Progress towards an experiment for electromagnetic dipole moments of unstable particles at the LHC

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on behalf of the SELDOM team

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Outline

- Physics motivations
- Experimental method
  - short-lived particles, e.g. charm and beauty baryons, τ lepton
  - long-lived particles, e.g. Λ baryon (not covered in this talk)
- EDM/MDM sensitivities
- R&D and preparatory studies
- Summary

Introduction

Electromagnetic dipole moments are static properties of particles, never measured for short-lived **charm**, **beauty** baryons, and **τ** lepton

δ= electric dipole moment (EDM) $$\boldsymbol{\delta} = d\mu_N \frac{\mathbf{S}}{2}$$

- EDM searches are sensitive to new physics. Violation of P, T and CP via CPT theorem.

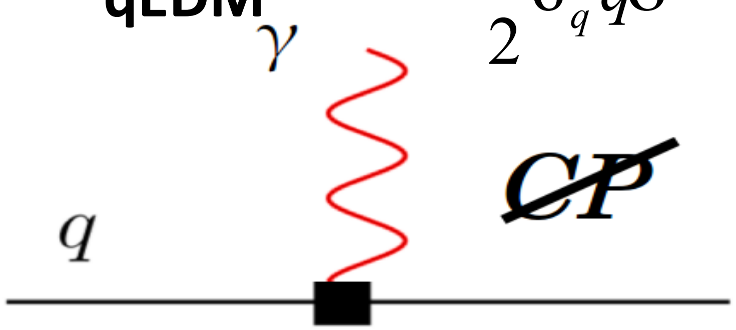
μ= magnetic dipole moment (MDM) $$\boldsymbol{\mu} = g\mu_N \frac{\mathbf{S}}{2}$$

- MDM measurements for **QCD model** and baryon substructure test (SM test for τ lepton)

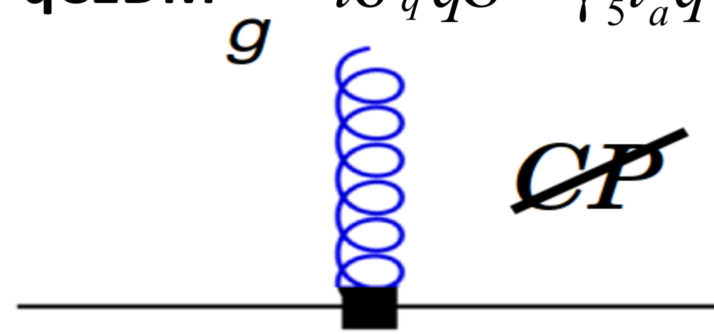
EDM physics motivations

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

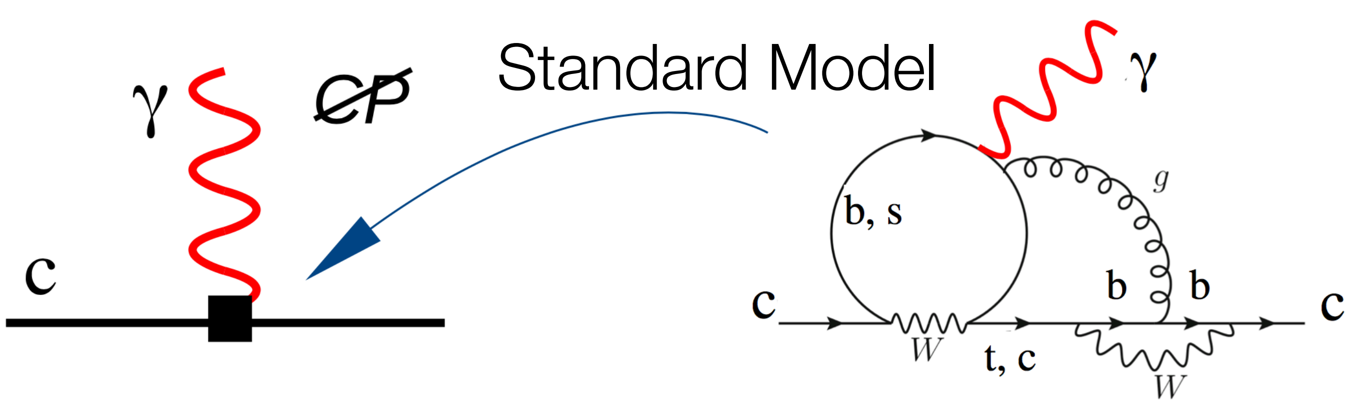


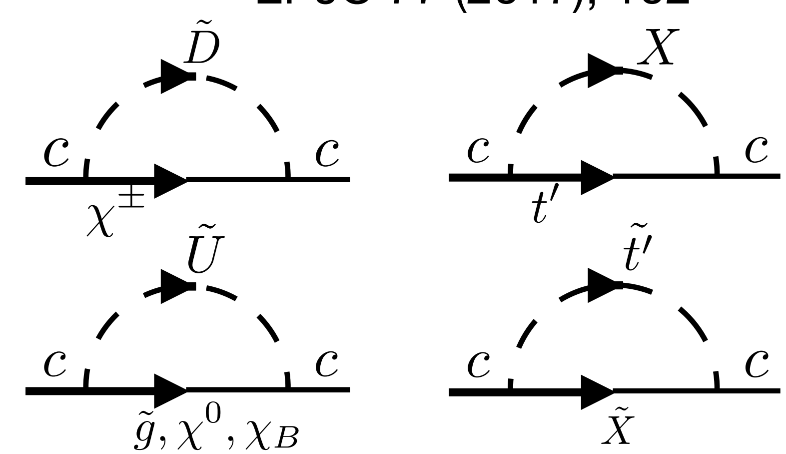
Charm EDM in SM-CKM ~10^{-32} *e* cm

Khriplovich, Lamoreaux (1997)

Charm EDM with new physics ~$5 \cdot 10^{-17}$ *e* cm

EPJC 77 (2017), 102

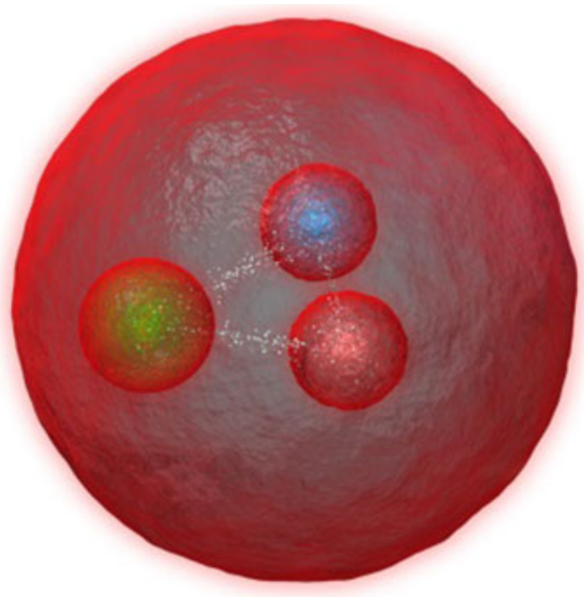


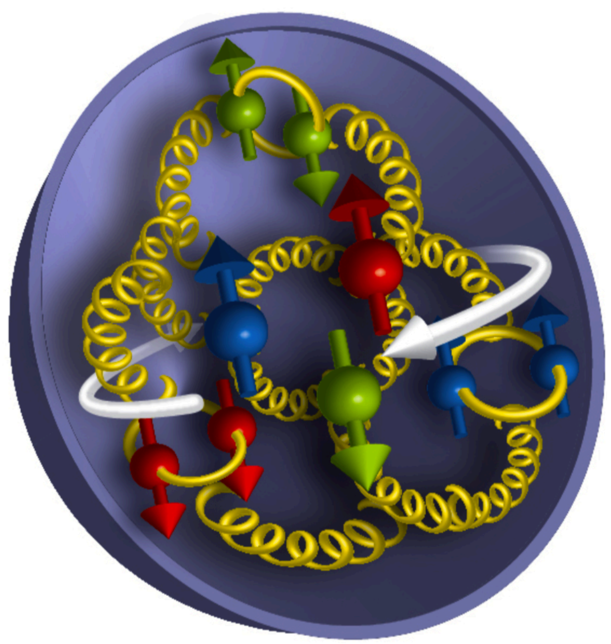


- EDM observation = clear signature of **new physics**

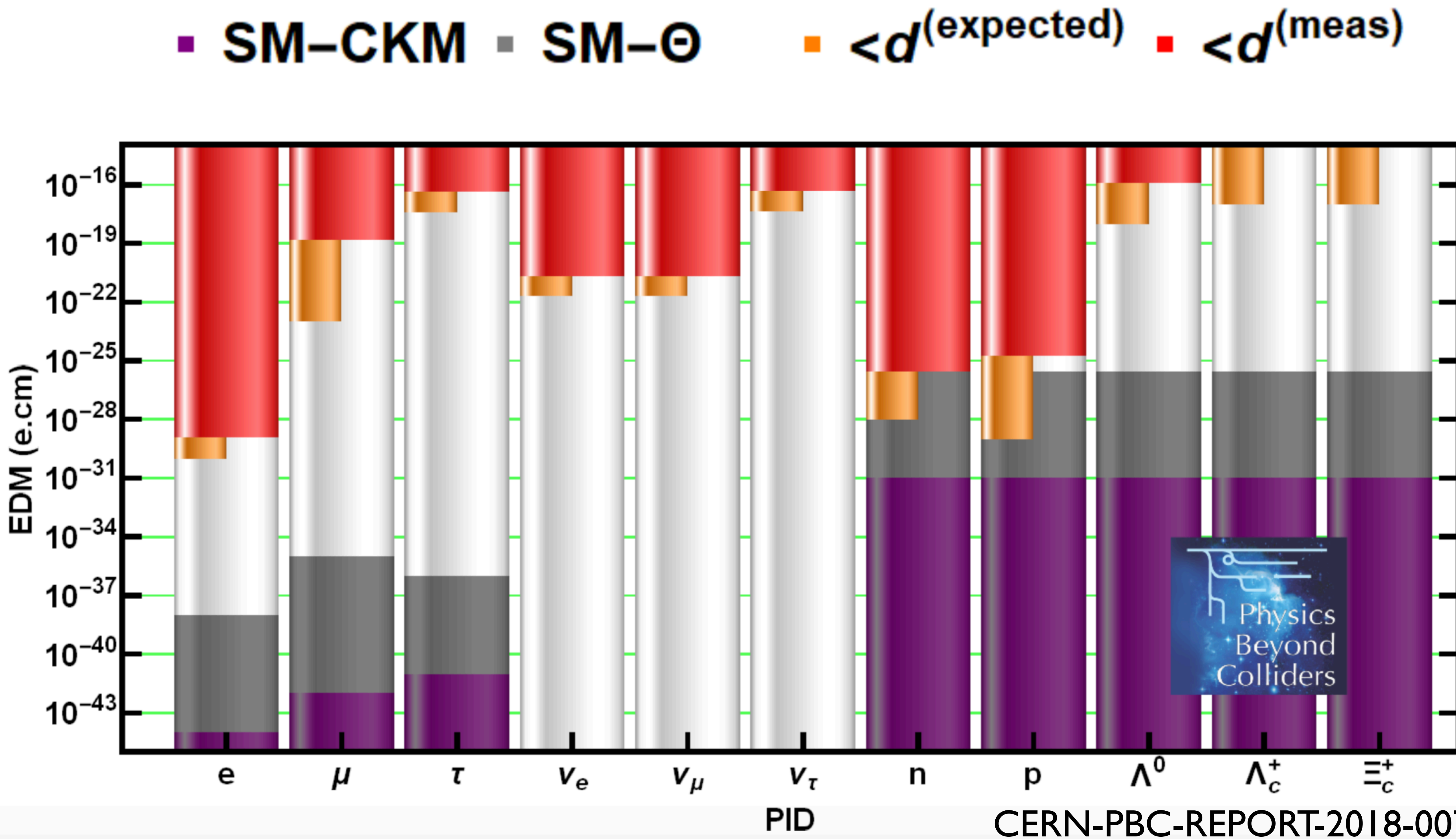
MDM physics motivations

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





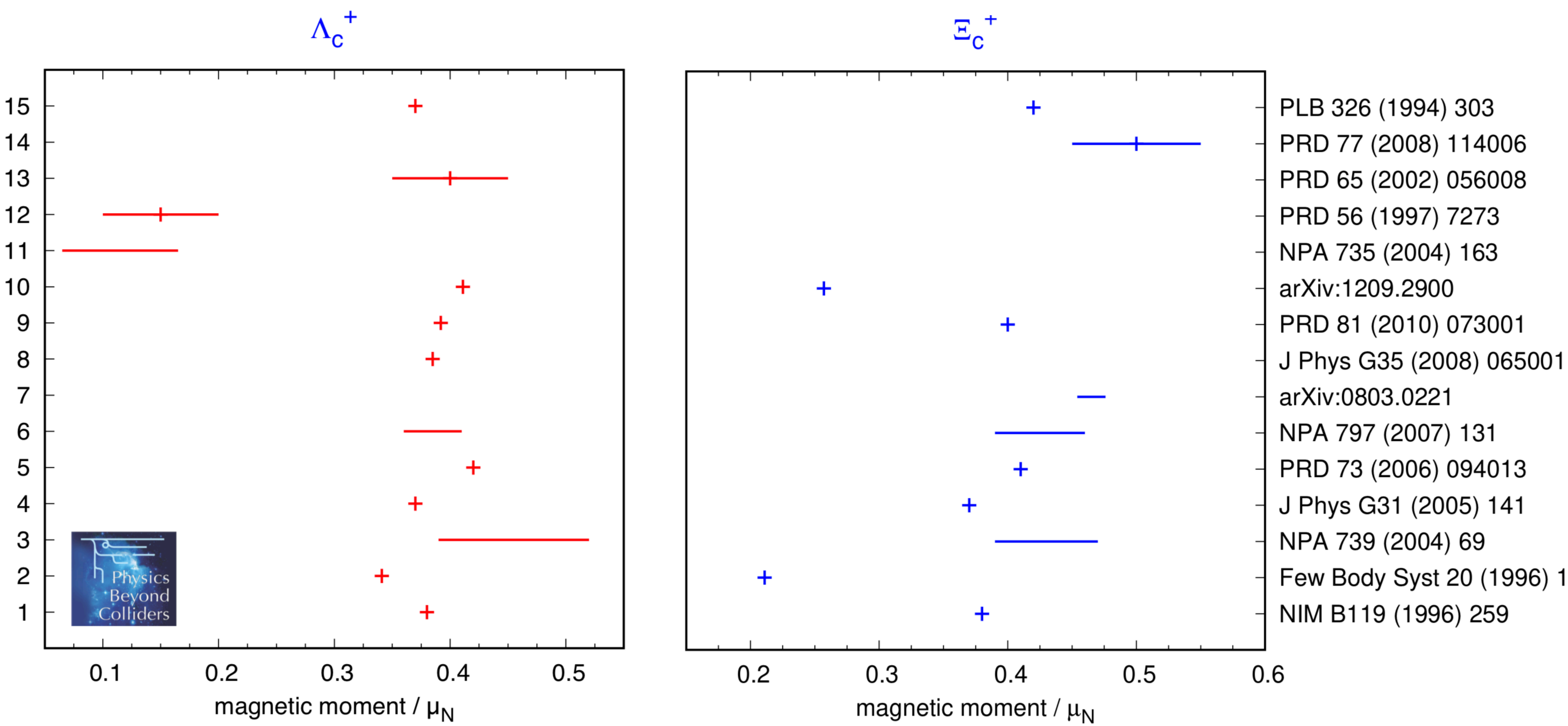
Status of EDM measurements



CERN-PBC-REPORT-2018-007

MDM theoretical predictions

Provide experimental anchor points for heavy baryon MDM model predictions. Trigger further theory activity

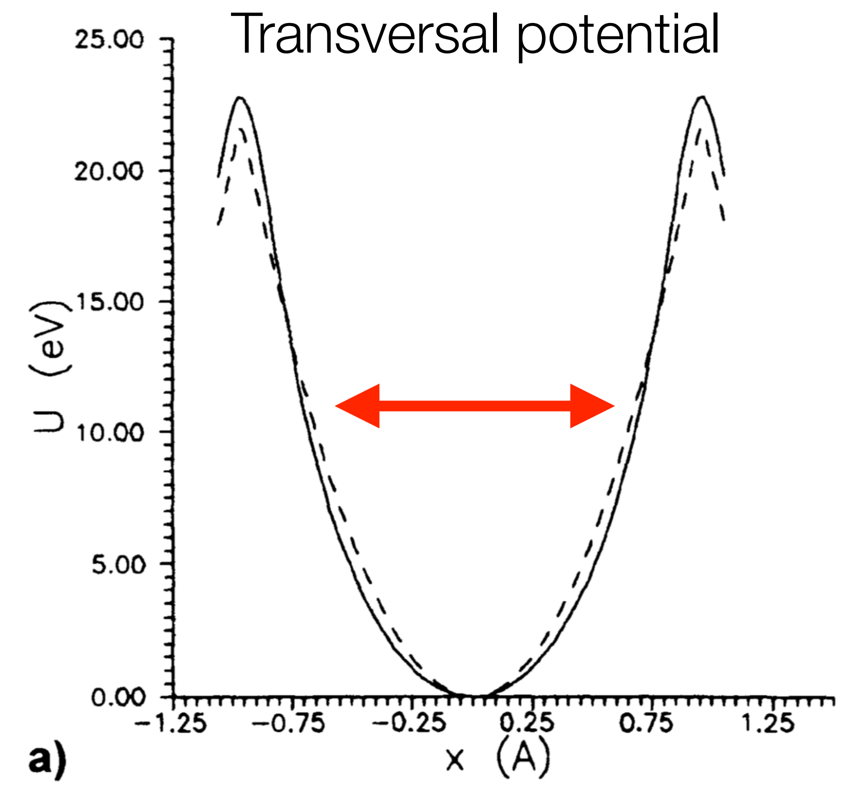


CERN-PBC-REPORT-2018-008

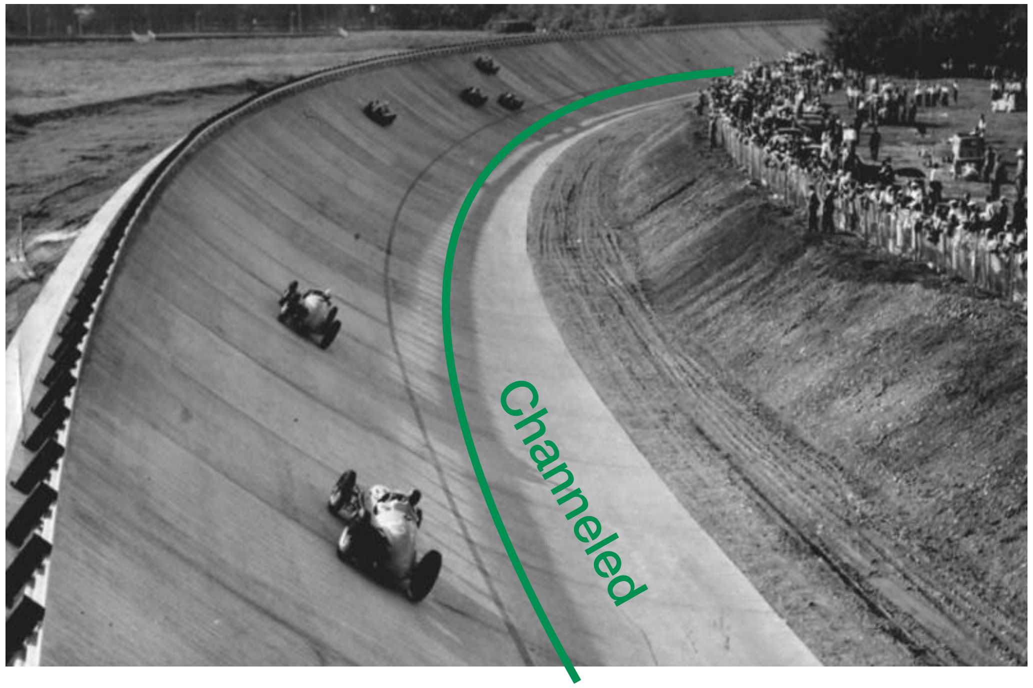
Experimental method for short-lived particles: $\Lambda_c^+, \Xi_c^+, \overline{\Xi}_b^+, \overline{\Omega}_b^+, \tau^+$ ($\tau \approx 10^{-13}$–10^{-12} s)

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, very high effective magnetic field B≈500 T
  - induce spin precession



Spin precession in bent crystals

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

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

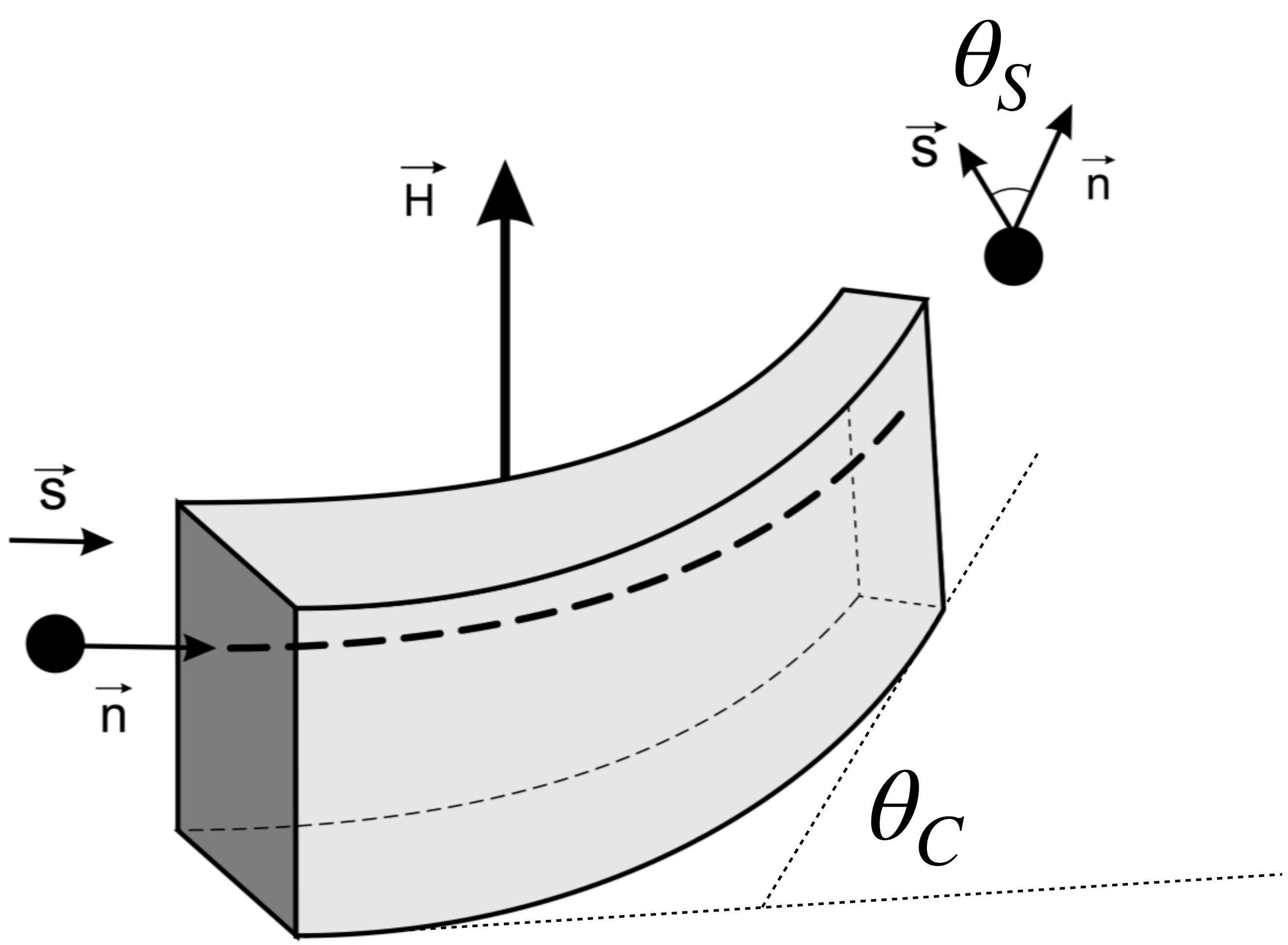


Fig. 1. Spin rotation in a bent crystal.

- 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

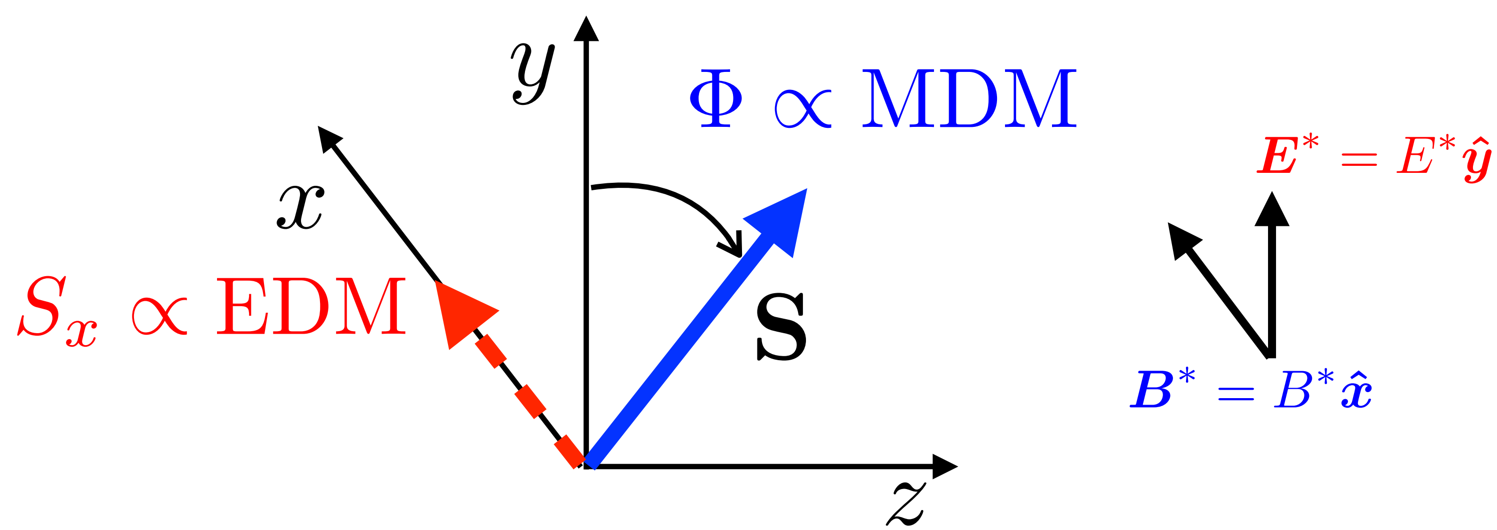
γ = Lorentz boost

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)

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

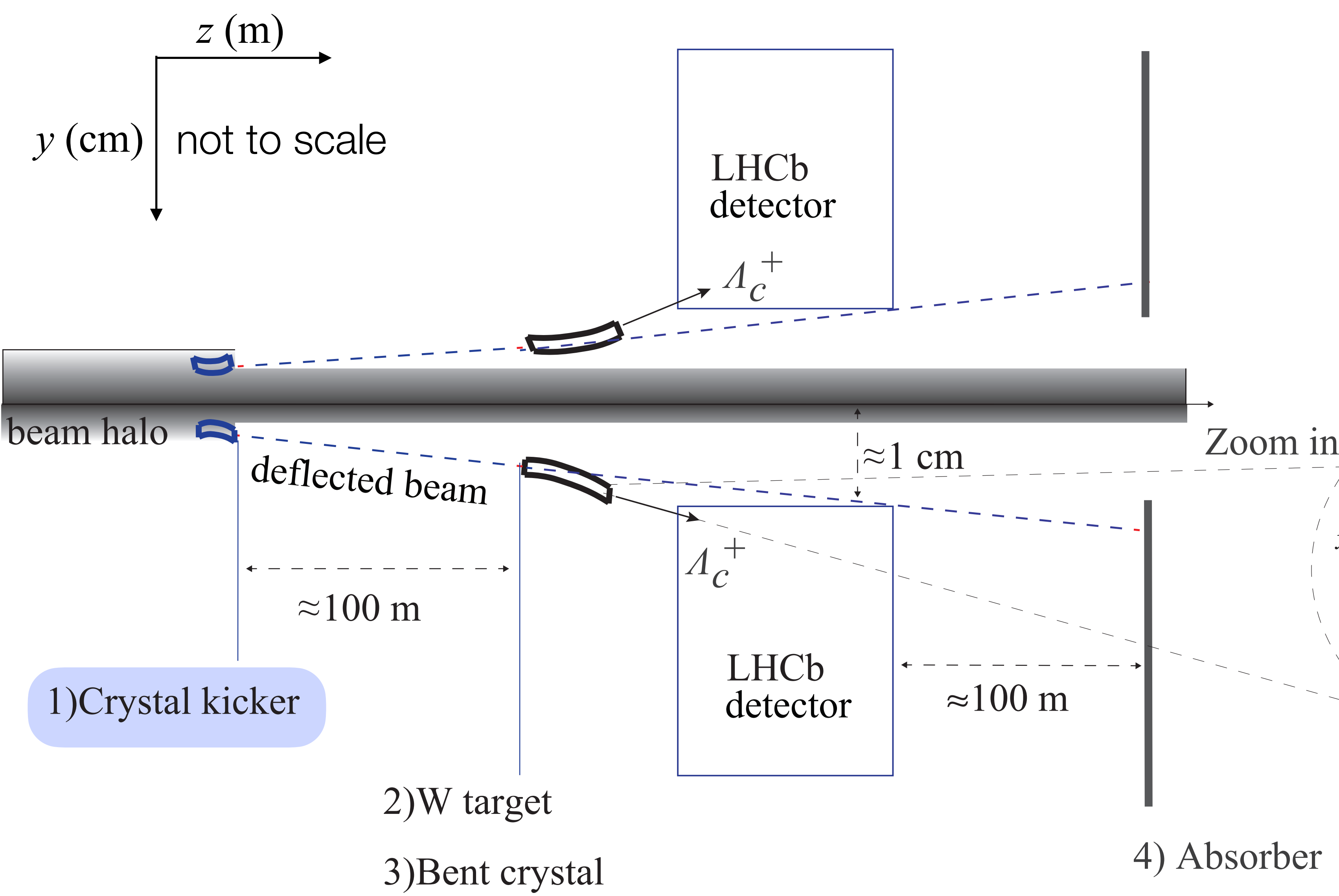


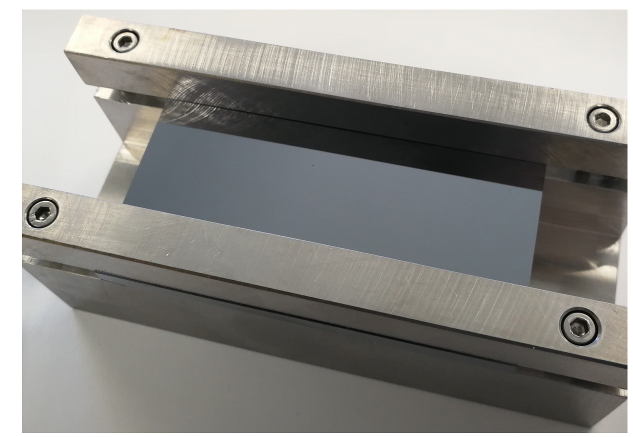
- MDM and EDM precession in the limit $\gamma \gg 1$, $d \ll g - 2$

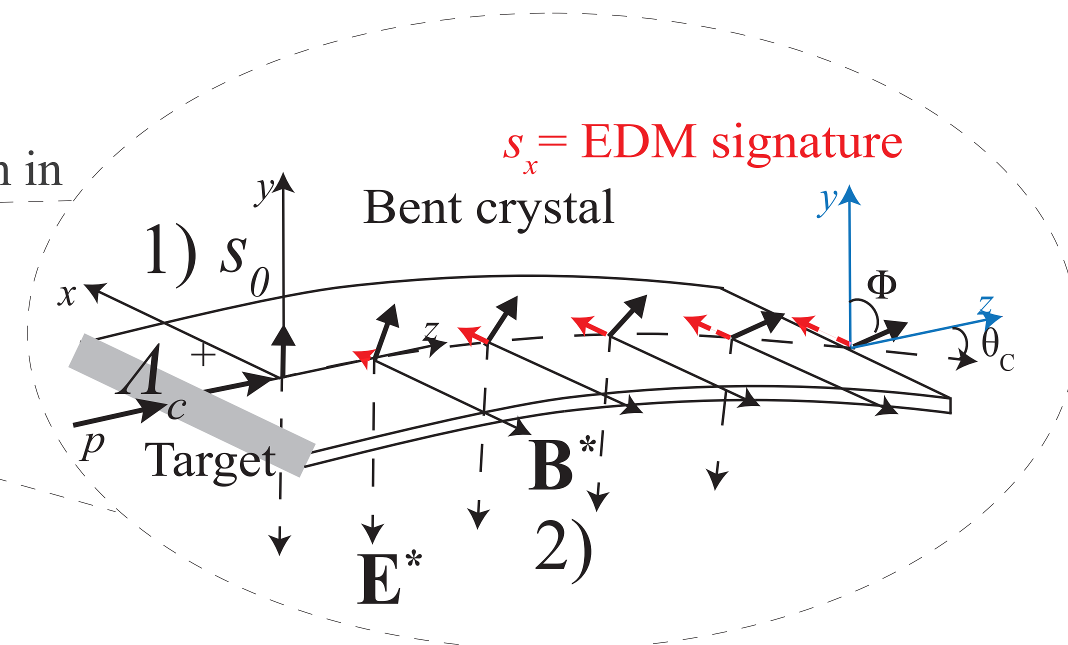
$$\theta_S \approx \frac{g-2}{2}\gamma\theta_C \qquad S_x \approx S_0 \frac{d}{g-2}[\cos(\Phi) - 1]$$

Novel fixed-target experiment at LHC for charm baryons

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



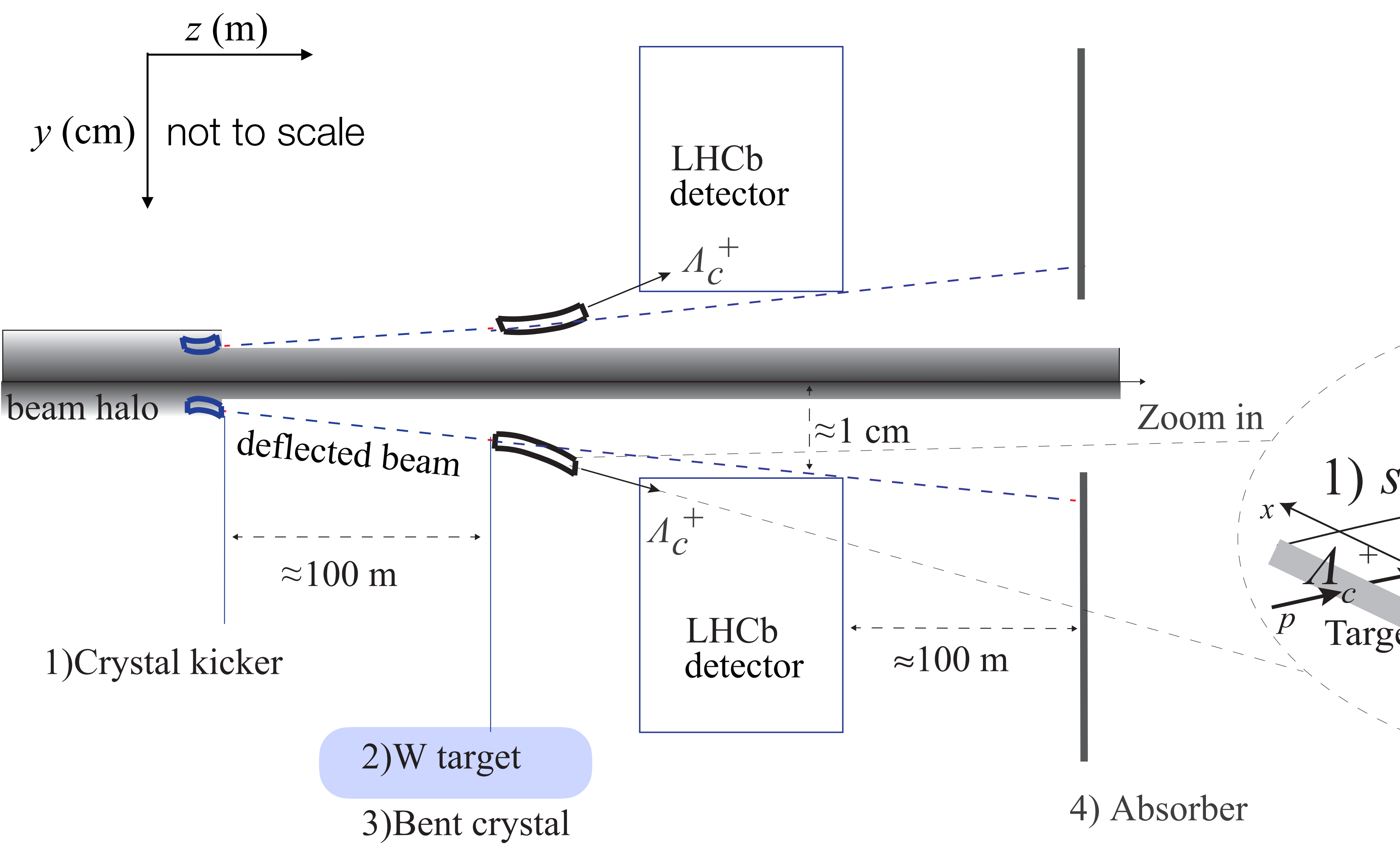


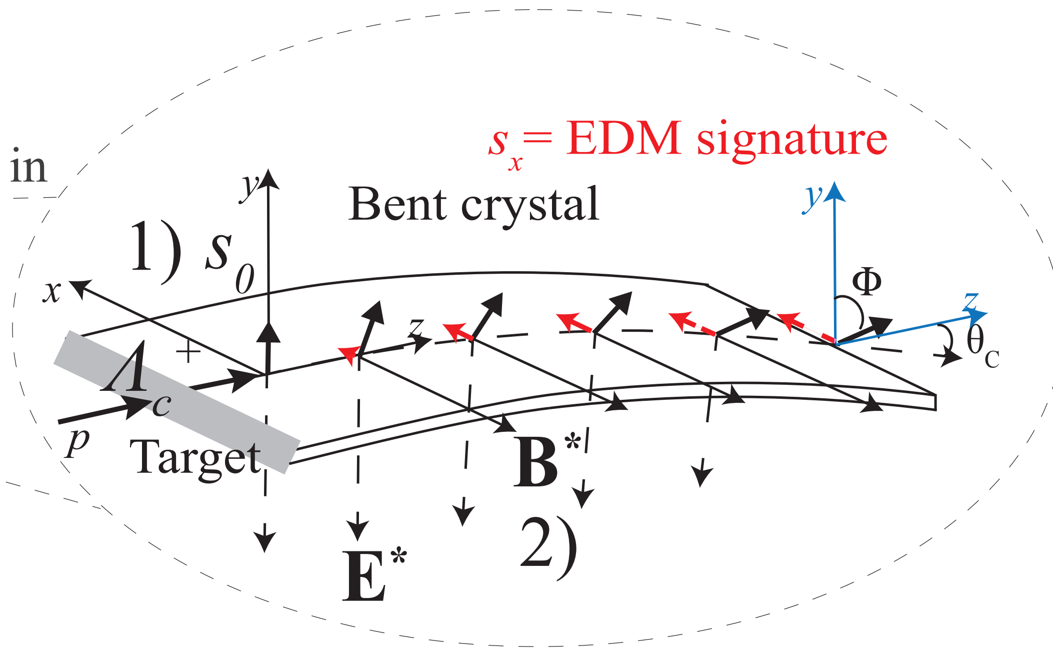


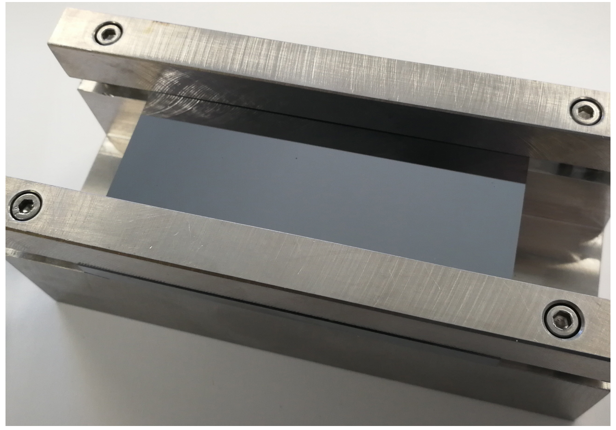
p extraction

Novel fixed-target experiment at LHC for charm baryons

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



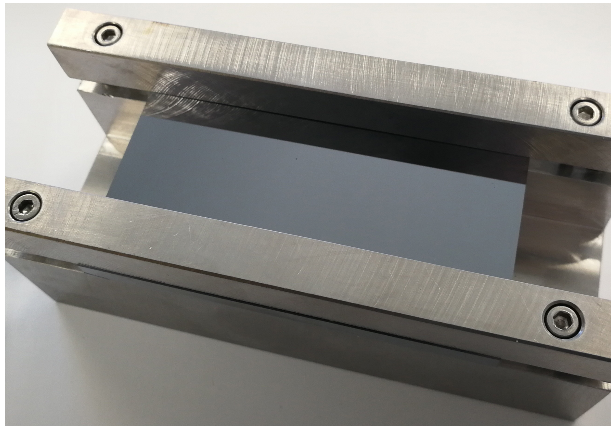


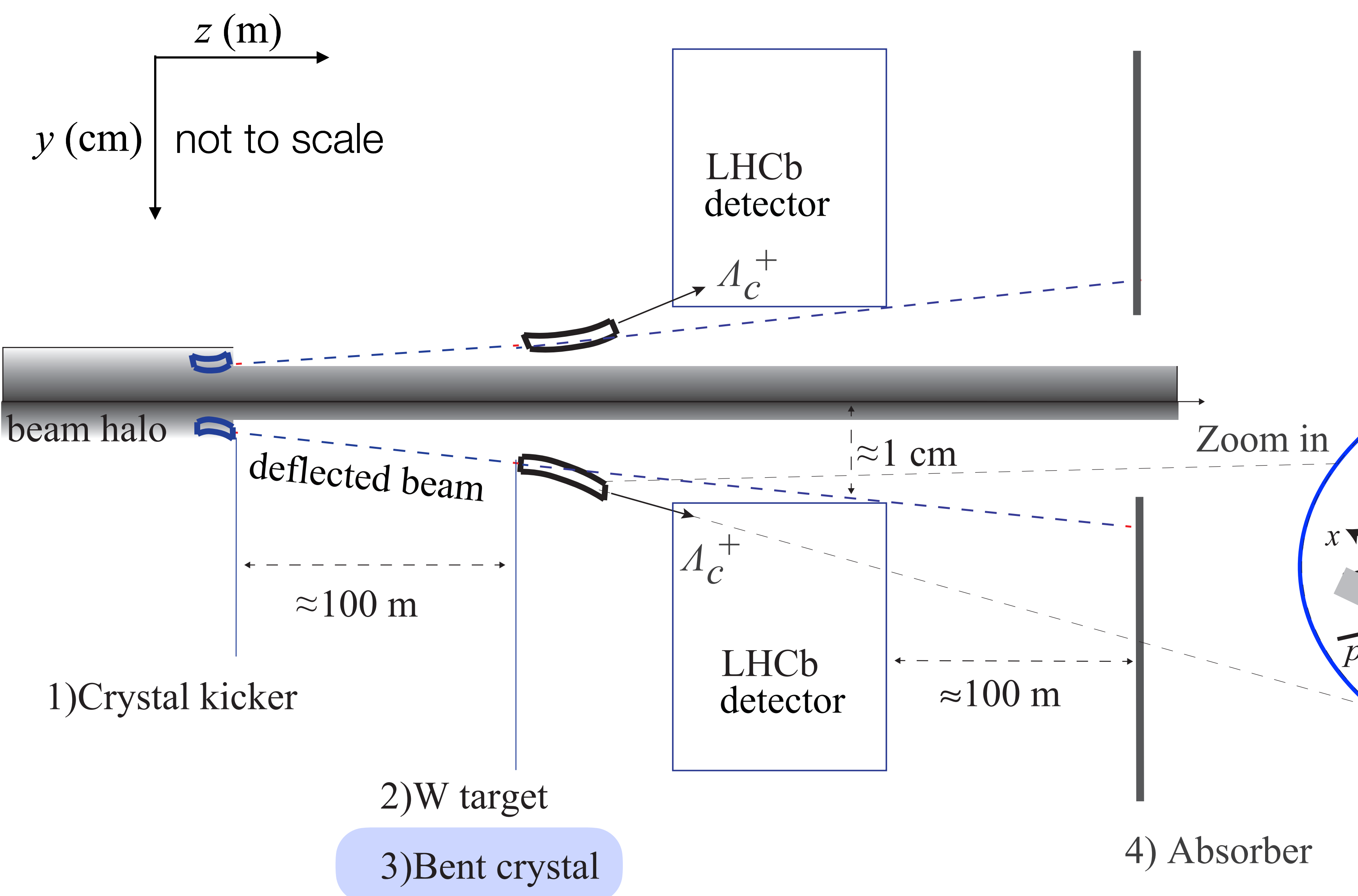


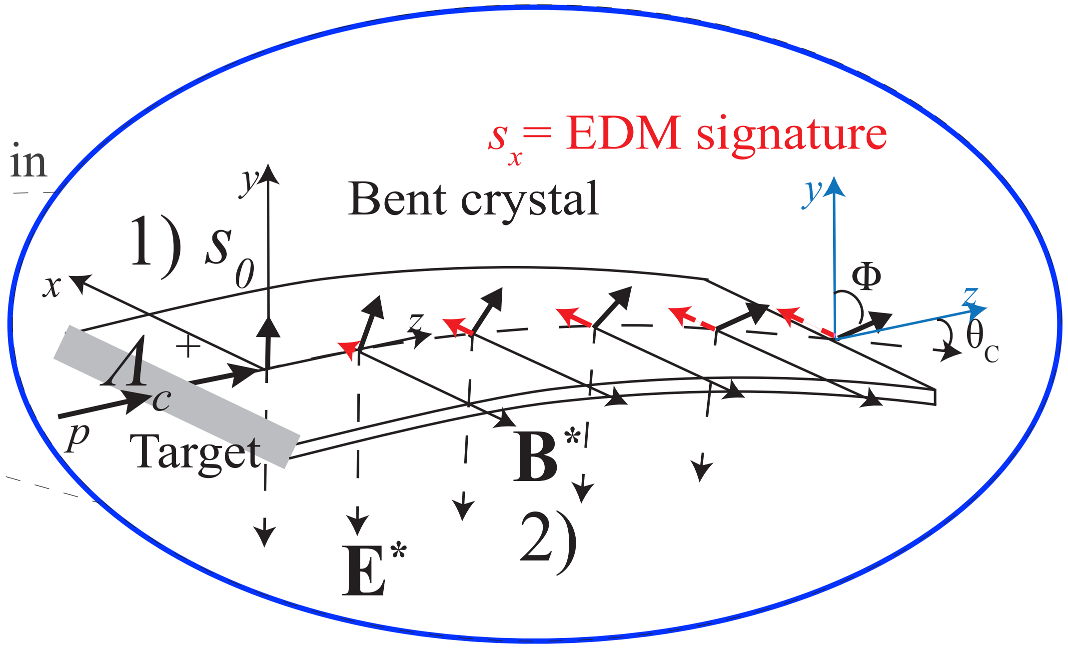
p extraction Λ_c^+ polarised production

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

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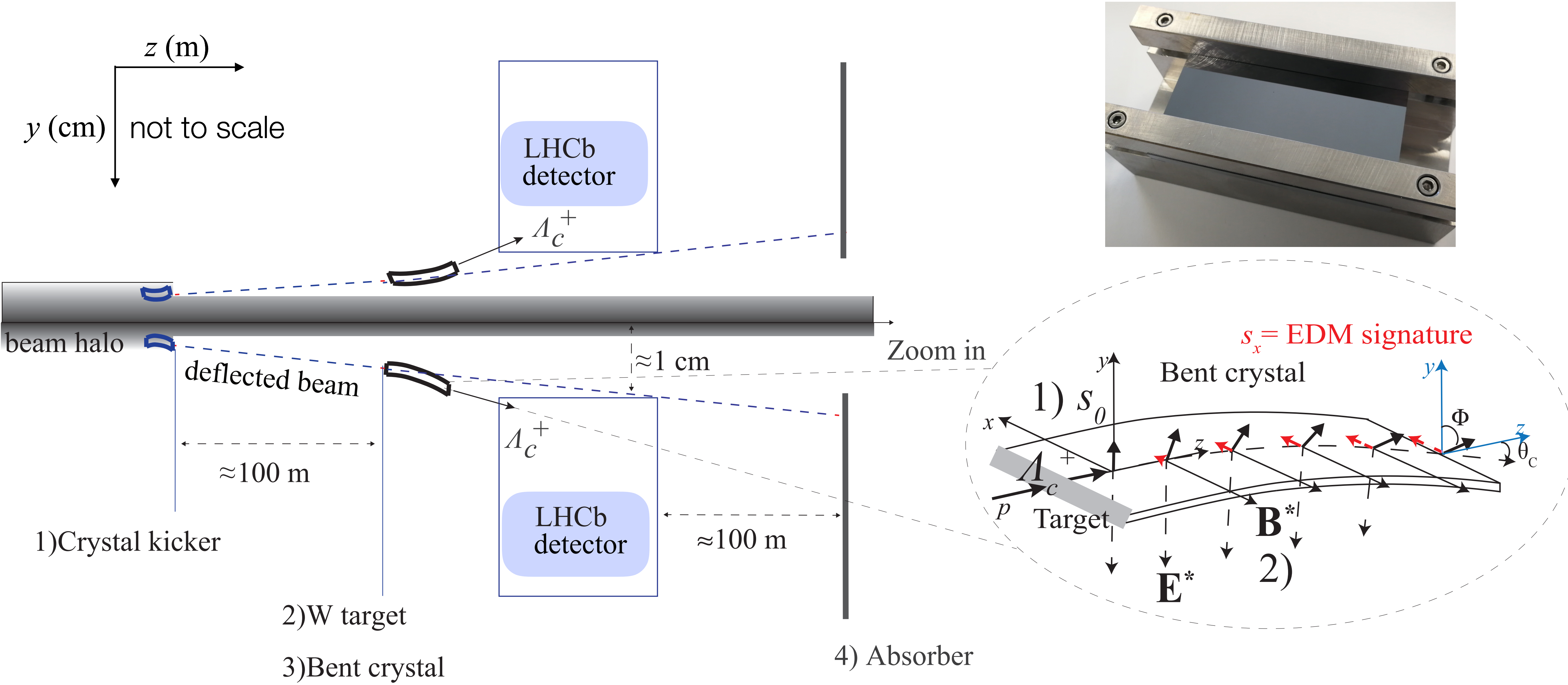
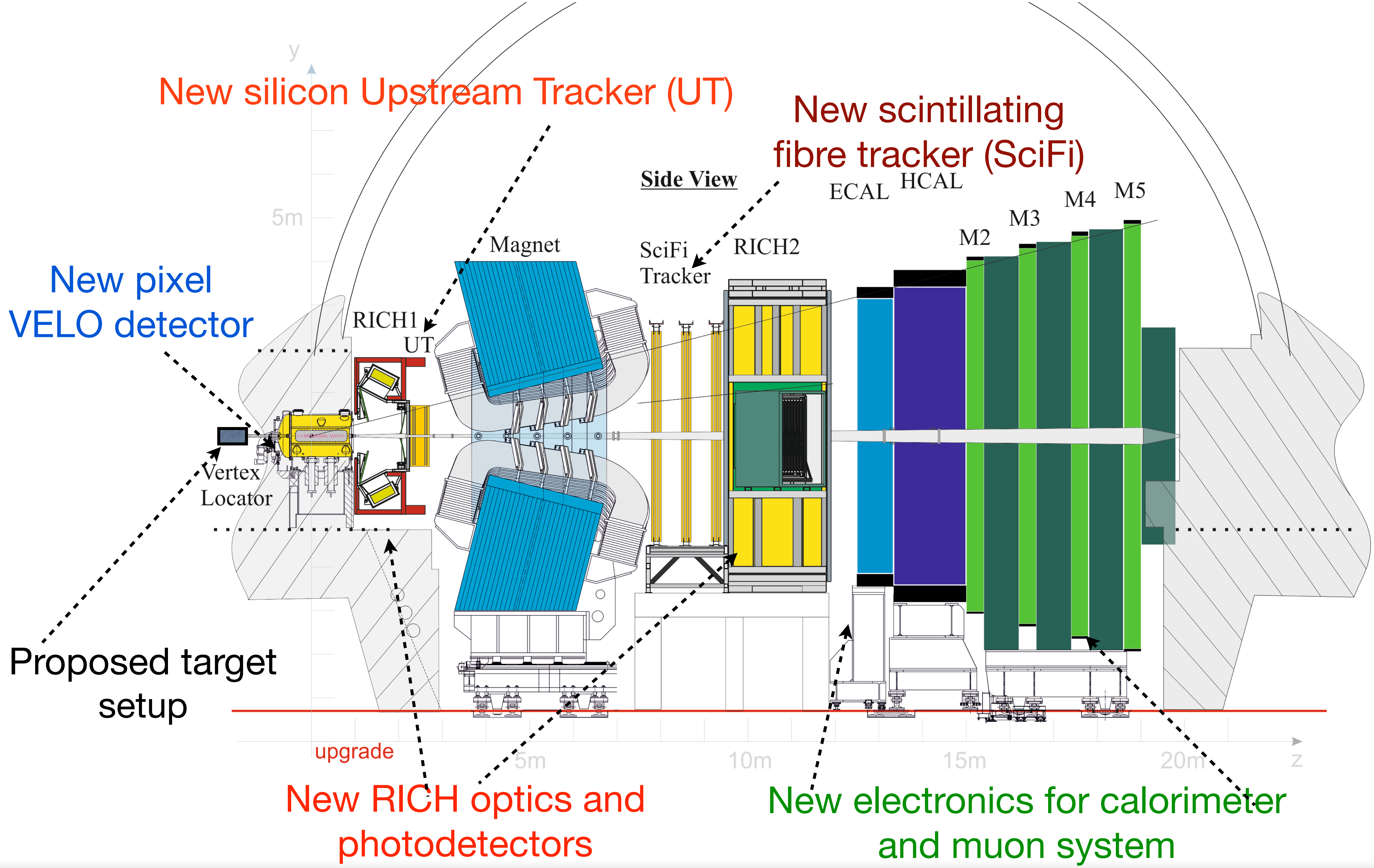


p extraction Λ_c^+ polarised production channeling spin precession event reconstruction

LHCb Upgraded detector

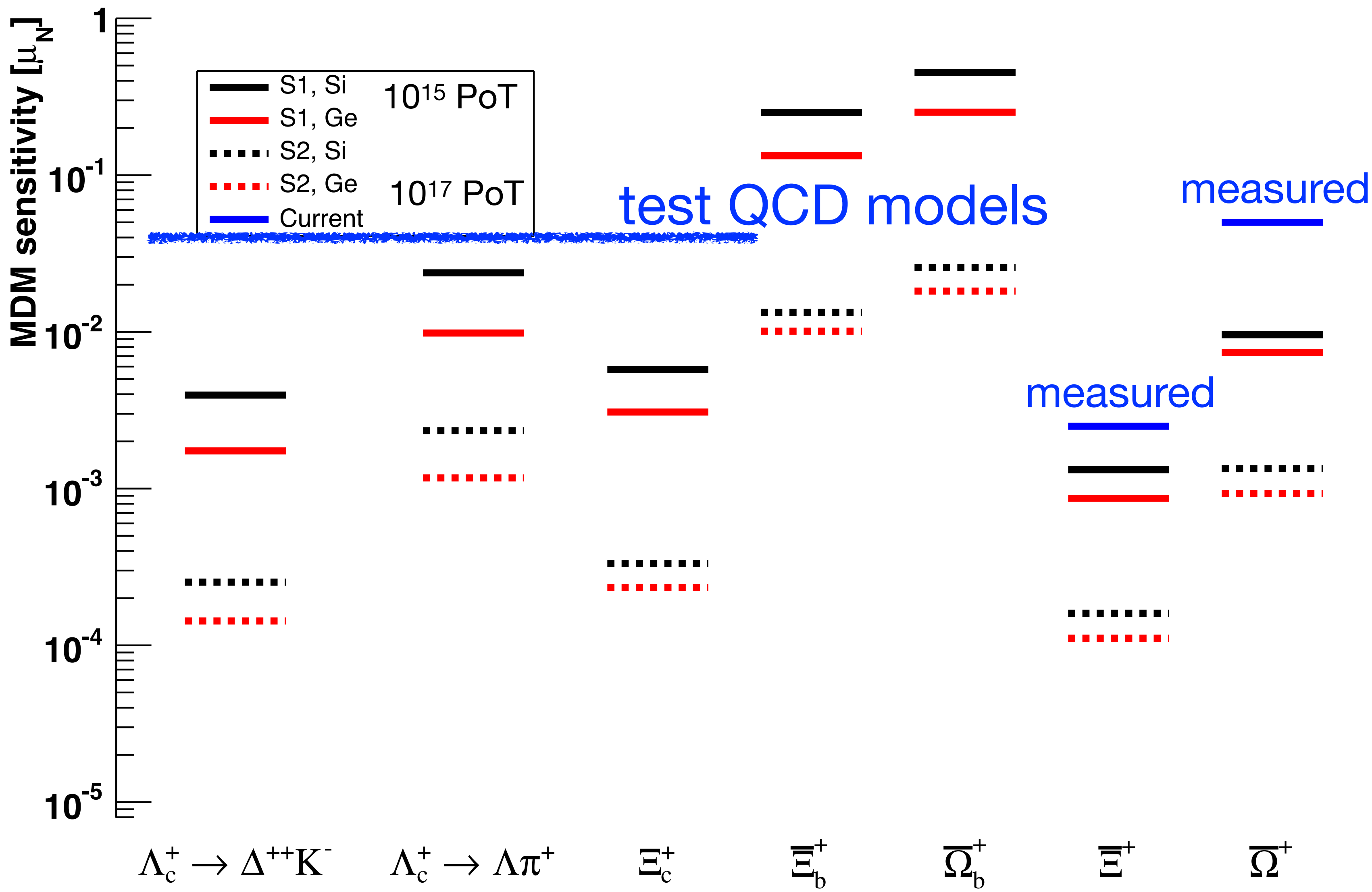
All sub-detectors read out at 40 MHz for a **fully software trigger**



Sensitivity on MDM

- S1 configuration: **LHCb** using **10^{15} PoT**
- S2 configuration: **dedicated experiment** using **10^{17} PoT**

PoT = proton on target
W target 5 mm thick



EPJC (2017) 77:828

Material of the crystal:

→ **Silicon**

→ **Germanium**

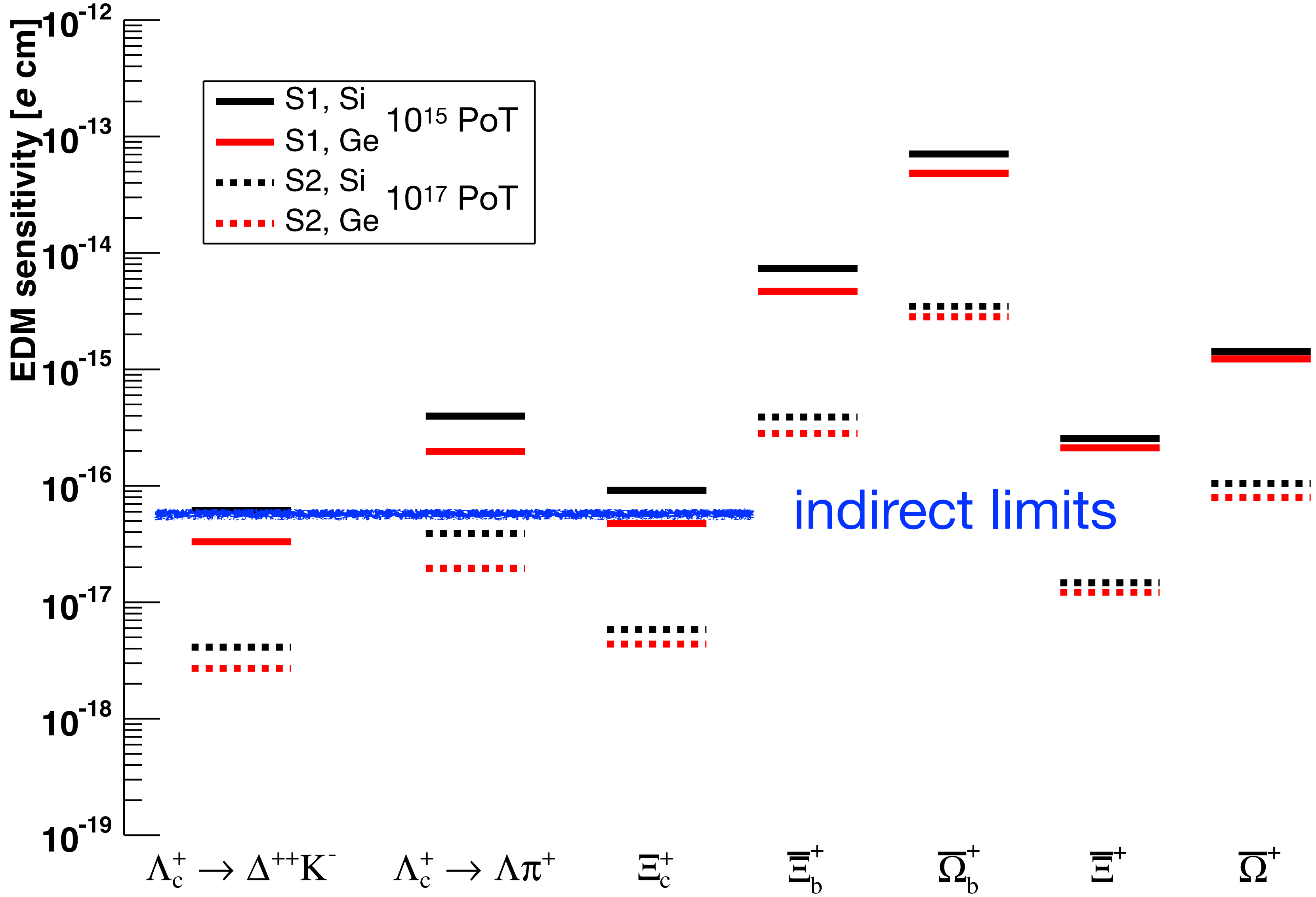
- Measurements are **statistically limited**

Sensitivity on EDM

- S1 configuration: **LHCb** using **10^{15} PoT**

PoT = proton on target
W target 5 mm thick

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



EPJC (2017) 77:828

Material of the crystal:

→ **Silicon**

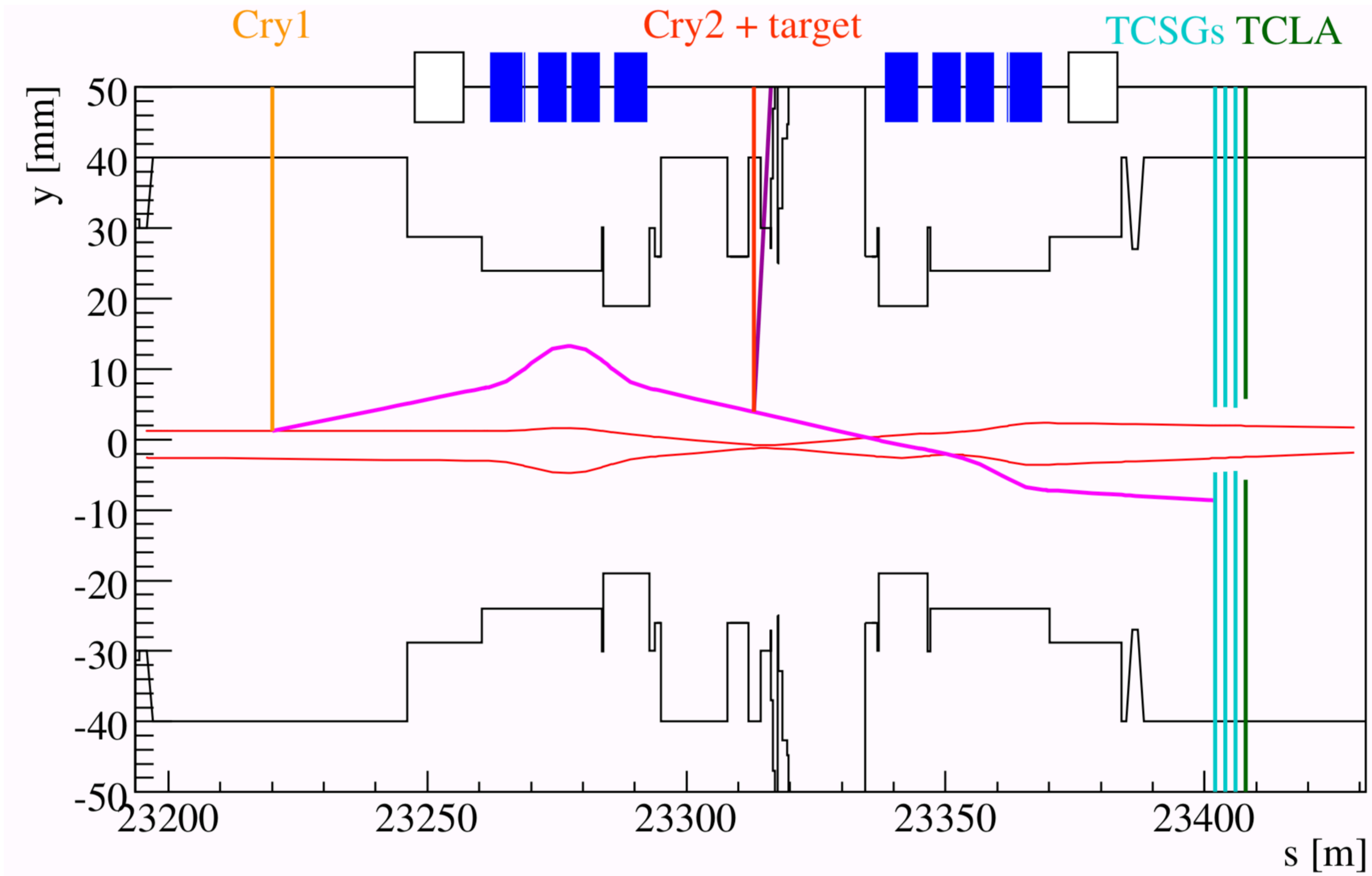
→ **Germanium**

- Measurements are **statistically limited**

R&D and preparatory studies

LHC machine studies

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

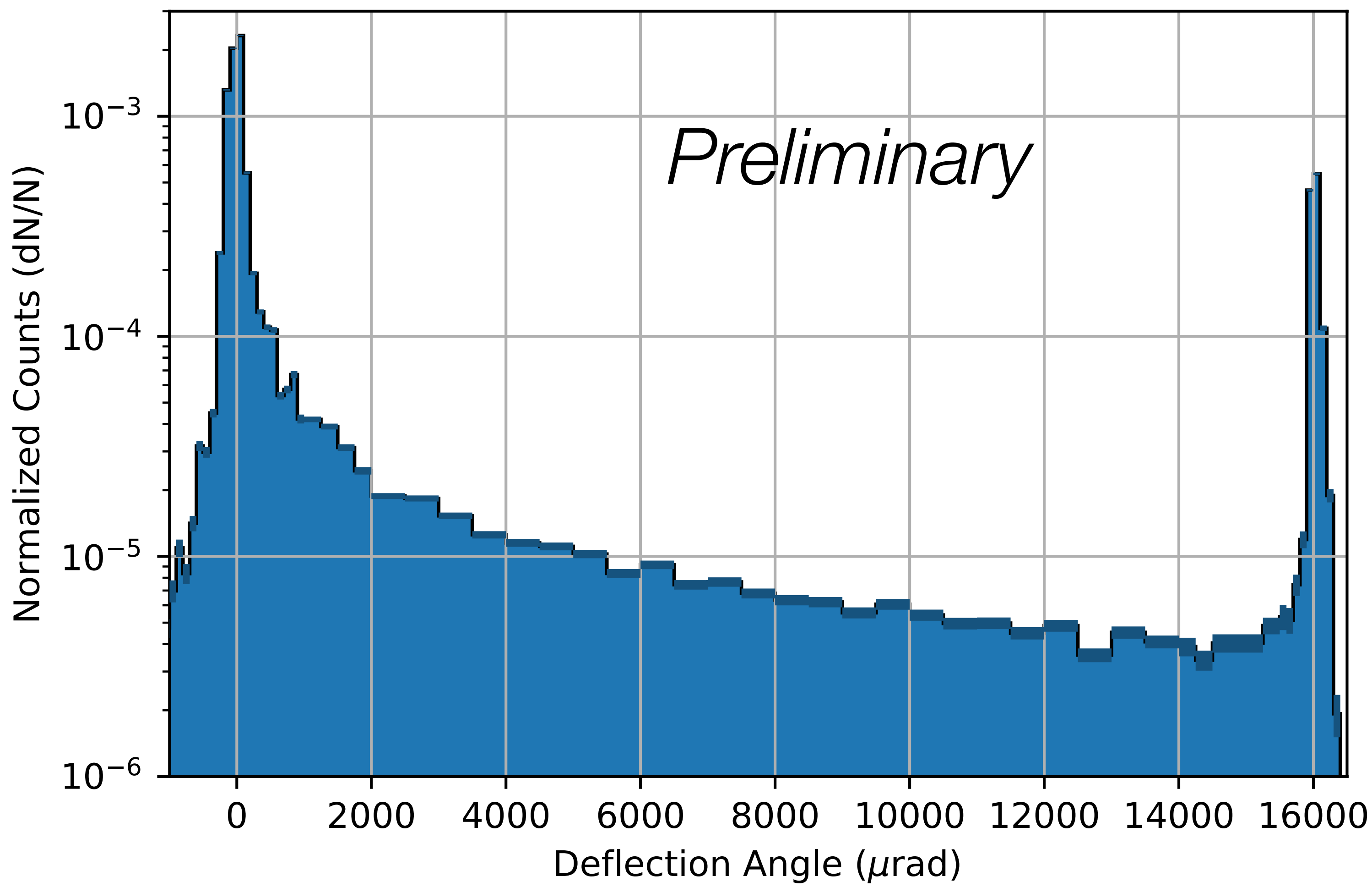


W. Scandale et al., PLB 758 (2016) 129–133

- **Channeling** of 6.5 TeV **at LHC** already **demonstrated** by UA9
- **Viable layout:** 10^6-10^7 proton/sec on target close to LHCb
- Improved performance for a potential dedicated experiment at the LHC

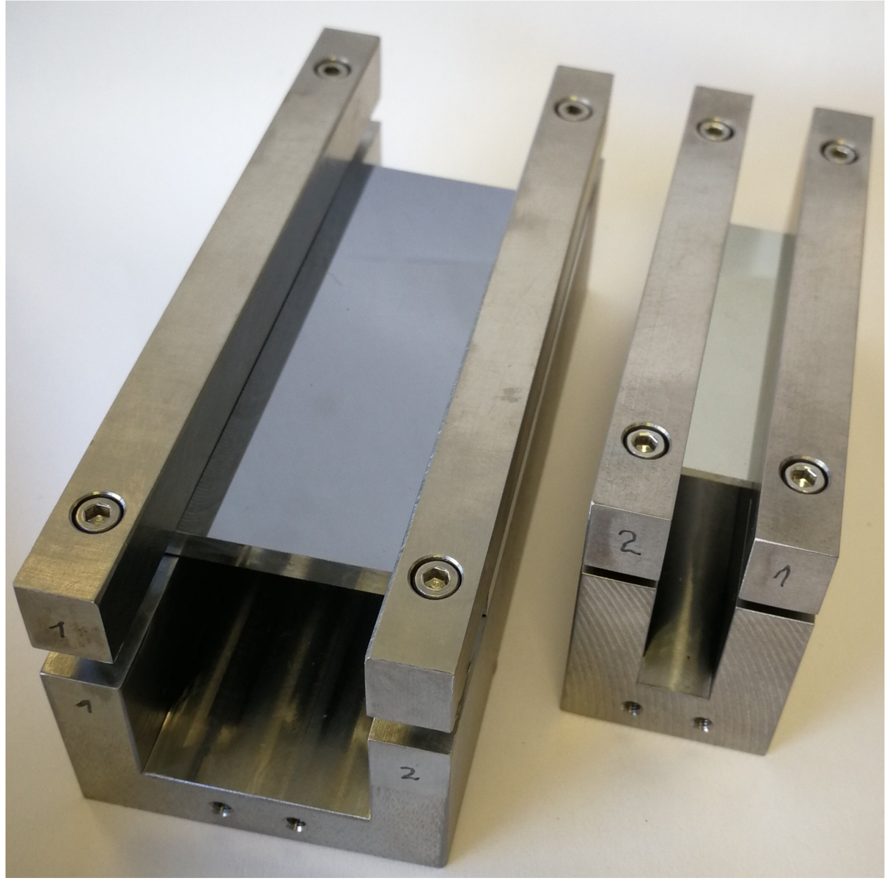
Long bent crystal results

Silicon crystal 8 cm long
Bending angle 16 mrad



Si: 8 cm long, bent @16.0 mrad

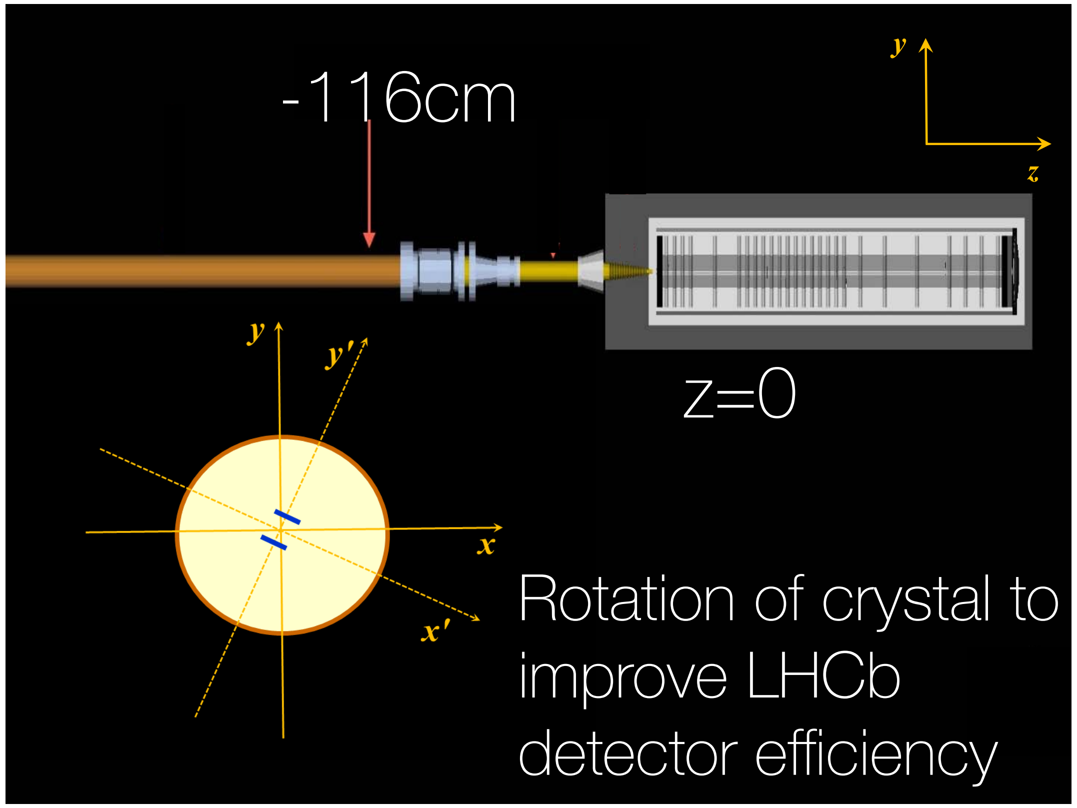
Ge: 5 cm long, bent @14.5 mrad



Courtesy of A. Mazzolari

- **Si** and **Ge** long bent crystals developed at INFN-Ferrara. Channeling efficiency >10% for 180 GeV/c pions

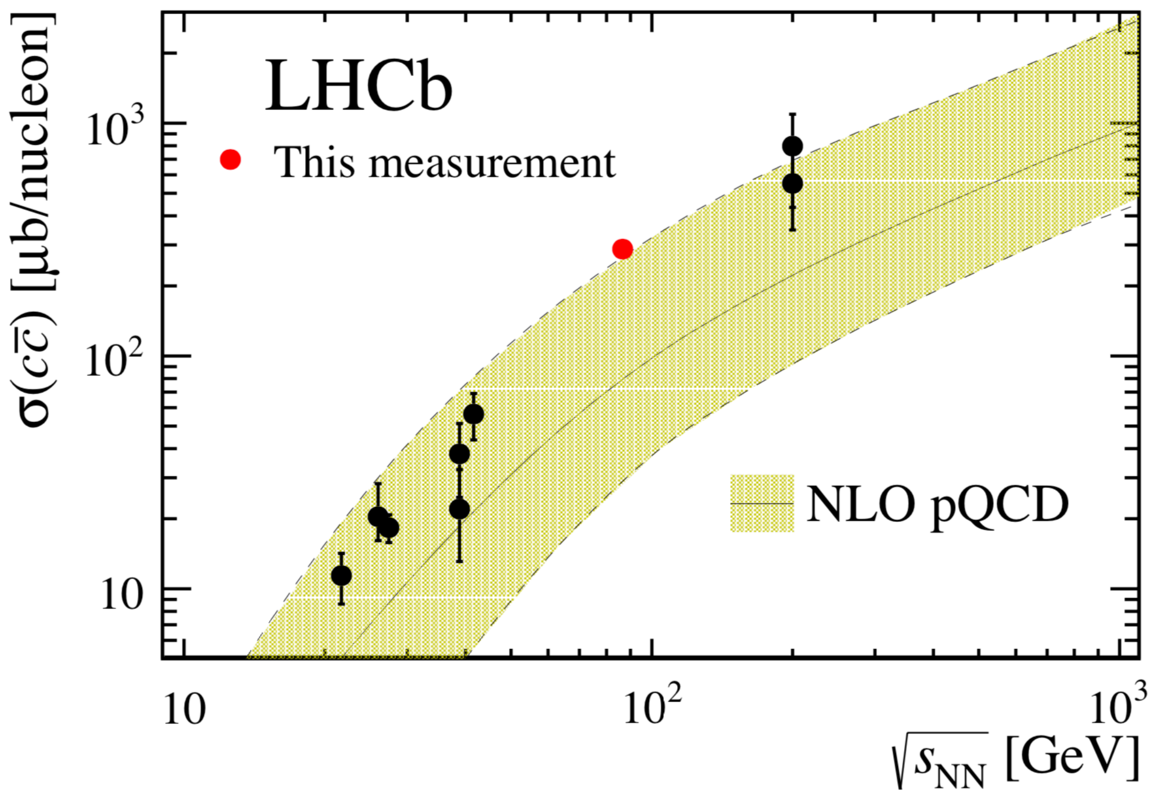
Preparatory studies in LHCb



- Good performance for signal reconstruction and background rejection studied using LHCb full **simulation** for the **new fixed-target setup**

- Program of preparatory **measurements** in LHCb started: Λ_c^+ polarisation and cross-section in **p-gas** fixed-target configuration (LHCb-PUB-2018-015)

Phys. Rev. Lett. 122, 132002 (2019)



New proposals for τ lepton

- A.S. Fomin , A. Korchin, A. Stocchi, S. Barsuk, P. Robbe, *Feasibility of τ lepton electromagnetic dipole moments measurements using bent crystals at LHC*, J. High Energ. Phys. 03 (2019) 156 (see backup slides)
- J. Fu, M. A. Giorgi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N. N., J. Ruiz Vidal, *Novel method for the direct measurement of the τ lepton dipole moments*, Phys. Rev. Lett. 123, 011801 (2019)

Novel method for the direct measurement of the τ lepton dipole moments

Target:

- production of $D_s^+(\rightarrow \tau^+ \upsilon_\tau)$

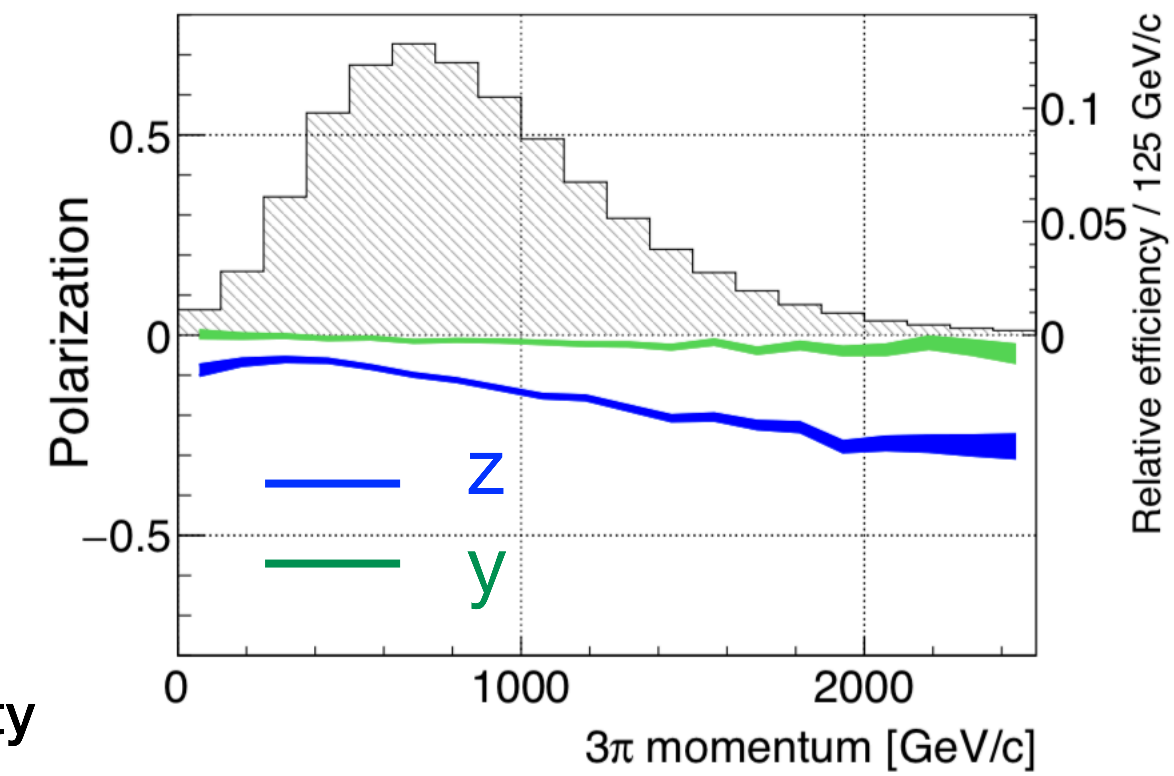
$$\tau^+ \rightarrow \pi^+\pi^-\pi^+\bar{\nu}_\tau$$

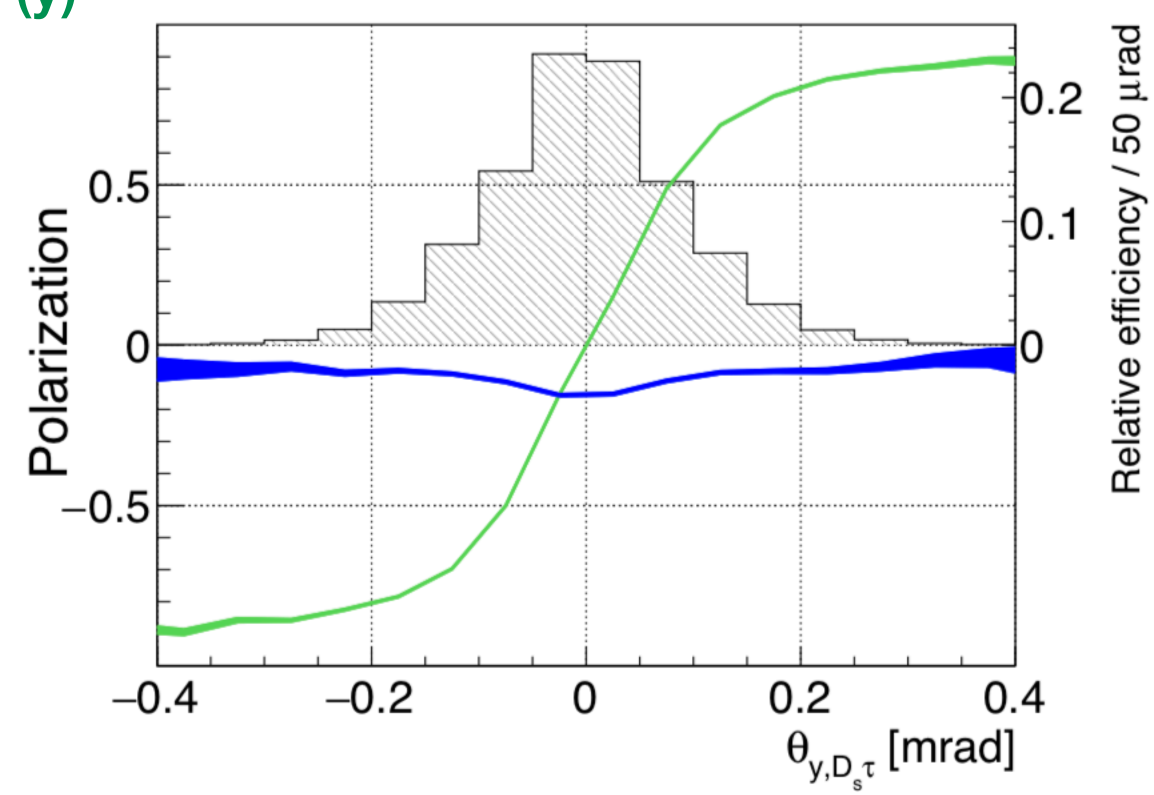
Single Crystal after target:

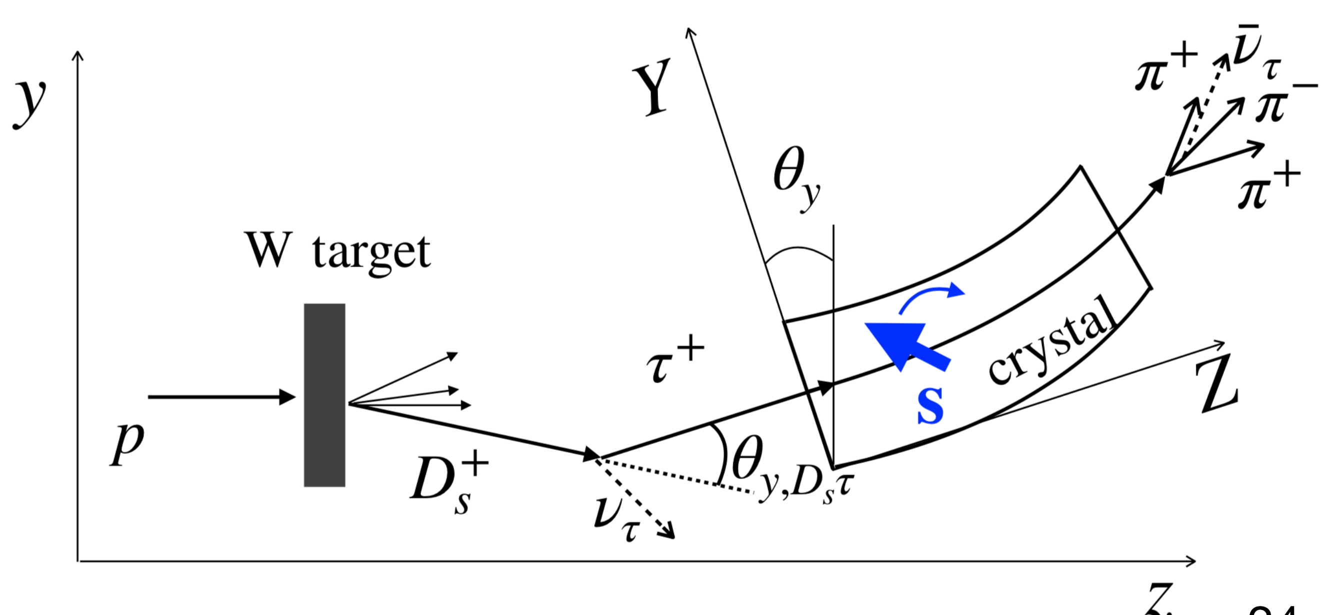
- τ spin precession

Spin polarisation:

- kinematic selection on $p_{3\pi}$>0.8 TeV, longitudinal (z) polarisation for MDM and enhanced EDM sensitivity
- Tagging θ(Ds,τ)≶0 (e.g. 2 crystals, other) transverse (y) polarisation for enhanced MDM sensitivity

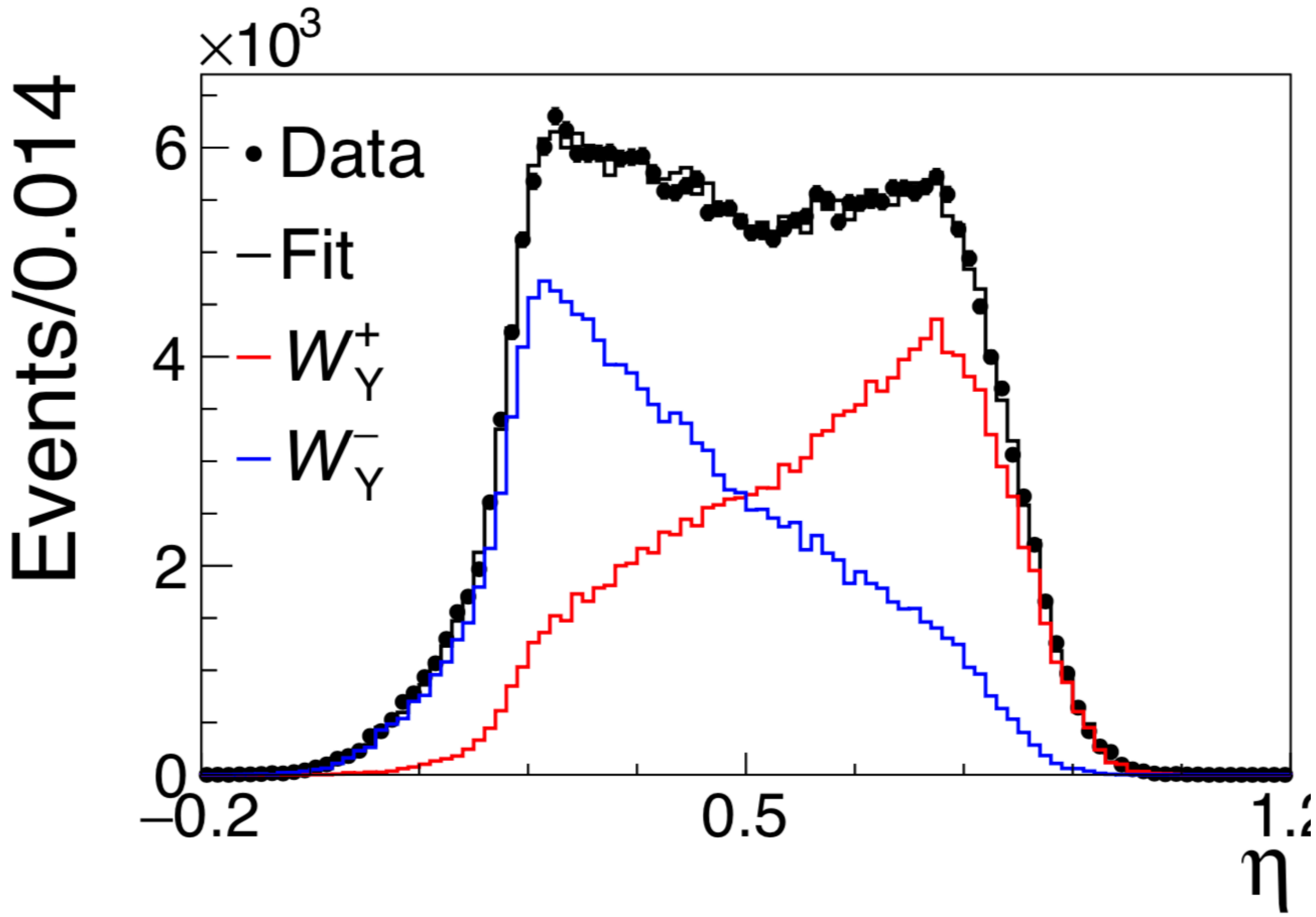


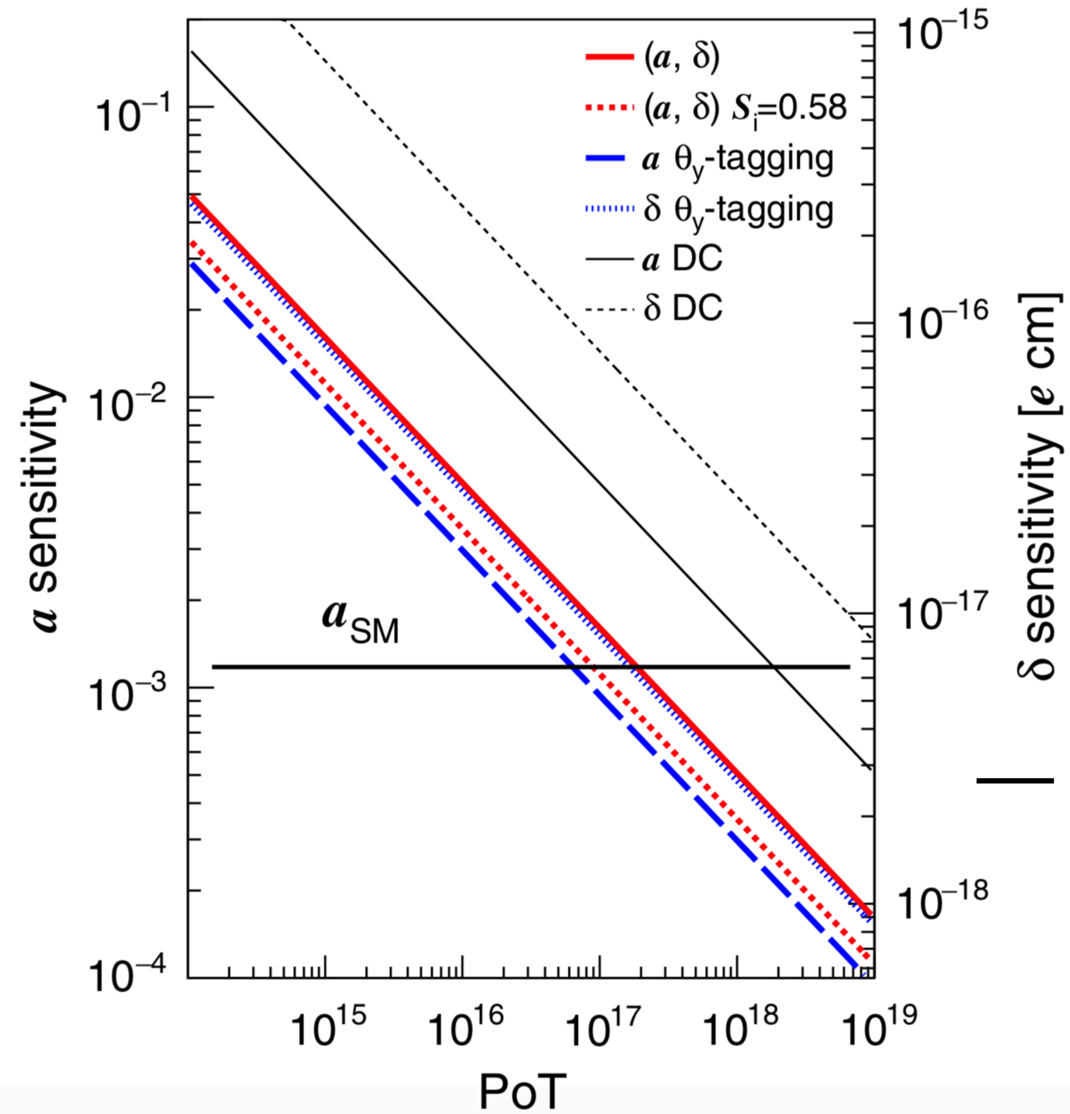




J. Fu, M. A. Giorgi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N.N., J. Ruiz Vidal, Phys. Rev. Lett. 123, 011801 (2019)

Novel method for the direct measurement of the τ lepton dipole moments





S. Eidelman and M. Passera, Mod. Phys. Lett. A 22, 159 (2007).

Multivariate classifier based on reconstructed τ variables to determine the polarisation and average event information S=0.42

$$S_i^2 = \frac{1}{N_{\tau^+}^{\mathrm{rec}}\sigma_i^2} = \left\langle \left(\frac{\mathcal{W}_i^+(\eta) - \mathcal{W}_i^-(\eta)}{\mathcal{W}_i^+(\eta) + \mathcal{W}_i^-(\eta)} \right)^2 \right\rangle$$

Test g-2 SM prediction with ~10^{17} PoT

EDM sensitivity ~10^{-17} e cm

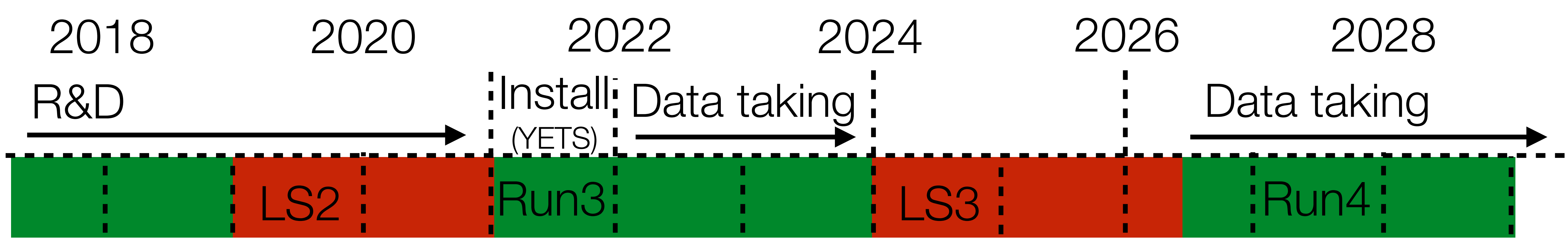
Challenging: dedicated experiment needed

J. Fu, M. A. Giorgi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N.N., J. Ruiz Vidal, Phys. Rev. Lett. 123, 011801 (2019)

Summary

- The proposal for measuring MDM/EDM of unstable particles extends the LHC physics program
- **Milestones** achieved: feasibility detector studies, long bent crystal prototypes, preparatory studies in LHCb, machine layout, physics program extended
- **Next steps**: produce a technical design report and if approved proceed with installation, data taking
- **<u>Workshop</u>** 3-4 October 2019 in Milano

Proposed timeline



- LHCb

Acknowledgements

- **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

SELDOM webpage

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References for baryons

- E. Bagli, L. Bandiera, G. Cavoto, V. Guidi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Mazzolari, A. Merli, N. Neri, J. Ruiz Vidal, *Electromagnetic dipole moments of charged baryons with bent crystals at the LHC*, arXiv:1708.08483 (2017), Eur. Phys. J. C **77** (2017) 828.
- A.S. Fomin , A.Yu. Korchin, A. Stocchi, O.A. Bezshyyko, L. Burmistrov, S.P. Fomin, I.V. Kirillin, L. Massacrier , A. Natochii, P. Robbe, W. Scandale, N.F. Shul'ga, *Feasibility of measuring the magnetic dipole moments of the charm baryons at the LHC using bent crystals*, JHEP **1708** (2017) 120.
- V. G. Baryshevsky, *On the search for the electric dipole moment of strange and charm baryons at LHC and parity violating (P) and time reversal (T) invariance violating spin rotation and dichroism in crystal*, arXiv:1708.09799 (2017).
- L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N. Neri, P. Robbe, J. Ruiz Vidal, CERN-LHCb-INT-2017-011, *Proposal to search for baryon EDMs with bent crystals at LHCb*.
- F. J. Botella, L. M. Garcia Martin, D. Marangotto, F. Martinez Vidal, A. Merli, N. Neri, A. Oyanguren, J. Ruiz Vidal, *On the search for the electric dipole moment of strange and charm baryons at LHC*, Eur. Phys. J. C **77** (2017) 181.
- V. G. Baryshevsky, *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*, Phys. Lett. B**757** (2016) 426.
- L. Burmistrov, G. Calderini, Yu Ivanov, L. Massacrier, P. Robbe, W. Scandale, A. Stocchi, *Measurement of short living baryon magnetic moment using bent crystals at SPS and LHC*, CERN-SPSC-2016-030 ; SPSC-EOI-012.

References for τ lepton

- J. Fu, M. A. Giorgi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N. Neri, J. Ruiz Vidal, *Novel method for the direct measurement of the τ lepton dipole moments*, Phys. Rev. Lett. 123, 011801 (2019)
- A.S. Fomin , A. Korchin, A. Stocchi, S. Barsuk, P. Robbe, *Feasibility of τ lepton electromagnetic dipole moments measurements using bent crystals at LHC*, J. High Energ. Phys. (2019) 2019: 156.

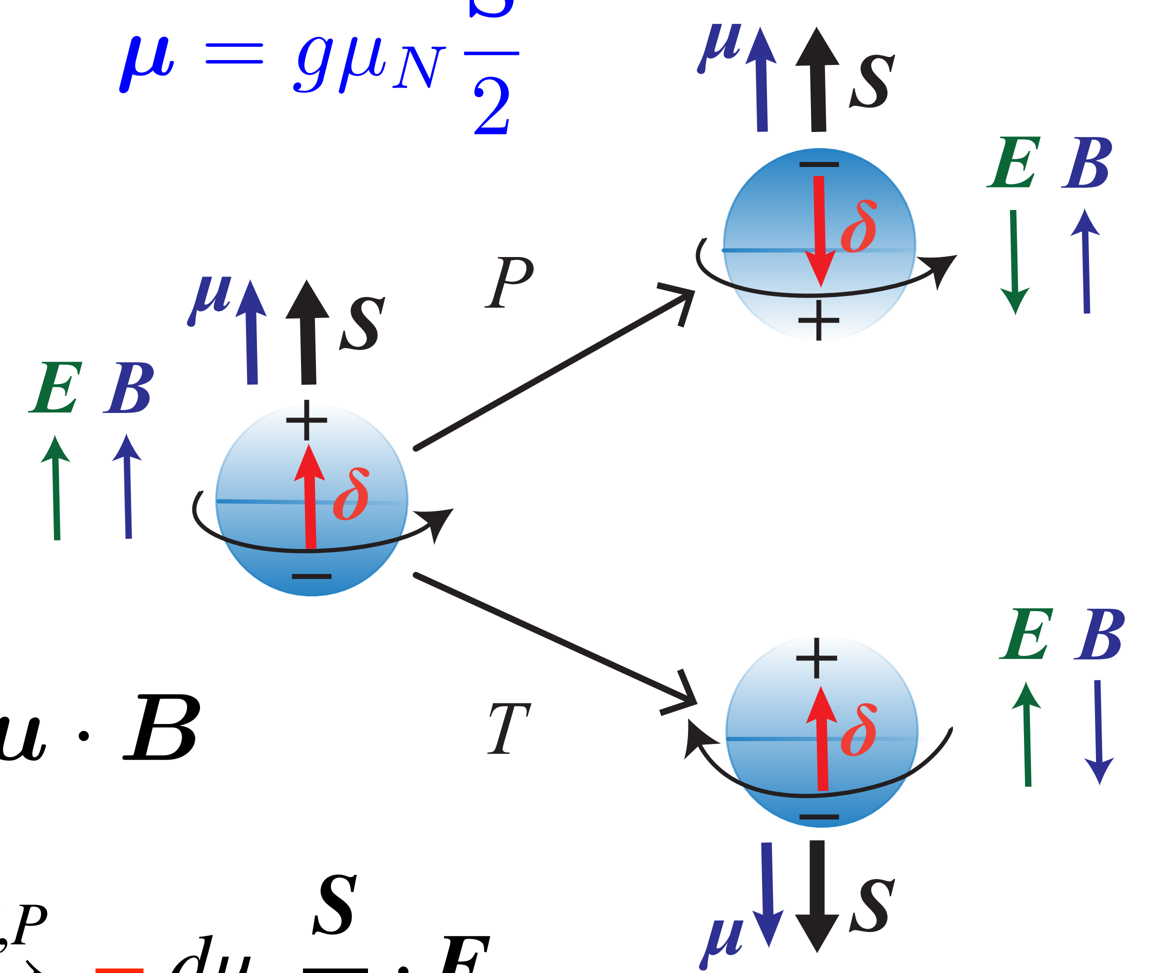
Backup slides

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)



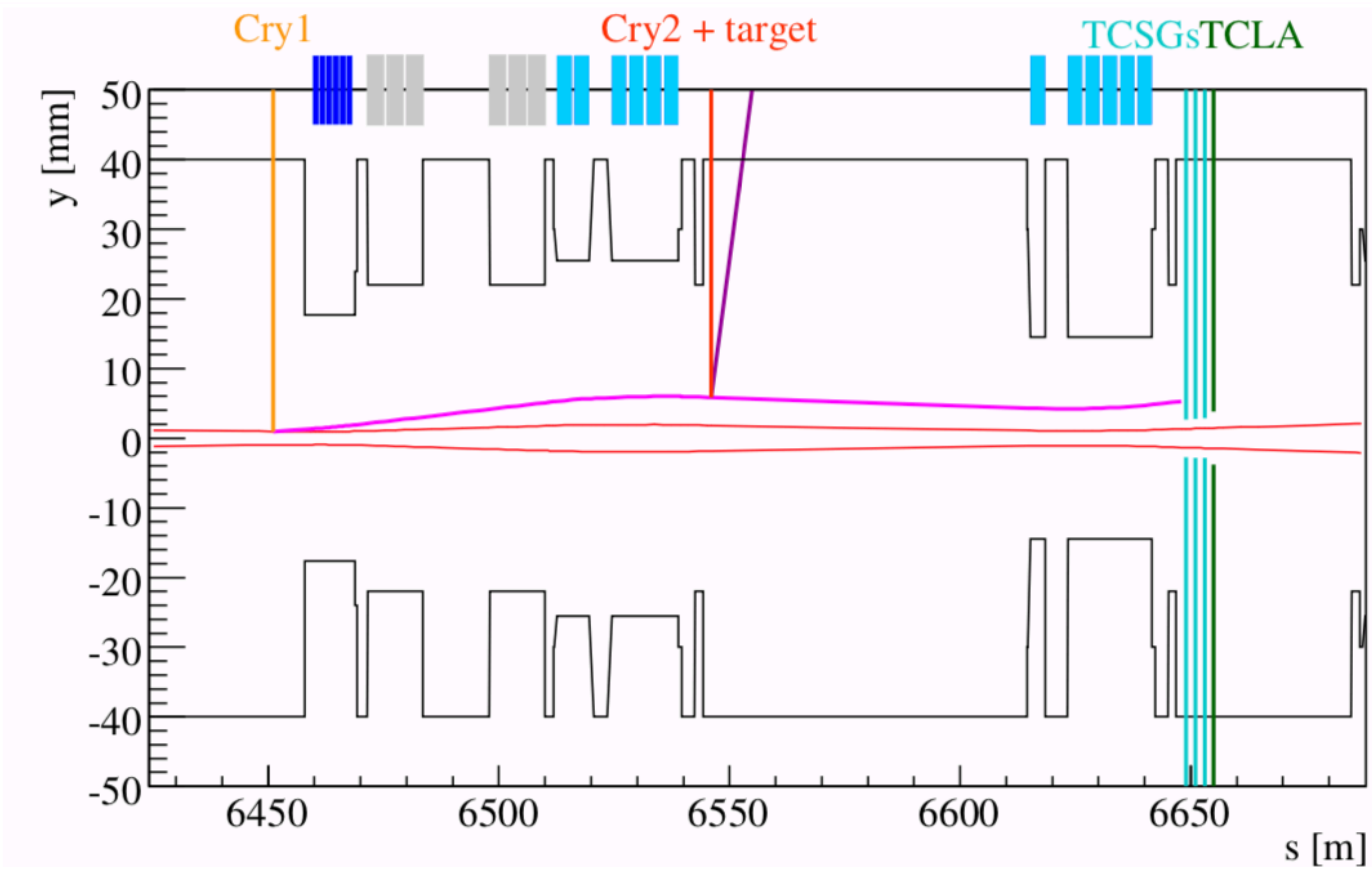
- Hamiltonian $H = -\boldsymbol{\delta} \cdot \boldsymbol{E} - \boldsymbol{\mu} \cdot \boldsymbol{B}$

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*

Layout for dedicated experiment

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

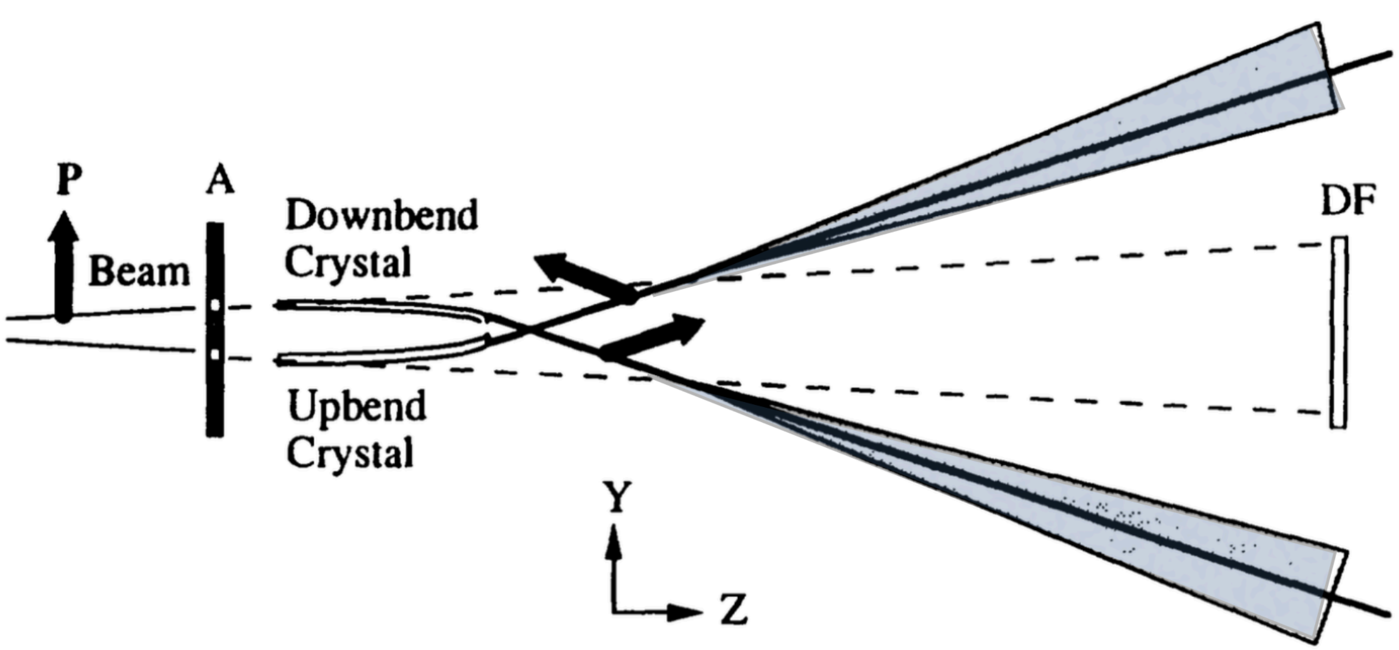


- At IR3 with optimised detector acceptance and reduced crystal bending (5 mrad), about x100 channeled particles can be achieved

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



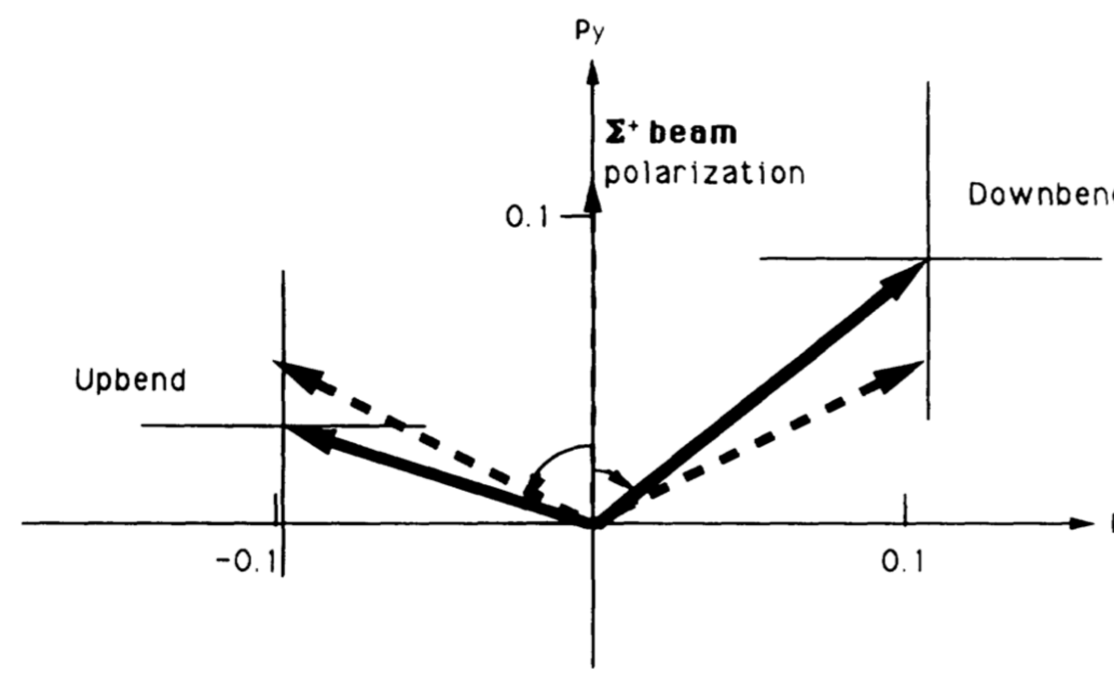


FIG. 3. Measured polarizations and uncertainties (1σ statistical errors) after spins have been processed by the two crystals. The dashed arrows show the expected precessions.

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)

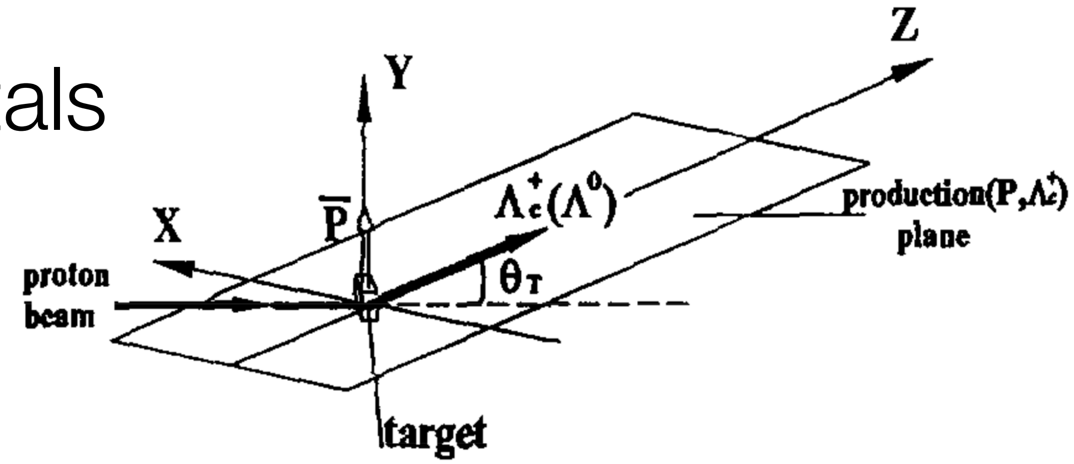


Fig. 3. Schematic diagram of the Λ_c^+ (Λ^0) polarization production.

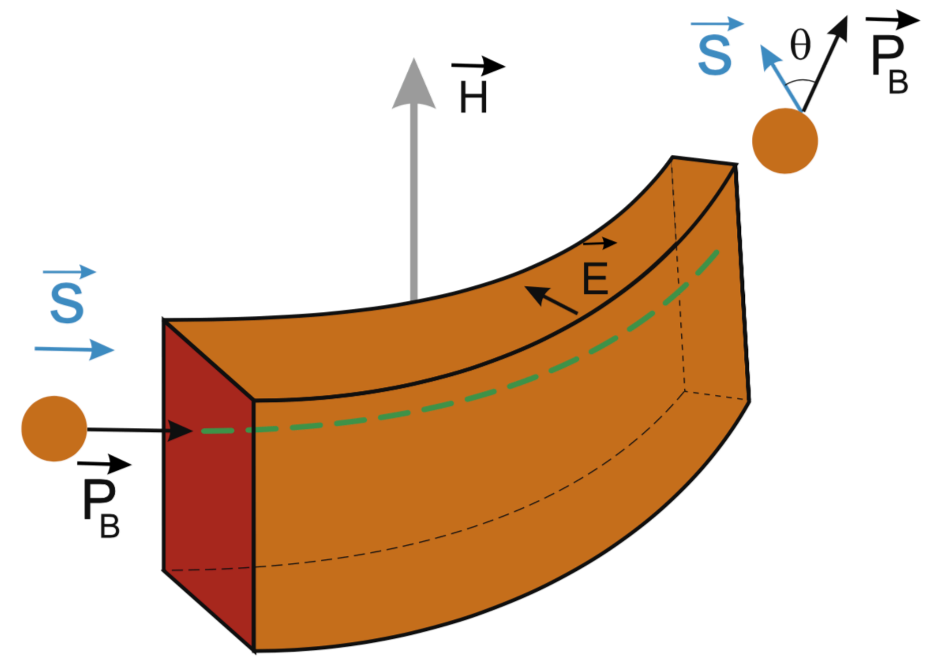
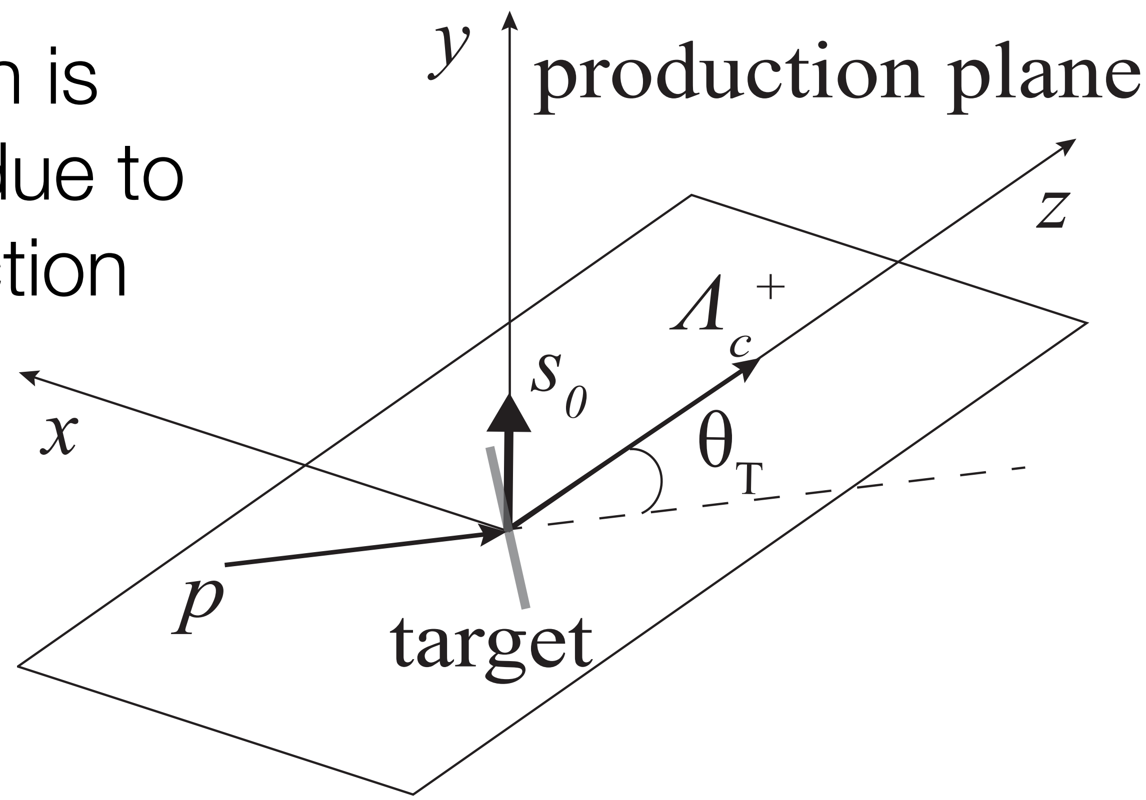
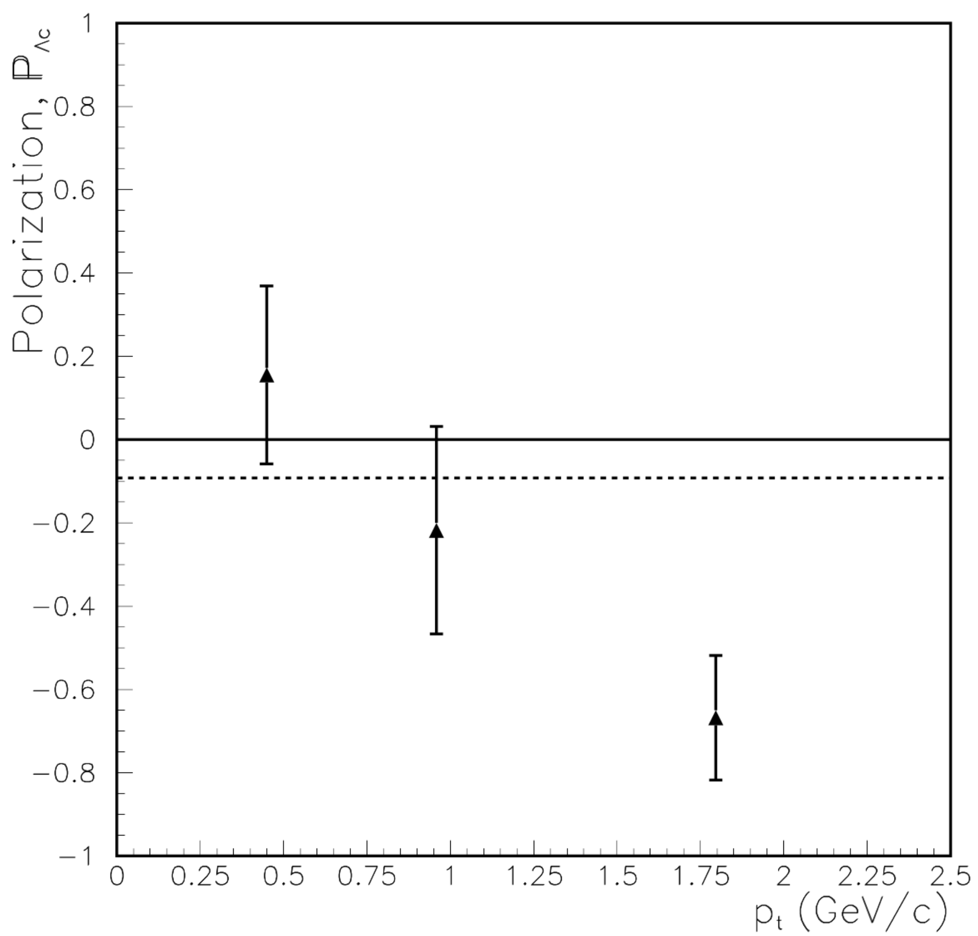


Fig. 1. Spin rotation in a bent crystal.

Charm baryon polarisation

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





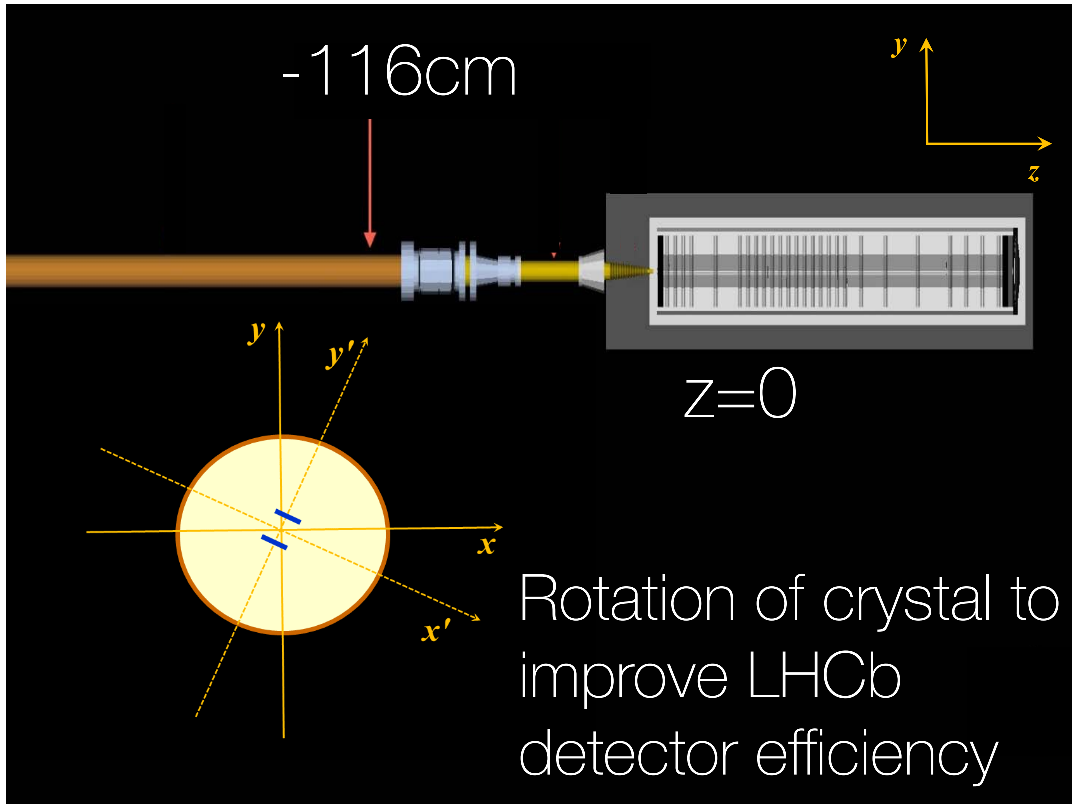
- Λ_c^+ polarisation vs transverse momentum measured by E791 experiment in 500 GeV/c π^--N reactions

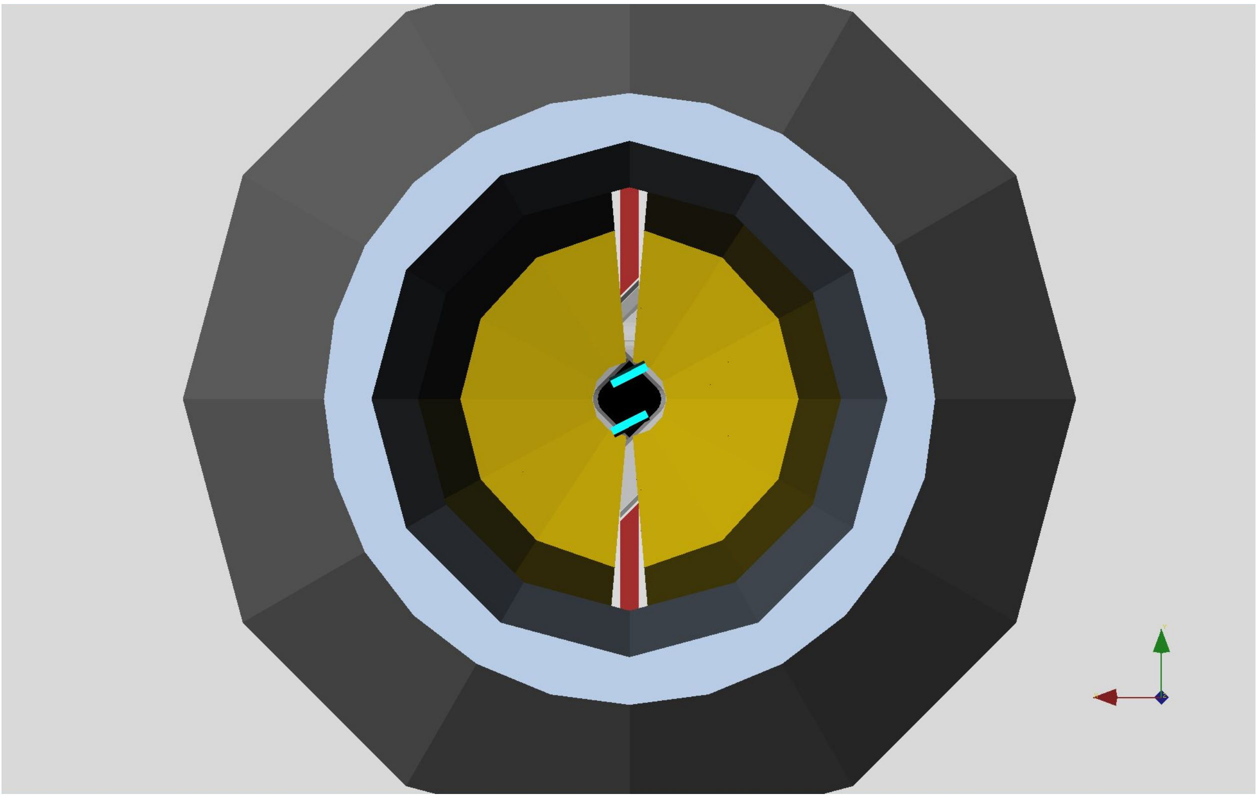
- Increases with Λ_c^+ transverse momentum

Detector simulation studies

Simulation studies

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



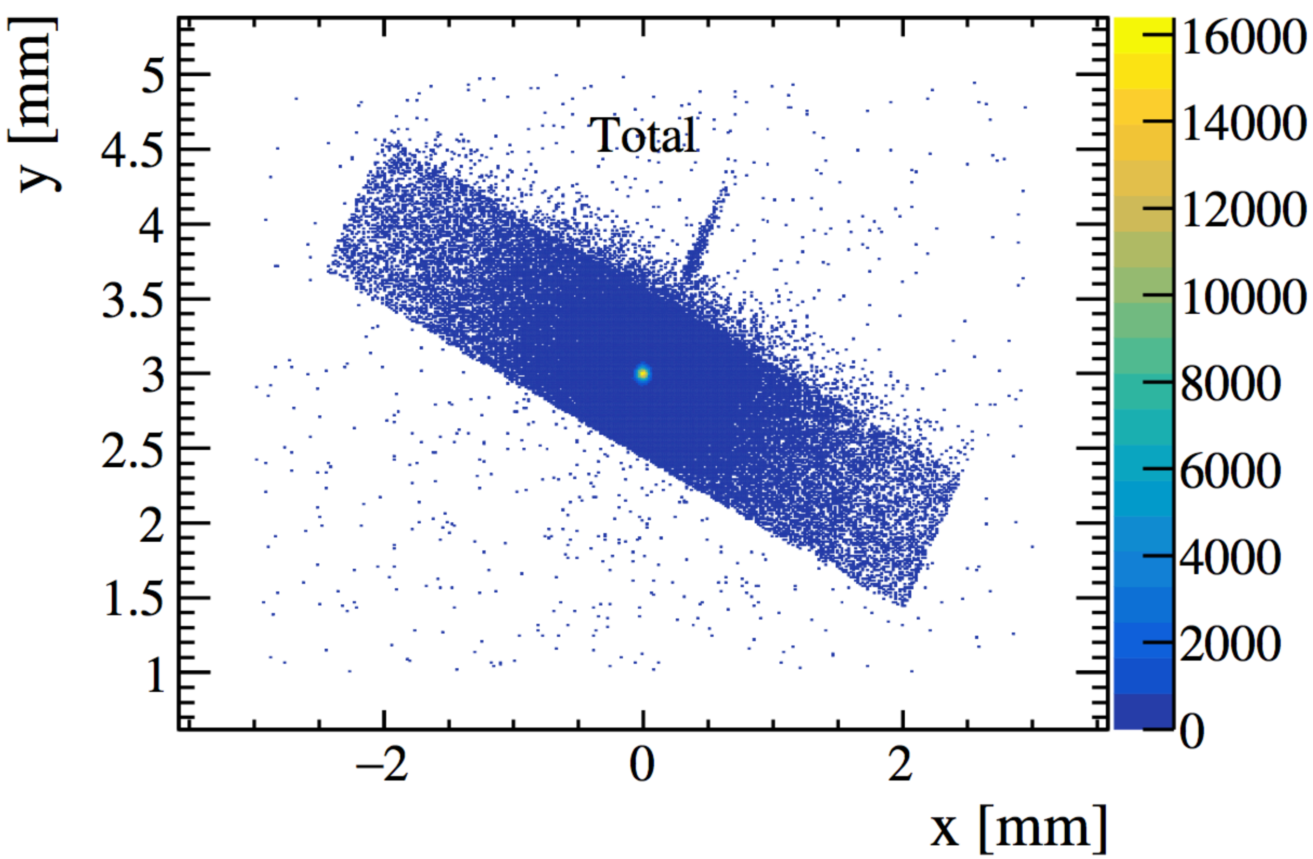


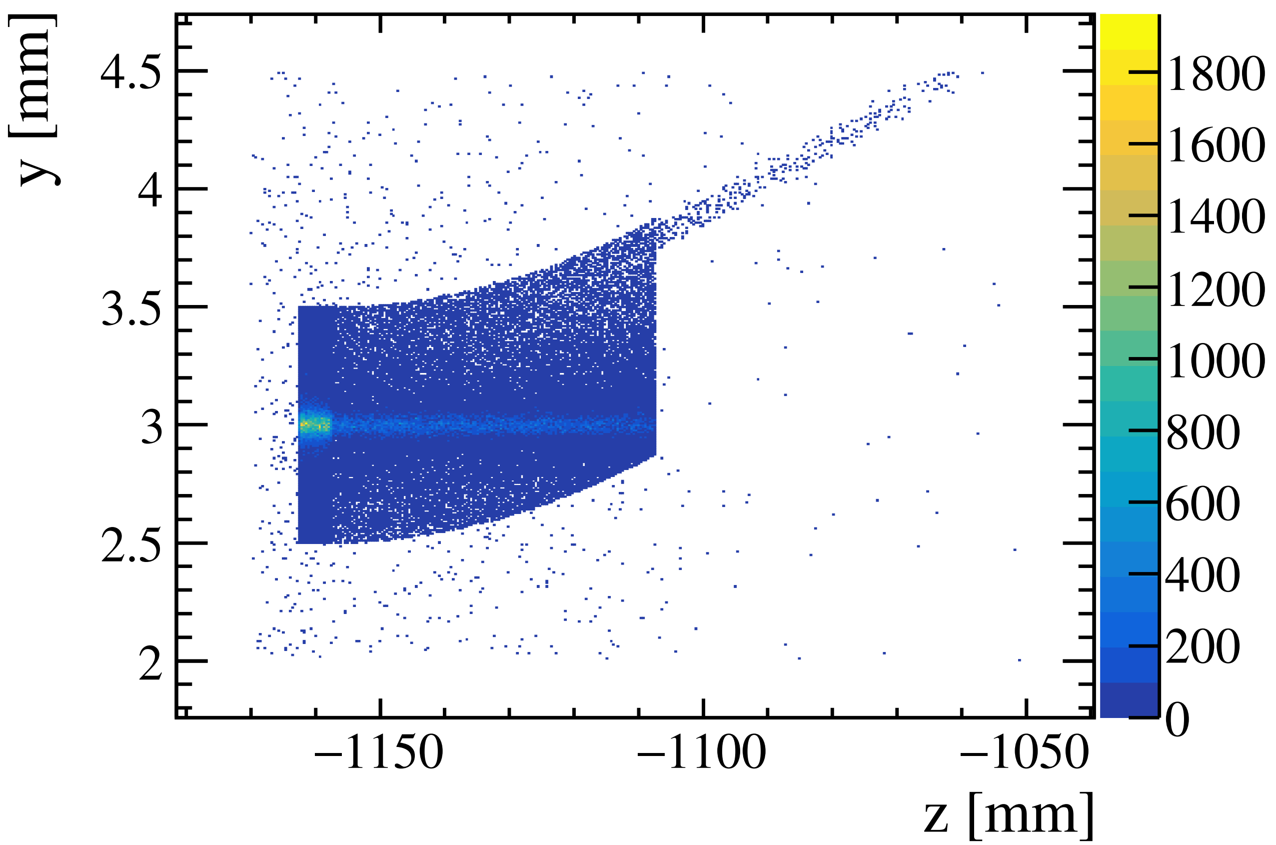
- Use EPOS for fixed-target minimum bias events, PYTHIA for baryons produced in pW hard collisions

- Signal reconstruction and background rejection studied using LHCb full simulation

Fixed-target simulation

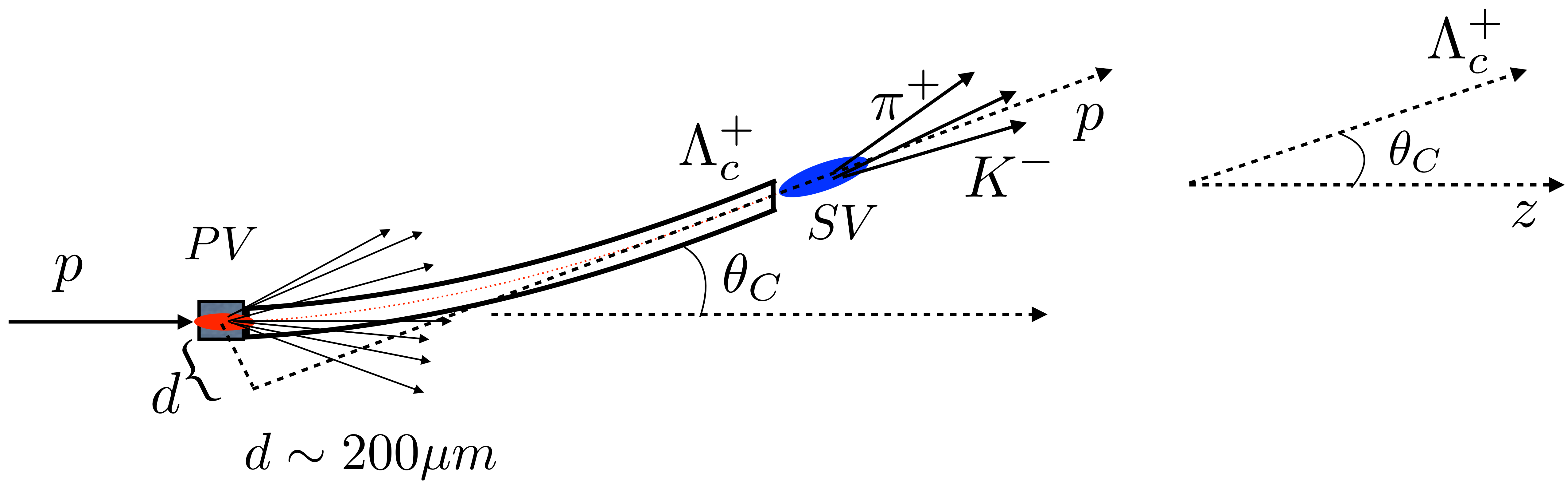
- Radiography of the target in (0, 0.3, -116) cm
- Distribution of origin vertex of stable charged particles in simulated events
- Simulated processes include: hadronic interactions, pair production, Bremsstrahlung, Compton, δ rays





Identification of signal events

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

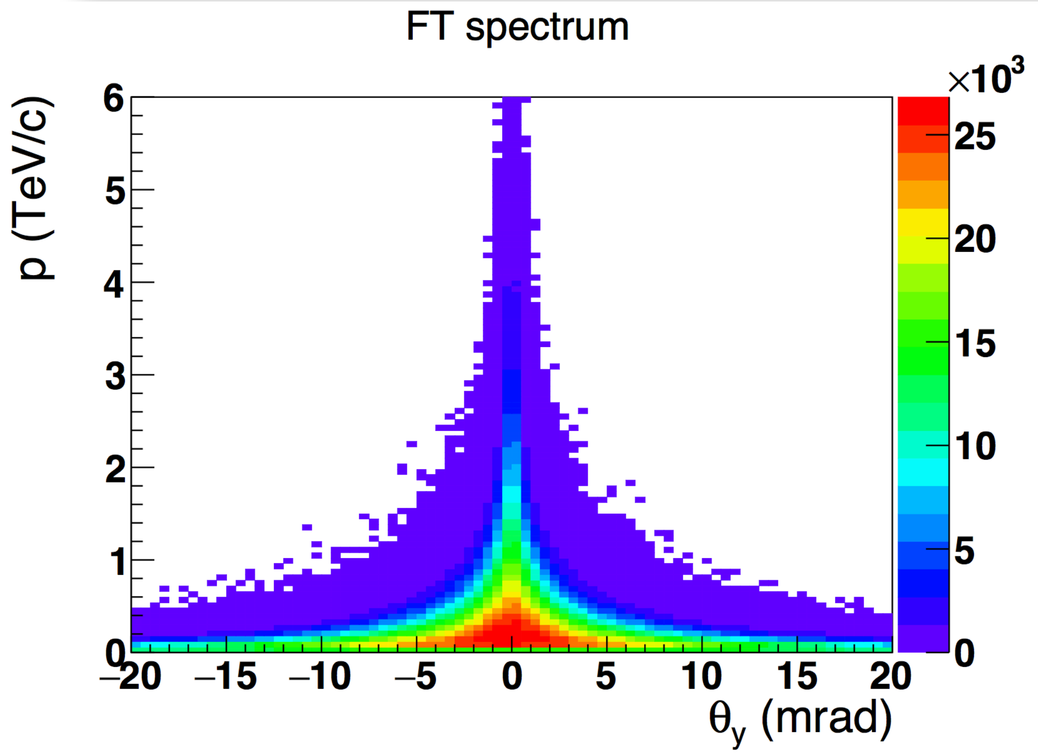


- Use PV to identify Λ_c^+ produced in W target, and Λ_c^+ vertex helps to identify decays outside of the crystal (max spin precession)

- Λ_c^+ angle determined by crystal bending angle, e.g. θ_C=15 mrad

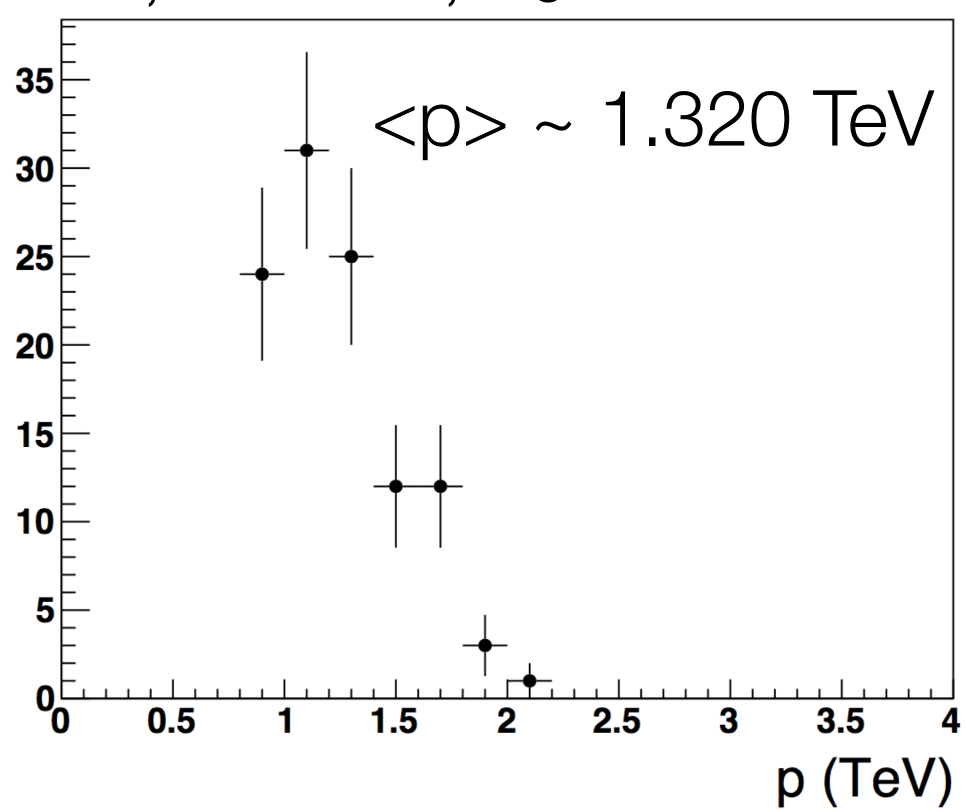
- Channeled baryons have high momentum ≳1 TeV/c

Λ_c^+ momentum distribution

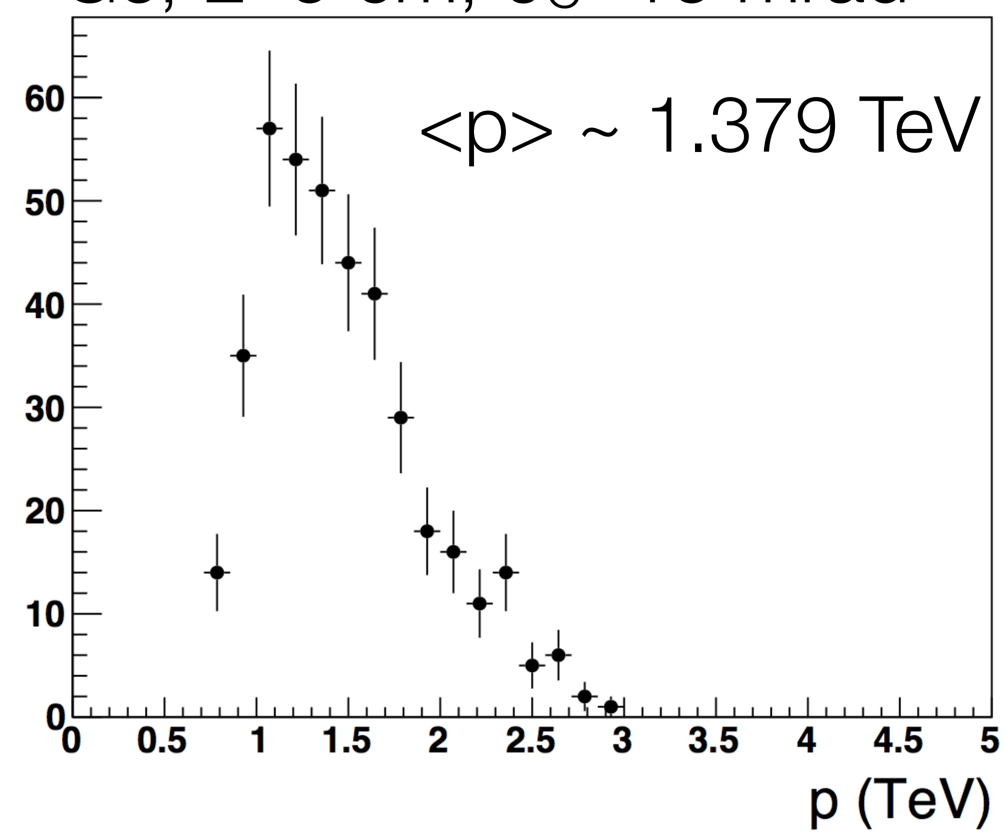


- At production (top)
- After channeling and p>800 GeV/c (bottom)

Si, L~7 cm, θ_C~14 mrad

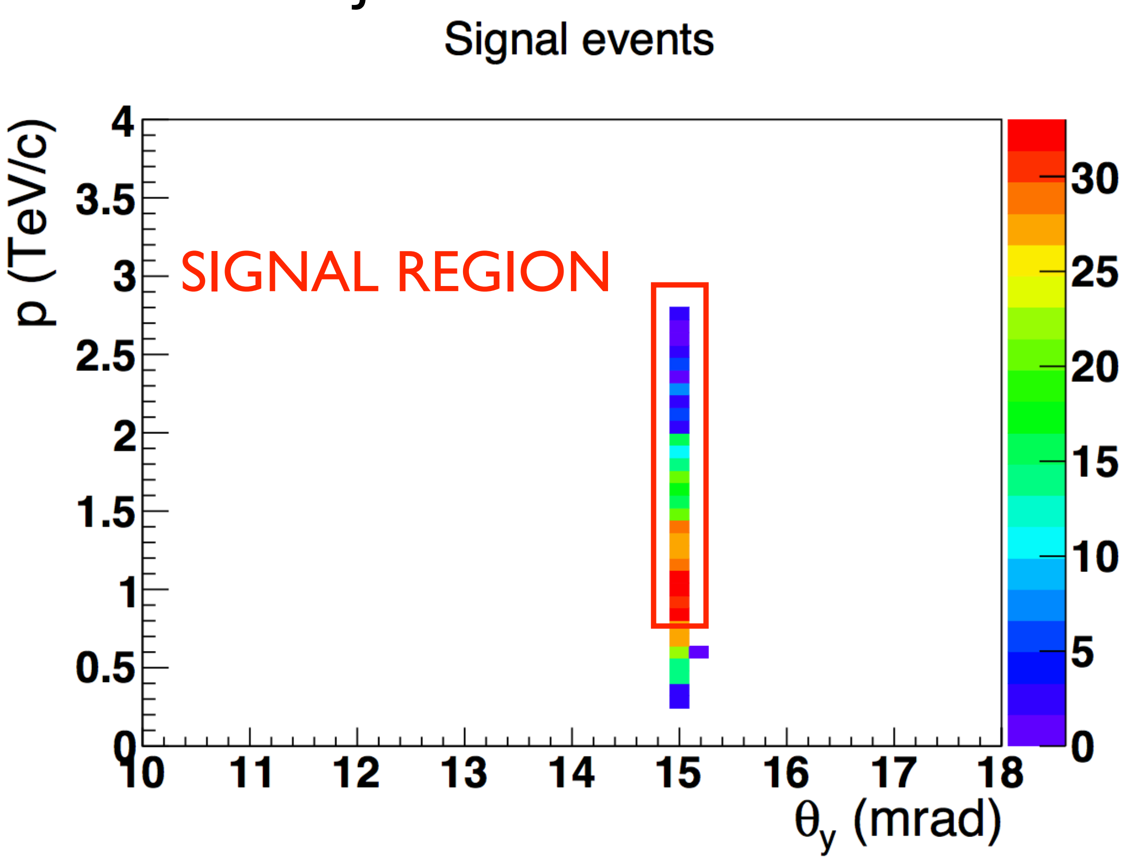


Ge, L~5 cm, θ_C~15 mrad

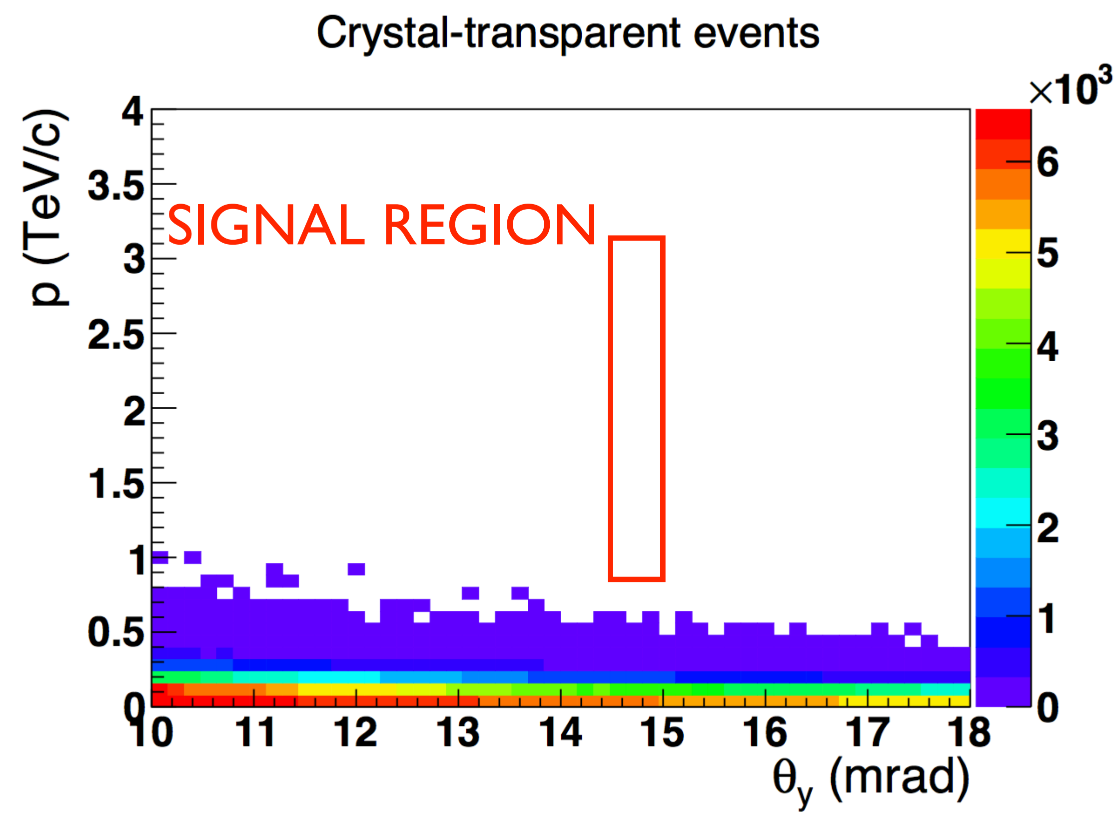


Background rejection

- Rejection of unchanneled Λ_c^+ produced in W target



Channeled particles



Unchanneled particles

- Signal region: $14.8<\theta<15.2$ mrad [$\sigma(\theta)\sim25\mu$rad], $p_{\Lambda c}>$ 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)

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

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

$$|S_0| \approx 0.6$$

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

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

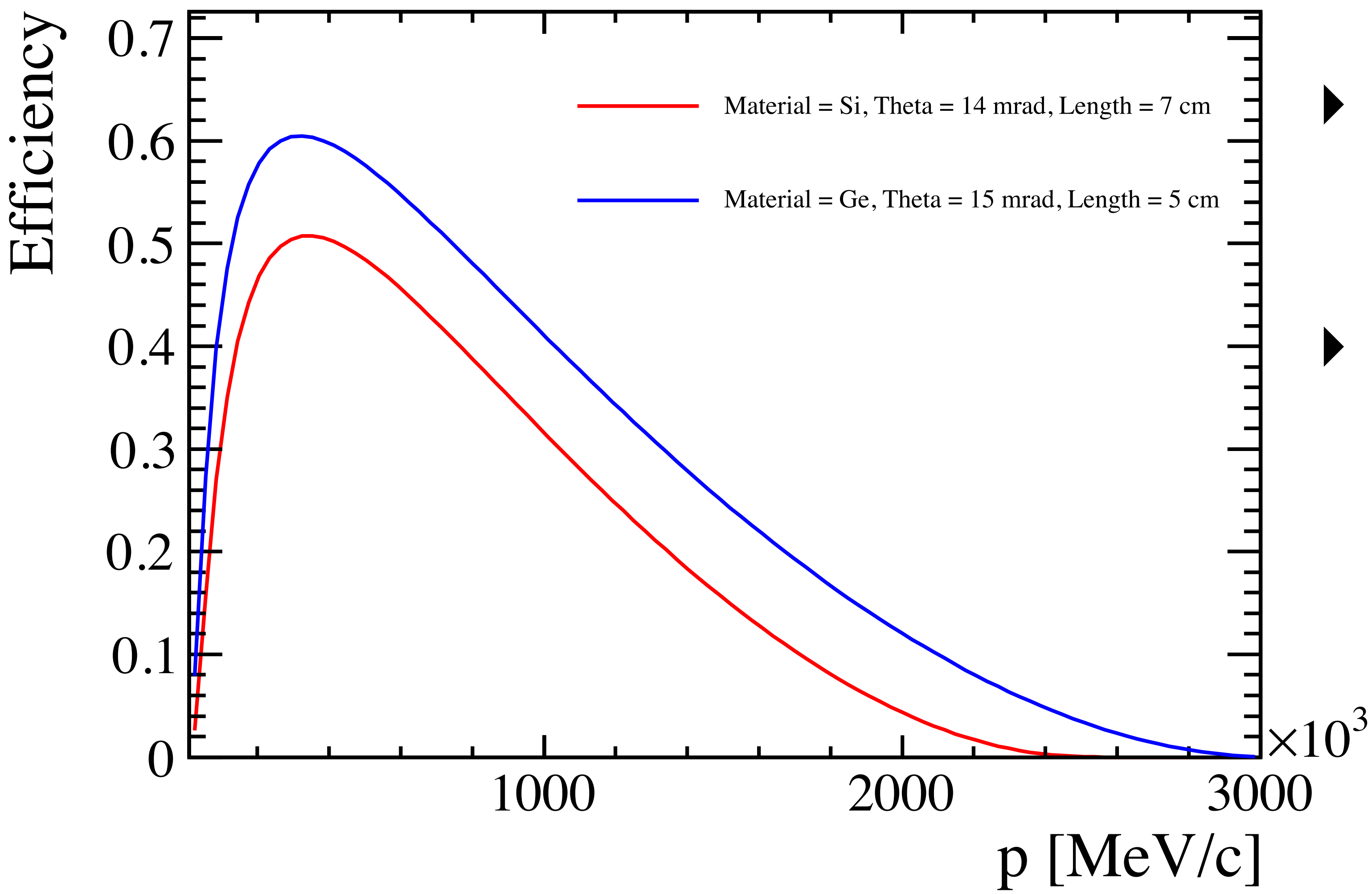
$$\frac{dN}{d\Omega} \propto 1 + \alpha_f\, \boldsymbol{S}\cdot\boldsymbol{p}$$

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

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

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

Channeling efficiency



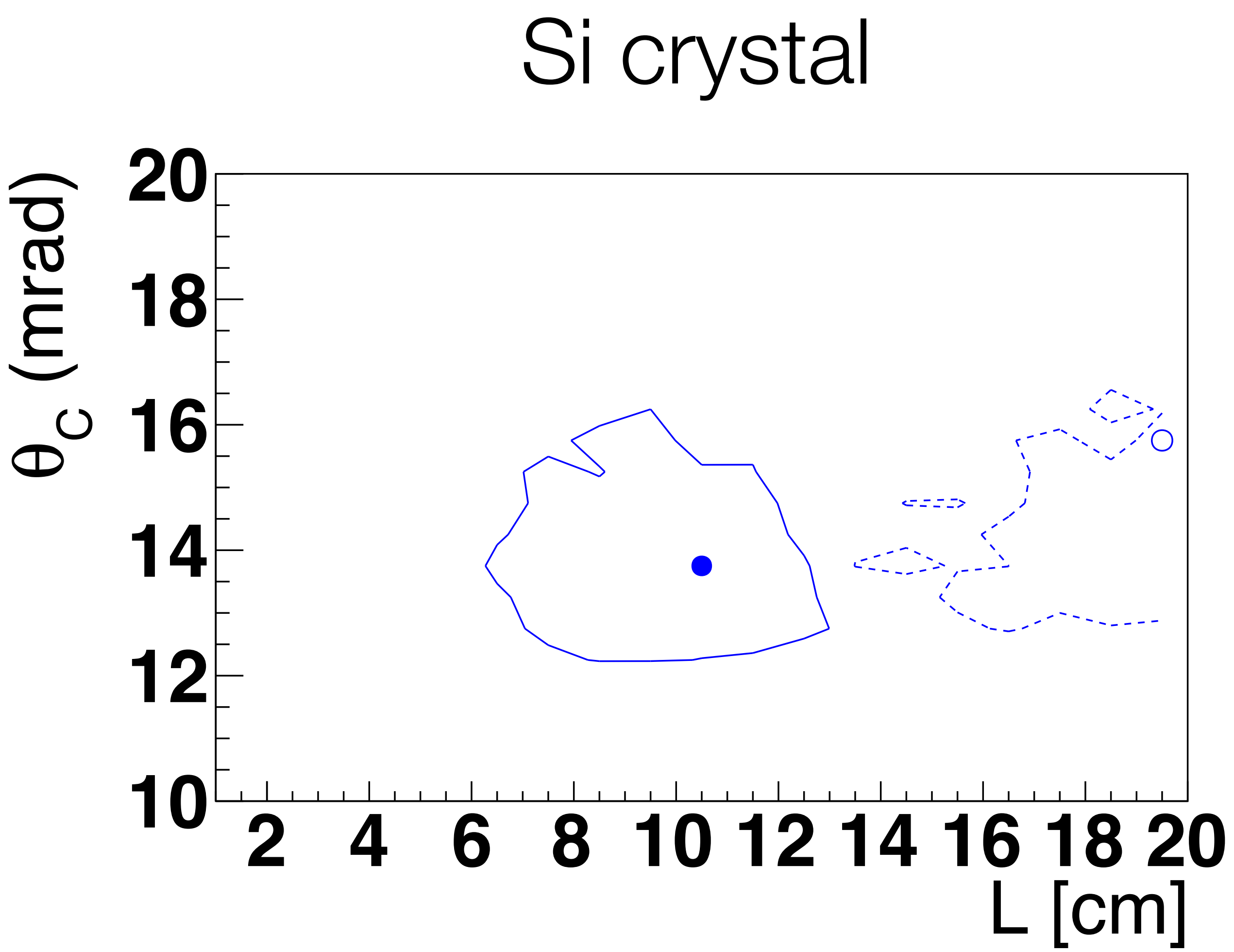
- Channeling efficiency for Λ_C^+ particles within Lindhard angle
- Total channelling efficiency: Lindhard angle, dechanneling, Λ_C^+ decay flight: $1 \cdot 10^{-5}$ (Si), $4 \cdot 10^{-5}$ (Ge)

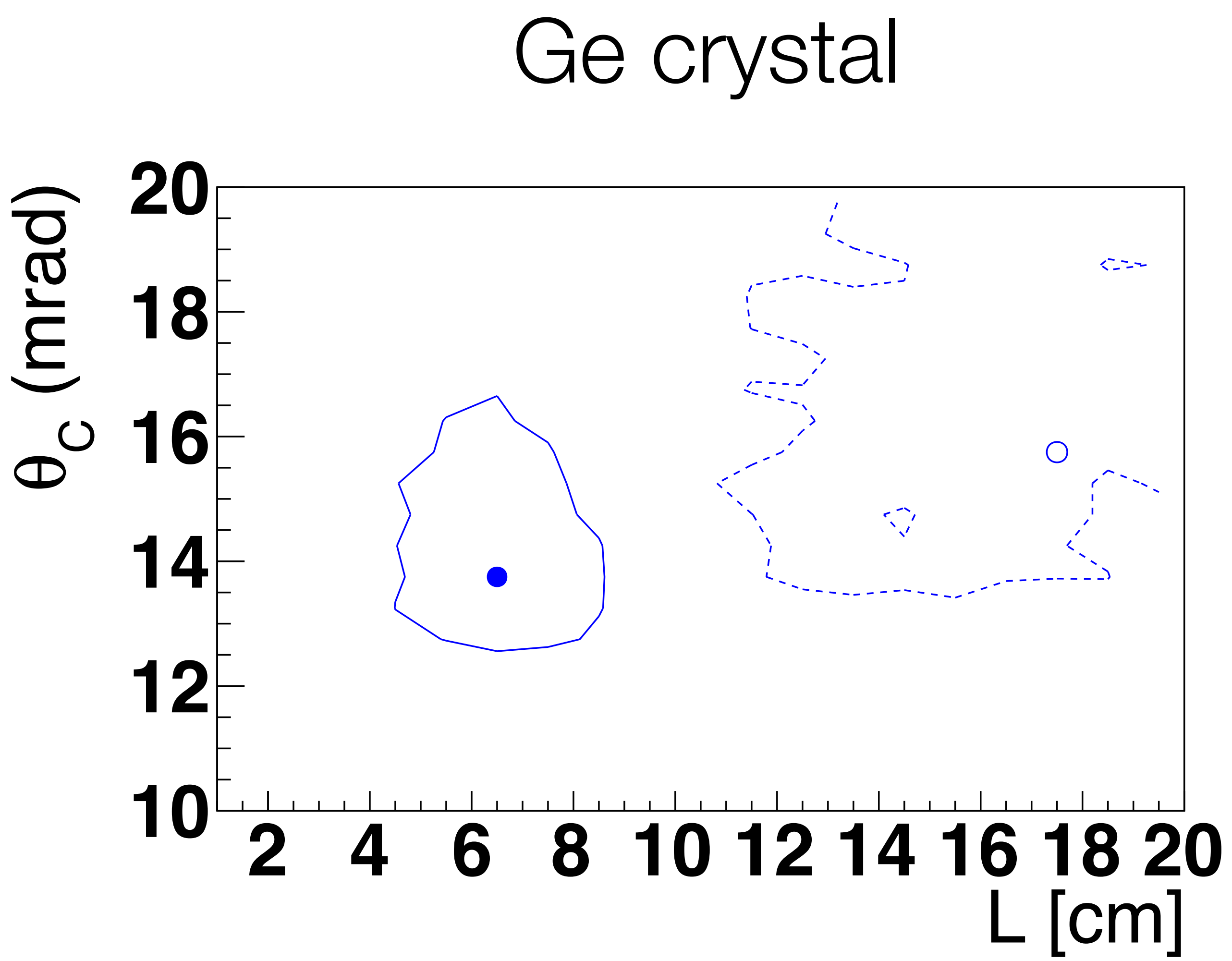
$$w(\theta_C, R) = \left(1 - \frac{R_c}{R}\right)^2 \exp\left(-\frac{\theta_C}{\theta_D \frac{R_c}{R}(1 - \frac{R_c}{R})^2}\right)$$

- 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





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

Future plans for τ lepton

Future plans

- New proposals for τ lepton MDM/EDM direct determination using bent crystals

- A.S. Fomin , A. Korchin, A. Stocchi, S. Barsuk, P. Robbe, *Feasibility of τ lepton electromagnetic dipole moments measurements using bent crystals at LHC*, arXiv:1810.06699
- J. Fu, M. A. Giorgi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N. Neri, J. Ruiz Vidal, *Novel method for the direct measurement of the τ lepton dipole moments*, arXiv:1901.04003

- Large statistics needed for interesting measurements, i.e. PoT$\gtrsim 10^{17}$ [2.5 cm W target]
- Many challenges: dedicated experiment needed
- Preparatory studies in LHCb

Feasibility of τ lepton electromagnetic dipole moments measurement using bent crystal at the LHC

Crystal 1:

- directing a part of LHC primary halo on Target

Target:

- production of $D_s^+(\to\tau^+\upsilon_\tau)$

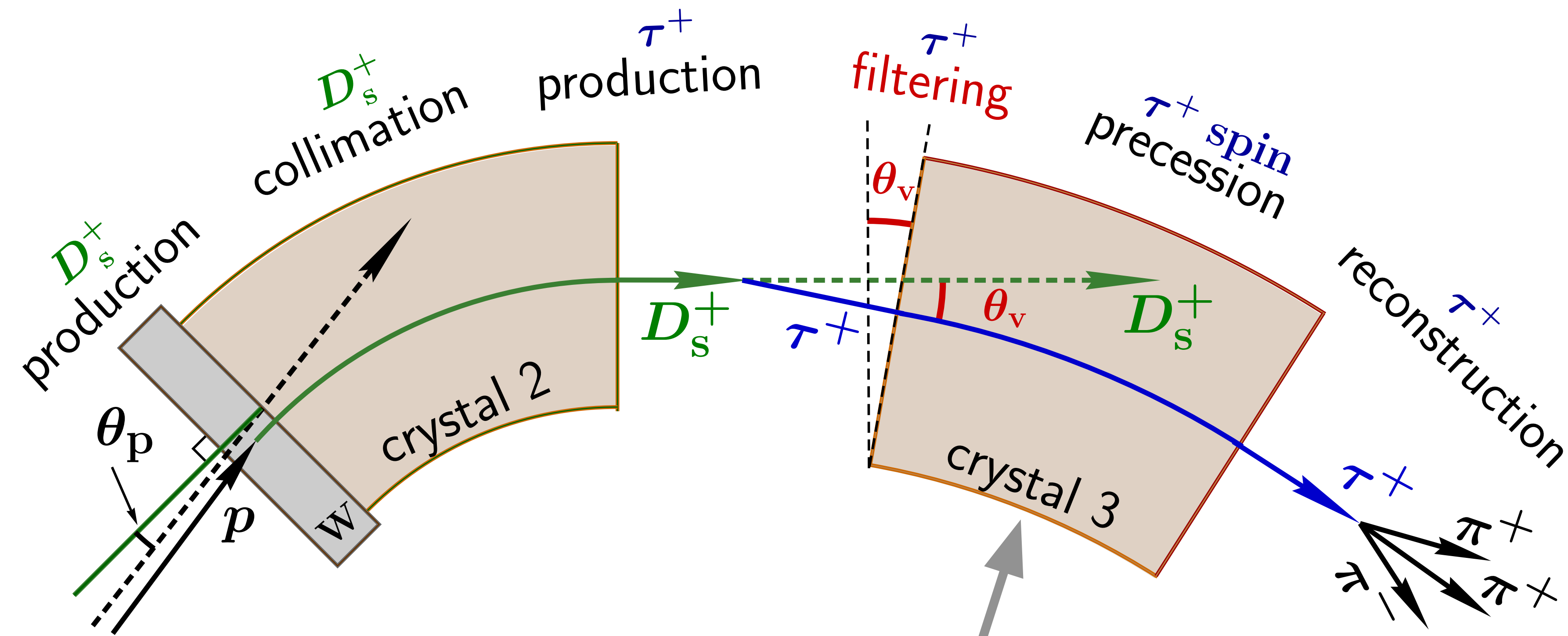
$$\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$$

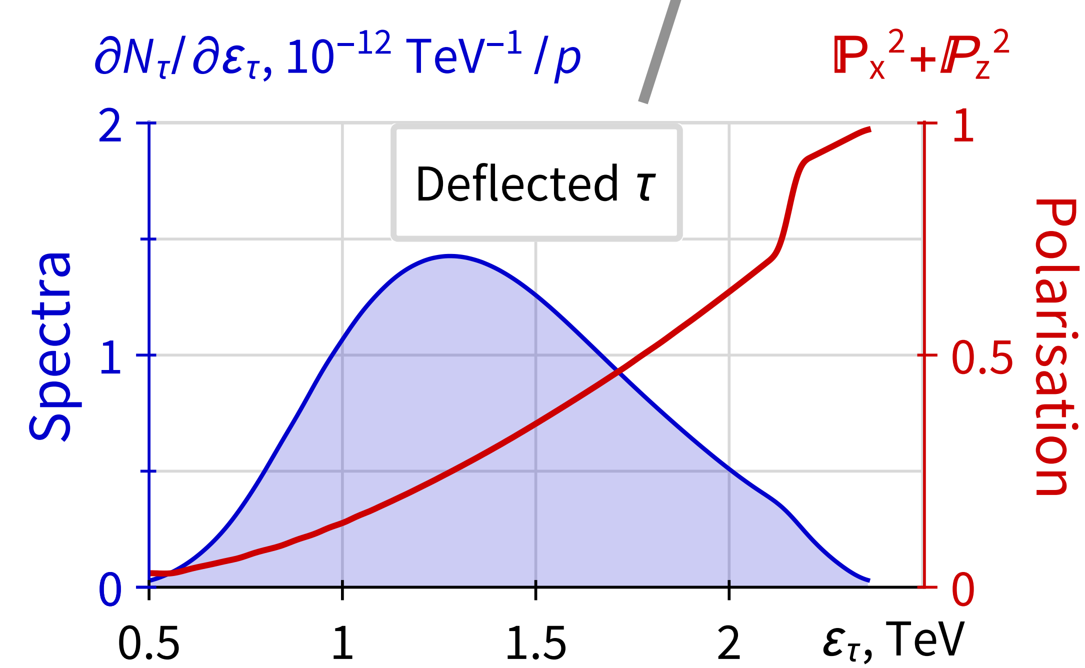
Crystal 2:

- deflection and “collimation” of D_s^+

Crystal 3:

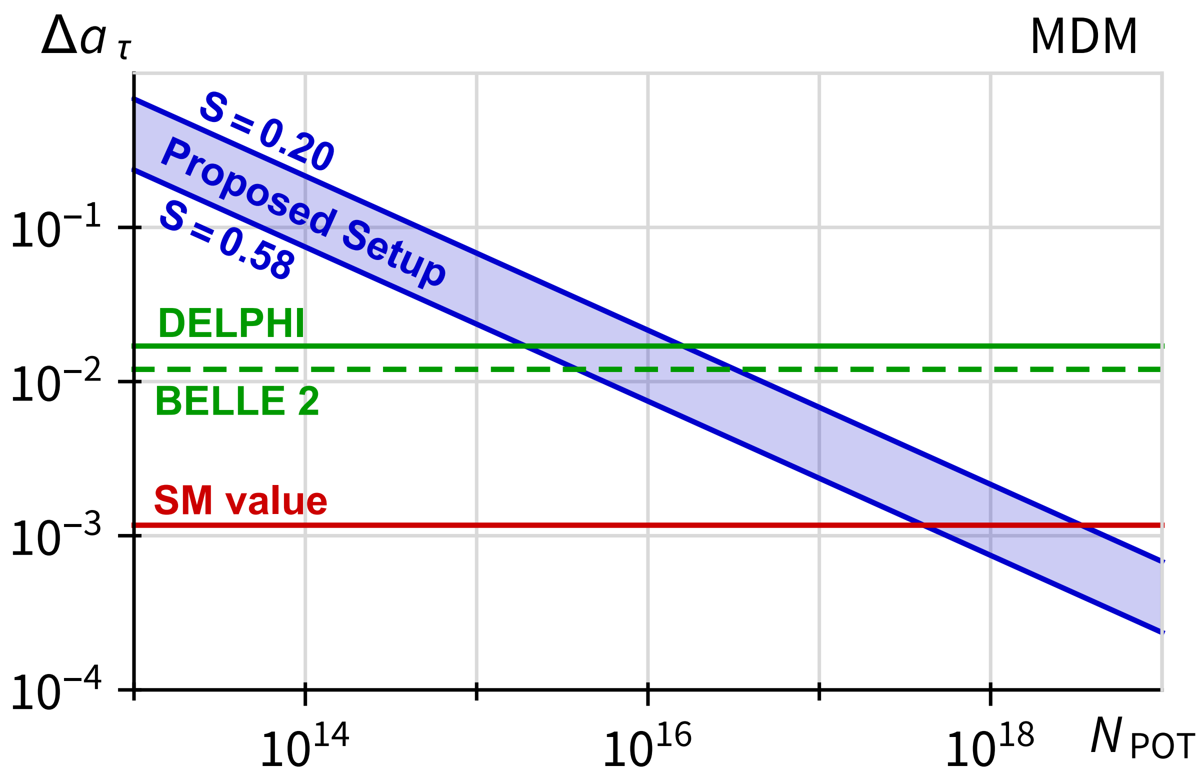
- selecting τ produced by D_s^+
- filtering τ initial polarisation
- τ spin precession

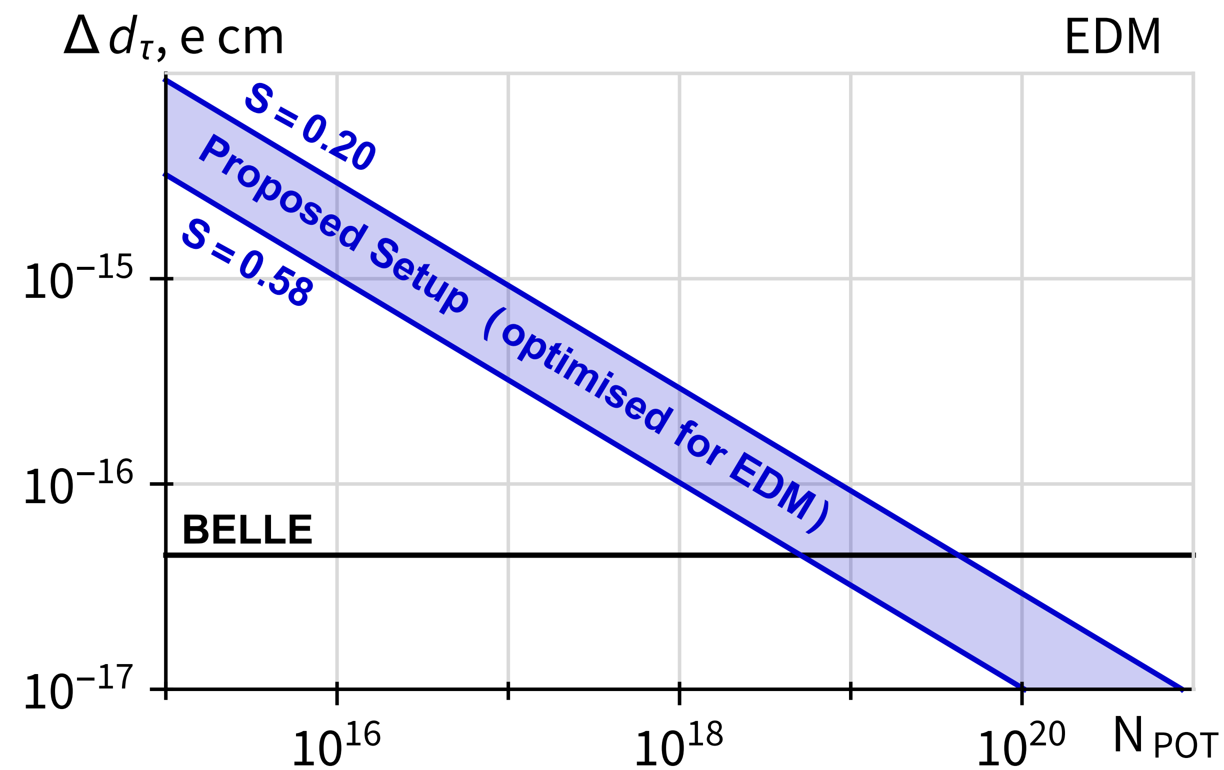




A. Fomin, A. Korchin, A. Stocchi, S. Barsuk, P. Robbe, JHEP (2019) 2019: 156, IC Channeling 2018.

Feasibility of τ lepton electromagnetic dipole moments measurement using bent crystal at the LHC





MDM: 10^{16} PoT — to reach the present accuracy [DELPHI: J. Abdallah et al. EPJC 35:159–170, 2004]

10^{18} PoT — to reach an accuracy equivalent to the Standard Model value

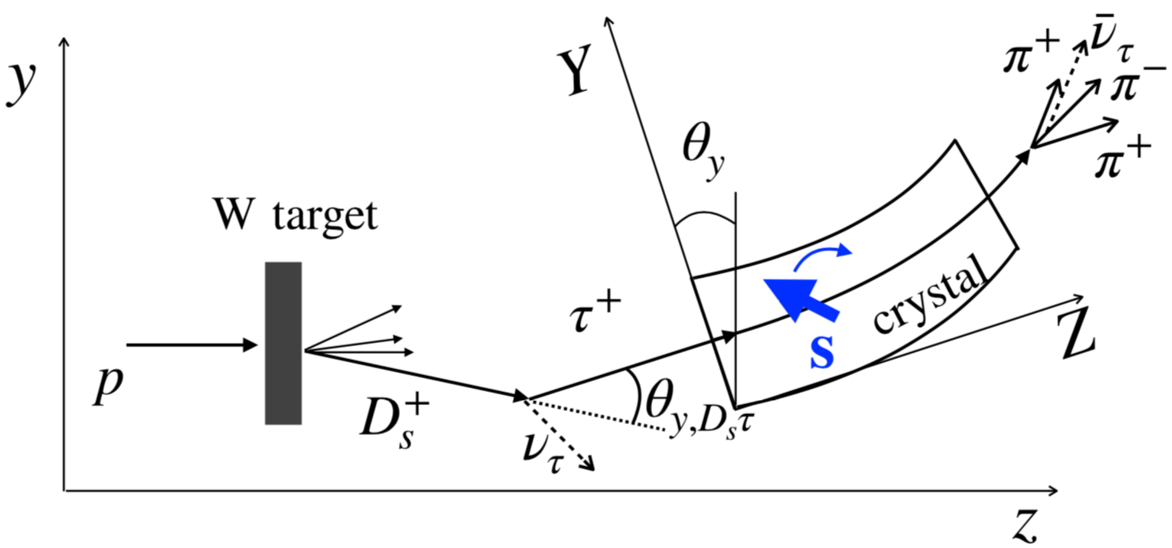
EDM: 10^{19} PoT — to reach the present accuracy [BELLE: K. Inami et al. PLB 551:16–26, 2003]

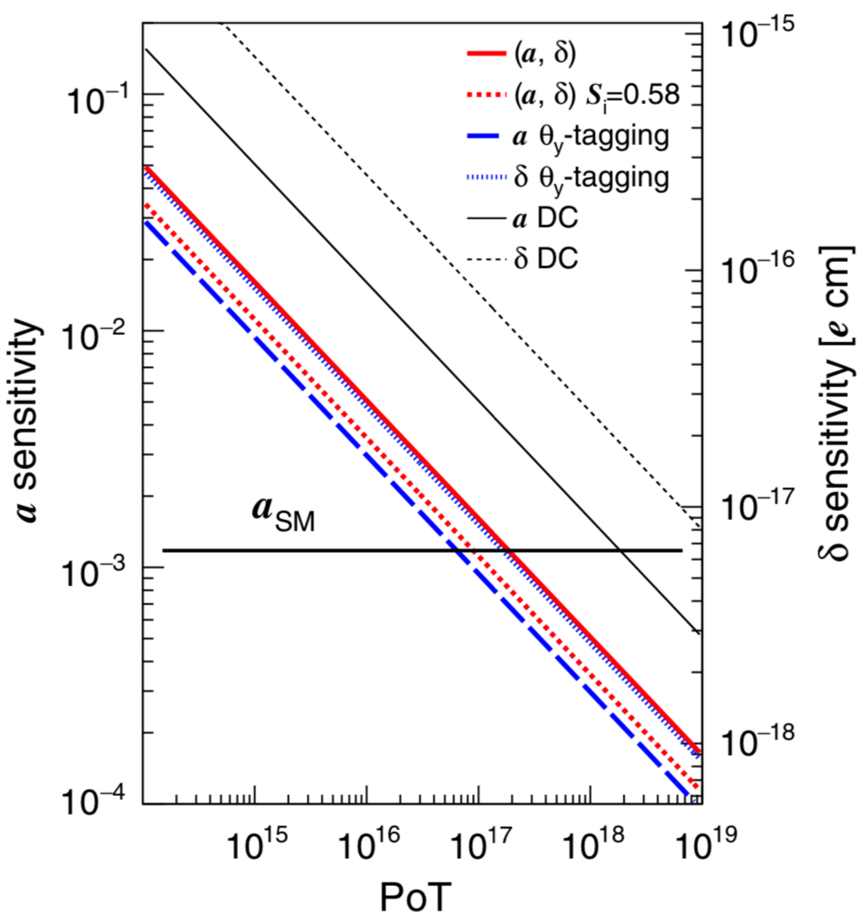
A. Fomin, A. Korchin, A. Stocchi, S. Barsuk, P. Robbe, JHEP (2019) 2019: 156, IC Channeling 2018.

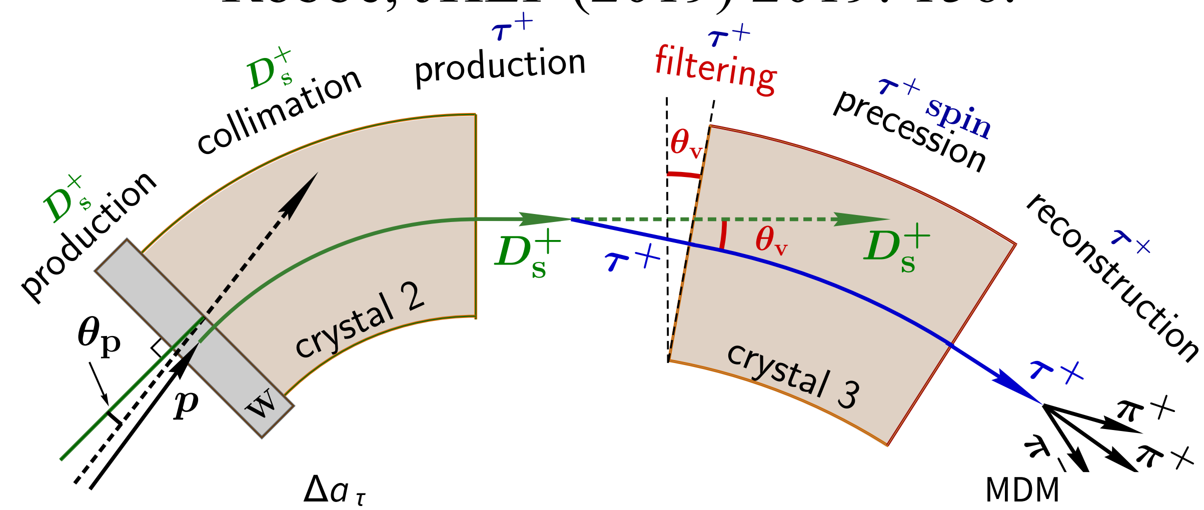
Future plans for τ MDM/EDM

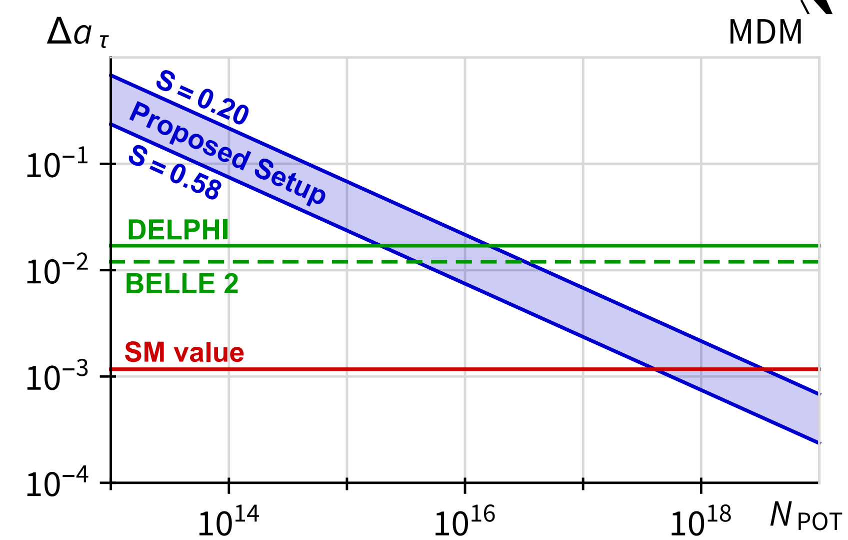
Fu, Giorgi, Henry, Marangotto, Martinez Vidal, Merli, Neri, Ruiz Vidal, Phys. Rev. Lett. 123, 011801 (2019)

Fomin, Korchin, Stocchi, Barsuk, Robbe, JHEP (2019) 2019: 156.









Requires a future dedicated experiment

Preparatory measurements are possible in LHCb