Direct measurement of short-lived particle dipole moments at the LHC

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erc

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Acknowledgements

▸ **DIPOLE-b** team: S. Aiola, E. Bagli, L. Bandiera, G. Cavoto, N. Conti, F. De Benedetti, D. De Salvador, J.Fu, M.A. Giorgi, V. Guidi, L. Henry, D. Marangotto, F. Martinez Vidal, V. Mascagna, A. Mazzolari, A. Merli, N. Neri, M. Prest, J. Ruiz Vidal, E. Spadaro Norella, G. Tonani, E. Vallazza

▸ **Contributions** also from: G. Arduini, S. Barsuk, O.A. Bezshyyko, L. Burmistrov,, A.S. Fomin, S.P. Fomin, F. Galluccio, M. Garattini, P. Hermes, 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
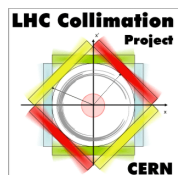
Outline

▸ Introduction

▸ Experimental method for Λ_c^+, Ξ_c^+ baryons

   - R&D and preparatory studies

▸ Proposals for the τ lepton

▸ Summary

In backup slides, not discussed in this talk

   - Experimental method for Λ baryons

Electromagnetic dipole moments

Dipole moments are static properties of particles, not measured yet for short-lived **charm**, **beauty** baryons, and **τ** lepton

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

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

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

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

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
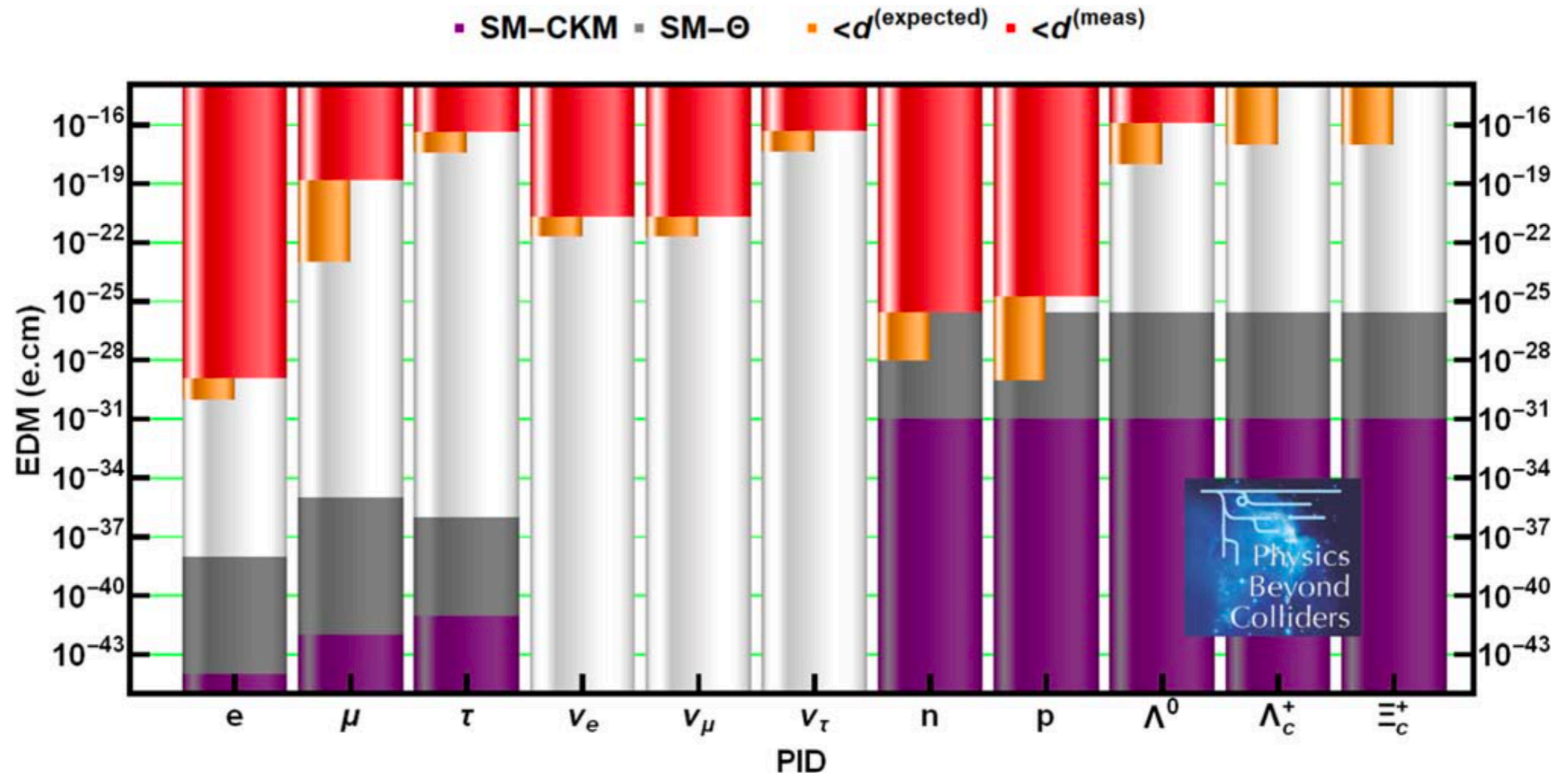
MDM theoretical predictions

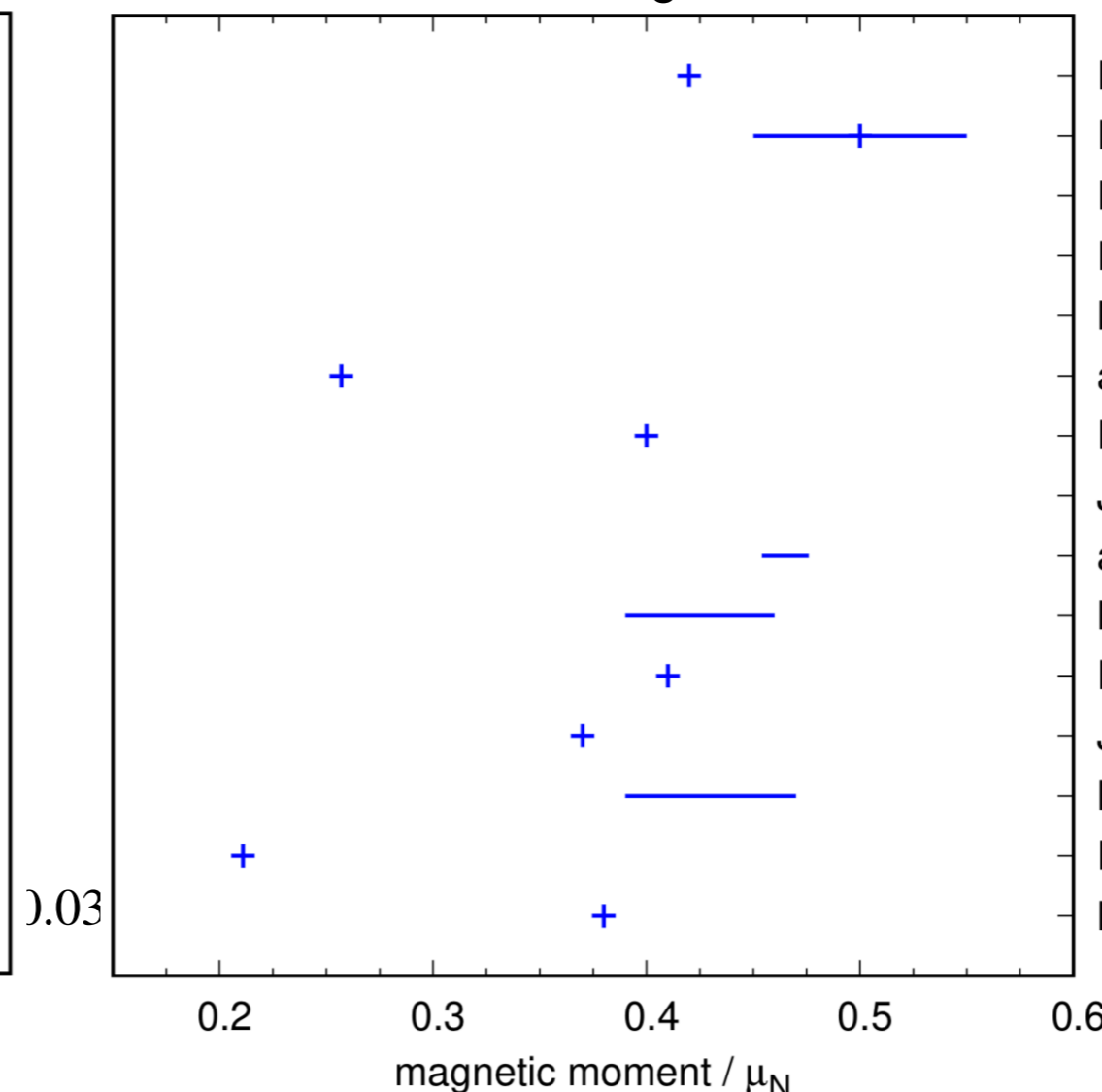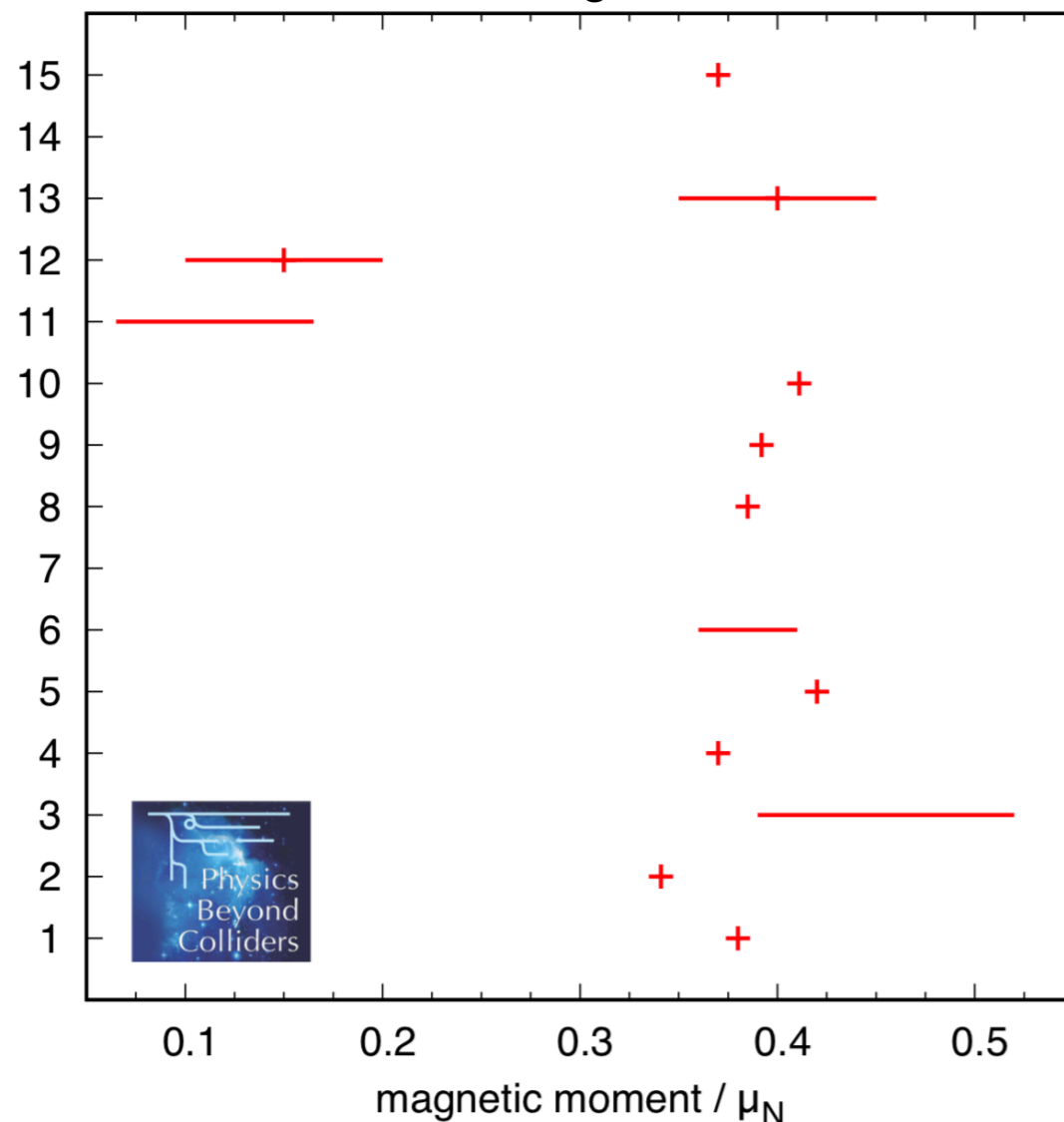For τ **lepton** : SM prediction $(g_\tau-2)/2 = 117721(5)\times10^{-8}$

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

Λ_c^+ Ξ_c^+

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

Transversal potential

a)

Channeled
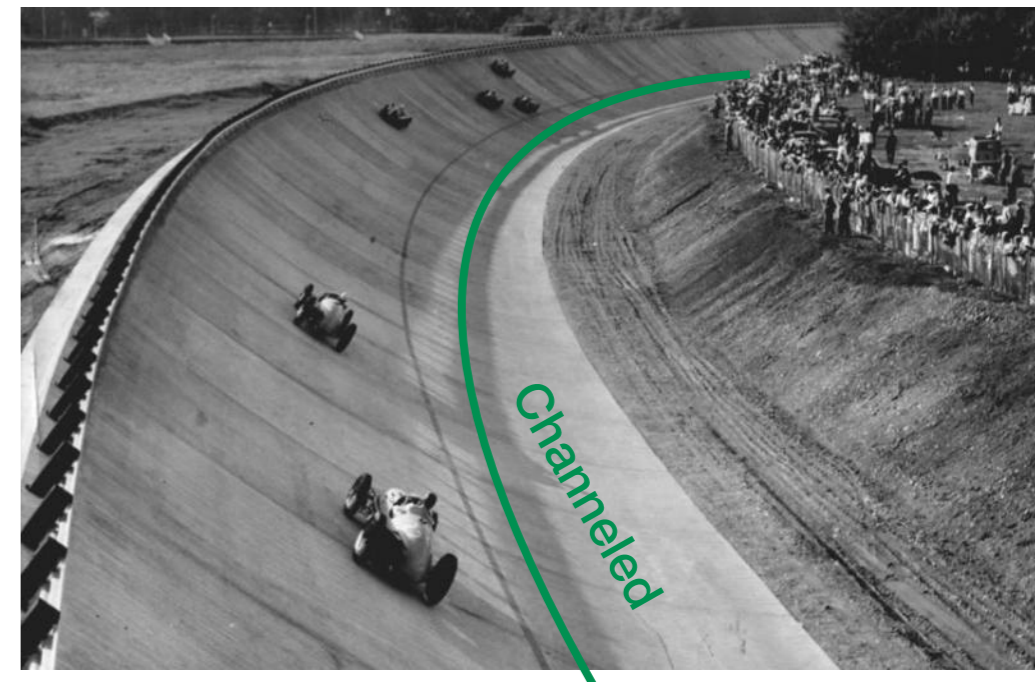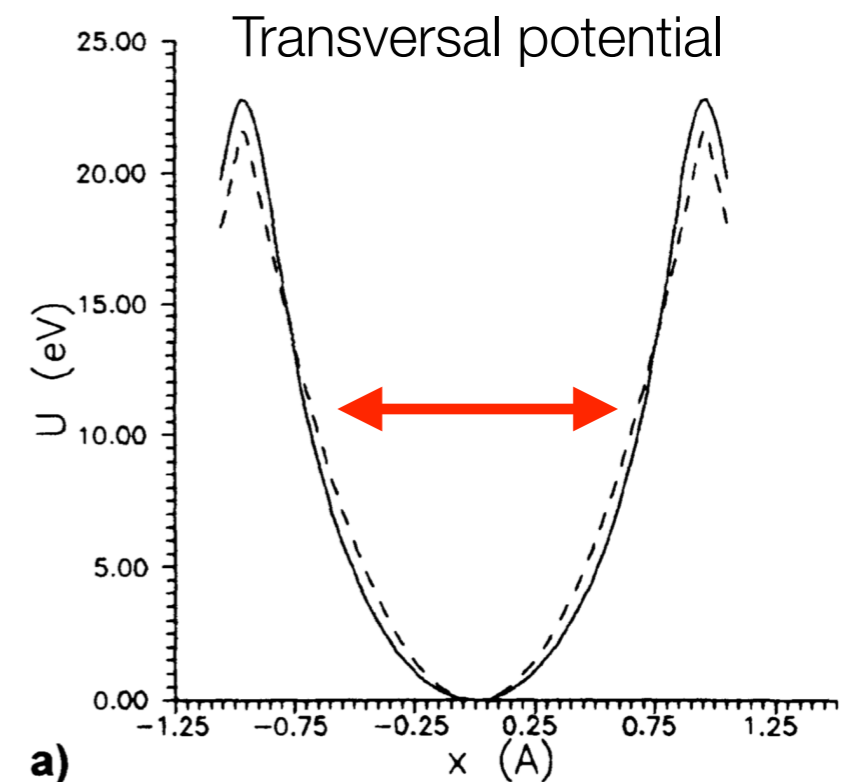
Spin precession in bent crystals

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

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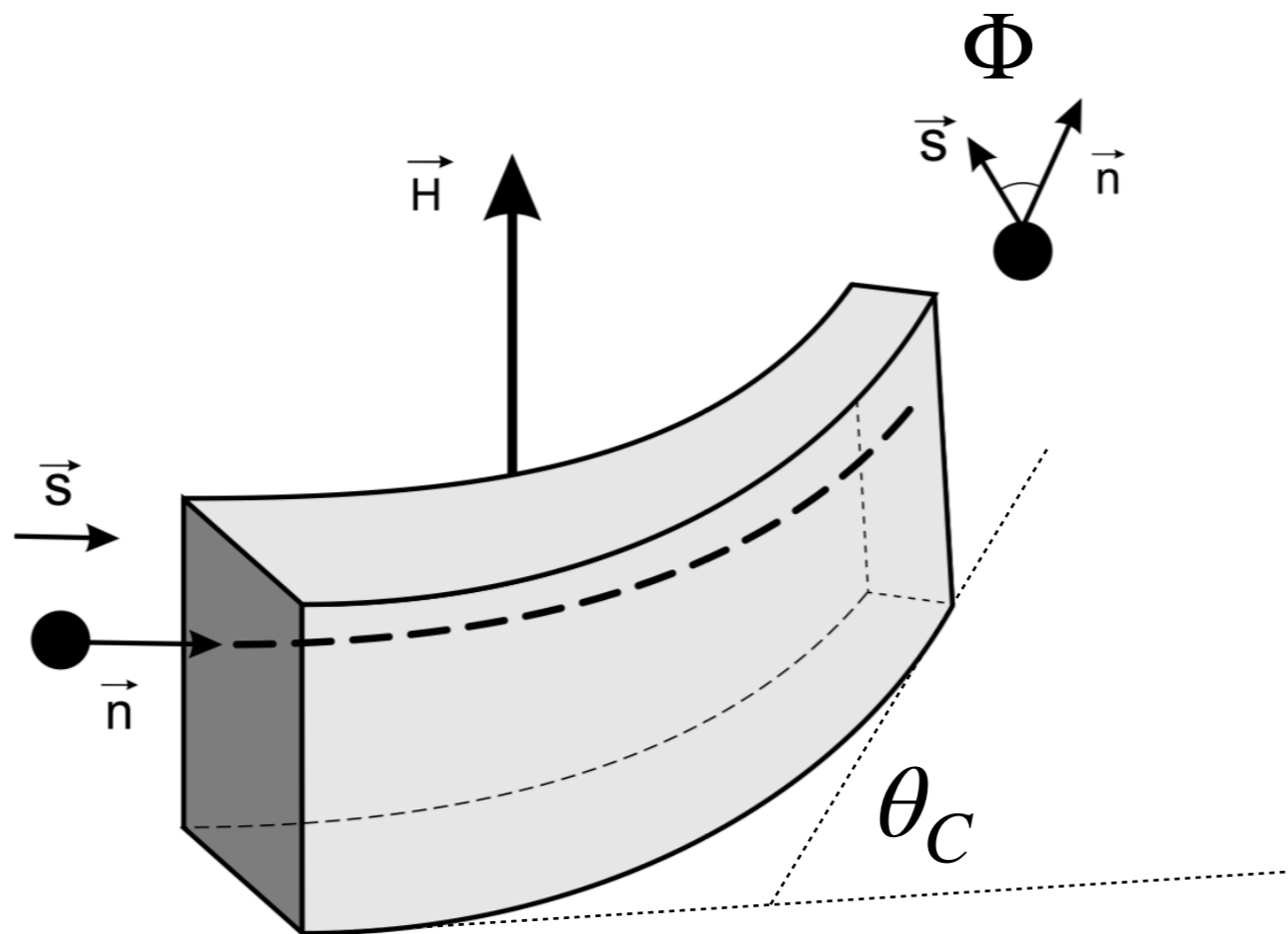

Fig. 1. Spin rotation in a bent crystal.

▸ 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

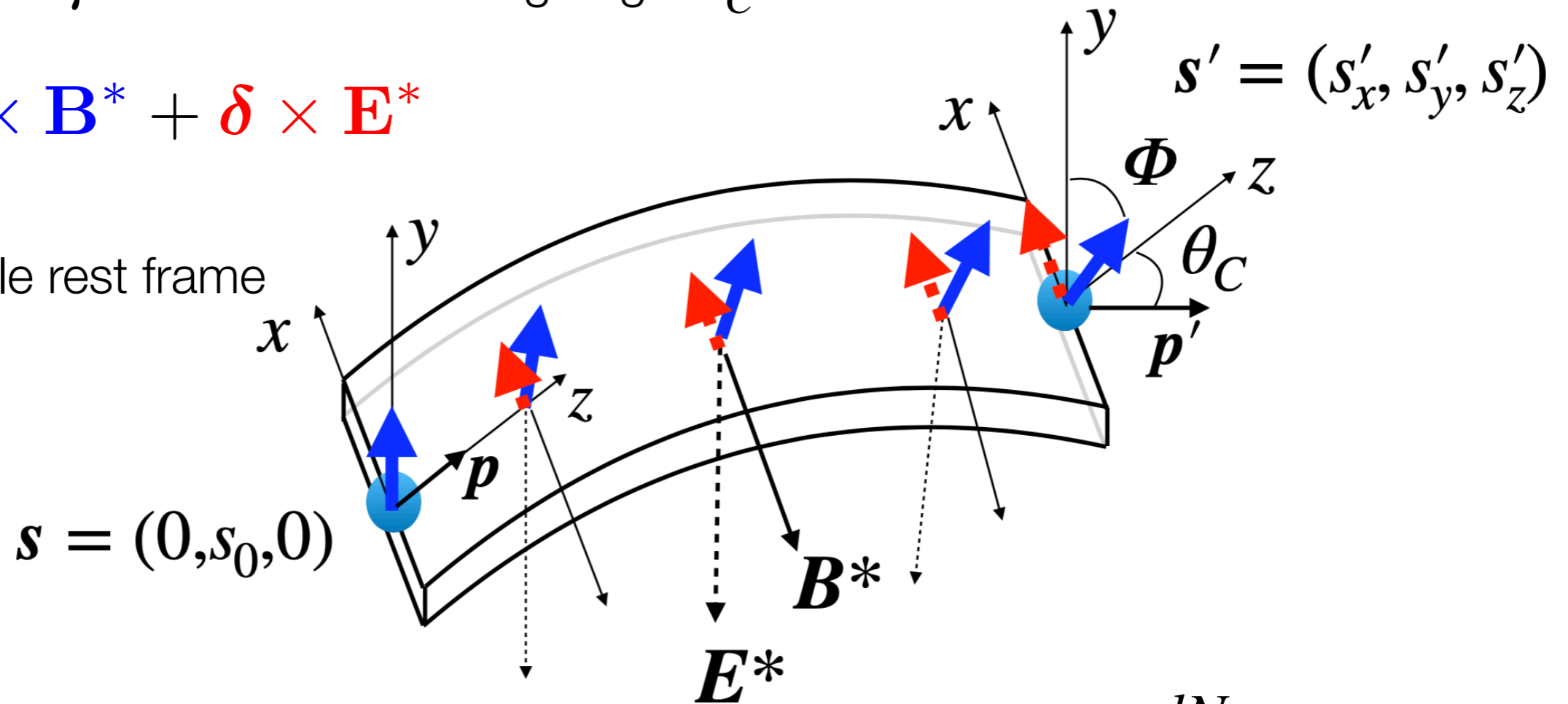▸ Experimental proof by E761 Fermilab experiment with **Σ+** hyperon

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

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

- Spin precession angle $\Phi \simeq \dfrac{g-2}{2}\gamma\theta_C$ 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

$$s' = (s'_x, s'_y, s'_z)$$

$$s = (0, s_0, 0)$$

$$\boldsymbol{B}^*$$

$$\boldsymbol{E}^*$$

- Sensitivity to MDM and EDM via spin-polarisation analyser $\dfrac{dN}{d\Omega'} \propto 1 + \alpha s' \cdot \hat{k}$
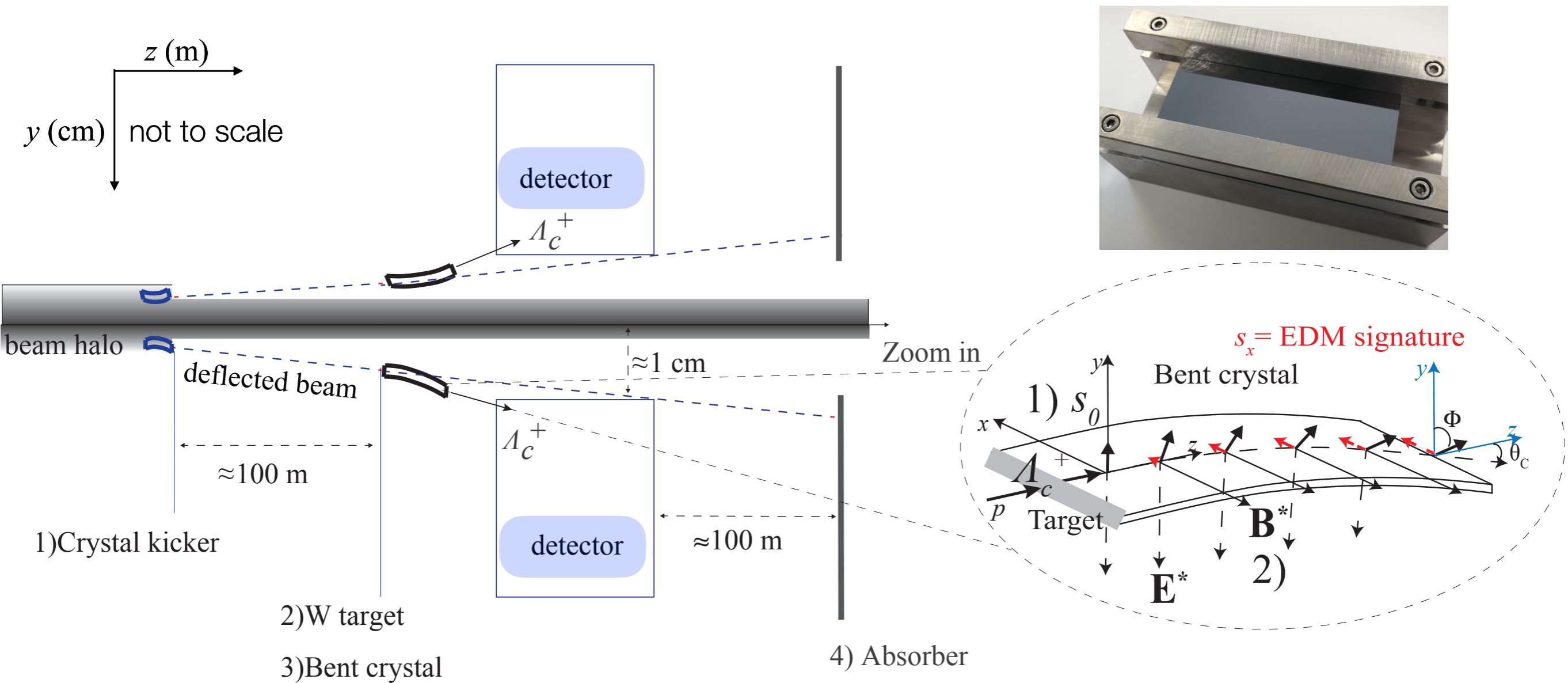
$$\Phi \approx \frac{g-2}{2}\gamma\theta_C$$

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

EPJC (2017) 77:181

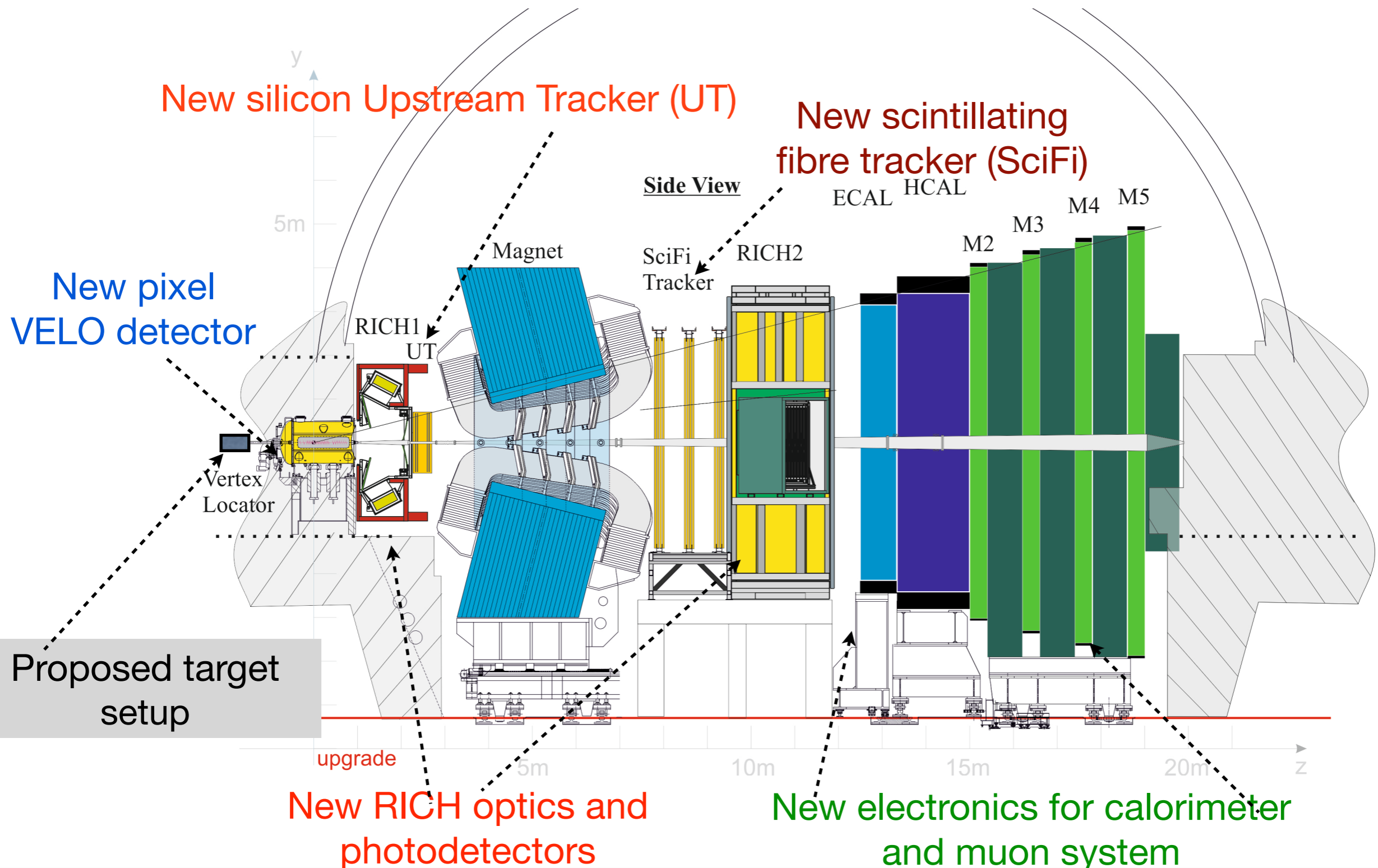# **Novel** fixed-target experiment at LHC for charm baryons

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

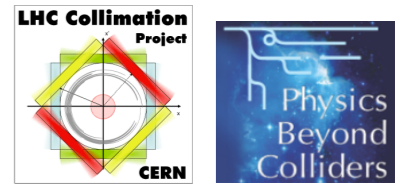p extraction Λ_c^+ polarised production channeling spin precession event reconstruction

Fixed-target setup upstream of LHCb

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

New silicon Upstream Tracker (UT)

New scintillating fibre tracker (SciFi)

New pixel VELO detector

Proposed target setup

New RICH optics and photodetectors

New electronics for calorimeter and muon system
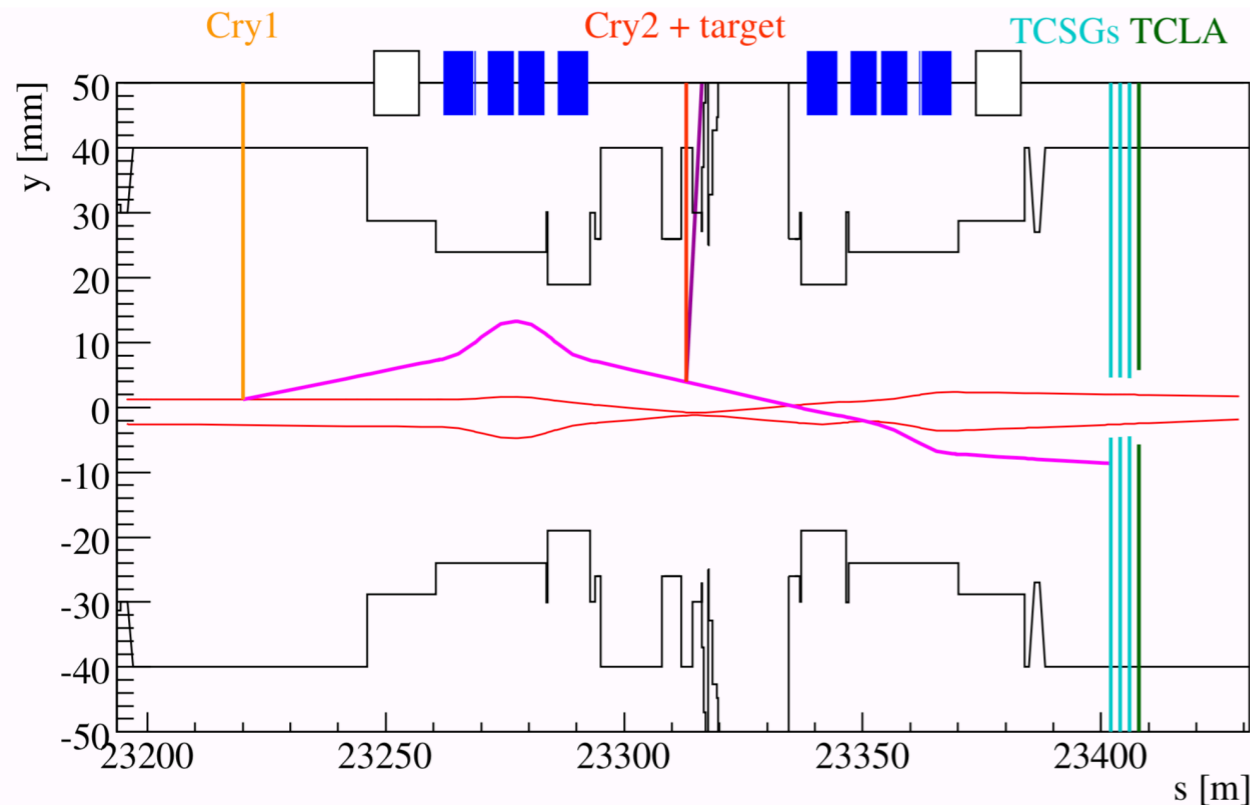
R&D and preparatory studies
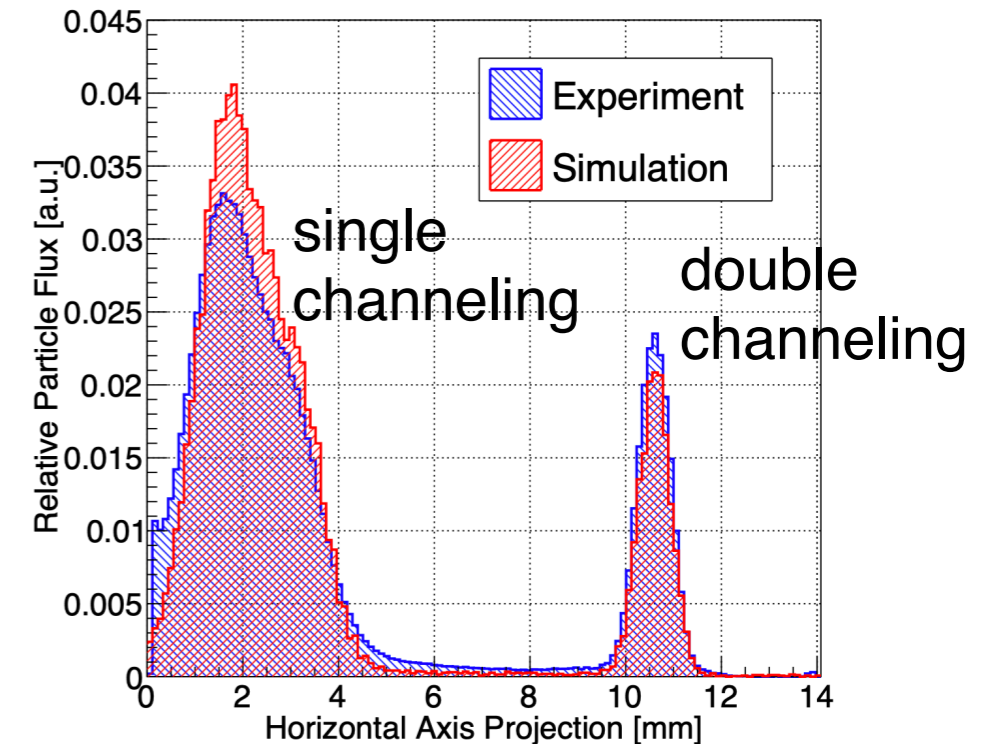
LHC (SPS) machine studies

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

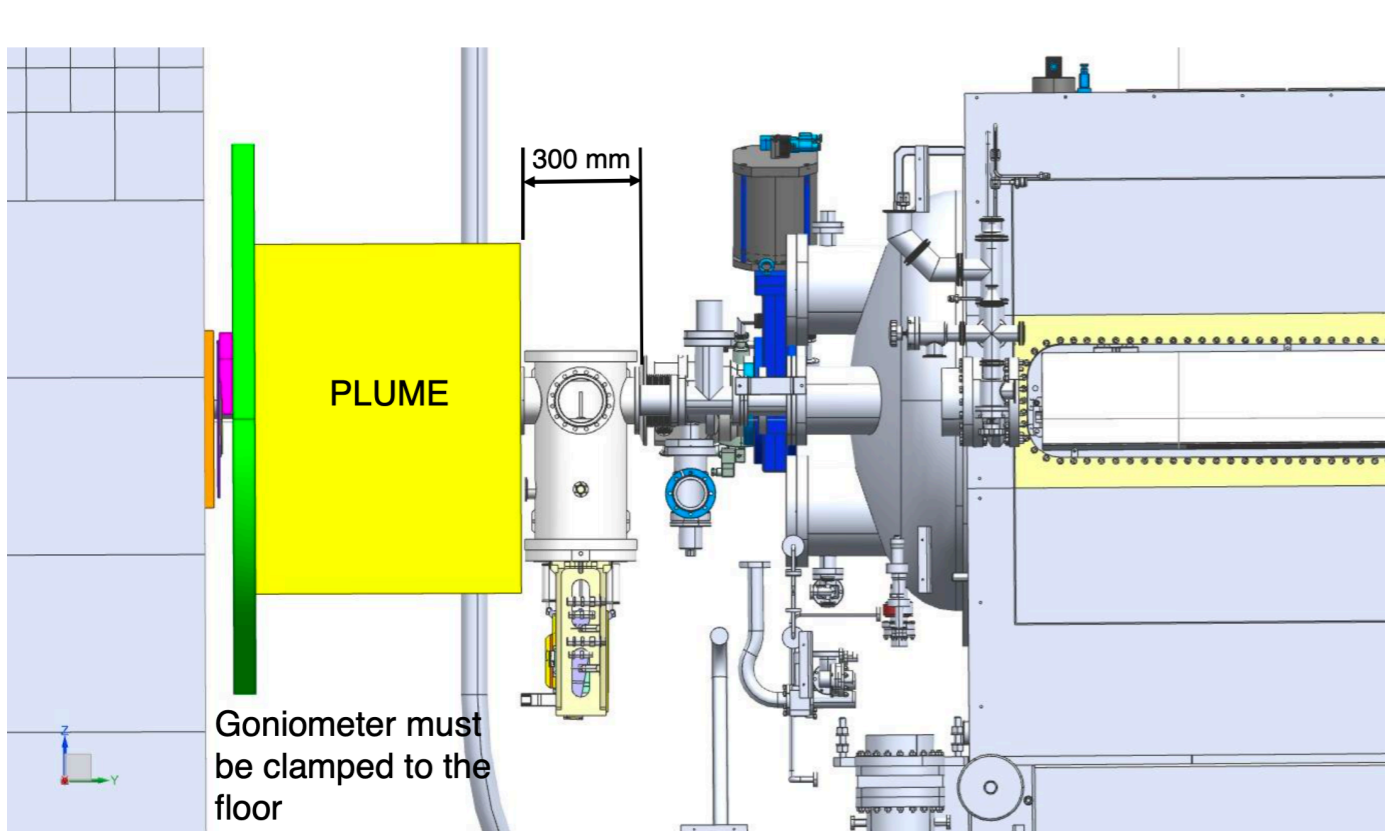- **Layout test** at SPS ✔. Test in **LHC** planned, possibly during Run3

Double channeling test in LHC

▸ Install crystals at IR3 during Run3

- possibility to use existing dipole magnet with

  BL= 1.9Tm or 4.8 Tm as spectrometer
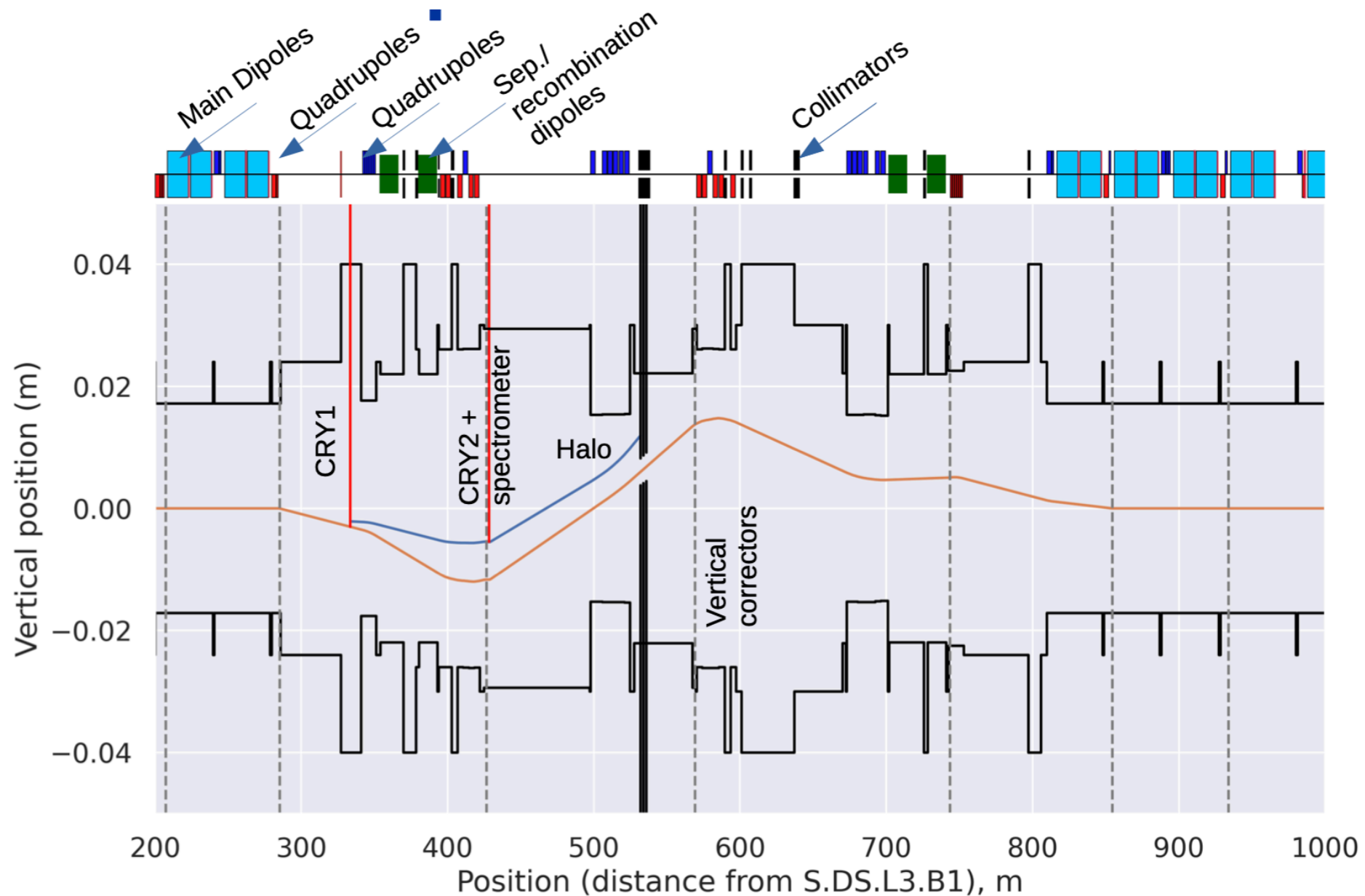
Fixed-target setup and crystal goniometer

300 mm

PLUME

Goniometer must be clamped to the floor

▸ 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

Guides for extraction
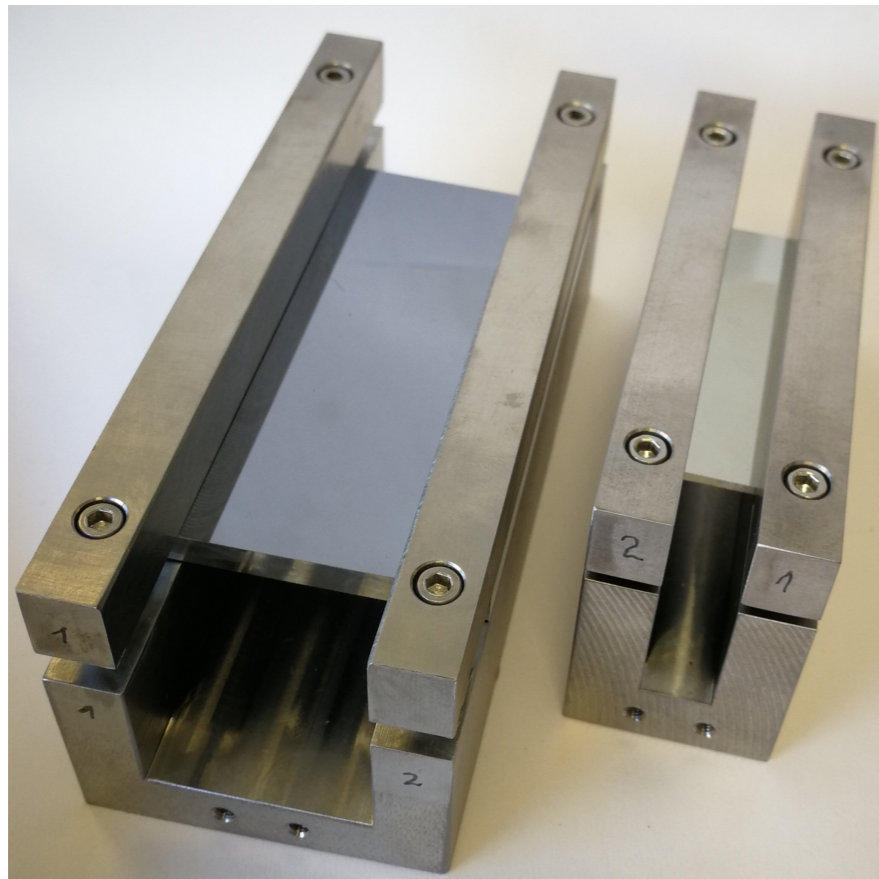
Crystal holder

Rotation mechanism
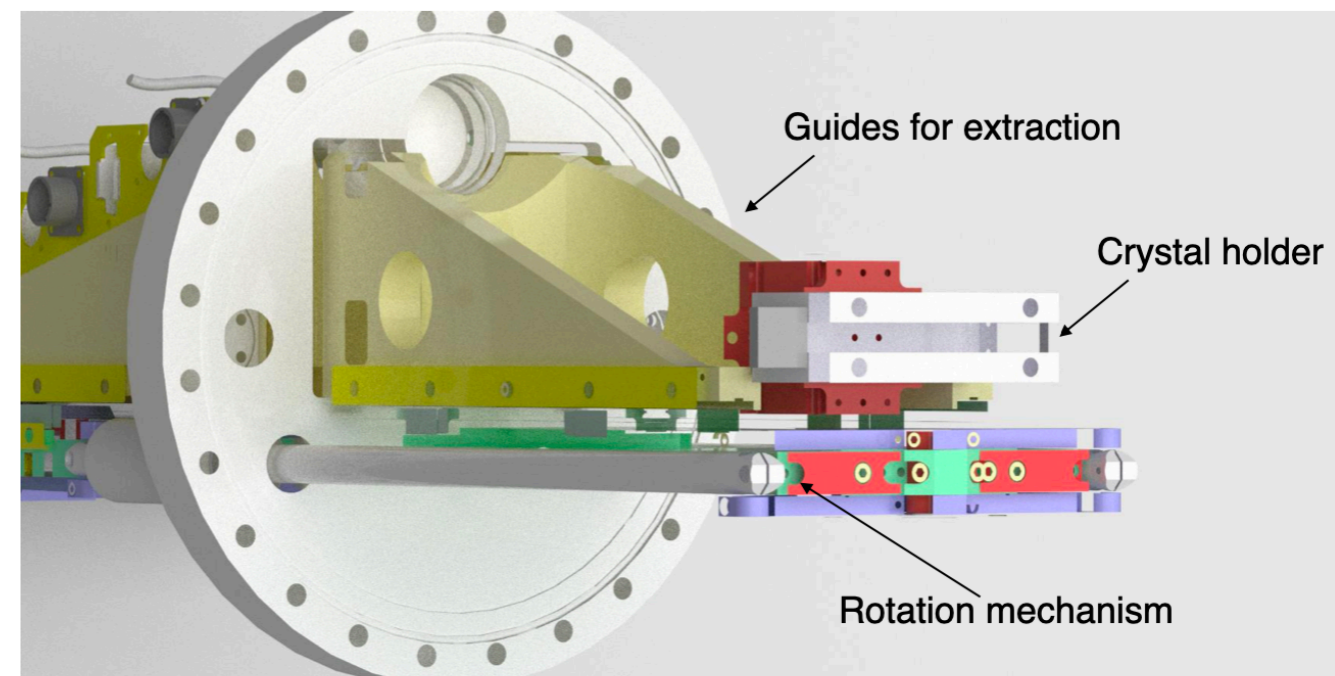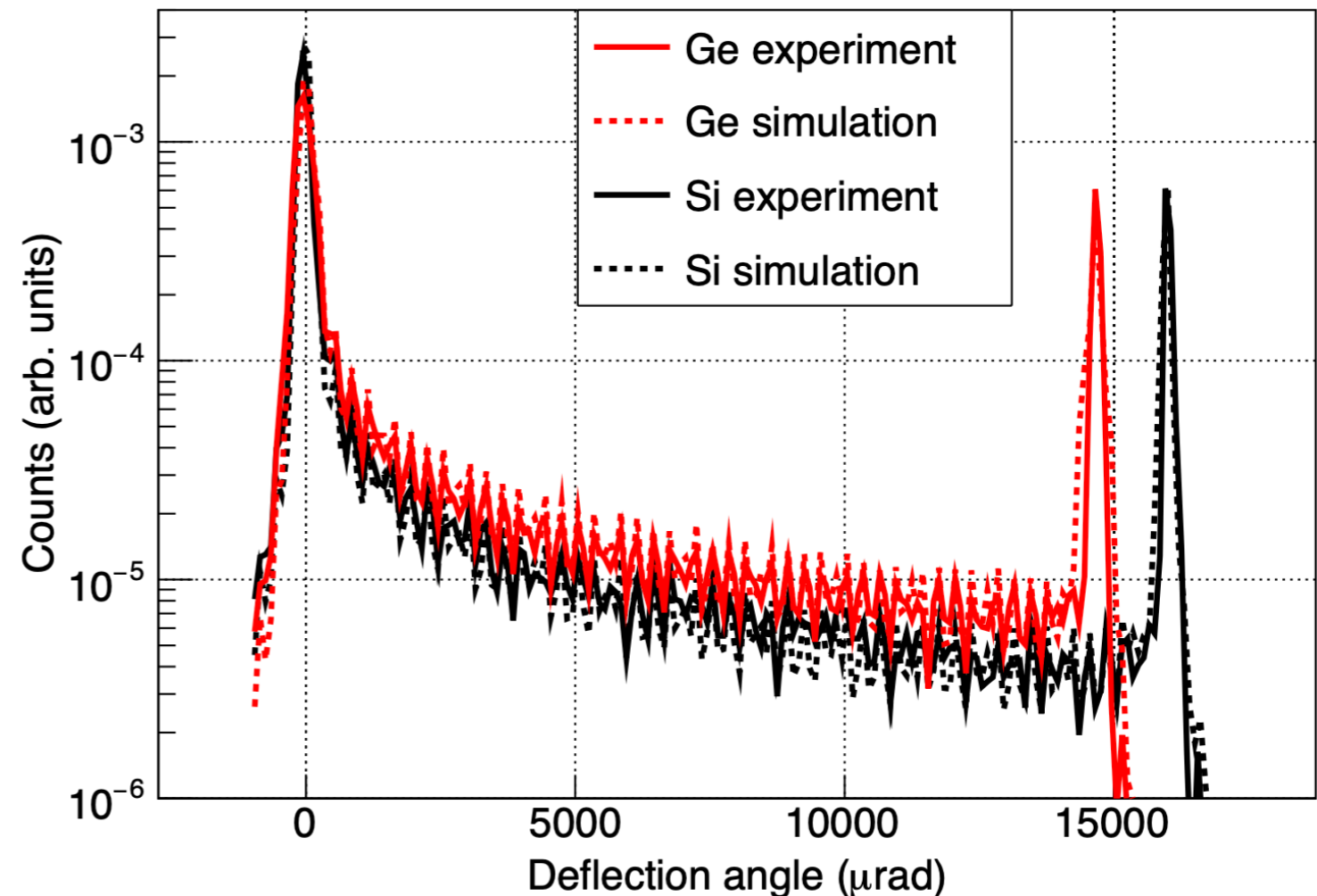
Long bent crystal prototypes

Si: 8 cm long, bent @16.0 mrad

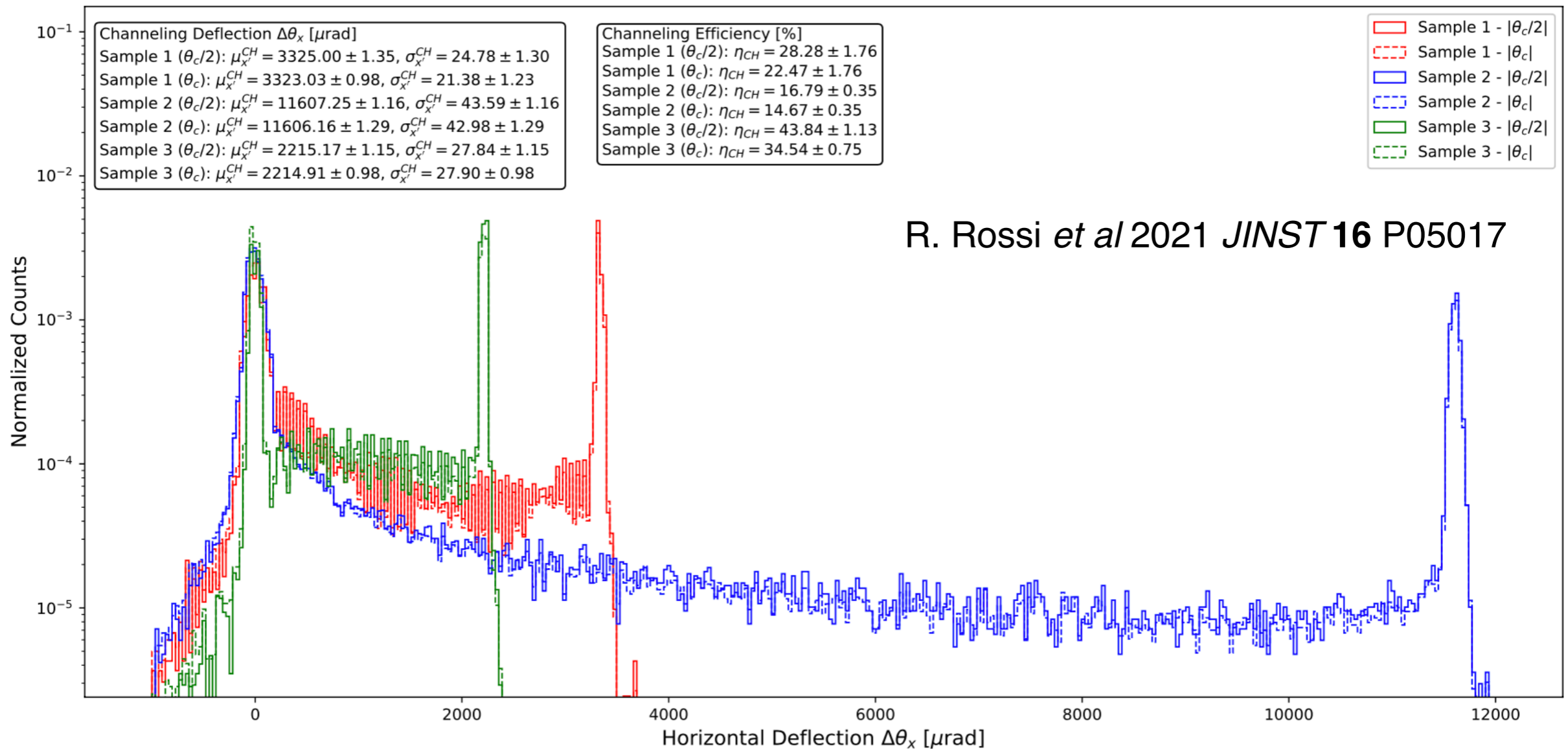**Ge**: 5 cm long, bent @14.5 mrad

PRD 103, 072003 (2021)

Courtesy of A. Mazzolari

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

Long bent crystal prototypes

Channeling Deflection $\Delta\theta_x$ [μrad]
Sample 1 ($\theta_c/2$): $\mu_{x'}^{CH} = 3325.00 \pm 1.35$, $\sigma_{x'}^{CH} = 24.78 \pm 1.30$
Sample 1 (θ_c): $\mu_{x'}^{CH} = 3323.03 \pm 0.98$, $\sigma_{x'}^{CH} = 21.38 \pm 1.23$
Sample 2 ($\theta_c/2$): $\mu_{x'}^{CH} = 11607.25 \pm 1.16$, $\sigma_{x'}^{CH} = 43.59 \pm 1.16$
Sample 2 (θ_c): $\mu_{x'}^{CH} = 11606.16 \pm 1.29$, $\sigma_{x'}^{CH} = 42.98 \pm 1.29$
Sample 3 ($\theta_c/2$): $\mu_{x'}^{CH} = 2215.17 \pm 1.15$, $\sigma_{x'}^{CH} = 27.84 \pm 1.15$
Sample 3 (θ_c): $\mu_{x'}^{CH} = 2214.91 \pm 0.98$, $\sigma_{x'}^{CH} = 27.90 \pm 0.98$

Channeling Efficiency [%]
Sample 1 ($\theta_c/2$): $\eta_{CH} = 28.28 \pm 1.76$
Sample 1 (θ_c): $\eta_{CH} = 22.47 \pm 1.76$
Sample 2 ($\theta_c/2$): $\eta_{CH} = 16.79 \pm 0.35$
Sample 2 (θ_c): $\eta_{CH} = 14.67 \pm 0.35$
Sample 3 ($\theta_c/2$): $\eta_{CH} = 43.84 \pm 1.13$
Sample 3 (θ_c): $\eta_{CH} = 34.54 \pm 0.75$

R. Rossi *et al* 2021 *JINST* **16** P05017

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

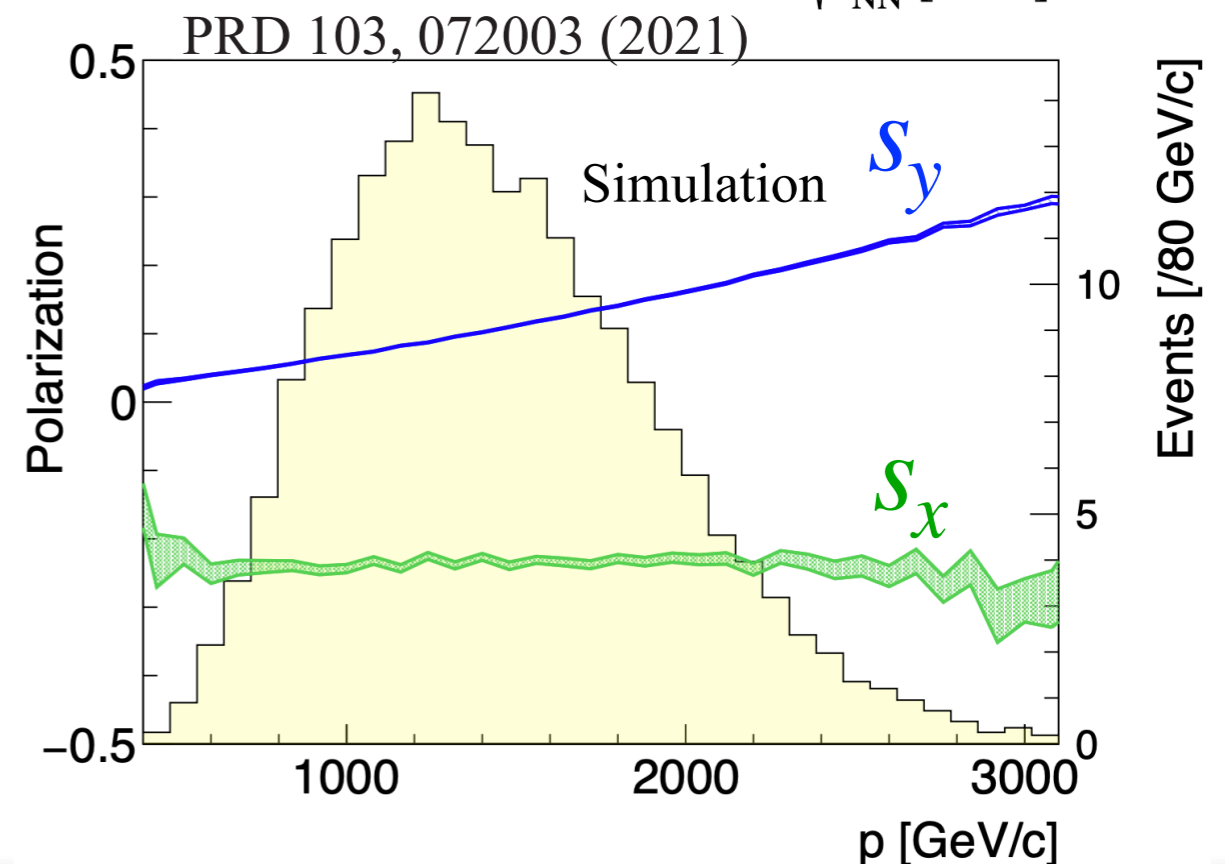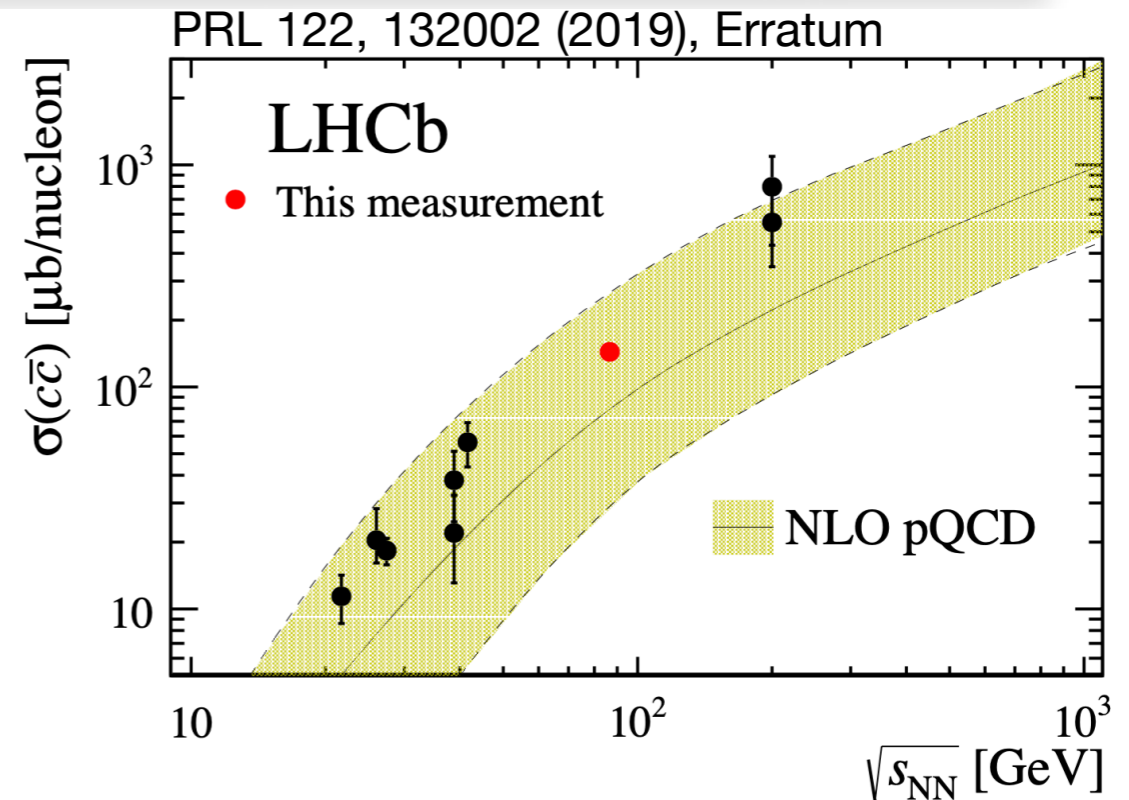| Length (cm)	bending (mrad)	chan. eff. (%)
8.0	11.6	14.7
8.0	3.3	22.5
2.5	2.2	34.5

Production of Λ_c^+ baryons

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

Expected Λ_c^+ **cross-section** at $\sqrt{s}$=115 GeV: $\sigma(\Lambda_c^+) \sim 11$ 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

PRL 122, 132002 (2019), Erratum

LHCb

This measurement

NLO pQCD

$\sigma(c\bar{c})$ [µb/nucleon]

$\sqrt{s_{NN}}$ [GeV]

PRD 103, 072003 (2021)

Simulation

S_y

S_x

Polarization

Events [/80 GeV/c]

p [GeV/c]

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	$\mathcal{B}$ (%)	ϵ_{3trk}	$\mathcal{B}_{eff}$ (%)
$pK^-\pi^+$	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	$\cdots$	$\cdots$	20.2

$\Lambda_c^+ \to pK^-\pi^+$
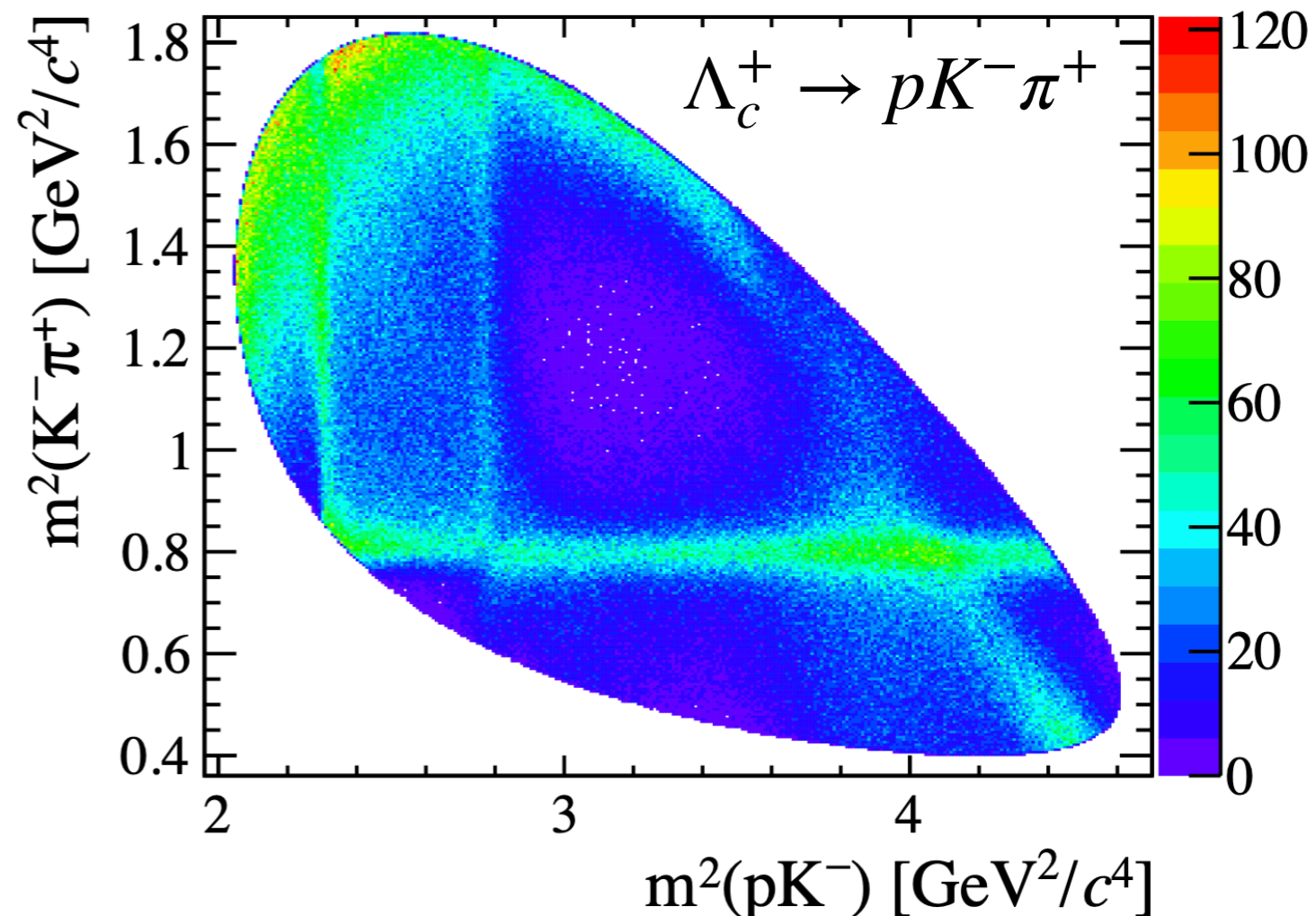
Sensitivity on MDM/EDM
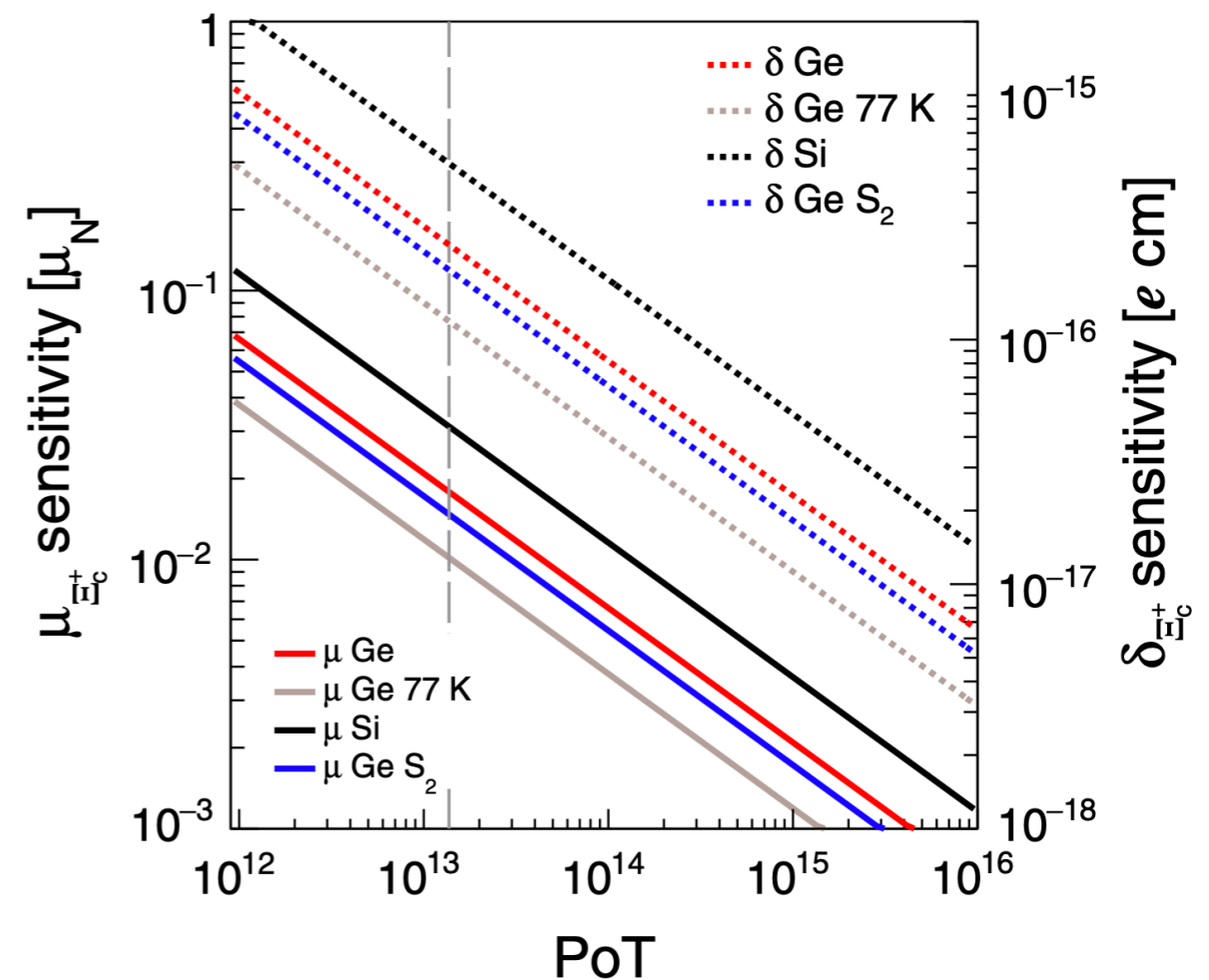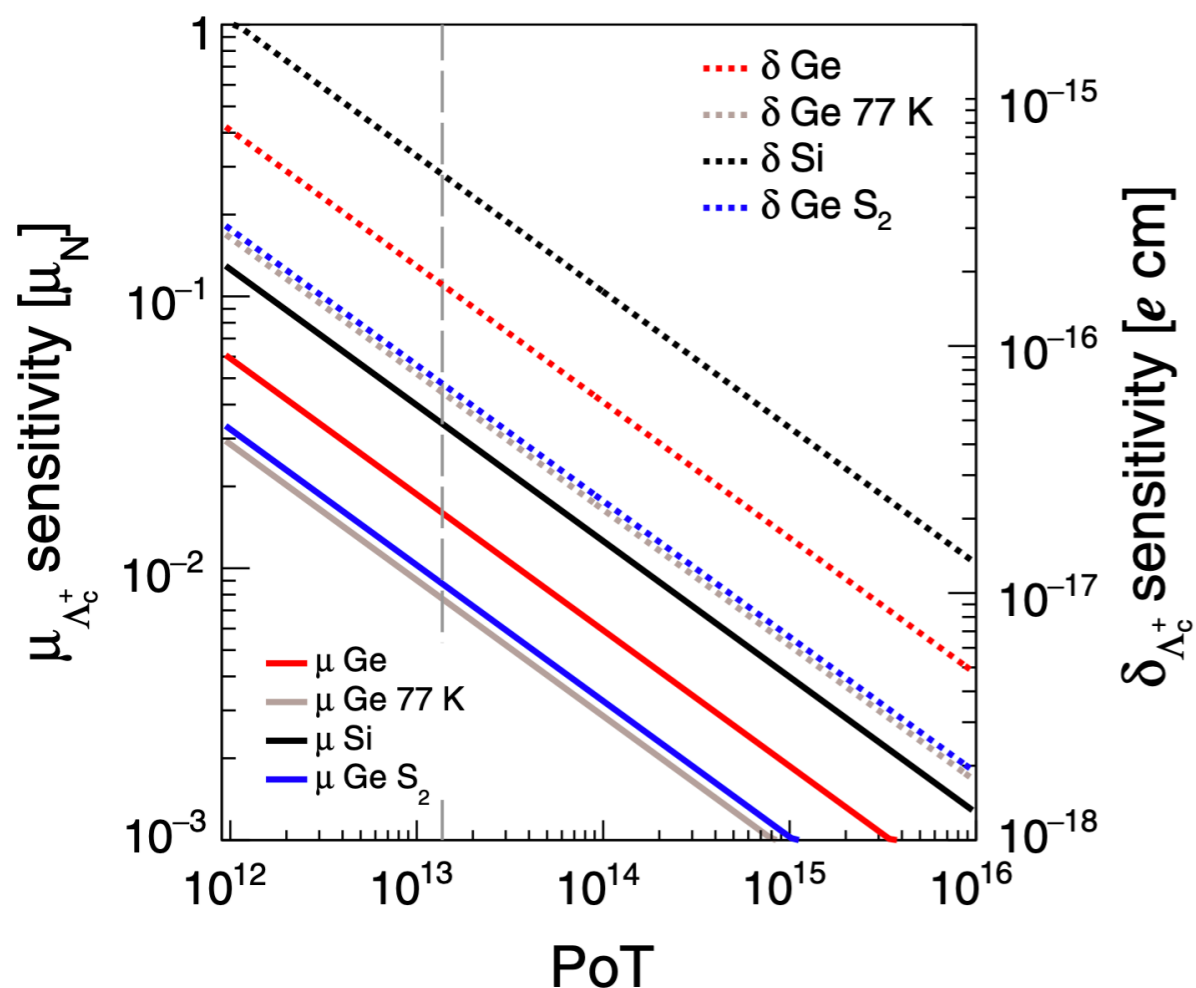
▸ S1 configuration: **LHCb detector, Ge (Si) 16 mrad, 10 cm**

▸ S2 configuration: **dedicated experiment, Ge 7 mrad, 7 cm**

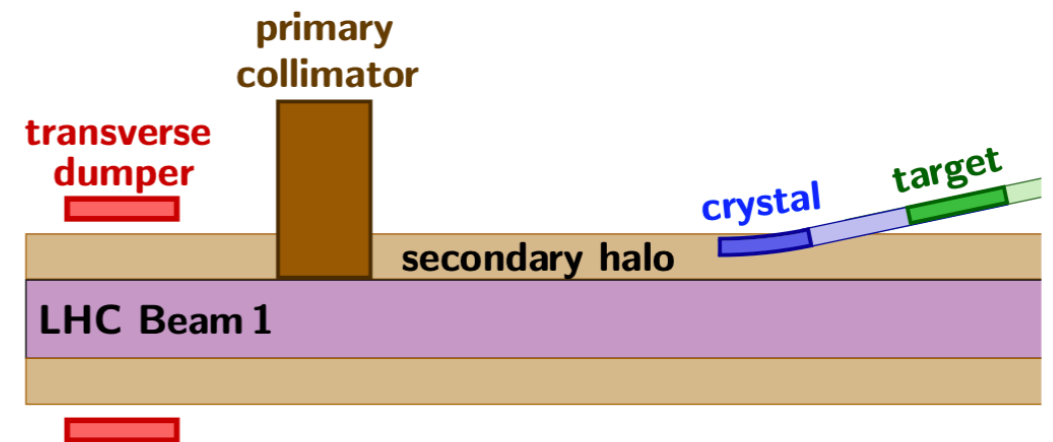Λ_c^+ **baryon**   PRD 103, 072003 (2021) Ξ_c^+ **baryon**

▸ Measurements are **statistically limited**

New ideas to increase statistics

▶ Active excitation of bunches

A. Fomin, D. Mirarchi, S. Redaelli
PBC meeting, 2 July 2021

- random noise **excitation** with transverse dumper for **selected bunches**. Increase secondary halo and delivered PoT **x8**

▶ Double-lens technique

V. M. Biryukov, arXiv:2105.13628
V. M. Biryukov, J. Ruiz Vidal to appear on arXiv

- beam-optic system of **two crystal lenses**, increase number of channeled short-lived particles per incident primary proton **x15**
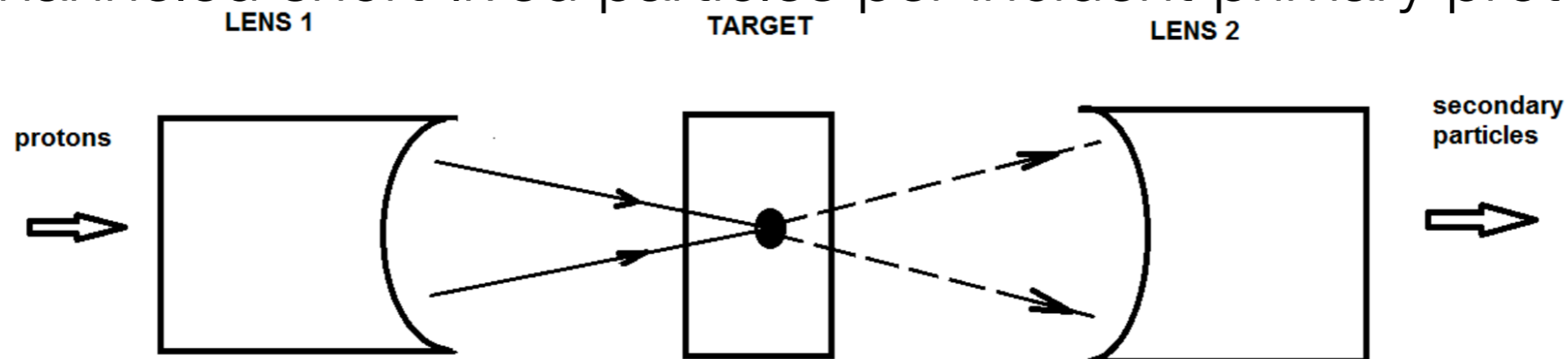
Proposals for τ lepton

- 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 $\tau^+ \to \pi^+ \pi^- \pi^+ \overline{\nu}_\tau$
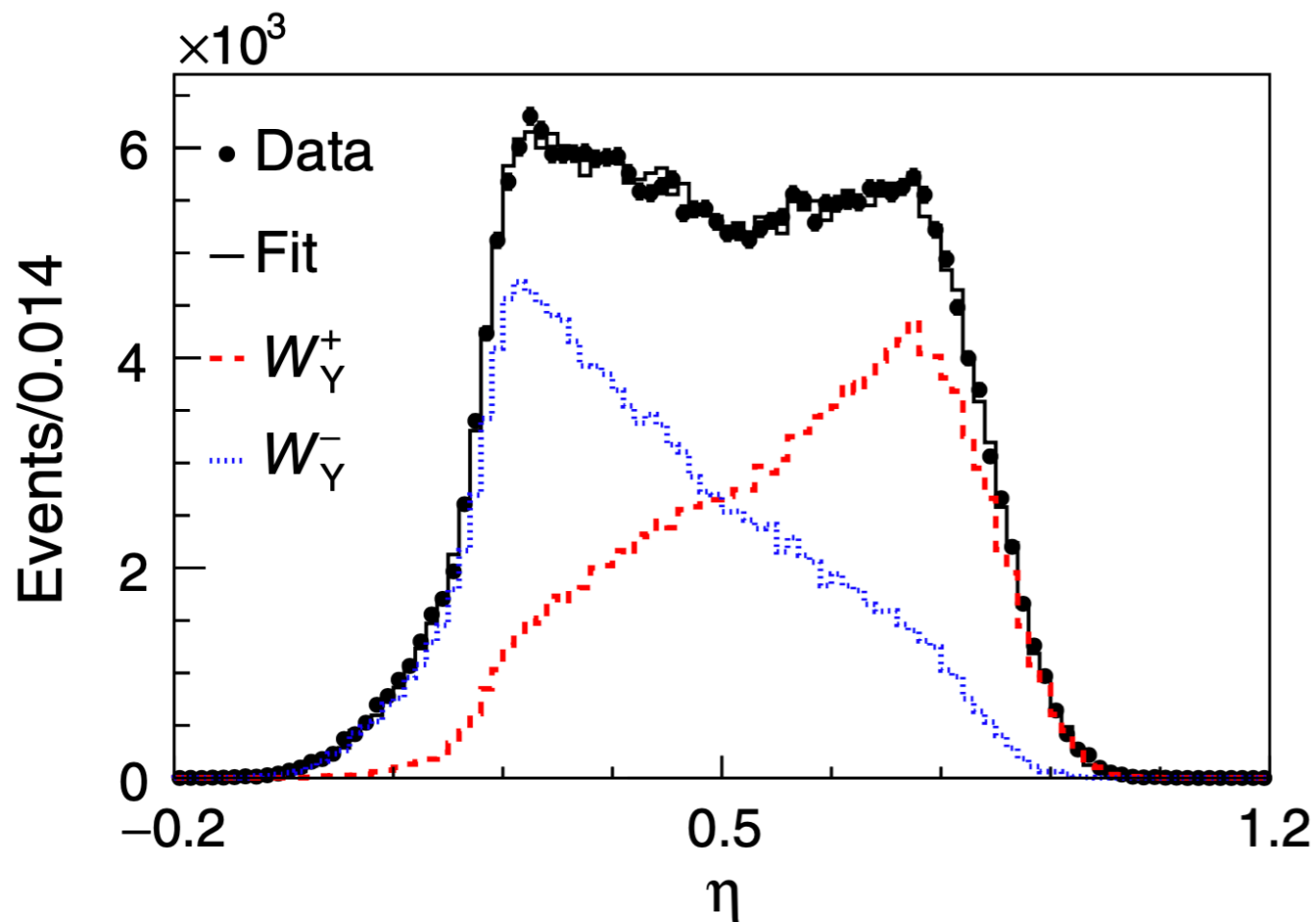
‣ **Bent crystal** for spin precession
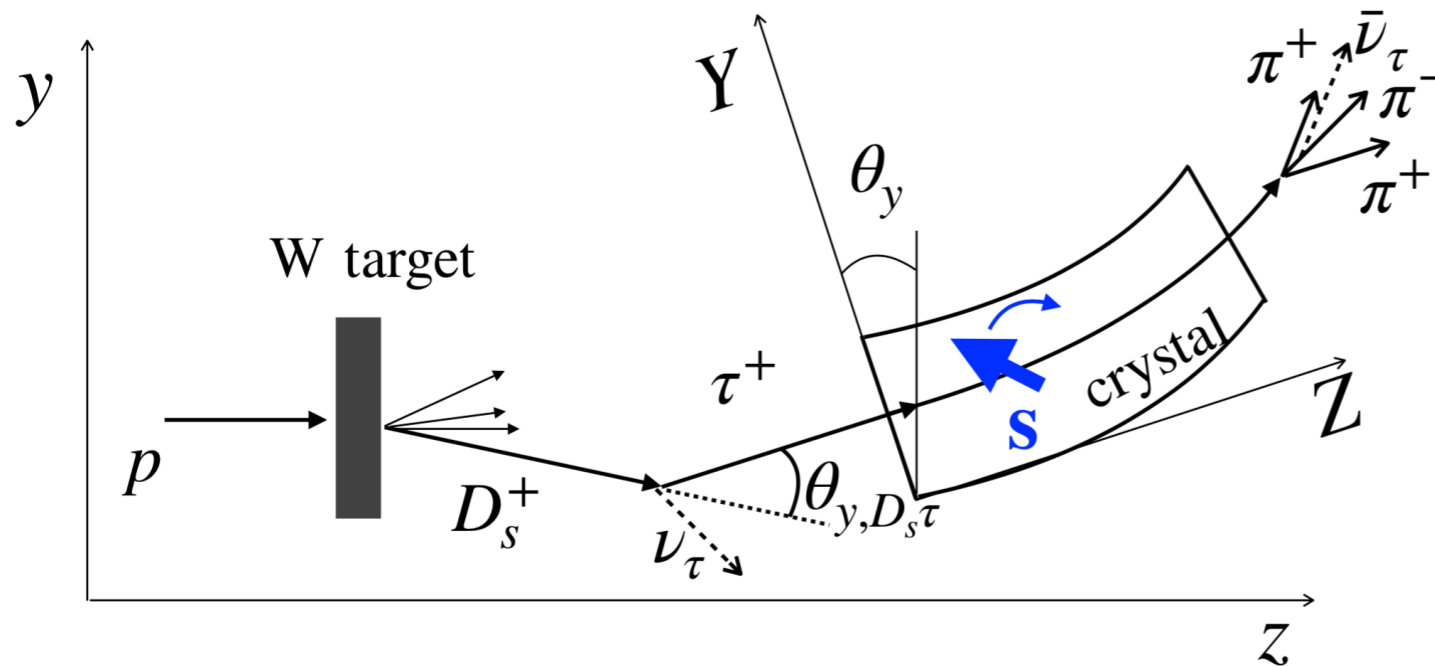
Spin polarisation

- kinematic selection on $p_{3\pi} > 0.8$ TeV, longitudinal (z) polarisation for MDM and enhanced EDM sensitivity
- Tagging $\theta(Ds,\tau) \lessgtr 0$ (e.g. 2 crystals, other) transverse (y) polarisation for enhanced MDM sensitivity
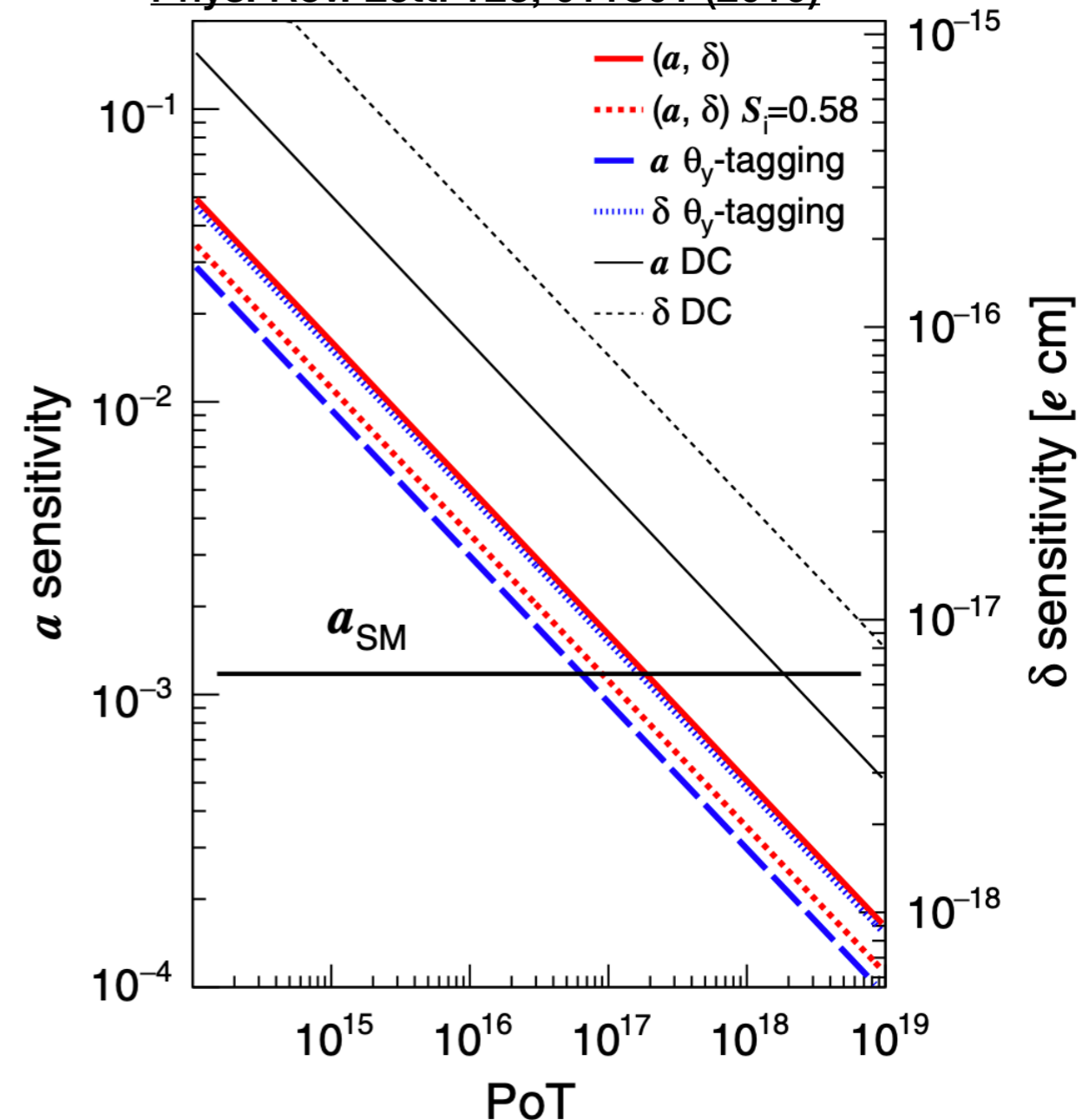
J. Fu, M. A. Giorgi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N.N., J. Ruiz Vidal, Phys. Rev. Lett. 123, 011801 (2019)
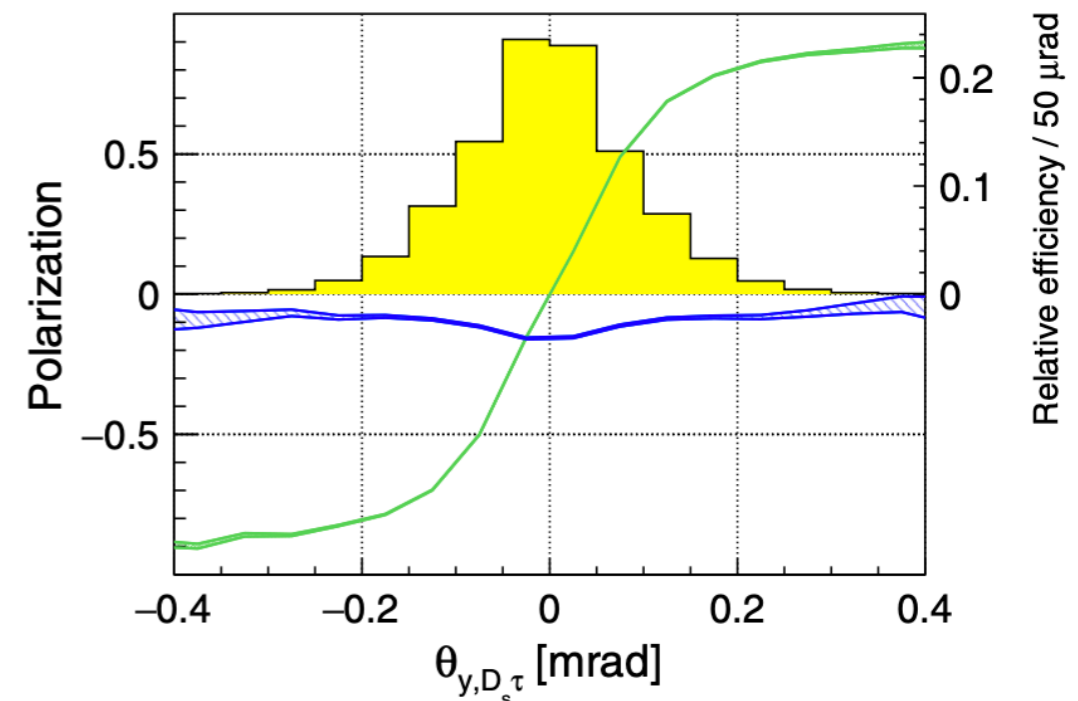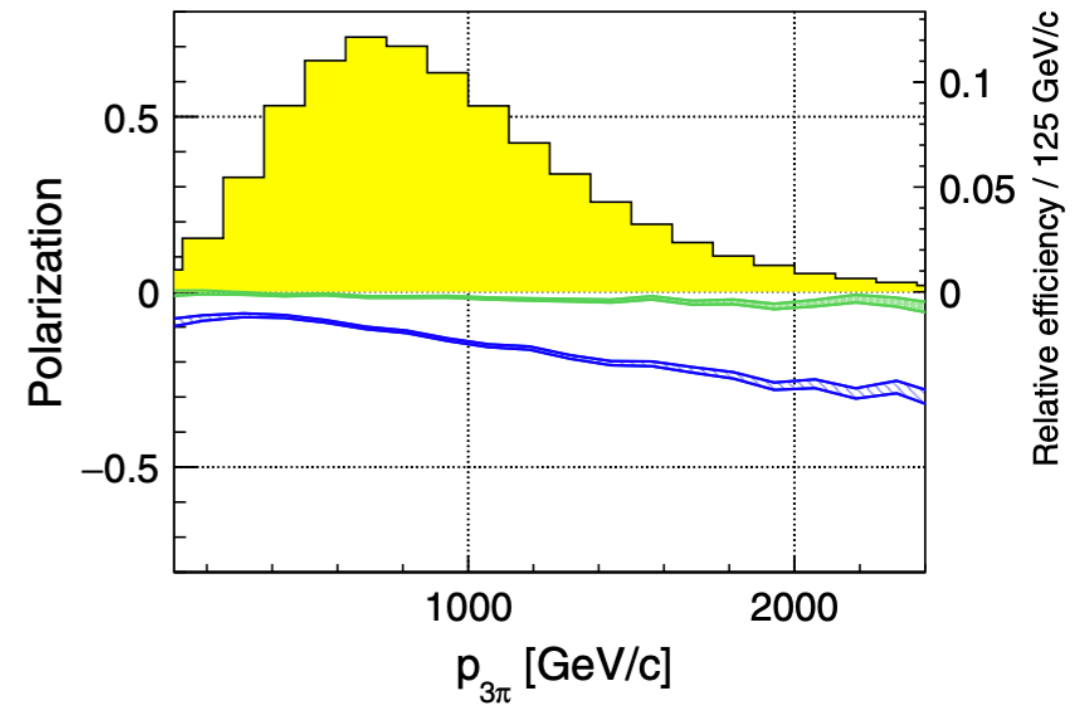
Sensitivity to dipole moments for τ lepton

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

▸ Direct measurements for **MDM/EDM** of Λ_c^+, Ξ_c^+ baryons and τ lepton are proposed

- **Milestones** achieved: feasibility detector studies, long bent crystal prototypes, preparatory studies in LHCb, machine layout, physics program extended

- Machine **test in LHC** in preparation, possibly during Run3

▸ **First measurements** for Λ_c^+, Ξ_c^+ baryons are possible in 2 year data taking

- fixed-target setup to be installed upstream of the LHCb detector. Possibly a dedicated experiment as next step

▸ Challenging for the τ **lepton**, requires a dedicated experiment at LHC

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

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)

Future plans

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

- ▸ Large statistics needed for interesting measurements, i.e. PoT ≳ 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 $D_s^+(\rightarrow \tau^+ \upsilon_\tau)$
  $$\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}_\tau$$
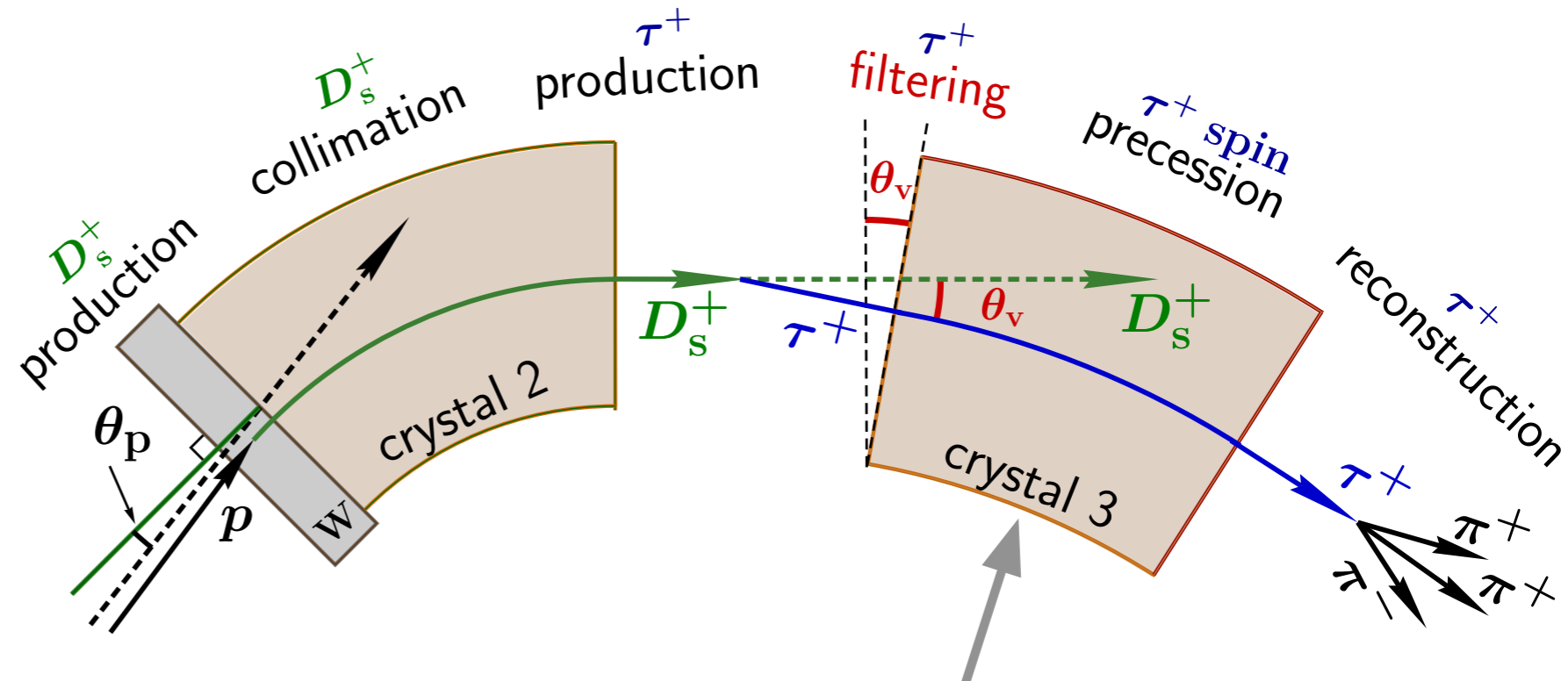
Crystal 2:

- deflection and "collimation" of D_s^+

Crystal 3:

- selecting τ produced by D_s^+
- filtering τ initial polarisation
- τ spin precession
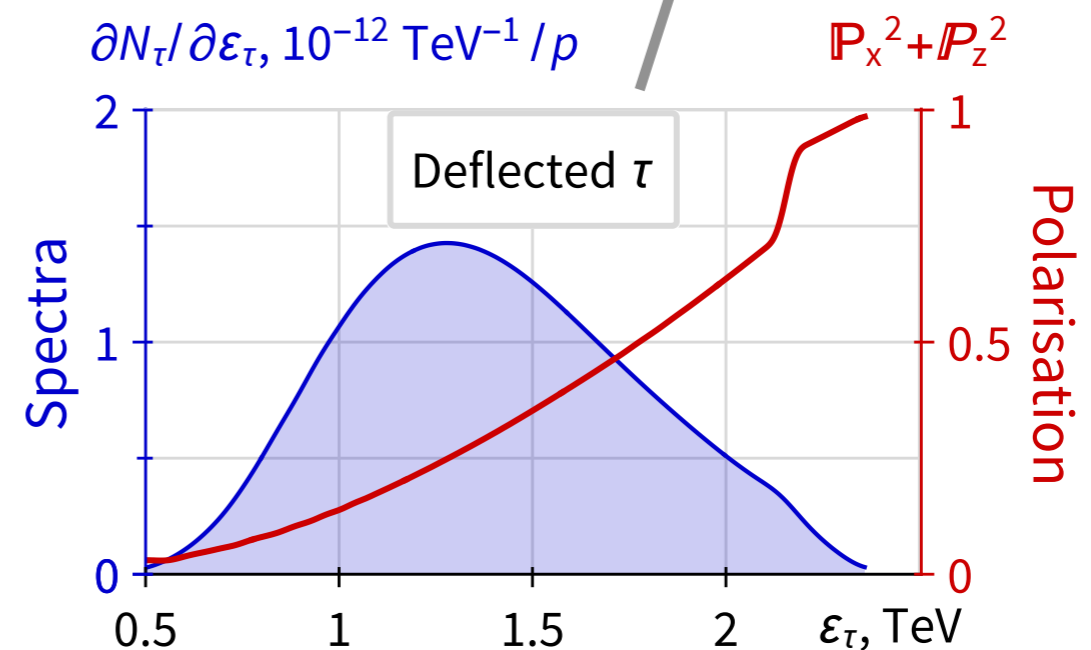
Feasibility of τ lepton electromagnetic dipole moments measurement using bent crystal at the LHC
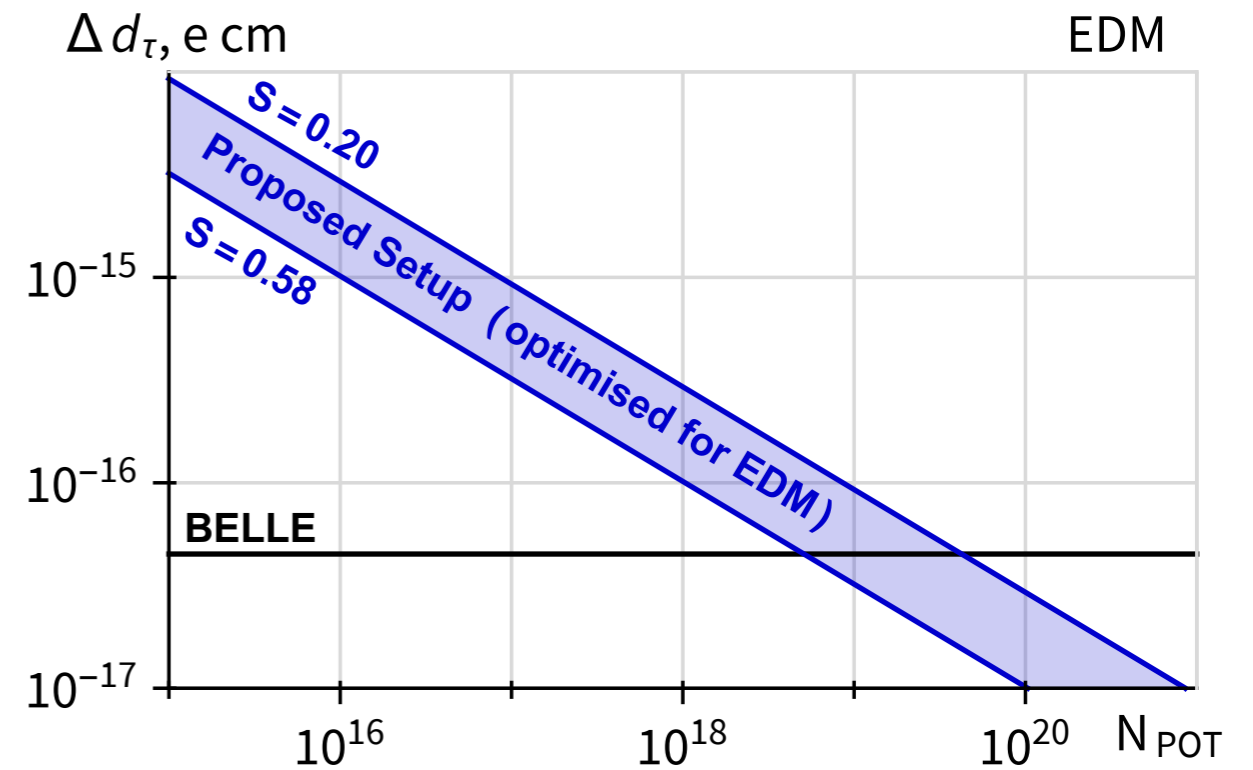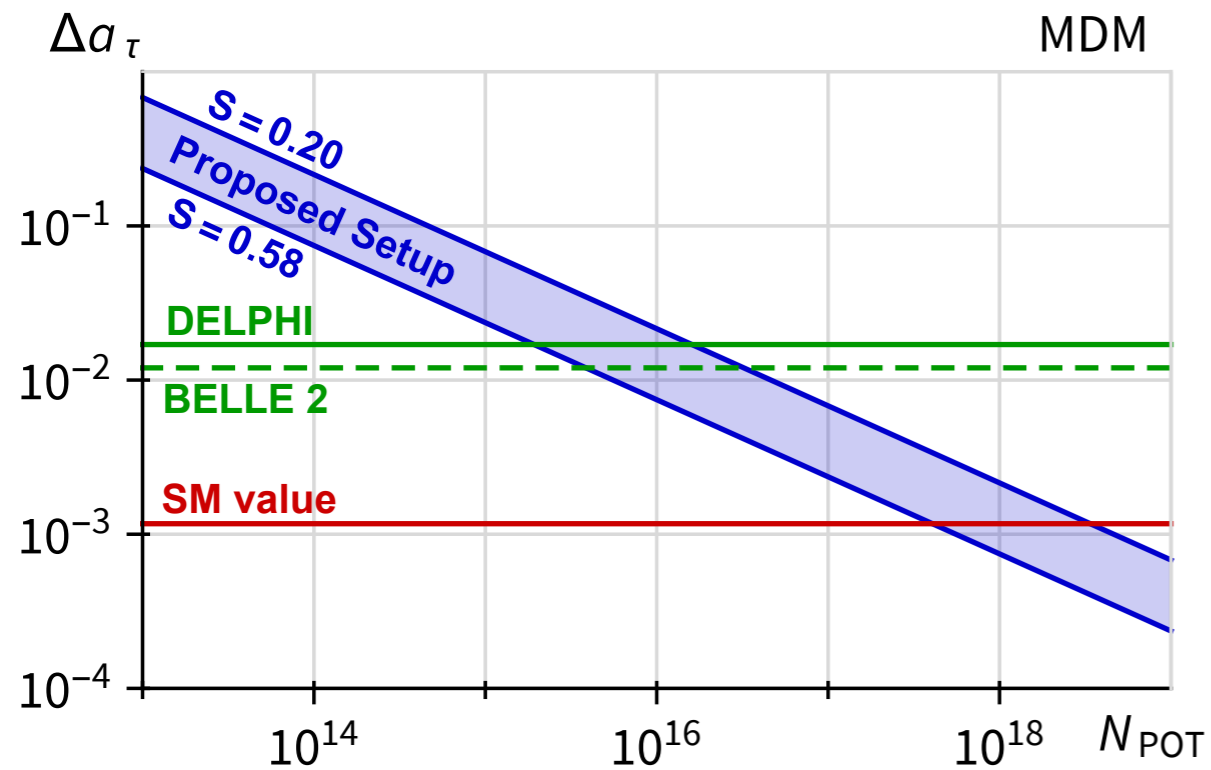
MDM: 10^{16} PoT — to reach the present accuracy [DELPHI: J. Abdallah et al. EPJC 35:159–170, 2004]

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]

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** $\mu_\Lambda = (-0.6138 \pm 0.0047) \mu_N$ 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

INFN   erc

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
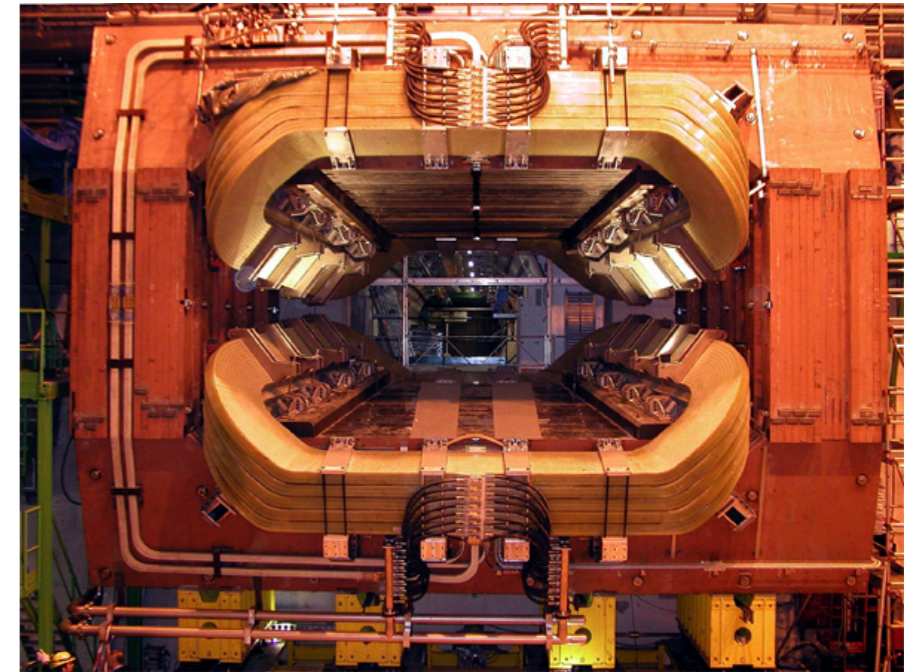
  - e.g. $\Lambda_b^0 \to J/\psi\Lambda$, $\Xi_c^0 \to \Lambda K^- \pi^+$, $\Lambda_c^+ \to \Lambda \pi^+ \pi^- \pi^+$

  - Large longitudinal polarisation (up to 90%) due to parity violation in the weak decay

$$\Lambda_c^+ \to \Lambda \pi^+ \pi^+ \pi^-$$
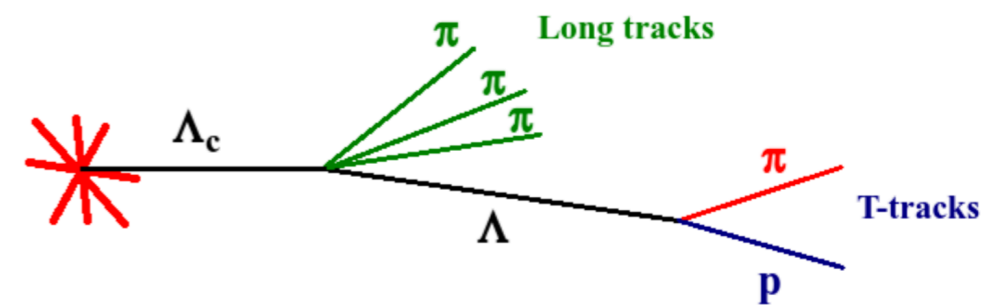
- ▸ Challenge: reconstruction of Λ baryons decaying at the end of the magnet

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   T₁ T₂ T₃   RICH

S_y = EDM signature
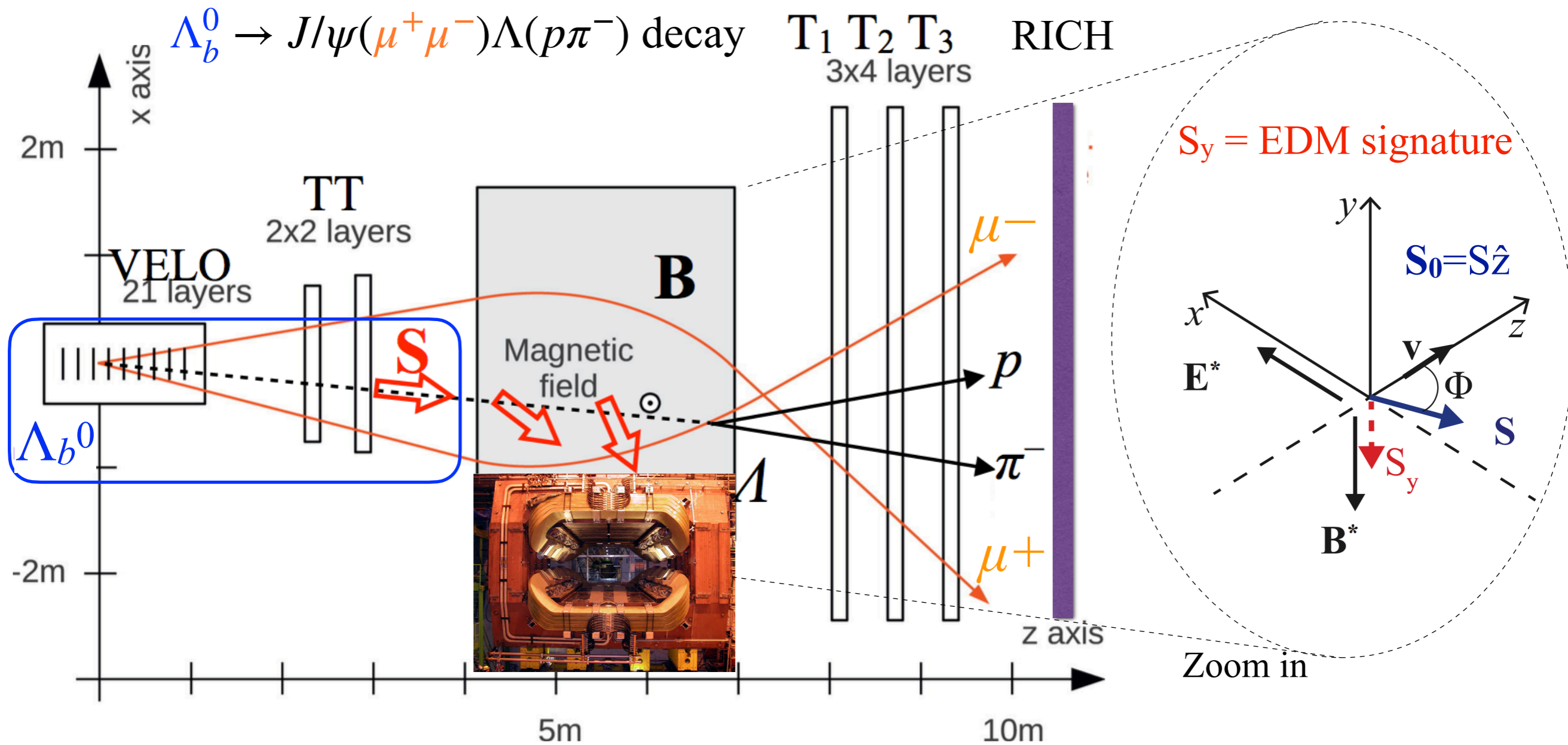
Λ polarised production

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   T₁ T₂ T₃   RICH
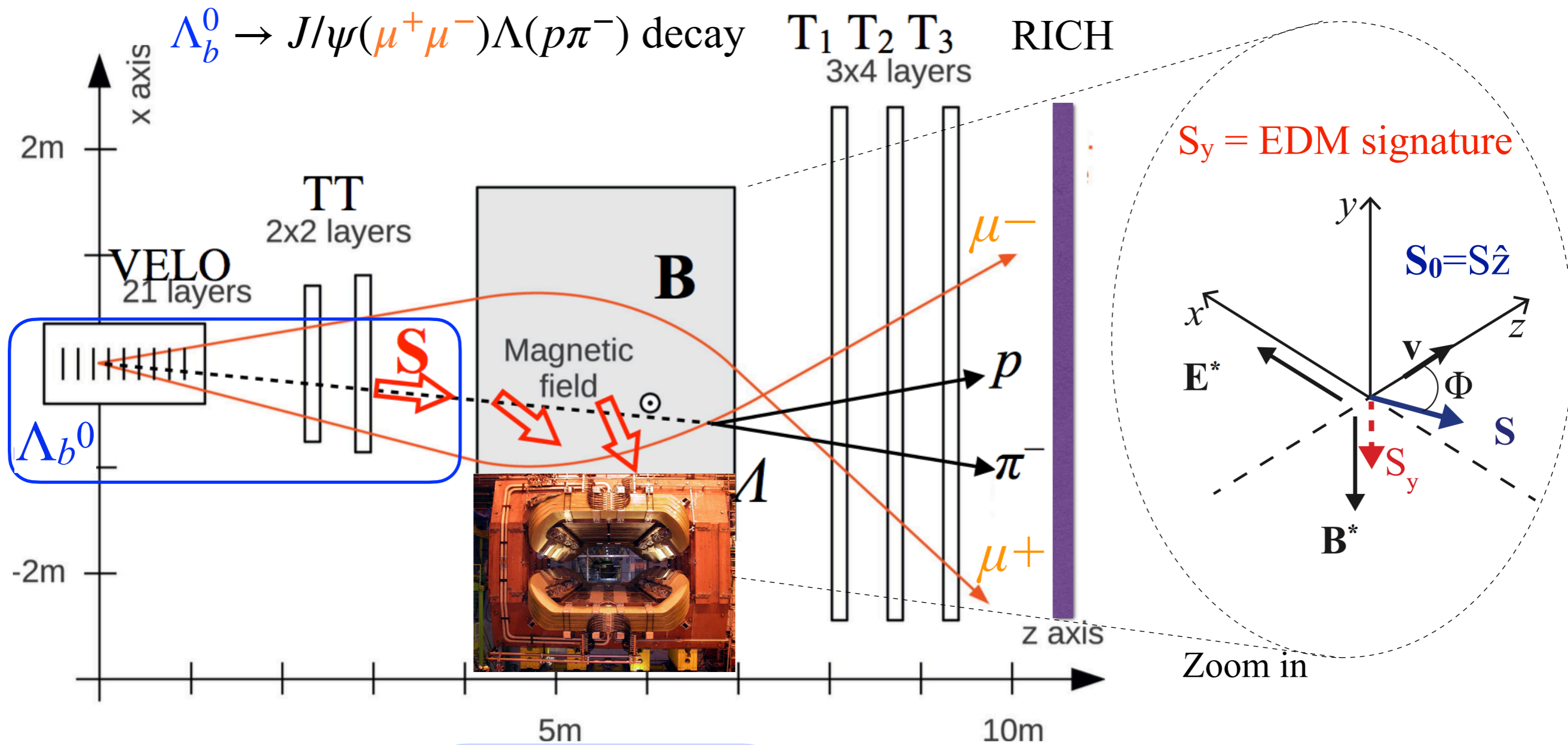
Λ polarised production   spin precession

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

S_y = EDM signature

$S_0 = S\hat{z}$

Zoom in

Λ polarised production   spin precession   event reconstruction
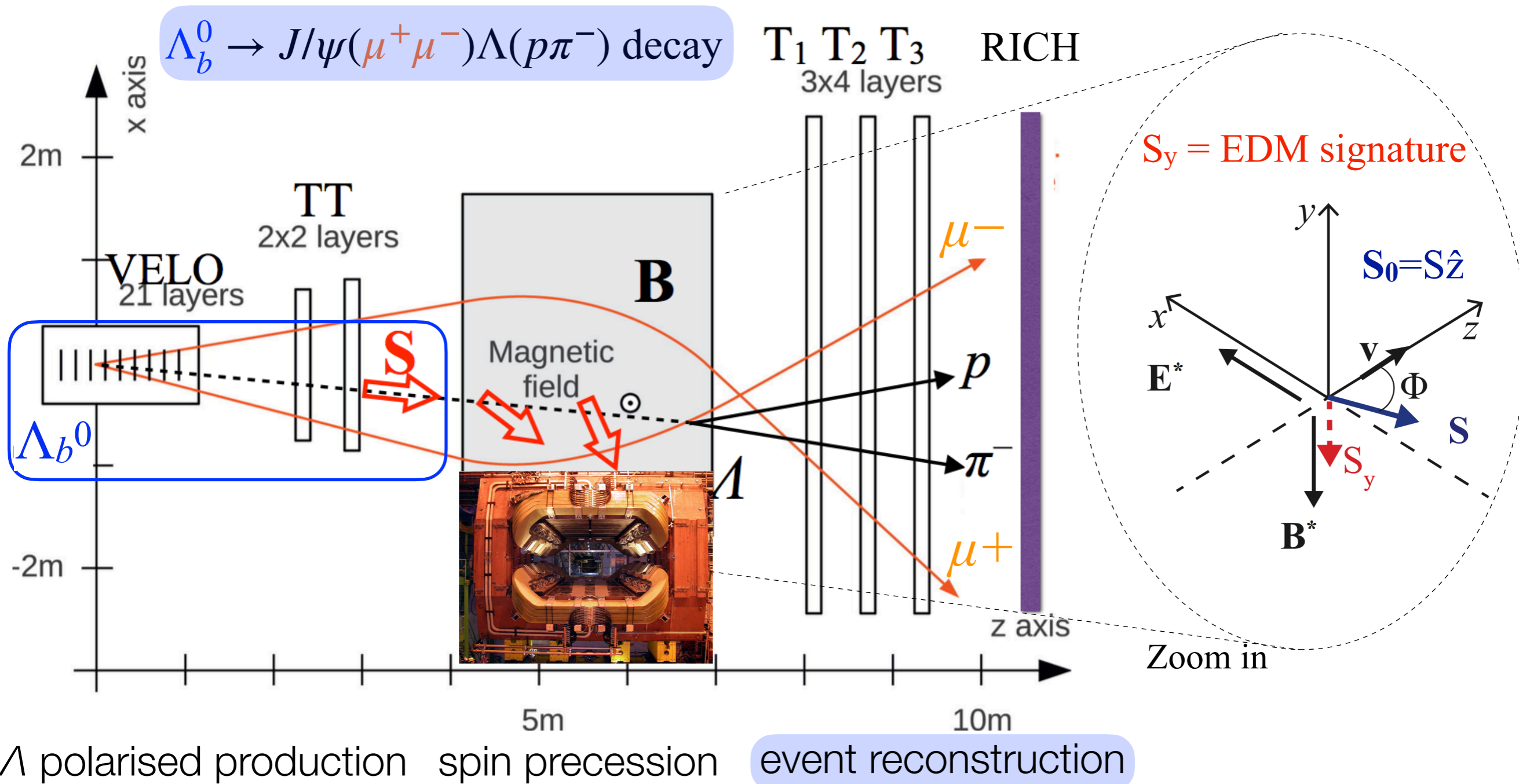
Simulations studies for Λ reconstruction

- Fit the entire decay chain $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$ imposing geometric and kinematic constraints
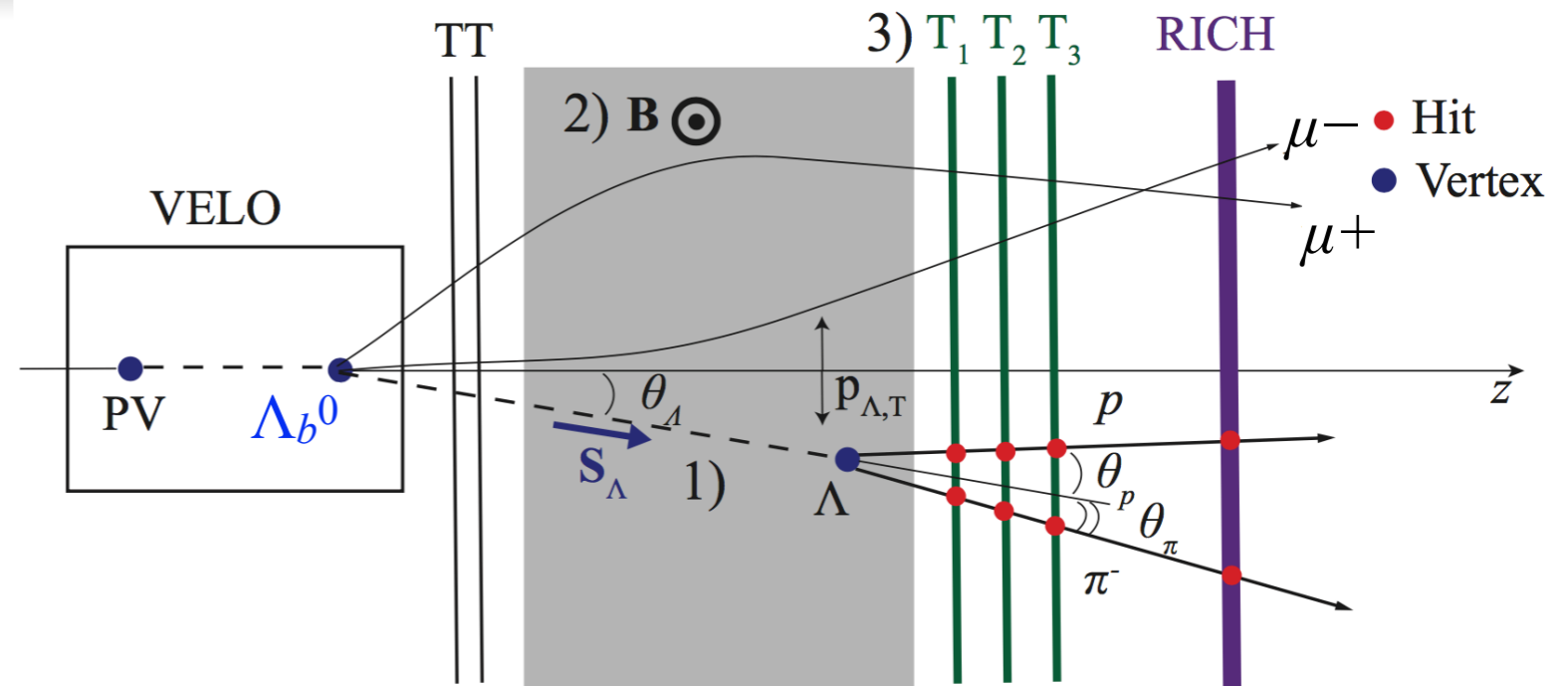
1) Polarized Λ baryons 2) Magnetic field region 3) LHCb detector

$$\Lambda \to p\pi^-$$

LHCb simulation
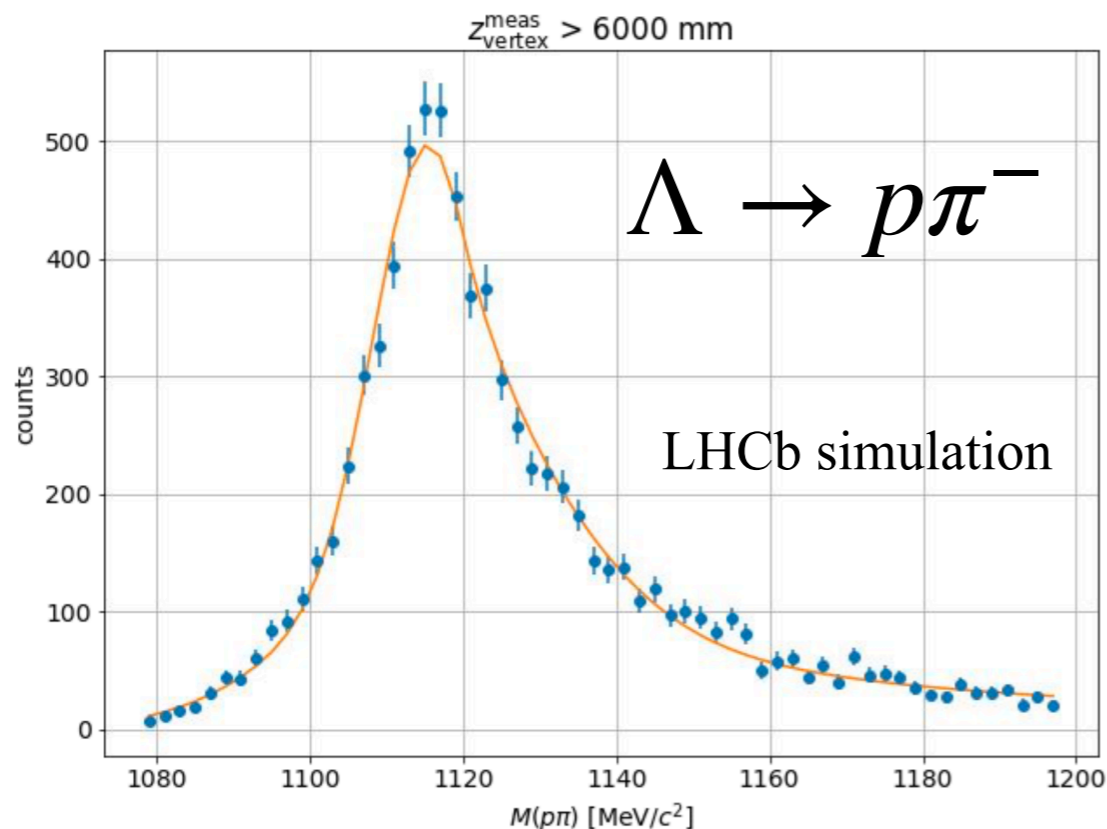
- Reconstructed m(pπ-) invariant mass for Λ candidates decaying at the end of the magnet

- Trigger and selection strategy for Run3 data being optimised

$\Lambda_b^0 \to J/\psi\Lambda$ reconstruction on data

- Reconstruct the decay $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$ exploiting existing dimuon trigger on Run2 data ✓

- Λ reconstructed decay vertex after the LHCb magnet (6m) ✓

$\Lambda \to p\pi^-$

LHCb unofficial

$\Lambda_b^0 \to J/\psi\Lambda$

LHCb unofficial
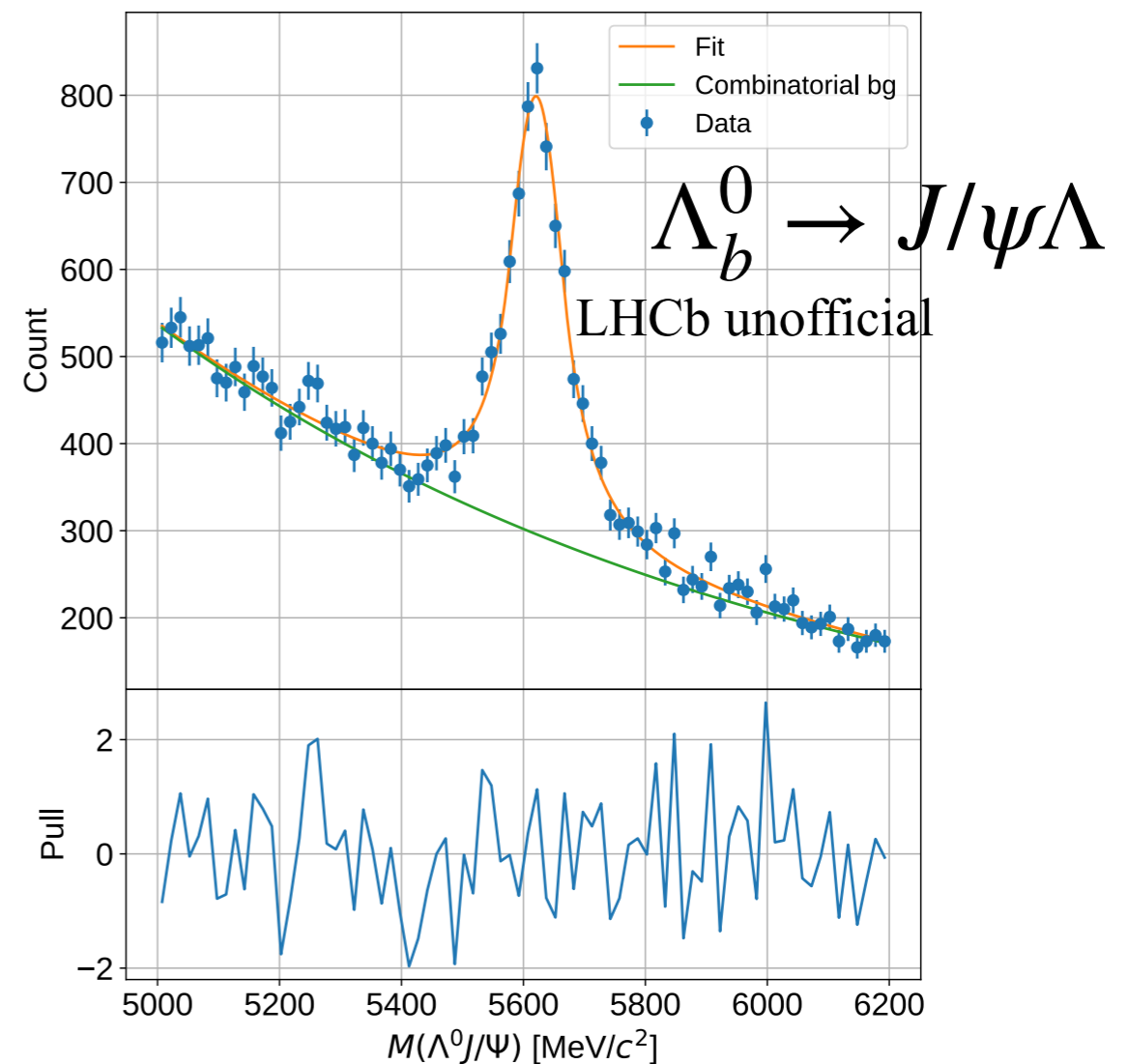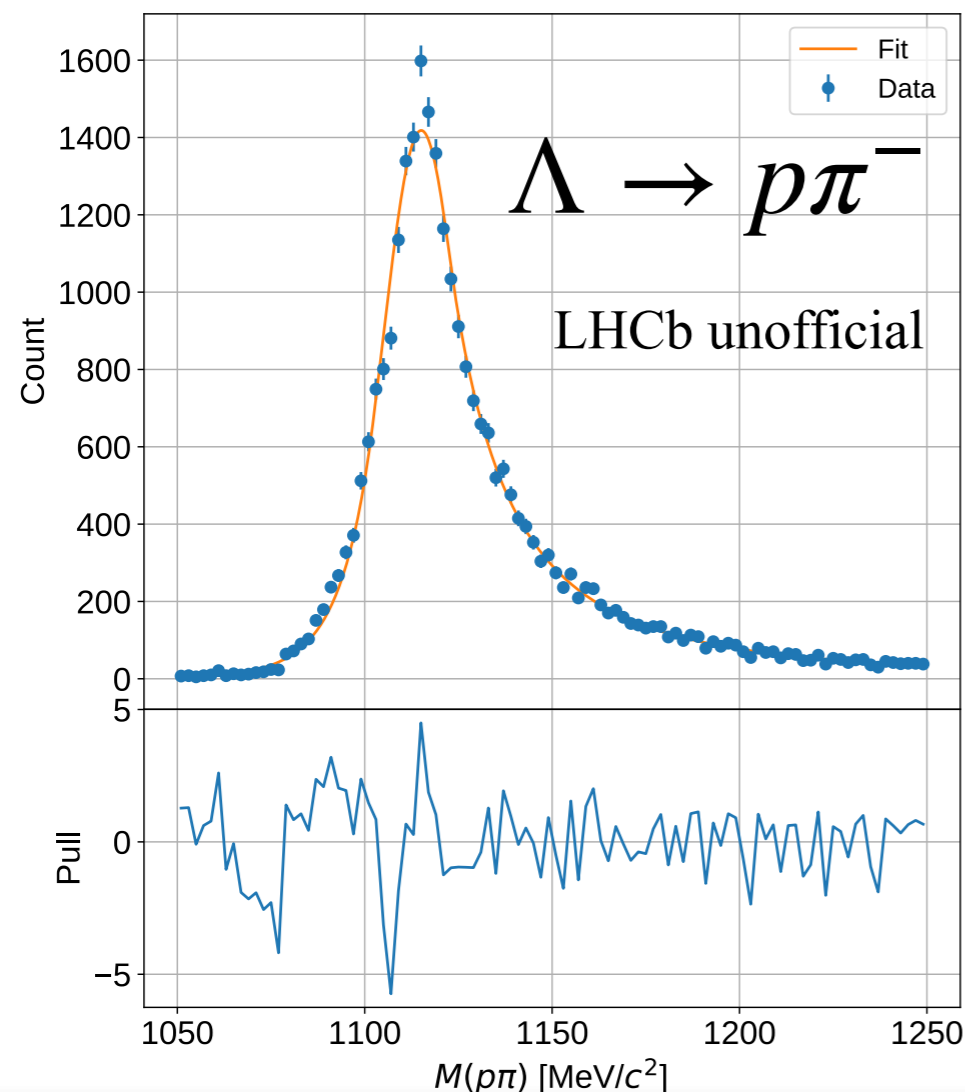
Sensitivity on MDM/EDM

▸ For initial longitudinal polarisation $\mathbf{s}_0 = s_0\hat{z}$

▸ Spin rotation after LHCb magnet (B field)

$$\mathbf{s} = \begin{cases} s_x = -s_0 \sin\Phi \\ s_y = -s_0 \dfrac{d\beta}{g} \sin\Phi \\ s_z = s_0 \cos\Phi \end{cases} \qquad \Phi \approx \frac{g\mu_B BL}{\beta\hbar c} \approx \frac{\pi}{4} \qquad BL \approx 4\text{ T m}$$

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
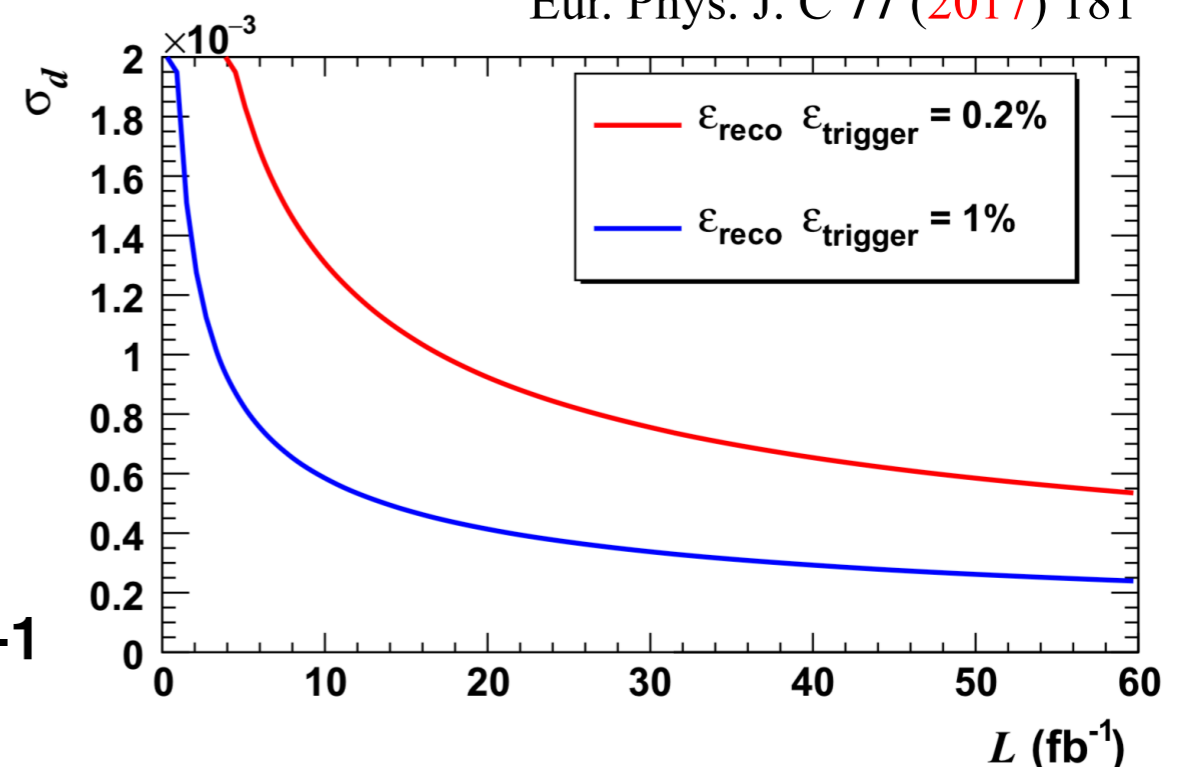
Detector simulation studies

Simulation studies

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

-116cm

z=0

Rotation of crystal to improve LHCb detector efficiency
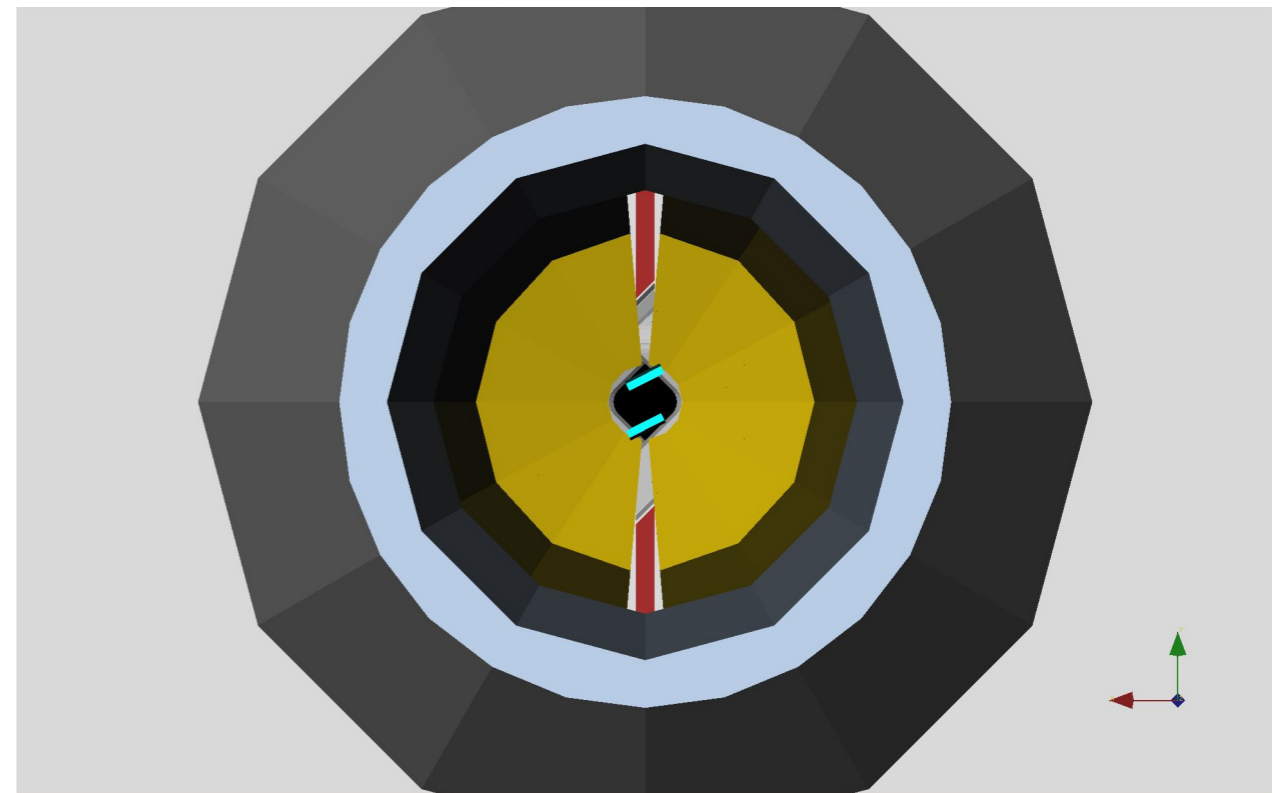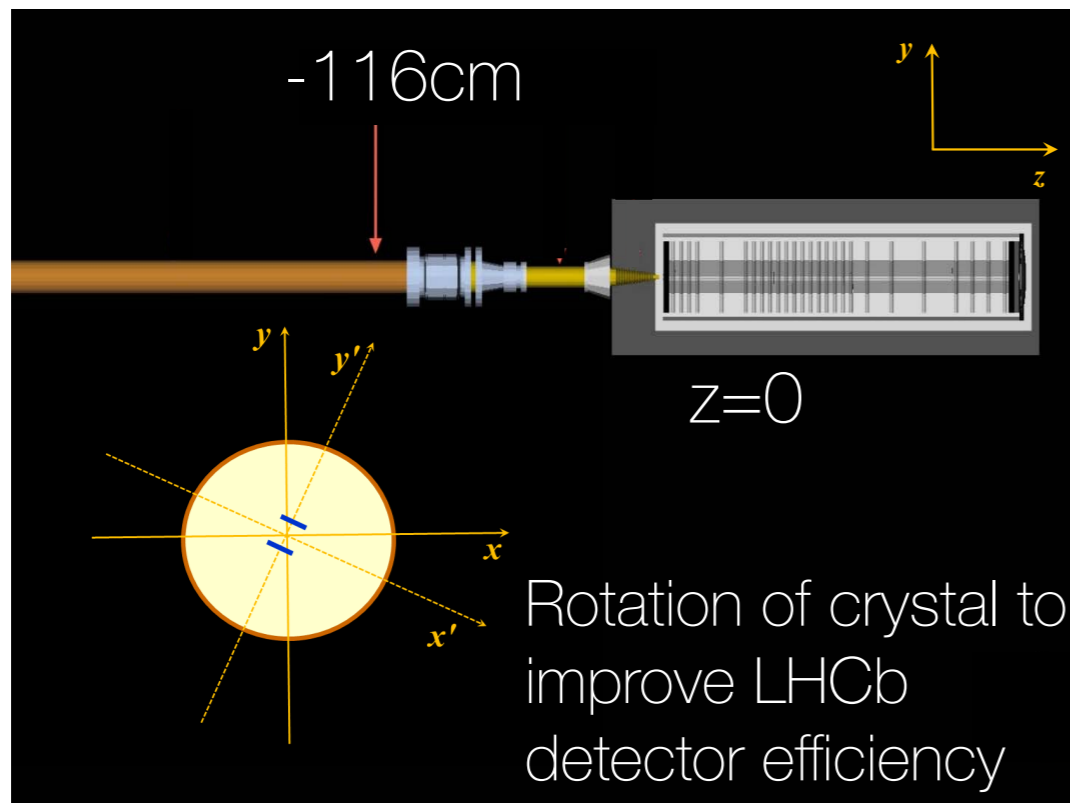
▸ Use EPOS for fixed-target minimum bias events, PYTHIA for baryons produced in pW hard collisions

▸ 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
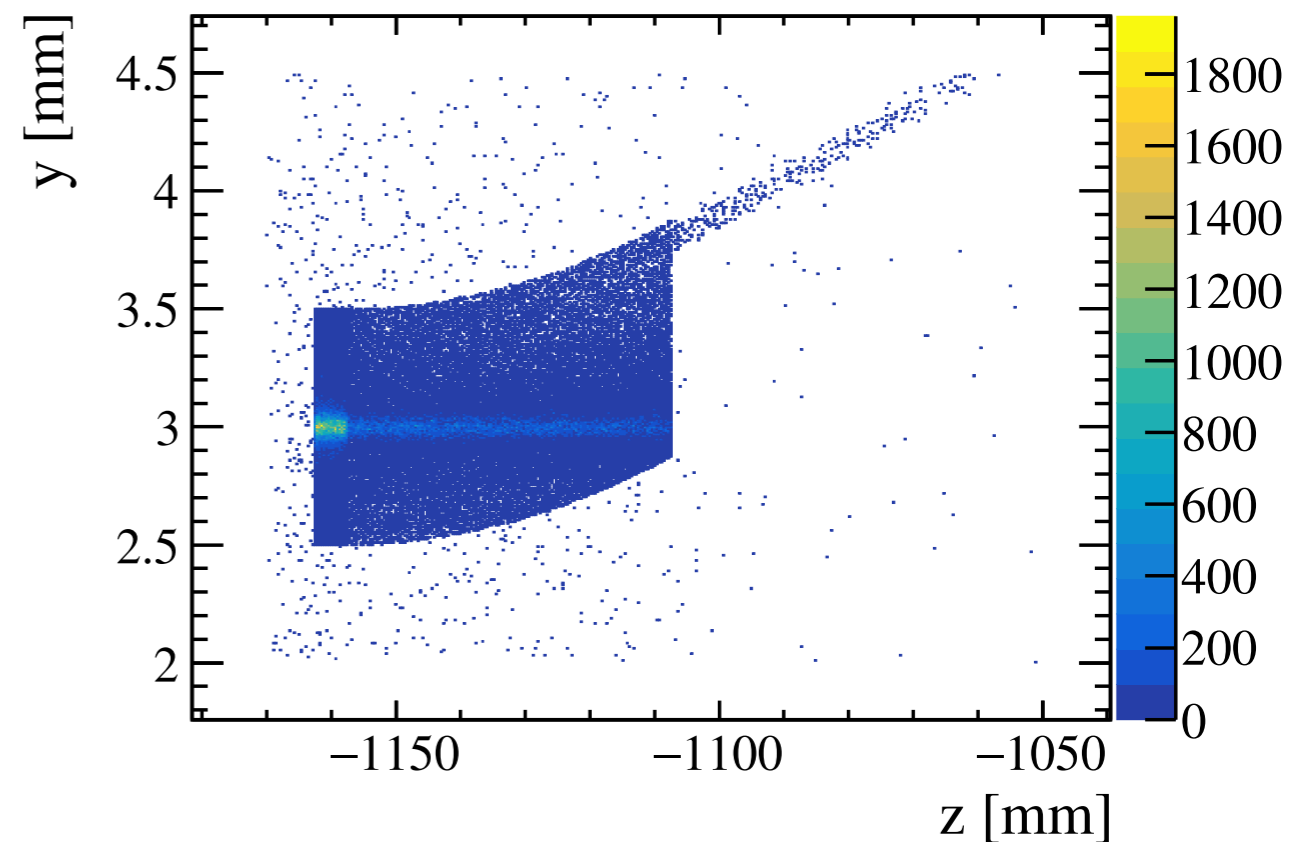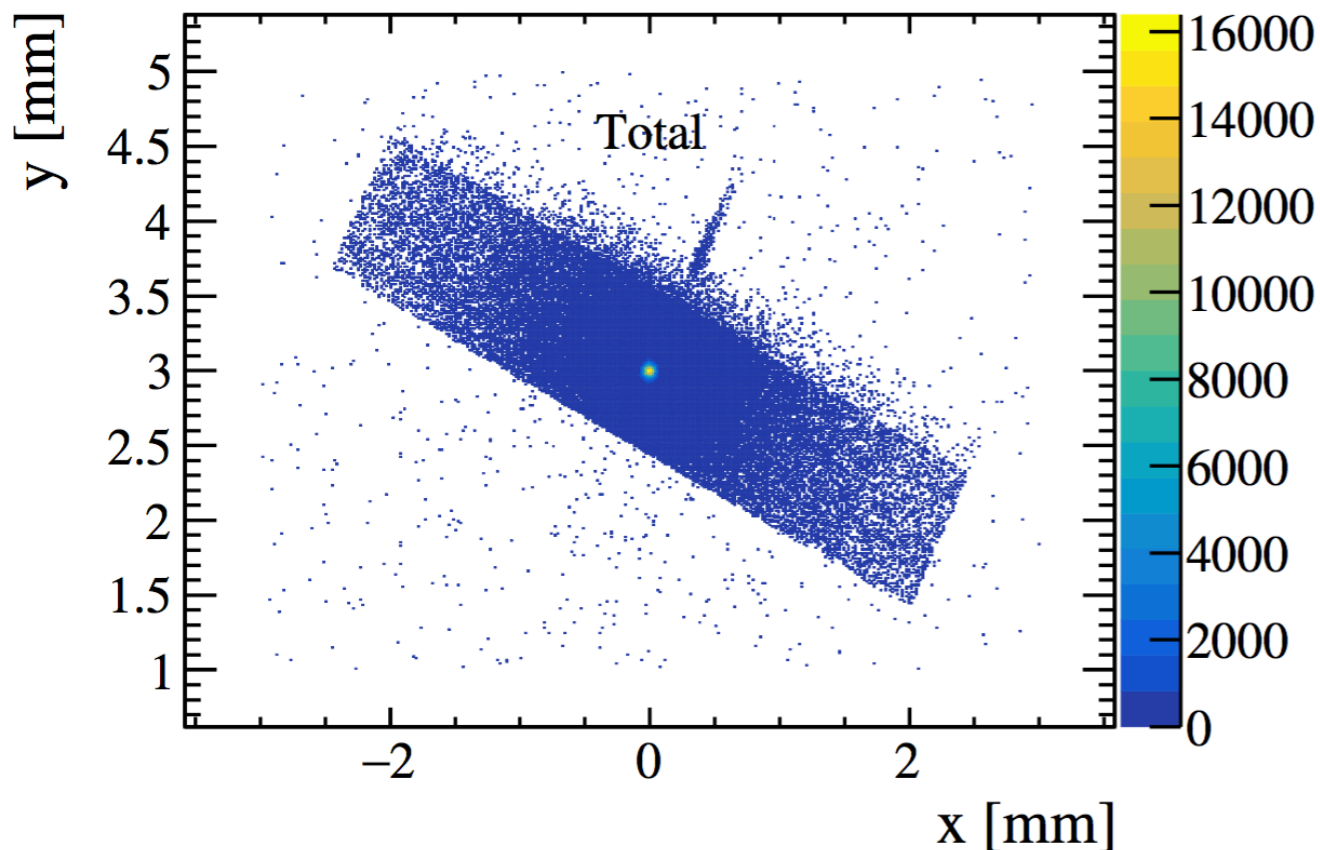
Identification of signal events

▸ About 10^{-4} Λ_c^+ produced in the target are channeled in the bent crystal
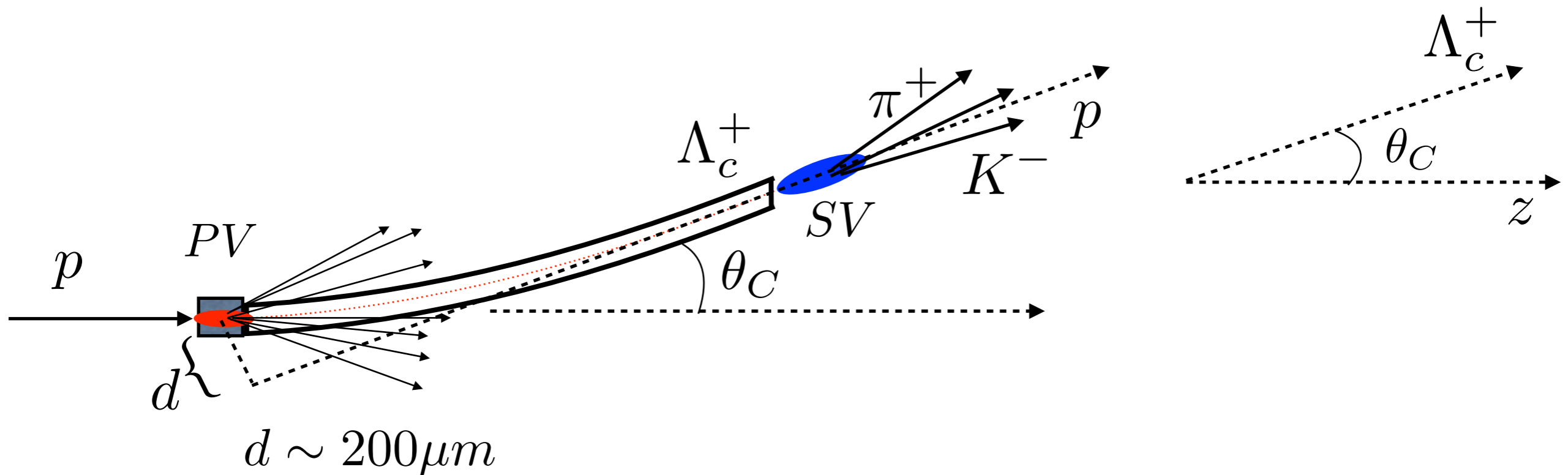
▸ Use PV to identify Λ_c^+ produced in W target, and Λ_c^+ vertex helps to identify decays outside of the crystal (max spin precession)

▸ 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

FT spectrum
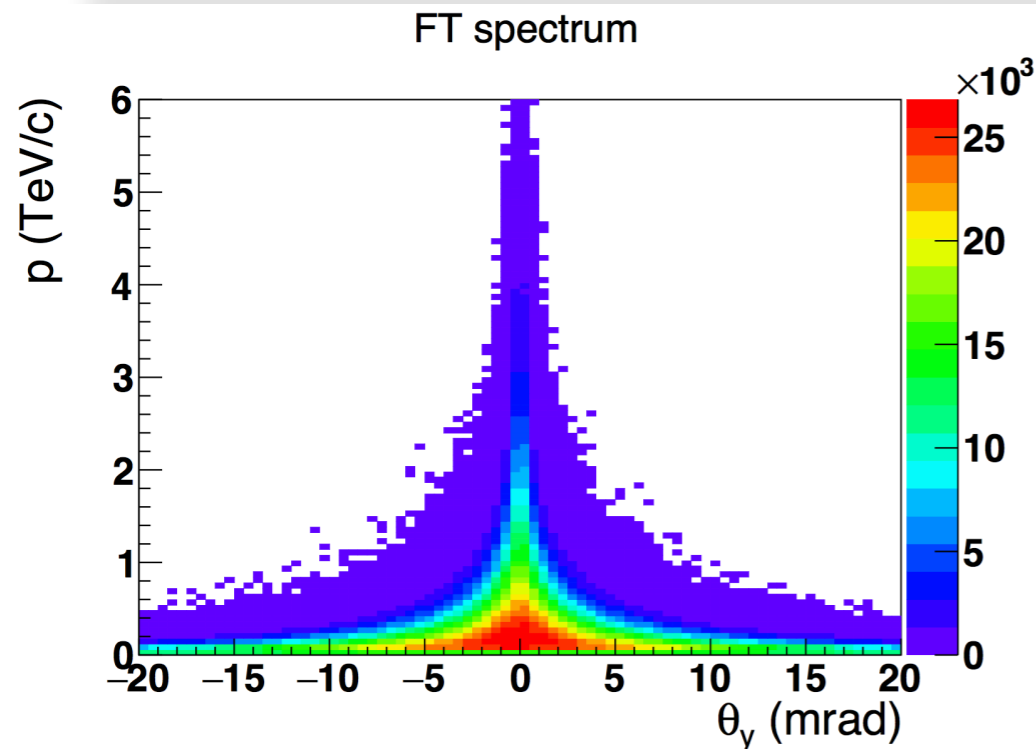
- ▸ At production (top)

- ▸ After channeling and p>800 GeV/c (bottom)

Si, L~7 cm, θ_C~14 mrad

<p> ~ 1.320 TeV

Ge, L~5 cm, θ_C~15 mrad

<p> ~ 1.379 TeV
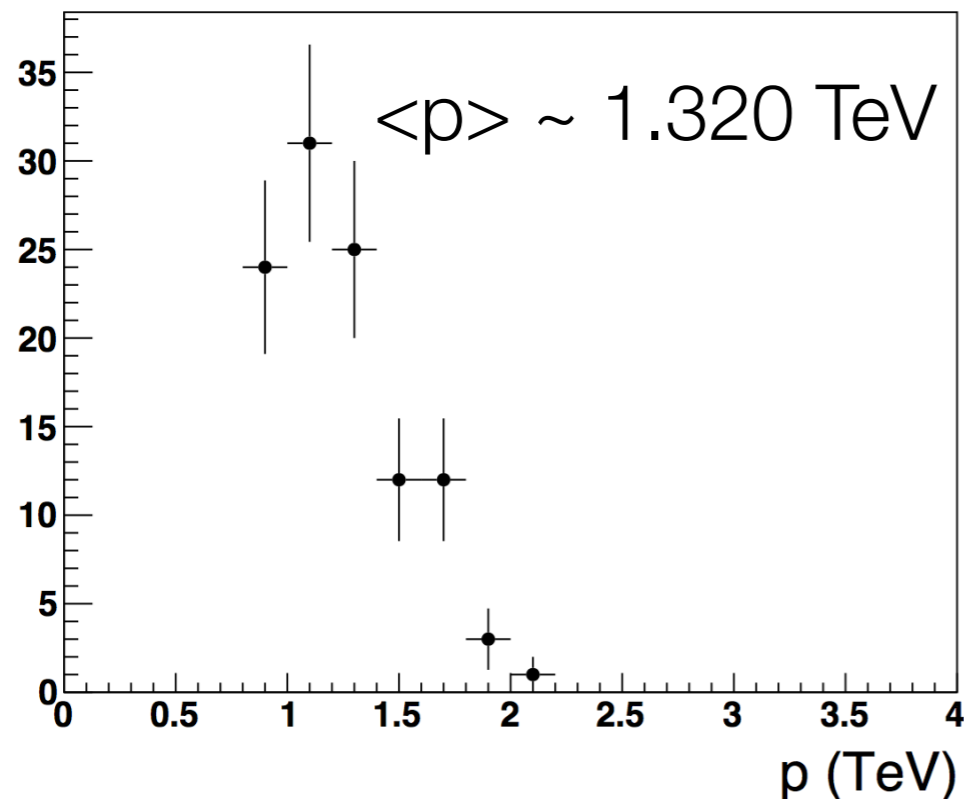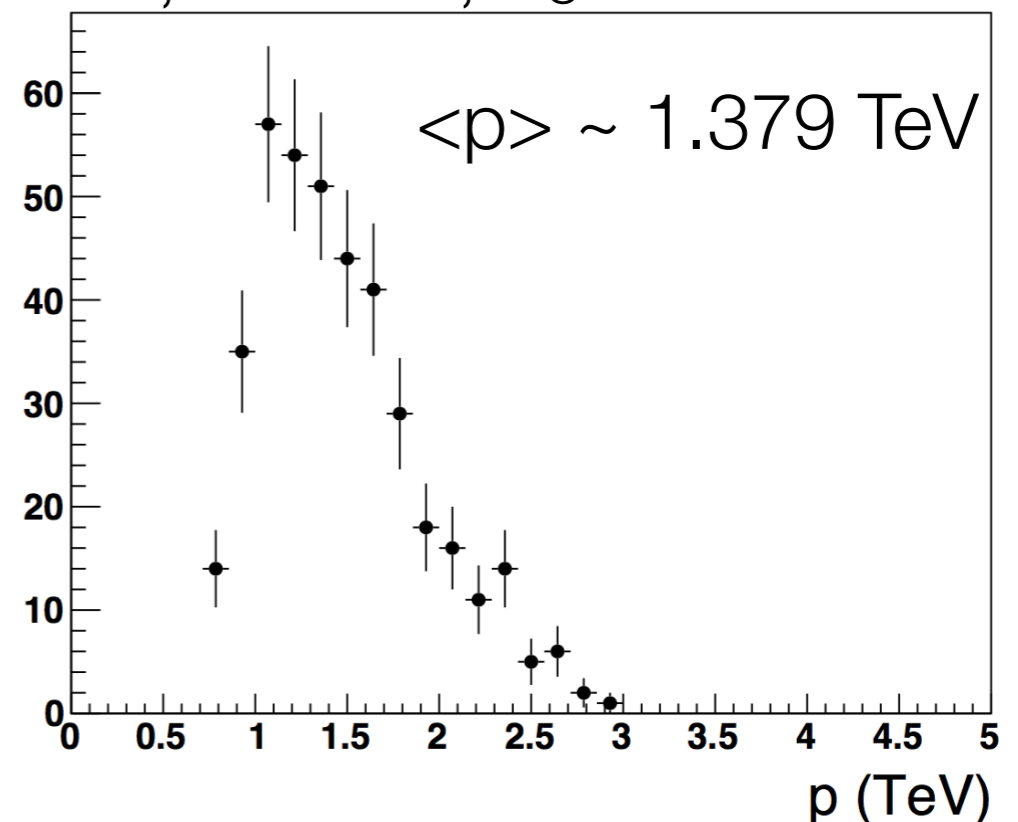
Background rejection

- Rejection of unchanneled Λ_c^+ produced in W target
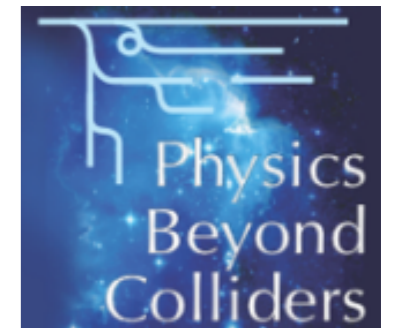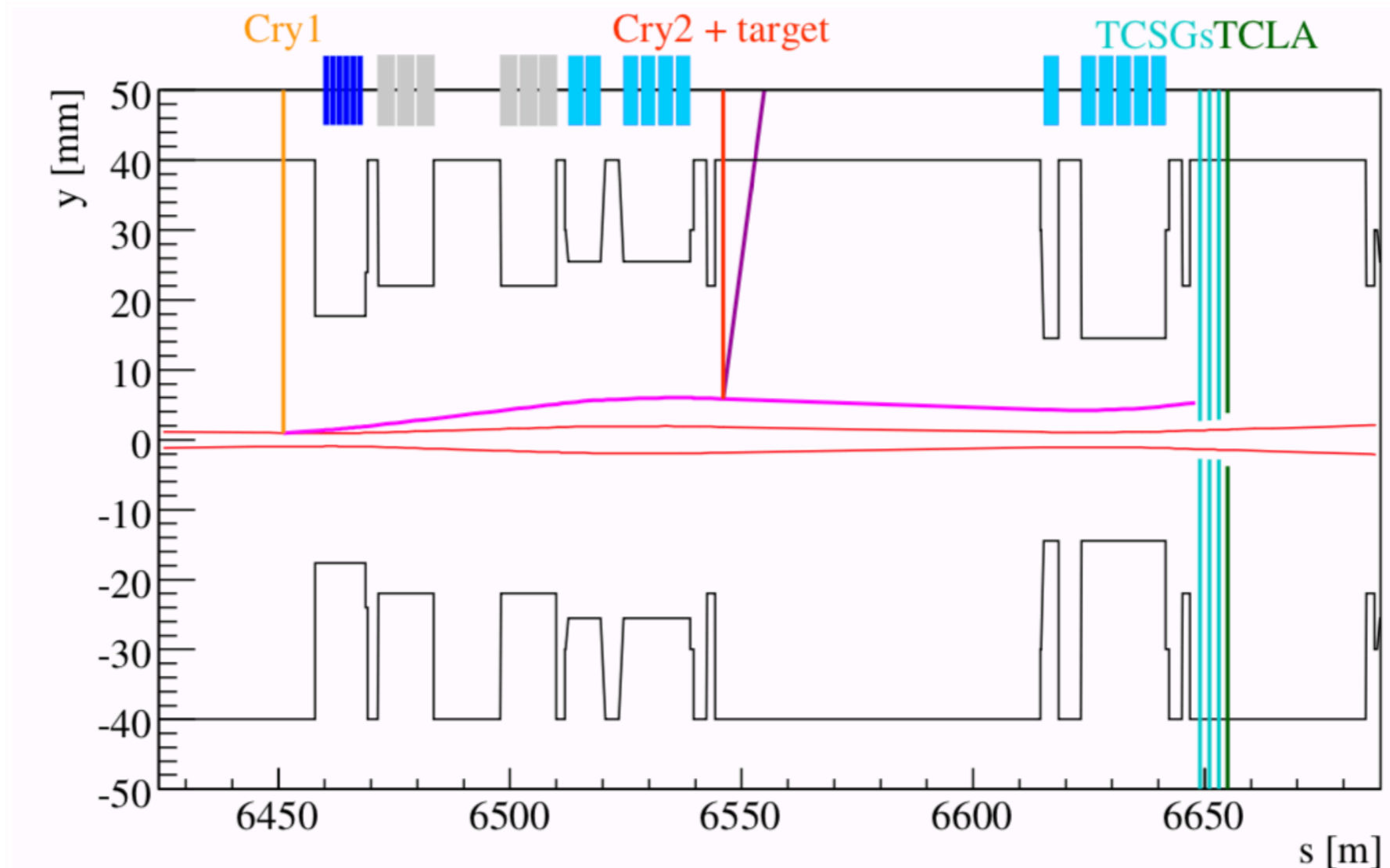

Signal events
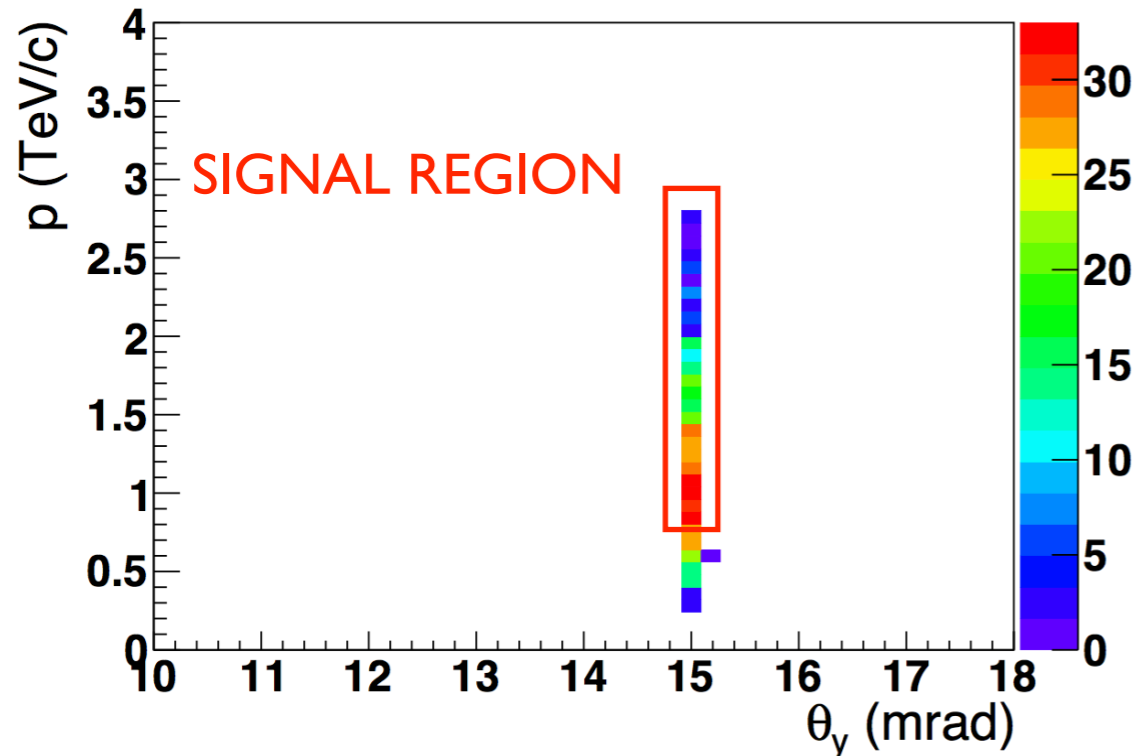
Crystal-transparent events
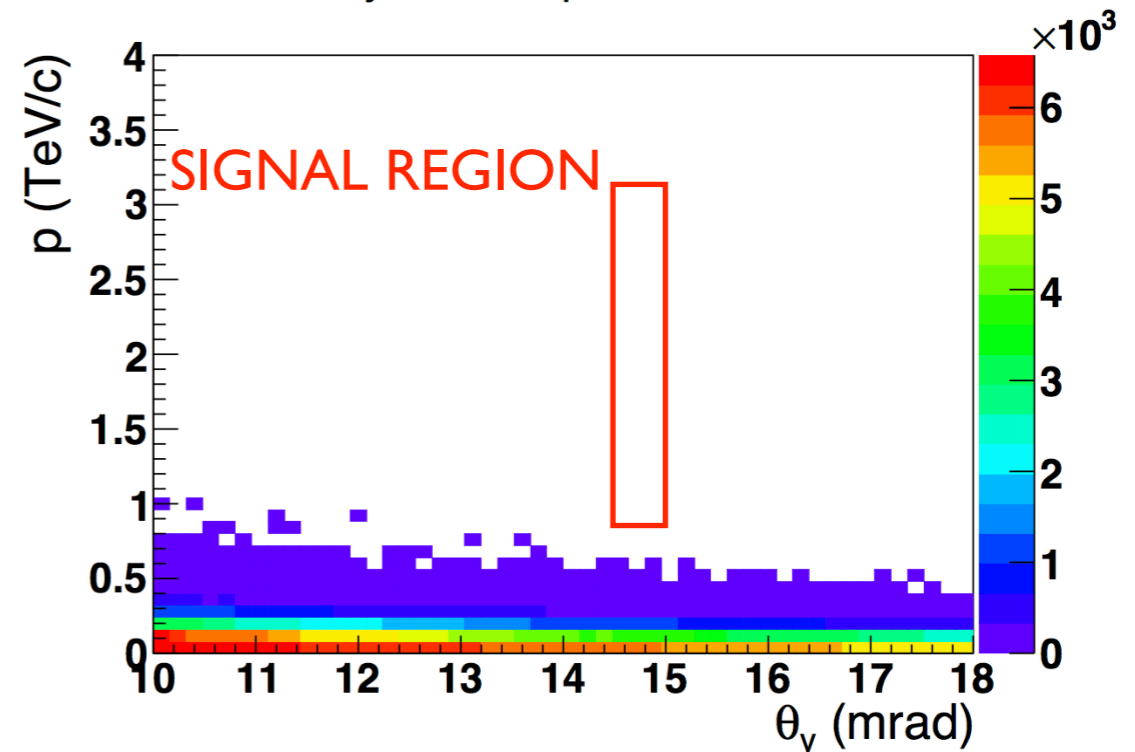
Channeled particles

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

Layout for dedicated experiment

*D. Mirarchi, A. S. Fomin, S. Redaelli, W. Scandale EPJC 80 (2020) 10, 929*
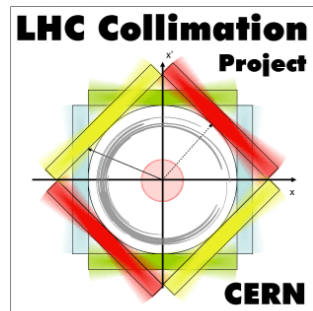
▸ At IR3 with optimised detector acceptance and reduced crystal bending (5 mrad), about x100 channeled particles can be achieved
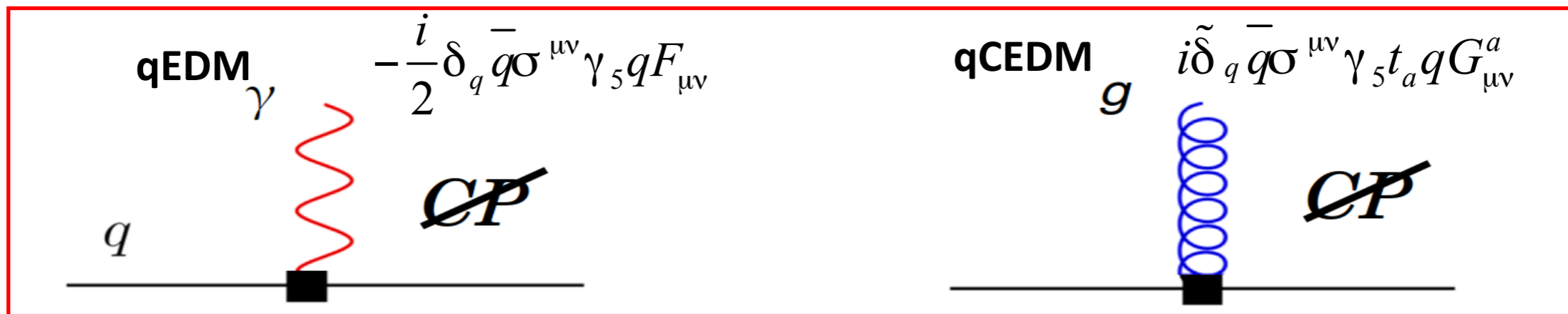
EDM/MDM sensitivity studies

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**

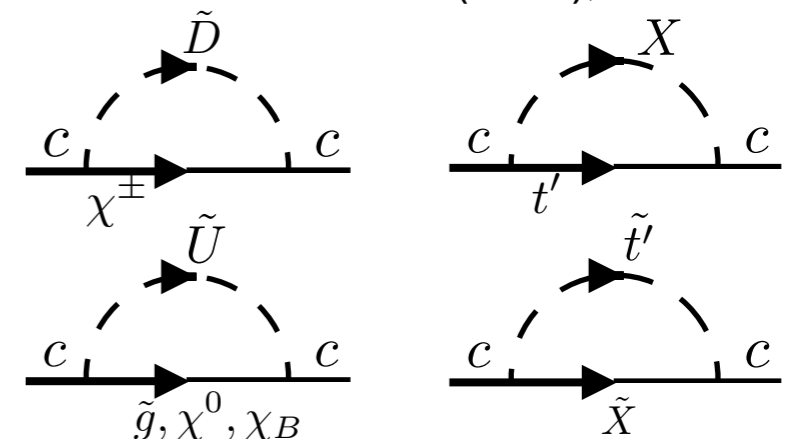▸ Measurement of MDM of particles and antiparticles for a **test of CPT symmetry**
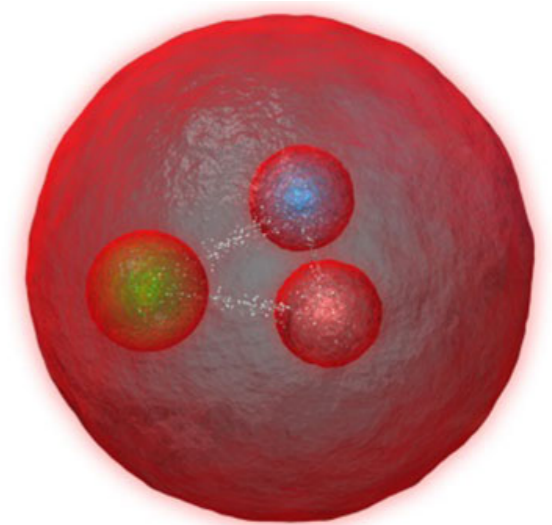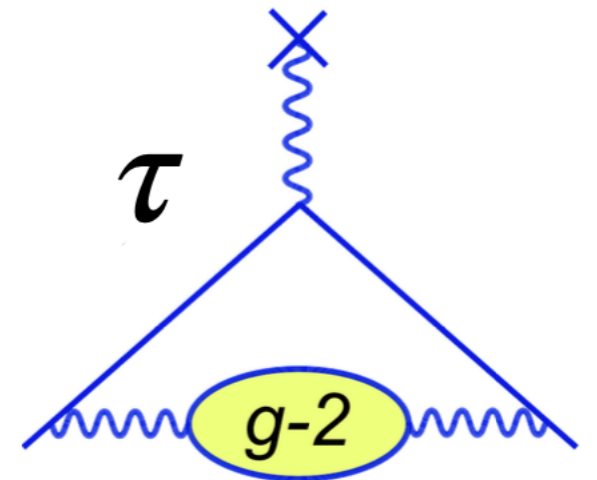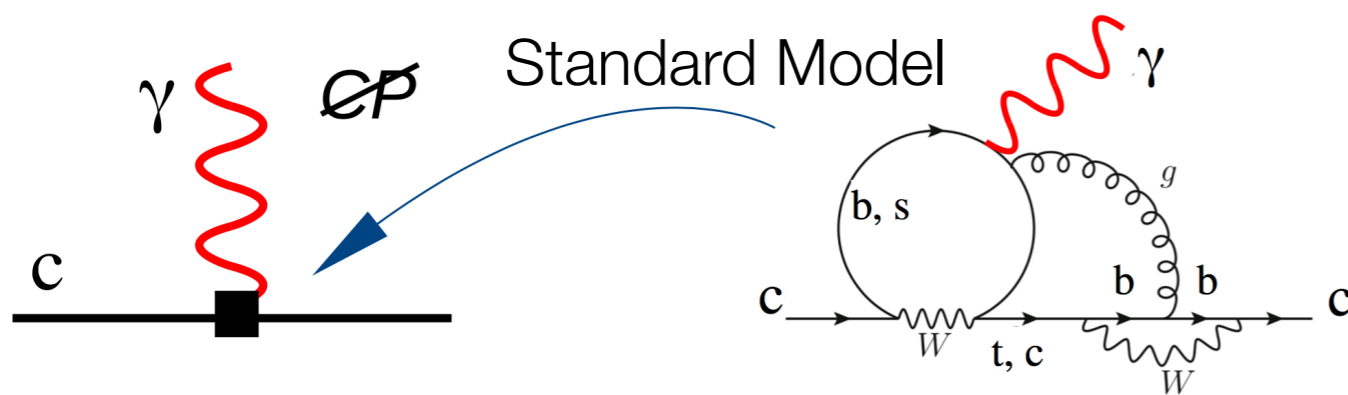
Heavy baryon EDM

- ► 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 γ $\quad -\dfrac{i}{2}\delta_q\,\bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu}$ $\qquad$ **qCEDM** g $\quad i\tilde{\delta}_q\,\bar{q}\sigma^{\mu\nu}\gamma_5 t_a q G^a_{\mu\nu}$

q $\quad \cancel{CP}$ $\qquad\qquad\qquad \cancel{CP}$

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

Khriplovich, Lamoreaux (1997)

Standard Model

γ $\quad \cancel{CP}$ $\qquad$ γ

c $\qquad$ b, s $\qquad$ g $\qquad$ c $\qquad$ b $\quad$ b $\qquad$ c

W $\quad$ t, c $\quad W$

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

EPJC 77 (2017), 102

$\tilde{D}$ $\qquad$ X

c $\quad \chi^{\pm} \quad$ c $\qquad$ $c \quad t' \quad c$

$\tilde{U}$ $\qquad$ $\tilde{t'}$

$c \quad \tilde{g},\chi^0,\chi_B \quad c \qquad c \quad \tilde{X} \quad c$

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

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
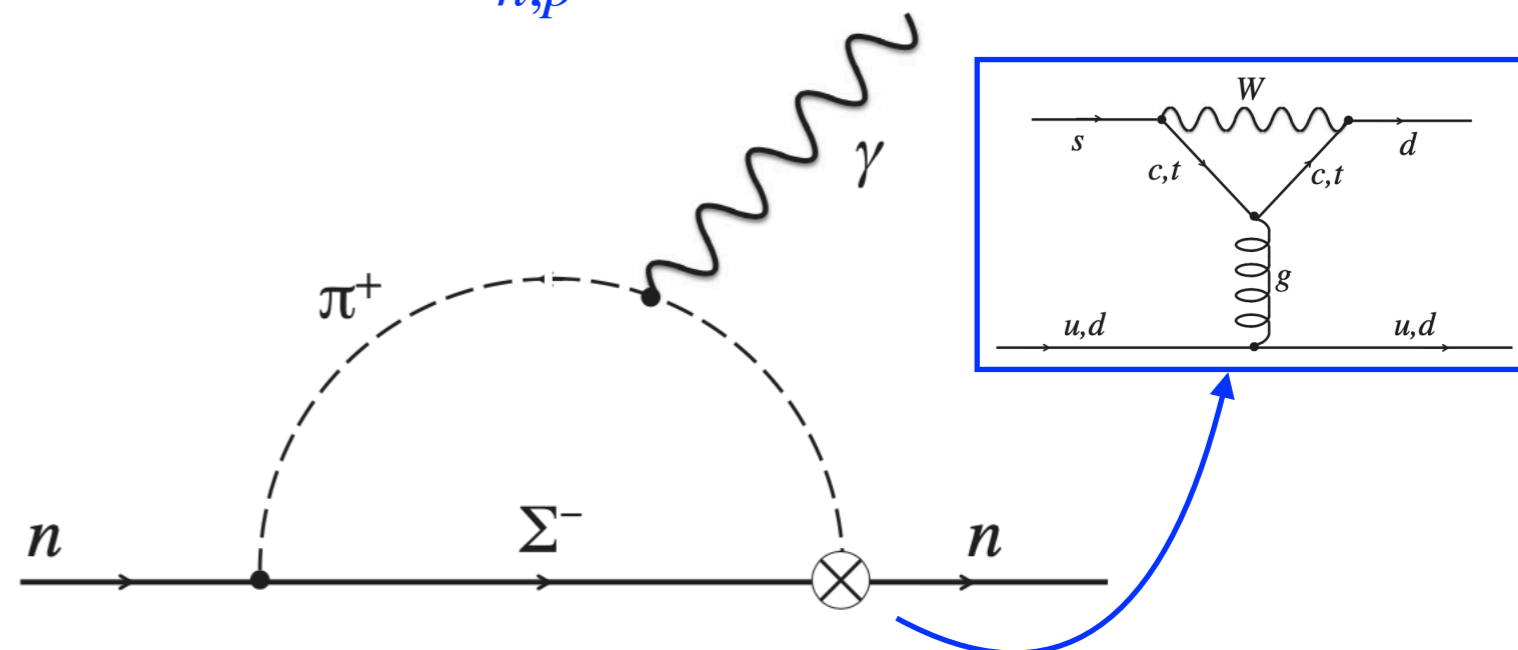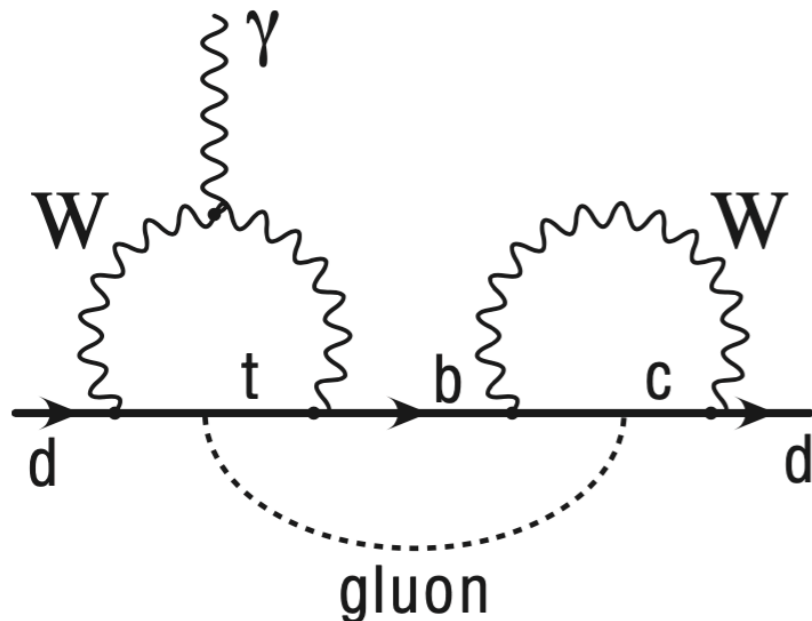
Example of SM CKM contributions

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

"Long distance" contribution
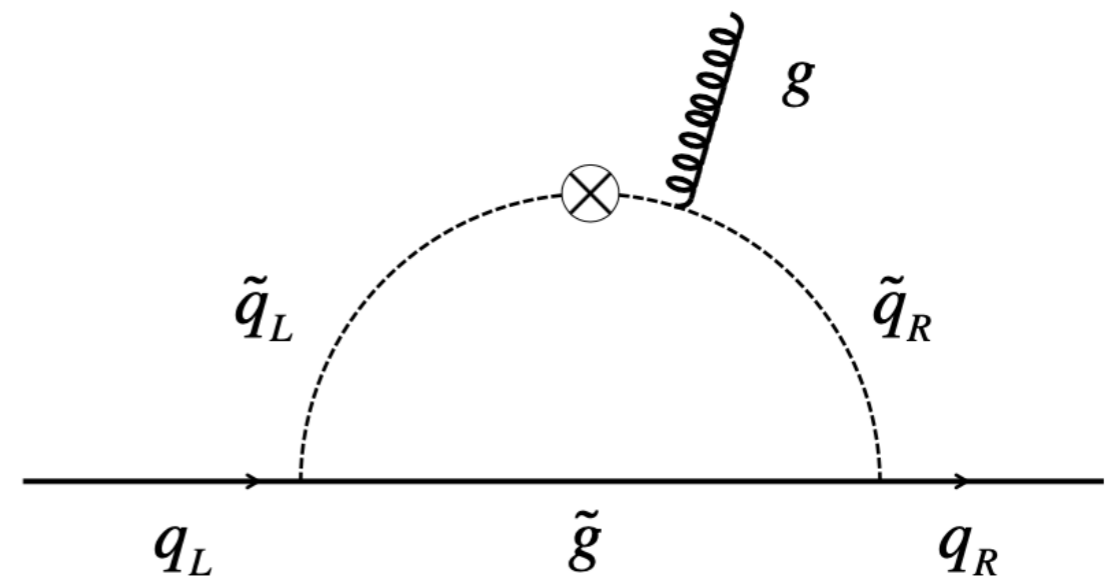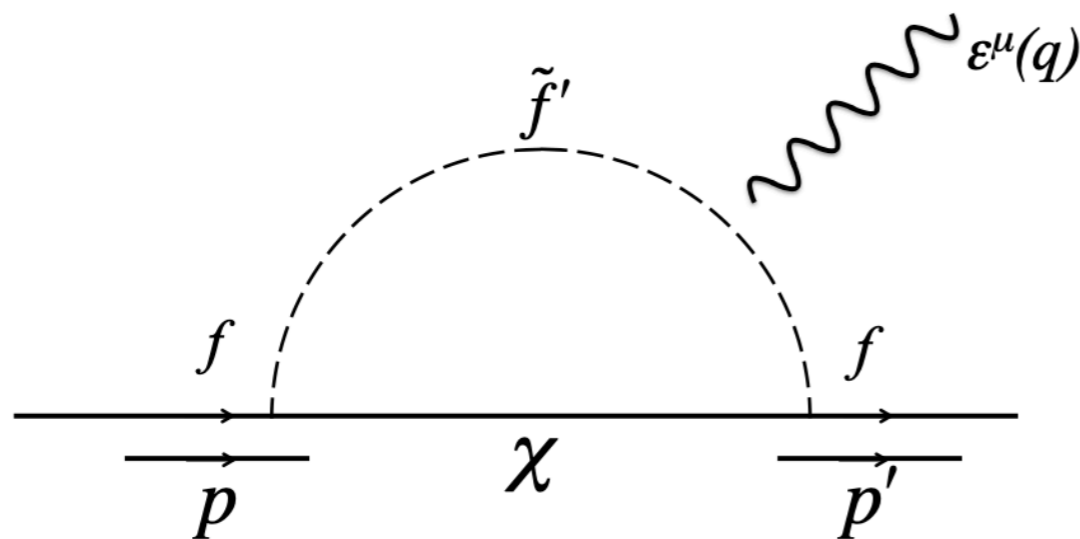
$$\delta_{n,p} \approx (1-6) \times 10^{-32} e\text{cm}$$

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}

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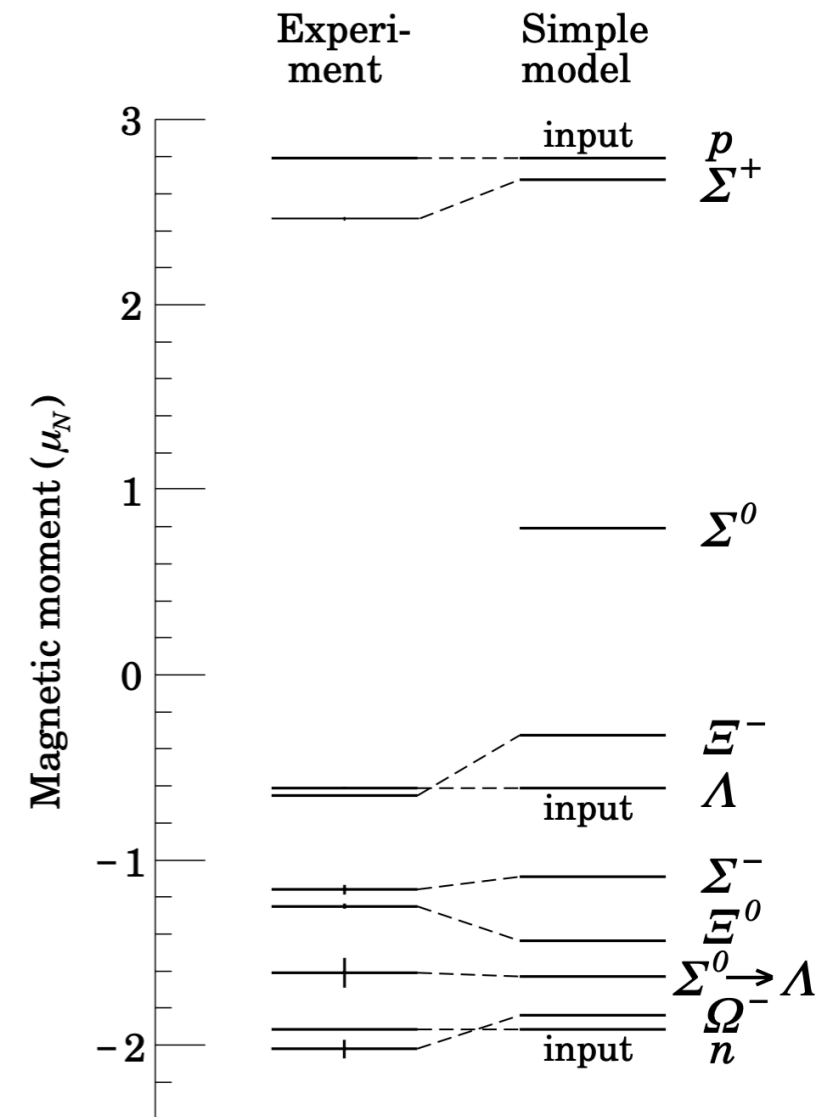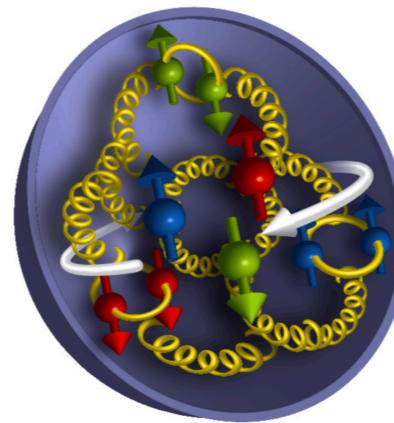
Examples of BSM contributions

Intrinsic MDM of baryons

- $g \neq 2$ due to internal substructure, not point-like fermions

- From baryon MDM to quark MDM using quark model

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

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

- ▶ 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

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)

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

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

$$|S_0| \approx 0.6$$

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

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

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

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

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

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

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
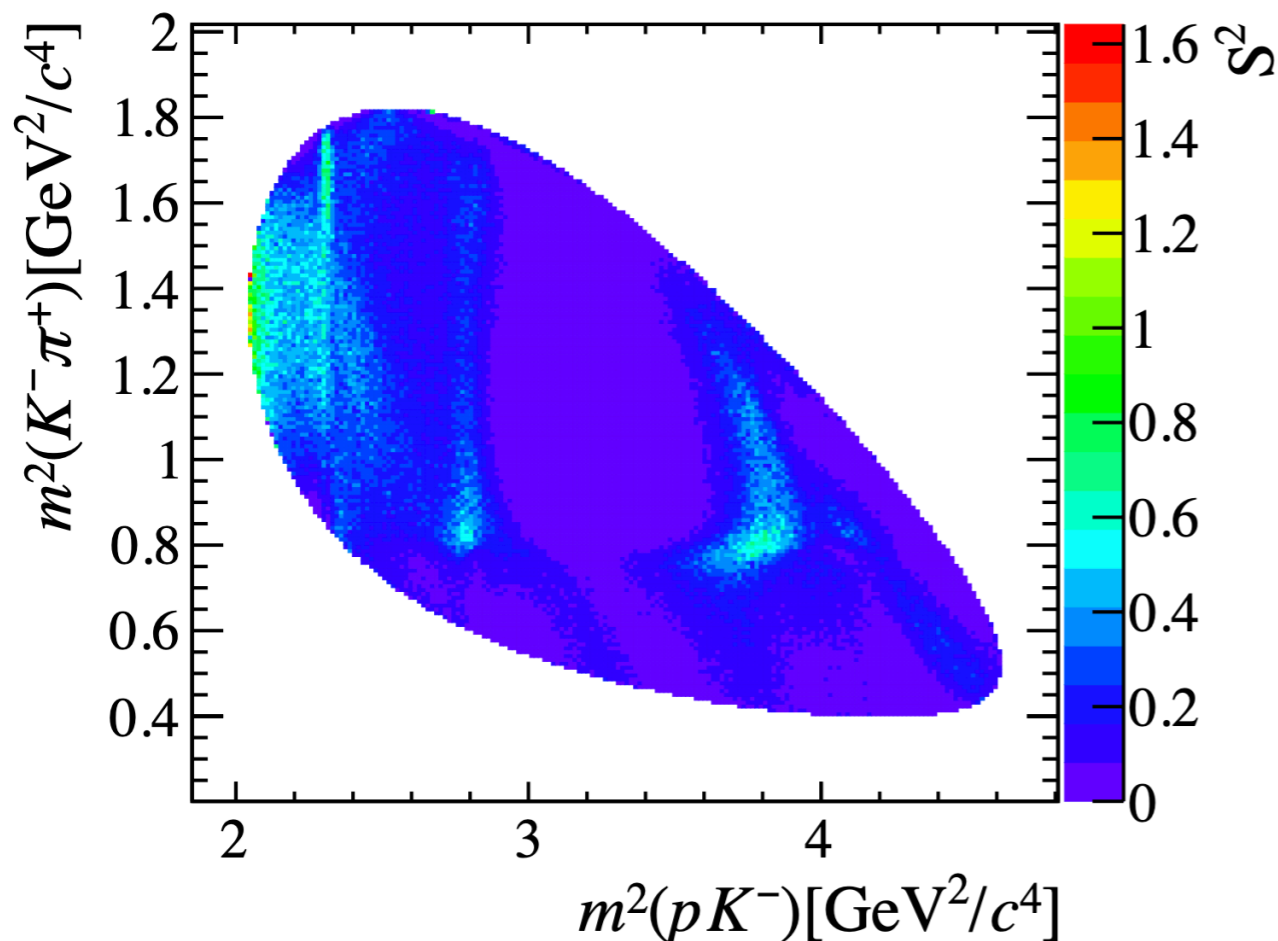
Decay distribution

PRD 103, 072003 (2021)

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

$\boldsymbol{\xi}$ = 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
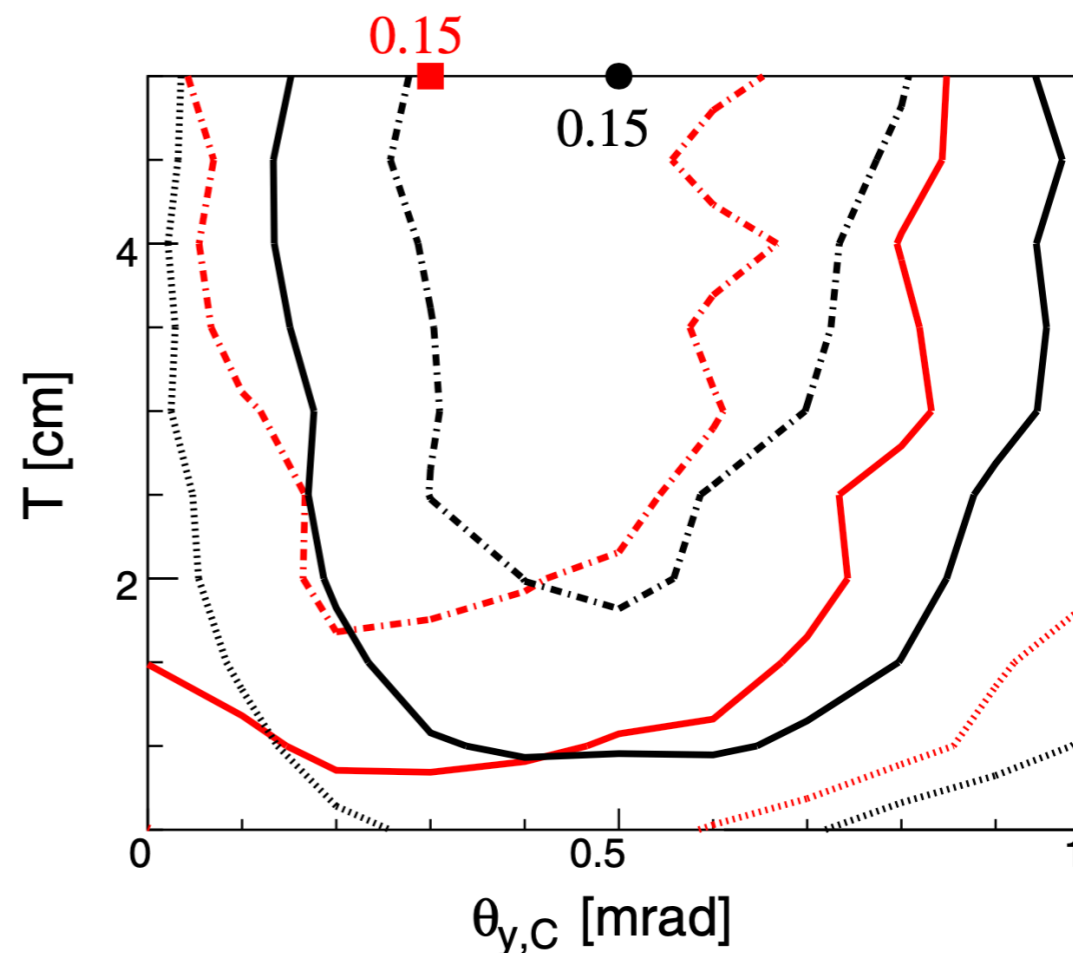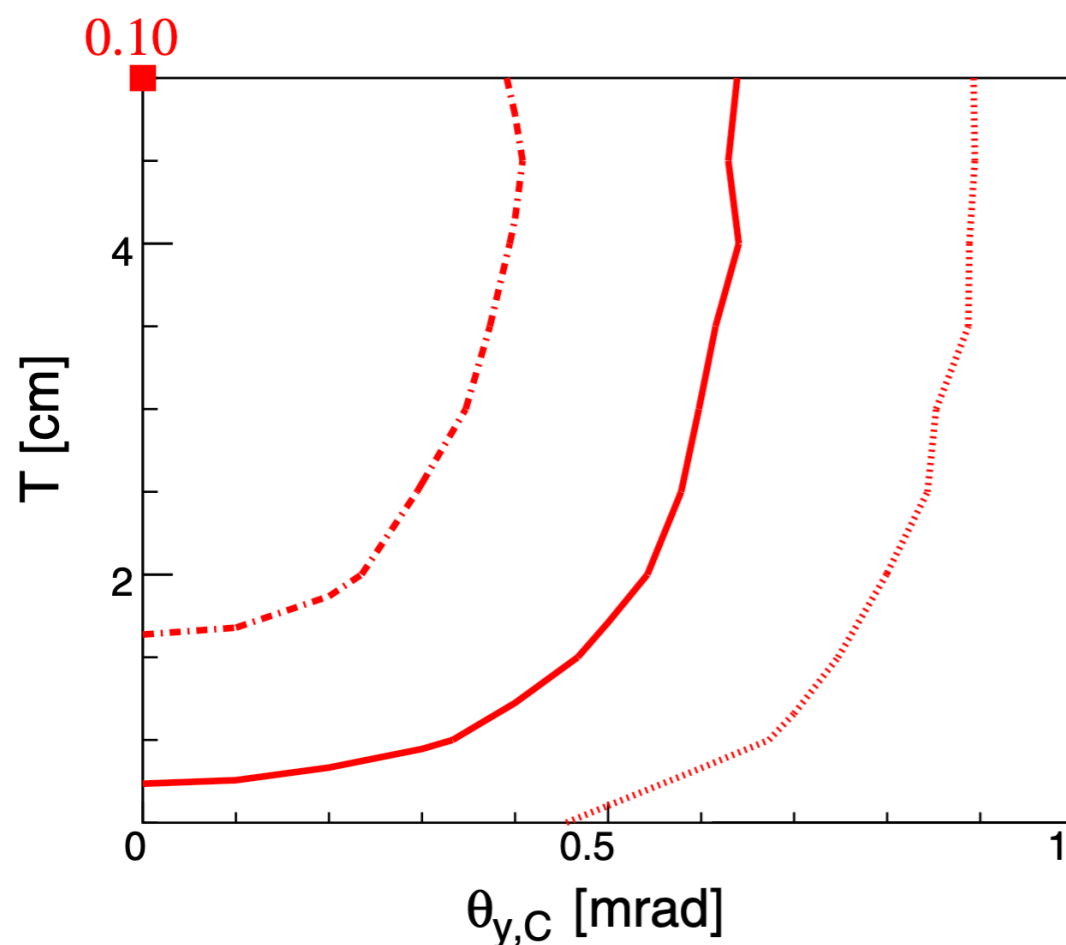

Regions of minimal uncertainty of **EDM** (black circle) and **MDM** (red square) defined as +20%, +50%, 100% uncertainty with respect to the minimum (point markers)

Channeling efficiency simulations

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)
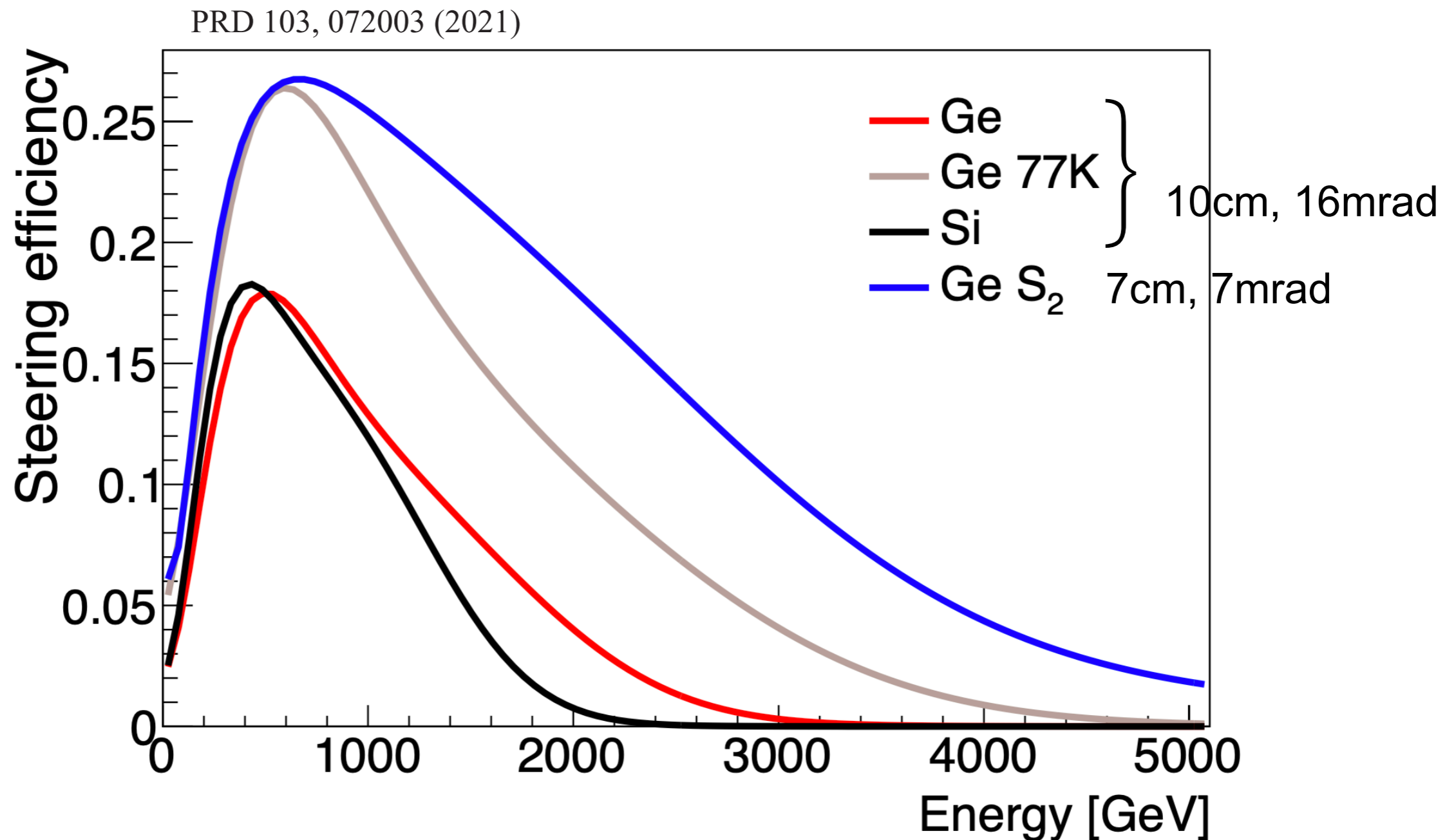
Channeling efficiency vs energy

PRD 103, 072003 (2021)

Si 8.0cm, 16.0 mrad
Ge 5.5cm, 14.7 mrad
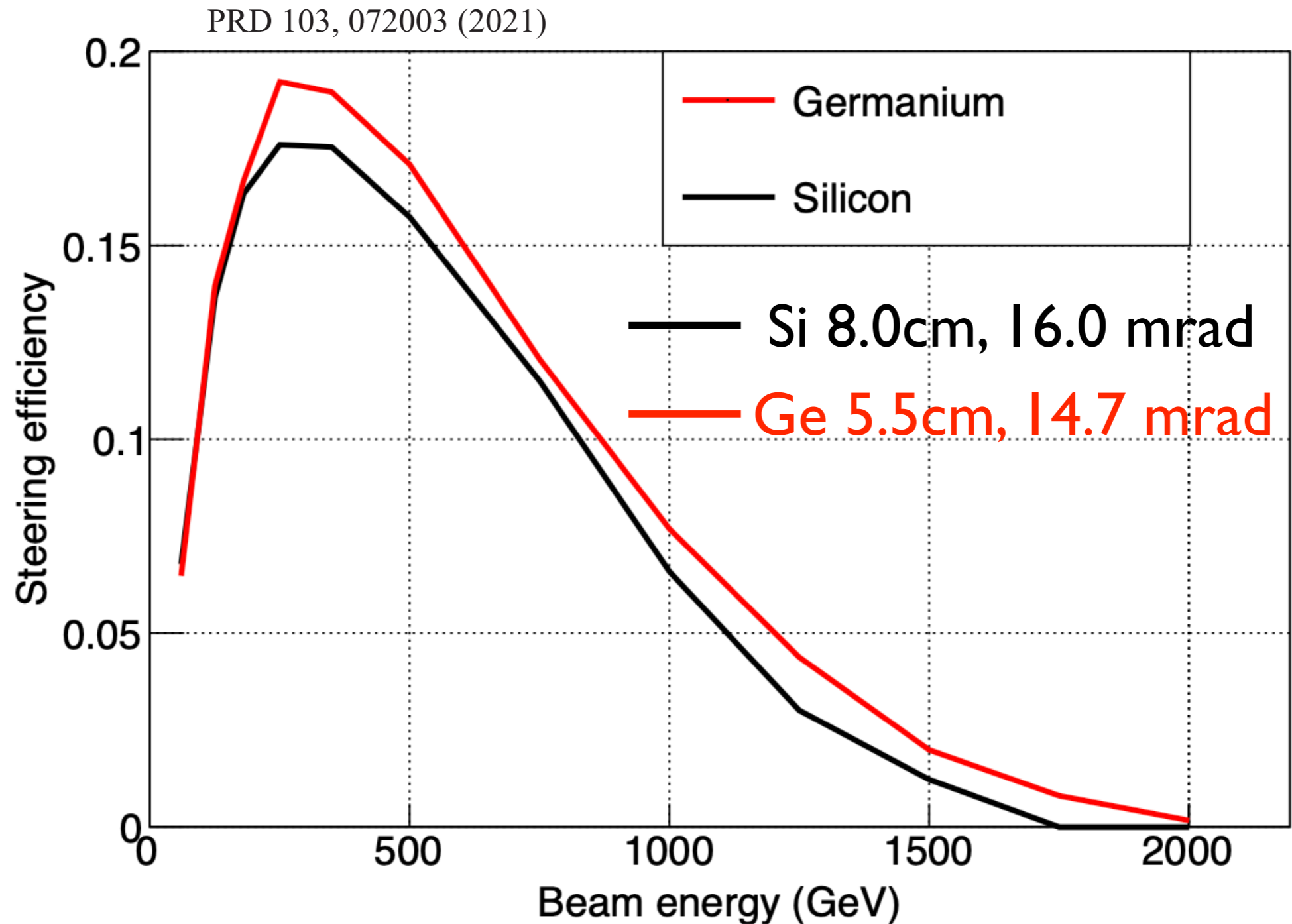
MDM of short-lived baryons

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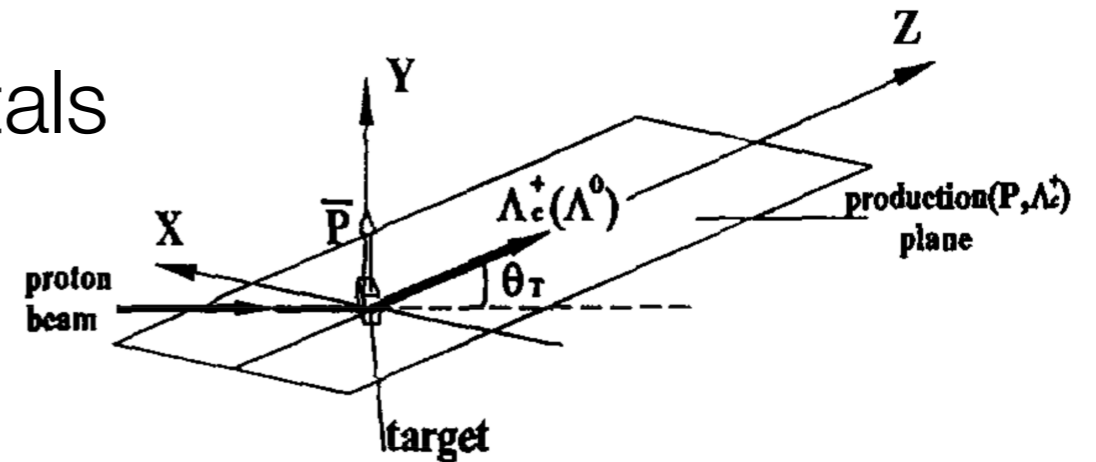
- A. S. Fomin et al., JHEP 08 (2017) 120

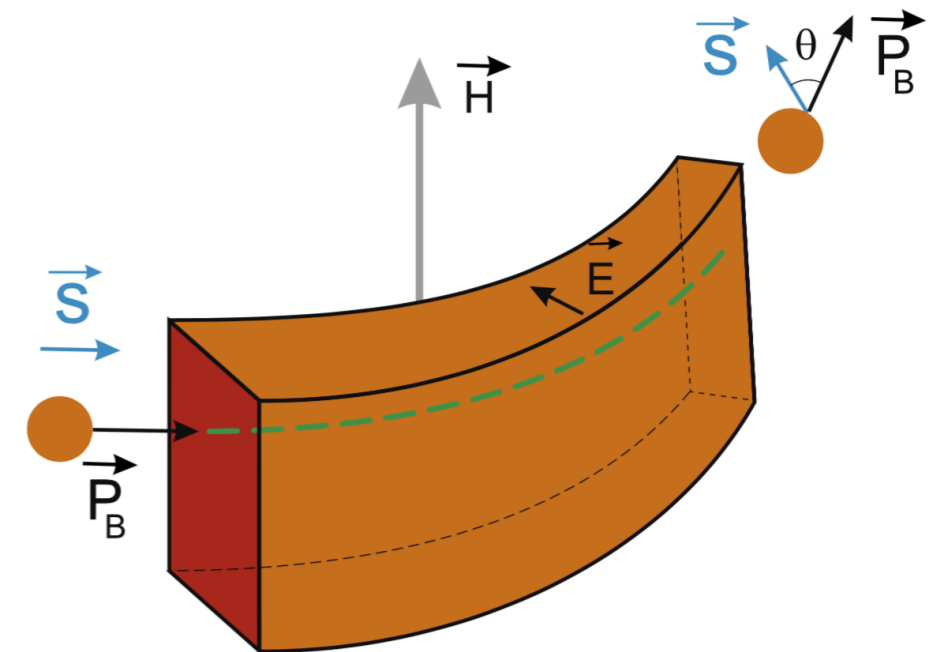Fig. 3. Schematic diagram of the Λ_c^+ (Λ^0) polarization production.

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

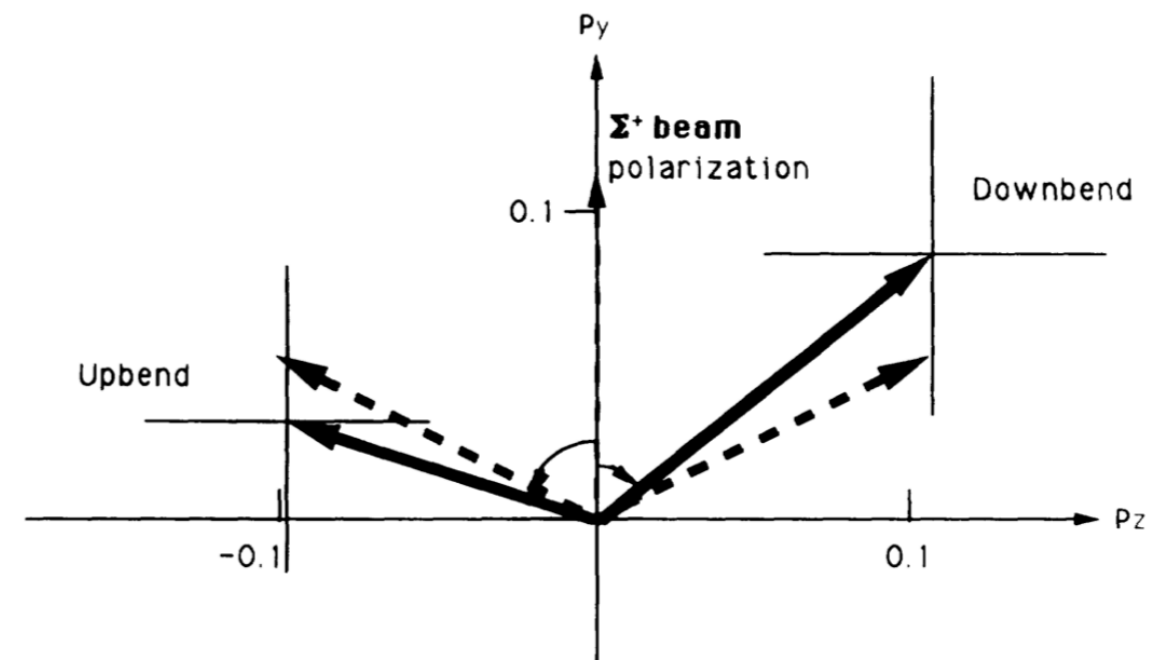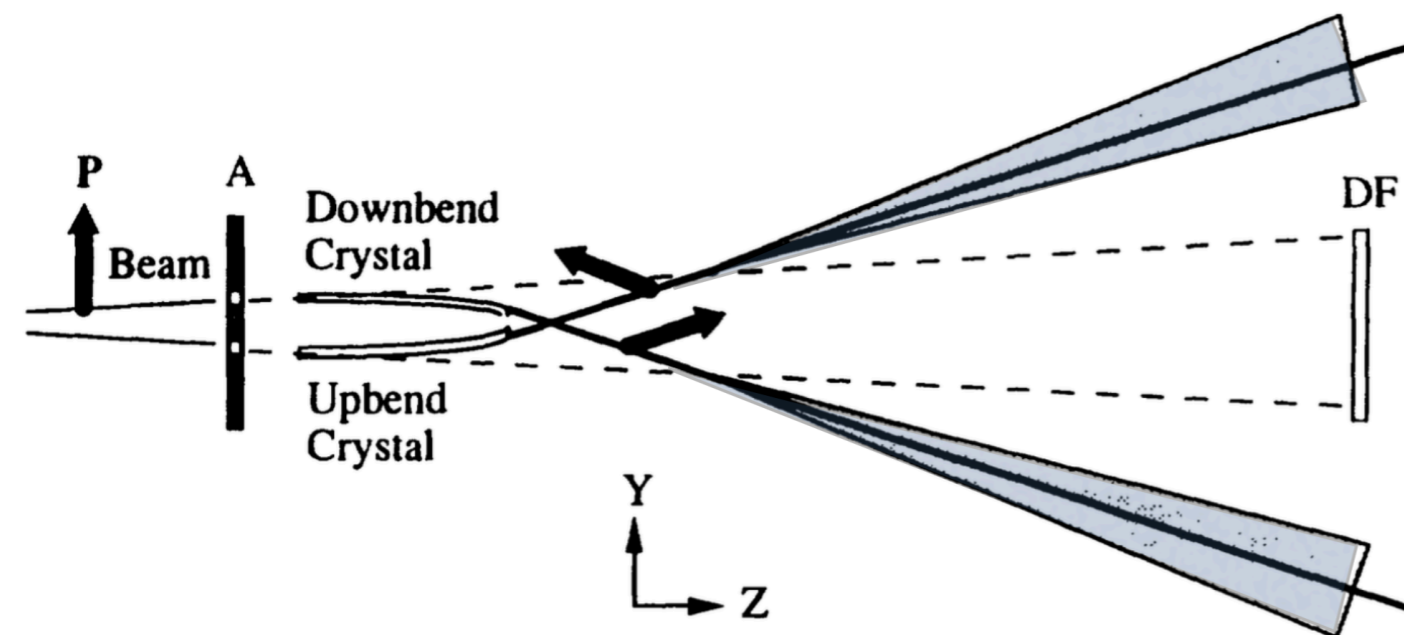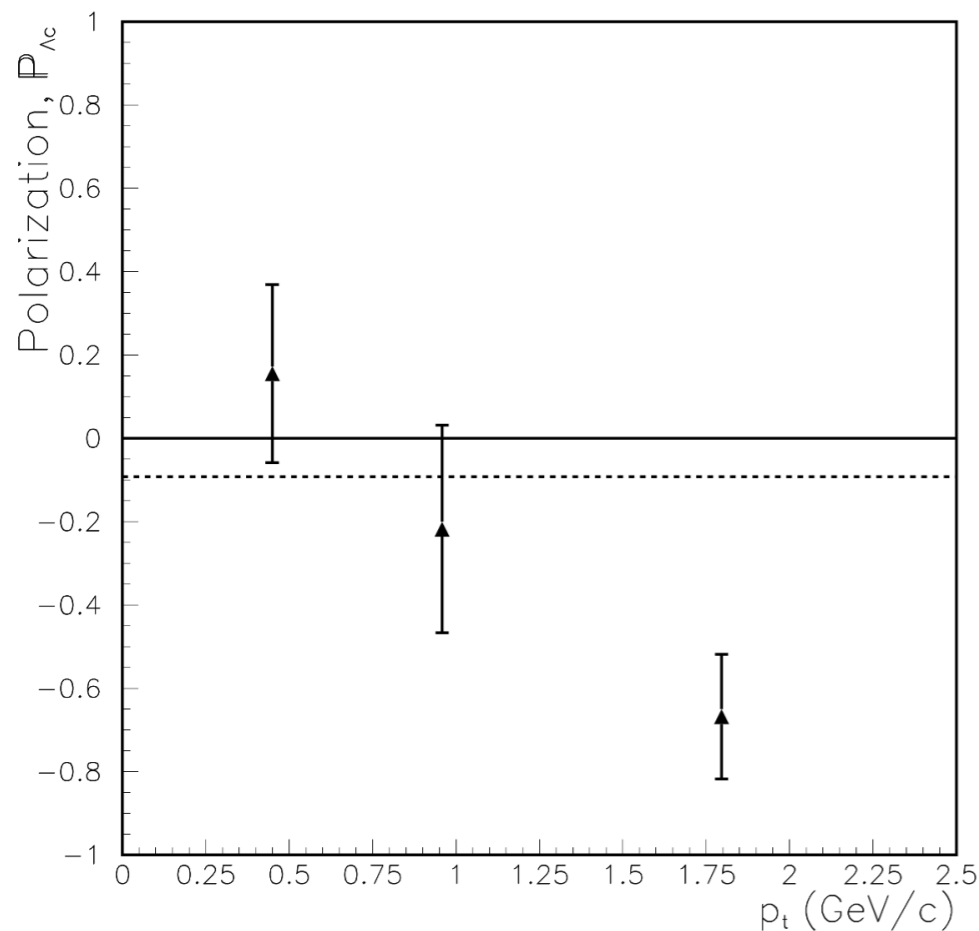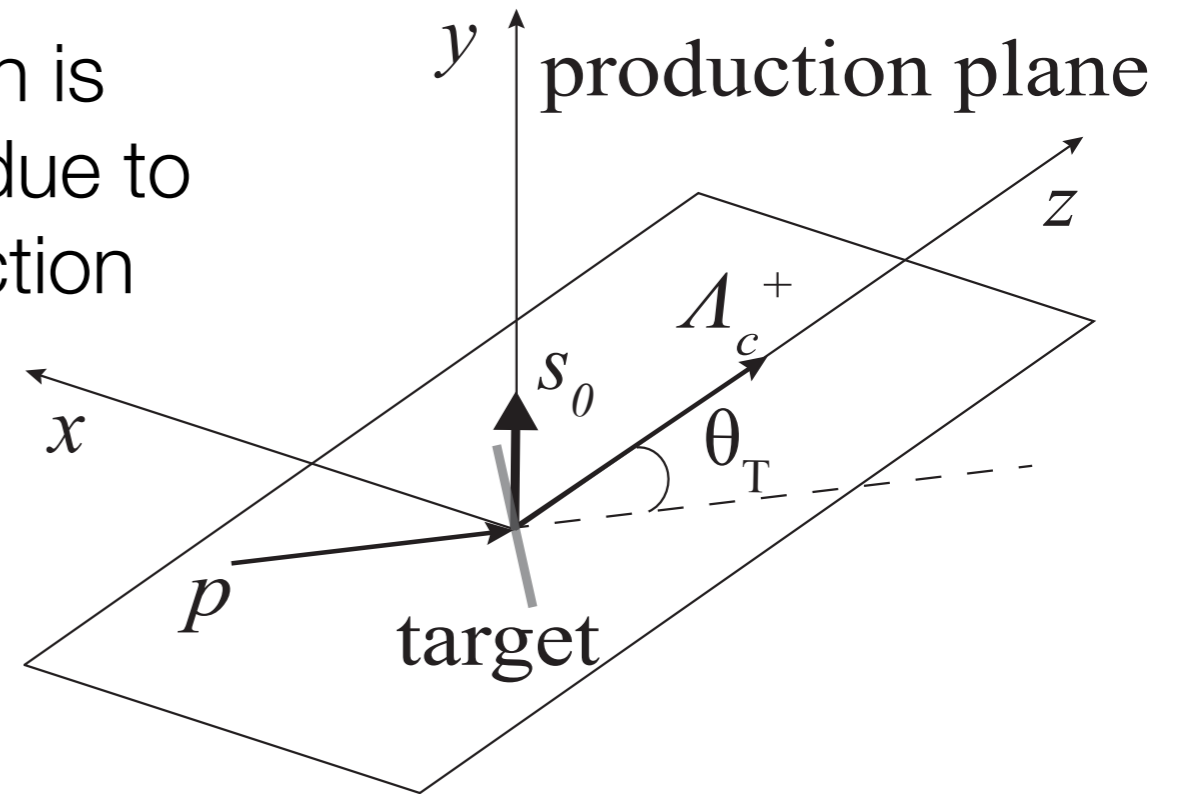FIG. 3. Measured polarizations and uncertainties (1σ statistical errors) after spins have been precessed by the two crystals. The dashed arrows show the expected precessions.

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