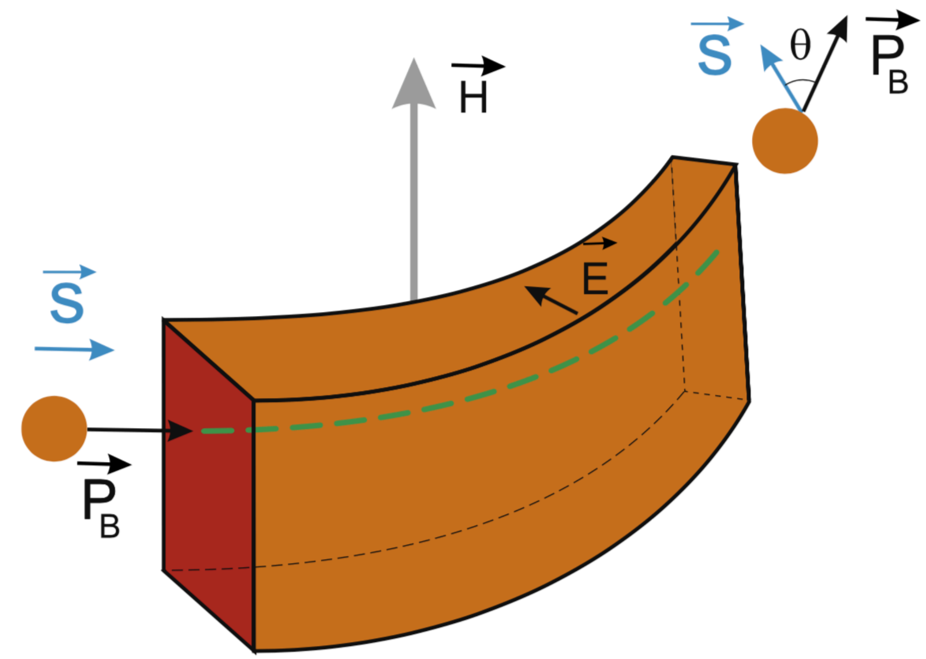
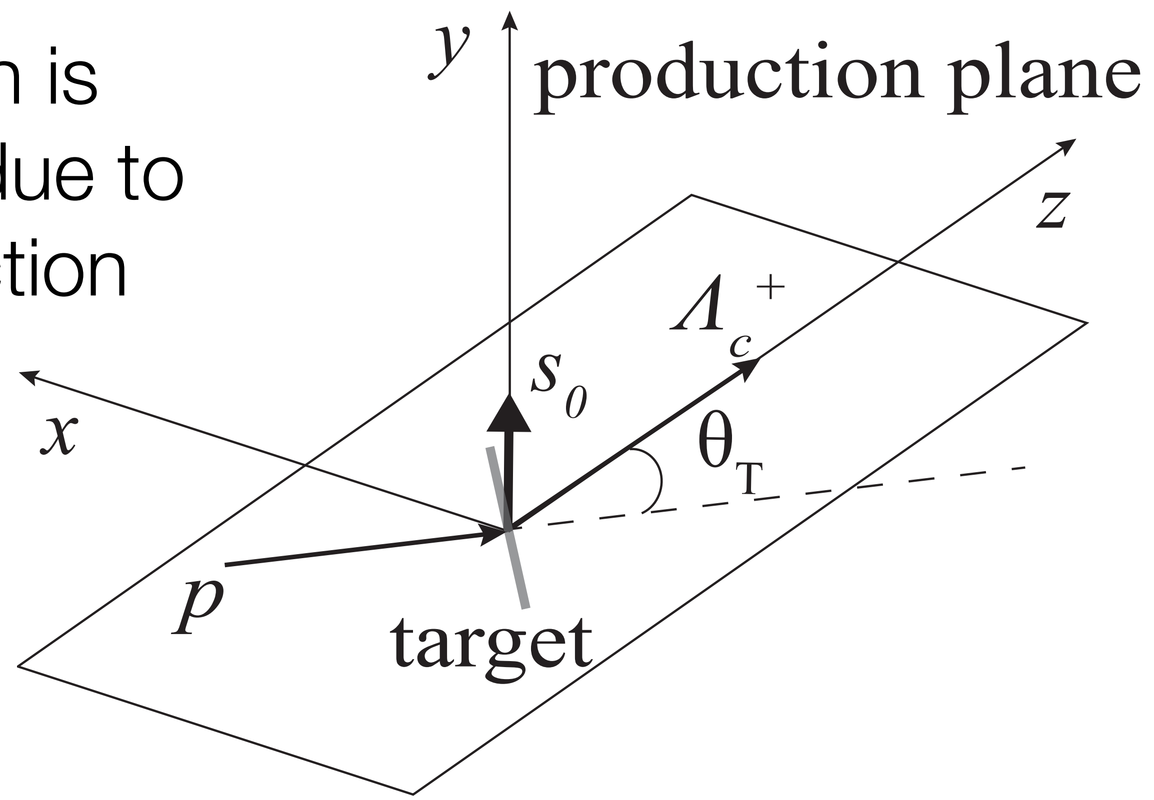
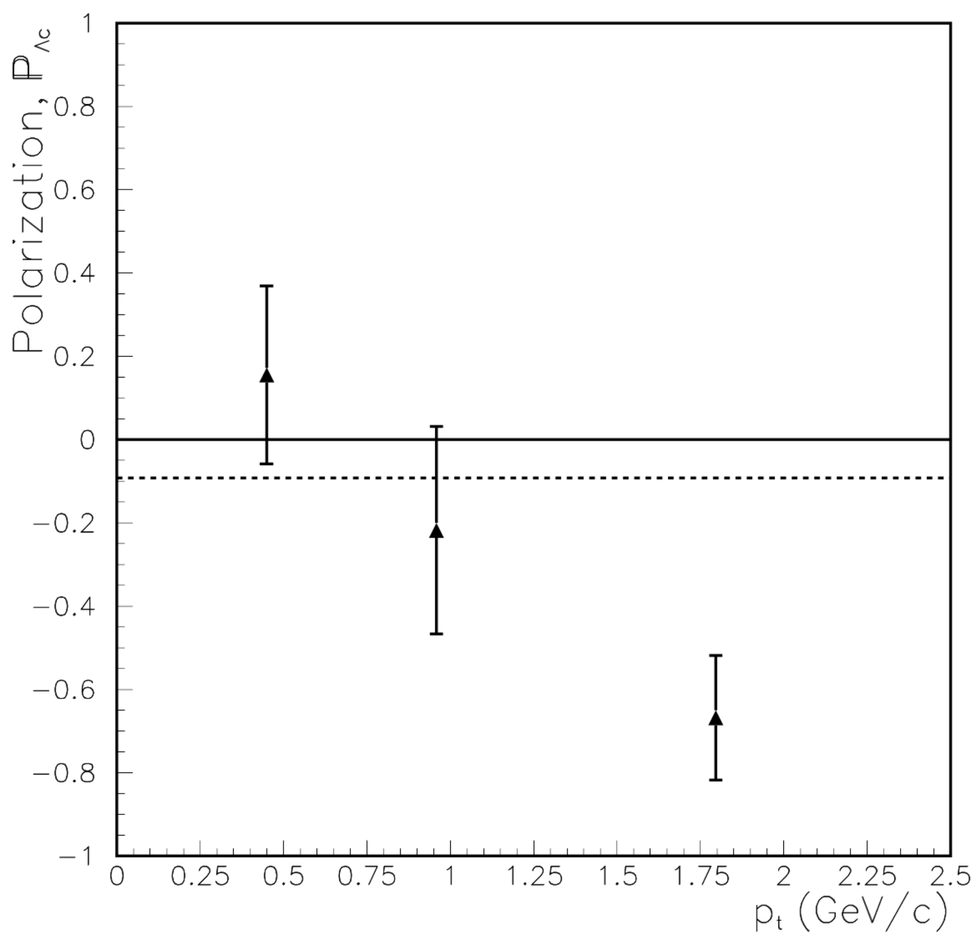


Fig. 1. Spin rotation in a bent crystal.

Charm baryon polarisation

- Fixed-target production: polarisation is perpendicular to production plane due to parity conservation in strong interaction





- Λ_c^+ polarisation vs transverse momentum measured by E791 experiment in 500 GeV/c π^--N reactions
- Increases with Λ_c^+ transverse momentum

EDM with bent crystals

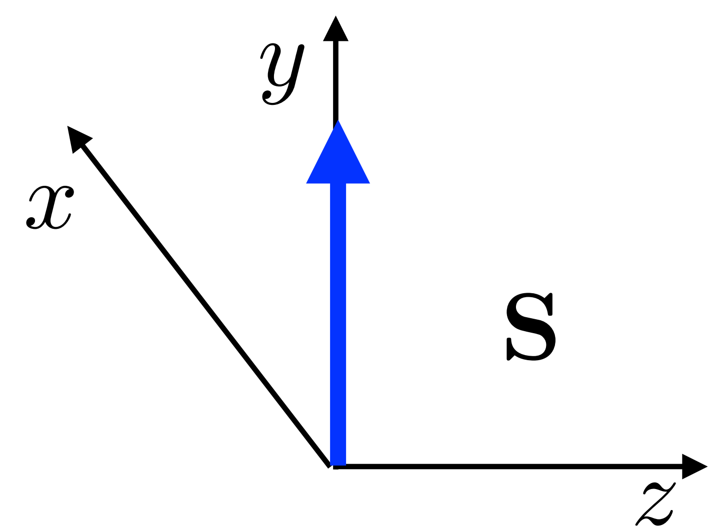
Fill the experimental gap in **heavy baryon** **electric** **dipole moment** searches. Method proposed in EPJC (2017) 77:181

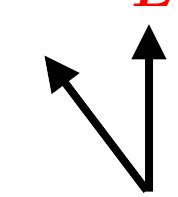
EDM with bent crystals

Fill the experimental gap in **heavy baryon electric dipole moment** searches. Method proposed in EPJC (2017) 77:181

Spin precession in crystal electromagnetic field ($\mathbf{E}^* \perp \mathbf{B}^*$ in particle rest frame)

$$\frac{d\mathbf{S}}{dt} = \boldsymbol{\mu} \times \mathbf{B}^*$$



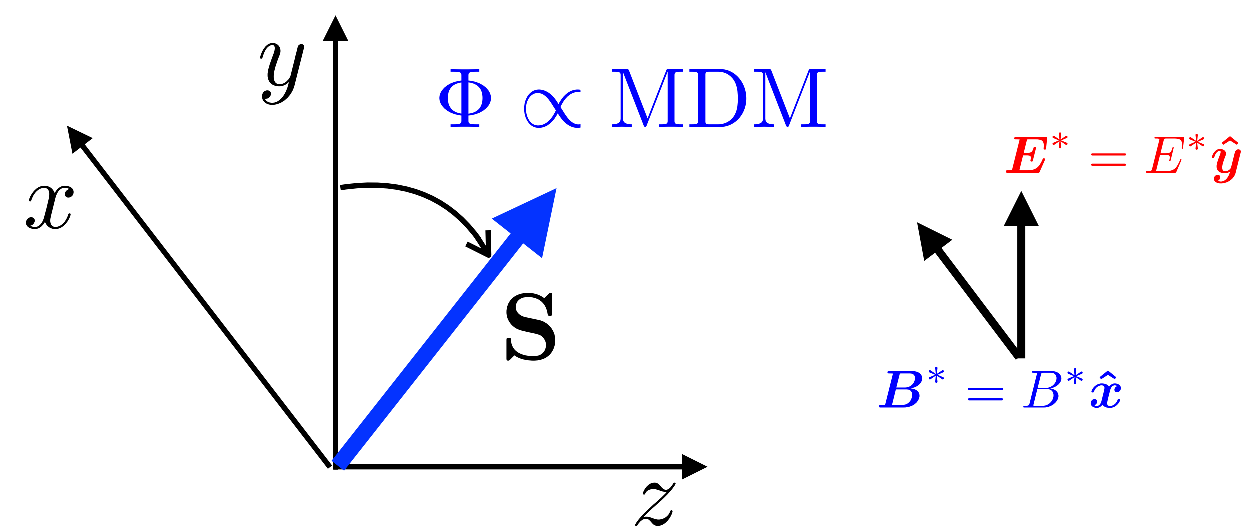


EDM with bent crystals

Fill the experimental gap in **heavy baryon electric dipole moment** searches. Method proposed in EPJC (2017) 77:181

Spin precession in crystal electromagnetic field (**E***⊥**B*** in particle rest frame)

$$\frac{d\mathbf{S}}{dt} = \boldsymbol{\mu} \times \mathbf{B}^*$$

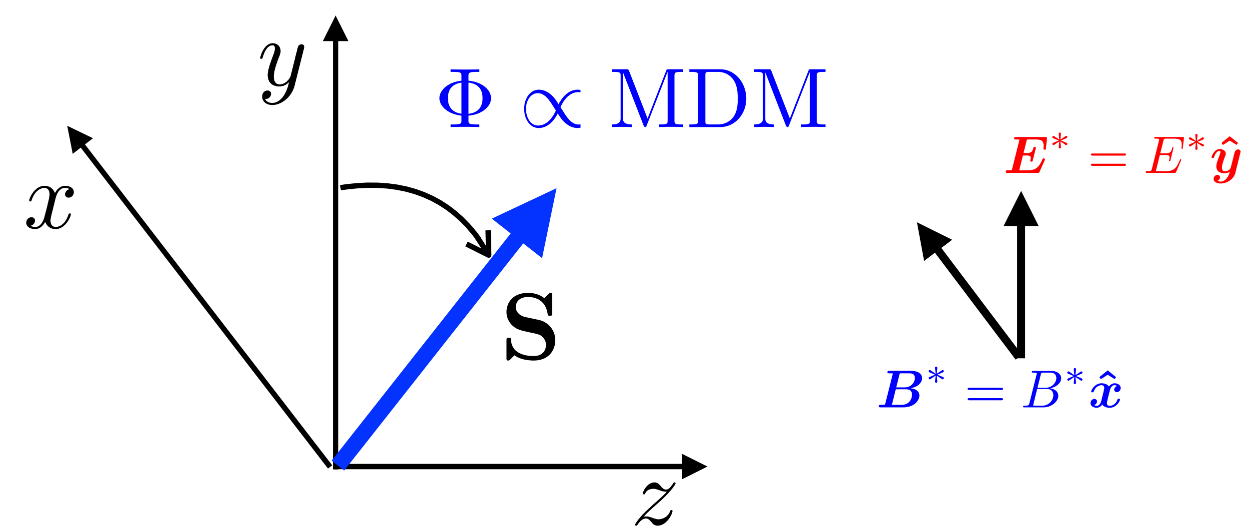


EDM with bent crystals

Fill the experimental gap in **heavy baryon electric dipole moment** searches. Method proposed in EPJC (2017) 77:181

Spin precession in crystal electromagnetic field (**E***⊥**B*** in particle rest frame)

$$\frac{d\mathbf{S}}{dt} = \boldsymbol{\mu} \times \mathbf{B}^* + \boldsymbol{\delta} \times \mathbf{E}^*$$

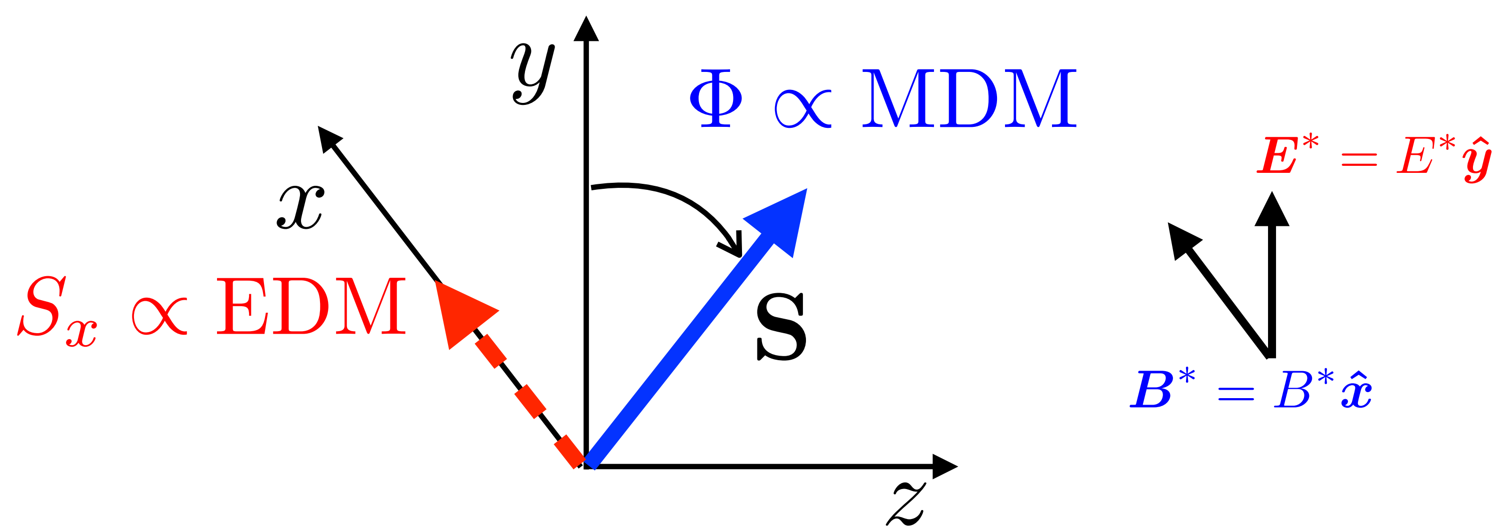


EDM with bent crystals

Fill the experimental gap in **heavy baryon electric dipole moment** searches. Method proposed in EPJC (2017) 77:181

Spin precession in crystal electromagnetic field (**E***⊥**B*** in particle rest frame)

$$\frac{d\mathbf{S}}{dt} = \boldsymbol{\mu} \times \mathbf{B}^* + \boldsymbol{\delta} \times \mathbf{E}^*$$

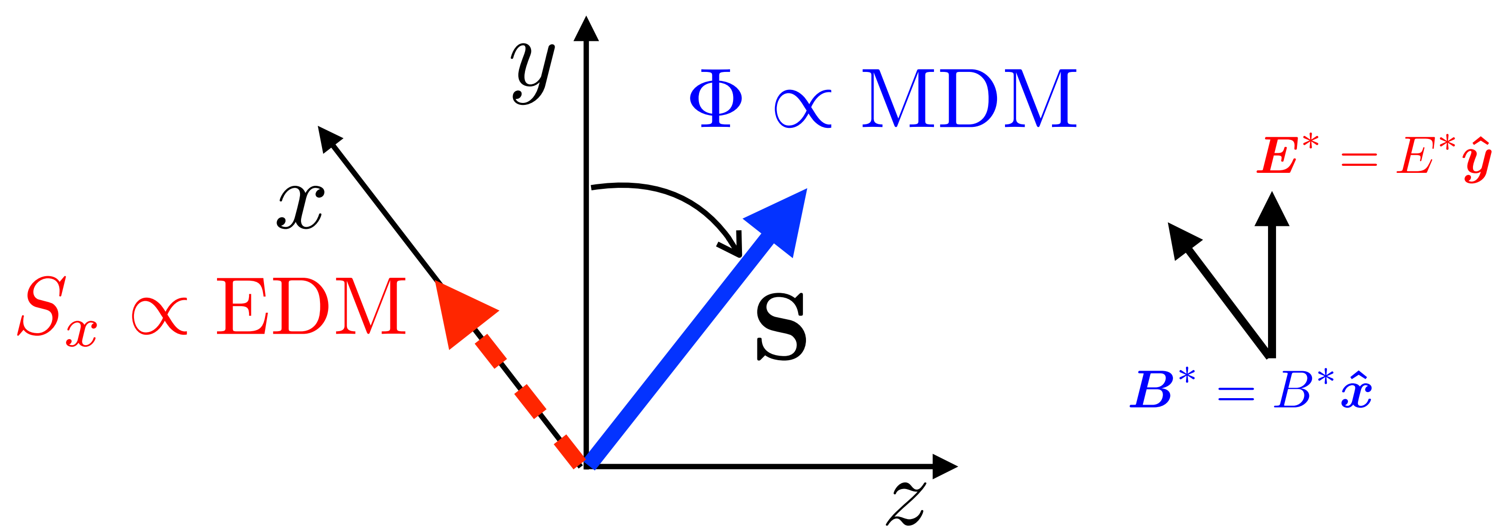


EDM with bent crystals

Fill the experimental gap in **heavy baryon electric dipole moment** searches. Method proposed in EPJC (2017) 77:181

Spin precession in crystal electromagnetic field ($\mathbf{E}^{*} \perp \mathbf{B}^{*}$ in particle rest frame)

$$\frac{d\mathbf{S}}{dt} = \boldsymbol{\mu} \times \mathbf{B}^{*} + \boldsymbol{\delta} \times \mathbf{E}^{*}$$



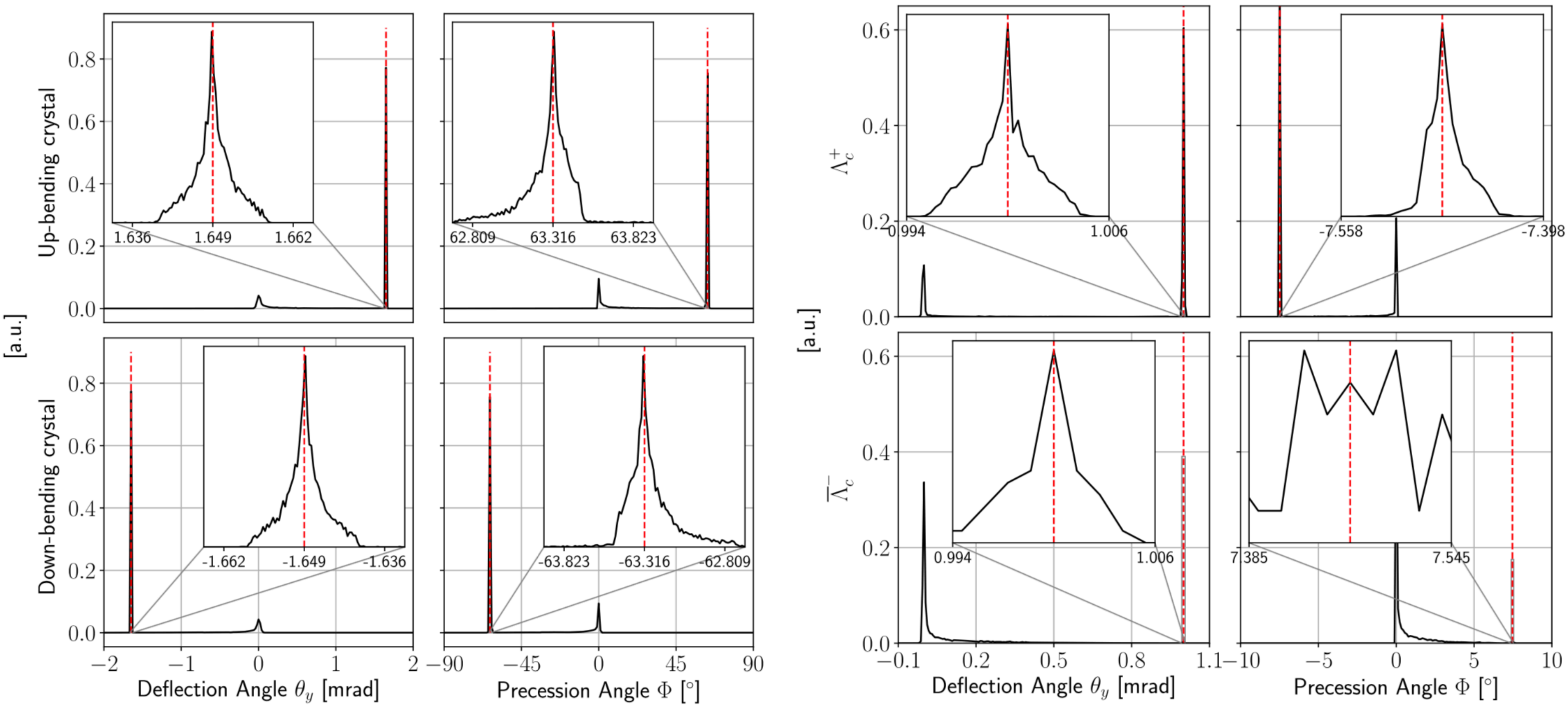
- MDM and EDM precession in the limit $\gamma \gg 1$, $d \ll g-2$

$$\Phi \approx \frac{g-2}{2}\gamma\theta_C \approx \frac{\pi}{2} \qquad S_x \approx S_0 \frac{d}{g-2}[\cos(\Phi) - 1]$$

GEANT4 simulations of spin precession

Σ^+ baryon at 375 GeV/c

Λ_c^+ baryon at 1 TeV/c



EPJC (2017) 77:828

- GEANT4 simulations of MDM/EDM spin precession in bent crystals in **agreement** with analytical calculations

Experimental proposal

Baryon	Requirements	EDM	MDM
Charm Λ_c^+, Ξ_c^+ lifetime $\sim 10^{-13}$ s	**Polarised baryons** Reconstruct **TeV baryons** uniquely produced at LHC Crystal **channeling,** effective **B field** $\approx 10^3$ T	First search sensitivity $\sim$**10^{-17} e cm**	First measurement for **QCD** & baryon internal structure test **<10^{-3} precision**

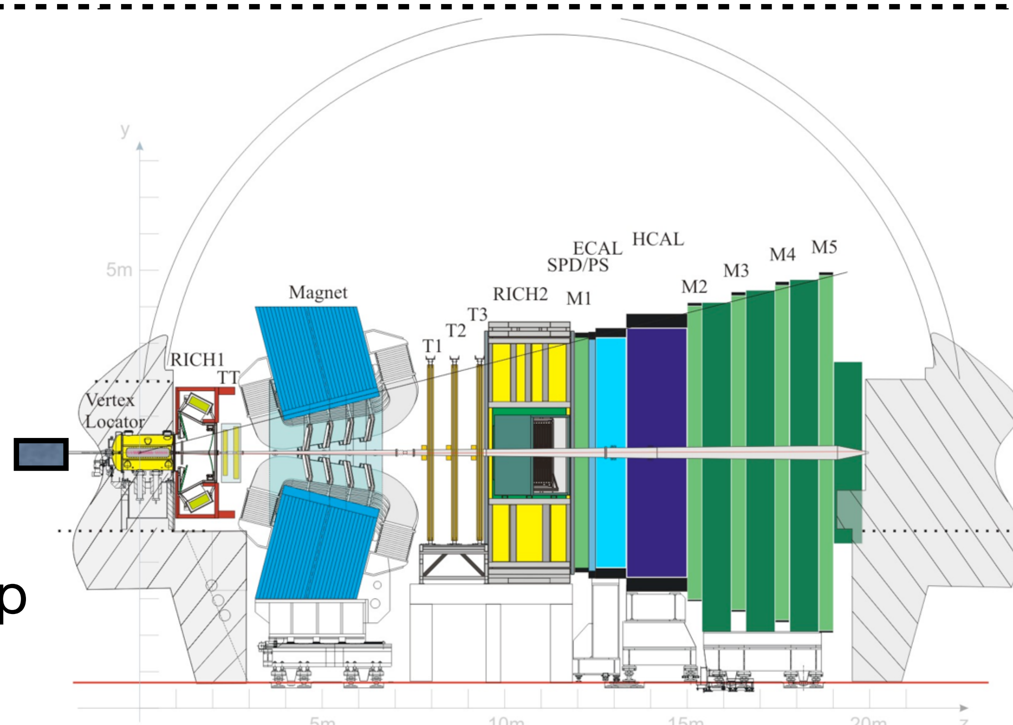
Experimental solution

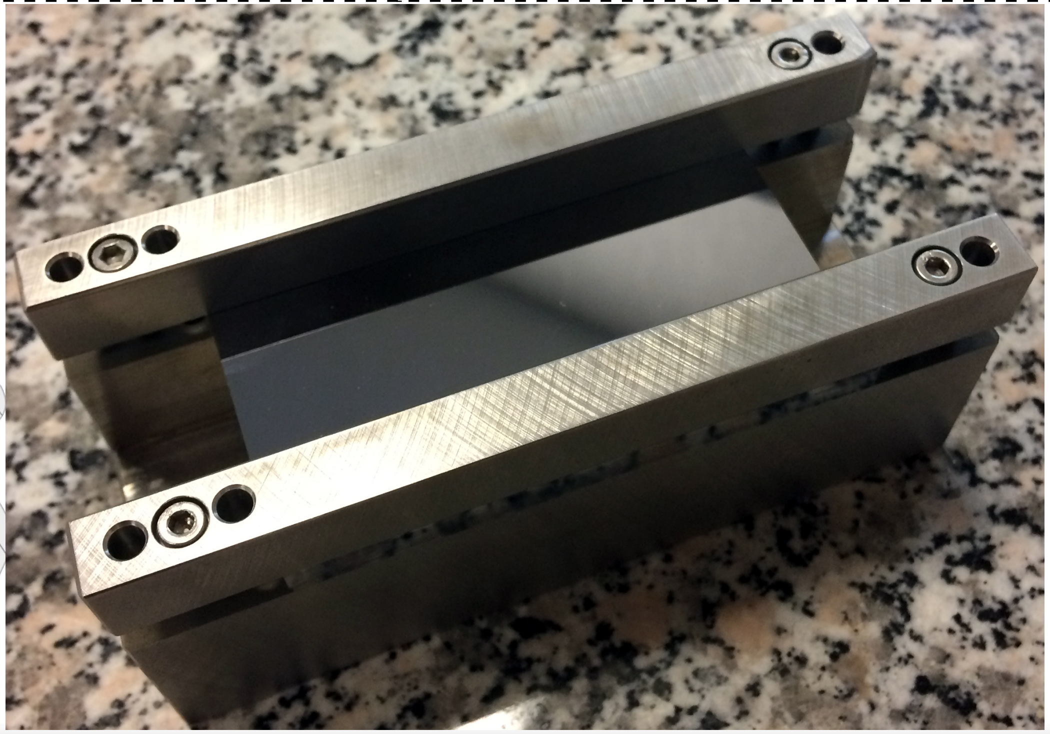
- Strong production of charm baryons in **fixed target**
- Use **LHCb** forward detector
- Crystal with **large bending angle** to deflect particles in detector acceptance $\gtrsim$ **15 mrad**

Experimental proposal

Baryon	Solution	EDM	MDM
Charm Λ_c^+, Ξ_c^+ lifetime $\sim 10^{-13}$ s	EPJC (2017) 77:181 **Fixed target setup** **LHCb detector** **Long bent crystals**	First search sensitivity **$\sim 10^{-17}$ e cm**	First measurement for **QCD** & baryon internal structure test **$<10^{-3}$ precision**

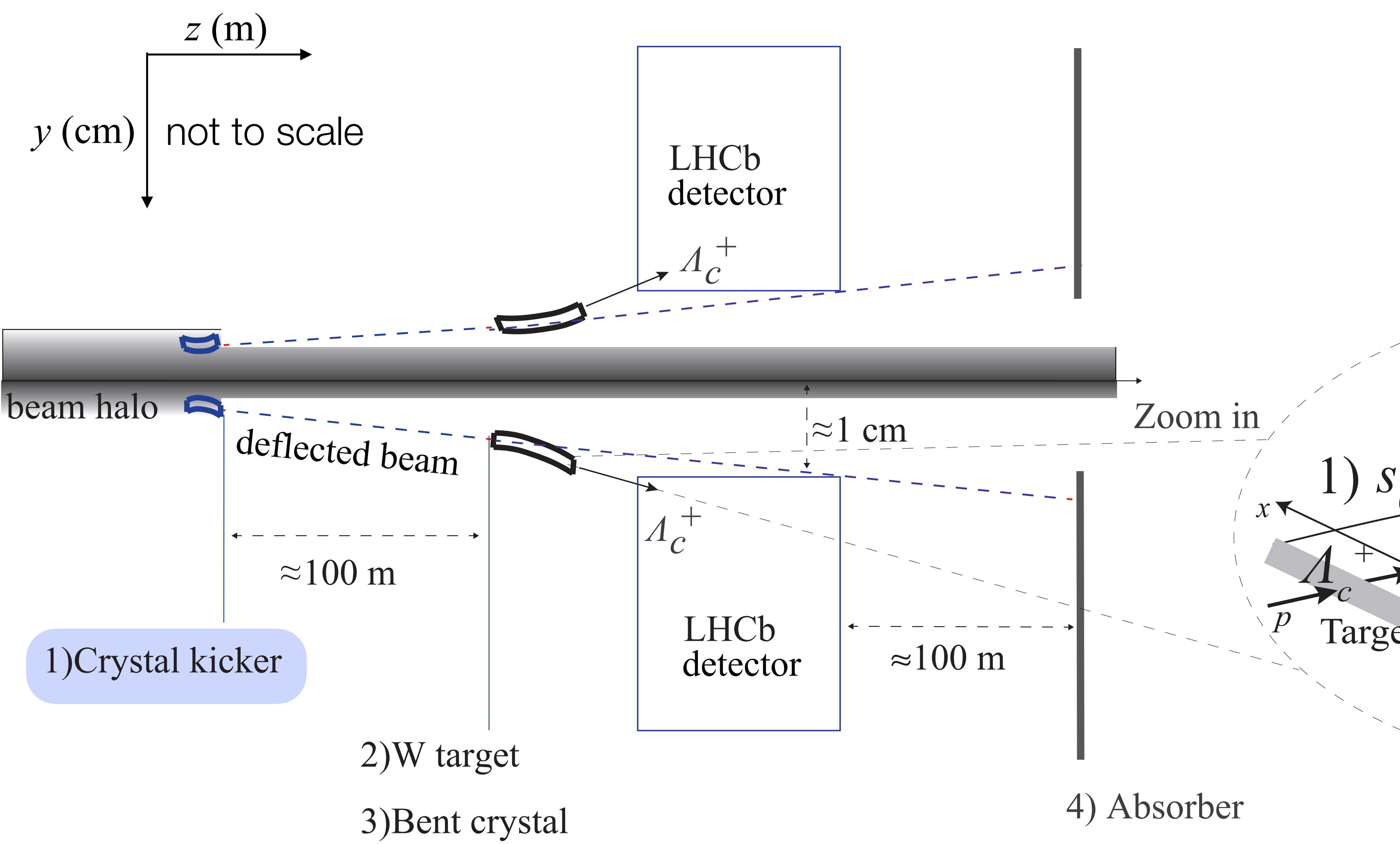
Fixed-target setup

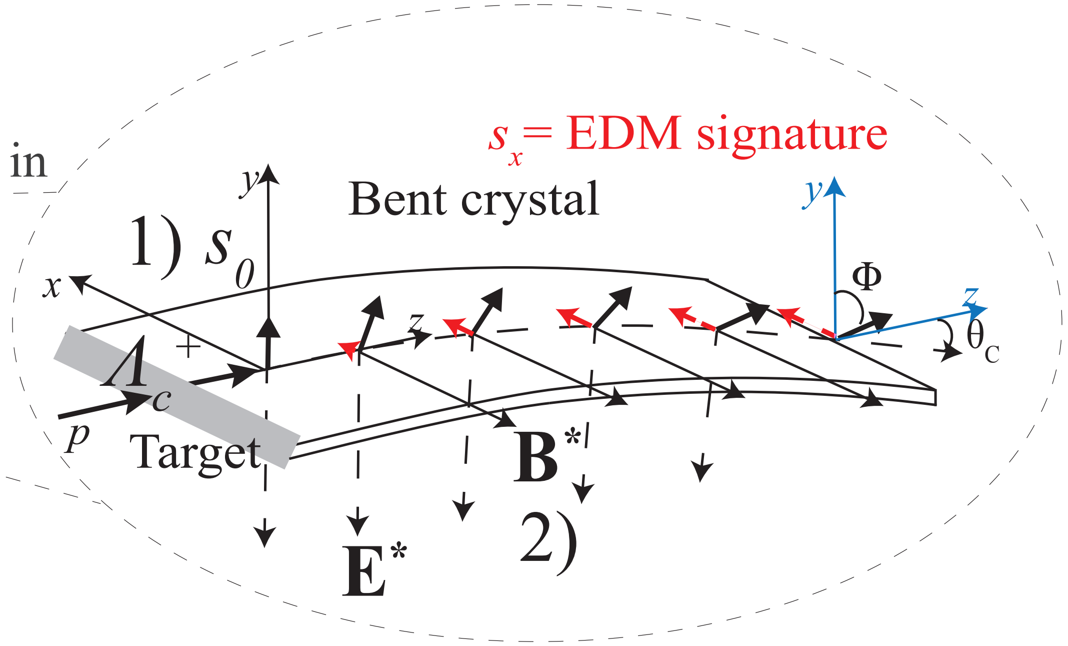


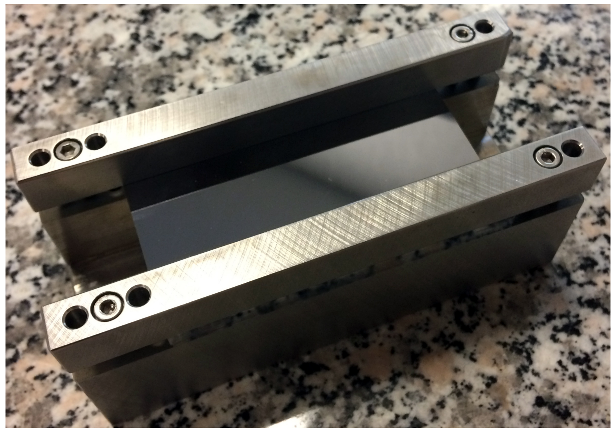


Novel fixed-target experiment at LHC for charm baryons

- EDM/MDM from spin precession of channeled baryons in **bent crystals**



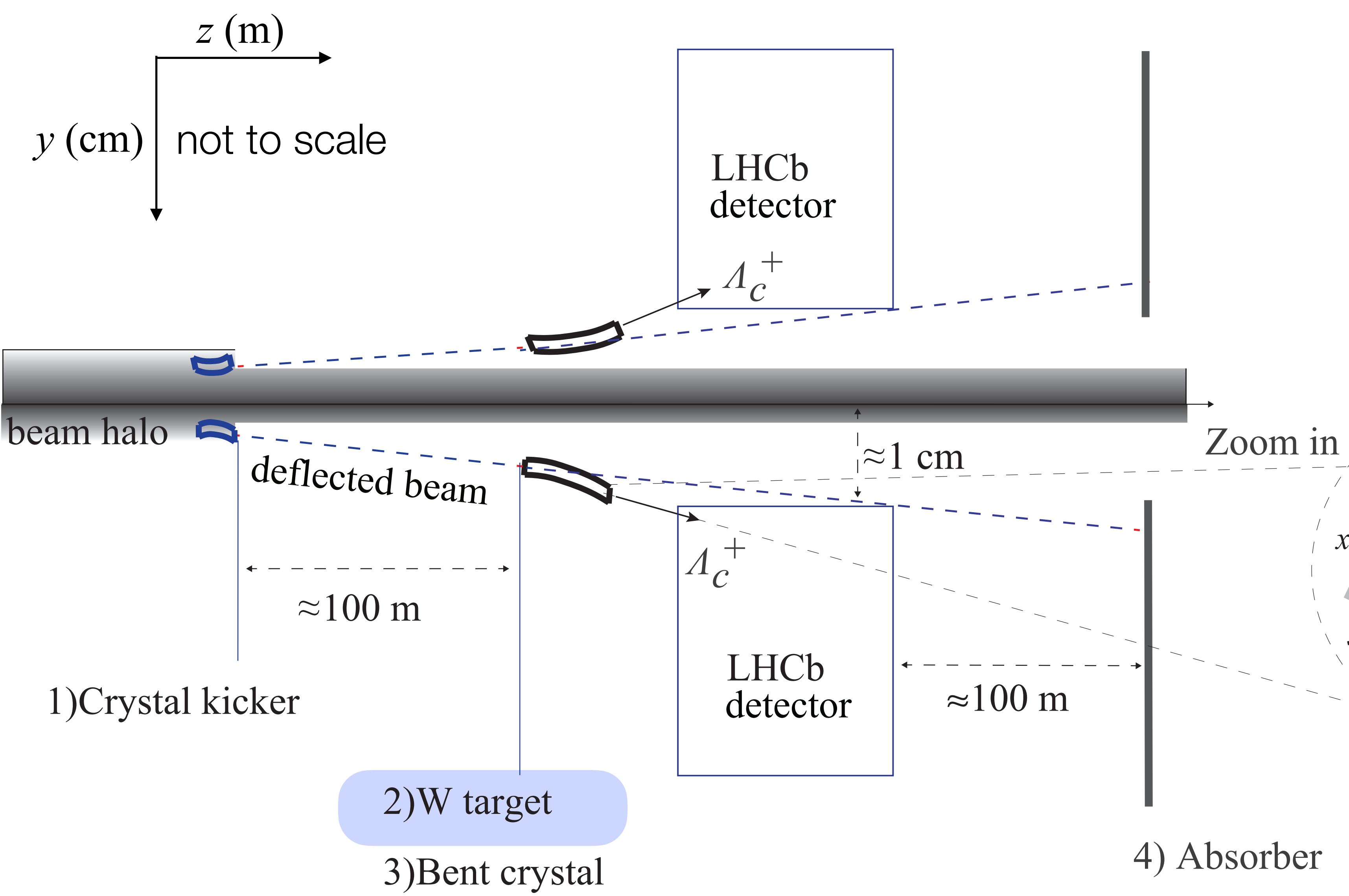


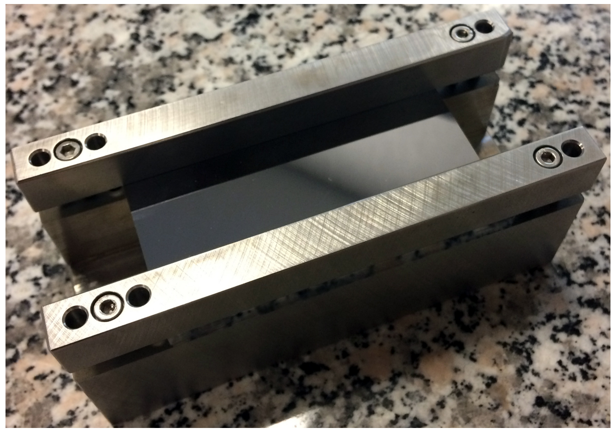


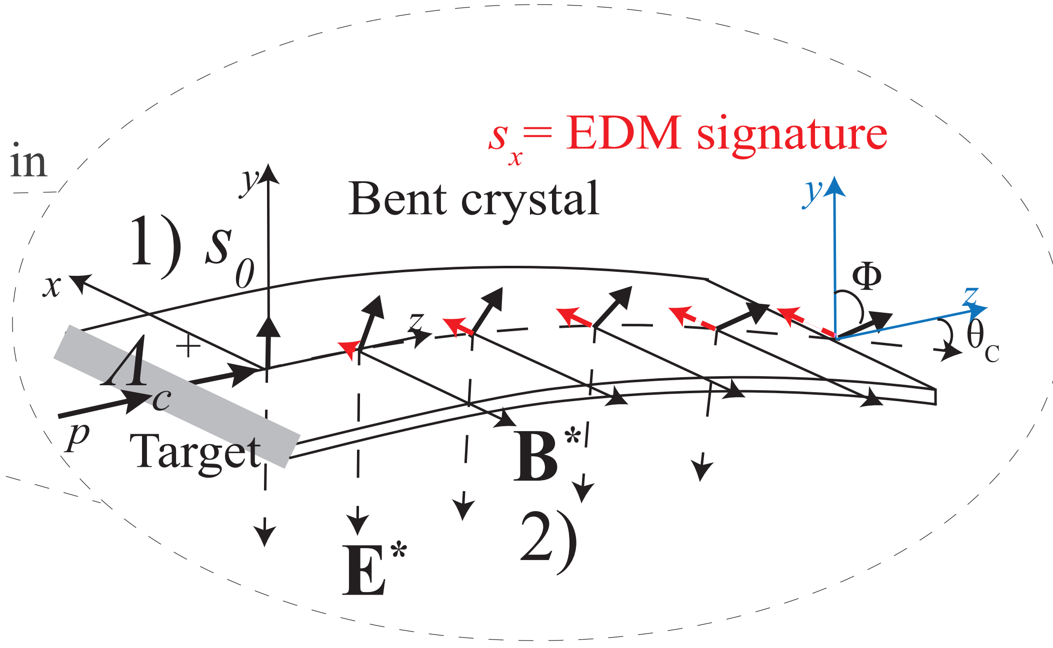
p extraction

Novel fixed-target experiment at LHC for charm baryons

- EDM/MDM from spin precession of channeled baryons in **bent crystals**



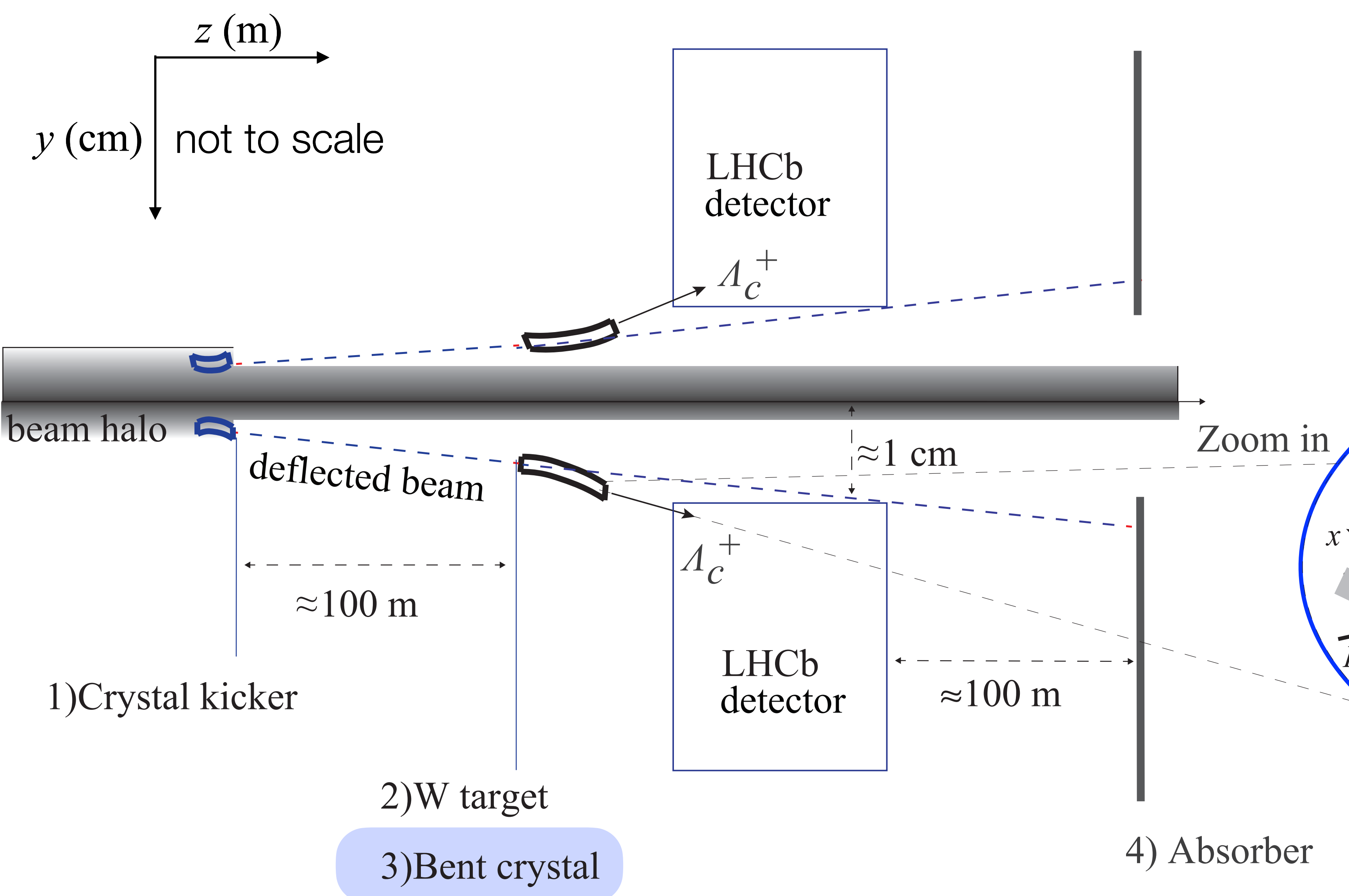


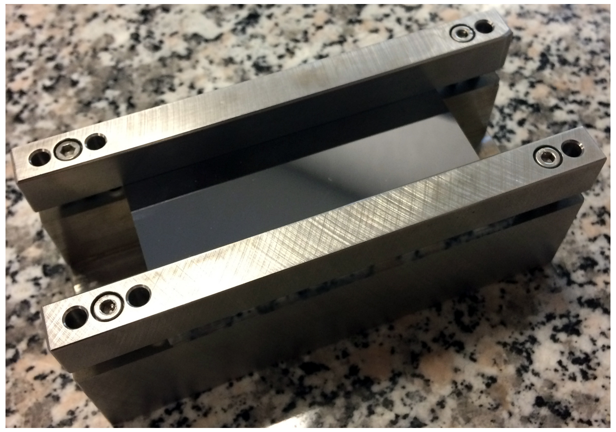


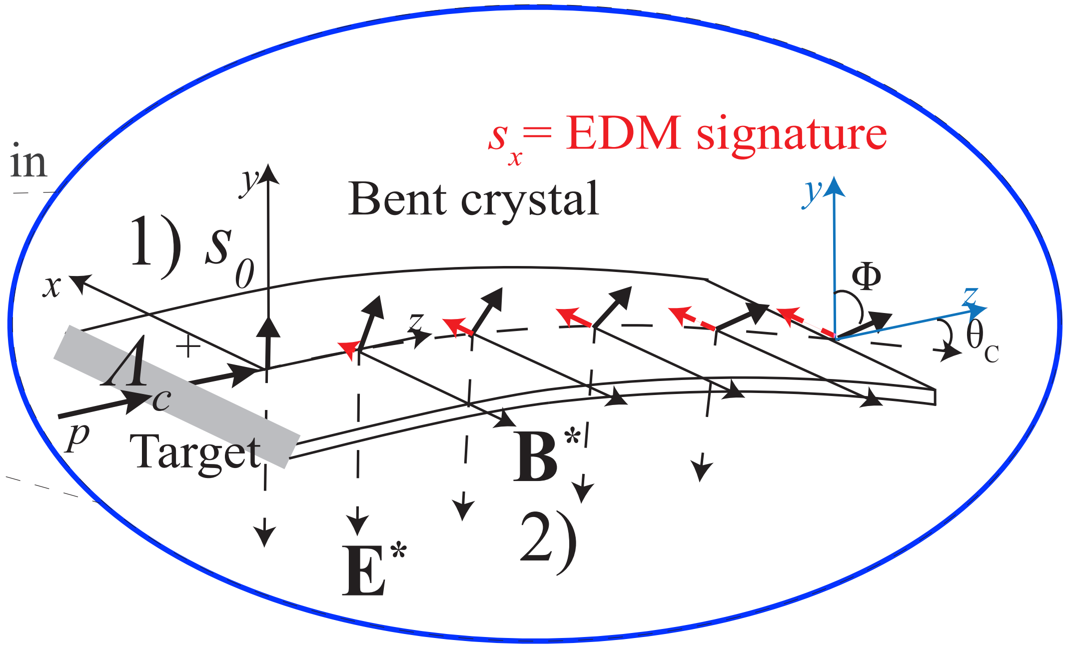
p extraction Λ_c^+ polarised production

Novel fixed-target experiment at LHC for charm baryons

- EDM/MDM from spin precession of channeled baryons in **bent crystals**



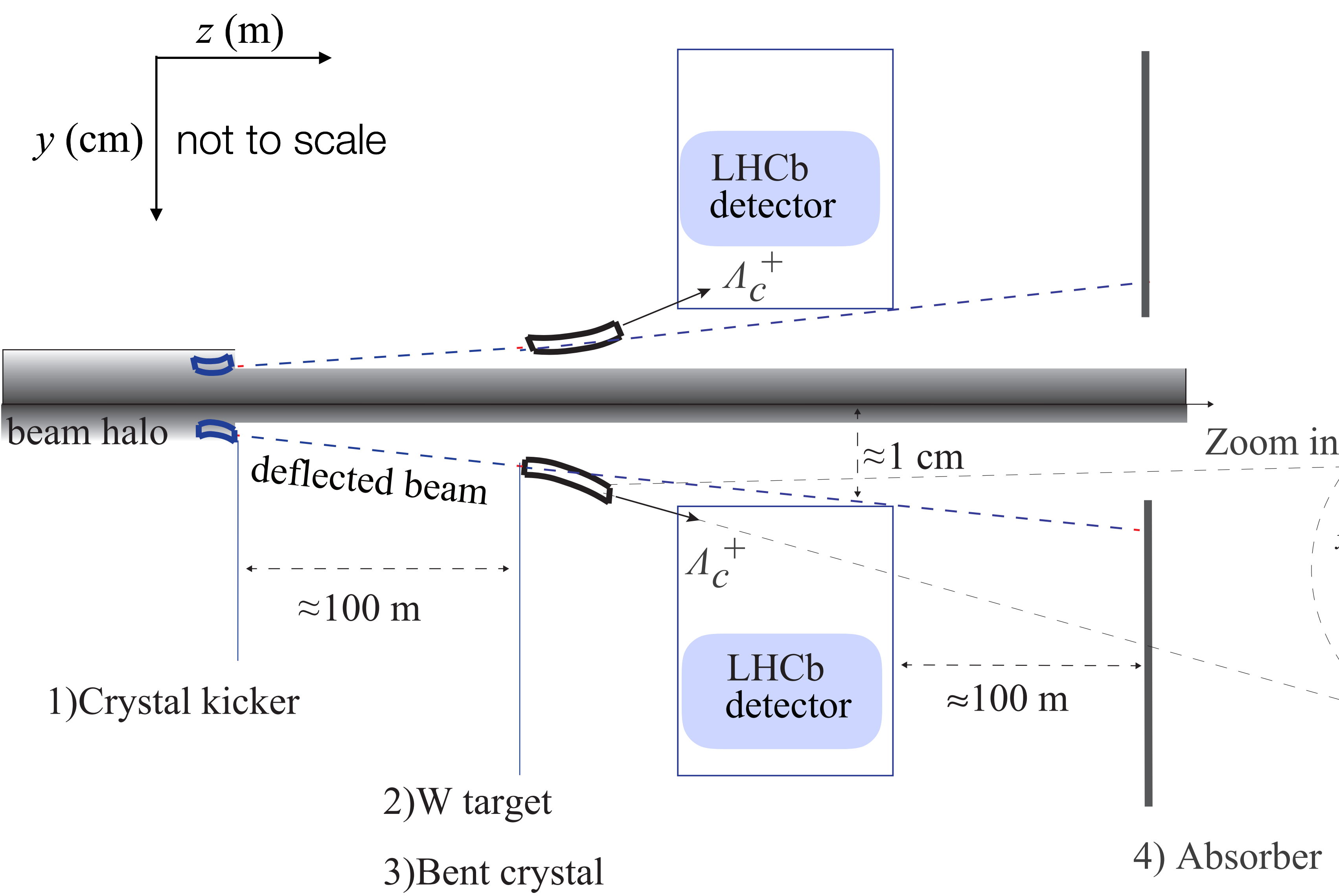


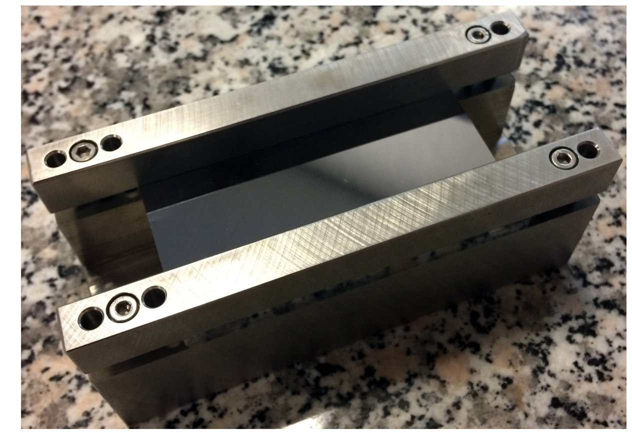


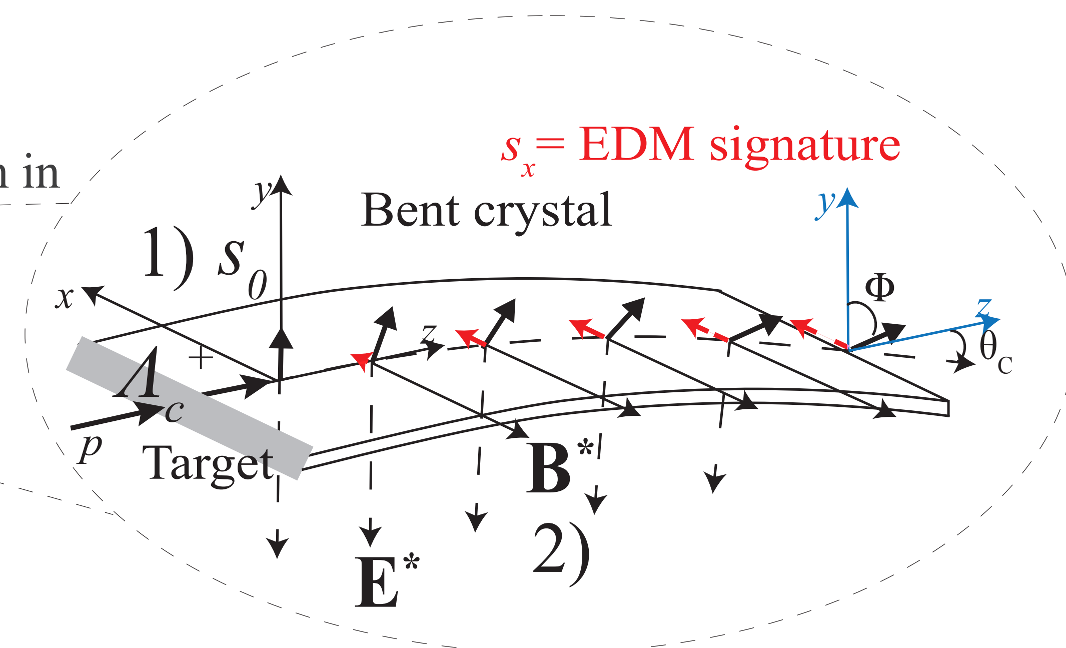
p extraction Λ_c^+ polarised production channeling spin precession

Novel fixed-target experiment at LHC for charm baryons

- EDM/MDM from spin precession of channeled baryons in **bent crystals**







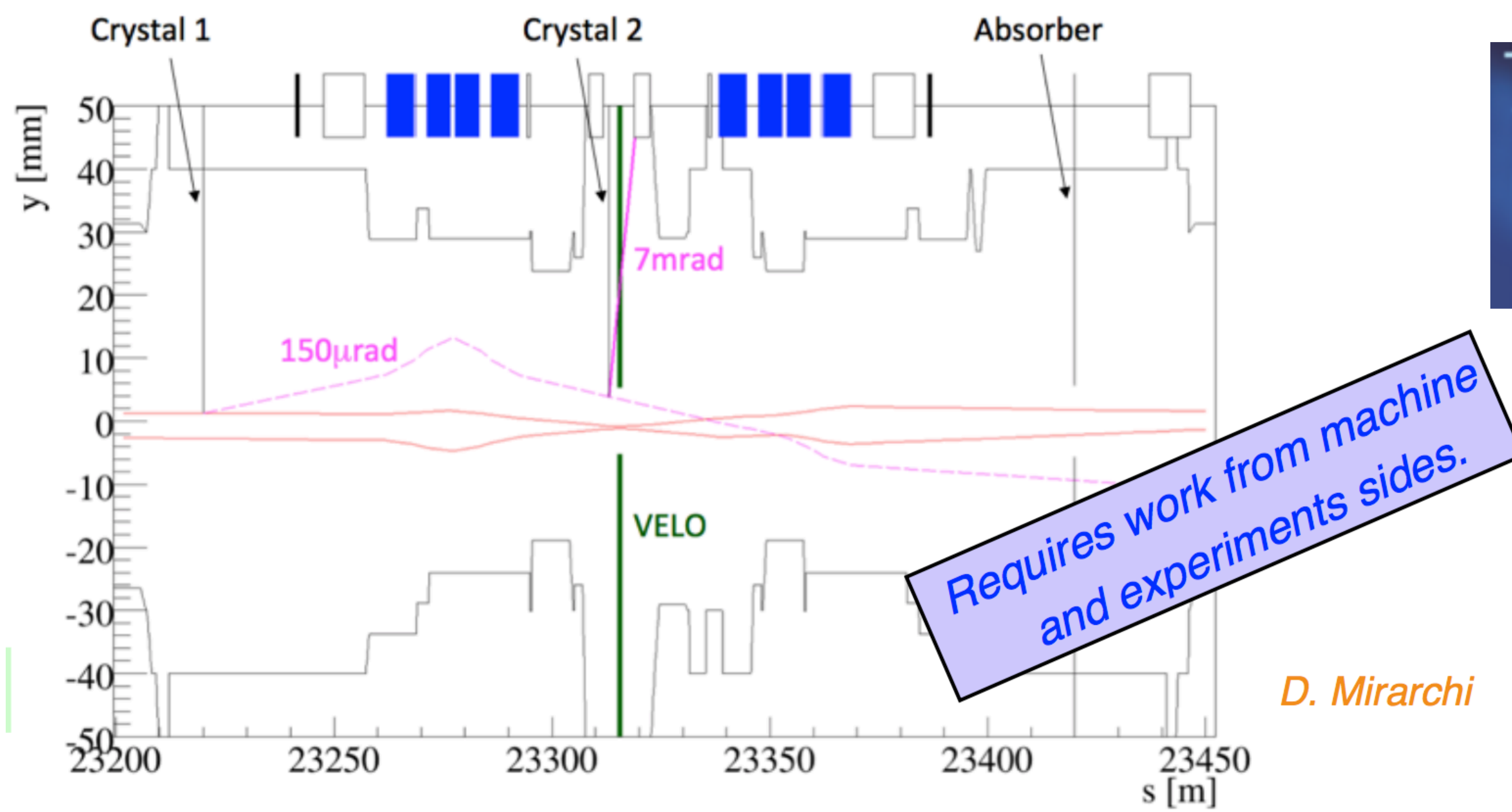
p extraction Λ_c^+ polarised production channeling spin precession event reconstruction

Detector simulation studies

Possible implementation at IP8

W. Scandale, Physics Beyond Colliders, 06/09/2016

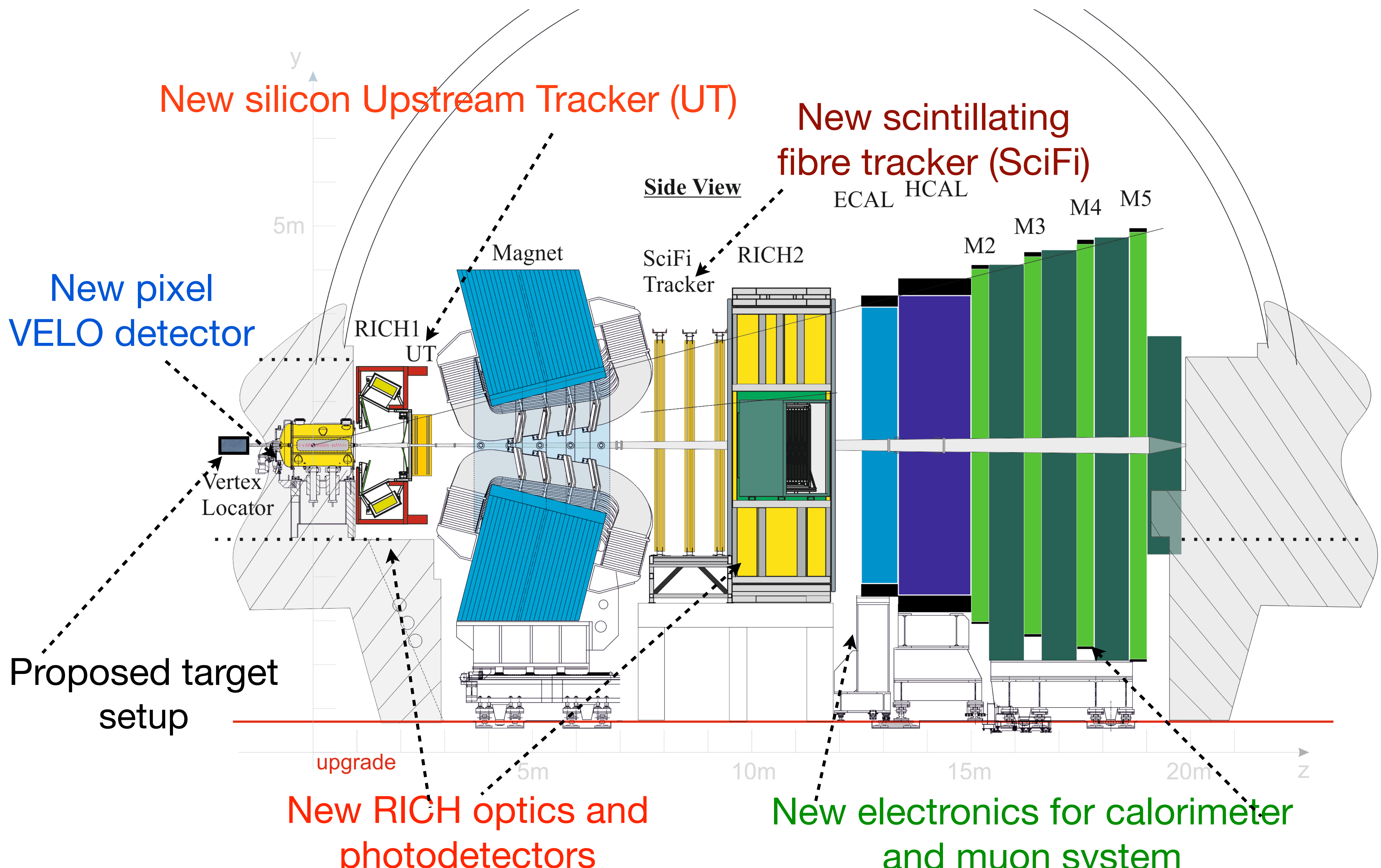
S. Redaelli, Physics Beyond Colliders, 01/03/2017



- **Channeling** of 6.5 TeV **at LHC** already **demonstrated** by UA9 collaboration W. Scandale et al., PLB 758 (2016) 129–133
- Detailed machine **simulations** are ongoing for **optimal layout** by the LHC collimation group lead by S. Redaelli

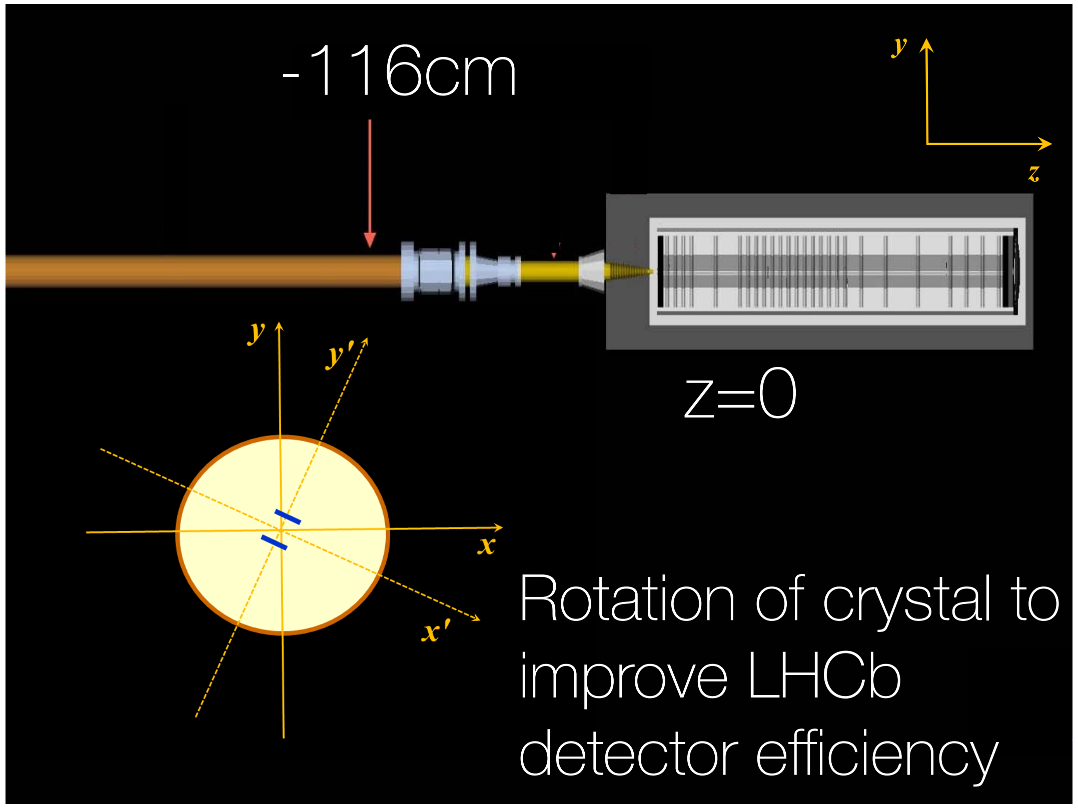
LHCb Upgraded detector

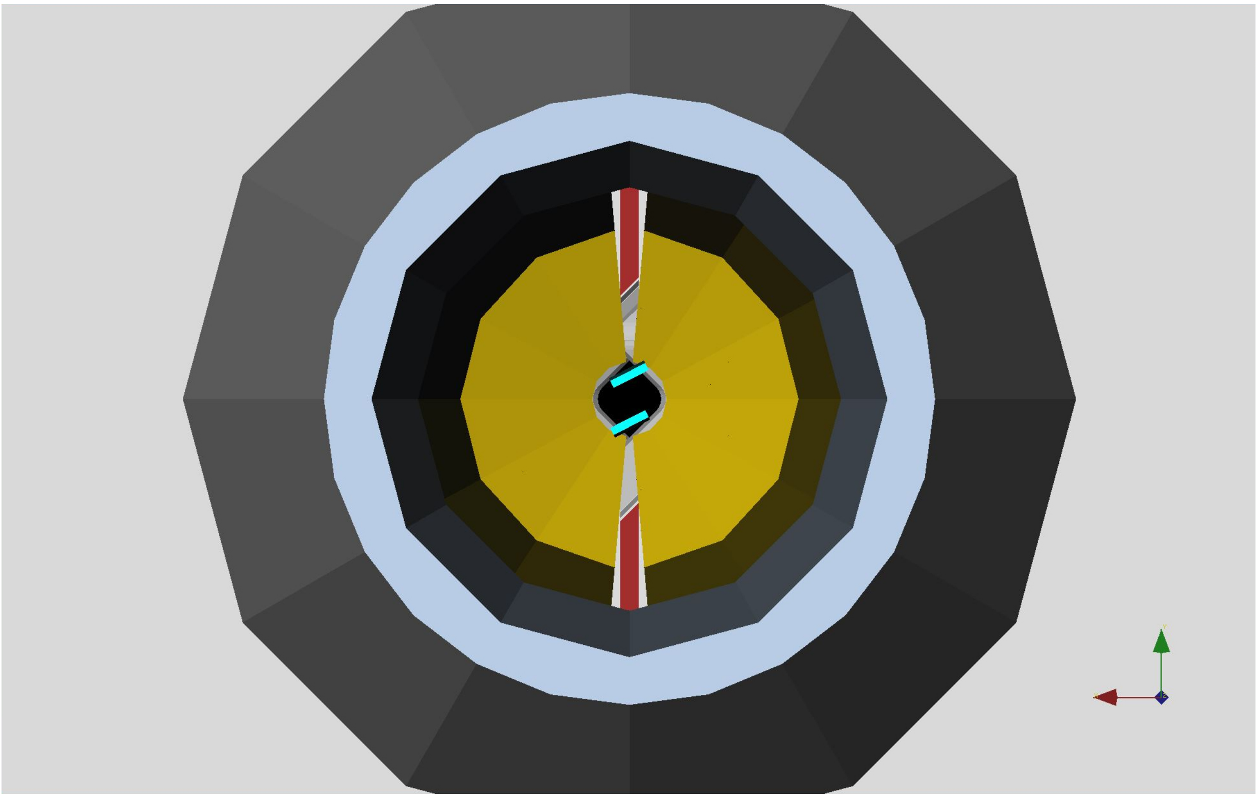
All sub-detectors read out at 40 MHz for a **fully software trigger**



Simulation studies

- Tungsten (W) 5 mm fixed target + bent crystal positioned in (0, 0.4, -116) cm, before the interaction point



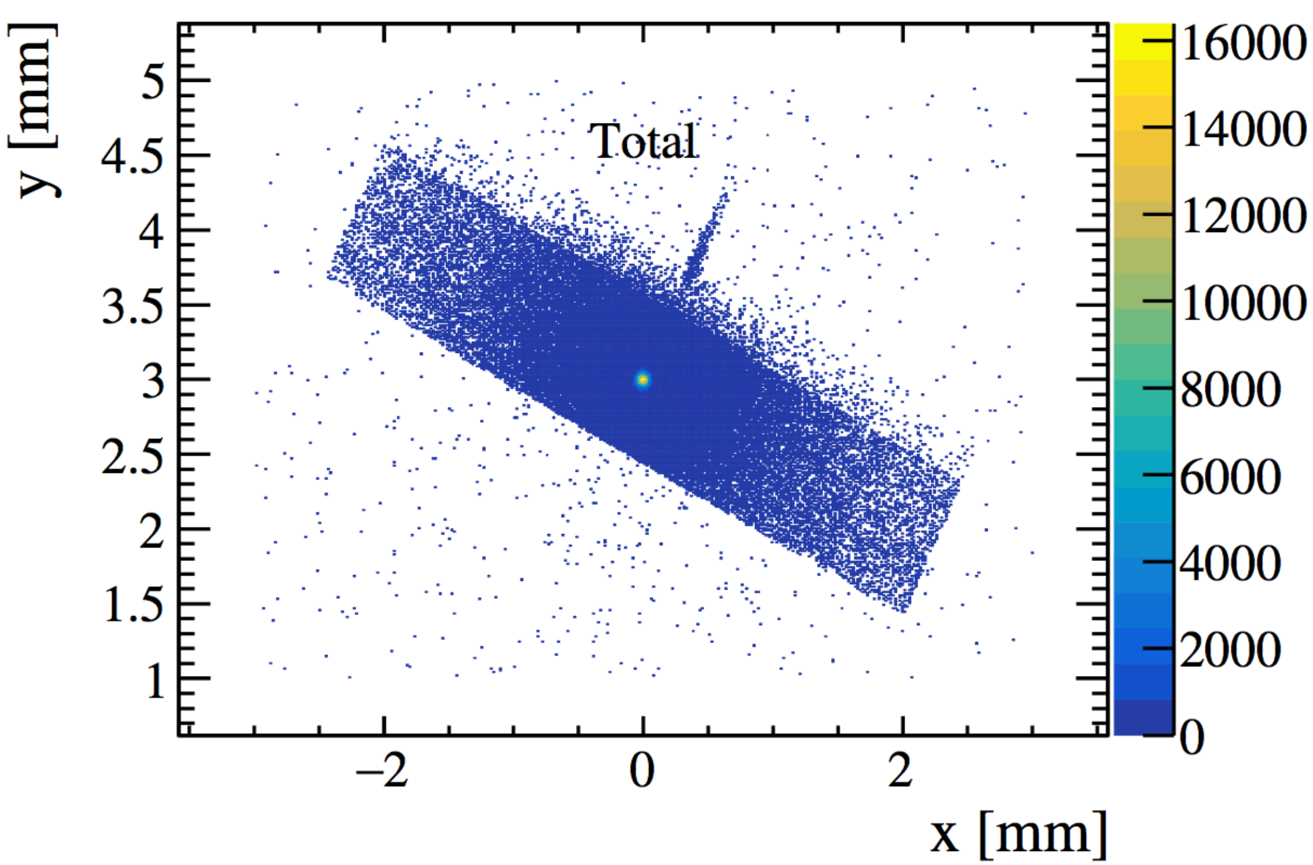


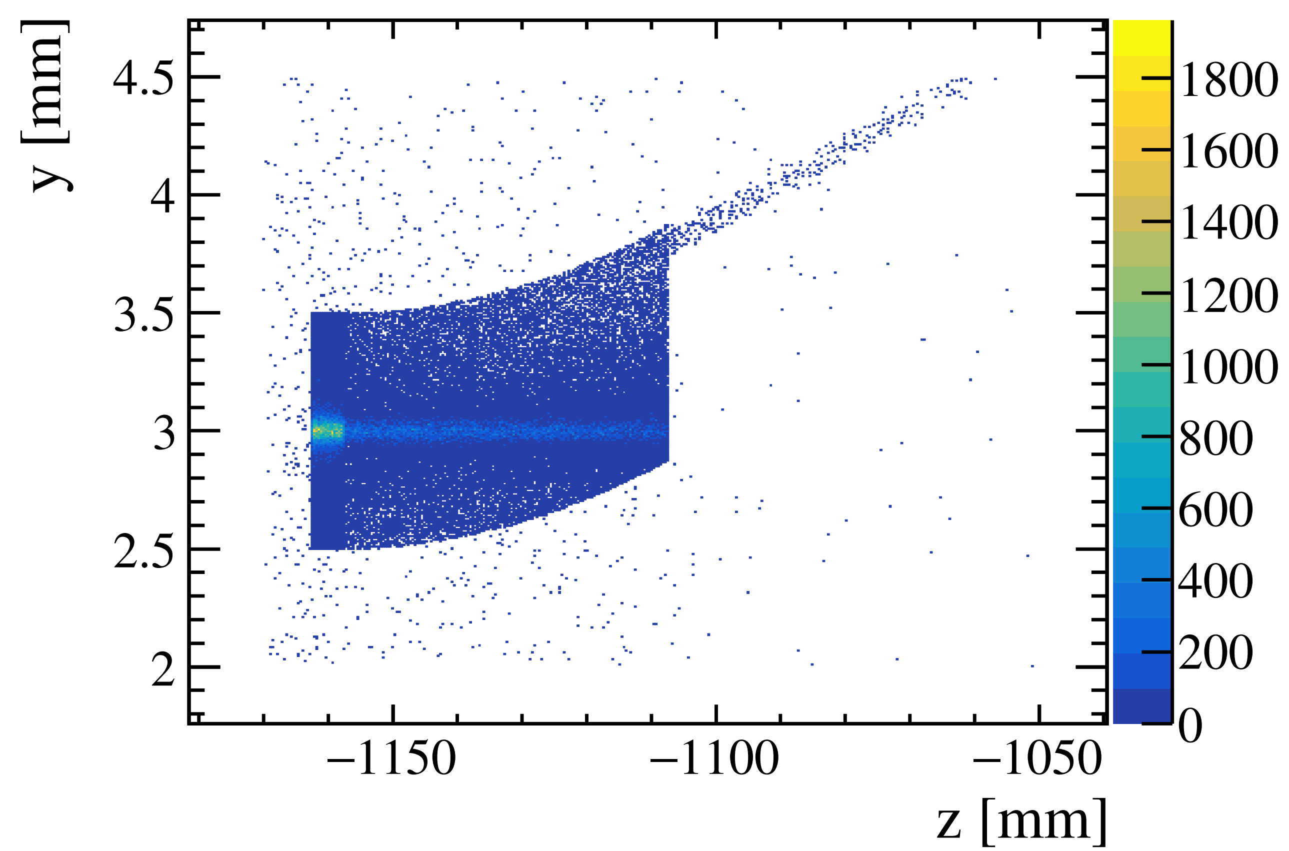
- Use EPOS for fixed-target minimum bias events, PYTHIA for baryons produced in pW hard collisions

- Signal reconstruction and background rejection studied using LHCb full simulation

Fixed-target simulation

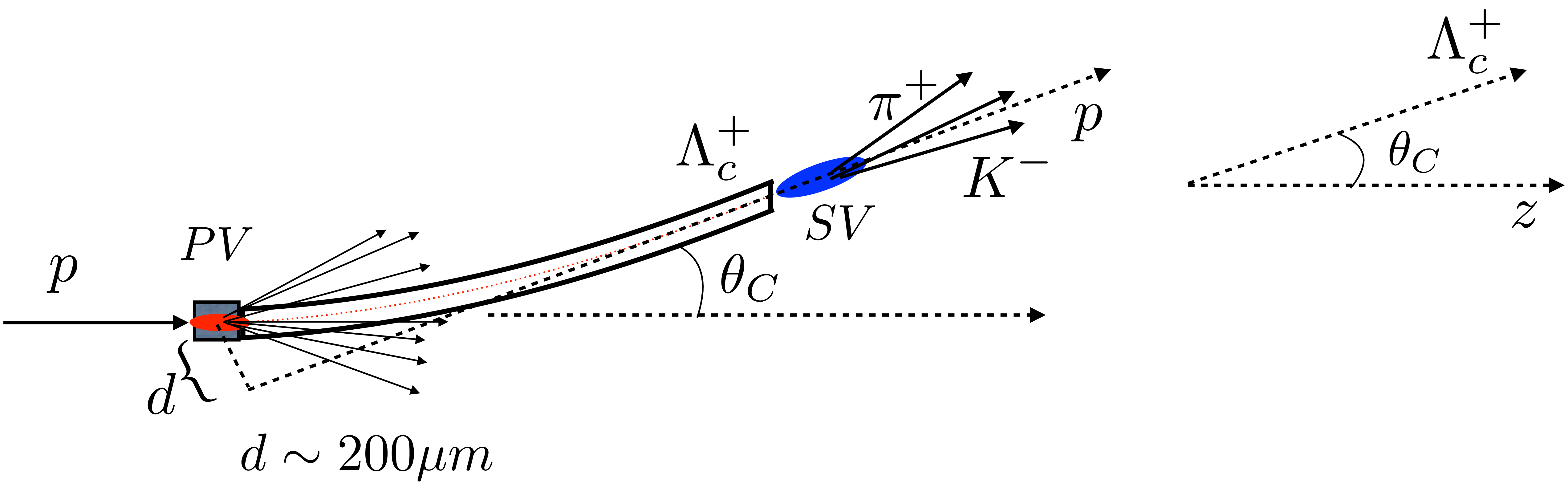
- Radiography of the target in (0, 0.3, -116) cm
- Distribution of origin vertex of stable charged particles in simulated events
- Simulated processes include: hadronic interactions, pair production, Bremsstrahlung, Compton, δ rays





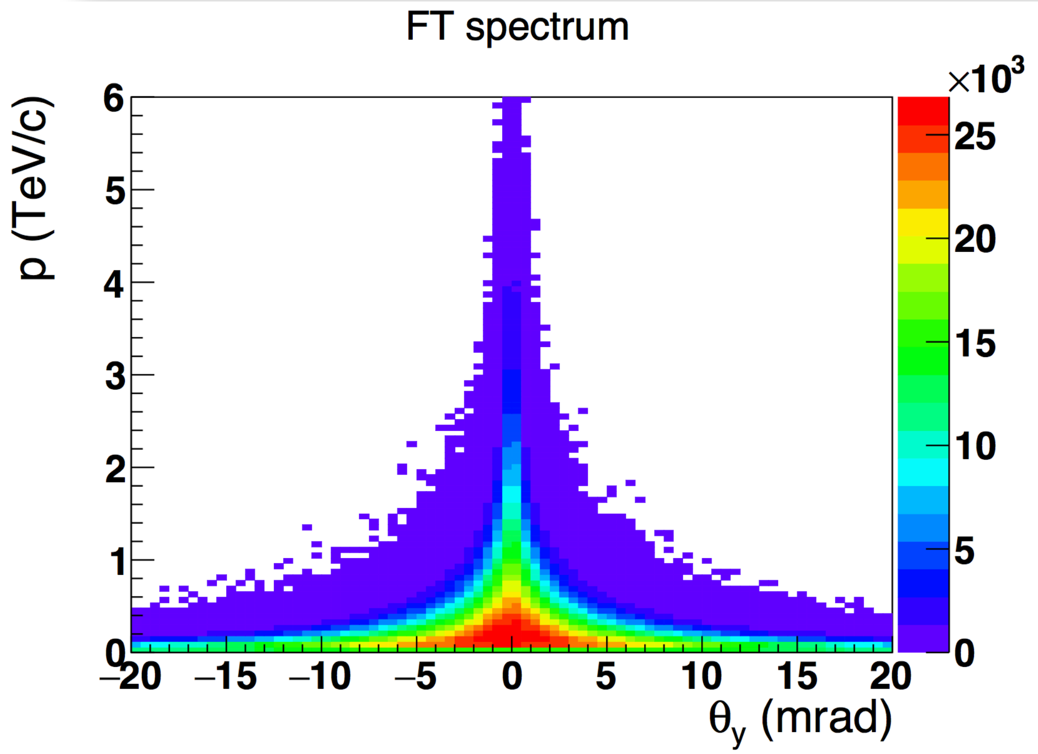
Identification of signal events

- About 10^{-4} Λ_c^+ produced in the target are channeled in the bent crystal



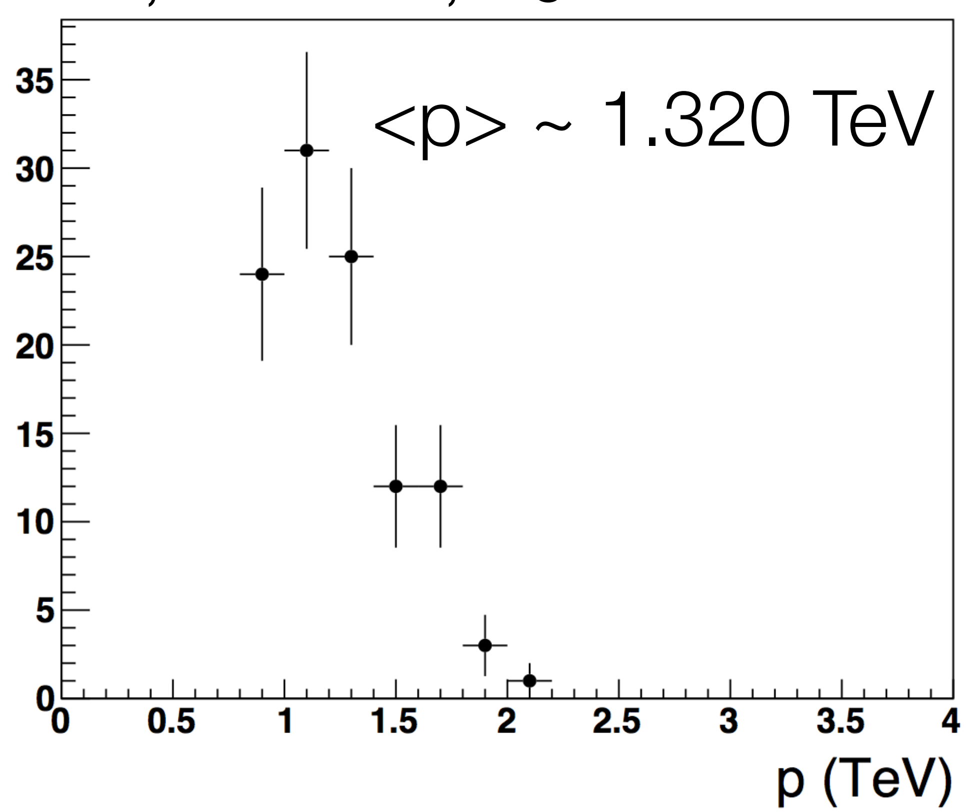
- Use PV to identify Λ_c^+ produced in W target, and Λ_c^+ vertex helps to identify decays outside of the crystal (max spin precession)
- Λ_c^+ angle determined by crystal bending angle, e.g. θ_C=15 mrad
- Channeled baryons have high momentum ≳1 TeV/c

Λ_c^+ momentum distribution

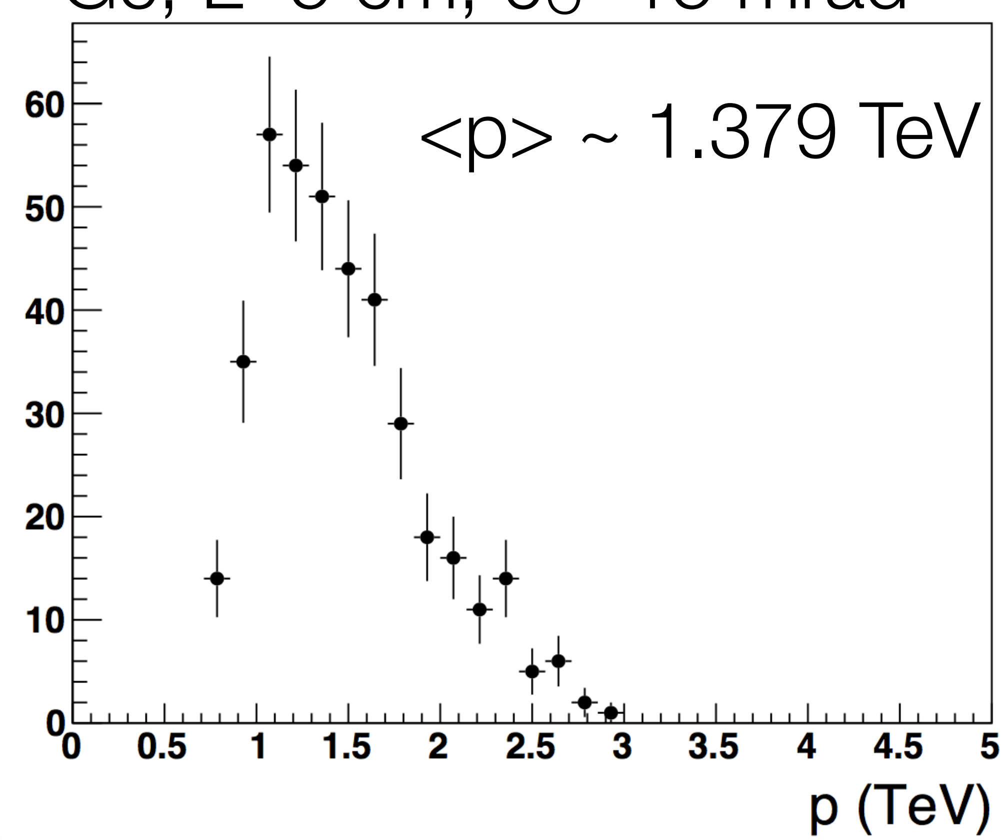


- At production (top)
- After channeling and p>800 GeV/c (bottom)

Si, L~7 cm, θ_C~14 mrad

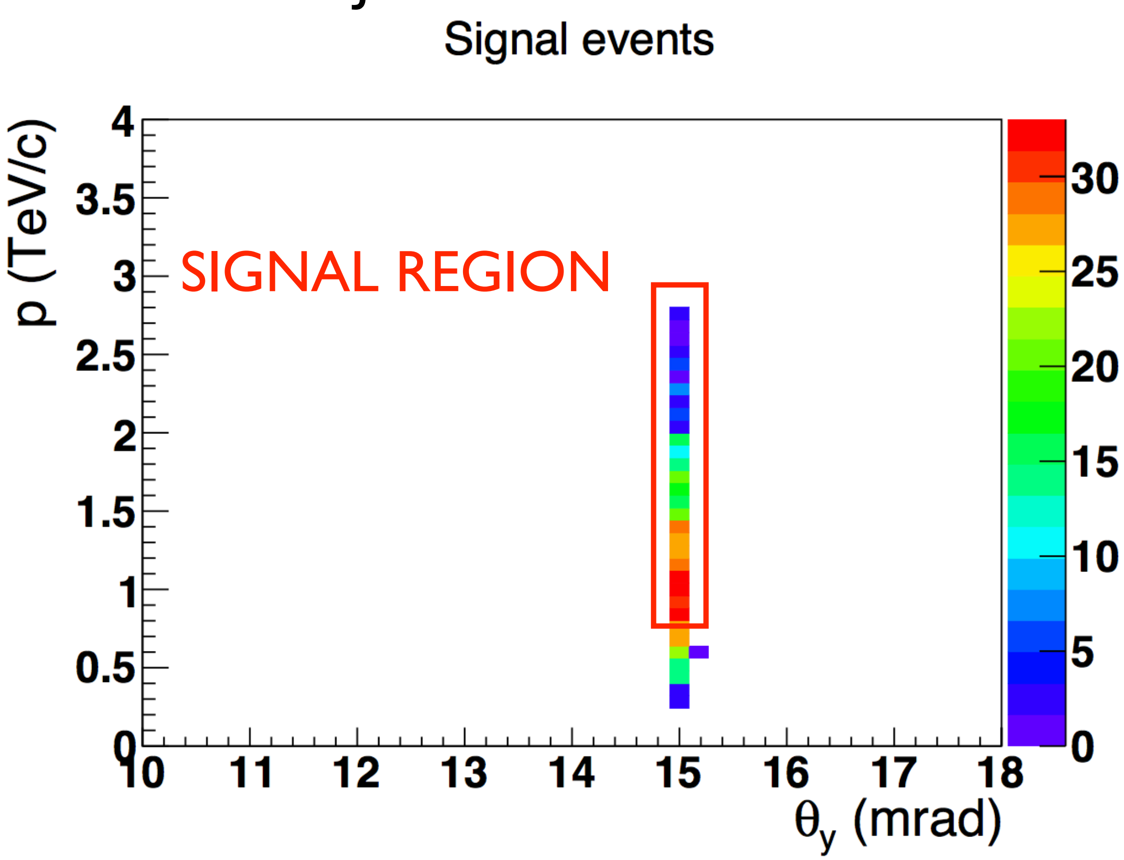


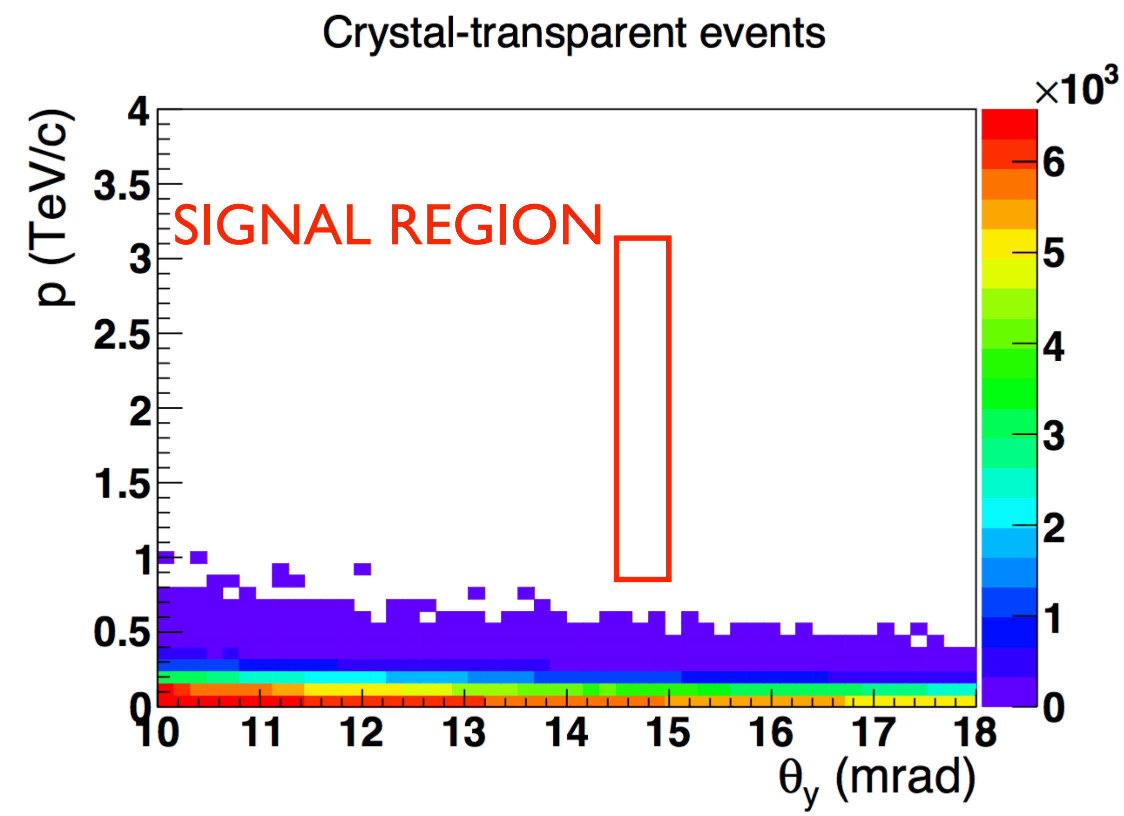
Ge, L~5 cm, θ_C~15 mrad



Background rejection

- Rejection of unchanneled Λ_c^+ produced in W target





Channeled particles

Unchanneled particles

- Signal region: 14.8<θ<15.2 mrad [σ(θ)~25μrad], $p_{\Lambda c}$> 800 GeV/c
- Background rejection 10^{-7} level and signal efficiency 80%
- High momentum Λ_c^+ most sensitive for EDM measurements

EDM/MDM sensitivity studies

Sensitivity to EDM/MDM

- Studies based on:
  - Λ_c^+ from fixed-target (Pythia + EvtGen)
  - Reconstruction, Decay flight efficiency (LHCb simulation)
  - Channeling efficiency (parametrization)
  - Fit to spin precession (pseudo experiments)

$$\boxed{N_{\Lambda_c^+}^{\text{reco}} = N_{\Lambda_c^+}\mathcal{B}(\Lambda_c^+ \to f)\varepsilon_{\text{CH}}\varepsilon_{\text{DF}}\varepsilon_{\text{det}}}$$

$$\sigma(pp \to \Lambda_c^+ X) \approx 18.2\mu\text{b}$$

$$|S_0| \approx 0.6$$

$$\epsilon_{\text{det}} \approx 20\,\% \qquad \epsilon_{\text{DF}} \approx 10\,\%$$

$$\epsilon_{\text{ch}} \approx 10^{-4}$$

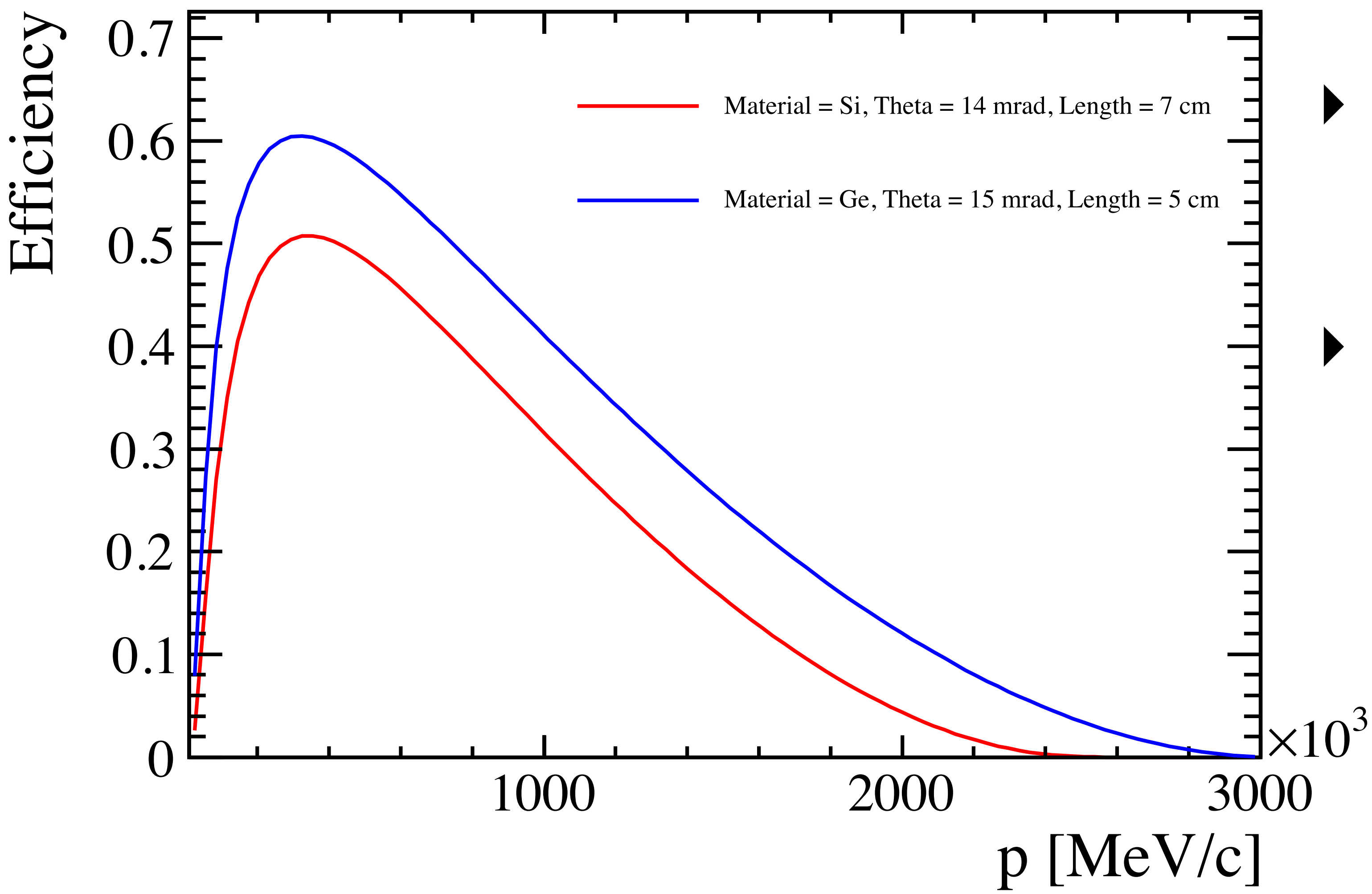
$$\frac{dN}{d\Omega} \propto 1 + \alpha_f\, \boldsymbol{S}\cdot\boldsymbol{p}$$

$$\alpha_{\Delta^{++}K^-} \approx -0.67$$

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

$$\boxed{\sigma_g \approx \frac{2}{\alpha_f s_0 \gamma \theta_C} \frac{1}{\sqrt{N_{\Lambda_c^+}^{\text{reco}}}}}$$

Channeling efficiency



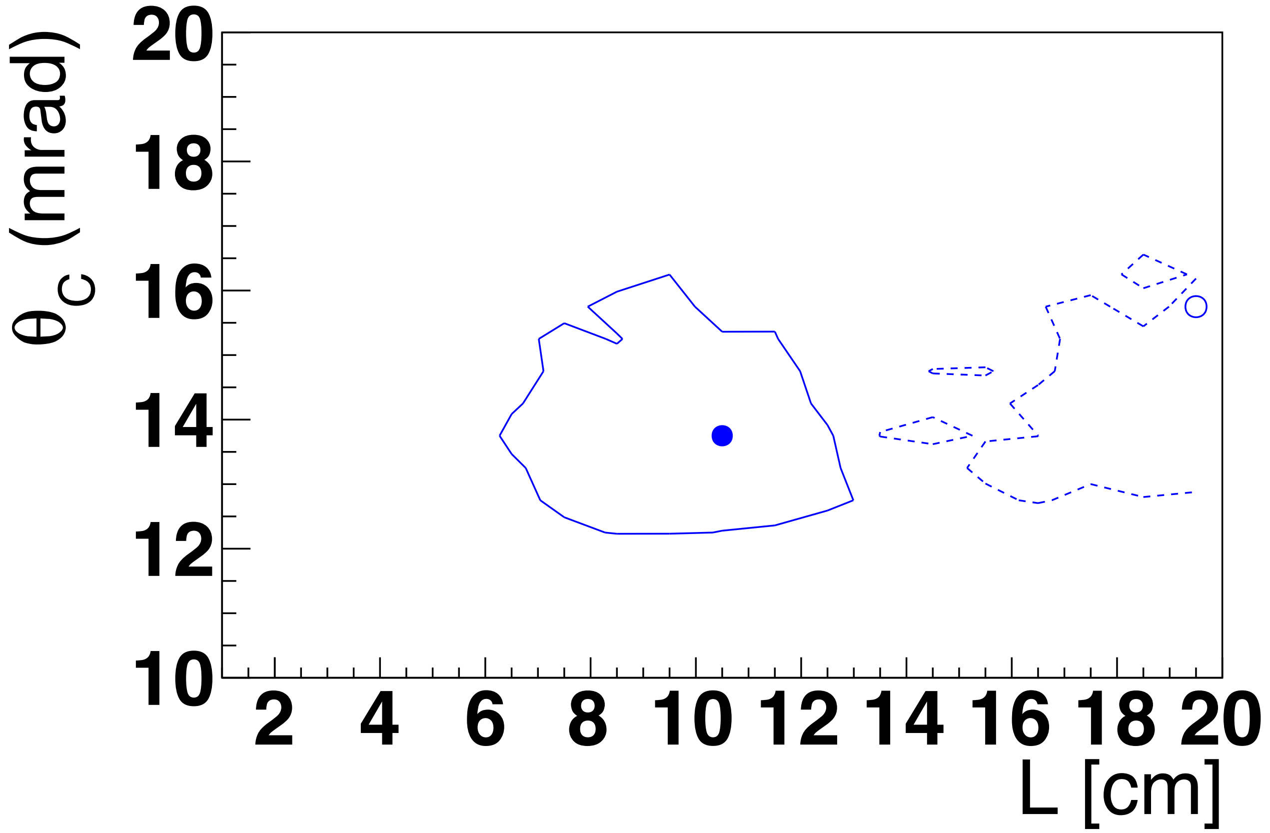
$$w(\theta_C, R) = \left(1 - \frac{R_c}{R}\right)^2 \exp\left(-\frac{\theta_C}{\theta_D \frac{R_c}{R}(1 - \frac{R_c}{R})^2}\right)$$

- Channeling efficiency for Λ_c^+ particles within Lindhard angle
- Total channelling efficiency: Lindhard angle, dechanneling, Λ_c^+ decay flight: $1 \cdot 10^{-5}$ (Si), $4 \cdot 10^{-5}$ (Ge)
- Parametrisation from Biryukov, Valery M. (et al.), *Crystal Channeling and Its Application at High-Energy Accelerators*, Springer Verlag (1997)

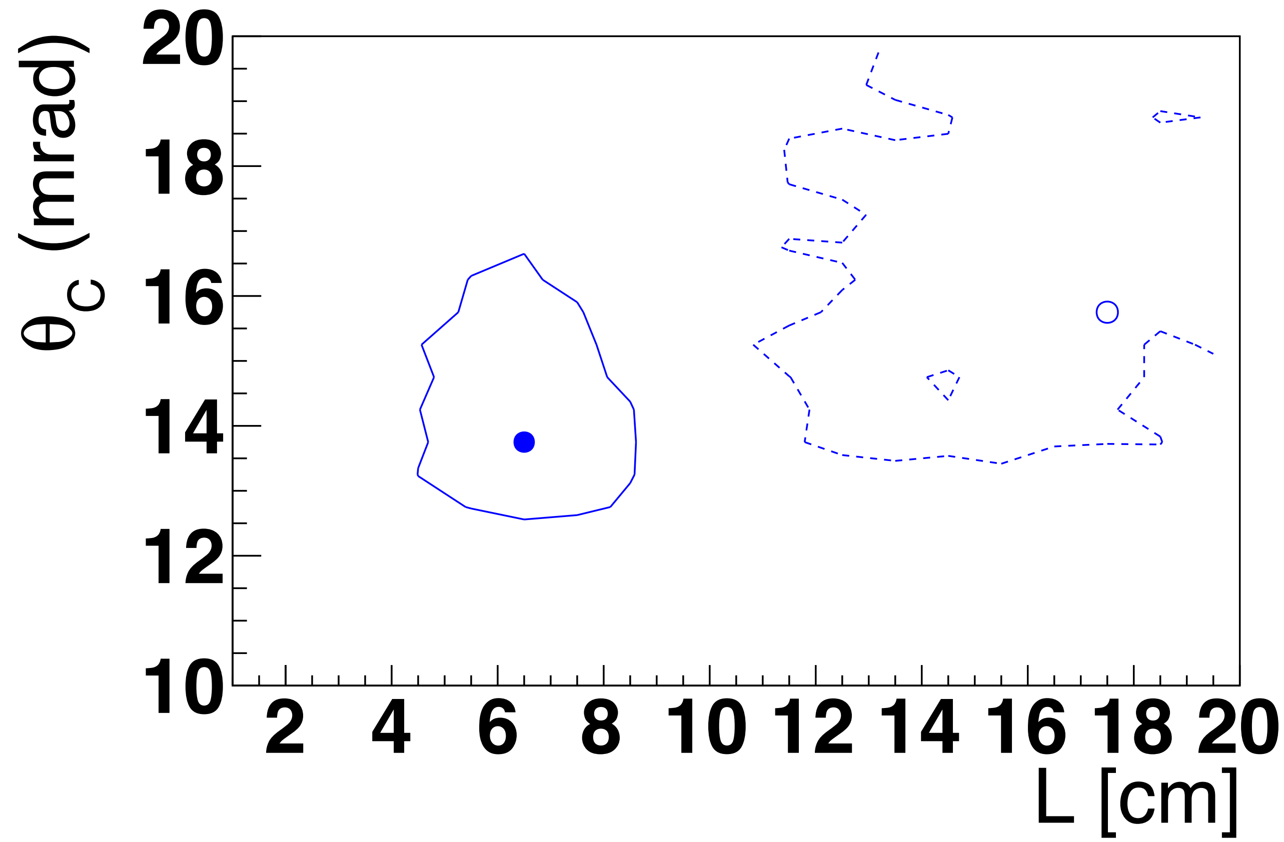
Crystal optimisation

- Optimised sensitivity to EDM and MDM.
  Channeling and reconstruction efficiency included

Si crystal



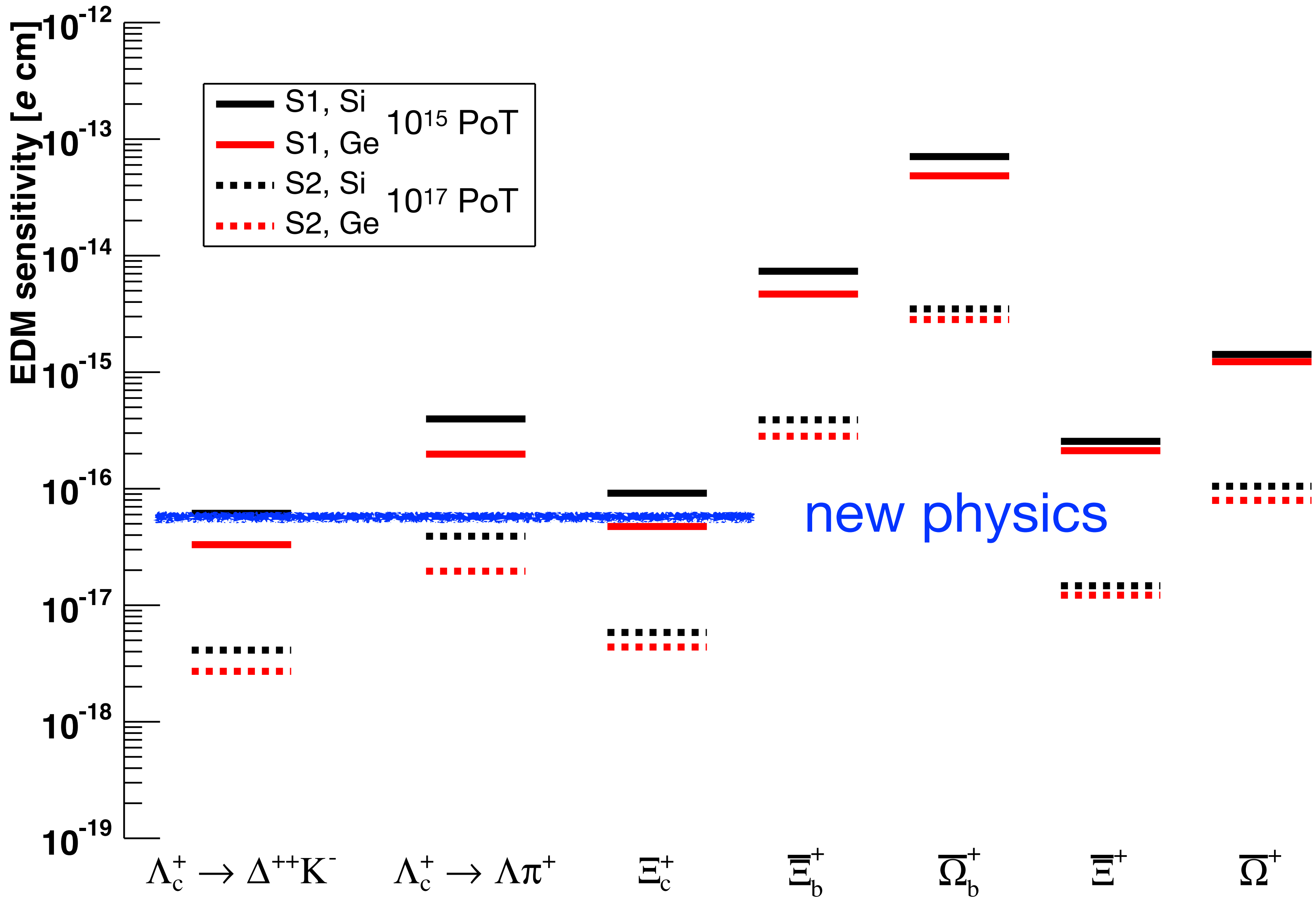
Ge crystal



Regions of minimal uncertainty of EDM (continuous line) and MDM (dotted line) defined as +20% uncertainty with respect to the minimum (point marker)

Sensitivity on EDM

Caveat: running conditions still to be assessed



PoT = proton on target
W target 5mm thick
F= 5×10^8 p/s for S1

EPJC (2017) 77:828

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

Material of the crystal:

→ **Silicon**
→ **Germanium**

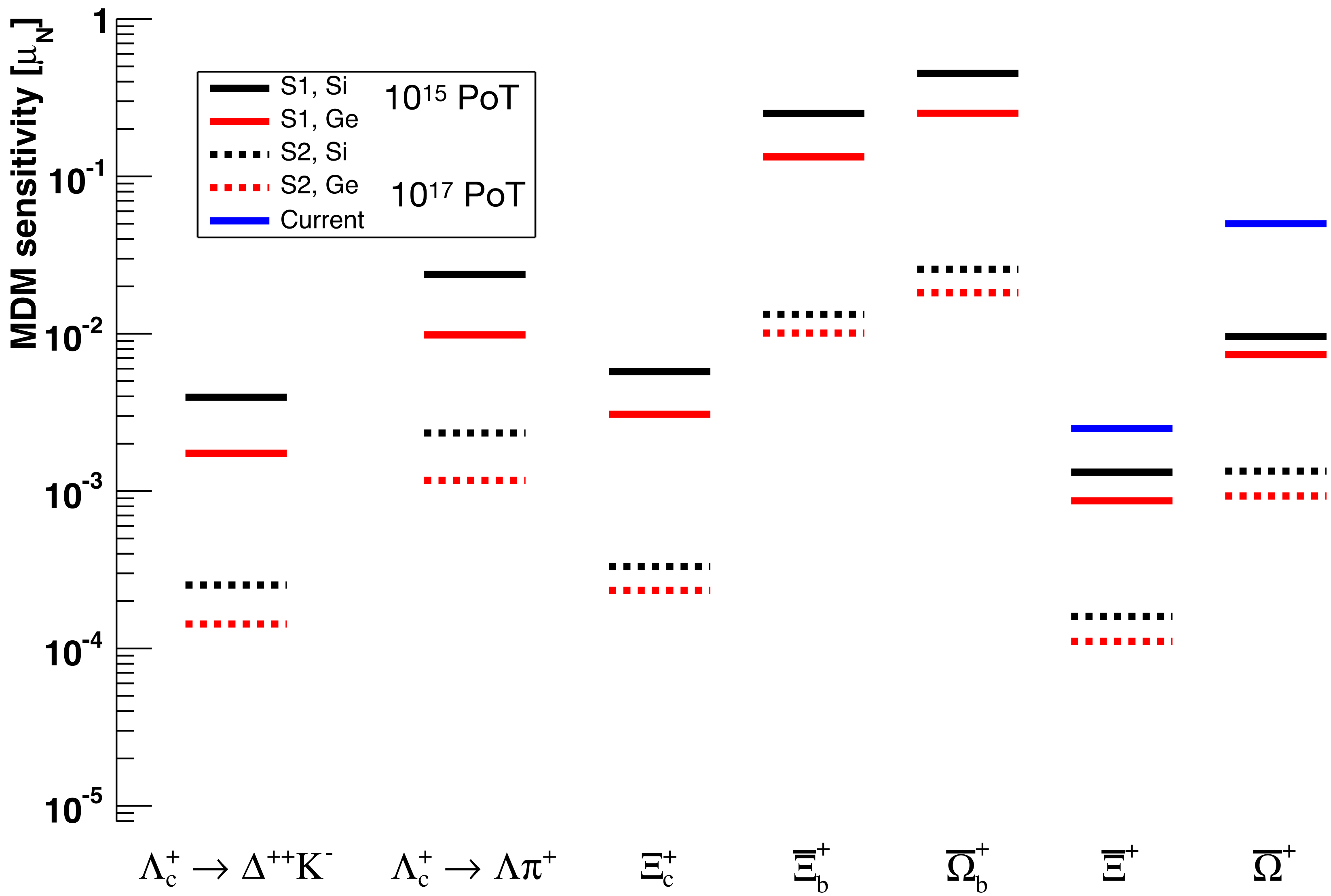
- Technique applies to all short-lived positive baryons
- Possibility to test new physics models

Sensitivity on MDM

Caveat: running conditions still to be assessed

PoT = proton on target
W target 5mm thick
F= 5×10^8 p/s for S1

EPJC (2017) 77:828



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

Material of the crystal:

→ **Silicon**
→ **Germanium**

- First MDM measurements. Interesting precision, below 10^{-2} for charm baryons

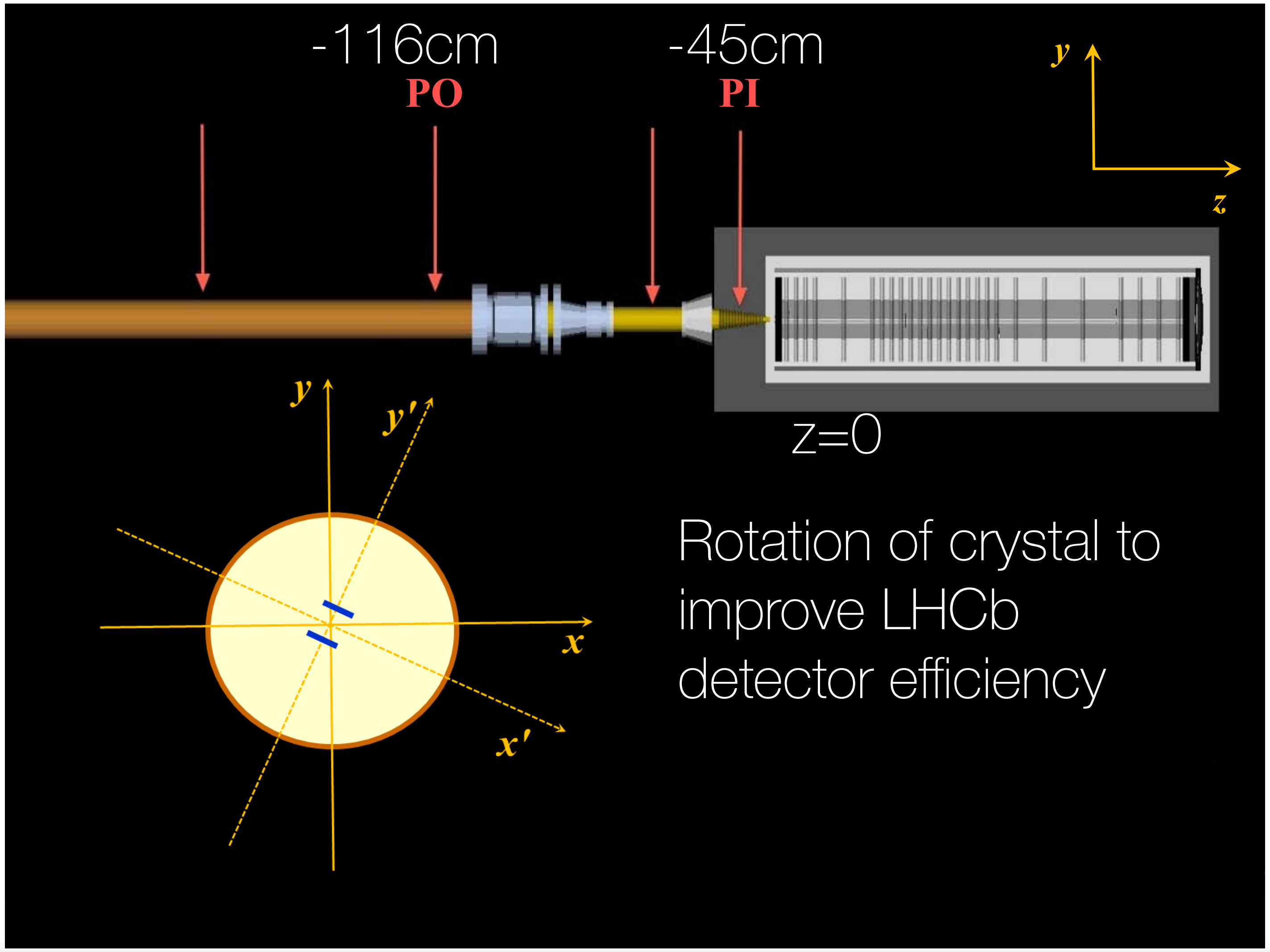
Summary

- **Experimental proposal** for **unique** baryon EDM/ MDM measurements in LHCb was presented
- **R&D** from crystal, LHC collimation, detector community is required to face remaining challenges
- Challenges / Preliminary results (available soon):
  - machine layout / detailed simulations ongoing
  - large bent crystal production / first prototype being tested on beam
- Proposal advanced within the **Physics Beyond Collider** study group. Under review by **LHCb** panel (FITPAN), aiming for data taking in Run3 (2021-2024)

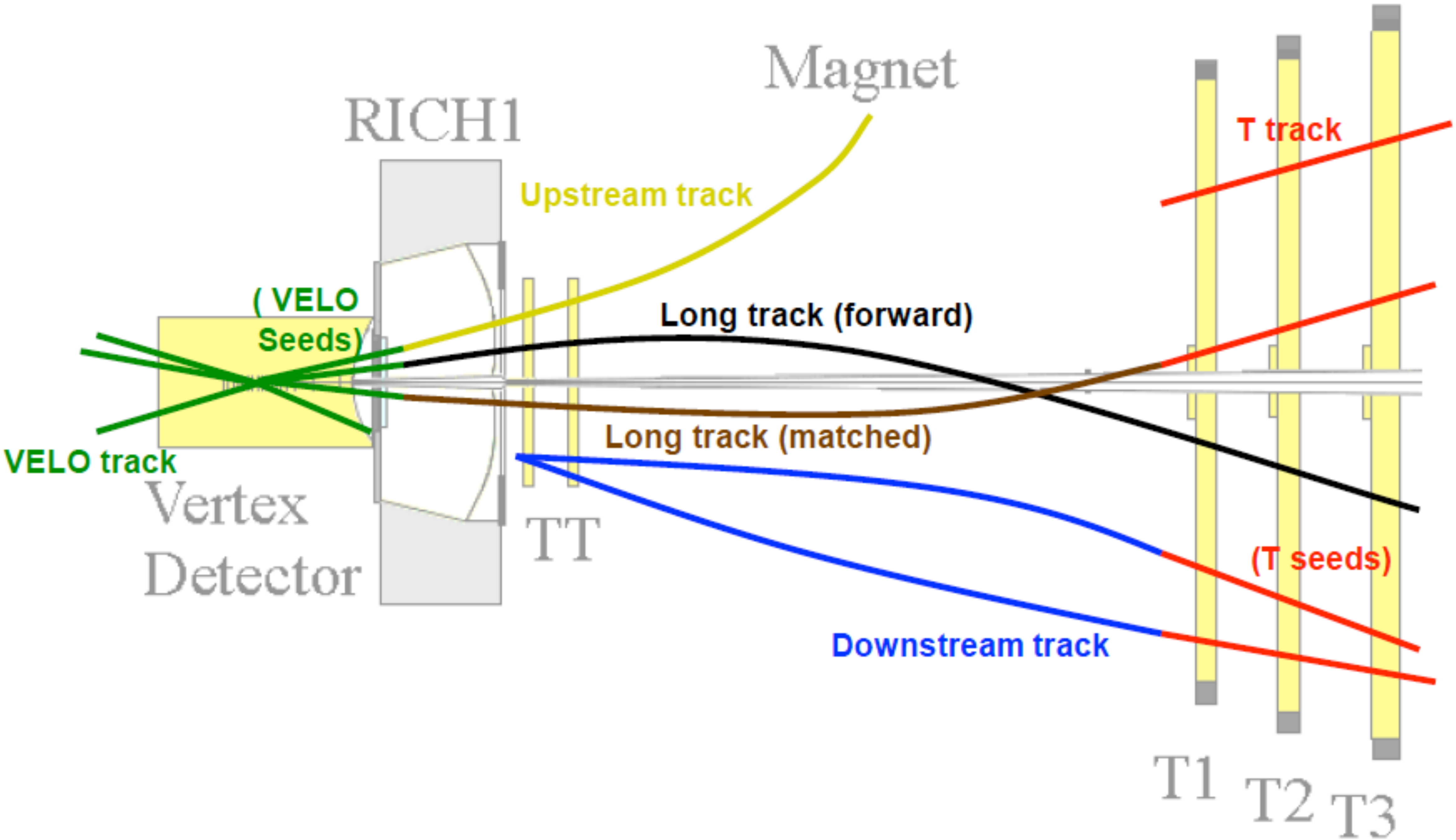
Backup slides

Fixed target & bent crystal

- Fixed target (W, d~0.5 cm) attached to a long bent crystal (Ge, L~5 cm, θ~15 mrad, Si, L~7 cm, θ~14 mrad)
- Bending angle θ>10 mrad determined by LHCb acceptance
- Close to VELO for optimal vertex resolution: e.g. distance from VELO sensors ~100 cm (PO)

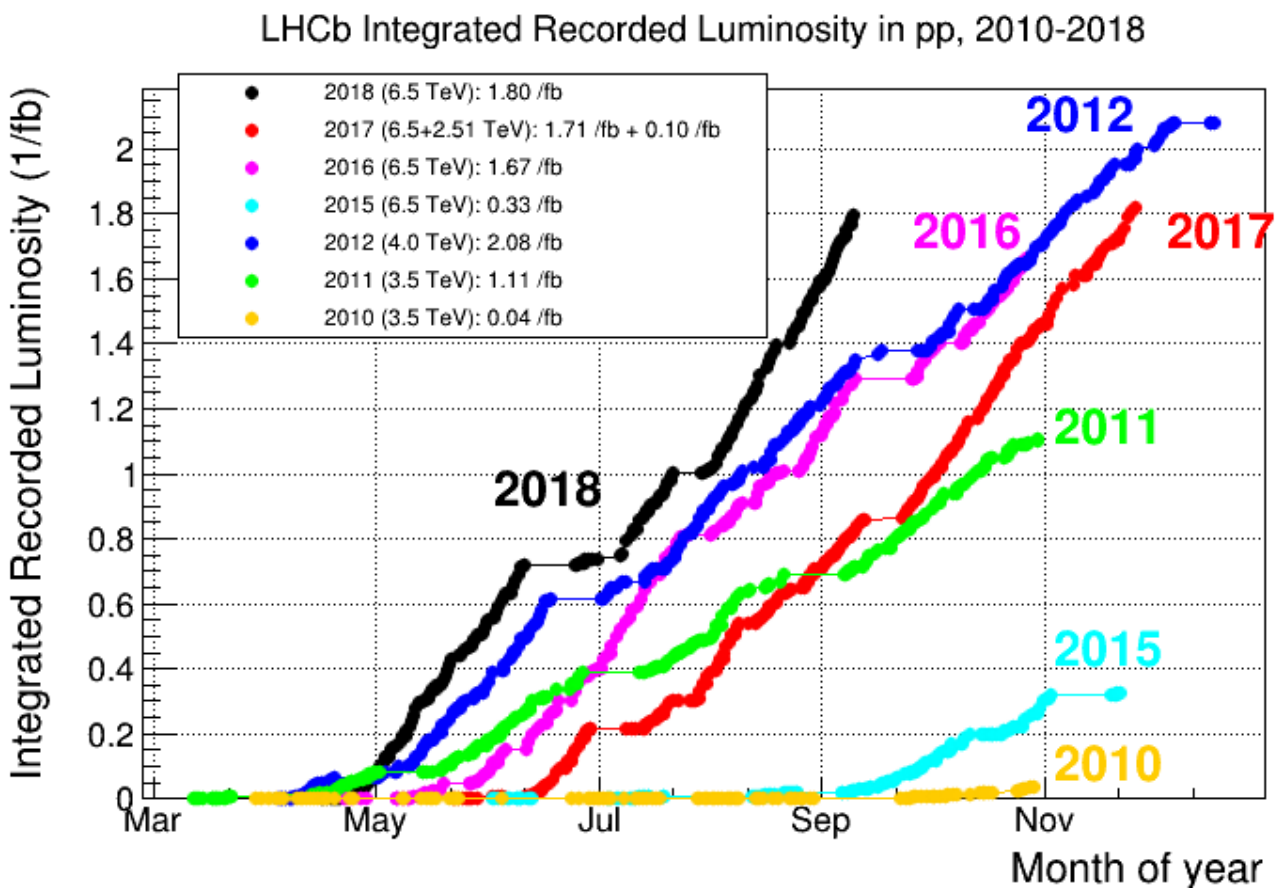


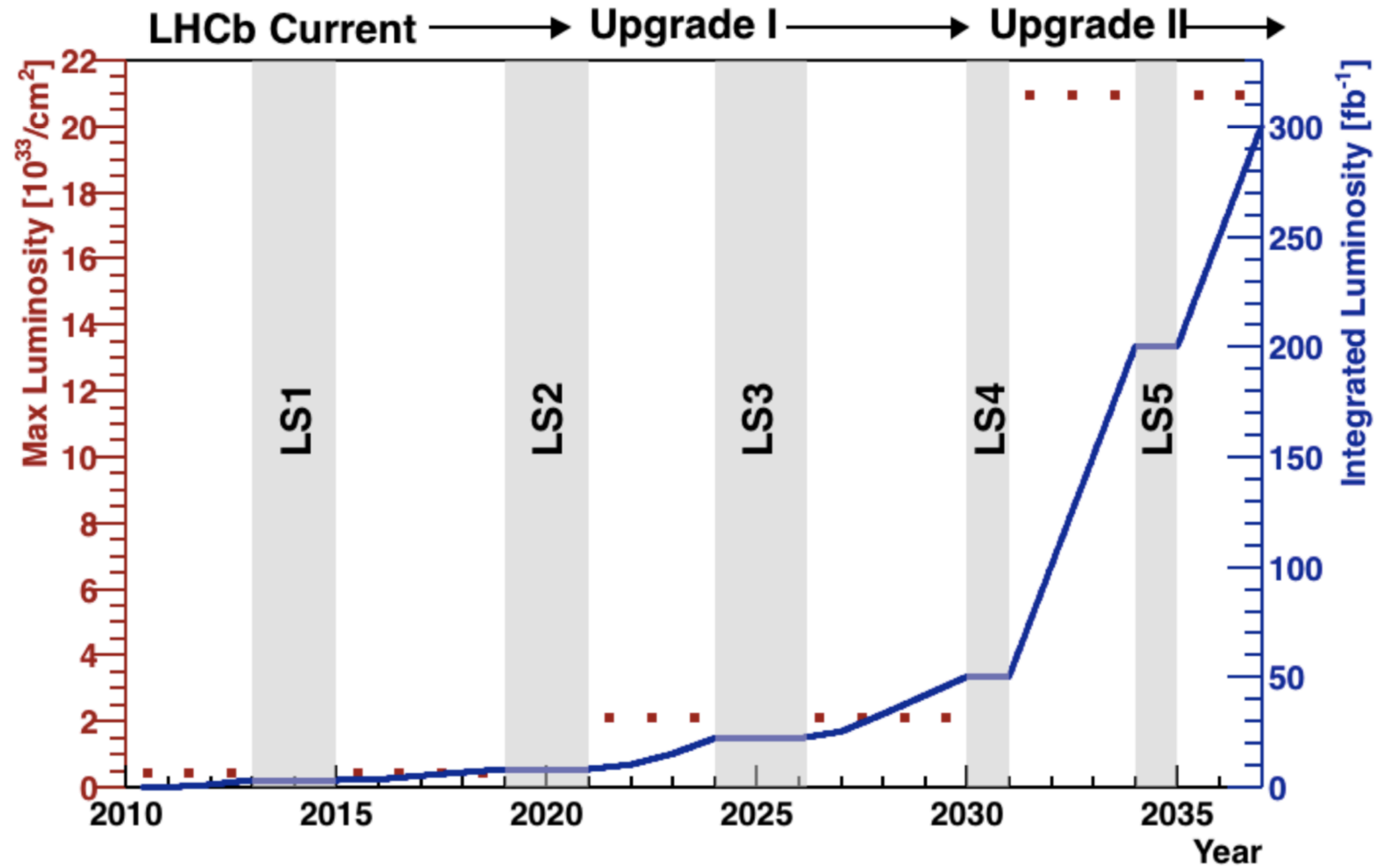
Track definitions at LHCb



Ghost track = is a fake track. For example it can be formed by matching a real track segment in the VELO (VELO seed) with a real track segment in the downstream tracker (T seed)

LHCb data sample and plans

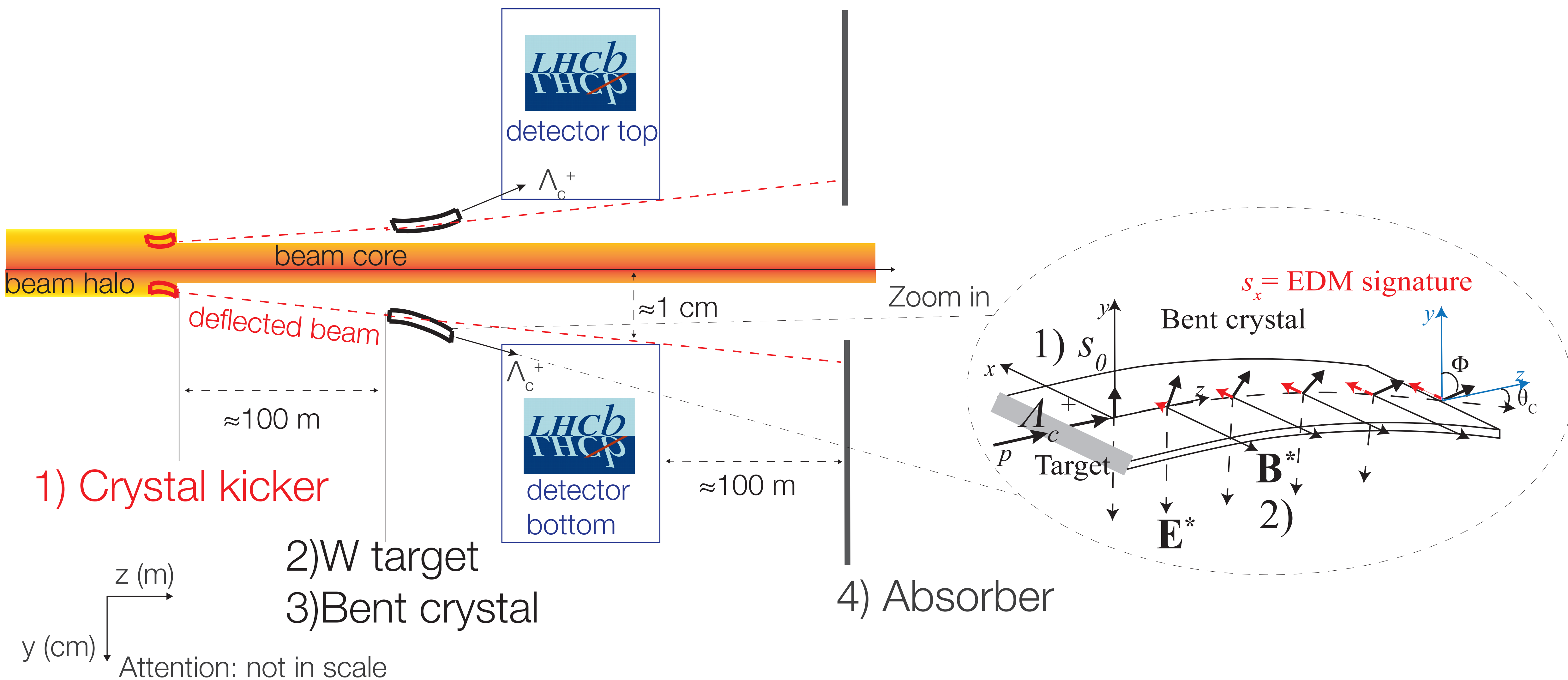




- Collecting ≳9 fb^{-1} in Run2 (2018). Major detector upgrade during LS2 (Upgrade I- 2020). Aim at 50 fb^{-1} before 2030
- First detector improvements in PID, tracking, and ECAL during LS3 (Upgrade 1b - 2025)
- Major detector upgrade during LS4 (Upgrade II - 2030). Aim at >300 fb^{-1} after 2030 - ….

Experimental layout

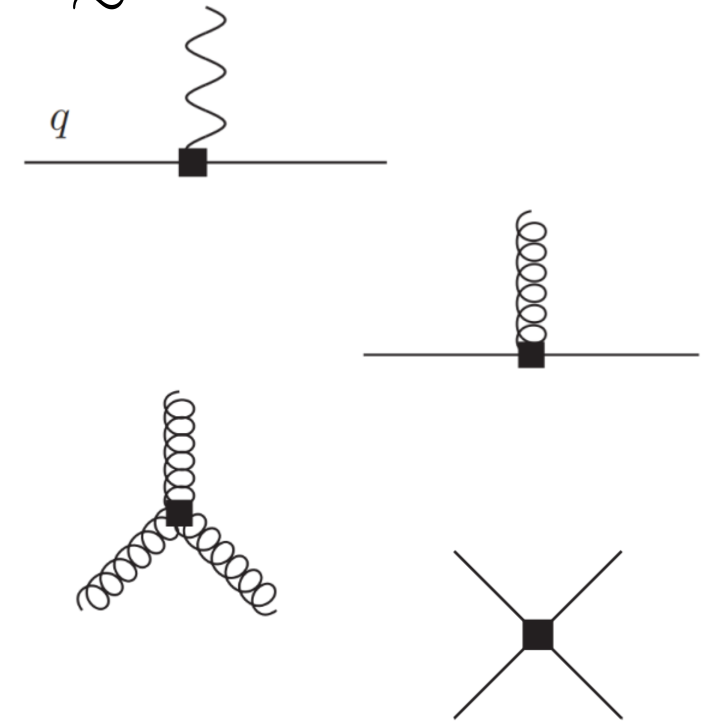
- Crystal kicker deflects LHC beam halo towards a W target, outside of the LHCb detector acceptance
- Baryons produced in W target and channeled in bent crystal (signal events) enter the detector acceptance



Baryon EDM - Effective Lagrangian

- EDM coupling: $$\mathcal{L}^{\mathrm{EDM}} = -\frac{i}{2}\delta\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu}$$
- CP-odd flavour diagonal effective $\mathcal{L}$ (scale 1 GeV)

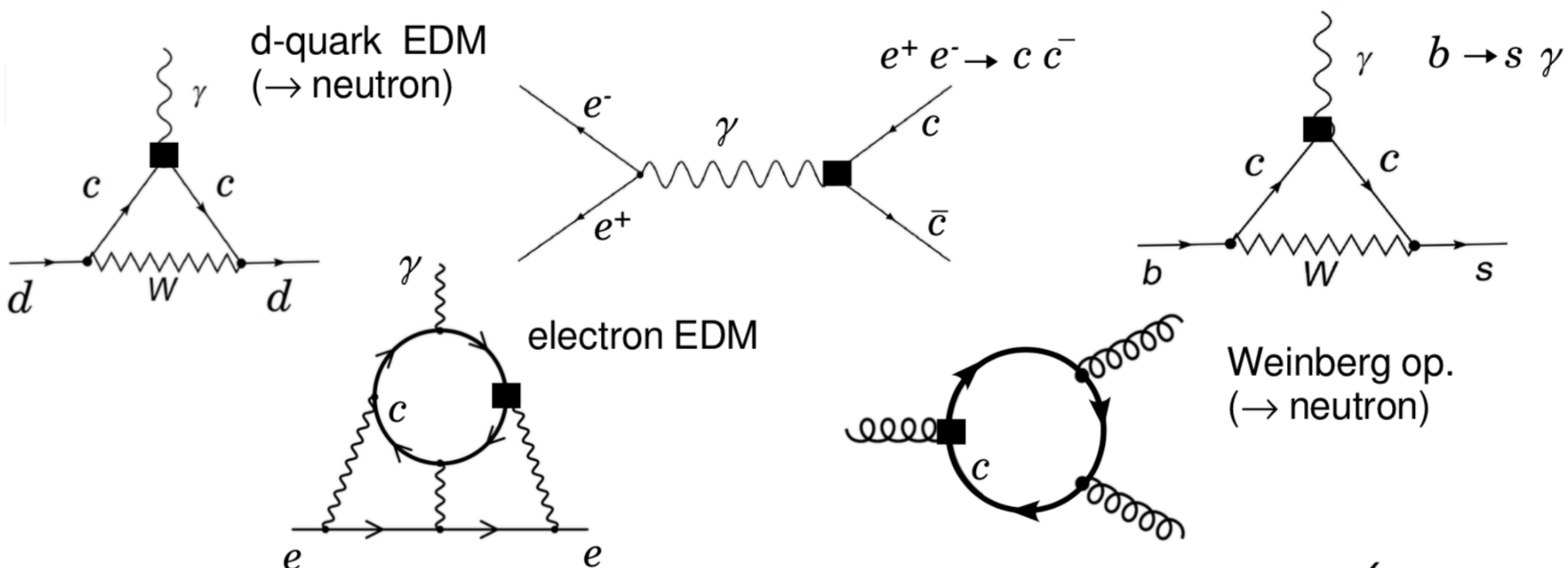
$$\begin{aligned}
\mathcal{L}_{\mathrm{eff}}^{\not{P}\not{T}} = &-\bar{\theta}\frac{g^2}{64\pi^2}\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta} && \theta\text{-QCD term} \qquad \theta \lesssim 10^{-10} \text{ from nEDM} \\
&-\frac{1}{2}\sum_{q=u,d\ \mathbf{S,C}}(\delta_q\bar{q}i\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu} && \text{qEDM} \\
&+\tilde{\delta}_q\bar{q}i\sigma^{\mu\nu}\gamma_5 t_a q G^a_{\mu\nu}) && \text{qCEDM} \\
&+\frac{d_W}{6}f_{abc}\epsilon^{\mu\nu\alpha\beta}G^a_{\alpha\beta}G^b_{\mu\rho}G^{c\rho}_{\nu} && \text{Weinberg op.} \\
&+\sum_{i,j,k,l=u,d\ \mathbf{S,C}} C_{ijkl}\bar{q}_i\Gamma q_j\bar{q}_k\Gamma' q_l && \text{4q op.}
\end{aligned}$$



- Negligibly small contribution from SM
- Background free search for new physics

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.

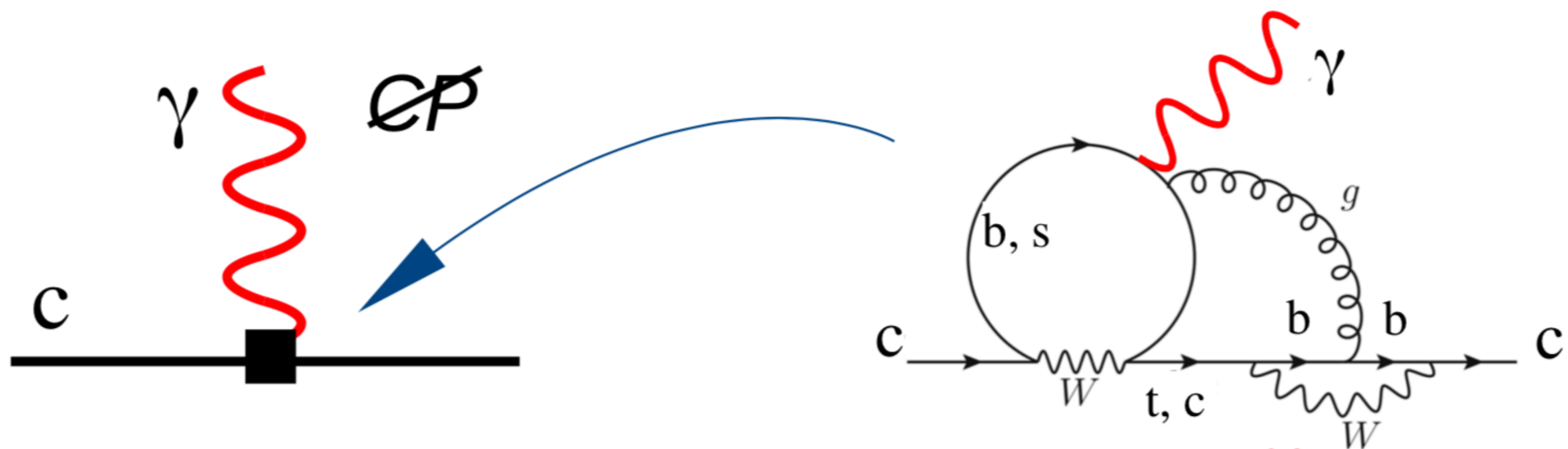


(*see backup*)

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

Constraints to BSM theories

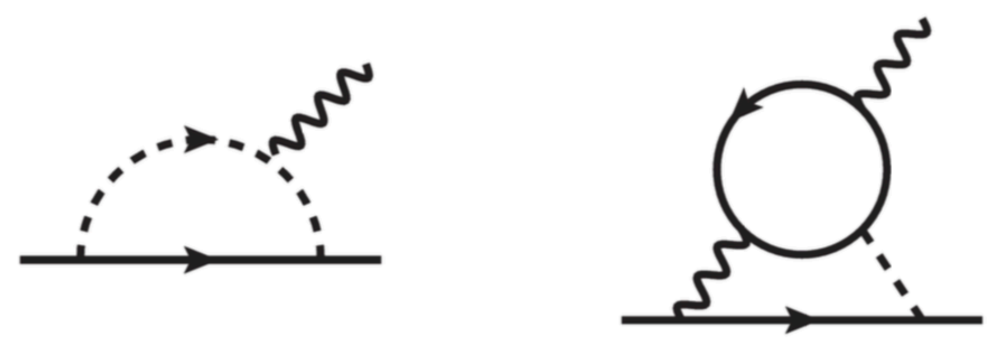
Standard Model has its leading contribution at **3-loop** level



$d_c \sim 10^{-32}$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

Experimental proposal

- Specifications:
  - Ge bent crystal ~15 mrad, 5 cm (Si bent crystal ~14 mrad, 7cm)
  - proton flux of ~10^8 p/s
  - target position (0, 0.4, -116) cm,
  - target azimuthal angle 65 degrees
- Studies summarised in detail in a LHCb internal note.

Installation and operations

- Installation during EYETS after LS2:
  - crystal kicker installation in LHC ~1-2 days. Designed by CERN and produced by a company
  - W target + bent crystal in front of the LHCb detector at z=-116cm. Outside the VELO detector vacuum vessel
- Operations: dedicated running with nominal pp collisions
  - aim at 10^{15} PoT for the EDM, MDM measurements
  - a dedicated run at $5\text{x}10^{8}$ p/s would take about 10 weeks, assuming 30% efficiency in data taking
  - Runs of 2 weeks/year at $5\text{x}10^{8}$ p/s during Run3 would allow $6 \cdot 10^{14}$ PoT by the end of 2023