New ideas for the direct determination of electromagnetic moments of charged and neutral fermions

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FPCP 2021, 9 June 2021

European Research Council
Established by the European Commission

Acknowledgements

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- **Contributions** also from: G. Arduini, S. Barsuk, O.A. Bezshyyko, L. Burmistrov,, A.S. Fomin, S.P. Fomin, F. Galluccio, M. Garattini, A.Yu. Korchin, I.V. Kirillin, Y. Ivanov, L. Massacrier, J. Mazorra, D. Mirarchi, S. Montesano, A. Natochii, E. Niel, S. Redaelli, P. Robbe, W. Scandale, N.F. Shul'ga, A. Stocchi
- **LHCb FITPAN** review members: T. Eric, M. Ferro-Luzzi, G. Graziani, R. Kurt, R. Lindner, C. Parkes, M. Palutan, G. Passaleva, M. Pepe-Altarelli, V. Vagnoni, G. Wilkinson
- Interesting **discussions/suggestions**: V. Baryshevsky, V. M. Biryukov

SELDOM webpage

@SeldomTeam

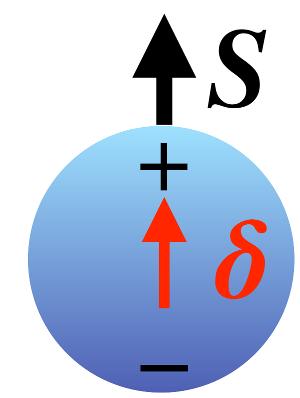
Outline

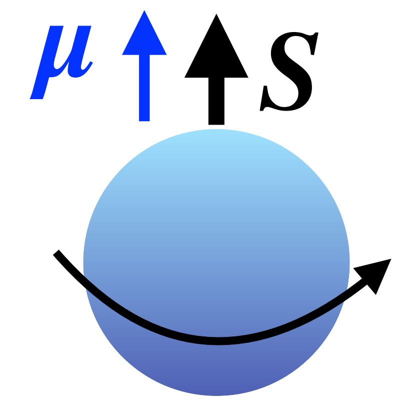
- Introduction
- Physics motivations for measurements of dipole moments
- Experimental method for charm baryons
  - R&D and preparatory studies
- Experimental method for strange baryons
- Proposal for the tau lepton
- Summary

Introduction

- Quantum system

$$\boldsymbol{\delta} = d\frac{q\hbar}{2m}\frac{\boldsymbol{S}}{\hbar} \qquad \boldsymbol{\mu} = g\frac{q\hbar}{2m}\frac{\boldsymbol{S}}{\hbar}$$





$\boldsymbol{\delta}$= electric dipole moment (EDM)
$\boldsymbol{\mu}$= magnetic dipole moment (MDM)

Hamiltonian

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

Time reversal, Parity:

$$d\mu_N \boldsymbol{S}\cdot\boldsymbol{E} \xrightarrow{T,P} -d\mu_N \boldsymbol{S}\cdot\boldsymbol{E}$$

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

	C	P	T
$\boldsymbol{\mu}$	−	+	−
$\boldsymbol{\delta}$	−	+	−
E	−	−	+
B	−	+	−
S	+	+	−

Physics motivations for EDM/MDM measurements

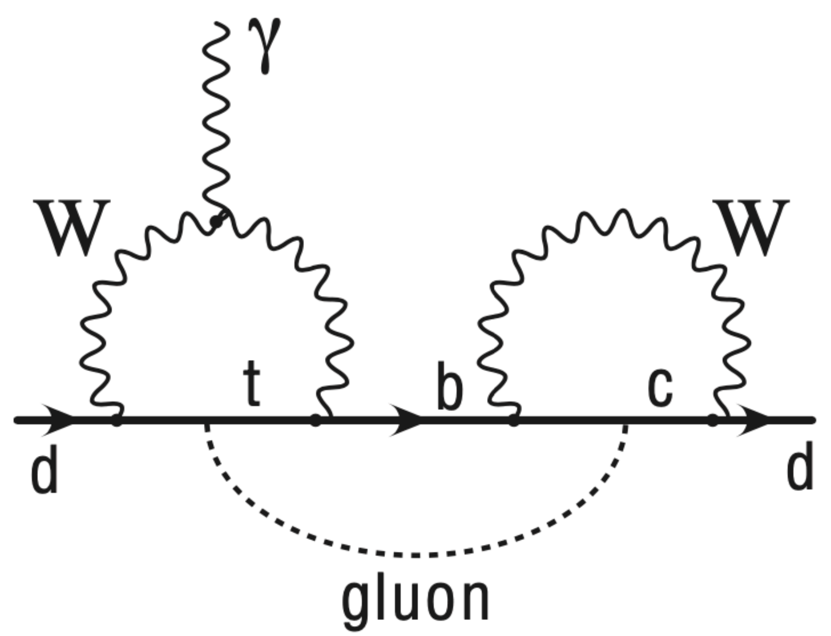
EDM: a probe for *CPV* beyond the SM

- $\mathscr{L}_{CPV} = \mathscr{L}_{CKM} + \mathscr{L}_{\bar{\theta}} + \mathscr{L}_{BSM}$
  - SM: negligible CKM contribution; $\bar{\theta}$-QCD for possible *CPV* in strong interaction, $\bar{\theta} \lesssim 10^{-10}$ from neutron EDM limit

Rev. Mod. Phys. **91**, 015001 (2019)

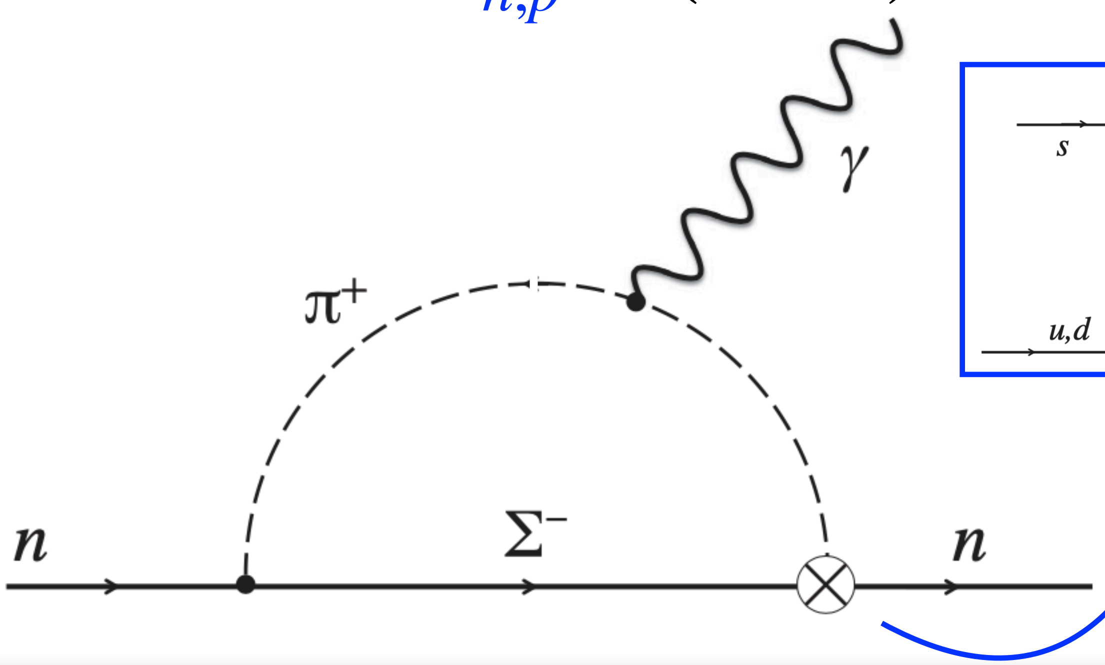
Example of SM CKM contributions

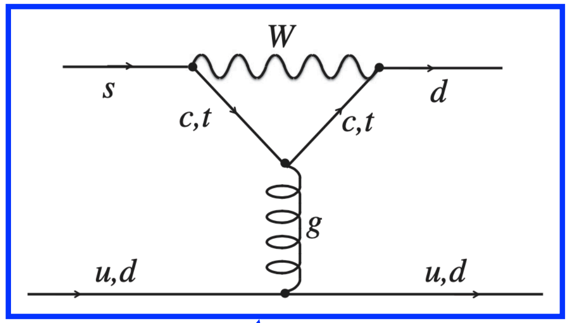
$$\delta_d \propto \mathrm{Im}(V_{tb}V_{td}^{*}V_{cd}V_{cb}^{*})m_d m_c^2 \alpha_s G_F^2 \approx 10^{-34} e\mathrm{cm}$$



"Long distance" contribution

$$\delta_{n,p} \approx (1-6) \times 10^{-32} e\mathrm{cm}$$





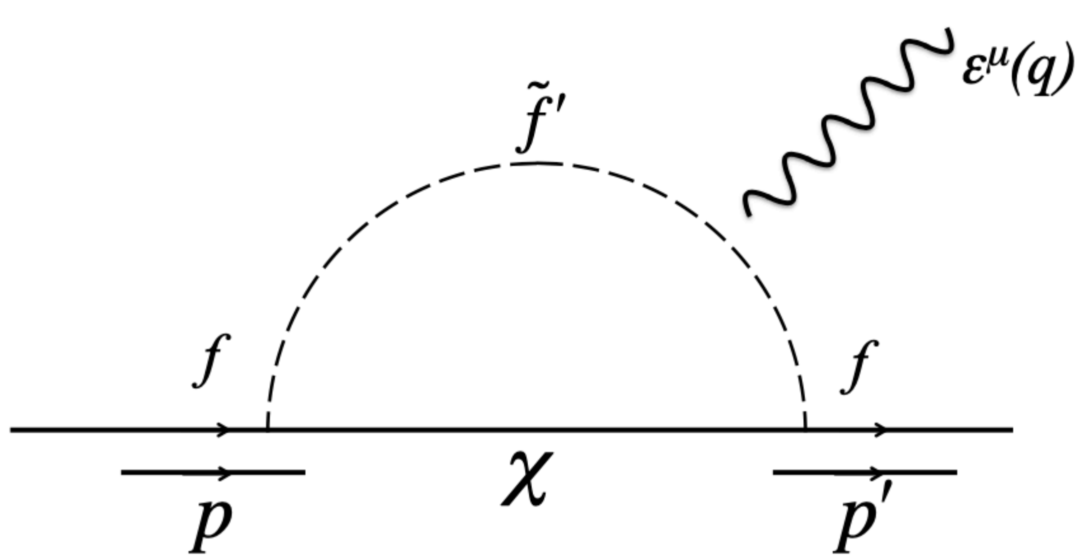
EDM: a probe for *CPV* beyond the SM

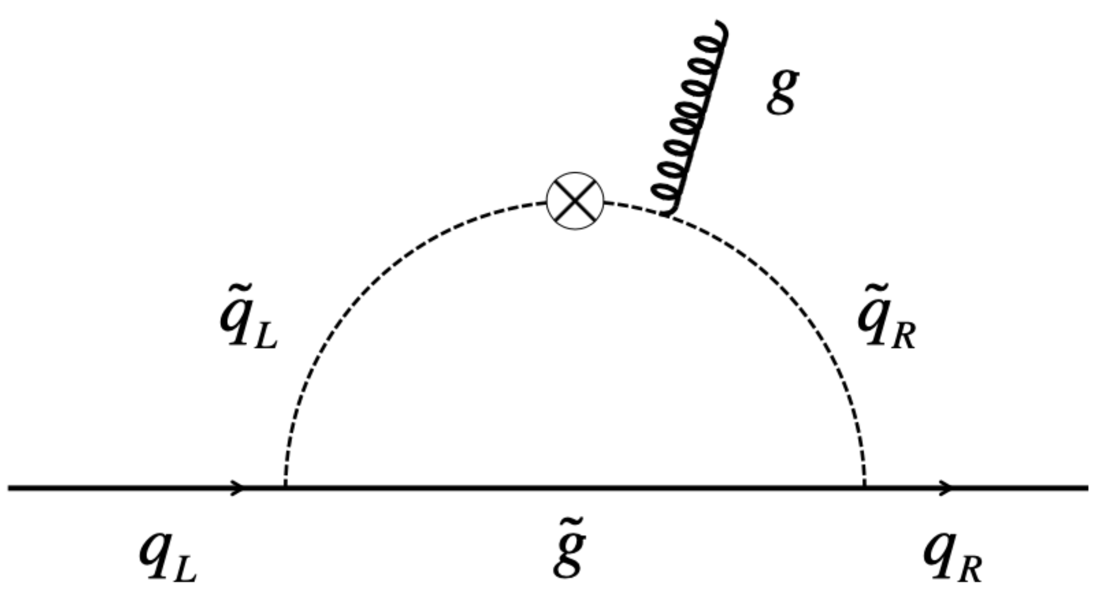
- $\mathscr{L}_{CPV} = \mathscr{L}_{CKM} + \mathscr{L}_{\bar{\theta}} + \mathscr{L}_{BSM}$
  - BSM: potential large contributions by new physics scale Λ_{NP} and CP-violating phase ϕ_{CPV}

$$\delta_{BSM} \approx (10^{-16} e\text{cm}) \left(\frac{250 \text{ GeV}}{\Lambda_{NP}} \right)^2 \sin \phi_{CPV} y_f F$$

Examples of BSM contributions

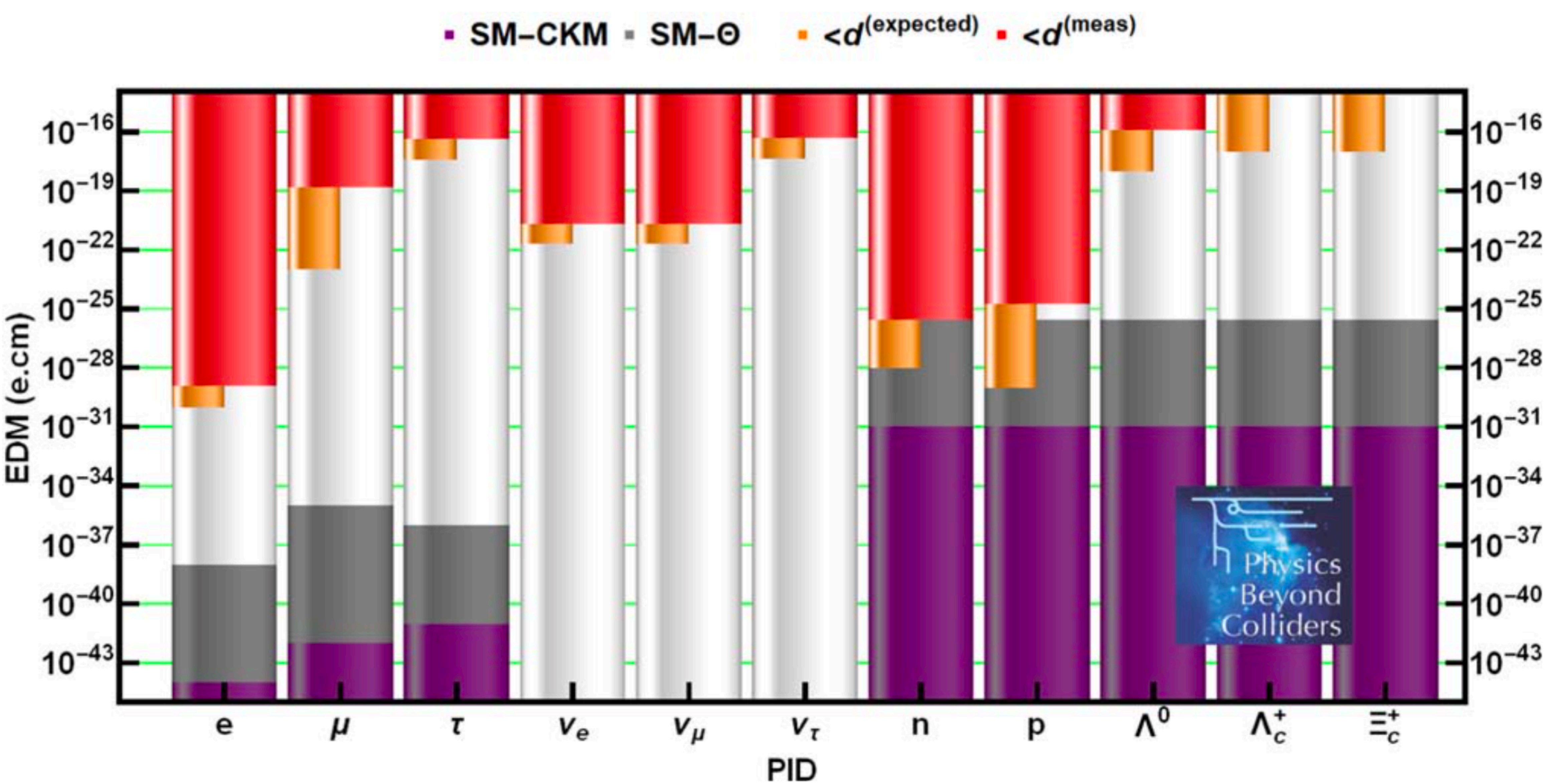
Rev. Mod. Phys. **91**, 015001 (2019)





Status of EDM measurements

- Need to measure many systems to disentangle the underlying source of *CPV*
- World-wide experimental effort is ongoing to improve current measurements and explore new systems



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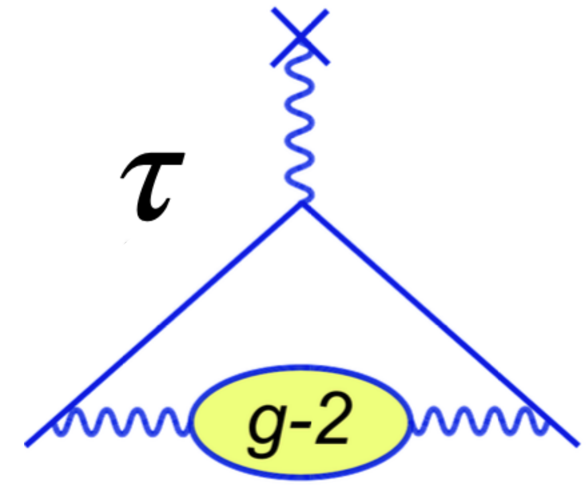
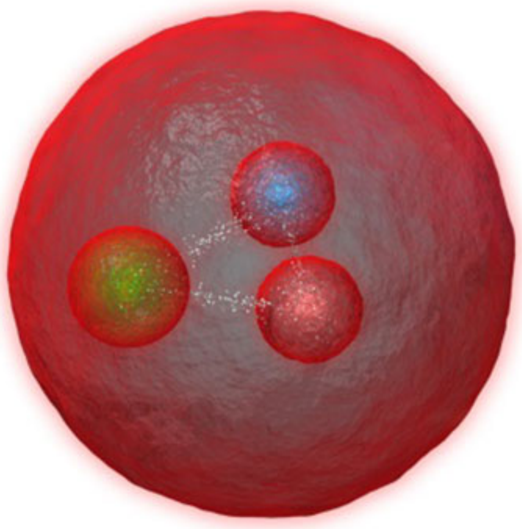
MDM of heavy fermions

- No direct measurements to date for short-lived **charm**, **beauty** baryons, and **τ** lepton
- Experimental anchor points for test of low-energy QCD models, related to **non-perturbative QCD** dynamics
- Further information on **baryon substructure**
- Measurement of MDM of particles and antiparticles for a **test of CPT symmetry**





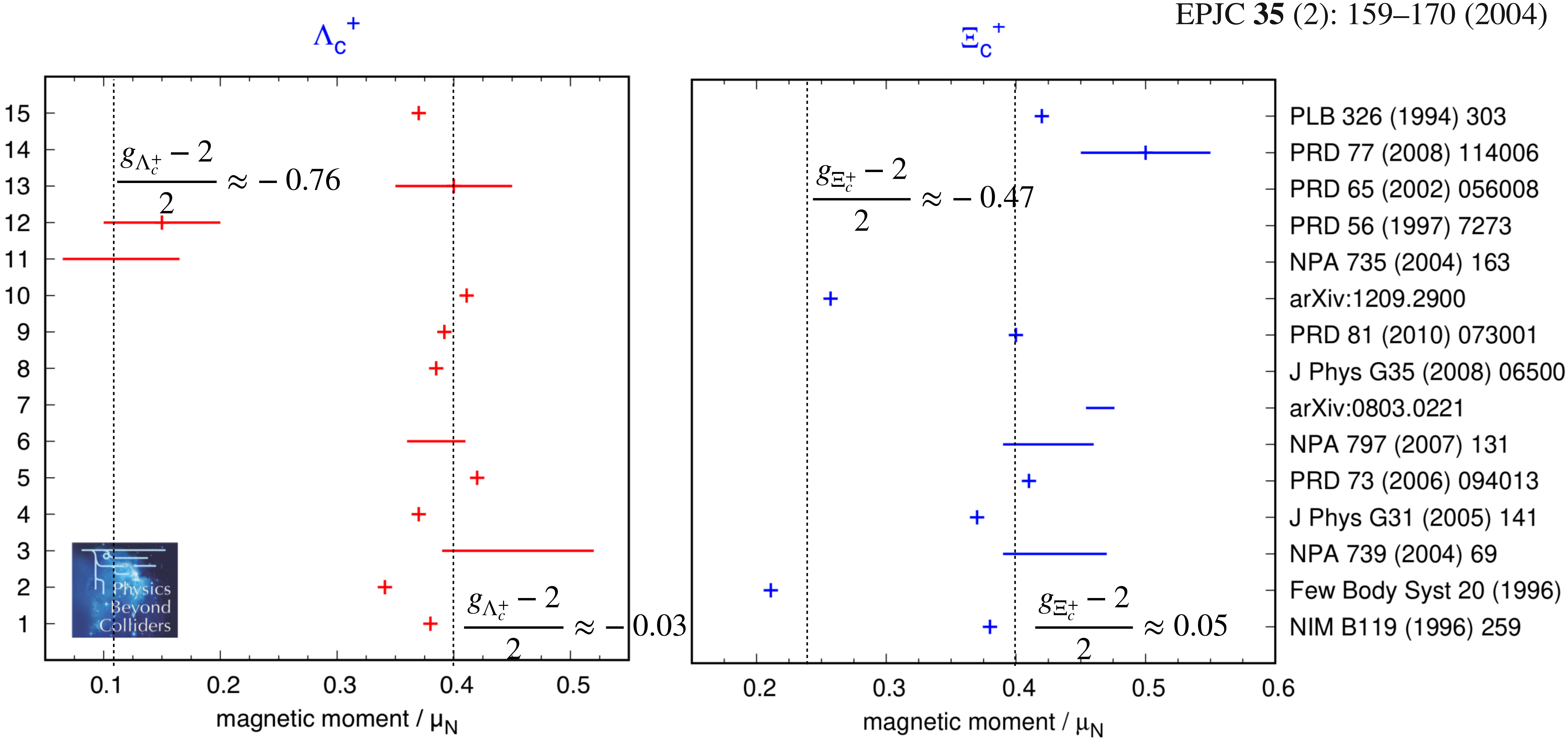
MDM theoretical predictions

For τ lepton : SM prediction $(g_\tau - 2)/2 = 117721(5)\times10^{-8}$

Modern Physics Letters A. **22** (3): 159–179 (2007)

Indirect experimental limit: $-0.052 < (g_\tau-2)/2 < 0.013$, 95% CL

EPJC **35** (2): 159–170 (2004)



CERN-PBC-REPORT-2018-008

Proposed experimental method for charm baryons at LHC: Λ_c^+, Ξ_c^+

$\tau \approx 10^{-13}$ s

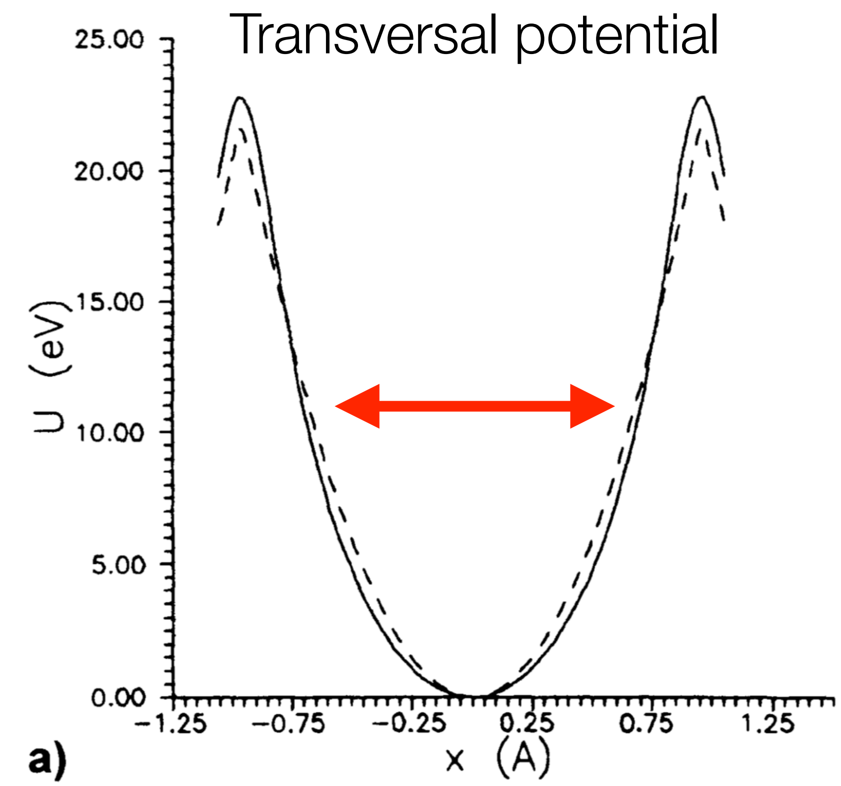
V. G. Baryshevsky, Phys.Lett.B 757 (2016) 426
L. Burmistrov et al, CERN-SPSC-2016-030, SPSC-EOI-012 (2016)
F. J. Botella et al., Eur.Phys.J.C 77 (2017) 181
A. S. Fomin et al., JHEP 1708 (2017) 120
E. Bagli et al., Eur.Phys.J.C 77 (2017) 828
A. S. Fomin et al., Eur.Phys.J.C 80(2020) 358
S. Aiola et al., Phys.Rev.D 103 (2021) 072003

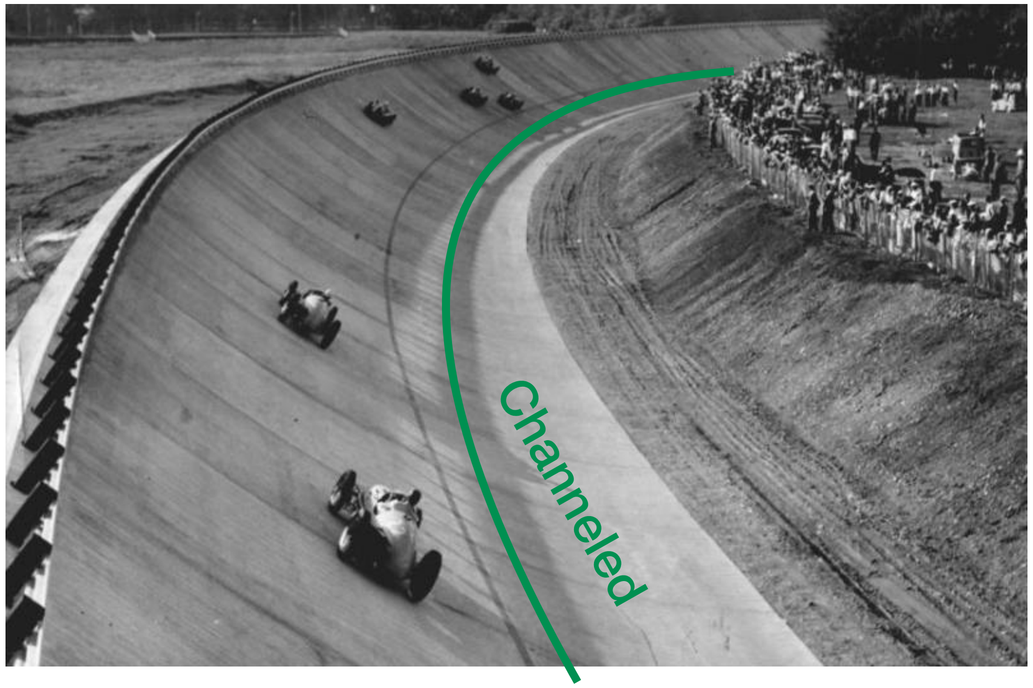
Channeling in bent crystals

Courtesy of Biryukov, Chesnokov, Kotov, “Crystal channeling and its applications at high-energy accelerators” (Springer)

Channeling in bent crystals

- Potential well between crystal planes
  $E \approx 1$ GV/cm
- Positive charge particle with momentum parallel to crystal plane (within few µrad) can be trapped
- 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.

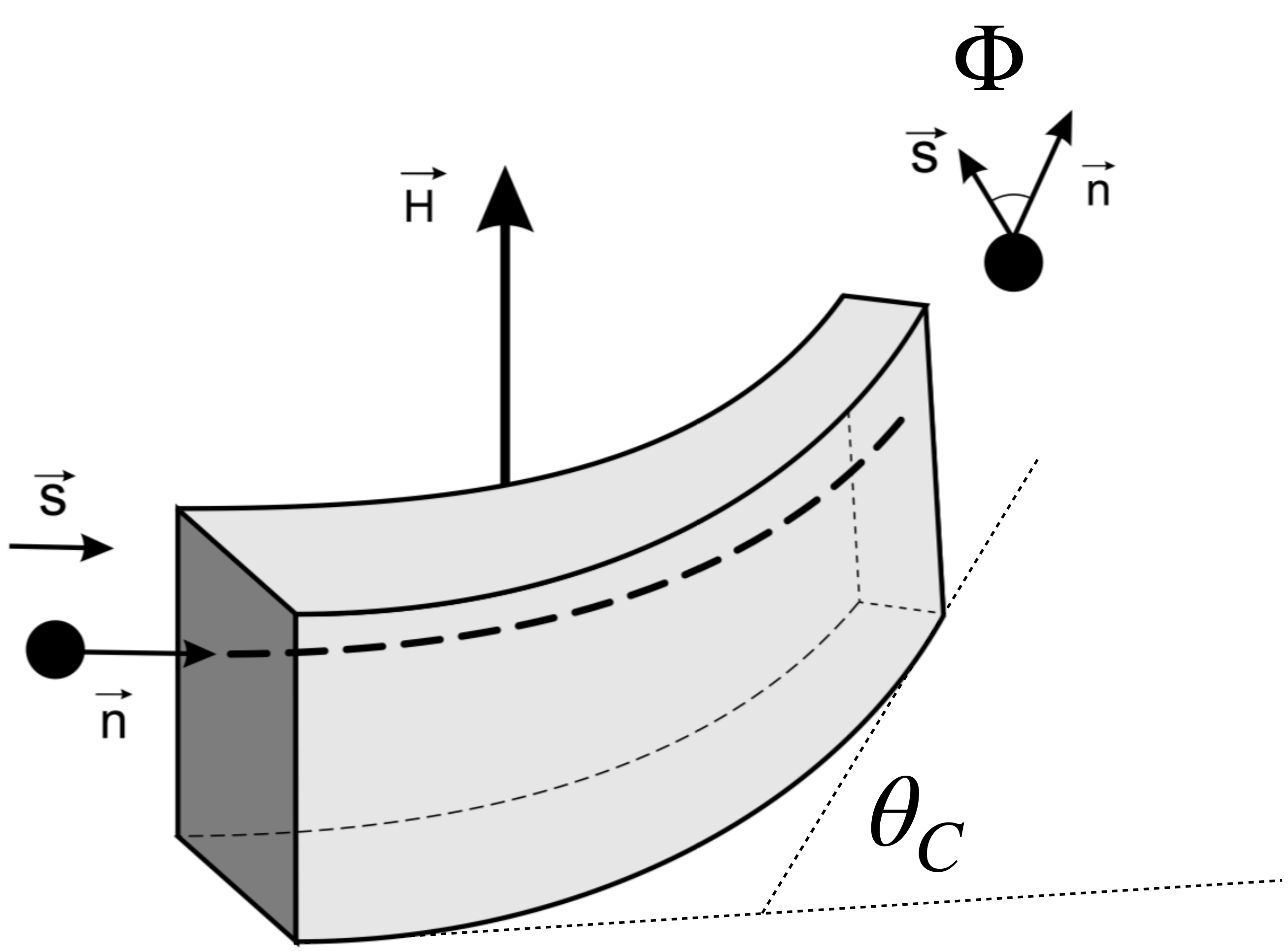


Fig. 1. Spin rotation in a bent crystal.

- Determine particle gyromagnetic factor from BMT equation

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

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

Φ = spin rotation angle
θ_C = crystal bending angle
g = gyromagnetic factor
γ = Lorentz boost

- Experimental proof by E761 Fermilab experiment with Σ^+ hyperon

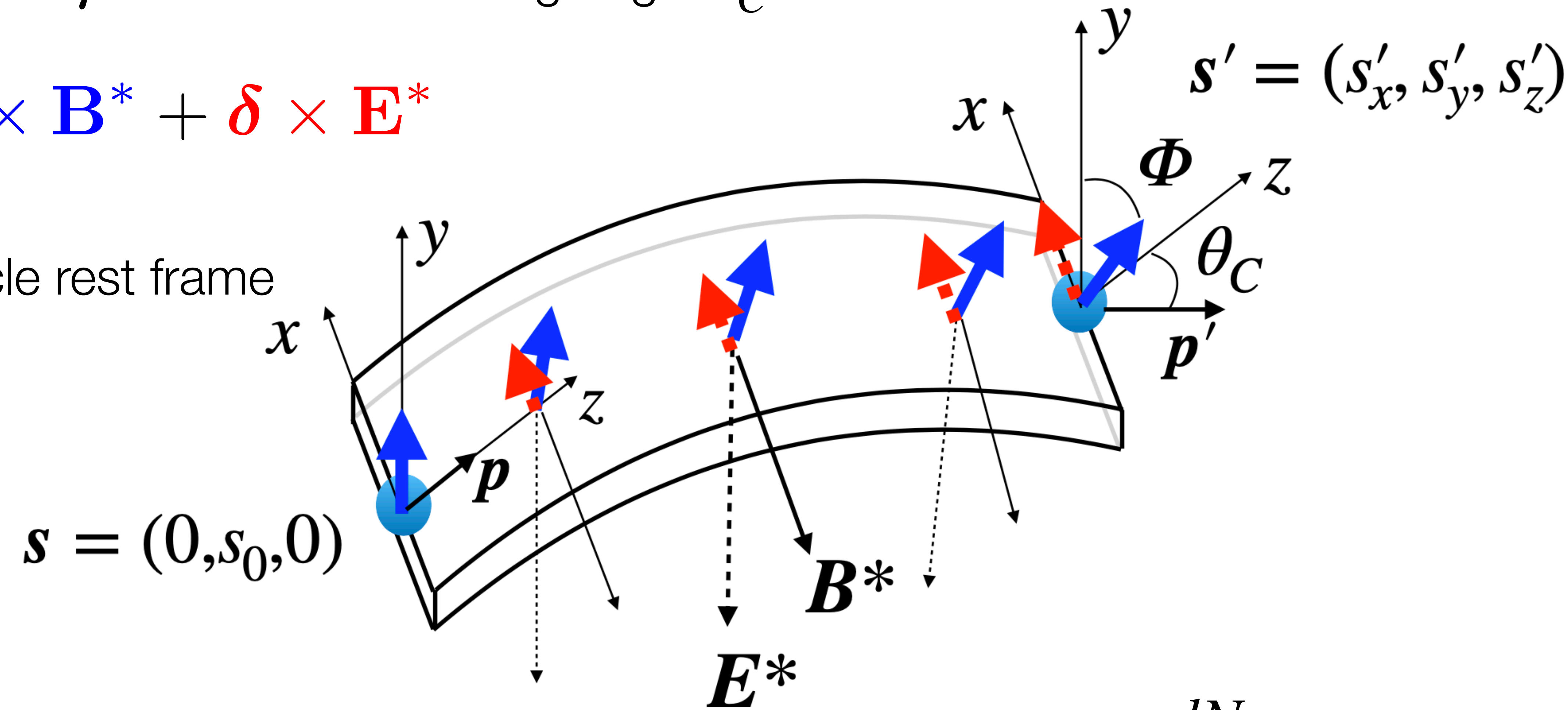
D. Chen et al., Phys. Rev. Lett. 69 (1992) 3286

Λ_c^+, Ξ_c^+ spin precession in bent crystals at LHC

- Spin precession angle $\Phi \simeq \frac{g-2}{2}\gamma\theta_C$ for baryons with large boost $\gamma \approx 500$ and bending angle $\theta_C \approx 15$ mrad

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

E*⊥B* in particle rest frame



- Sensitivity to MDM and EDM via spin-polarisation analyser $\frac{dN}{d\Omega'} \propto 1 + \alpha \mathbf{s}' \cdot \hat{\mathbf{k}}$

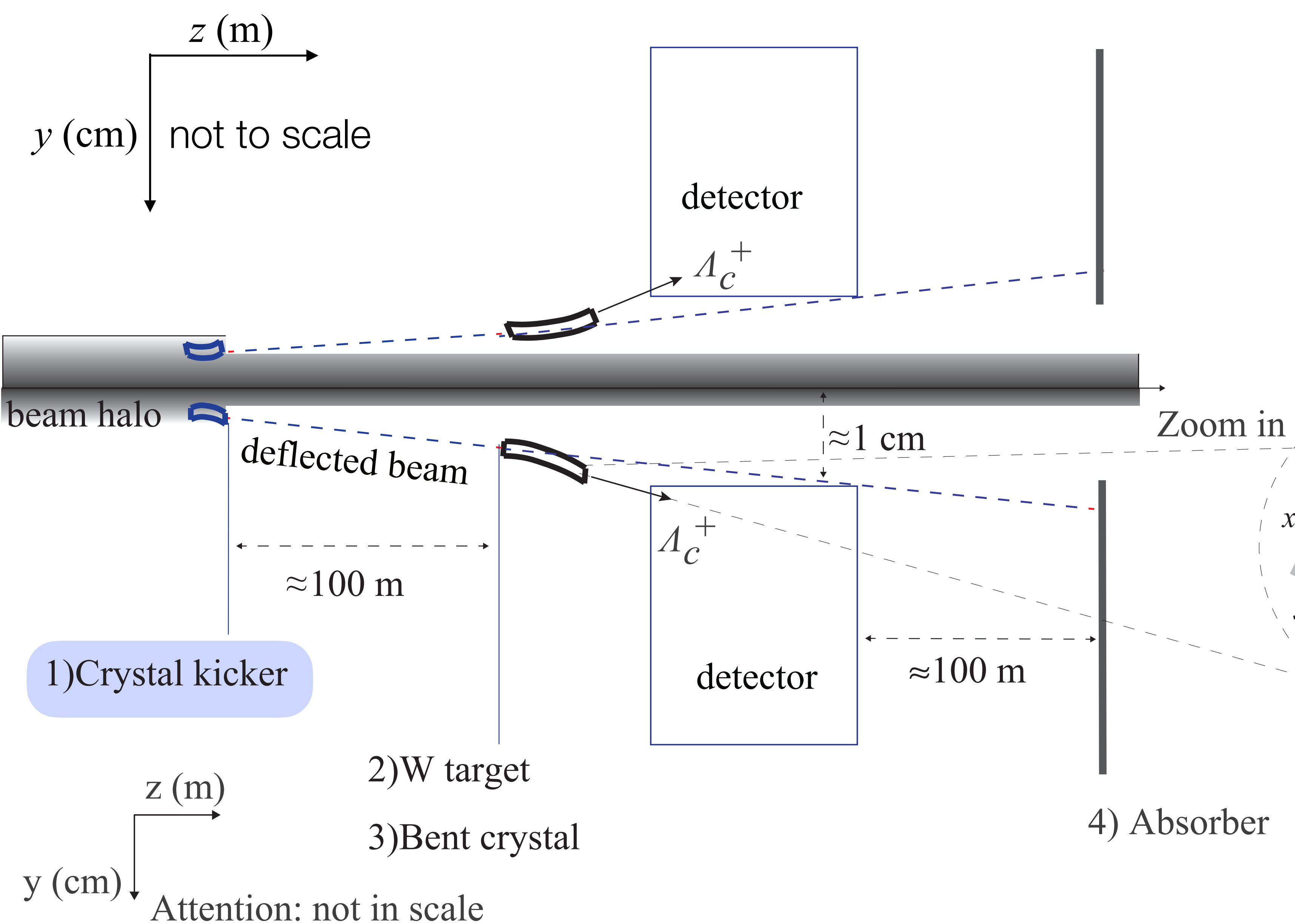
$$\Phi \approx \frac{g-2}{2}\gamma\theta_C$$

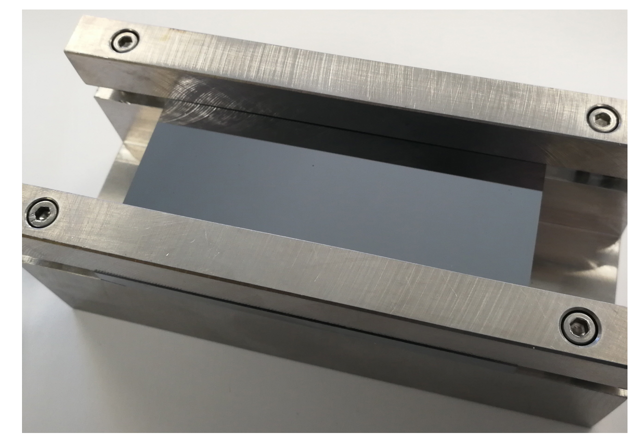
$$s'_x \approx s_0 \frac{d}{g-2}[\cos(\Phi) - 1]$$

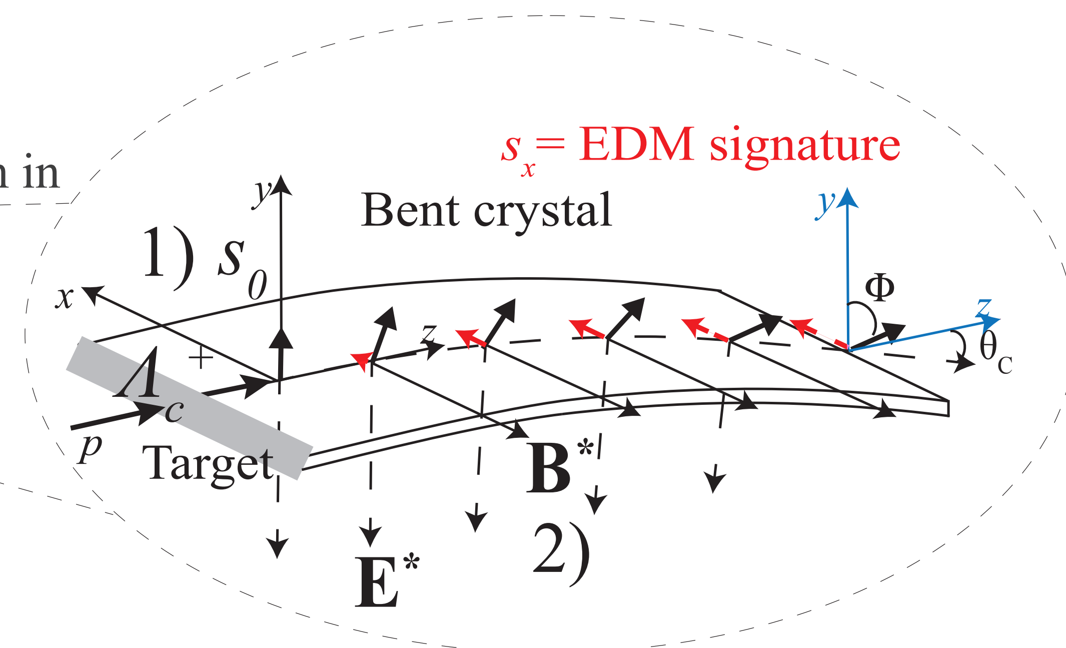
EPJC (2017) 77:181

Novel fixed-target experiment at LHC for charm baryons

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



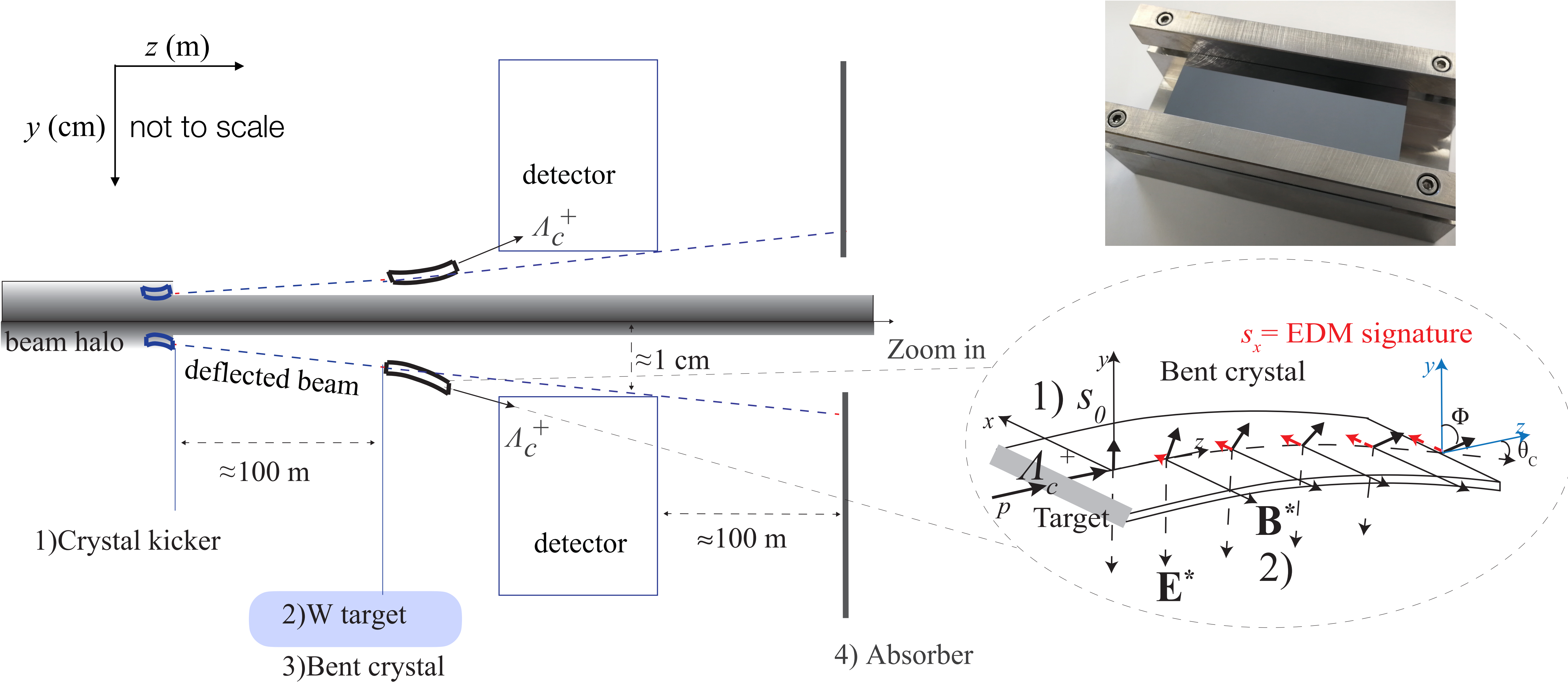




p extraction

Novel fixed-target experiment at LHC for charm baryons

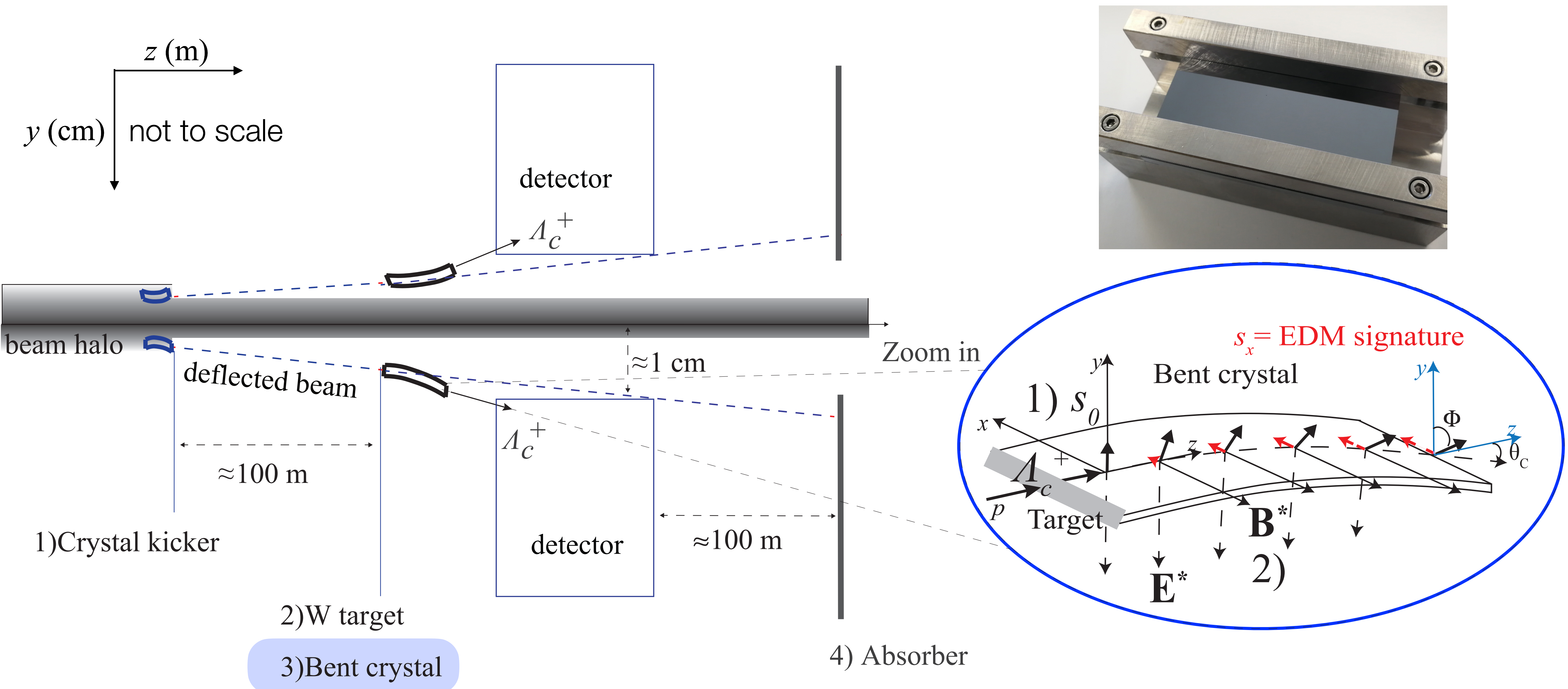
- EDM/MDM from spin precession of channeled baryons in **bent crystals**



p extraction Λ_c^+ polarised production

Novel fixed-target experiment at LHC for charm baryons

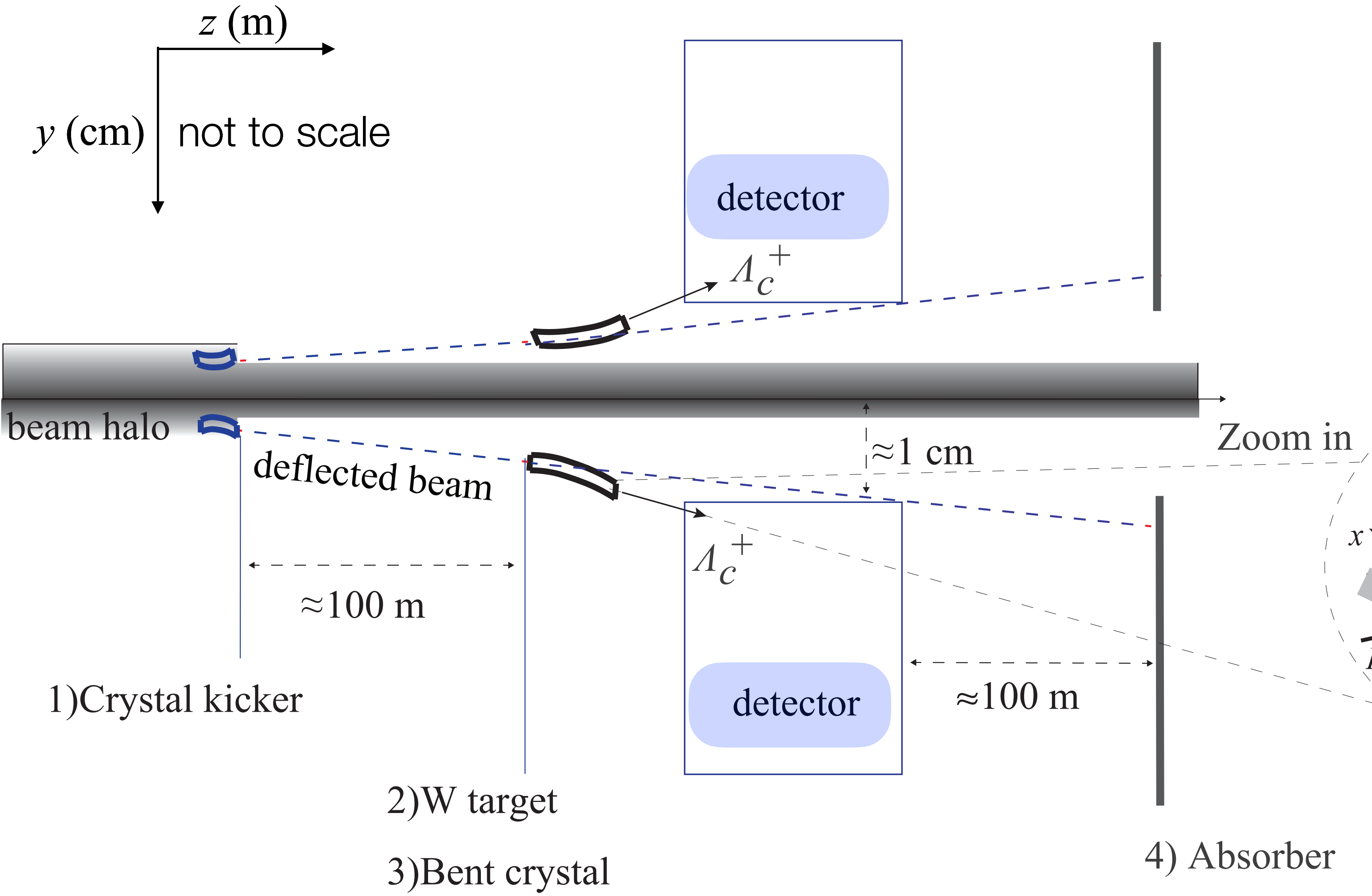
- EDM/MDM from spin precession of channeled baryons in **bent crystals**

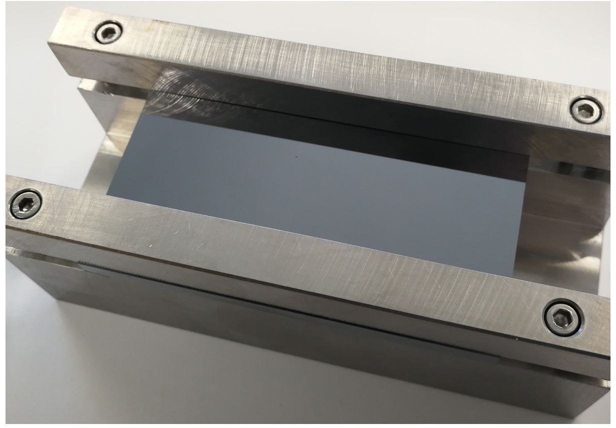


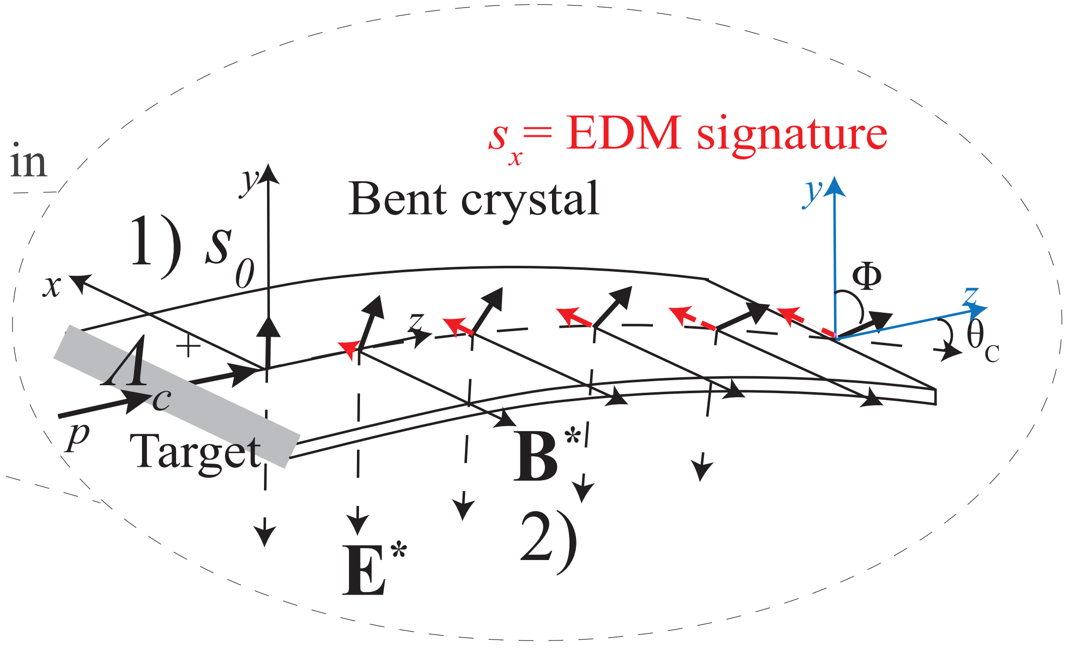
p extraction Λ_c^+ polarised production channeling spin precession

Novel fixed-target experiment at LHC for charm baryons

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



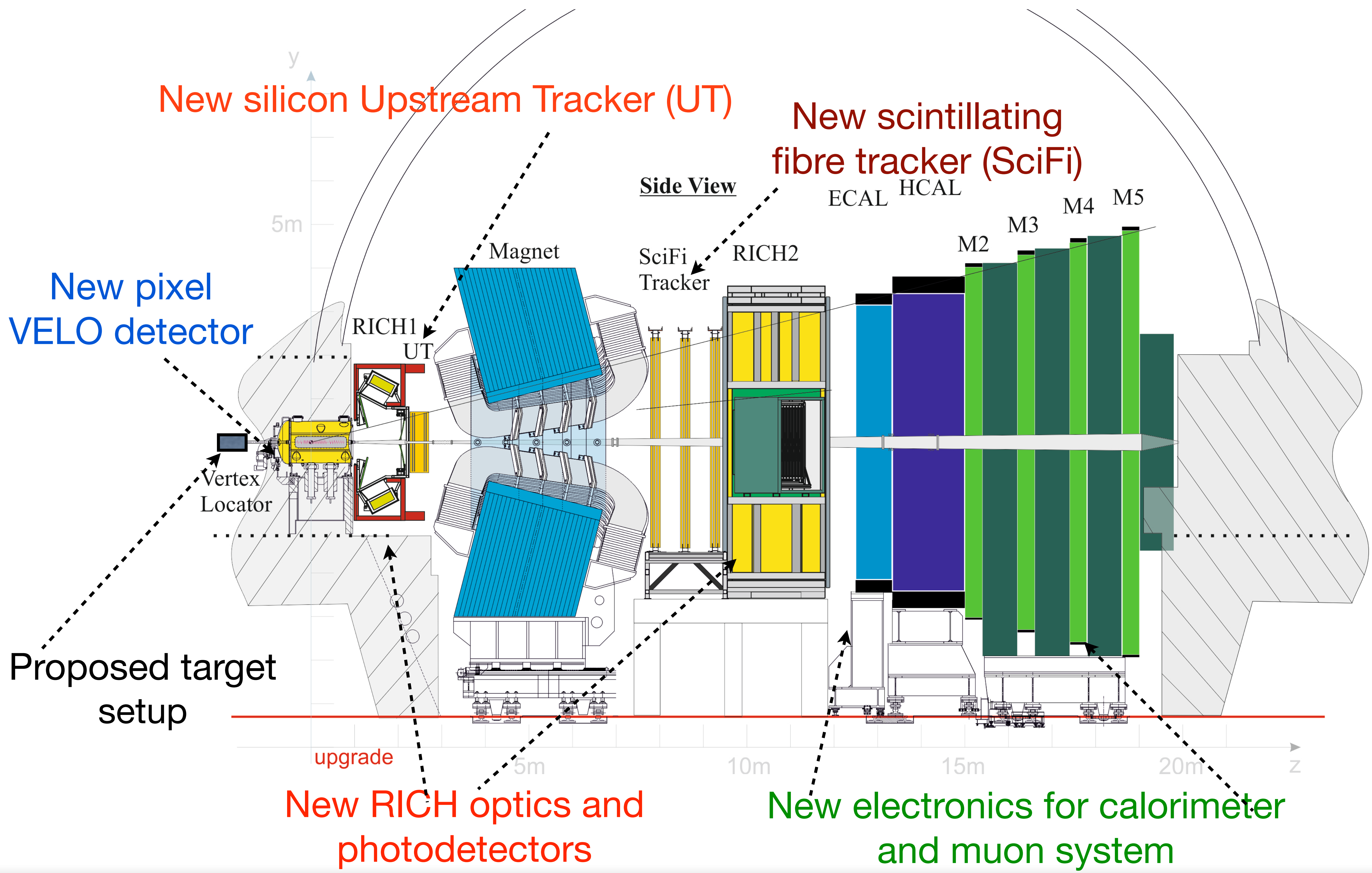




p extraction Λ_c^+ polarised production channeling spin precession event reconstruction

LHCb Upgrade detector

Possible implementation of the fixed-target experiment upstream of the LHCb detector



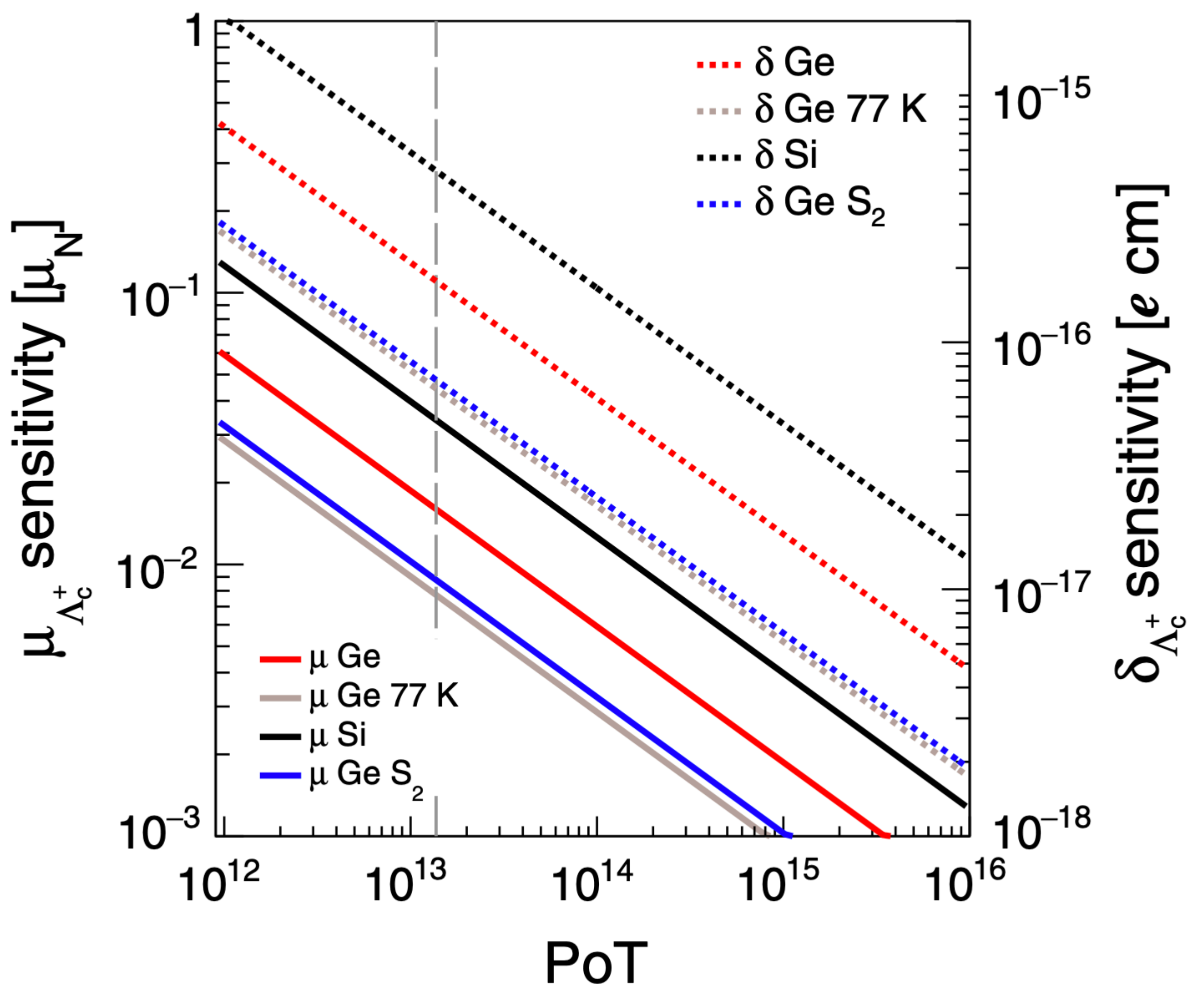
Sensitivity on MDM/EDM

- S1 configuration: **LHCb detector, Ge (Si) 16 mrad, 10 cm**
- S2 configuration: **dedicated experiment, Ge 7 mrad, 7 cm**

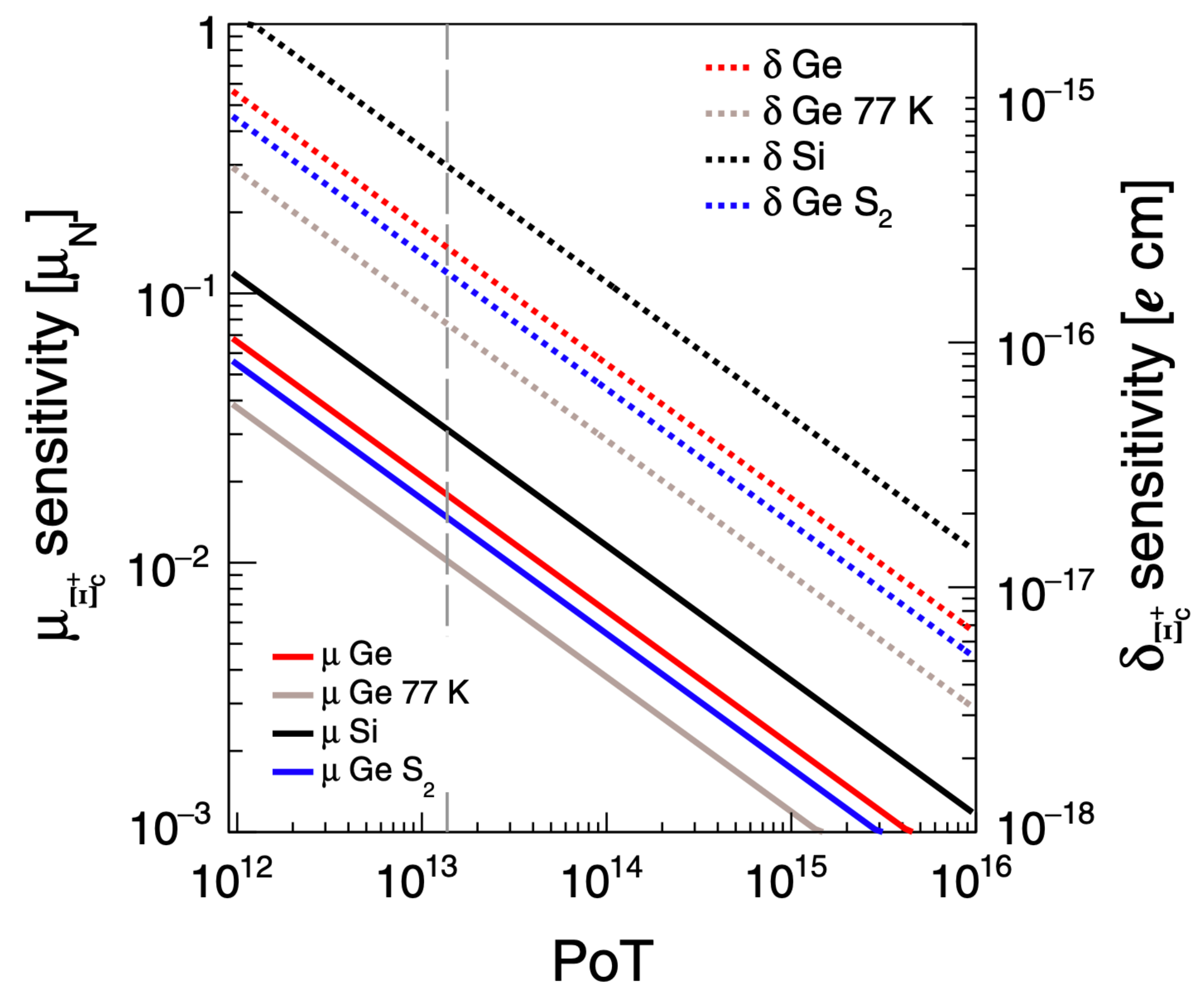
PoT = proton on target
W target 2 cm thick

PRD 103, 072003 (2021)

Λ_c^+ baryon



Ξ_c^+ baryon



- Measurements are **statistically limited**

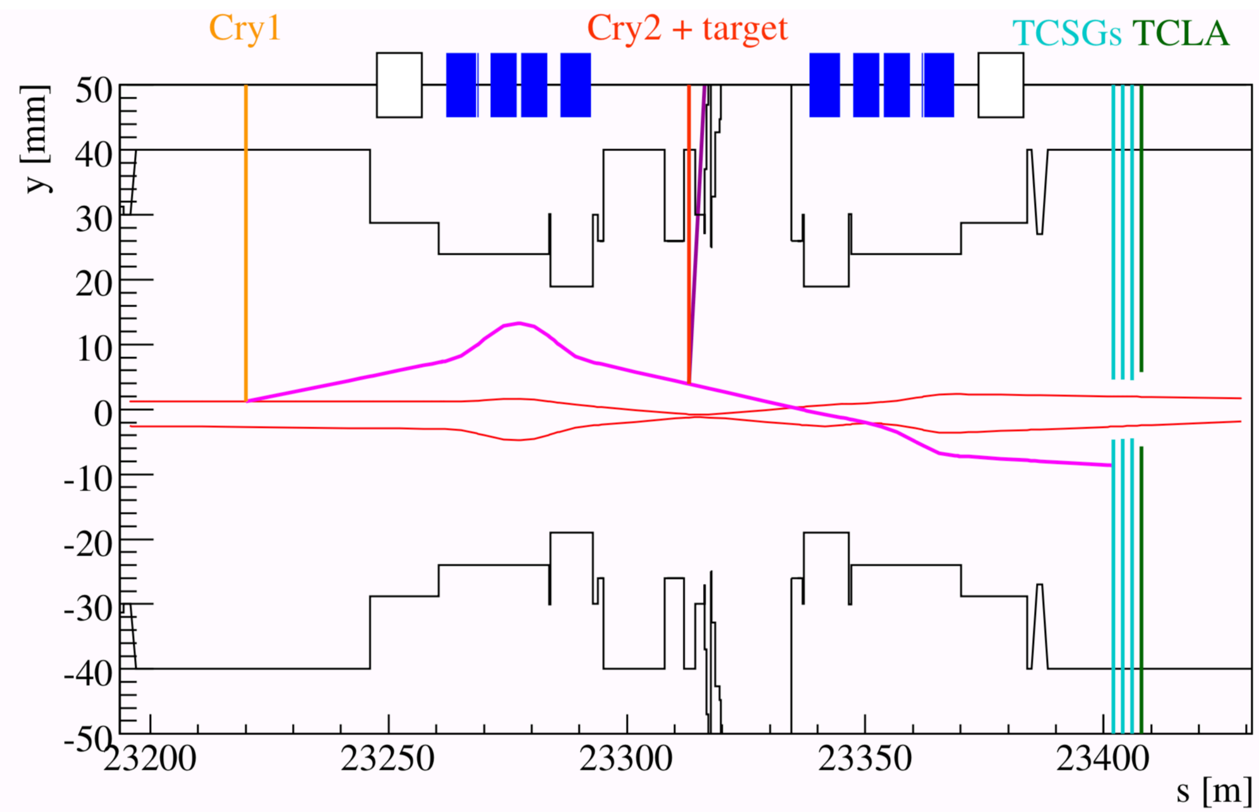
R&D and preparatory studies

LHC (SPS) machine studies

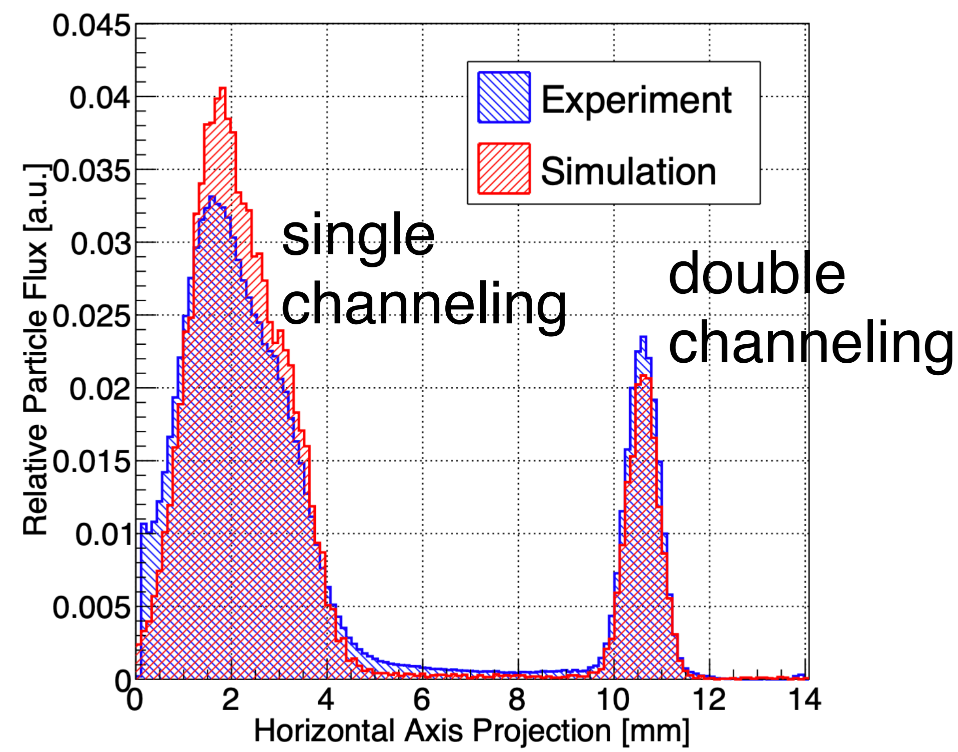
D. Mirarchi, A. S. Fomin, S. Redaelli, W. Scandale,
EPJC 80 (2020) 10, 929

W. Scandale et al., arXiv:2103.14681

LHC machine layout simulations



Experimental results at SPS



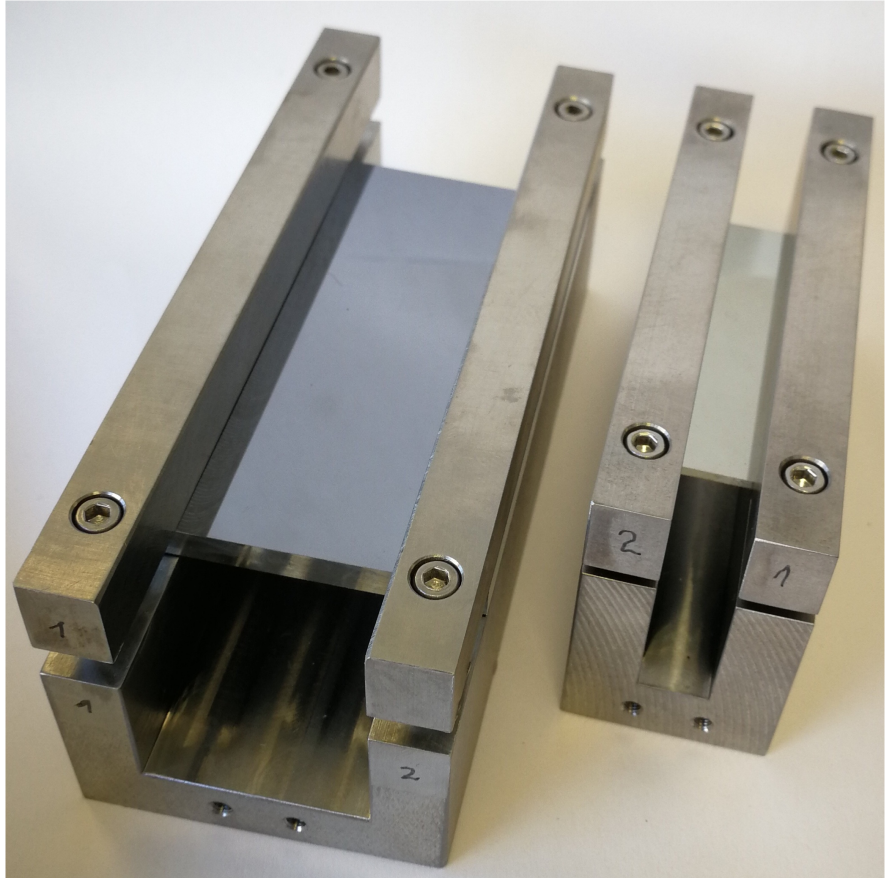
W. Scandale et al., PLB 758 (2016) 129–133

- **Channeling** of 6.5 TeV **at LHC** already **demonstrated** by UA9
- **Viable layout:** 10^6 p/s on target close to LHCb. Possibility to improve performance with a dedicated experiment at LHC
- Successful **layout test** done at SPS. Test in **LHC** possibly during Run3

Long bent crystal prototypes

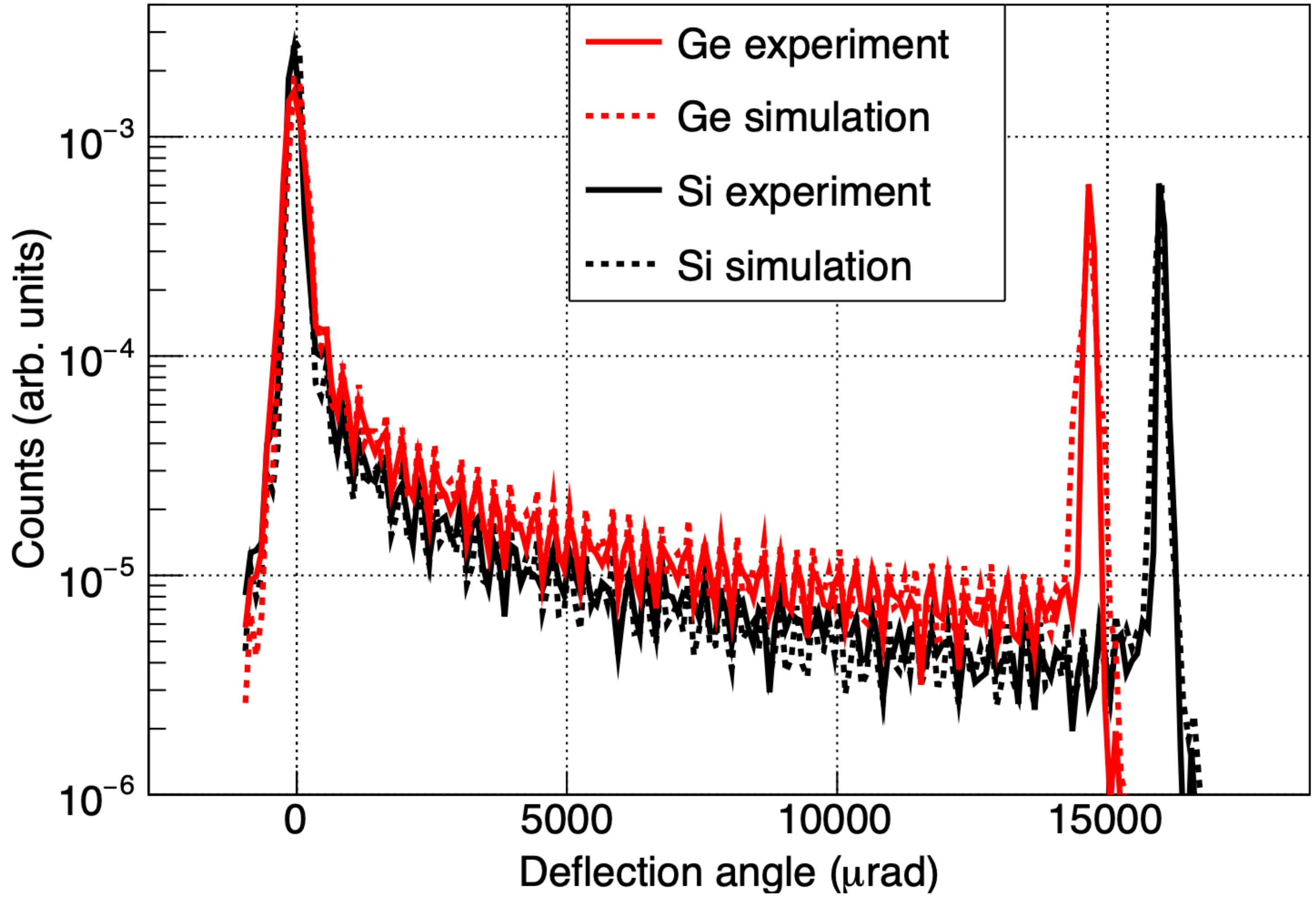
Si: 8 cm long, bent @16.0 mrad

Ge: 5 cm long, bent @14.5 mrad



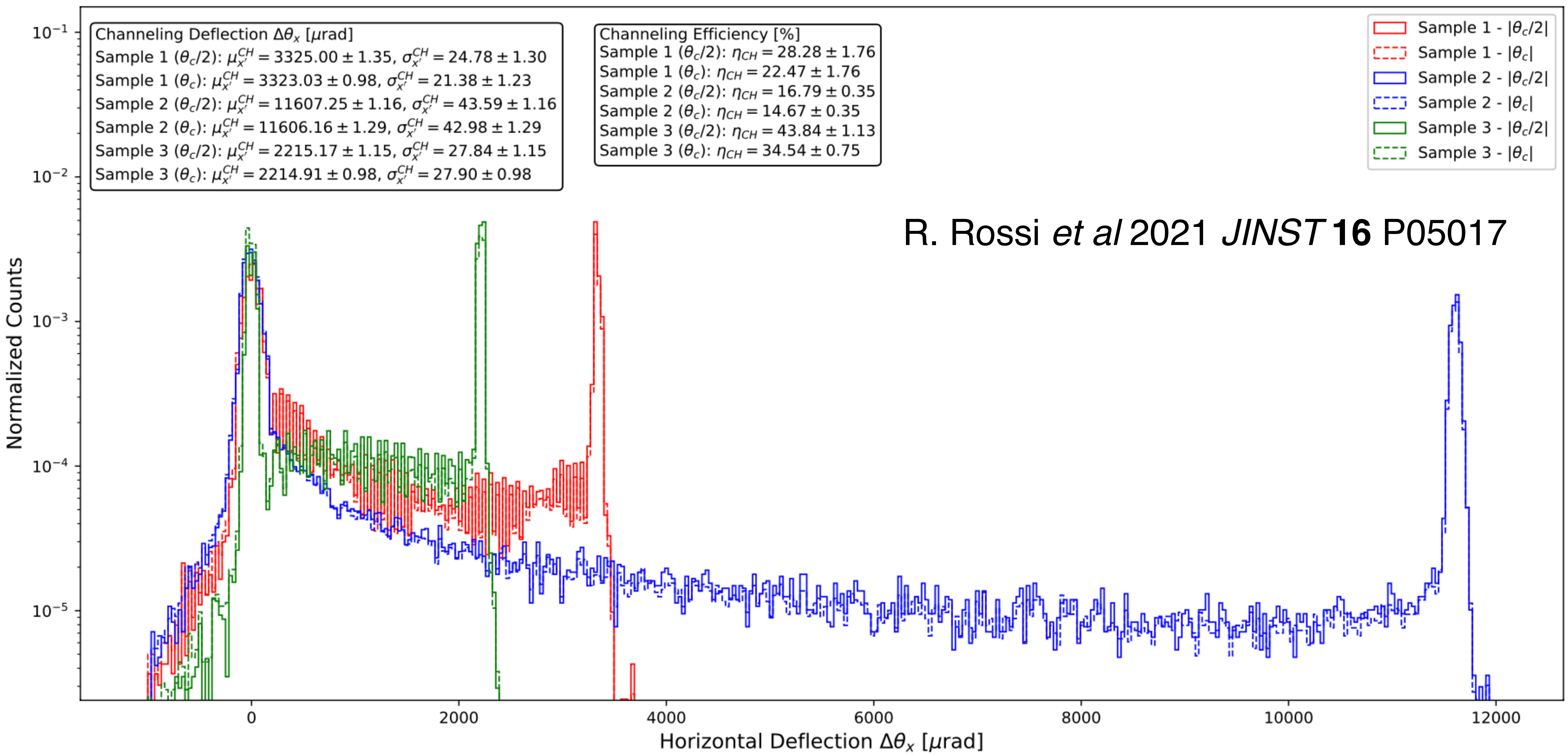
Courtesy of A. Mazzolari

PRD 103, 072003 (2021)



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

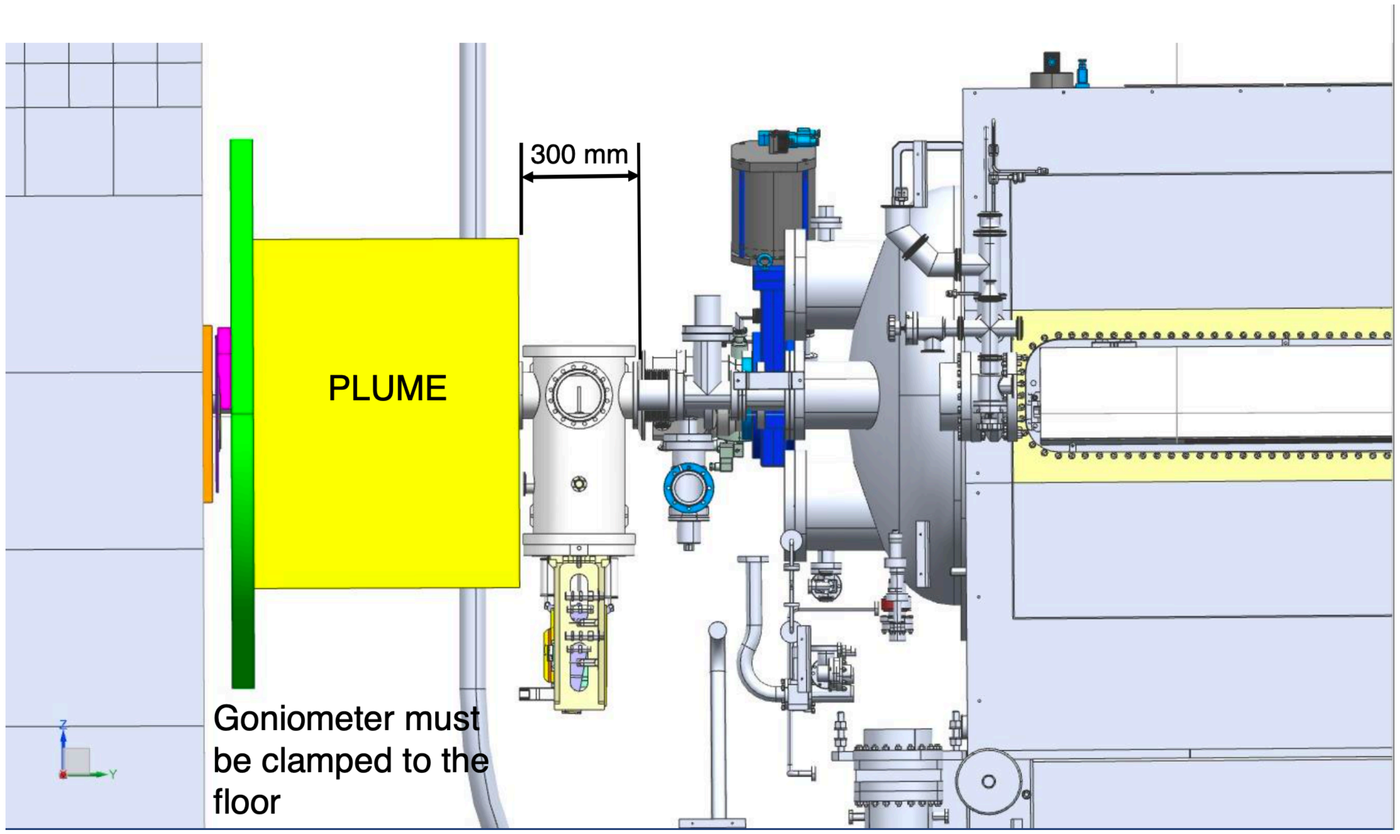
Long bent crystal prototypes



- **Si** crystals produced at INFN-Ferrara

length (cm)	bending (mrad)	ch. eff. (%)
8.0	11.6	14.7
8.0	3.3	22.5
2.5	2.2	34.5

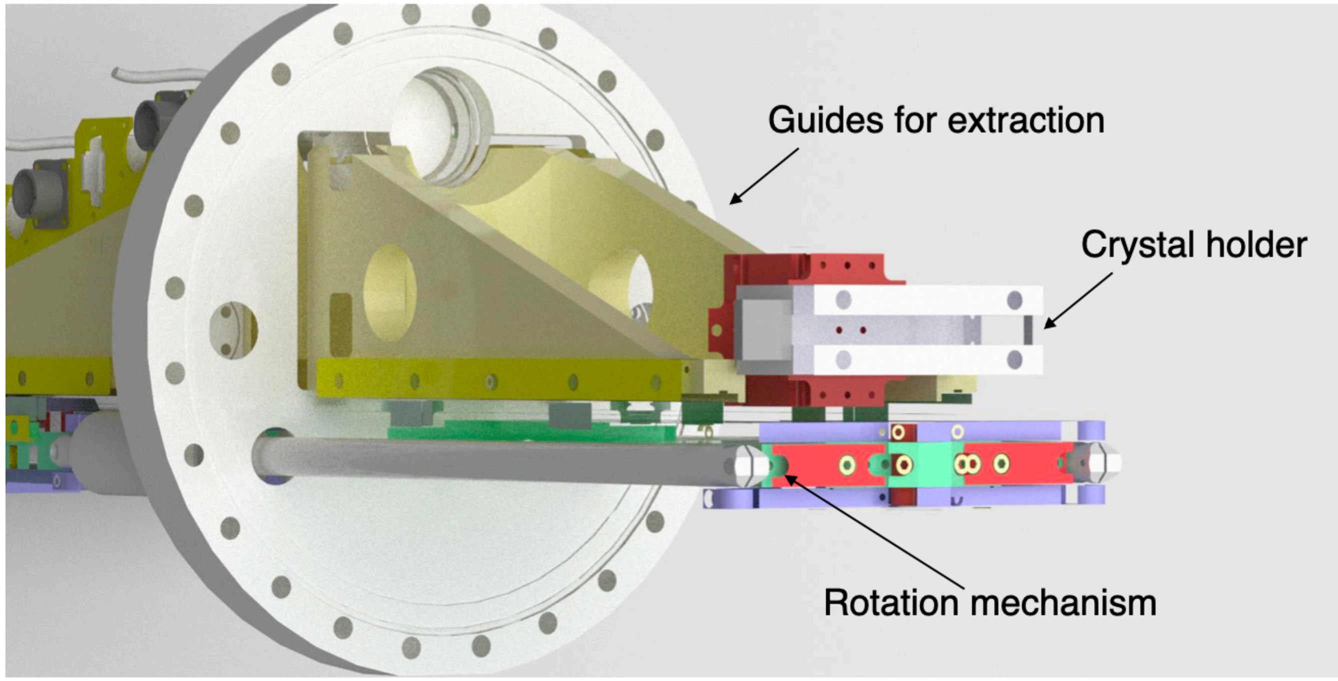
Fixed-target setup upstream of LHCb



- Goniometer for target+crystal positioned in the region upstream of the LHCb detector

- Goniometer internal structure: compatible with operations in ultra-high vacuum

- Accuracy on position ~20 μm, rotation angle ~20 μrad

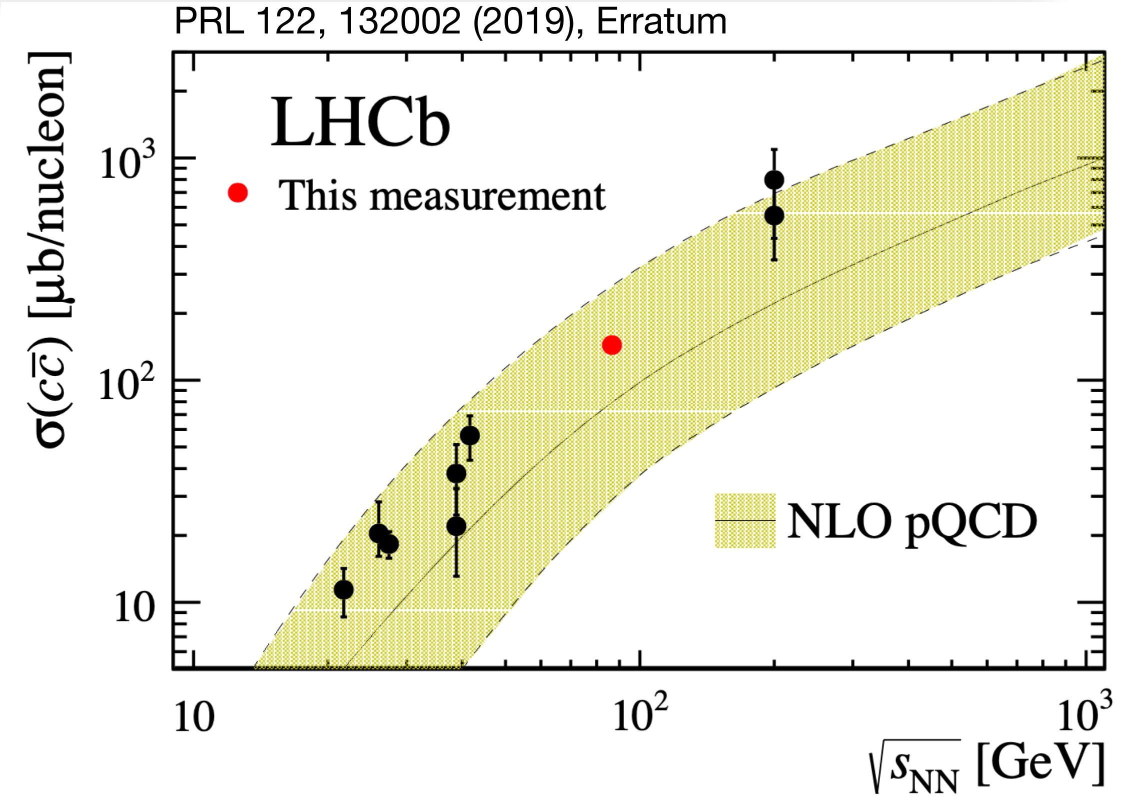


Production of Λ_c^+ baryons

Measured $c\bar{c}$ cross-section at $\sqrt{s_{NN}}$ = 86.6 GeV - $\sigma_{c\bar{c}}$ = 144 ± 12.1 ± 3.5 μb/nucleon

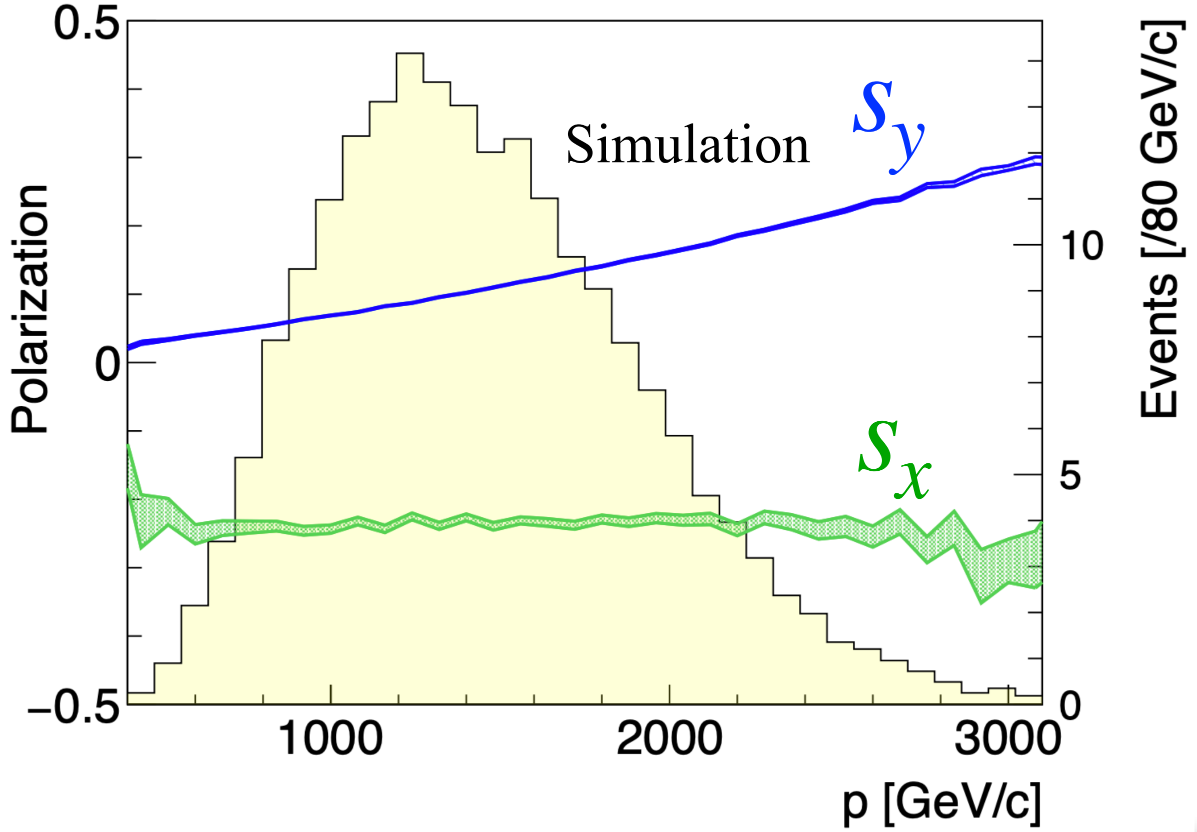
Expected Λ_c^+ **cross-section** at $\sqrt{s}$=115 GeV: σ(Λ_c^+) ~ 11 μb

Λ_c^+ **polarization** measurements ongoing using p-Gas collisions (signal yield of few hundreds)



Momentum and polarization for Λ_c^+ baryons produced in fixed-target (Ge crystal at 293 K)

s_y and s_x polarisations for Λ_c^+ baryons with $\theta_{y,C}$=0.3 mrad between impinging p and crystal

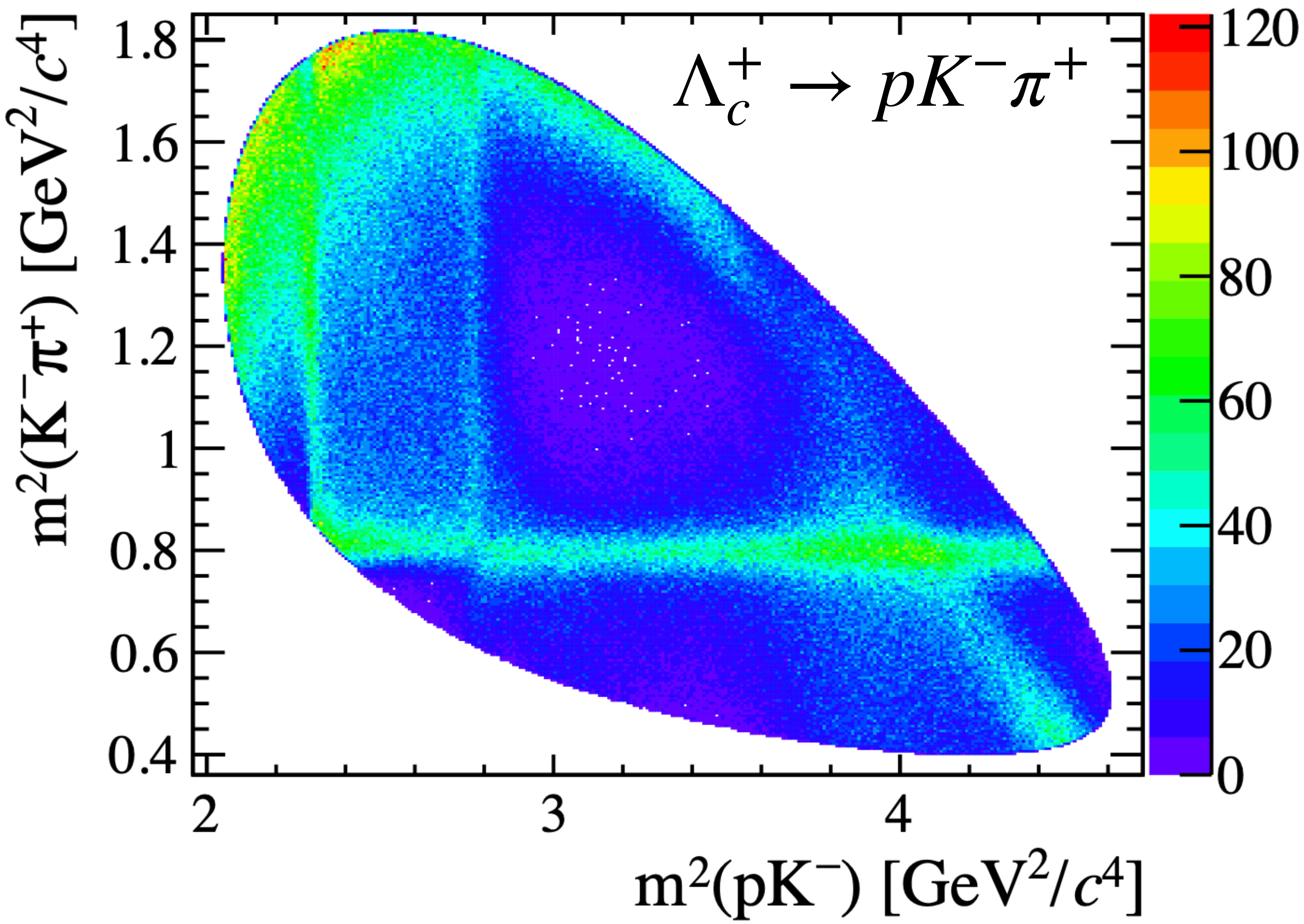


Use copious Λ_c^+, Ξ_c^+ 3-body decays

- Use many 3-body decays to increase the signal yield
- Extract maximum information via full amplitude analysis of the 3-body decays D. Marangotto, AHEP (2020) 7463073

PRD 103, 072003 (2021)

Λ_c^+ final state	$\mathcal{B}$ (%)	$\epsilon_{3\text{trk}}$	$\mathcal{B}_{\text{eff}}$ (%)
$pK^-\pi^+$	6.28 ± 0.32	0.99	6.25
$\Sigma^+\pi^-\pi^+$	4.50 ± 0.25	0.54	2.43
$\Sigma^-\pi^+\pi^+$	1.87 ± 0.18	0.71	1.33
$p\pi^-\pi^+$	0.461 ± 0.028	1.00	0.46
$\Xi^-K^+\pi^+$	0.62 ± 0.06	0.73	0.45
$\Sigma^+K^-K^+$	0.35 ± 0.04	0.51	0.18
pK^-K^+	0.106 ± 0.006	0.98	0.11
$\Sigma^+\pi^-K^+$	0.21 ± 0.06	0.54	0.11
$pK^-\pi^+\pi^0$	4.46 ± 0.30	0.99	4.43
$\Sigma^+\pi^-\pi^+\pi^0$	3.20	0.54	1.72
$\Sigma^-\pi^+\pi^+\pi^0$	2.1 ± 0.4	0.71	1.49
$\Sigma^+[p\pi^0]\pi^-\pi^+$	2.32	0.46	1.06
$\Sigma^+[p\pi^0]K^-K^+$	0.18	0.46	0.08
$\Sigma^+[p\pi^0]\pi^-K^+$	0.11	0.46	0.05
All	...	...	20.2



Proposed experimental method for neutral long-lived Λ baryons in LHCb

$\tau \approx 10^{-10}$ s

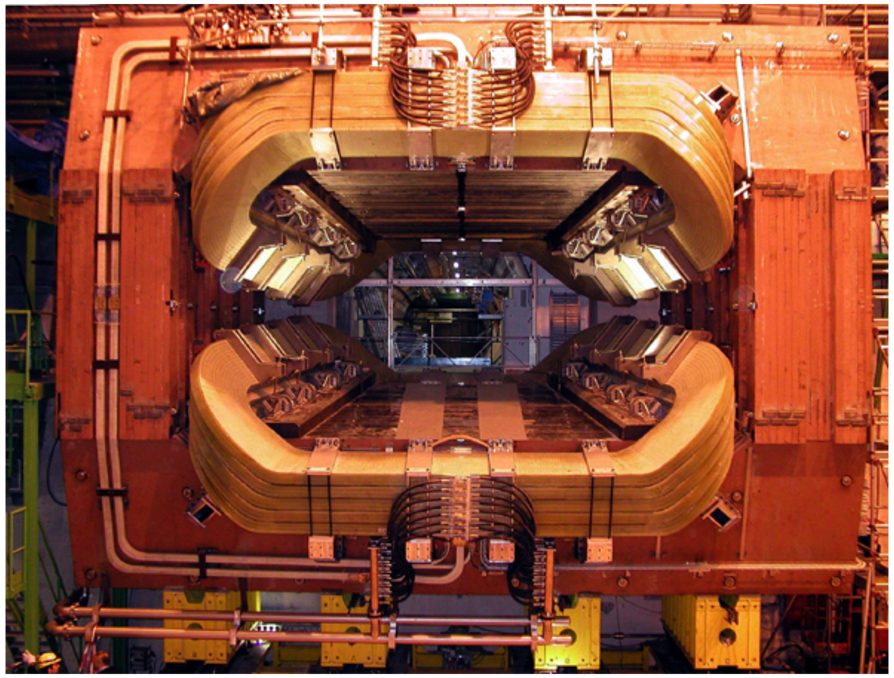
F. J. Botella et al., Eur.Phys.J.C 77 (2017) 181

Status of art for Λ baryon EDM/MDM

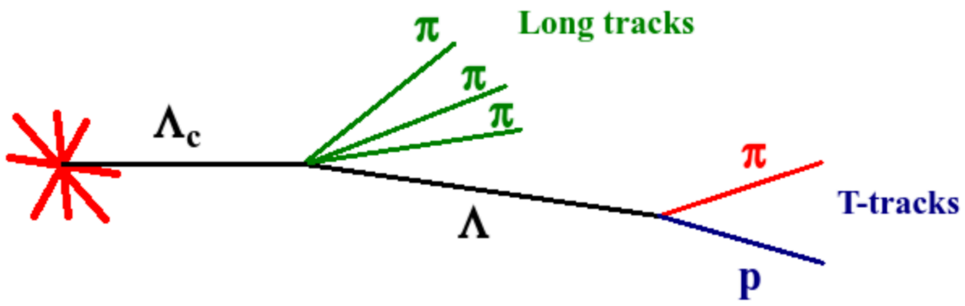
- Current limit on Λ baryon **EDM** $< 1.5 \times 10^{-16} e$cm at 95% CL L. Pondrom et al., Phys. Rev. D **23**, 814 (**1981**)
- Measurement of **MDM** $\mu_\Lambda=(-0.6138\pm0.0047)\mu_N$ but no measurement for $\overline{\Lambda}$ exists Phys.Rev.Lett. 41 (**1978**) 1348
- Measurement of MDM of $\overline{\Lambda}$ is needed for a **CPT** test
- New BESIII measurement of Λ **decay parameter** inconsistent with previous results
  $\alpha = 0.750 \pm 0.009 \pm 0.004$ Nature Phys. 15 (2019) 631-634
- Need **new measurements** to verify and improve previous results based on wrong α value

Λ baryons

- Long-lived Λ baryons can travel through the LHCb dipole magnet B~1T
- Spin precession in LHCb B field
- Select Λ (anti-Λ) from weak charm decays
  - e.g. $\Lambda_b^0 \to J/\psi\Lambda$, $\Xi_c^0 \to \Lambda K^-\pi^+$, $\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$
  - Large longitudinal polarisation (up to 90%) due to parity violation in the weak decay
- Challenge: reconstruction of Λ baryons decaying at the end of the magnet

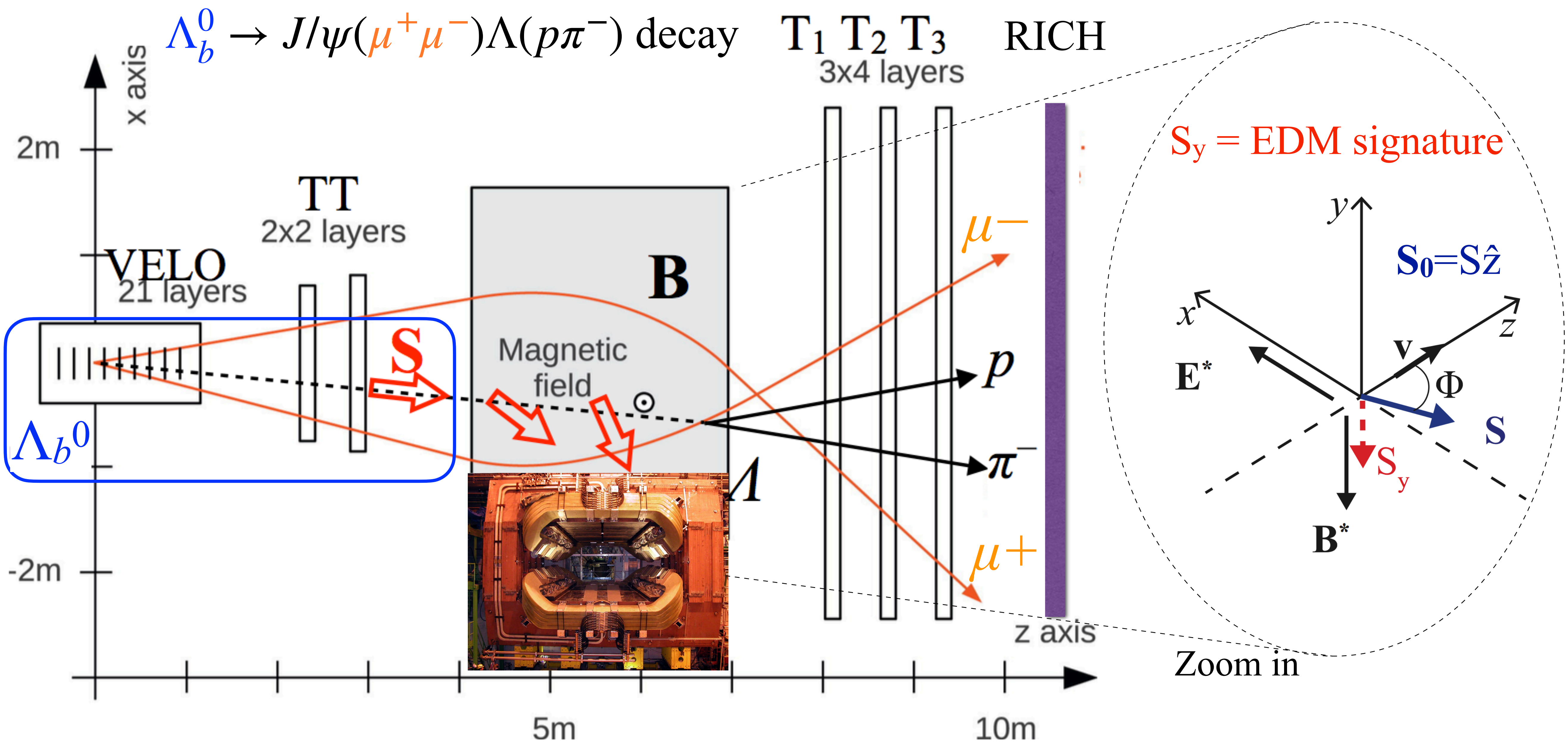


$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$



Novel experimental technique for strange baryons

- EDM/MDM from spin precession of Λ baryon in LHCb **dipole magnet**

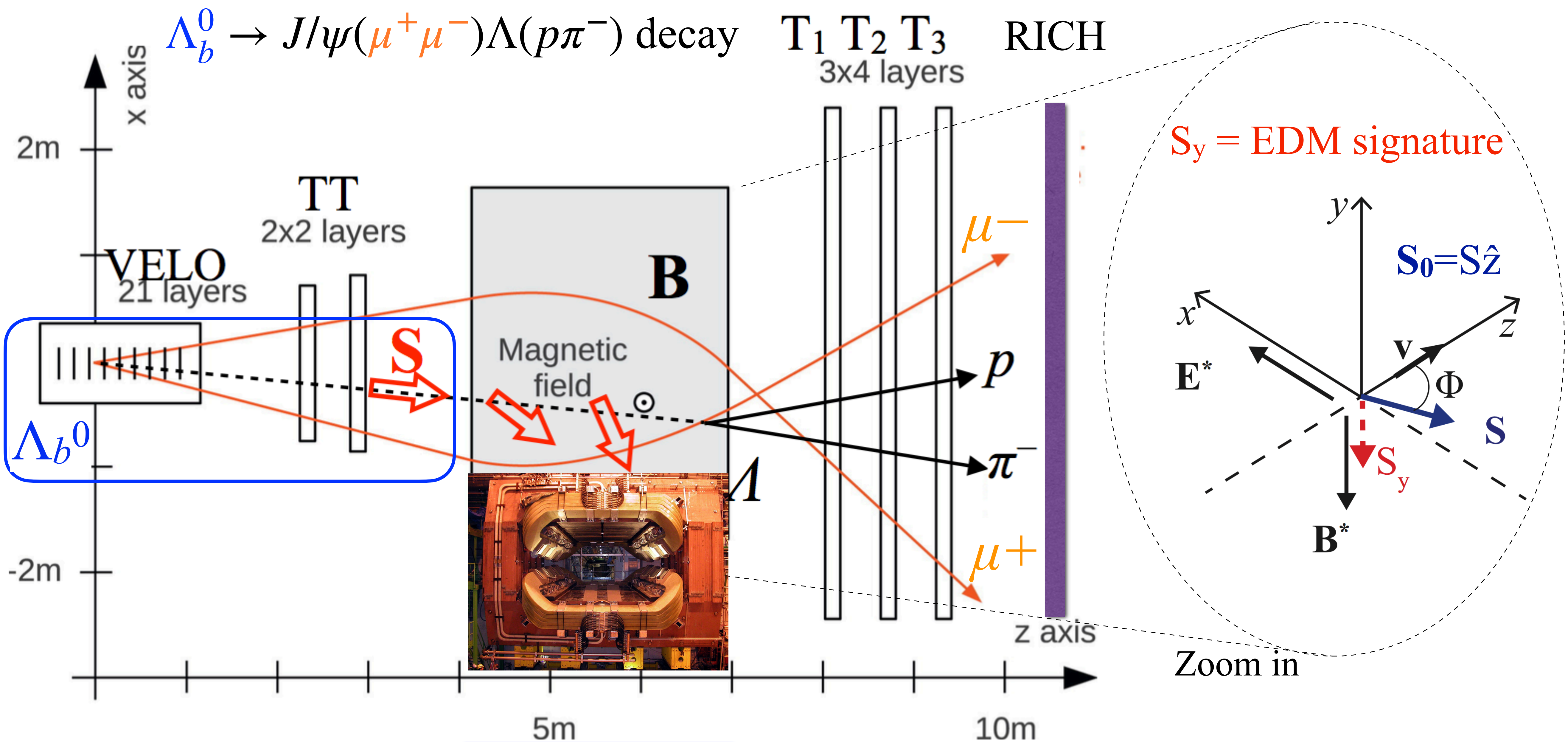


Λ polarised production

Novel experimental technique for strange baryons

- EDM/MDM from spin precession of Λ baryon in LHCb **dipole magnet**

$\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$ decay



Λ polarised production   spin precession

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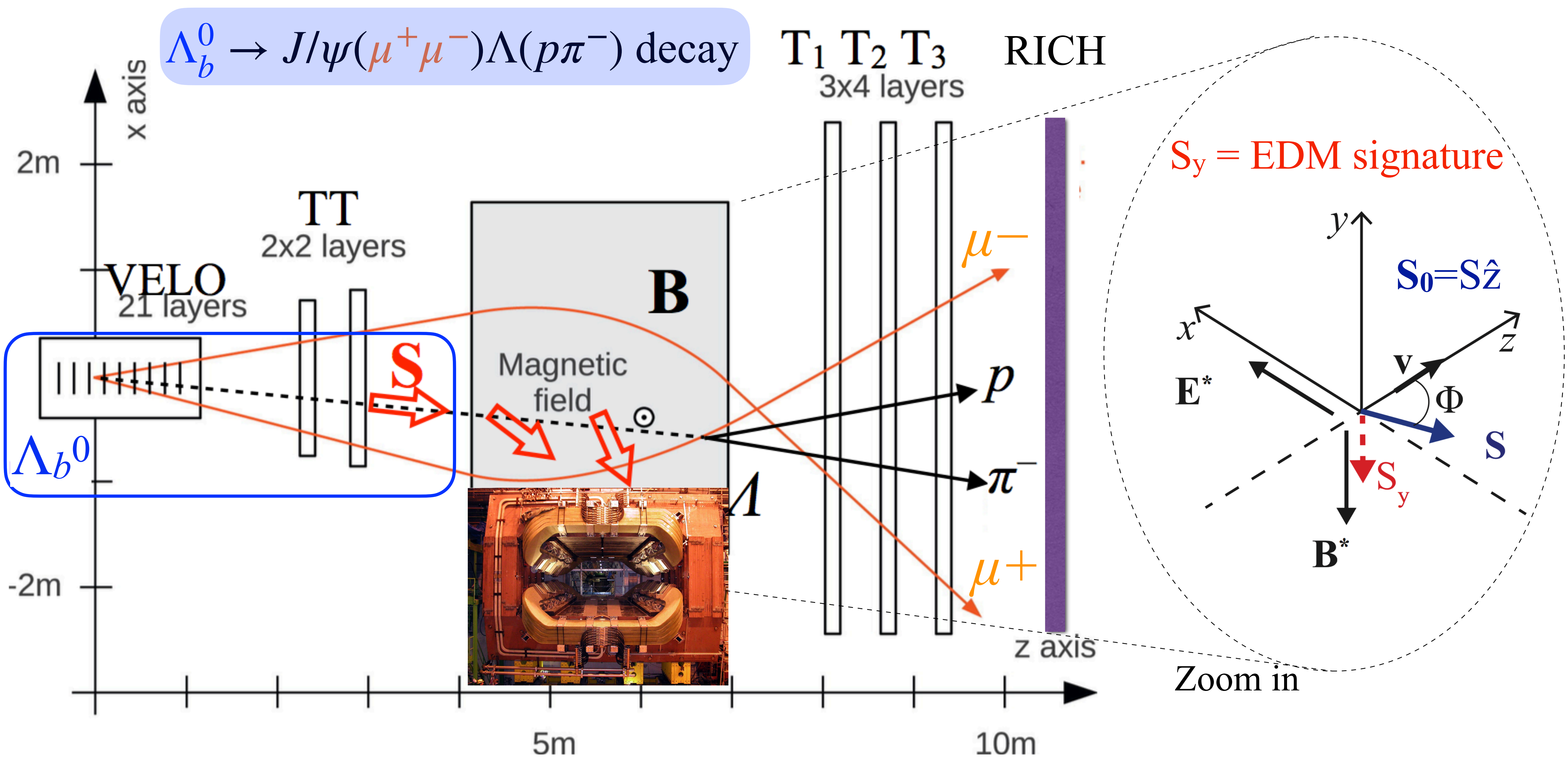


Λ polarised production spin precession event reconstruction

Sensitivity on MDM/EDM

- For initial longitudinal polarisation $\mathbf{s}_0 = s_0 \hat{z}$
- Spin rotation after LHCb magnet (B field)

$$\mathbf{s} = \begin{cases} s_x = -s_0 \sin \Phi \\ s_y = -s_0 \dfrac{d\beta}{g} \sin \Phi \\ s_z = s_0 \cos \Phi \end{cases}$$

$$\Phi \approx \frac{g\mu_B BL}{\beta \hbar c} \approx \frac{\pi}{4} \qquad BL \approx 4 \text{ T m}$$

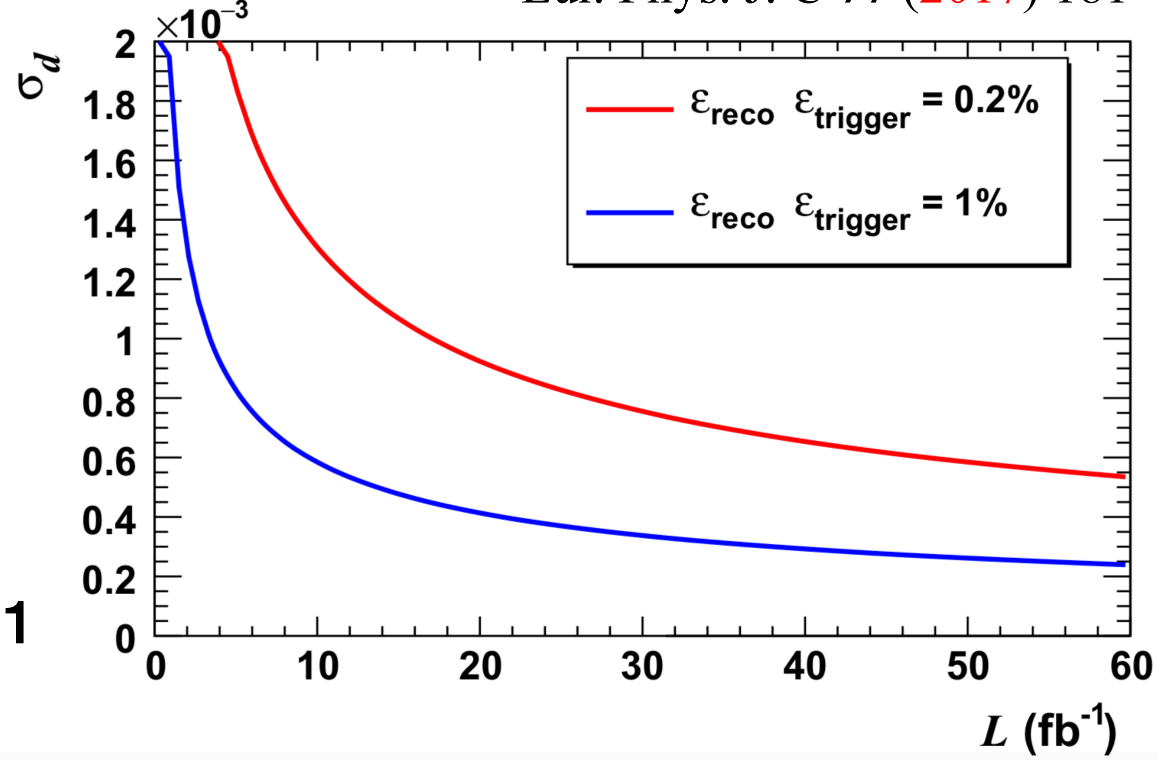
Spin analyser in Λ helicity frame

$$\frac{dN}{d\Omega'} \propto 1 + \alpha \mathbf{s} \cdot \hat{\mathbf{k}} \ ,$$

CPT test <10^{-3} via $\Lambda/\bar{\Lambda}$ MDM

EDM limit < 10^{-18} e cm with 50 fb^{-1}

Eur. Phys. J. C **77** (2017) 181

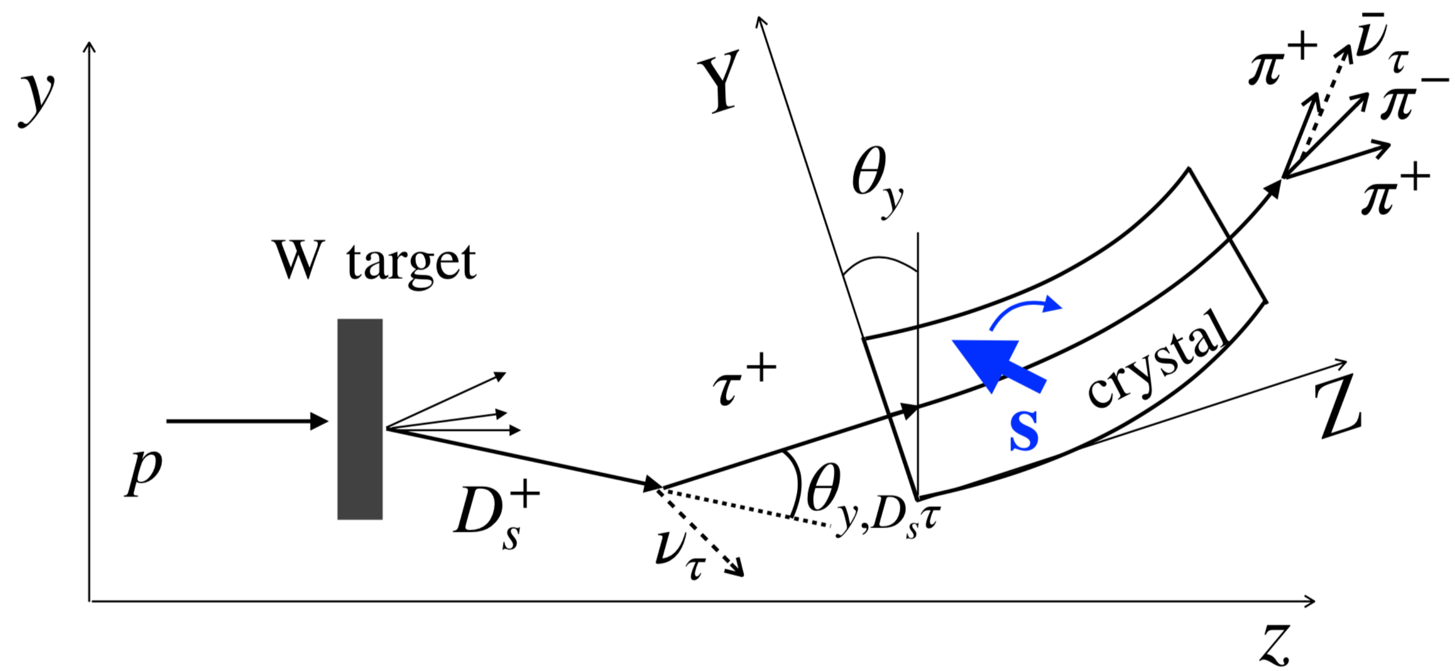


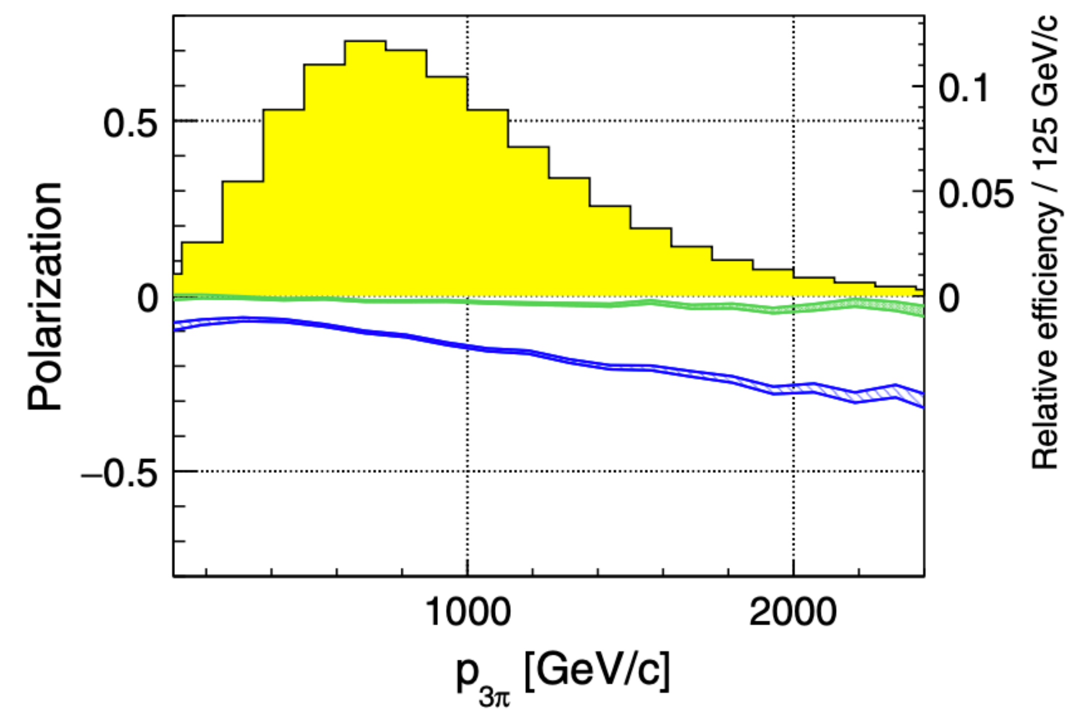
Proposals for τ lepton

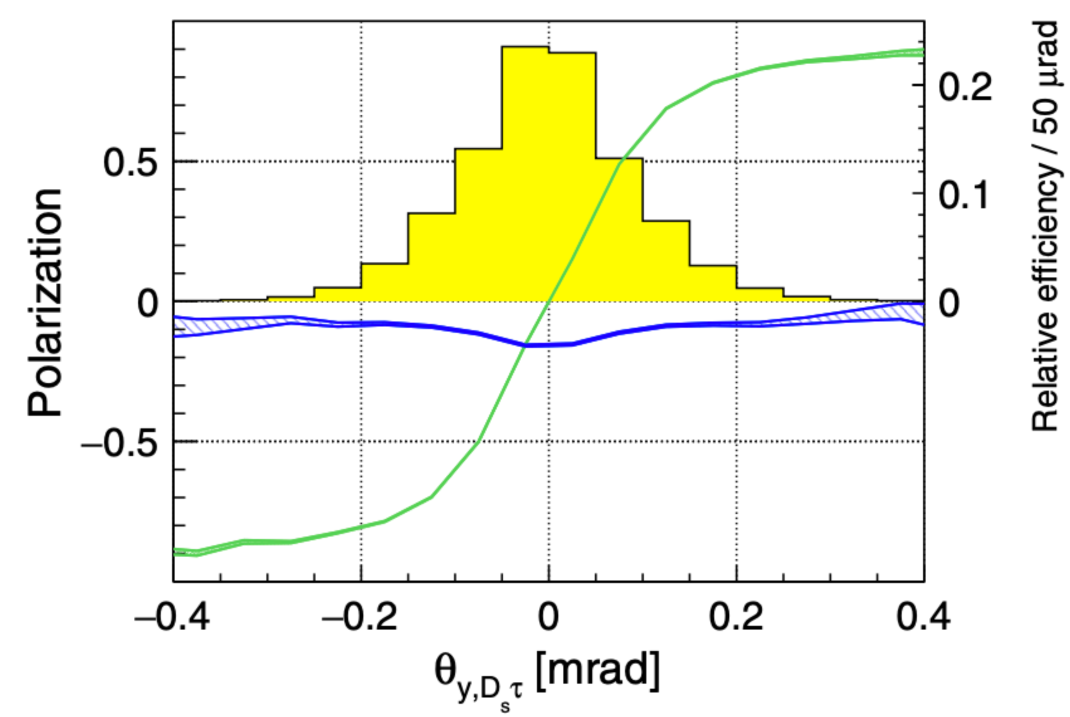
- A.S. Fomin , A. Korchin, A. Stocchi, S. Barsuk, P. Robbe, *Feasibility of τ lepton electromagnetic dipole moments measurements using bent crystals at LHC*, J. High Energ. Phys. 03 (2019) 156 (see backup slides)
- J. Fu, M. A. Giorgi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N. N., J. Ruiz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

Direct measurement of τ lepton dipole moments

- **Fixed-target** production: $D_s^+ \to \tau^+ \nu_\tau$ with $\tau^+ \to \pi^+ \pi^- \pi^+ \overline{\nu}_\tau$
- **Bent crystal** for spin precession







Spin polarisation

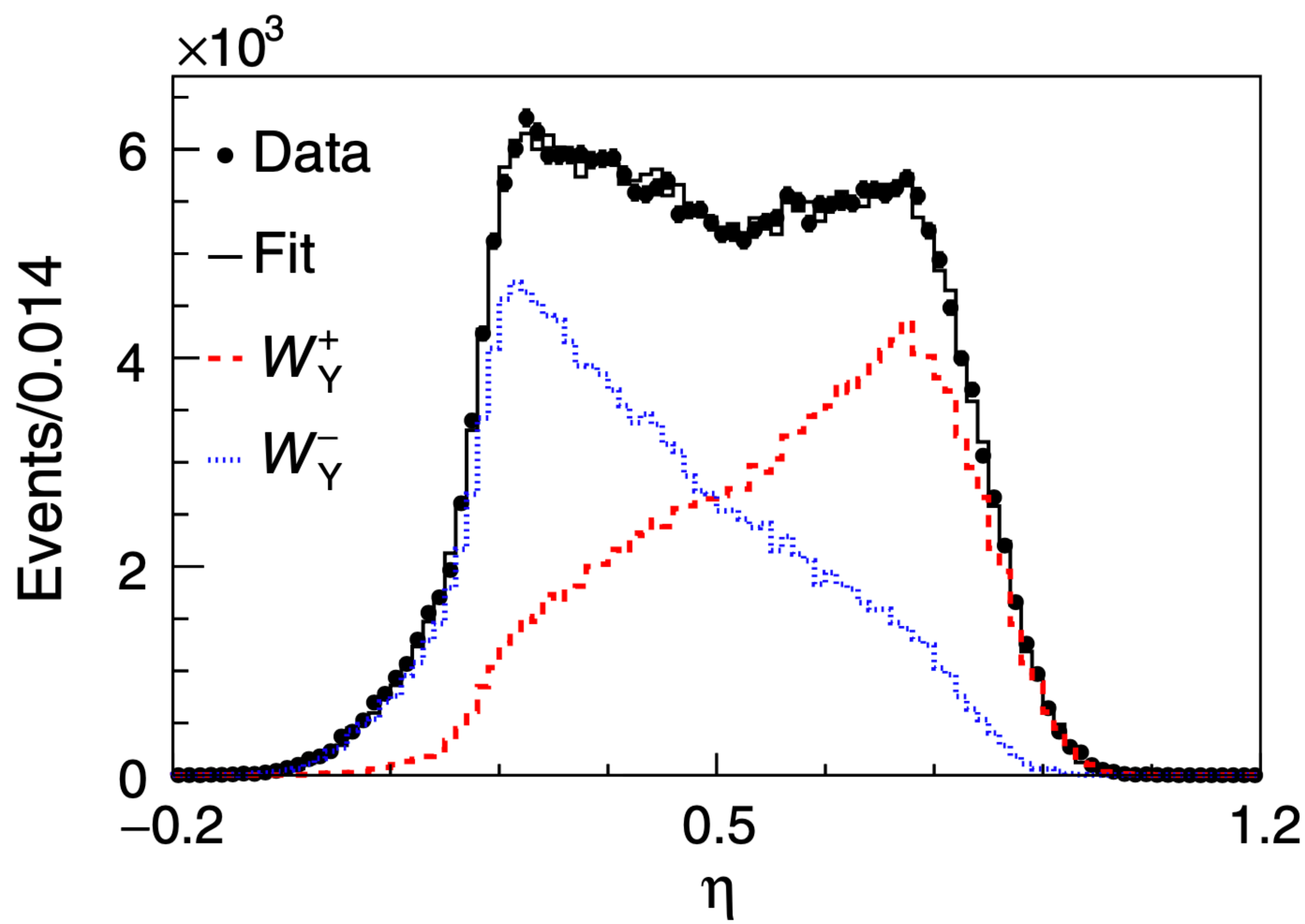
- kinematic selection on $p_{3\pi}$>0.8 TeV, longitudinal (z) polarisation for MDM and enhanced EDM sensitivity
- Tagging θ(Ds,τ)≤0 (e.g. 2 crystals, other) transverse (y) polarisation for enhanced MDM sensitivity

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)

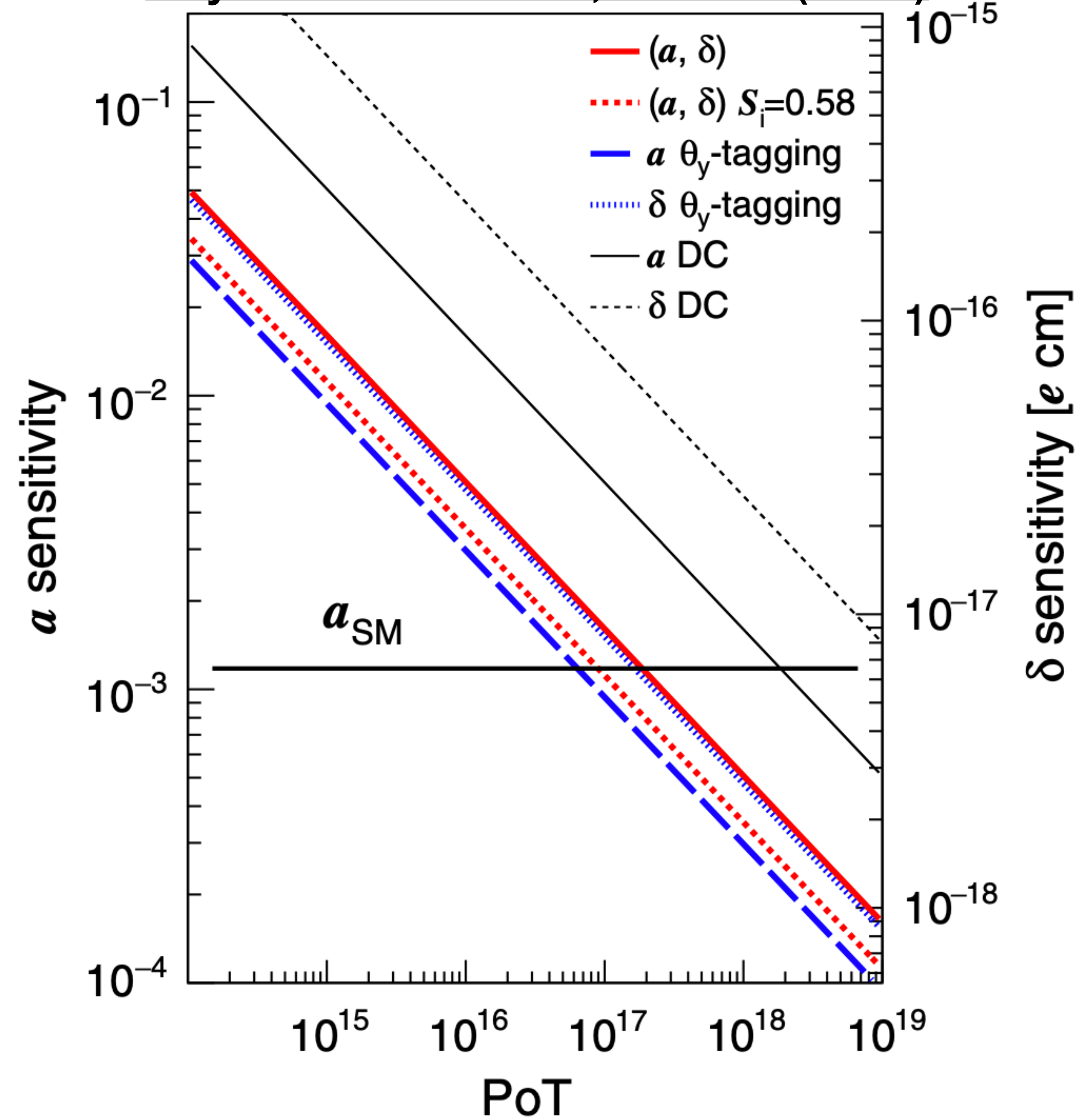
Sensitivity to dipole moments for τ lepton

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

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



Phys. Rev. Lett. 123, 011801 (2019)



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

EDM sensitivity ~10^{-17} e cm

Challenging: **dedicated experiment** needed

Summary

- Measurements of **MDM/EDM** of particles are sensitive to physics within and beyond the SM
- Measurements of MDM/EDM of **short-lived particles at LHC**, i.e. strange and charm baryons and tau lepton, are proposed
- **First measurements** are possible in 2 year data taking
  - **strange baryons**, using the LHCb detector
  - **charm baryons**, require a fixed-target setup to be installed upstream of the LHCb detector
- Challenging for **tau lepton**, requires a dedicated experiment at LHC

Status and next steps

- **Milestones** achieved: feasibility detector studies, long bent crystal prototypes, preparatory studies in LHCb, machine layout, physics program extended
- Machine **test in LHC** possibly during Run3
- Aim at installation and data taking in **LHCb** for first measurements in the near future
- Design a dedicated fixed-target experiment at LHC at high statistics for a more **ambitious physics program**: beauty baryons, tau lepton

Thanks for your attention!

References for baryons

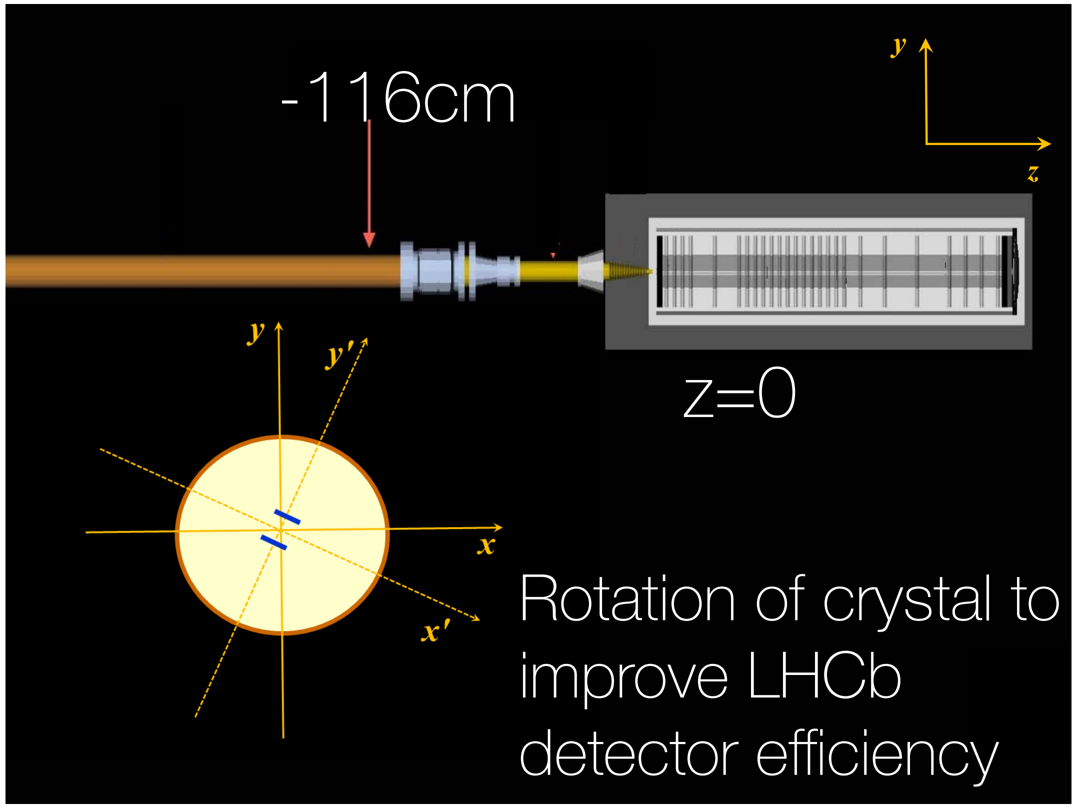
- S. Aiola, L. Bandiera, G. Cavoto, F. De Benedetti, J. Fu, V. Guidi, L. Henry, D. Marangotto, F. Martinez Vidal, V. Mascagna, J. Mazorra de Cos, A. Mazzolari, A. Merli, N. Neri, M. Prest, M. Romagnoni, J. Ruiz Vidal, M. Soldani, A. Sytov, V. Tikhomirov, E. Vallazza, *Progress towards the first measurement of charm baryon dipole moments*, arXiv:2010.11902 (2020), PRD 103, 072003 (2021) .
- 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.
- 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.
- 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.

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.

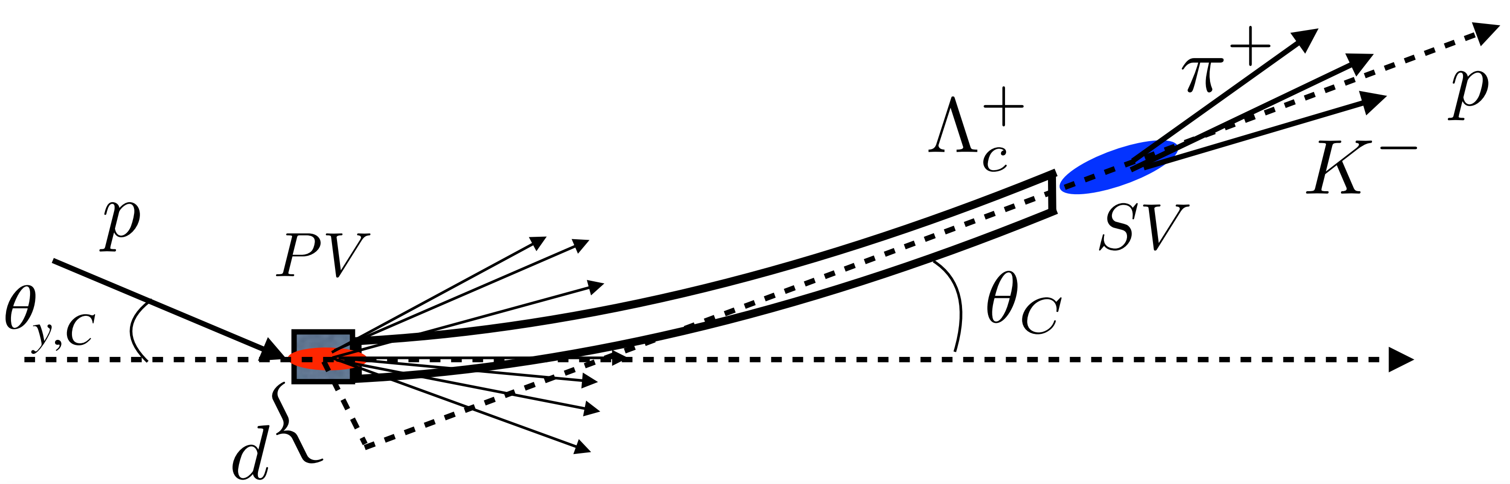
Backup slides

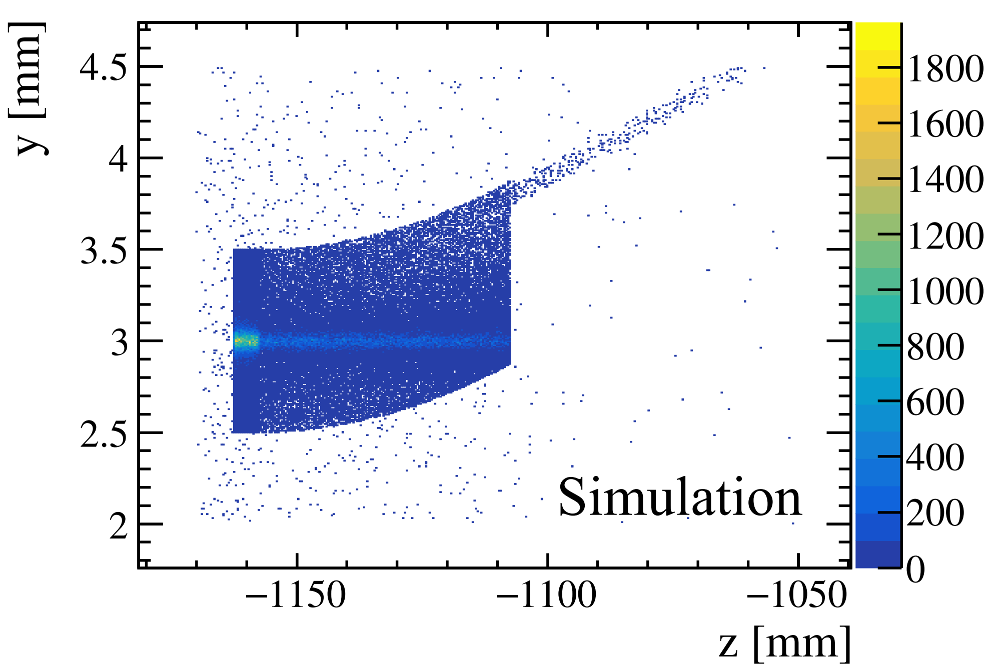
Preparatory studies in LHCb



- Good performance (signal and bkg) with LHCb detector: full **simulation** of **fixed-target setup:** W target 0.5-2.0 cm and bent crystal
- About 10^{-4} Λ_c^+ produced in the target are channeled in the bent crystal

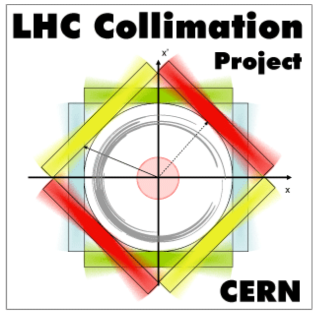
Good res. on production and decay vertex (7-8mm), θ_C angle (25μrad), m(pKπ) (20 MeV)

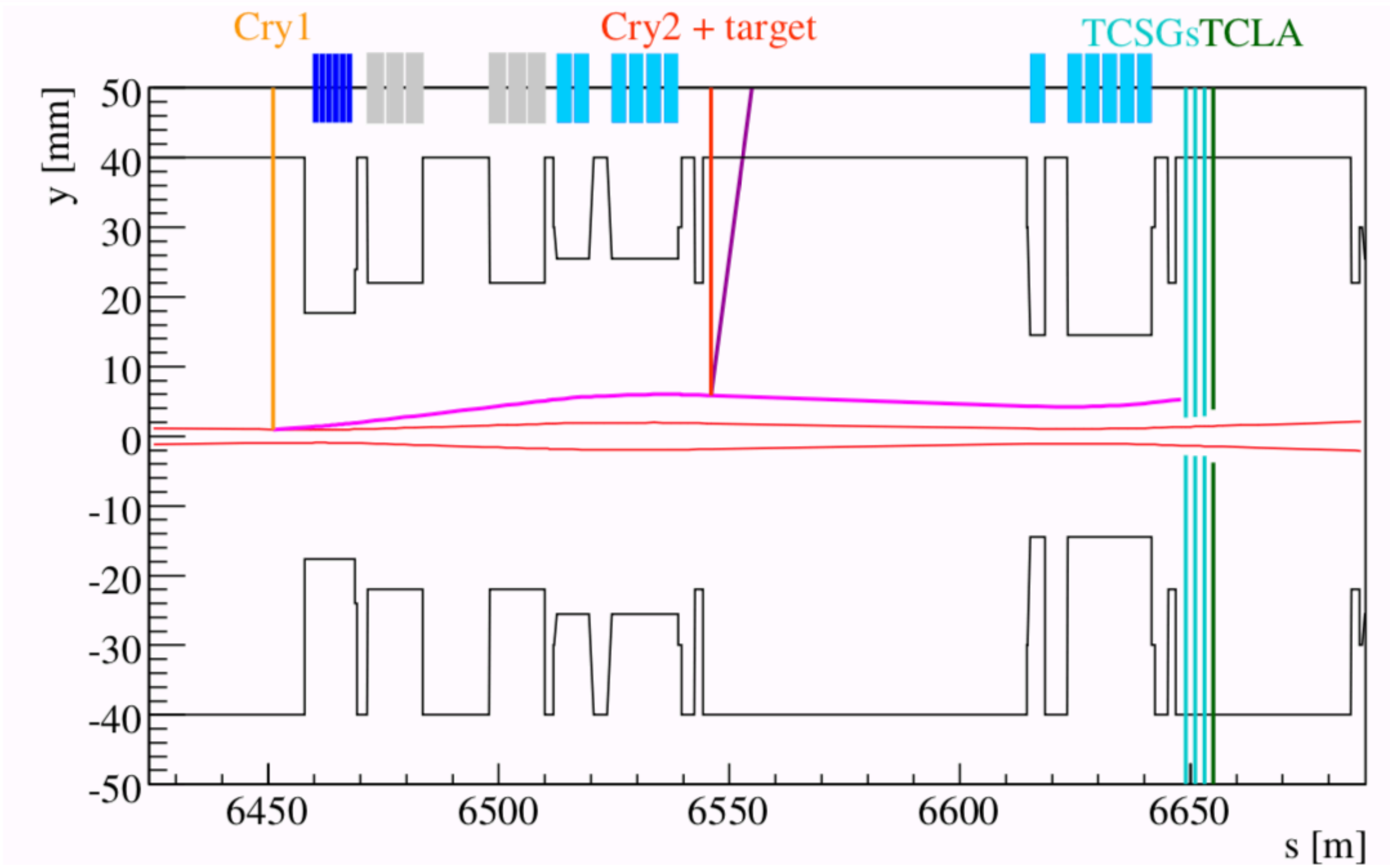


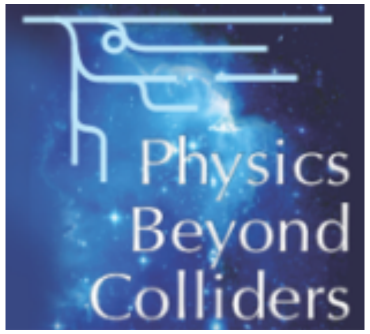


Layout for dedicated experiment

D. Mirarchi, A. S. Fomin, S. Redaelli, W. Scandale *EPJC 80 (2020) 10, 929*







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

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
- 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)
  - A. S. Fomin et al., JHEP 08 (2017) 120

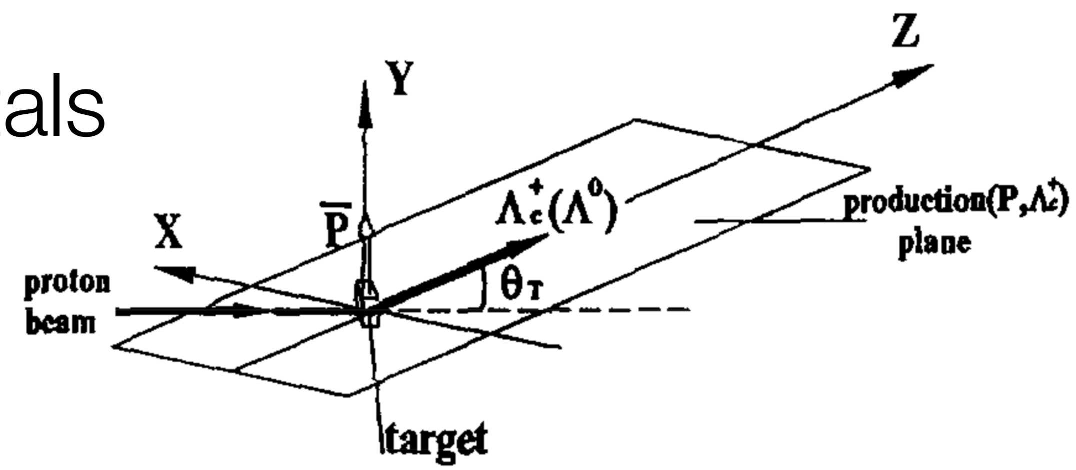


Fig. 3. Schematic diagram of the Λ_c^+ (Λ^0) polarization production.

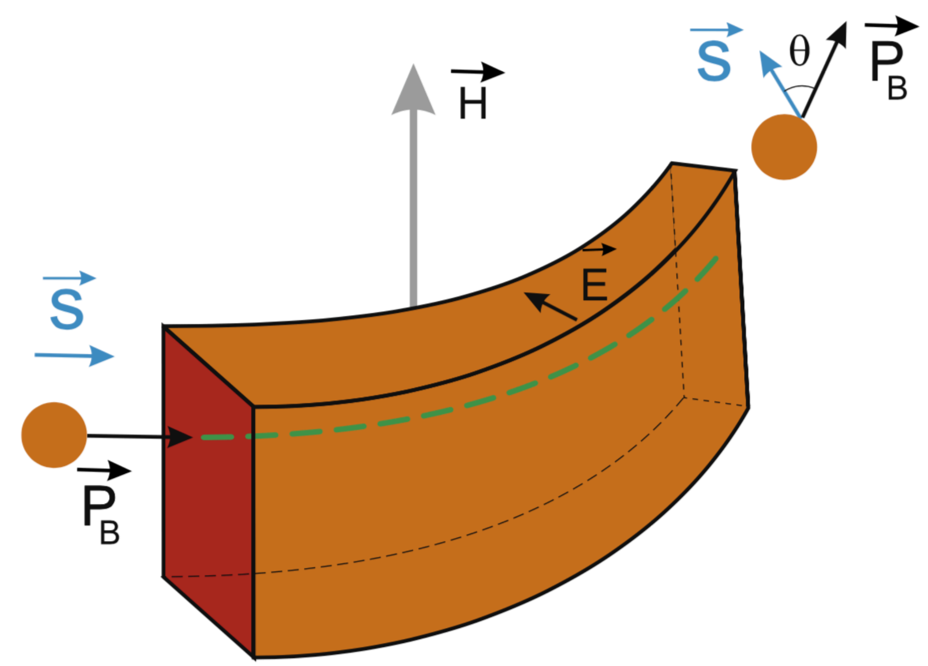
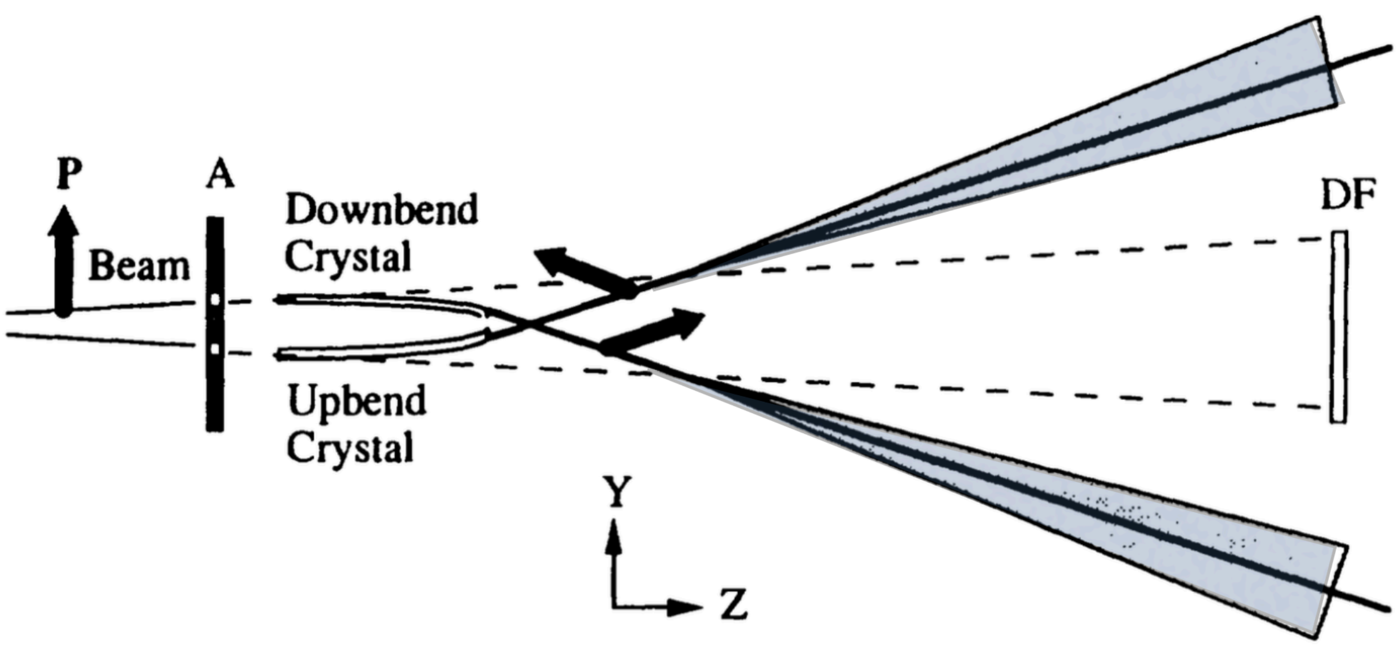


Fig. 1. Spin rotation in a bent crystal.

Proof of principle at Fermilab

- 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



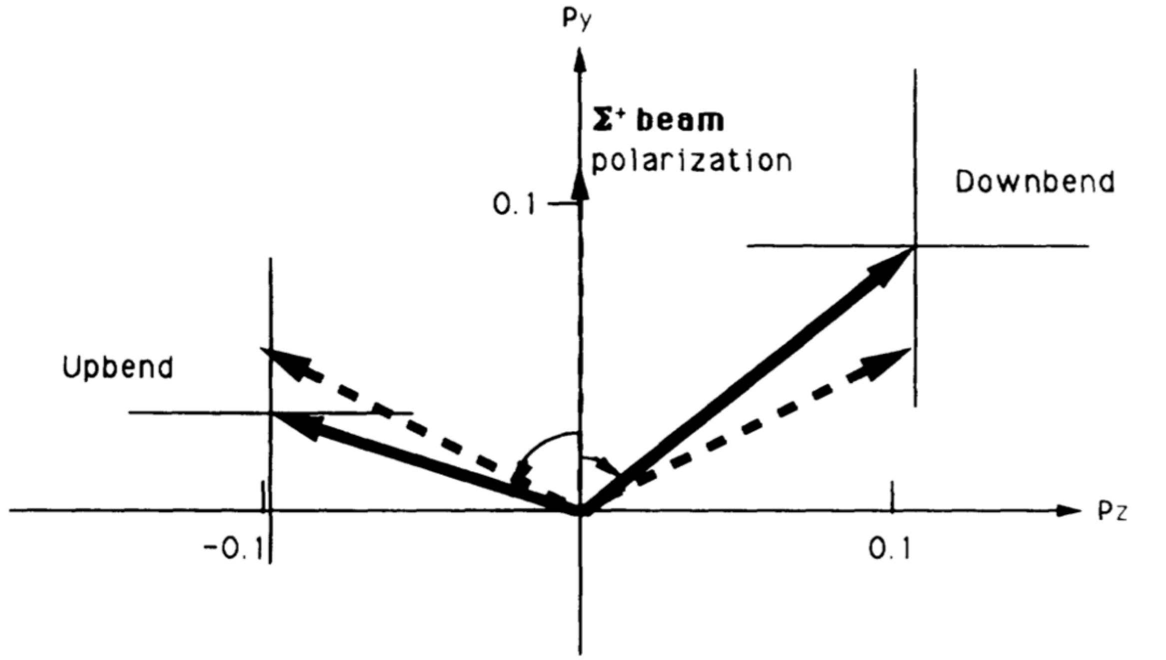
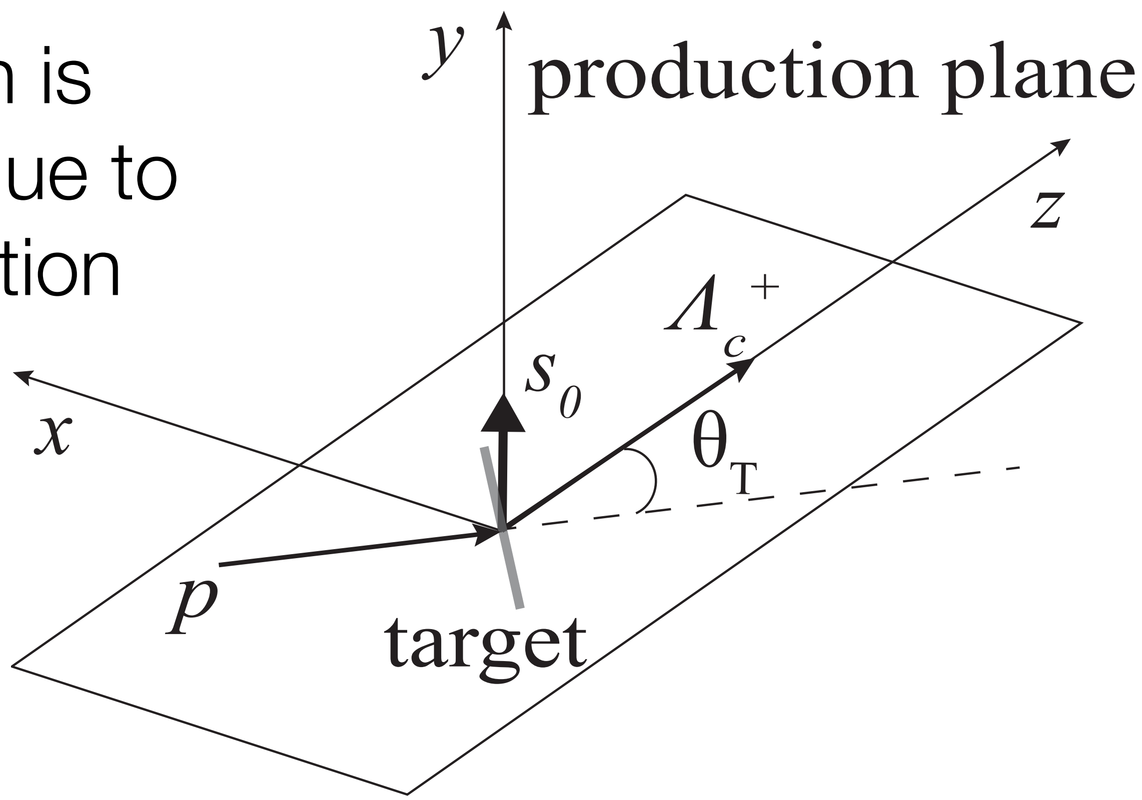
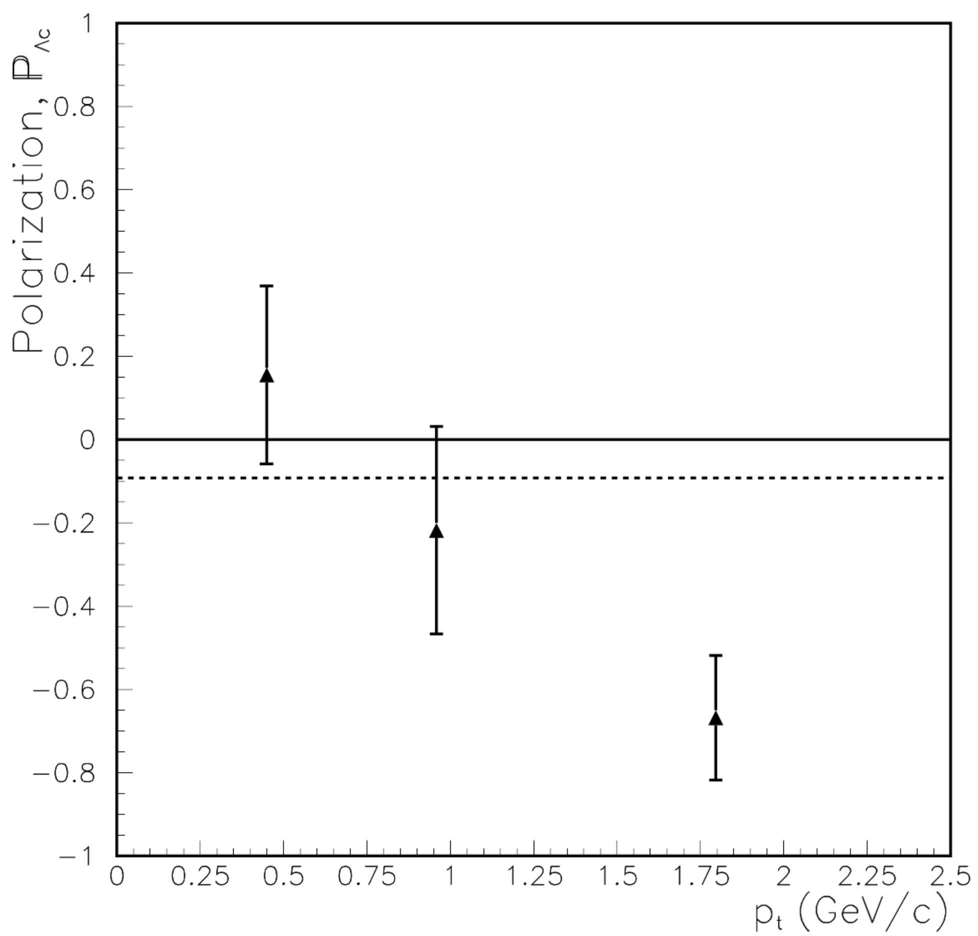


FIG. 3. Measured polarizations and uncertainties (1σ statistical errors) after spins have been precessed by the two crystals. The dashed arrows show the expected precessions.

Charm baryon polarisation

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





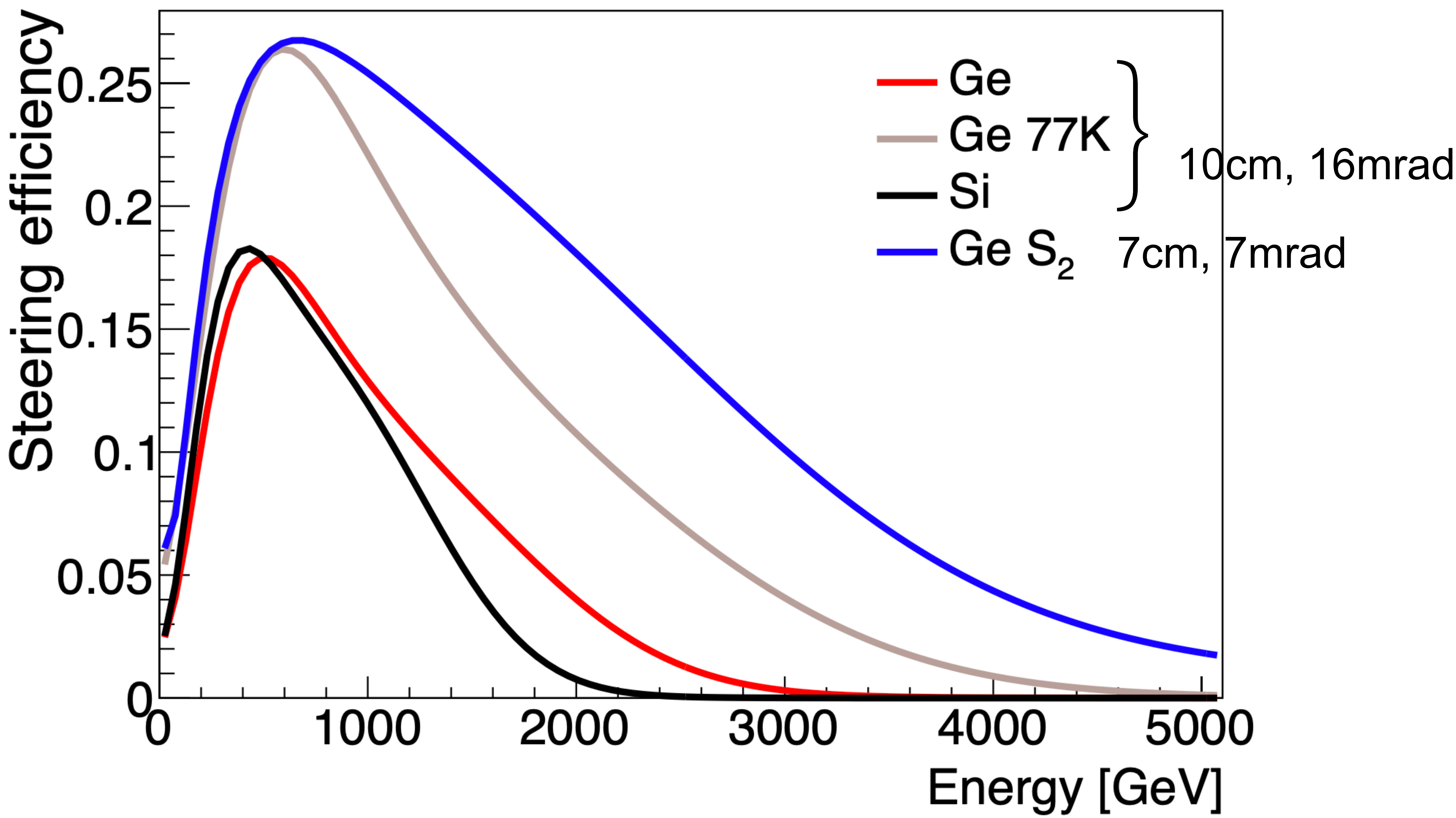
- Λ_c^+ polarisation vs transverse momentum measured by E791 experiment in 500 GeV/c π^--N reactions

- Increases with Λ_c^+ transverse momentum

X

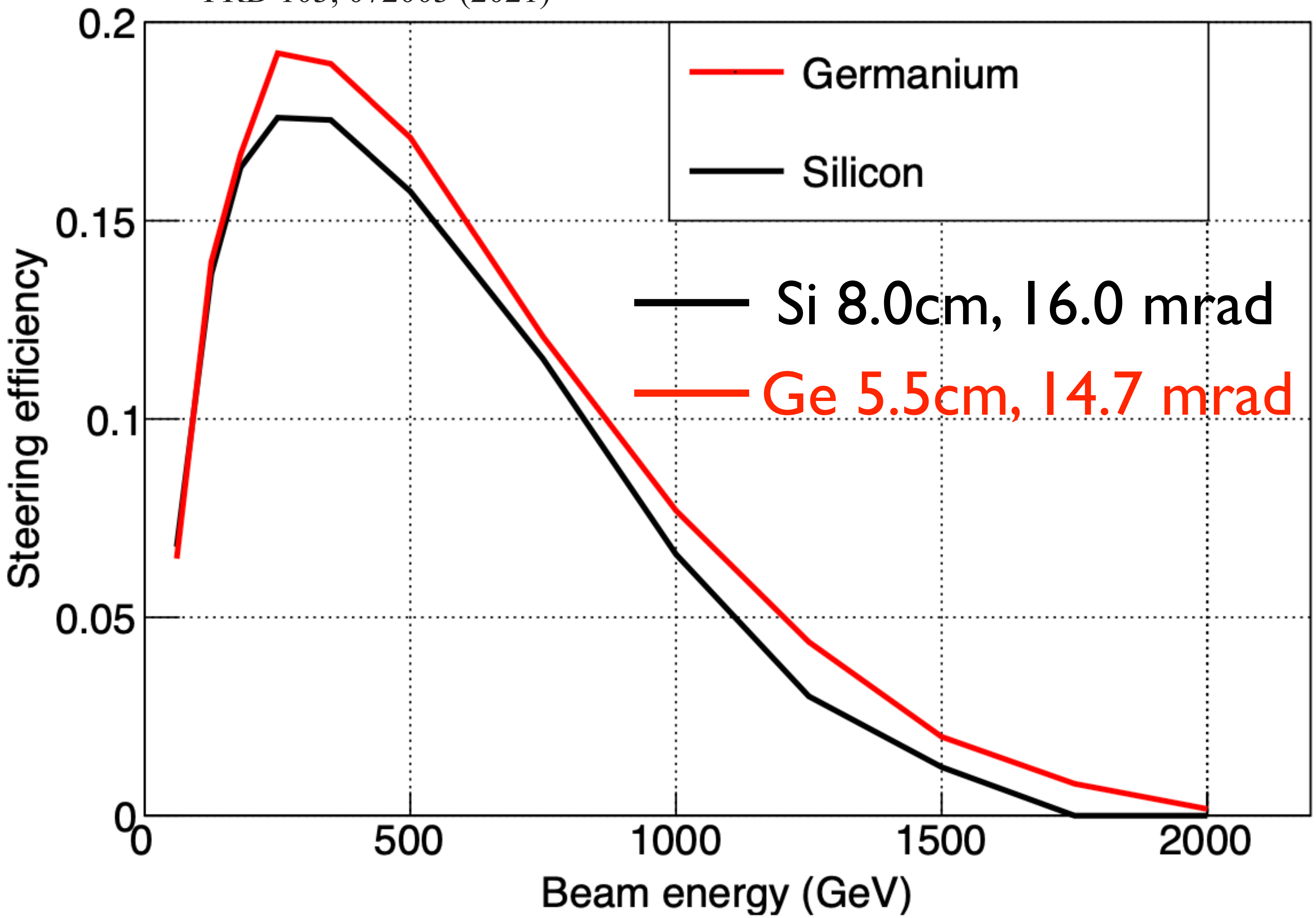
Channeling simulations: Ge provides better steering efficiency wrt Si, especially if cooled at T=77 K. R&D on **cryogenic Ge crystals** in progress

PRD 103, 072003 (2021)



Channeling efficiency vs energy

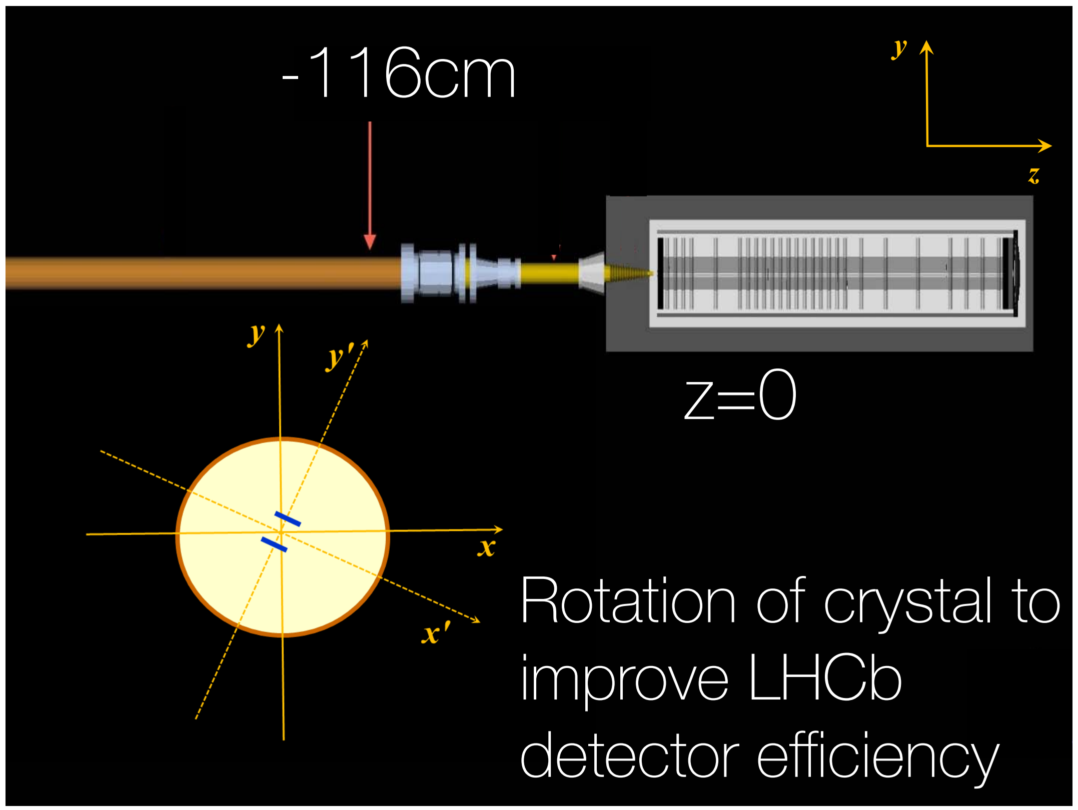
PRD 103, 072003 (2021)

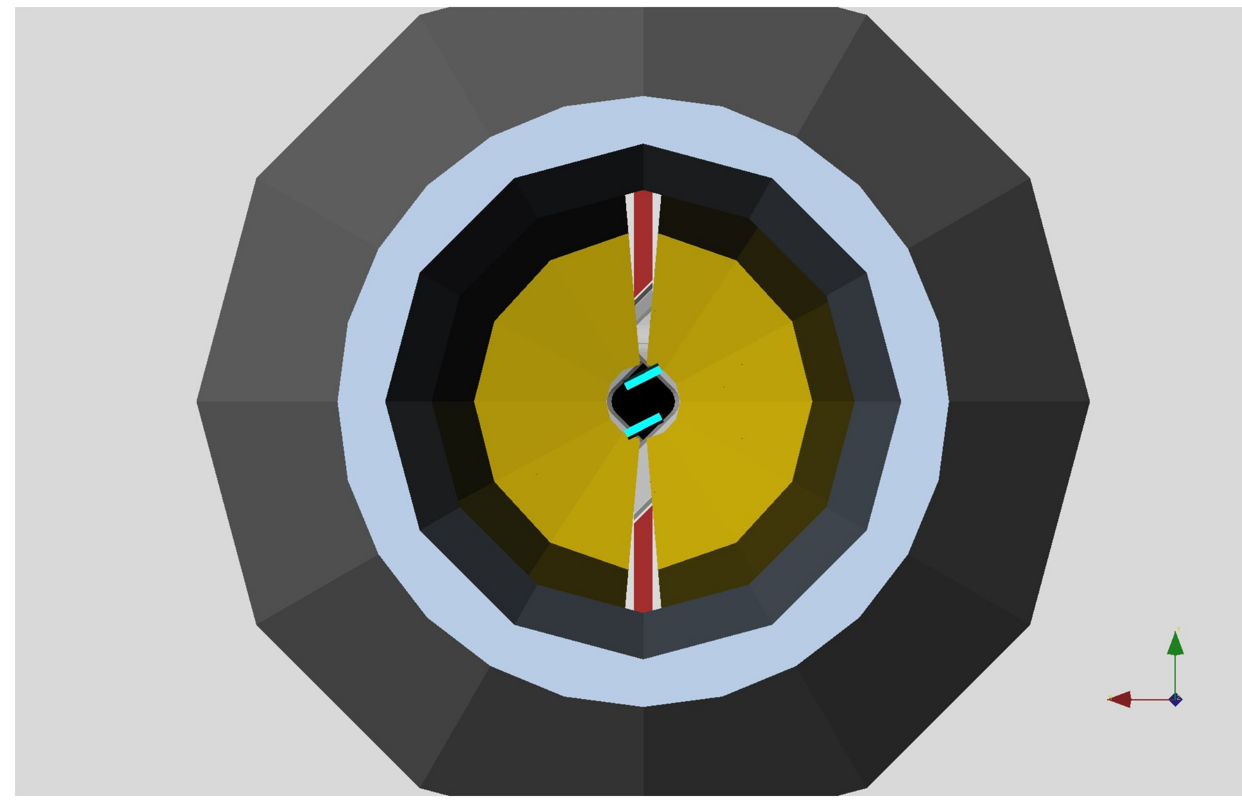


Detector simulation studies

Simulation studies

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



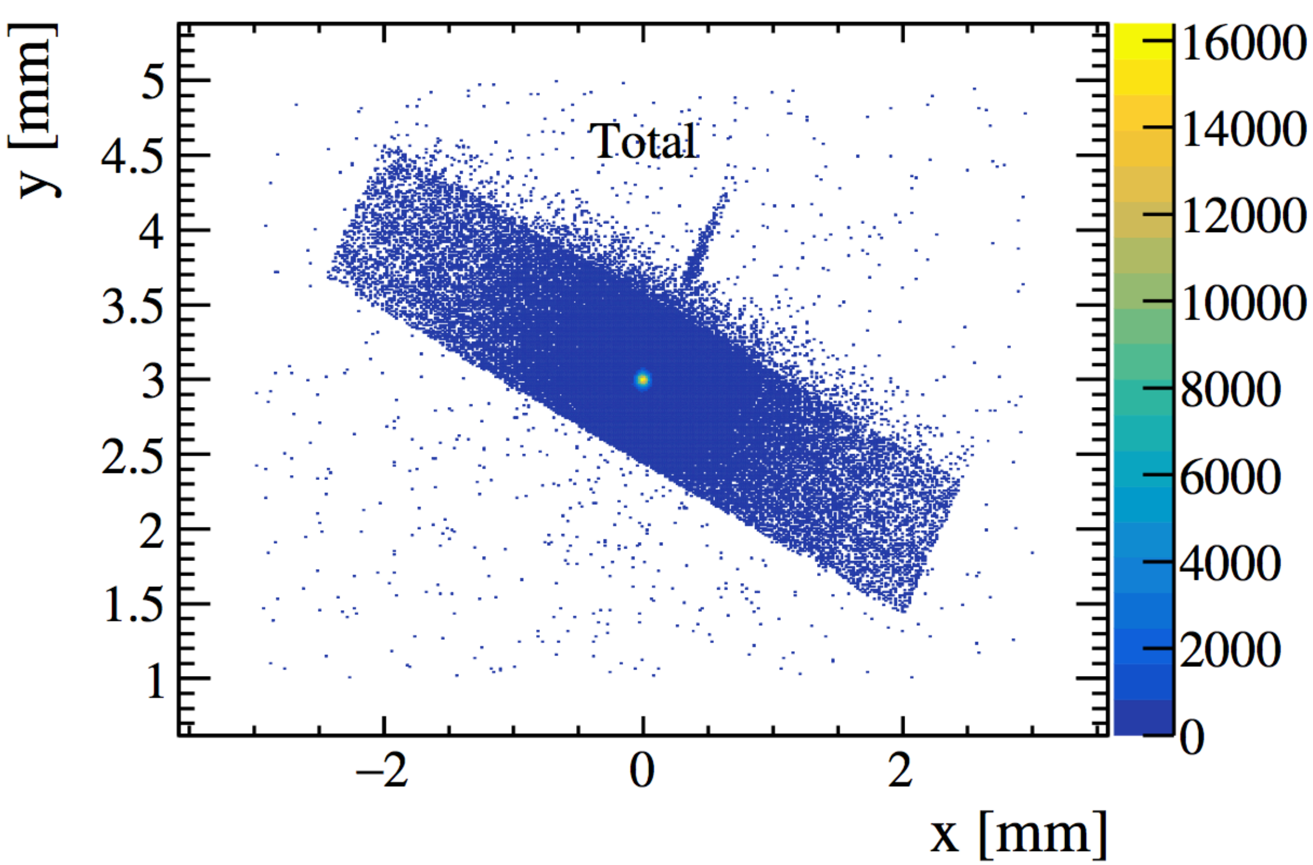


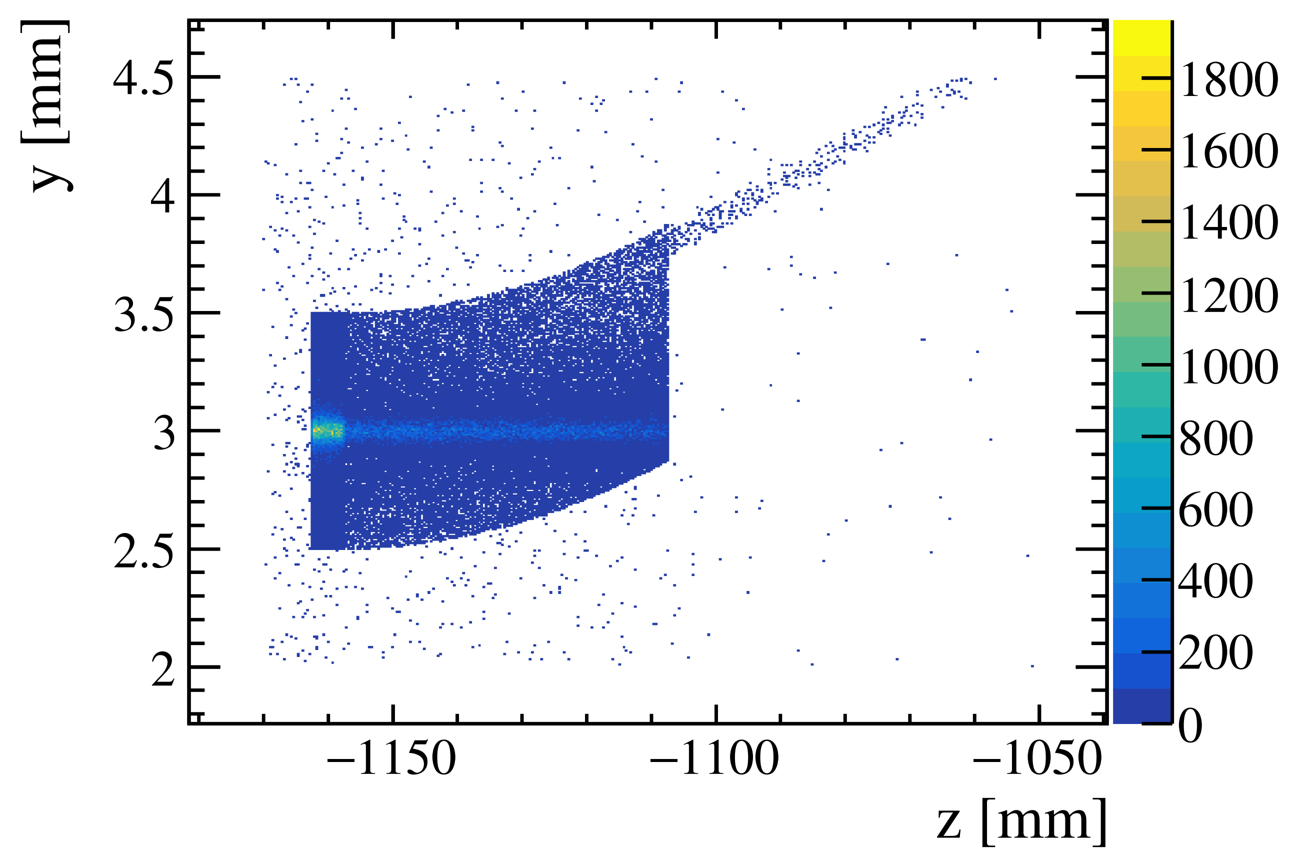
- Use EPOS for fixed-target minimum bias events, PYTHIA for baryons produced in pW hard collisions

- Signal reconstruction and background rejection studied using LHCb full simulation

Fixed-target simulation

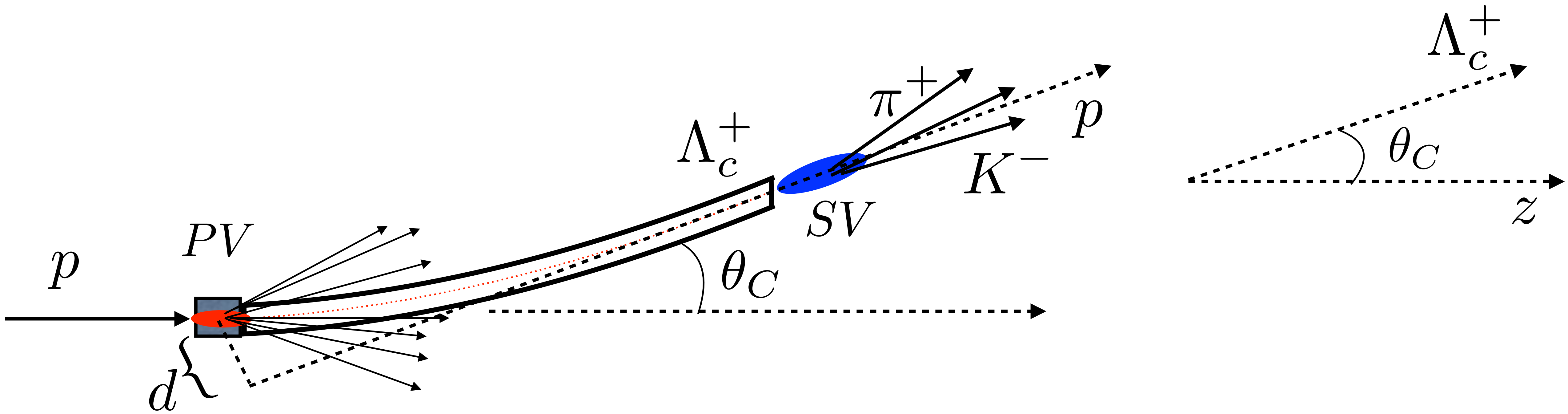
- Radiography of the target in (0, 0.3, -116) cm
- Distribution of origin vertex of stable charged particles in simulated events
- Simulated processes include: hadronic interactions, pair production, Bremsstrahlung, Compton, δ rays





Identification of signal events

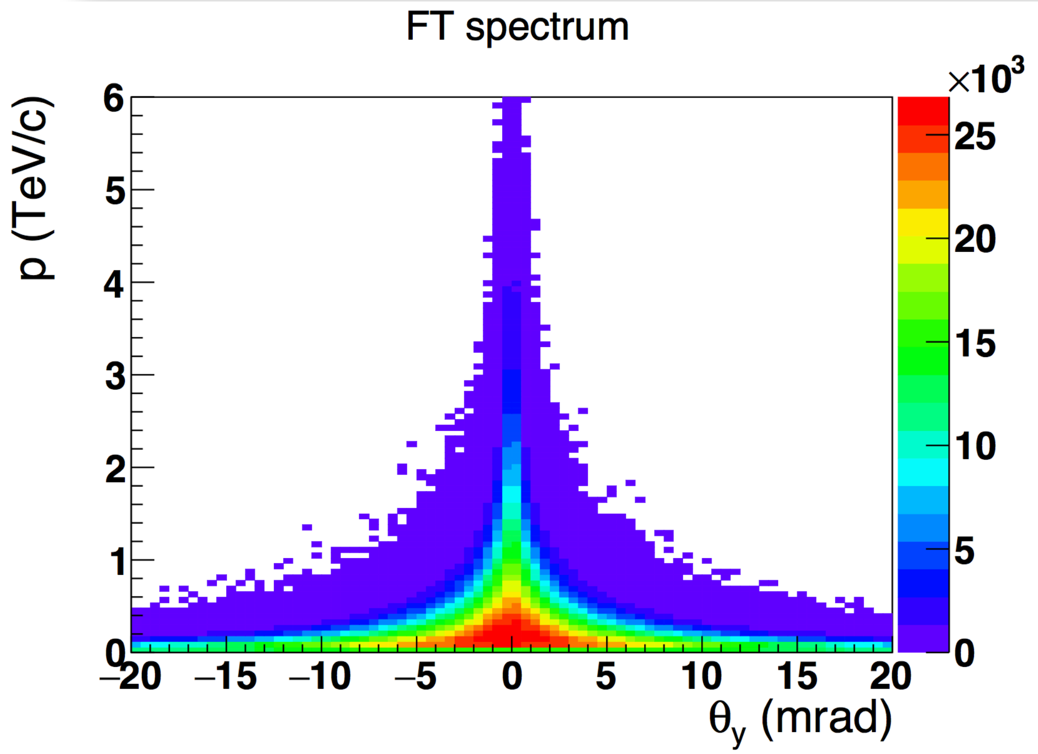
- About 10^{-4} Λ_c^+ produced in the target are channeled in the bent crystal



$d \sim 200 \mu m$

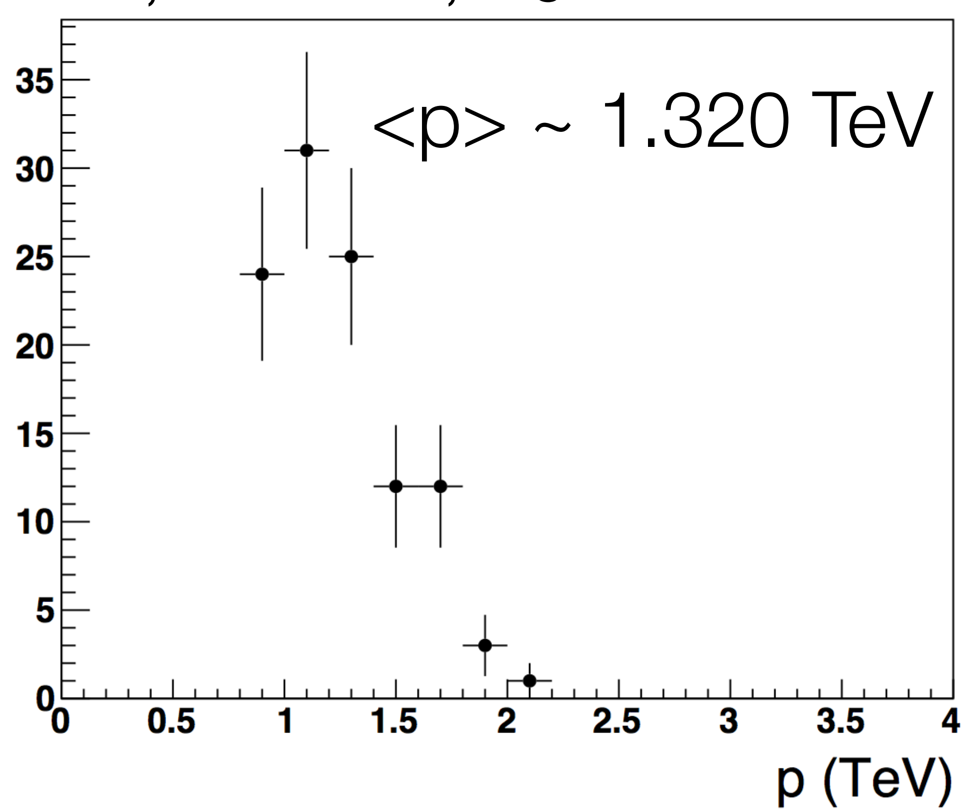
- Use PV to identify Λ_c^+ produced in W target, and Λ_c^+ vertex helps to identify decays outside of the crystal (max spin precession)
- Λ_c^+ angle determined by crystal bending angle, e.g. θ_C=15 mrad
- Channeled baryons have high momentum ≳1 TeV/c

Λ_c^+ momentum distribution

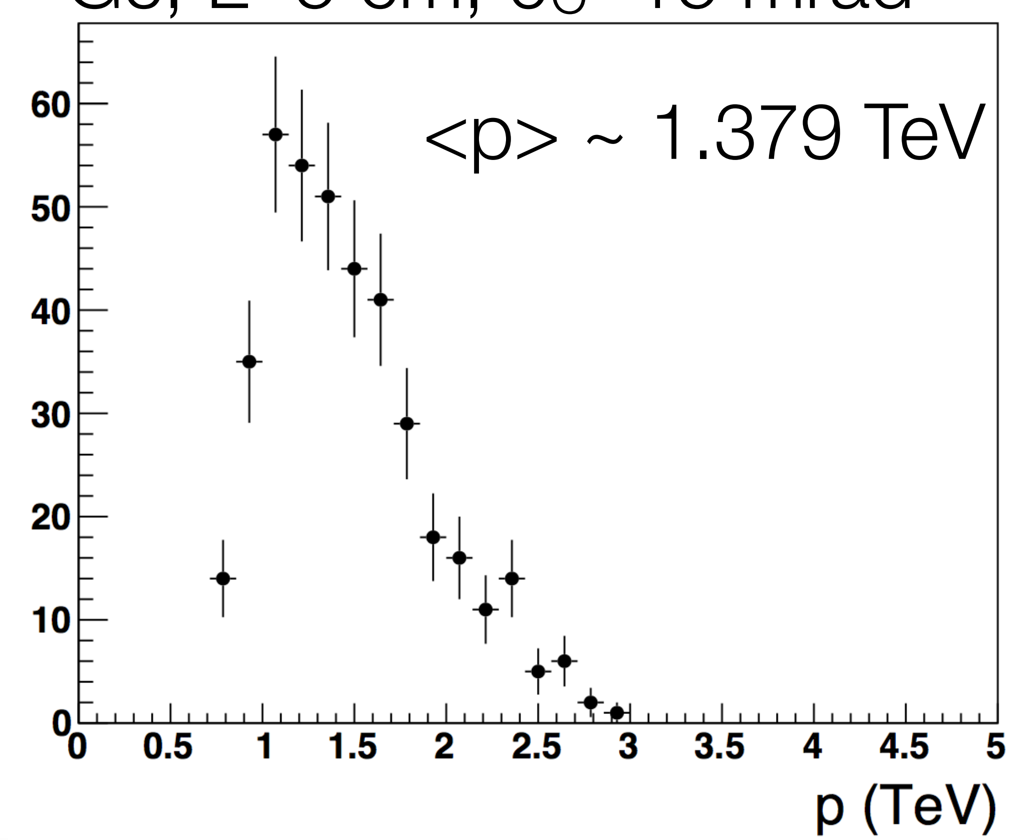


- At production (top)
- After channeling and p>800 GeV/c (bottom)

Si, L~7 cm, θ_C~14 mrad

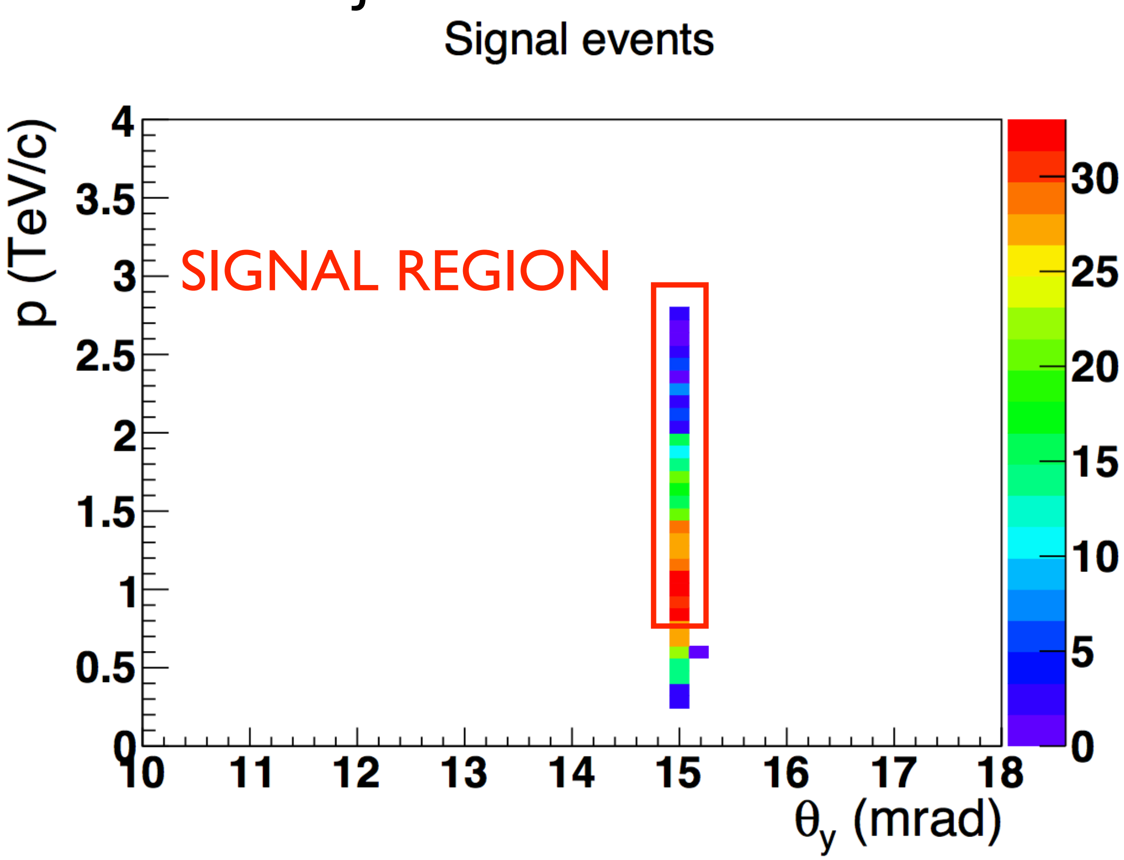


Ge, L~5 cm, θ_C~15 mrad

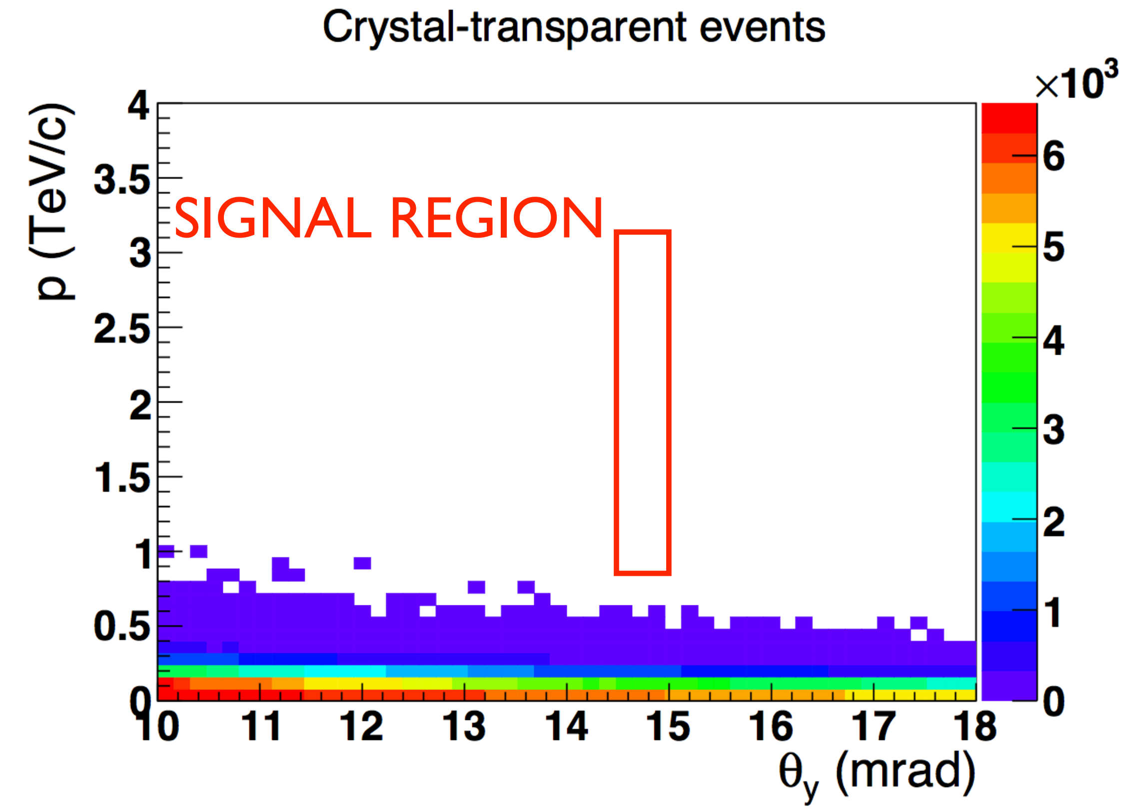


Background rejection

- Rejection of unchanneled Λ_c^+ produced in W target



Channeled particles



Unchanneled particles

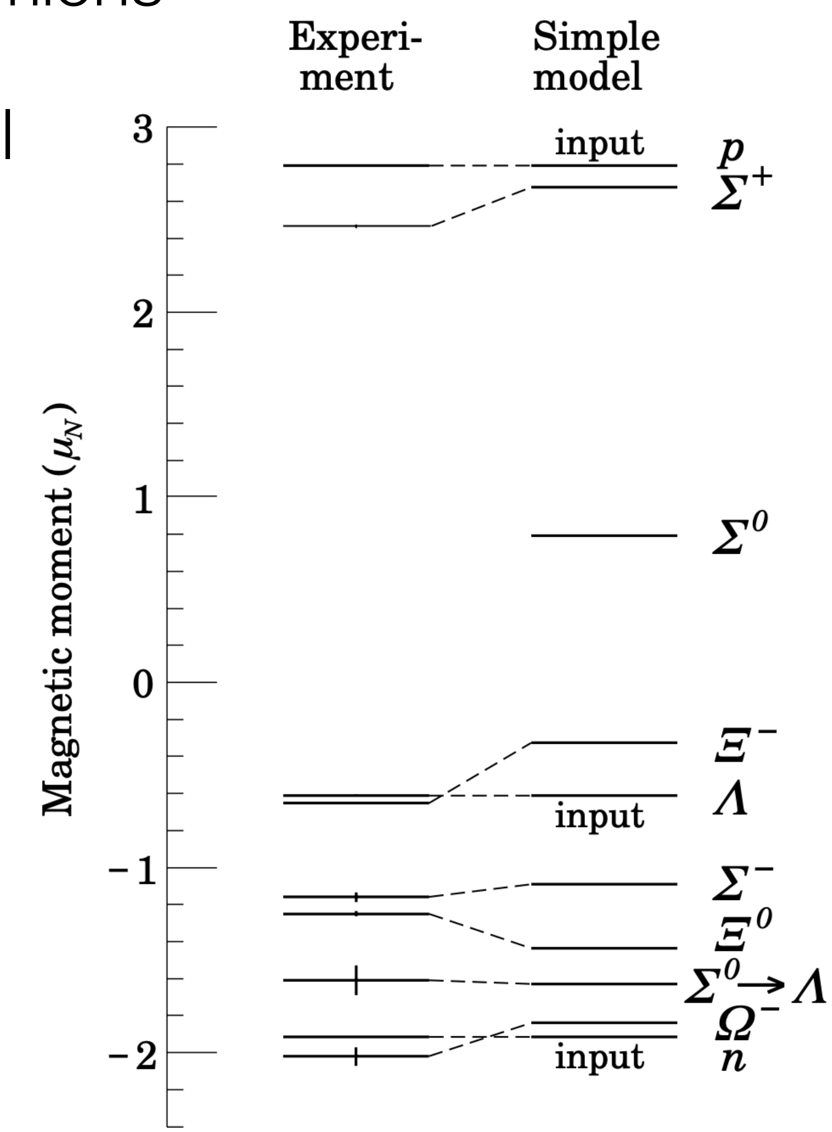
- Signal region: $14.8 < \theta < 15.2$ mrad [$\sigma(\theta) \sim 25 \mu$rad], $p_{\Lambda c} > 800$ GeV/c
- Background rejection 10^{-7} level and signal efficiency 80%
- High momentum Λ_c^+ most sensitive for EDM measurements

EDM/MDM sensitivity studies

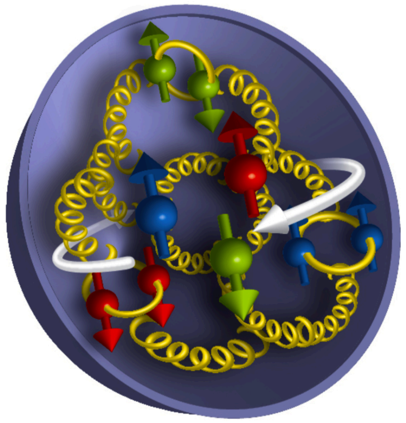
Intrinsic MDM of baryons

- $g \neq 2$ due to internal substructure, not point-like fermions
- From baryon MDM to quark MDM using quark model

$$\mu_p = (4\mu_u - \mu_d)/3 \qquad \mu_n = (4\mu_d - \mu_u)/3$$
$$\mu_{\Sigma^+} = (4\mu_u - \mu_s)/3 \qquad \mu_{\Sigma^-} = (4\mu_d - \mu_s)/3$$
$$\mu_{\Xi^0} = (4\mu_s - \mu_u)/3 \qquad \mu_{\Xi^-} = (4\mu_s - \mu_d)/3$$
$$\mu_\Lambda = \mu_s \qquad \mu_{\Sigma^0} = (2\mu_u + 2\mu_d - \mu_s)/3$$
$$\mu_{\Omega^-} = 3\mu_s$$



$$\mu_q = \frac{Q_q \hbar}{2m_q}$$ quark MDM



- Precise measurement of p MDM

$\mu_p = 2.79284734462\ (82)\ \mu_N$

G. Schneider et al., Science **358**, 1081 (2017)

- Test of *CPT* symmetry with $\bar{p}$ MDM

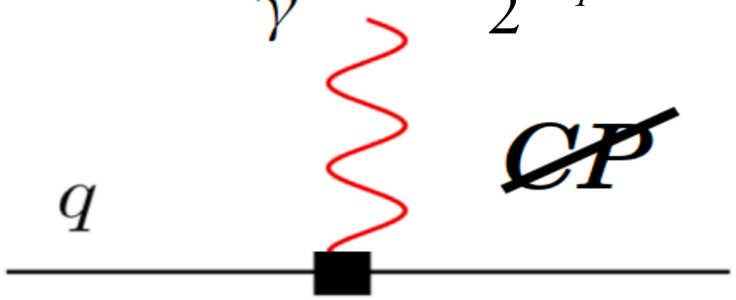
$\mu_{\bar{p}} = -2.7928473441(42)\mu_N$

C. Smorra et al., *Nature* 550 (2017) 7676, 371-374

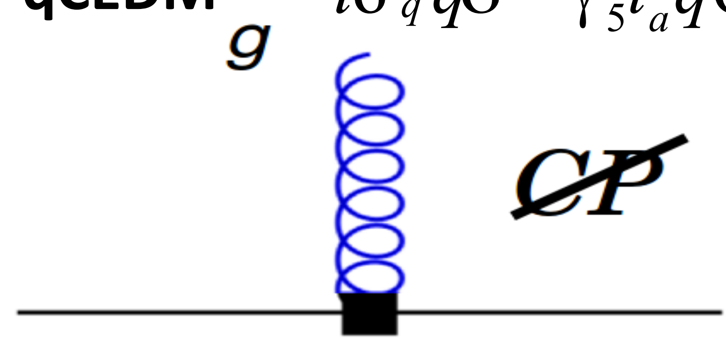
Heavy baryon EDM

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

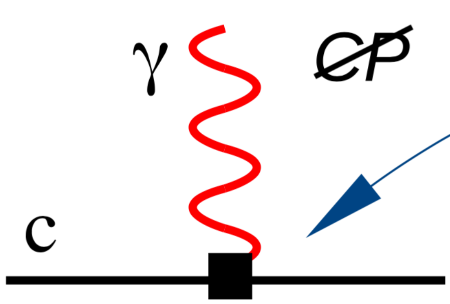


Charm EDM in SM-CKM ~10^{-32} *e* cm

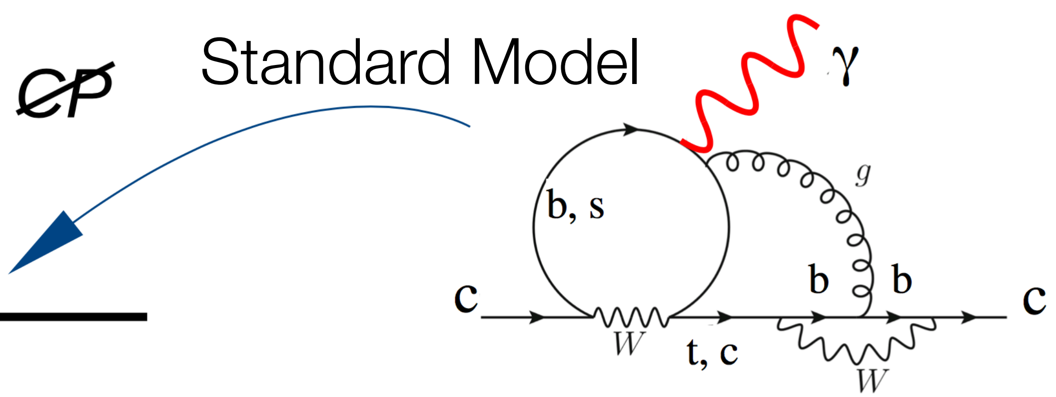
Khriplovich, Lamoreaux (1997)

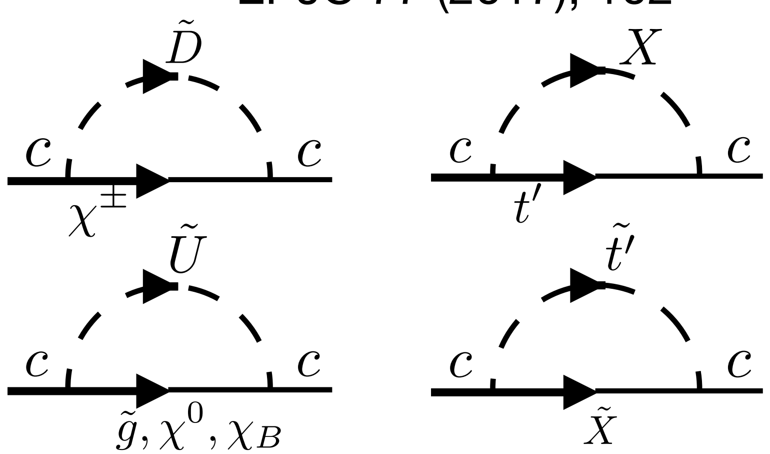
Charm EDM with new physics ~$5\cdot10^{-17}$ *e* cm

EPJC 77 (2017), 102



Standard Model





Heavy baryon EDM observation = clear signature of **new physics**

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)

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

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

$$|S_0| \approx 0.6$$

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

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

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

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

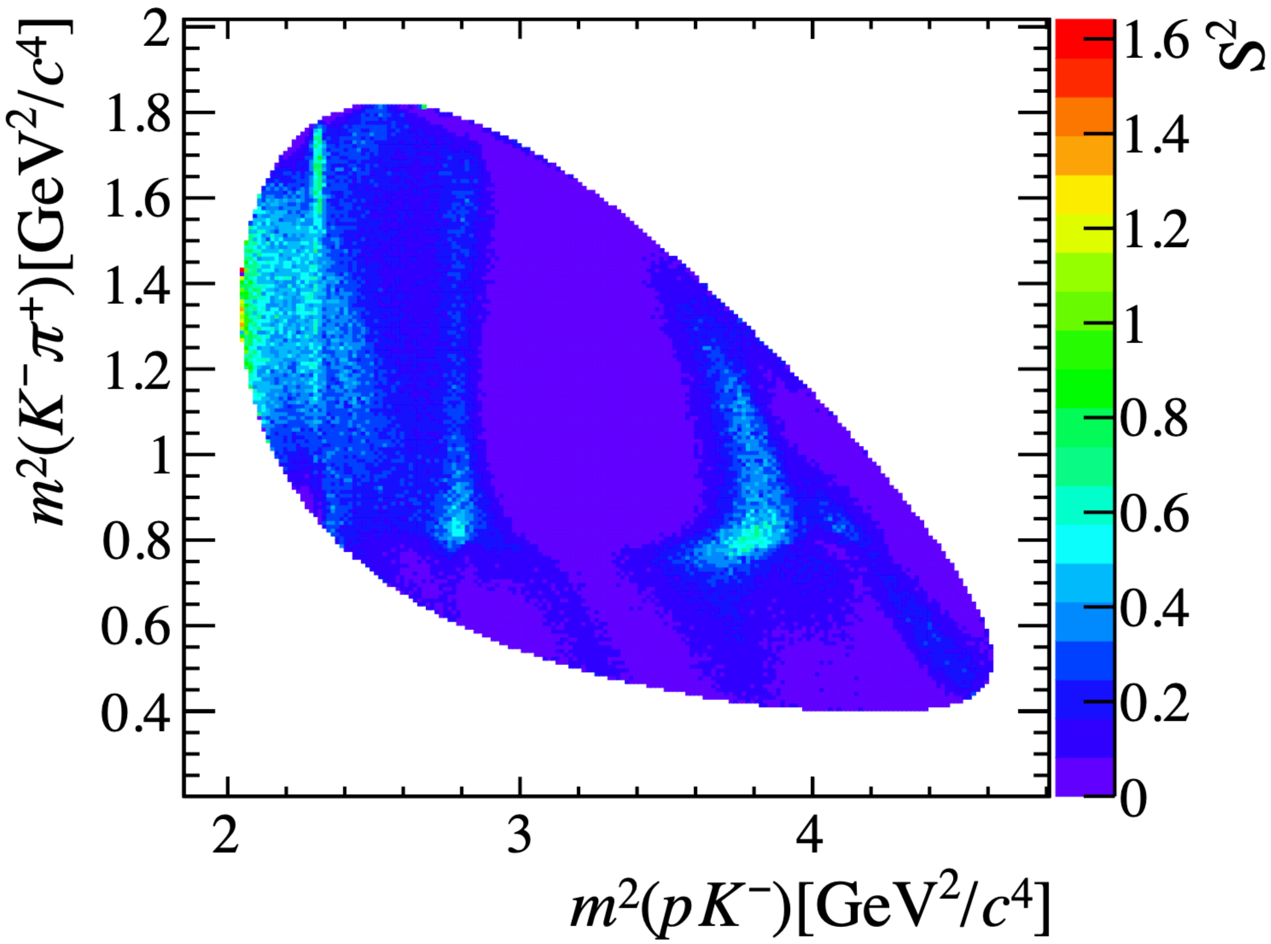
$$\sigma_d \approx \frac{g-2}{\alpha_f s_0 (\cos\Phi - 1)} \frac{1}{\sqrt{N_{\Lambda_c^+}^{\text{reco}}}}$$

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

MDM/EDM via full amplitude analysis

- High statistics LHCb *pp* data sample to study Λ_c^+, Ξ_c^+ decays
- Extract maximum information via full amplitude analysis of the 3-body decays   D. Marangotto, AHEP (2020) 7463073

PRD 103, 072003 (2021)



Decay distribution

$$W(\boldsymbol{\xi}\,|\,s) = f(\boldsymbol{\xi}) + s g(\boldsymbol{\xi})$$

$\boldsymbol{\xi}$ = phase space variable

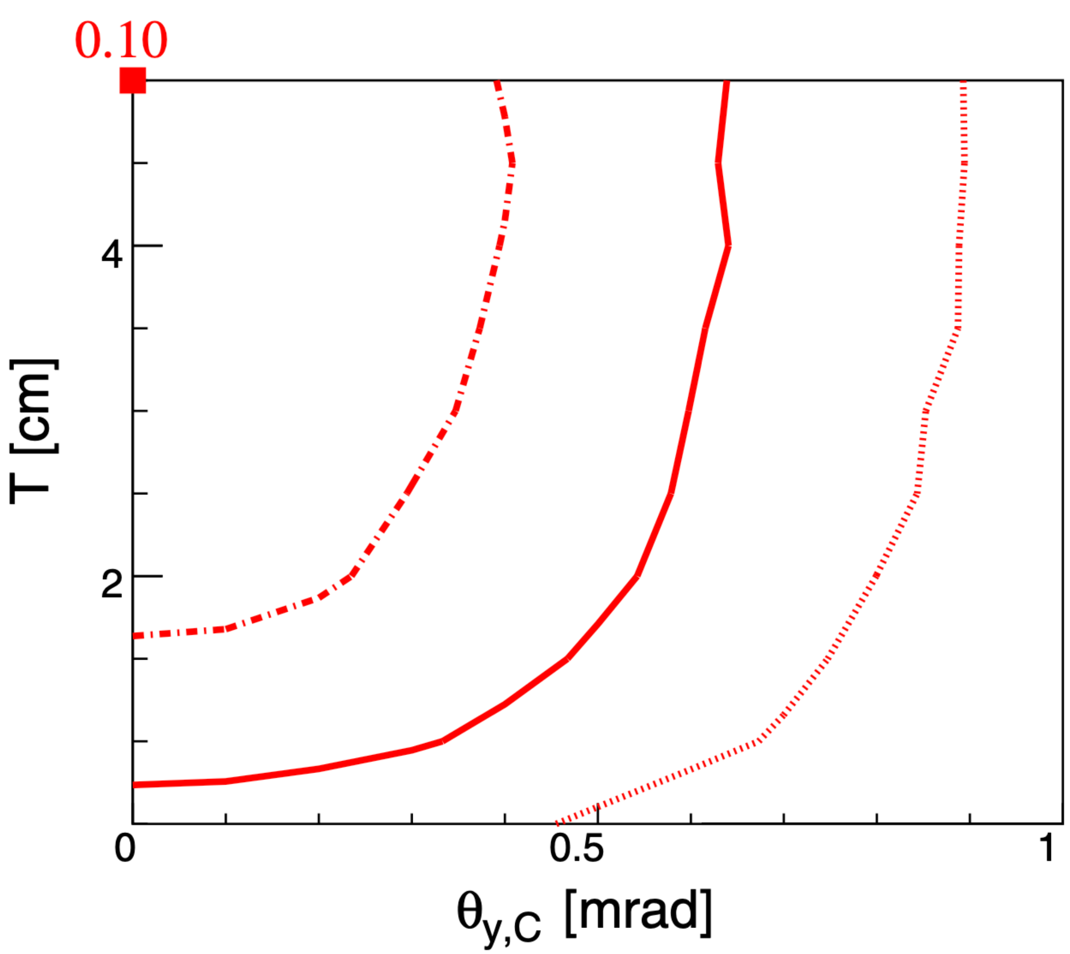
s=spin polarisation

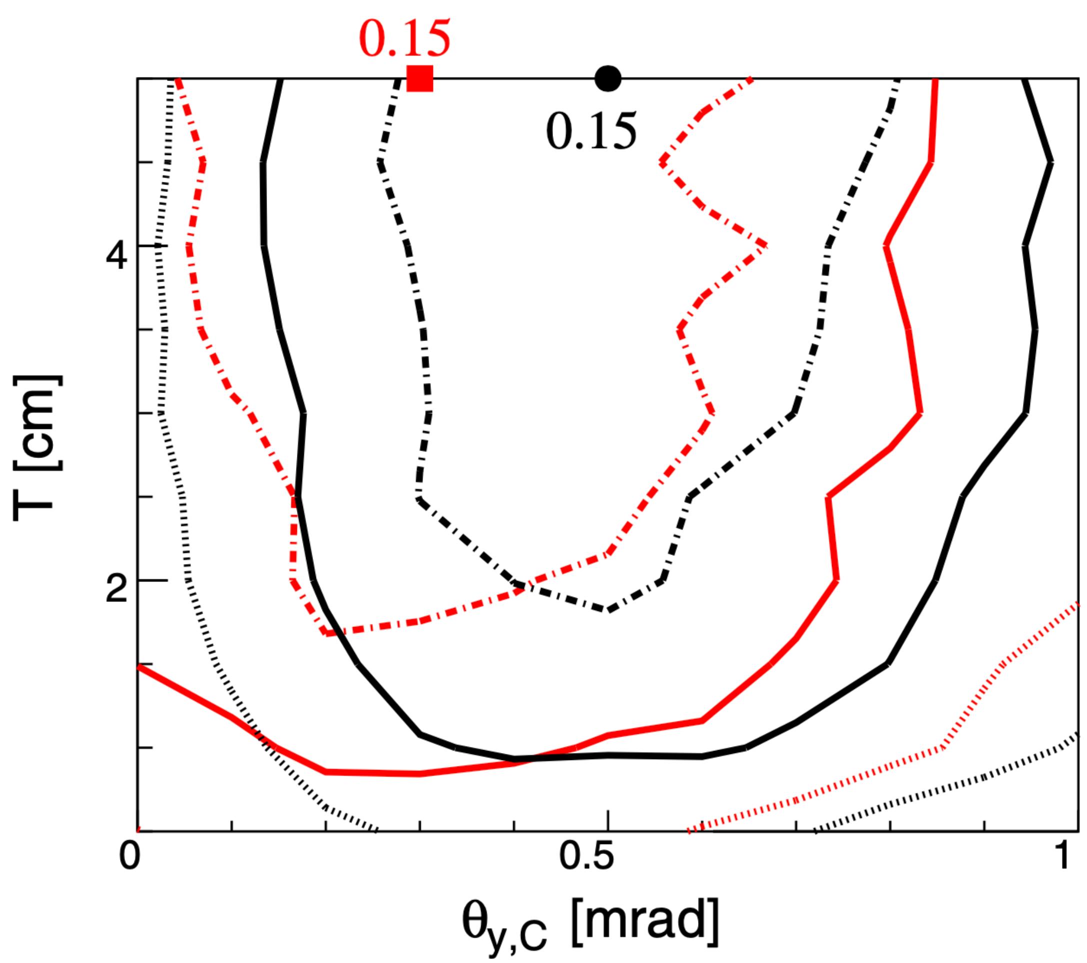
Sensitivity: average event information

$$S^2 = \int \frac{g^2(\boldsymbol{\xi})}{f(\boldsymbol{\xi}) + s_0 g(\boldsymbol{\xi})} d\boldsymbol{\xi}$$

Crystal optimisation

- Optimised sensitivity to **MDM** and **EDM** for Ge crystal. Channeling and reconstruction efficiency included





Regions of minimal uncertainty of **EDM** (black circle) and **MDM** (red square) defined as +20%, +50%, 100% uncertainty with respect to the minimum (point markers)

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 $D_s^+(\to\tau^+\upsilon_\tau)$

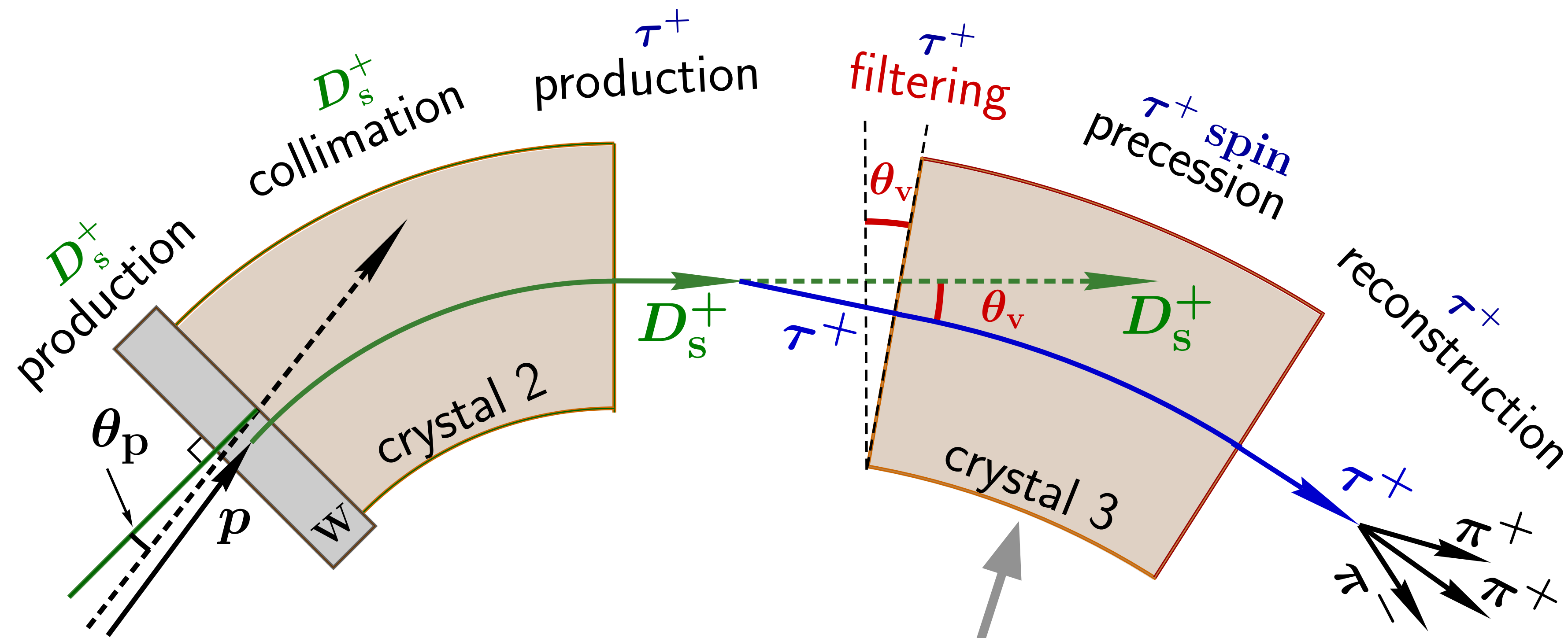
$$\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$$

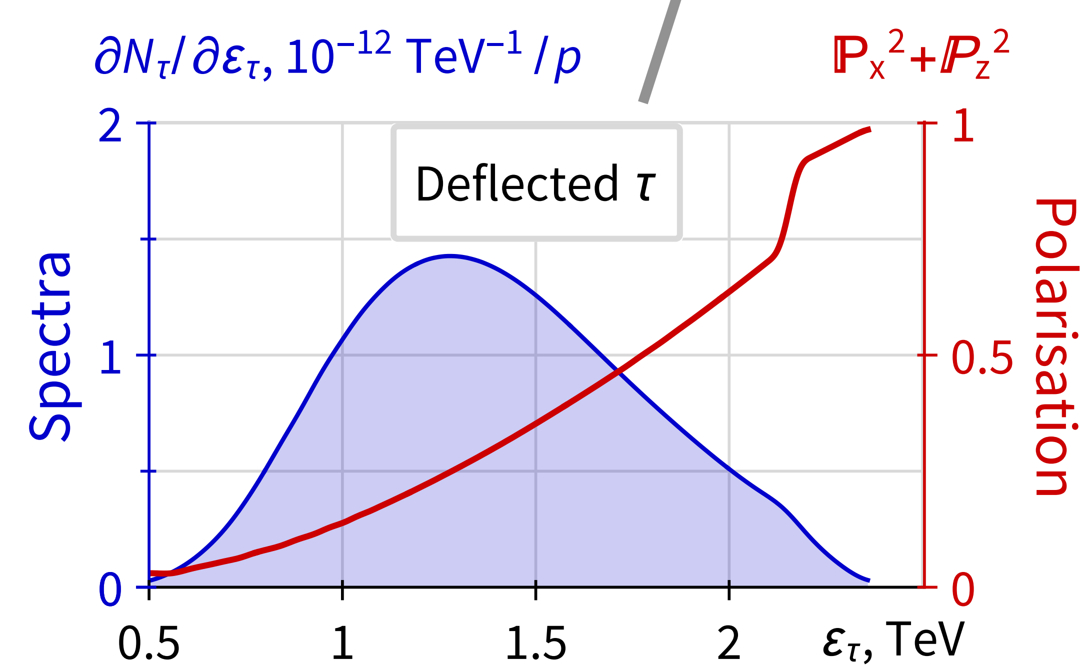
Crystal 2:

- deflection and "collimation" of D_s^+

Crystal 3:

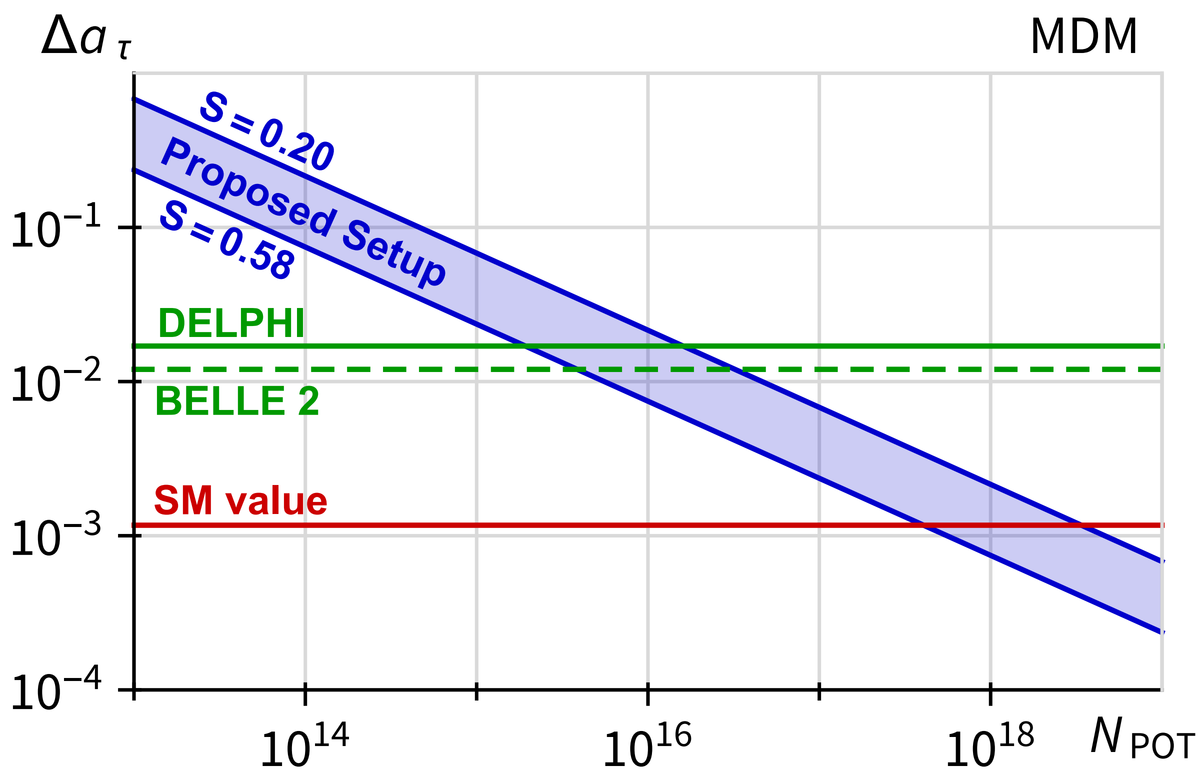
- selecting τ produced by D_s^+
- filtering τ initial polarisation
- τ spin precession

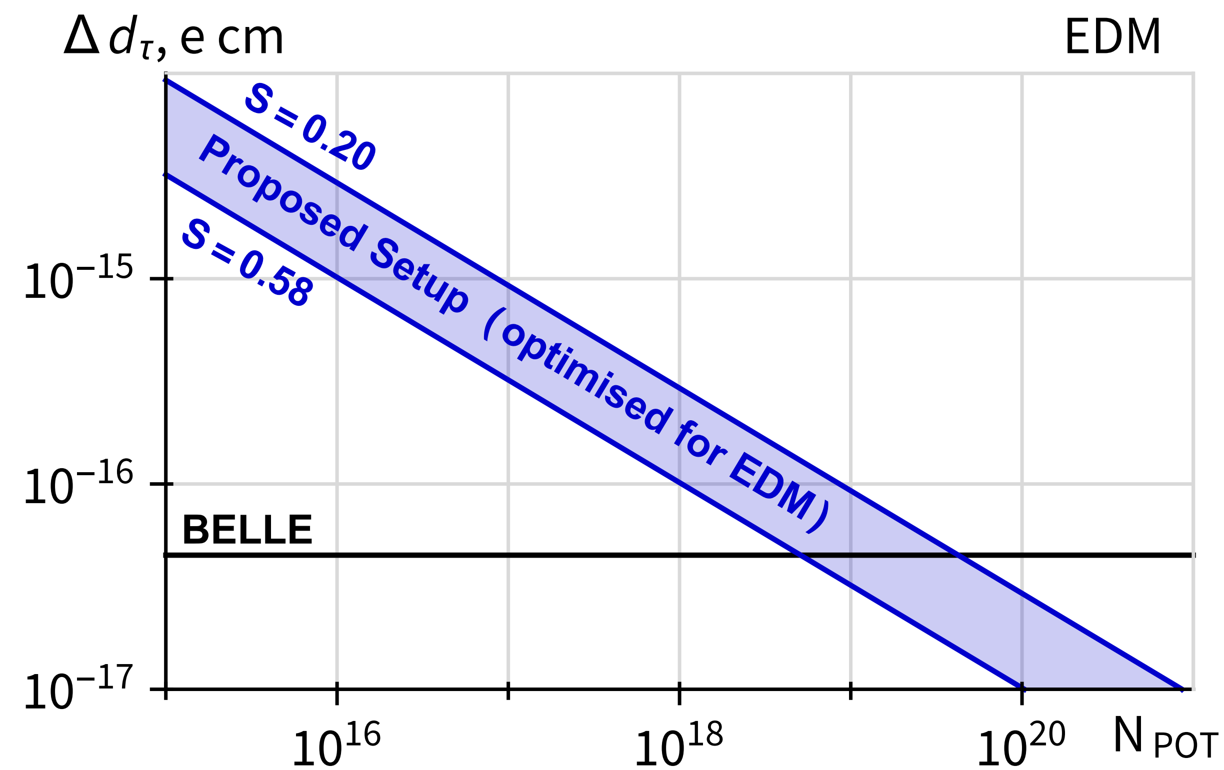




A. Fomin, A. Korchin, A. Stocchi, S. Barsuk, P. Robbe, JHEP (2019) 2019: 156, IC Channeling 2018.

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.