Prospects for direct measurements of short-lived particle dipole moments at the LHC

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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

Short CV

- 2005, PhD at University of Pisa
  - spent about 1 year at SLAC working in the BaBar experiment. Study of CP violation in B mesons
- 2005-2010, PostDoc in Pisa
  - BaBar experiment, SuperB project, R&D on silicon detectors
- 2011-2018, Staff Researcher at INFN Milano
  - LHCb experiment at CERN. Study of CP violation in b-hadrons. R&D on real-time tracking device
  - ERC CoG 2017 SELDOM
- 2017, Scientific Associate CERN

- Since 2018, Associate Professor at UNIMI
  - LHCb experiment
  - SELDOM project: dipole moments of strange and charm baryons

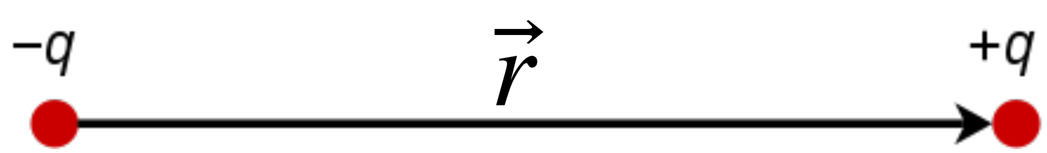
Introduction

What are magnetic and electric dipole moments of particles? Why are they interesting?

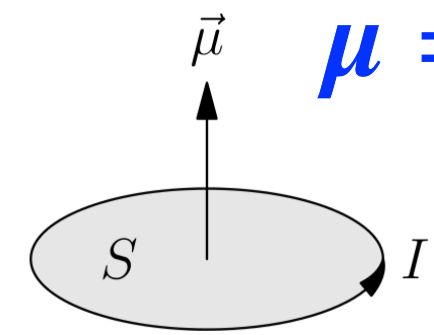
- Classic systems

$$\boldsymbol{\delta} = \int \mathbf{r}\rho(\mathbf{r})d^3r \qquad \boldsymbol{\mu} = \int \mathbf{r} \times \boldsymbol{j}(\mathbf{r})d^3r$$

$$\boldsymbol{\delta} = q\boldsymbol{r}$$



$$\boldsymbol{\mu} = I\boldsymbol{S}$$



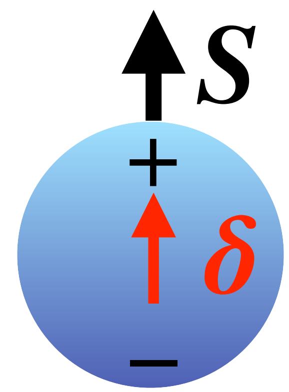
- Energy and torque

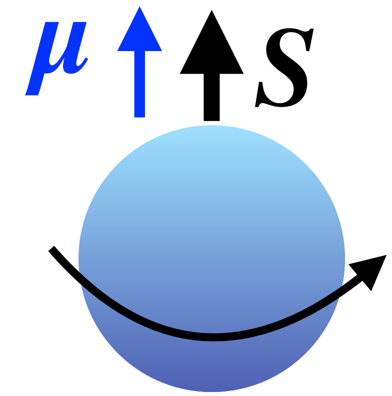
$$U = -\boldsymbol{\delta} \cdot \boldsymbol{E} \qquad U = -\boldsymbol{\mu} \cdot \boldsymbol{B}$$

$$\boldsymbol{\tau} = \boldsymbol{\delta} \times \boldsymbol{E} \qquad \boldsymbol{\tau} = \boldsymbol{\mu} \times \boldsymbol{B}$$

Introduction

- Quantum systems $\boldsymbol{\delta} = d \frac{q\hbar}{2m} \frac{\mathbf{S}}{\hbar}$ $\boldsymbol{\mu} = g \frac{q\hbar}{2m} \frac{\mathbf{S}}{\hbar}$





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

Particle magneton: $\mu = \frac{e\hbar}{2m}$

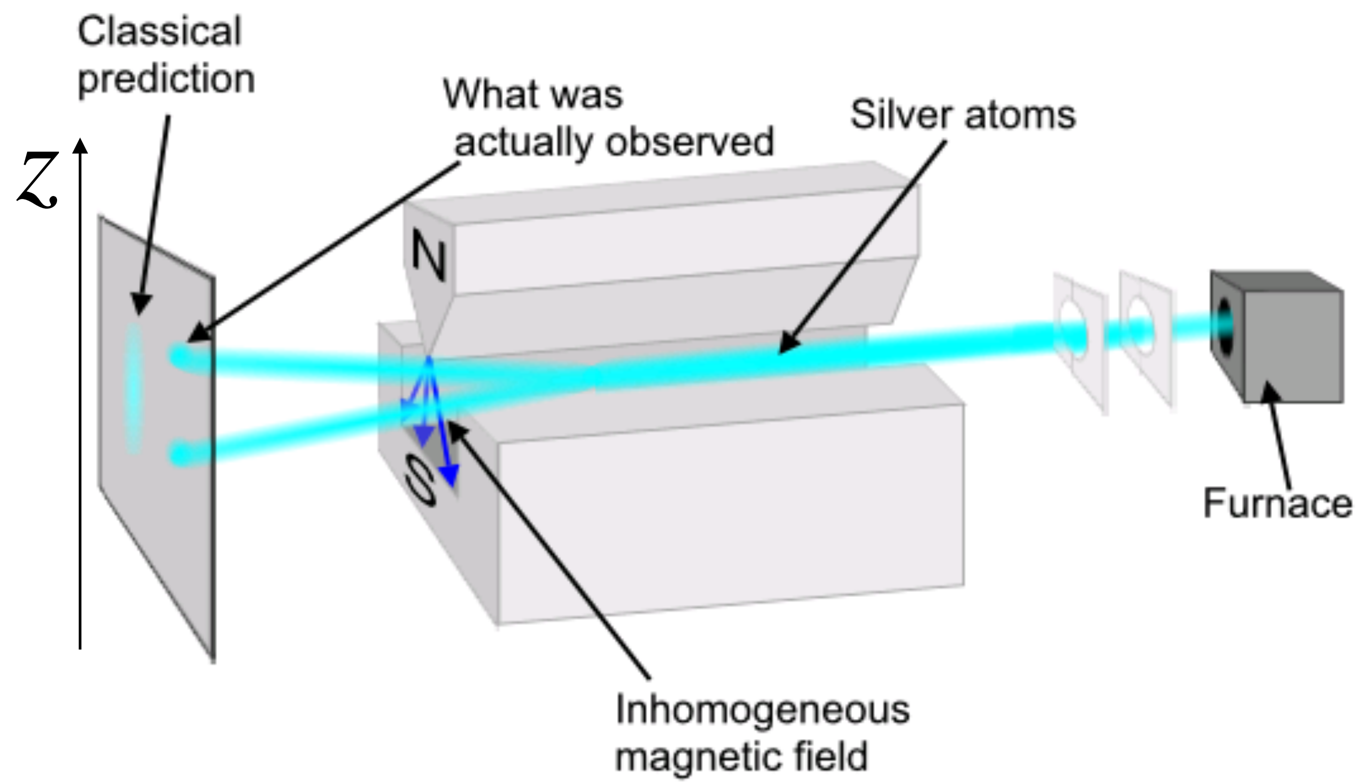
$\mu_B = \frac{e\hbar}{2m_e}$ Bohr magneton $\mu_N = \frac{e\hbar}{2m_p}$ nuclear magneton

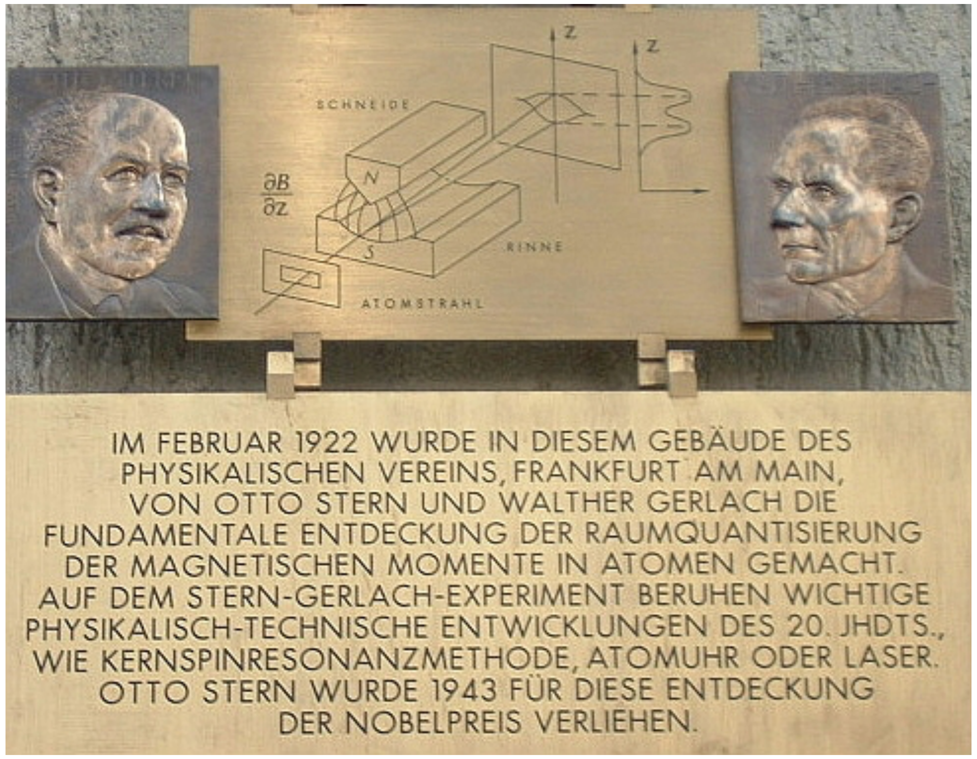
Stern-Gerlach experiment (1922)

The electron has intrinsic angular momentum, i.e. spin, and magnetic moment

$$\boldsymbol{\mu} \propto \boldsymbol{S}$$

$$F_z = \frac{\partial}{\partial z}(\boldsymbol{\mu} \cdot \boldsymbol{B}) \simeq \mu_z \frac{\partial B_z}{\partial z}$$

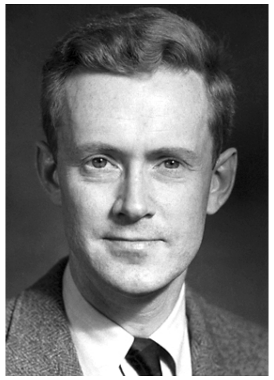




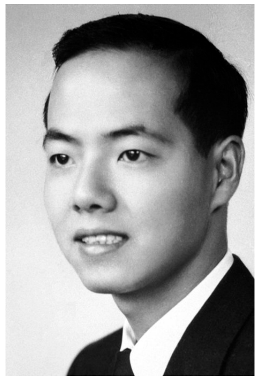
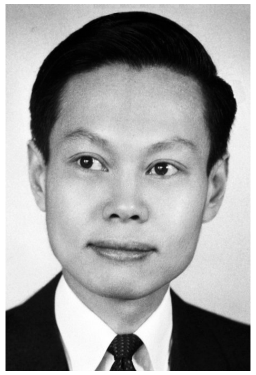
Plaque at the Frankfurt institute commemorating the experiment that strongly influenced developments in modern physics

Particle EDM and *P*/*T* violation

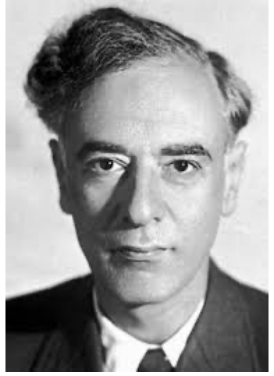
- E. M. Purcell, N.F. Ramsey, Phys. Rev. 78, 807 (1950)
  - particle EDM violates *P* symmetry




- T. D. Lee, C. N. Yang, Phys. Rev. 104, 254 (1956)
  - question of parity conservation in weak interactions
  - also particle EDM as experimental test of *P* symmetry

- L. Landau, Nucl. Phys. 3, 127 (1957)
  - particle EDM violates both *P* and *T* symmetries
  - *CPT* invariance implies EDM violates CP



Discrete symmetries

Charge conjugation: $C\psi = \overline{\psi}$

Parity: $P\psi(\vec{r}) = \psi(-\vec{r})$

Time reversal: $T\psi(t) = \psi^*(-t)$

Hamiltonian

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

Time reversal, Parity:

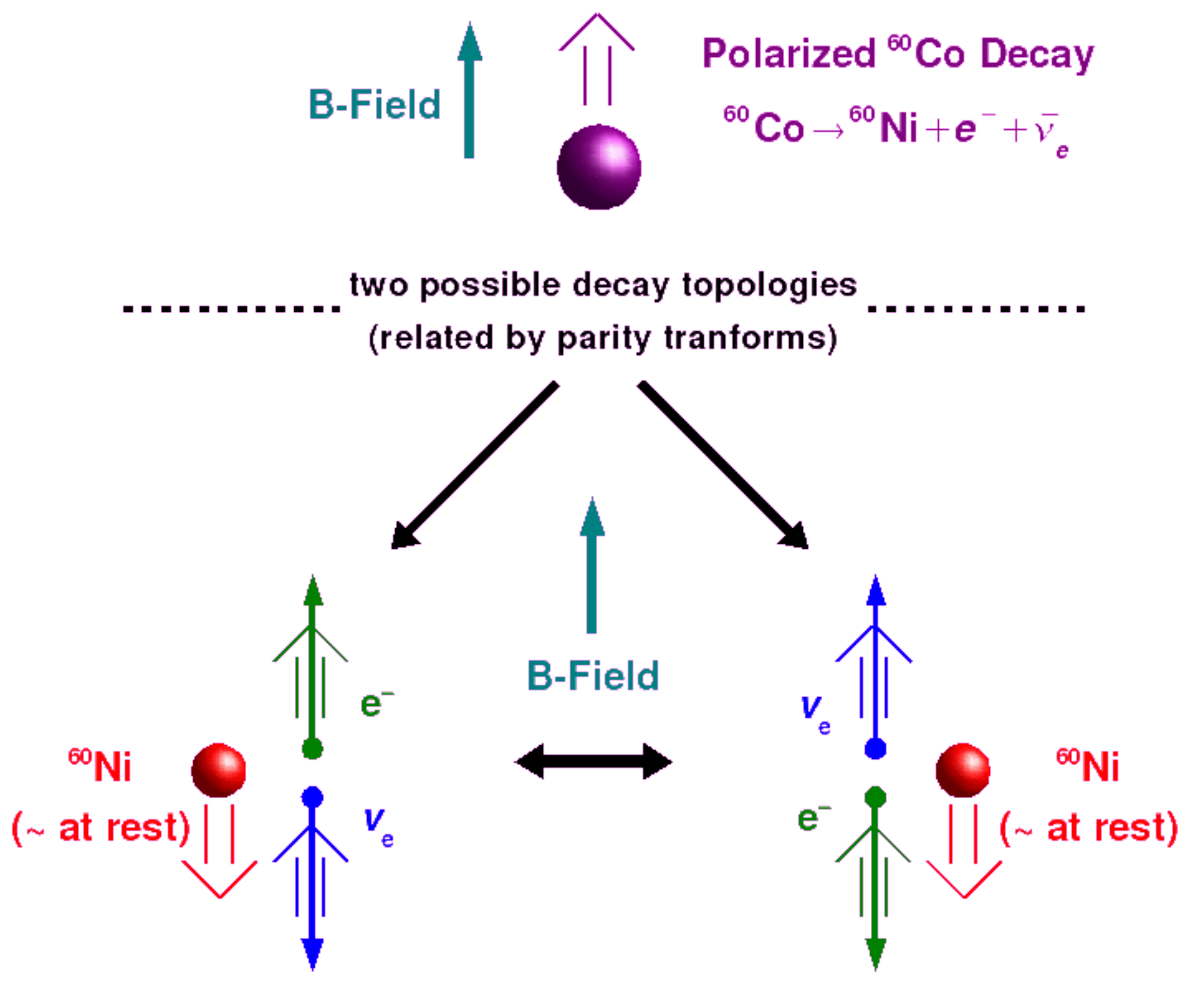
$$d\mu_N \boldsymbol{S} \cdot \boldsymbol{E} \xrightarrow{T,P} -d\mu_N \boldsymbol{S} \cdot \boldsymbol{E}$$

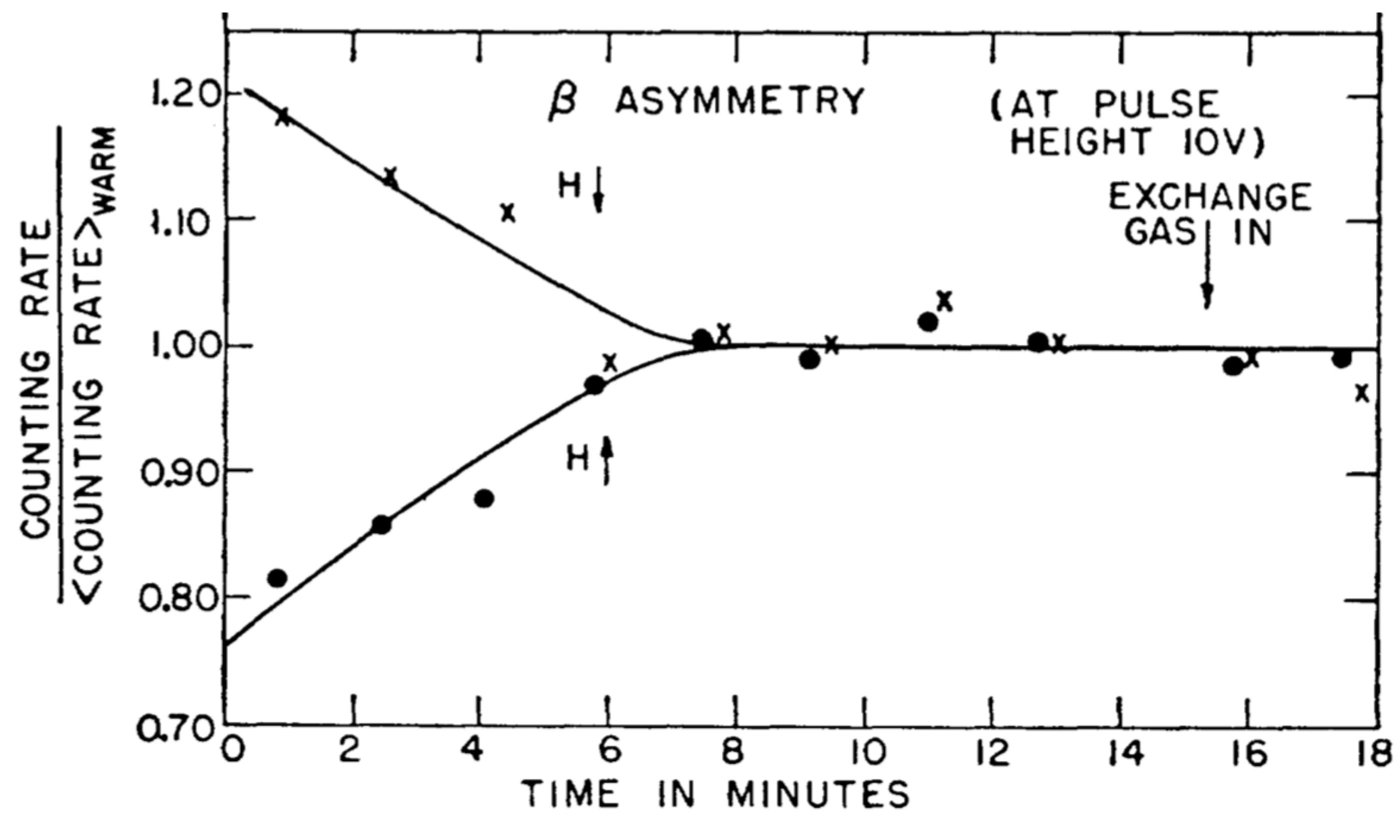
	C	P	T
$\boldsymbol{\mu}$	–	+	–
$\boldsymbol{\delta}$	–	+	–
E	–	–	+
B	–	+	–
S	+	+	–

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

Discovery of P violation (1957)

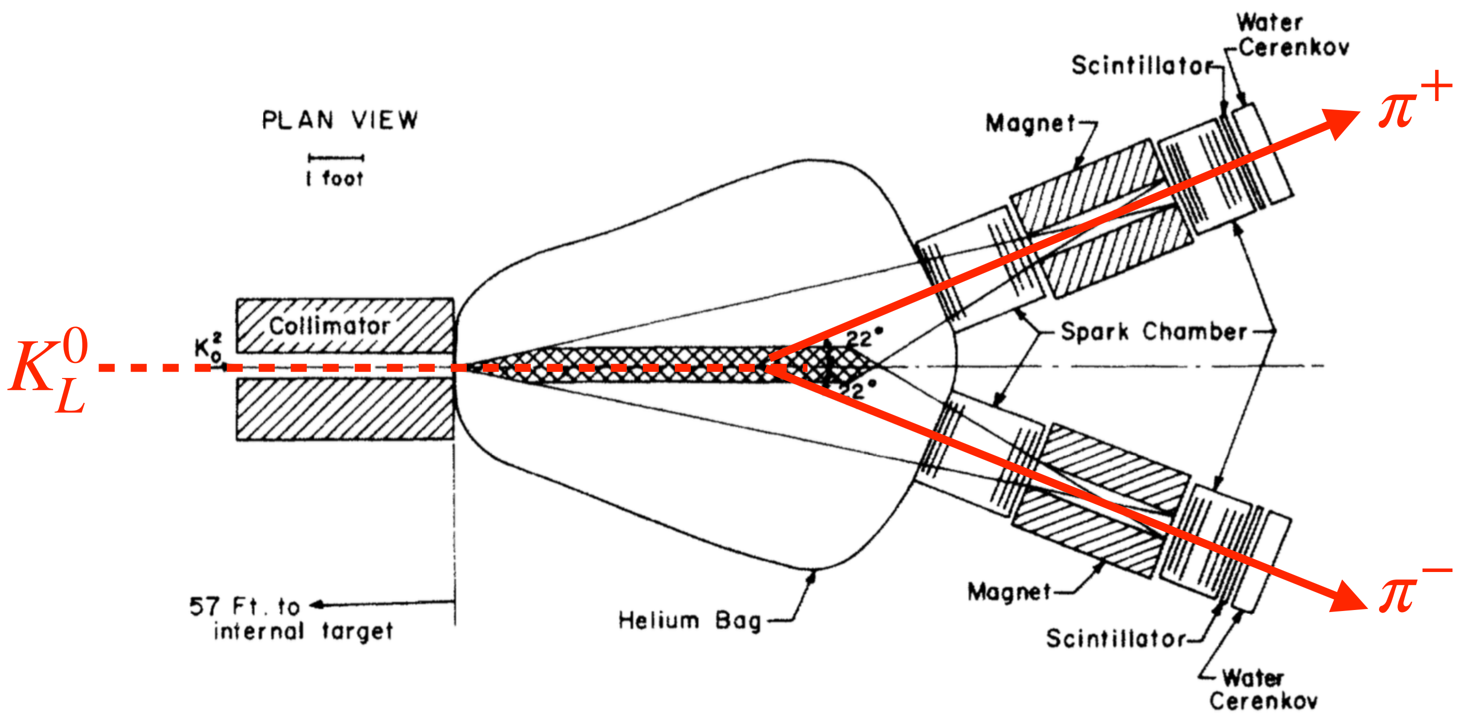
- C. S. Wu et al., Phys. Rev. 105, 1413 (1957)
  - Observation of P violation in ^{60}Co weak decays

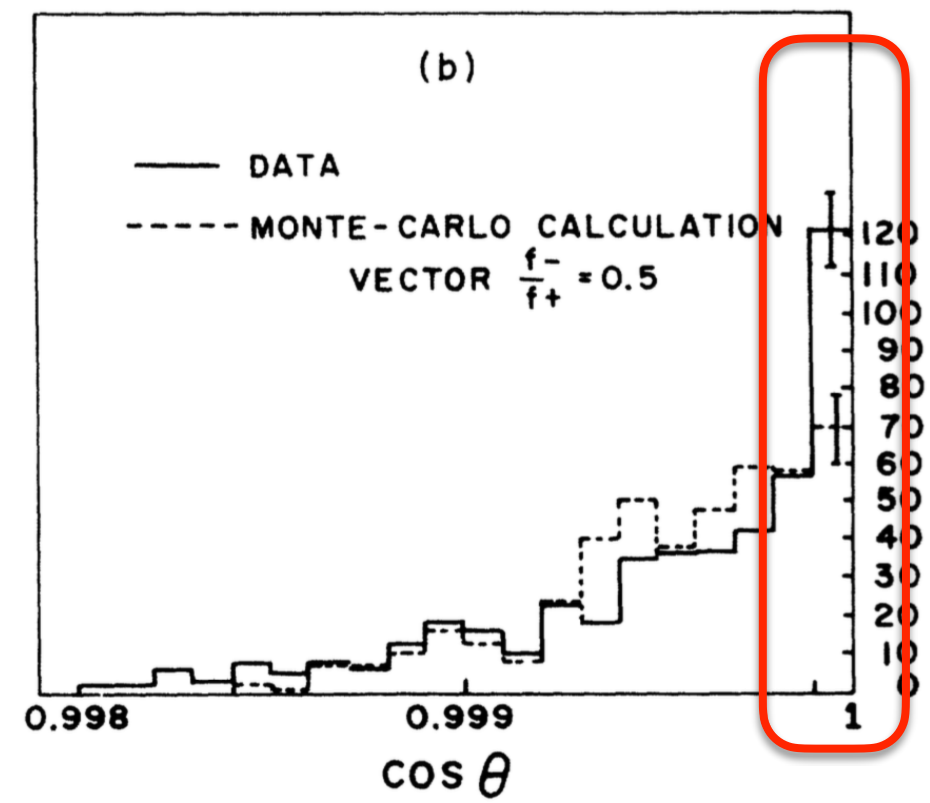




Discovery of CP violation (1964)

- J. H. Christenson, J. W. Cronin, V. L. Fitch, R. Turlay, Phys. Rev. Lett. 13, 138 (1964)
  - Observation of *CP* violation in neutral K meson decays



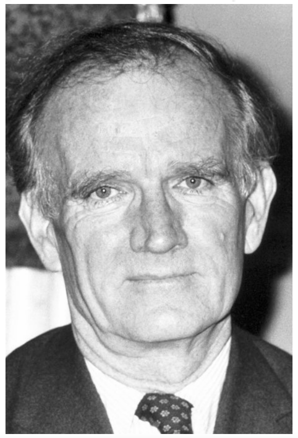


If *CP* is conserved:

$K_S \rightarrow \pi\pi$, *CP*=+1 eigenstate

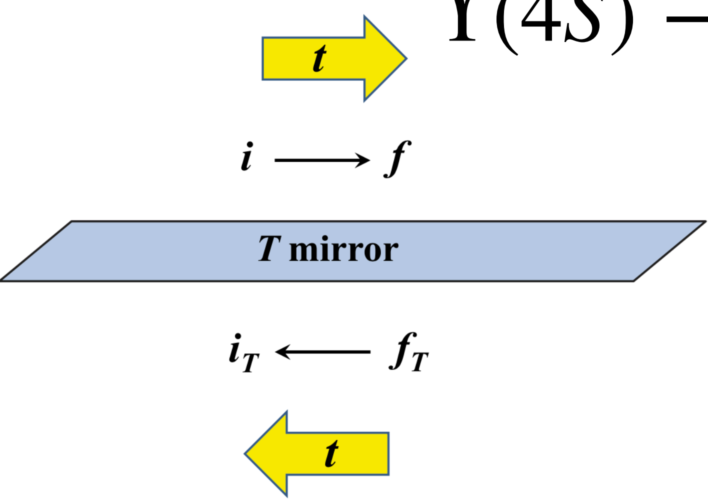
$K_L \rightarrow \pi\pi\pi$, *CP*=−1 eigenstate

Observation of $K_L \rightarrow \pi\pi$ decays implies *CP* violation

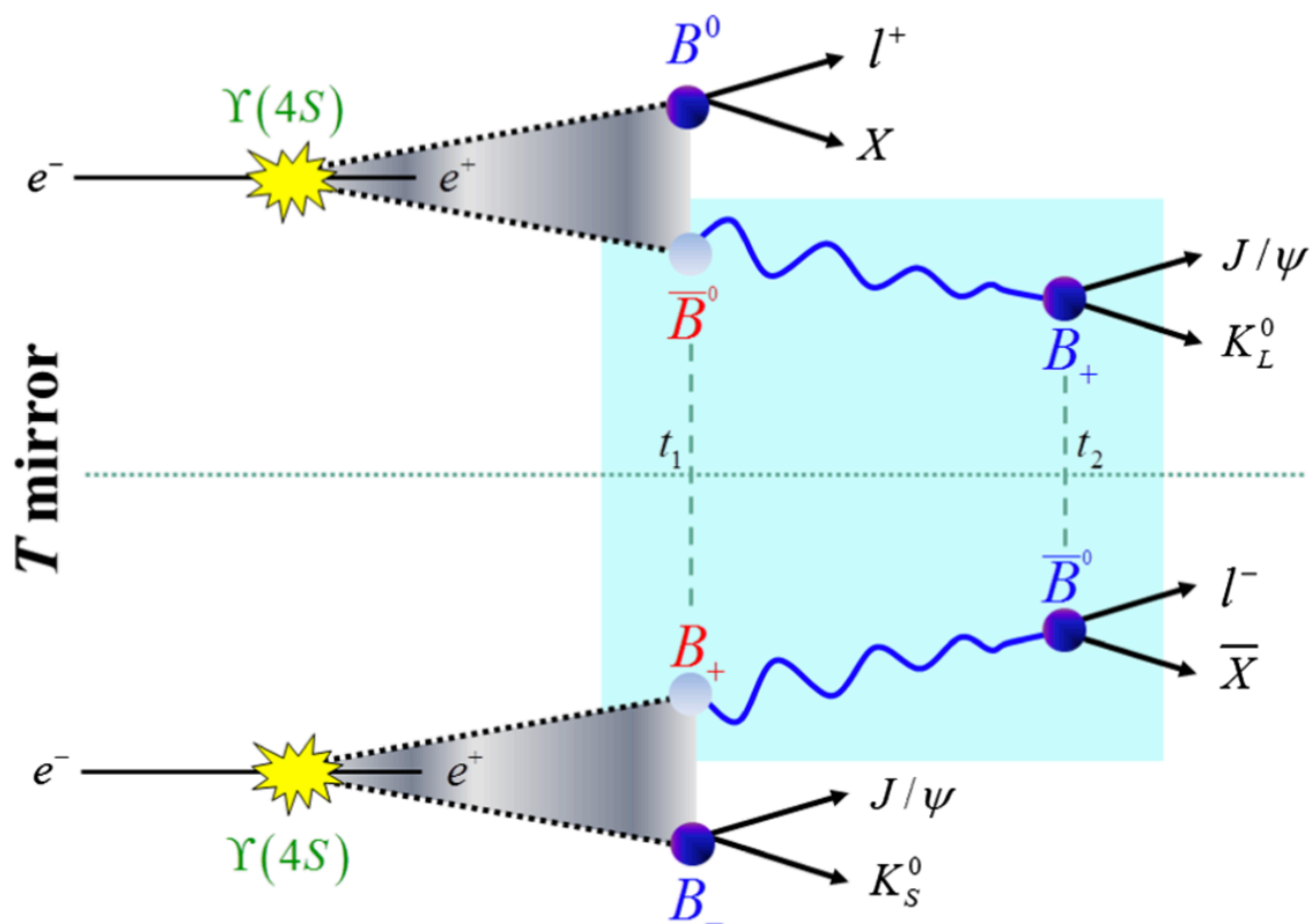


Direct *T* violation (2012)

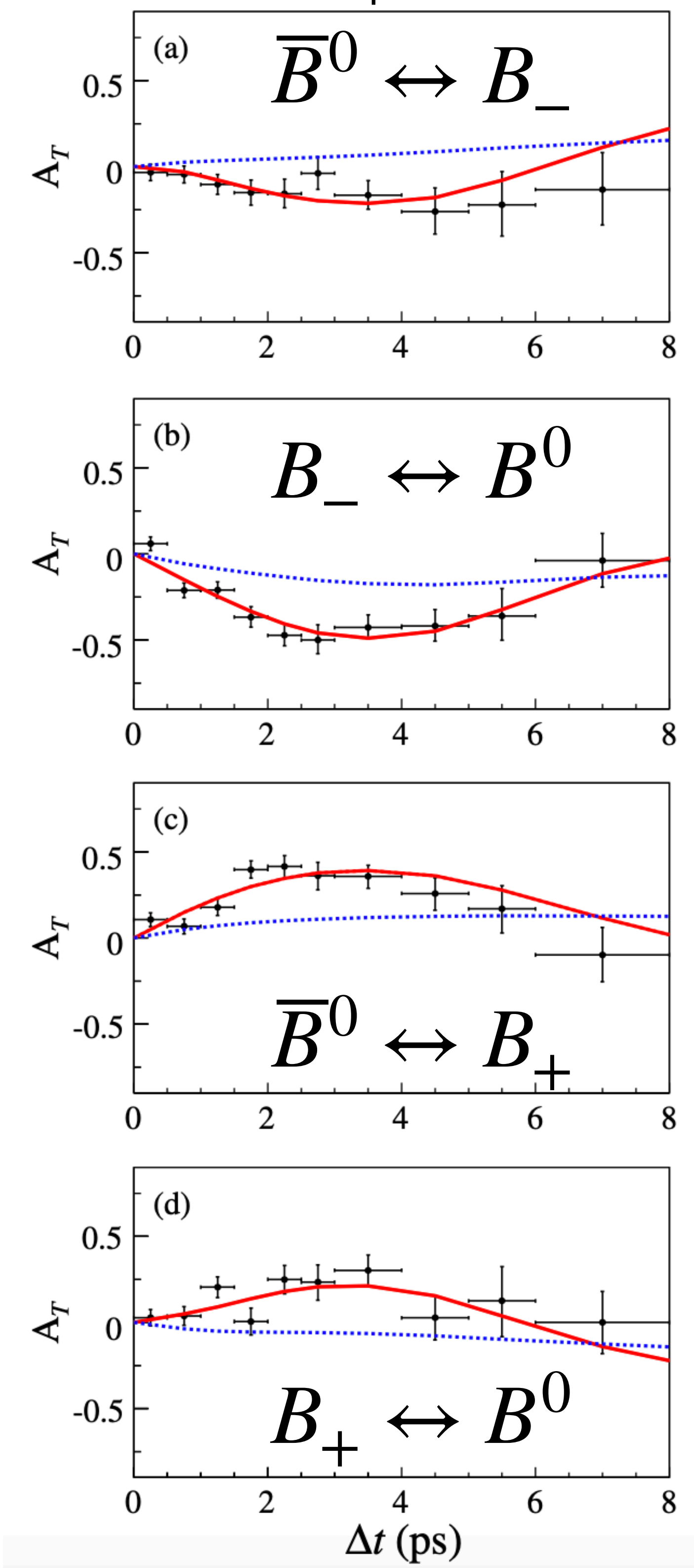
- J. P. Lees et al., Phys. Rev. Lett. 109, 211801 (2012)
  - *T* violation in quantum entangled *B* mesons from $\Upsilon(4S) \rightarrow B^0\overline{B}^0$ production



J. Bernabéu and F. Martínez-Vidal
Rev. Mod. Phys. **87**, 165 (2015)



BaBar experiment



CP violation in the SM

$V_{qq'}$ determines the strength of $qq'W^-$ couplings

if $V^*_{qq'} \neq V_{qq'}$ → different couplings for particles and antiparticles

→ allows for *CP* violation in the SM

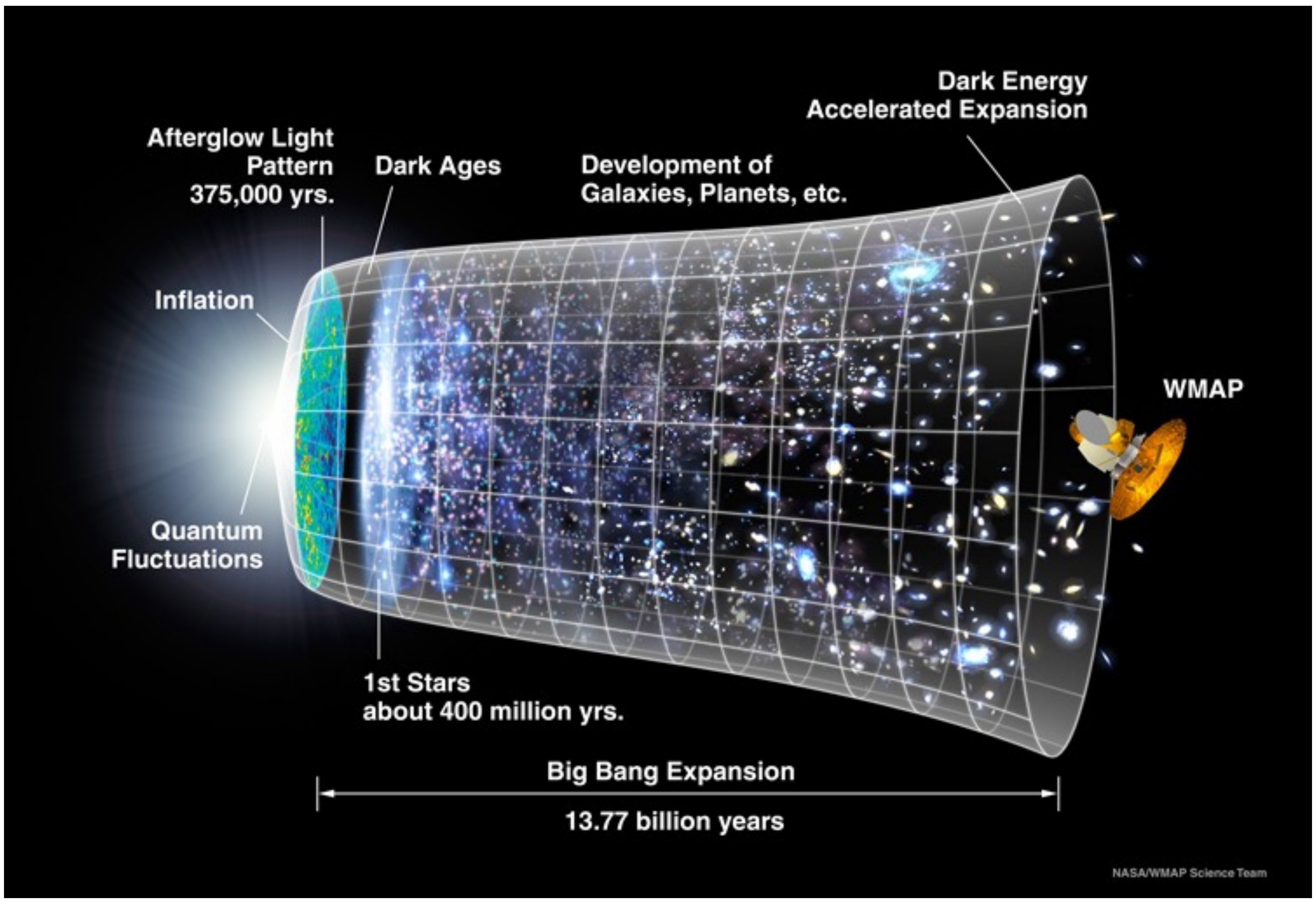
This is the so called CKM mechanism for the mixing of 3 family of quarks. Explains *CP* violation, matter - antimatter asymmetries, measured in *B, K* and *D* decays at accelerator experiments

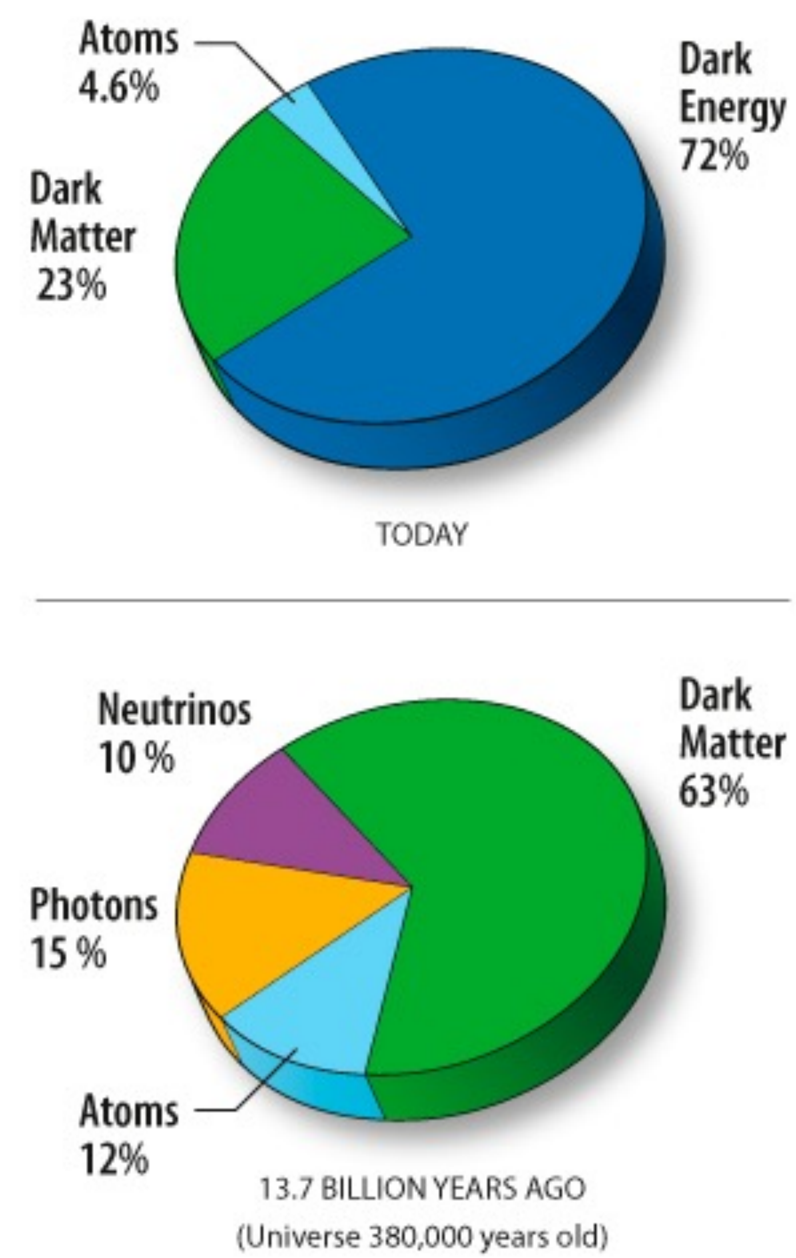
 

Physics motivations for EDM/MDM measurements

Matter-antimatter asymmetry problem

If equal amount of matter-antimatter was produced after the Big Bang, how do we explain the absence of antimatter in the Universe today?





Matter-antimatter asymmetry and *CP* violation

- *CPV* is necessary condition for baryogenesis (Sakharov, 1967)
- *CPV* in weak interactions via CKM mechanism in the SM is too small to explain the absence of antimatter in the Universe

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

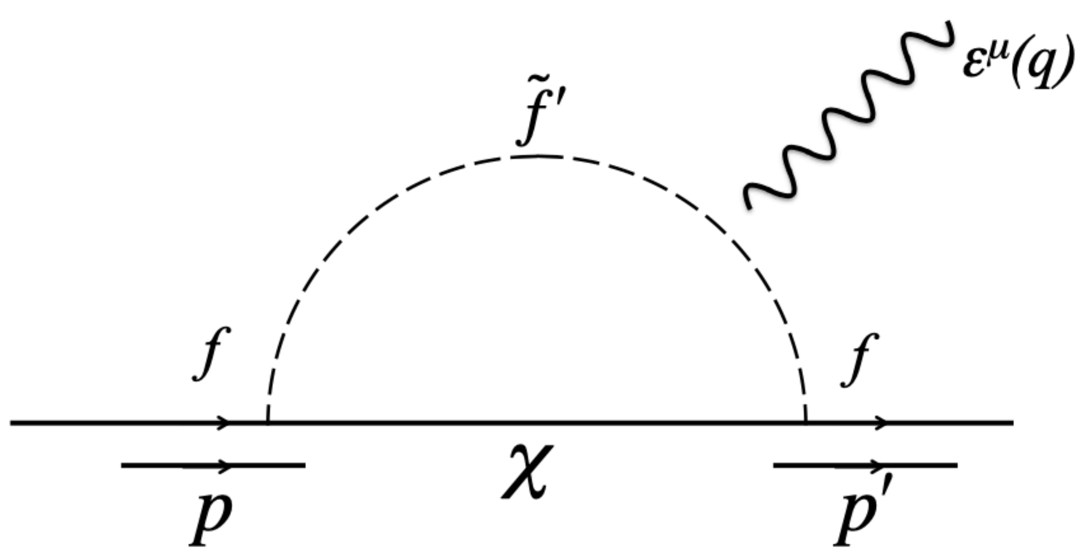
- New sources of *CPV* are expected to exist

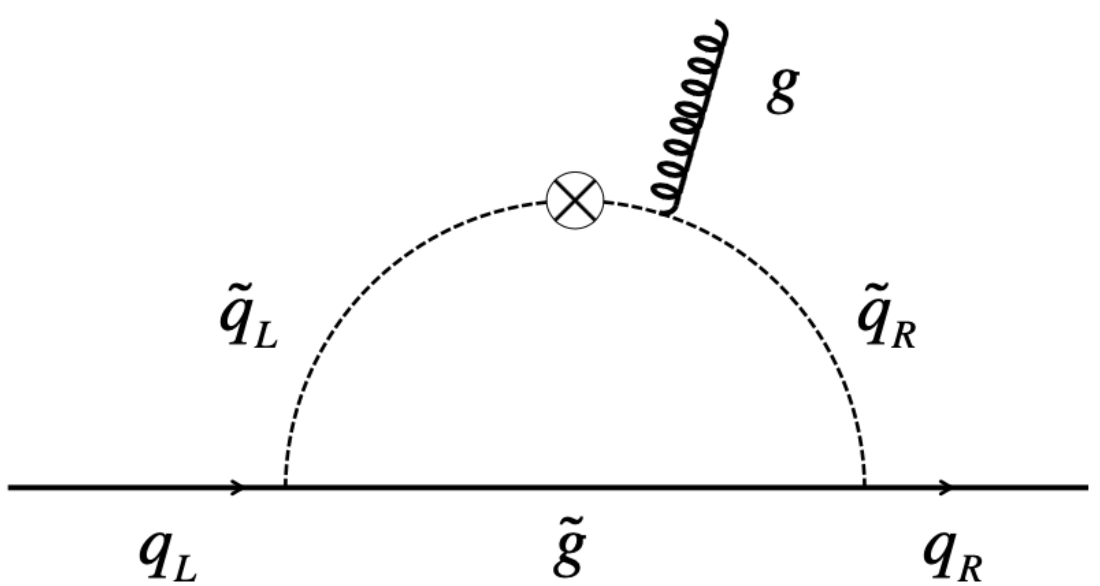
CP mirror

EDM: a probe for *CPV* beyond the SM

- $$\mathscr{L}_{CPV} = \mathscr{L}_{CKM} + \mathscr{L}_{\bar{\theta}} + \mathscr{L}_{BSM}$$
  - SM: negligible contribution from CKM matrix, $\bar{\theta}$-QCD term allows for possible *CPV* in strong interactions
  - BSM: potential relatively large contributions

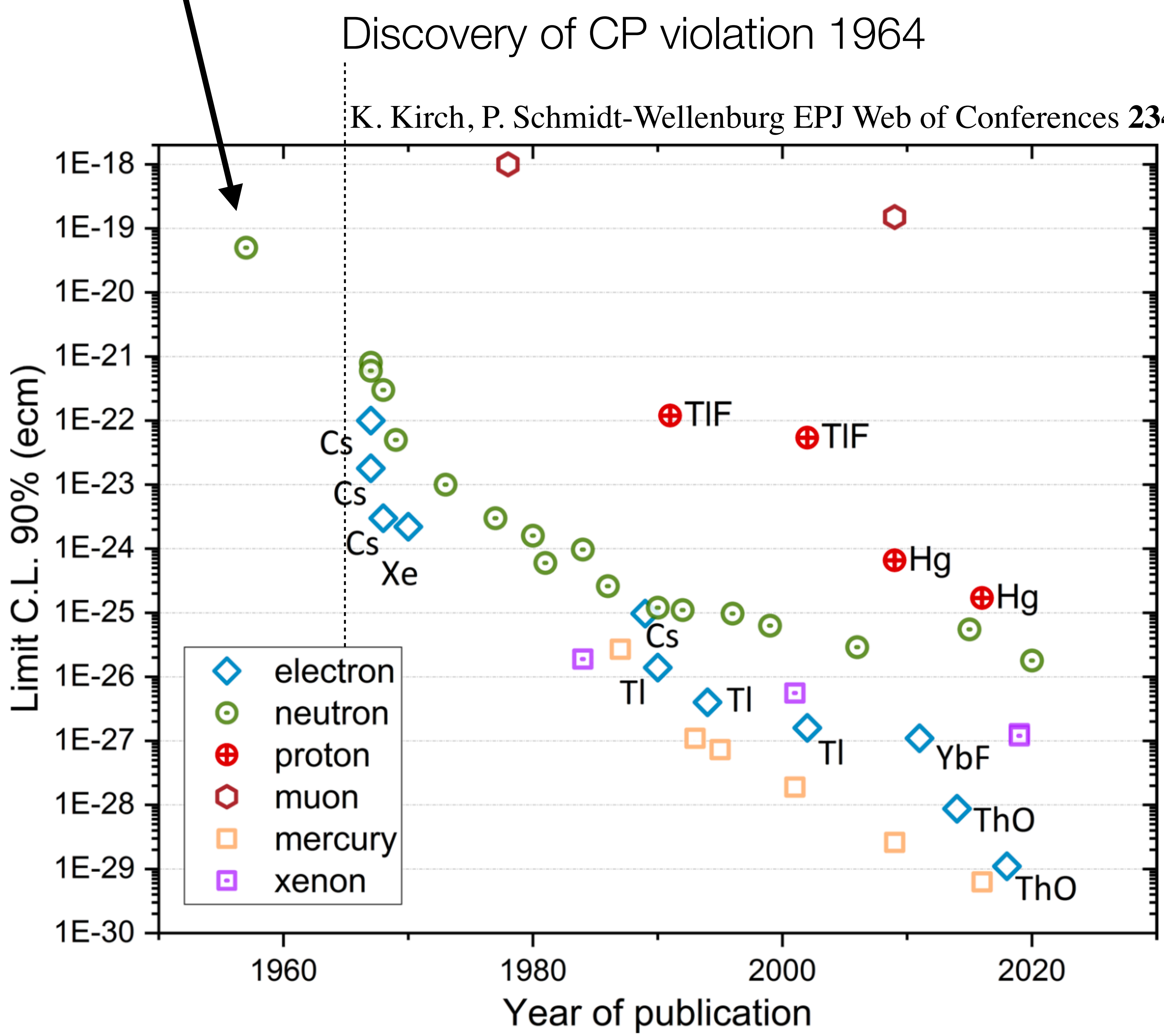
Examples of BSM contributions





History of EDM limits

J. H. Smith, E. M. Purcell, and N. F. Ramsey, Phys. Rev. 108, 120 (1957)



- Need to measure many systems to disentangle the underlying source of *CPV*
- Stringent experimental limit from neutron EDM→ $\bar{\theta} \lesssim 10^{-10}$ "strong *CP* problem"

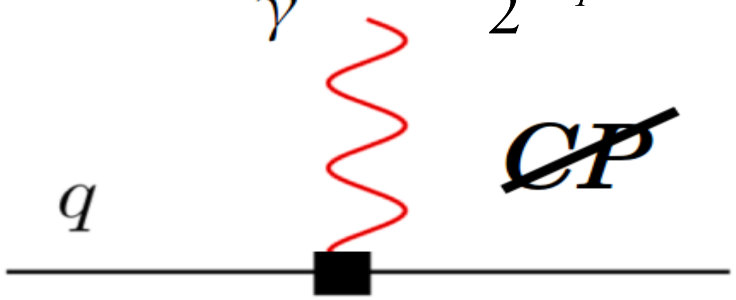
PRL 116, 161601 (2016)

PRL 124, 081803 (2020)
[PSI experiment]

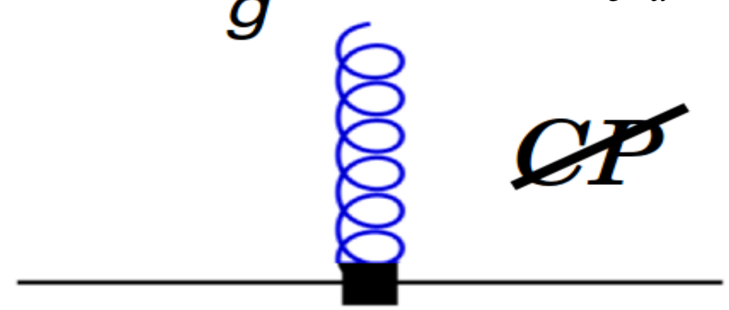
Heavy baryon EDM

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

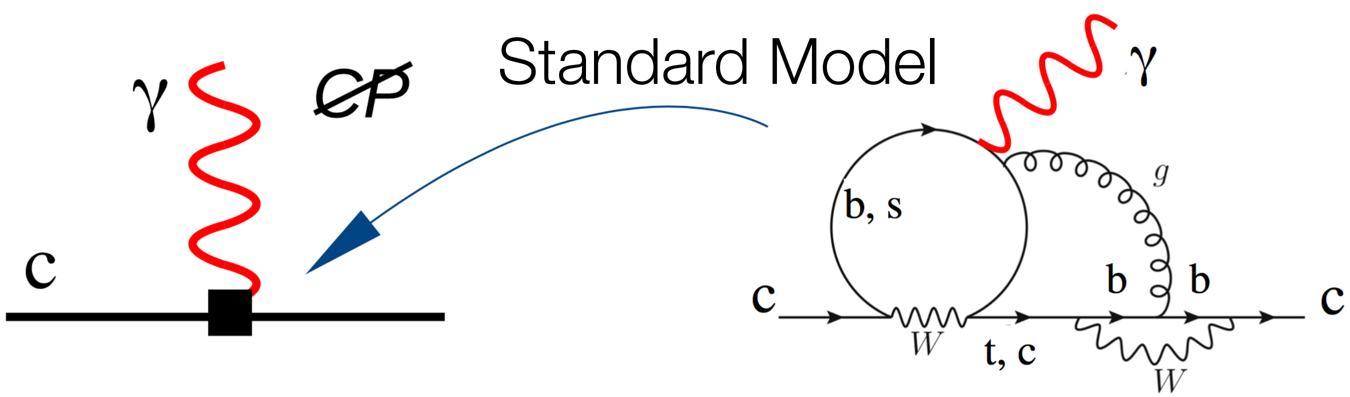


qCEDM $i\tilde{\delta}_q \bar{q}\sigma^{\mu\nu}\gamma_5 t_a q G^a_{\mu\nu}$



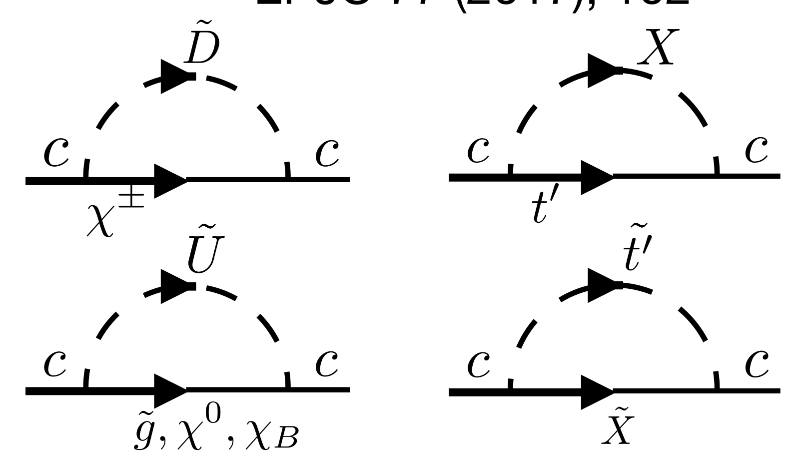
Charm EDM in SM-CKM ~10^{-32} *e* cm

Khriplovich, Lamoreaux (1997)



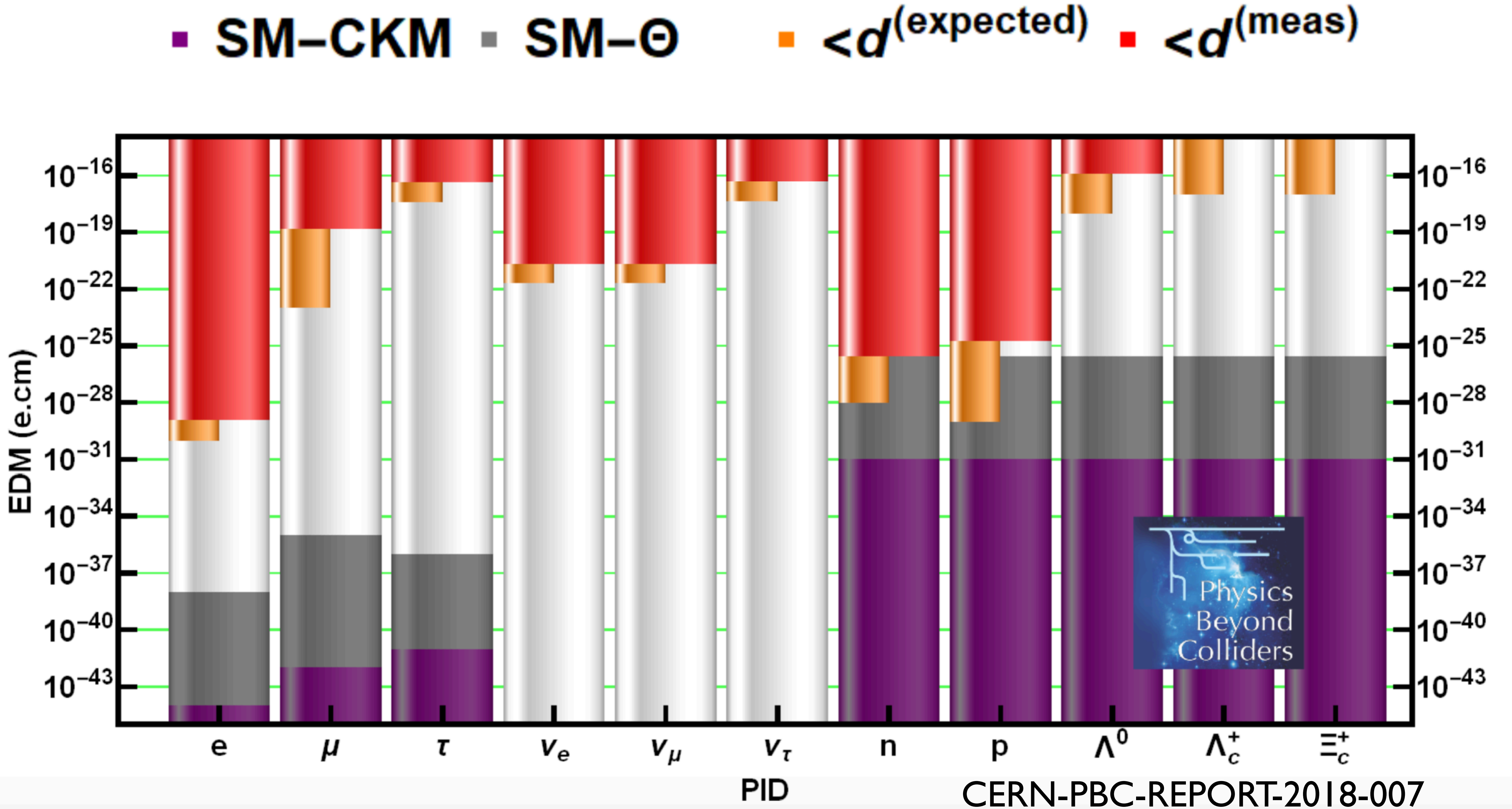
Charm EDM with new physics ~$5 \cdot 10^{-17}$ *e* cm

EPJC 77 (2017), 102



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

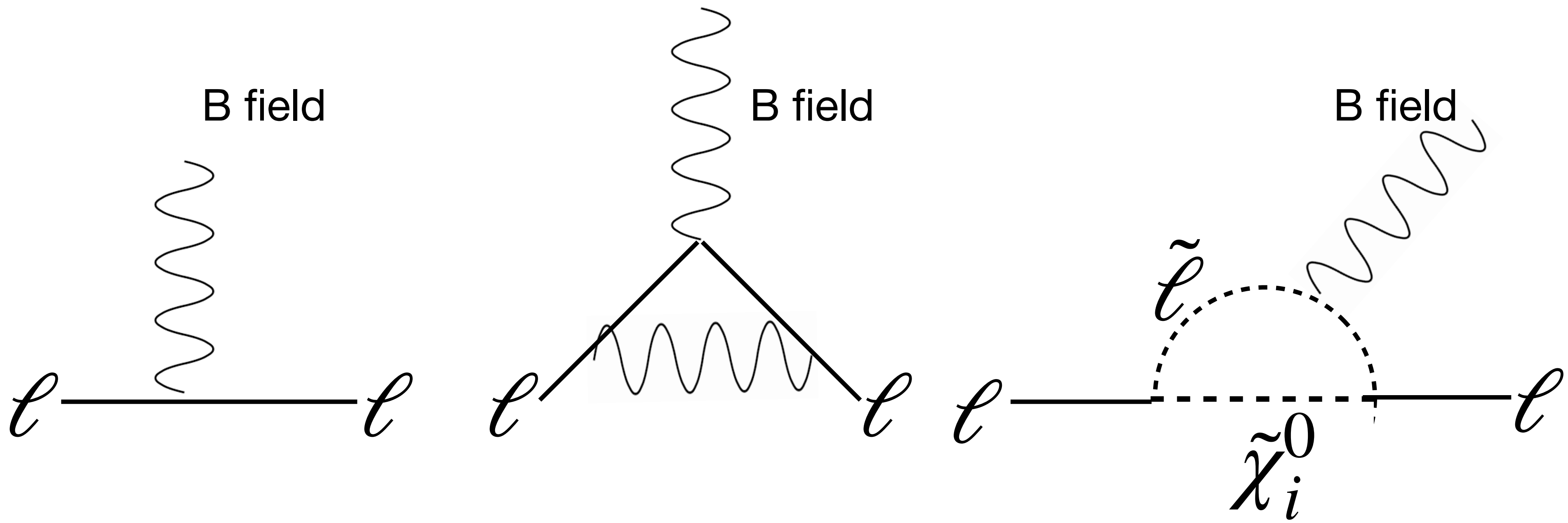
Status of EDM measurements



CERN-PBC-REPORT-2018-007

Lepton MDM $(g-2)$

- $g = 2$ for a point-like fermion
- quantum effects $a = \frac{g-2}{2}$, anomalous magnetic moment



Dirac interaction
$g = 2$

QED Schwinger interaction
$g - 2 = \alpha/\pi$

BSM SUSY interaction

- Precise calculations of g-2 of e, μ, τ to confront with precision measurements

For e

Physics Letters B. **379** (1–4): 283–291 (1996)
Physical Review Letters. **109** (11): 111807 (2012)
Physical Review D. **91** (3): 033006 (2015)

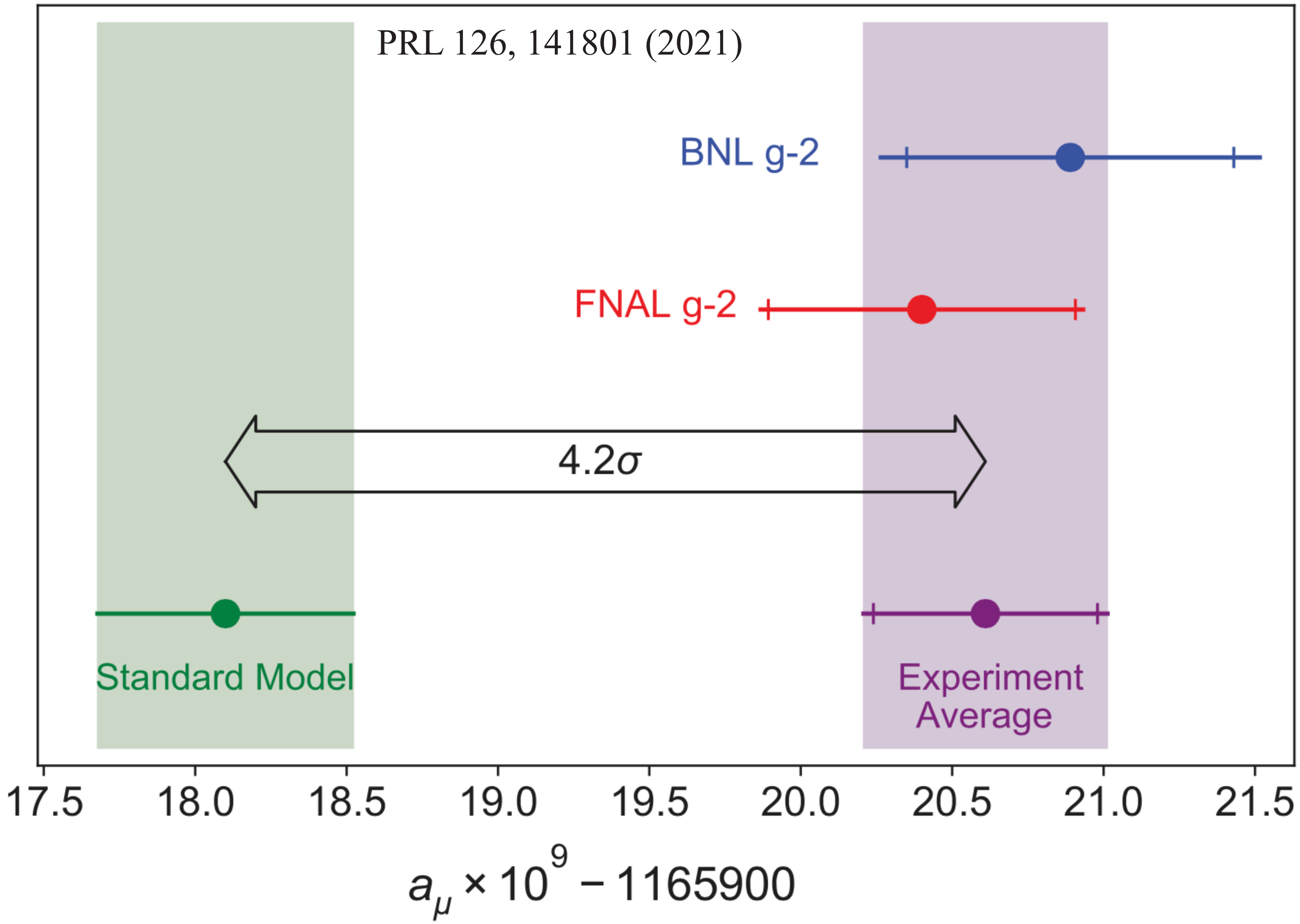
For μ

Phys. Rep. 887, 1 (2020)

For τ

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

Muon $g-2$ deviation from SM



Measurement of g_e

$g_e = 2.00231930436146\ (56)$
D. Hanneke et al., PRL **100,** 120801 (2008)

Indirect measurement of g_τ

$-0.052 < a_\tau < 0.013$, 95% CL

EPJC **35** (2): 159–170 (2004)

- $\approx 4.2\sigma$ deviation from SM predictions [1]*

[1] Phys. Rep. 887, 1 (2020)

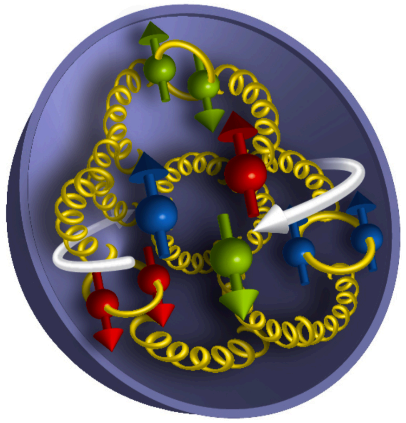
*Recent LQCD calculations Nature (2021) approach experiment average

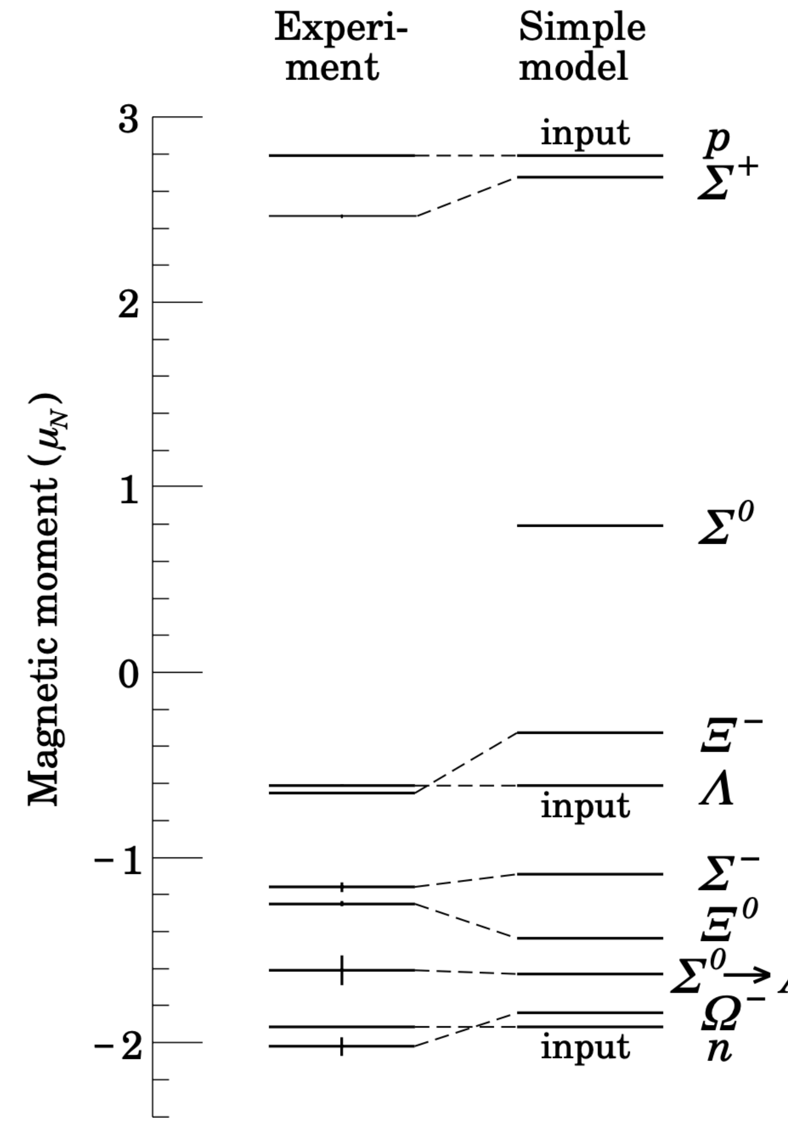
Intrinsic MDM of baryons

- $g \neq 2$ 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)

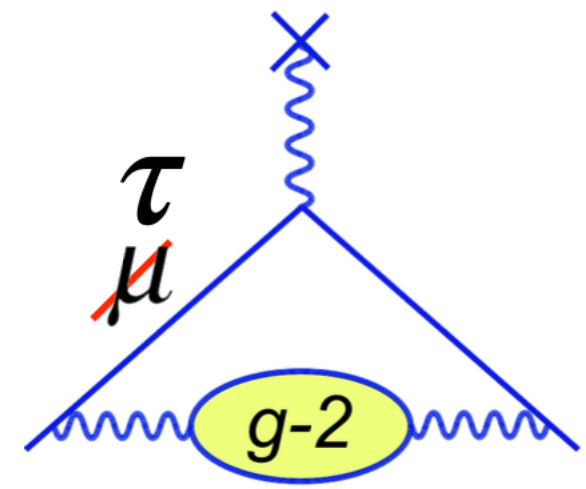
- Test of *CPT* symmetry with $\bar{p}$ MDM

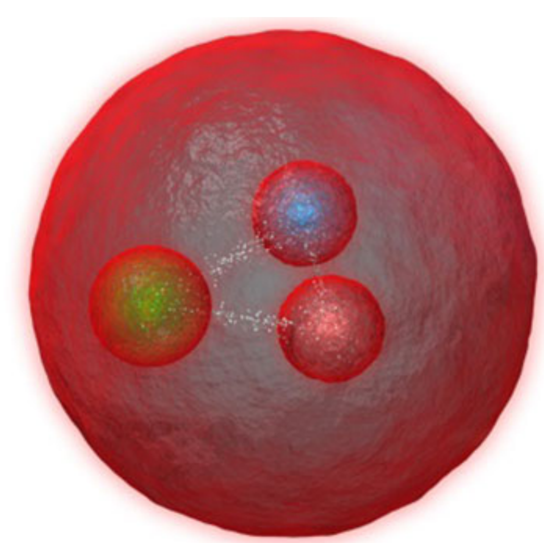
$\mu_{\bar{p}} = -2.7928473441(42)\mu_N$

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

Intrinsic MDM of heavy fermions

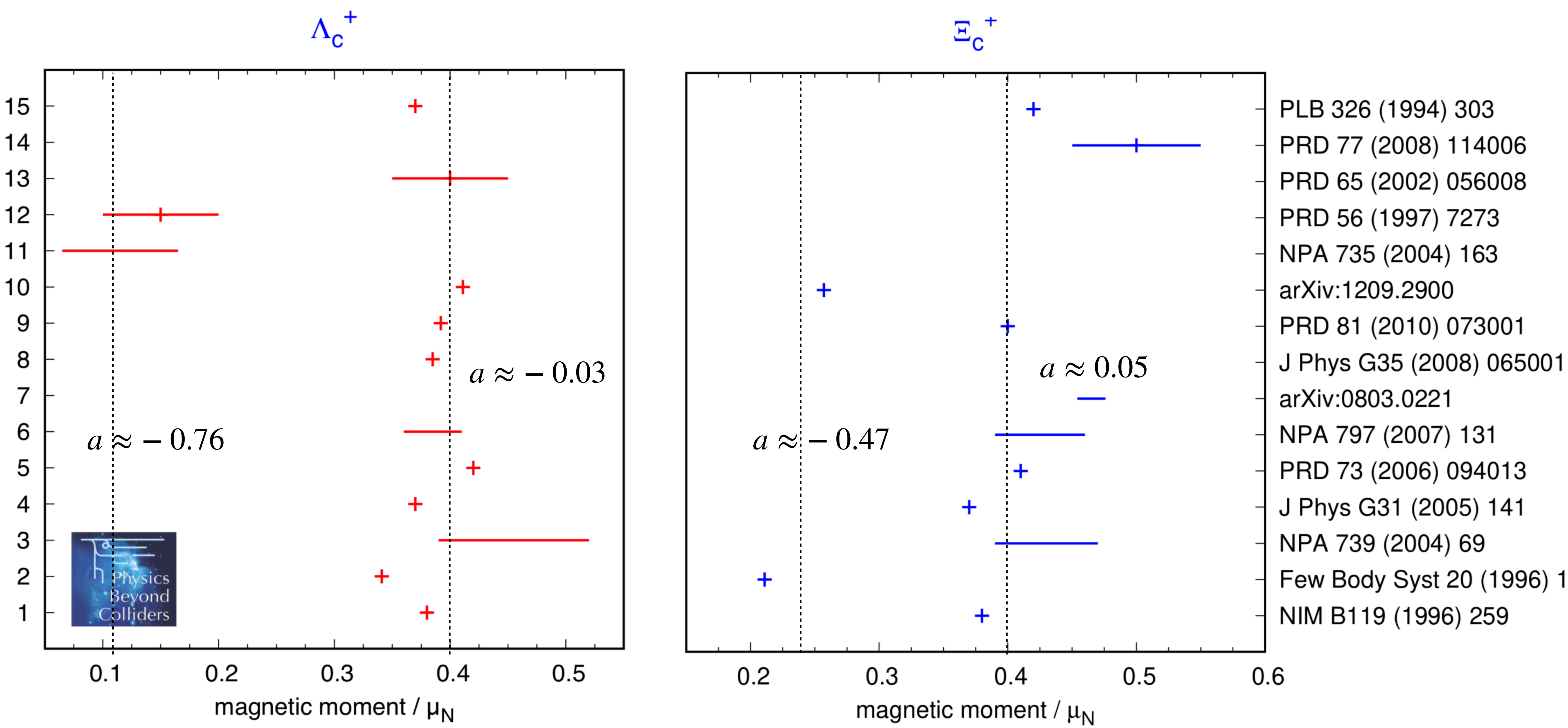
- No direct measurements to date for short-lived **charm**, **beauty** baryons, and **τ** lepton
- Experimental anchor points for test of low-energy QCD models, related to **non-perturbative QCD** dynamics
- Test of **baryon substructure**
- Measurement of MDM of particles and antiparticles would allow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





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 charm baryons: Λ_c^+, Ξ_c^+

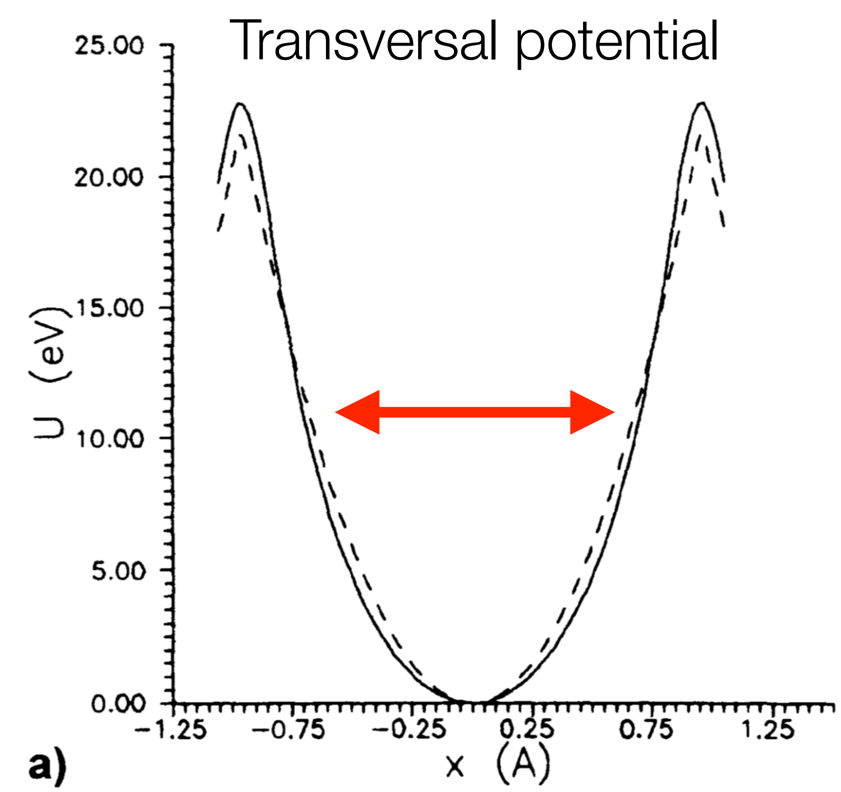
$\tau \approx 10^{-13}$ s

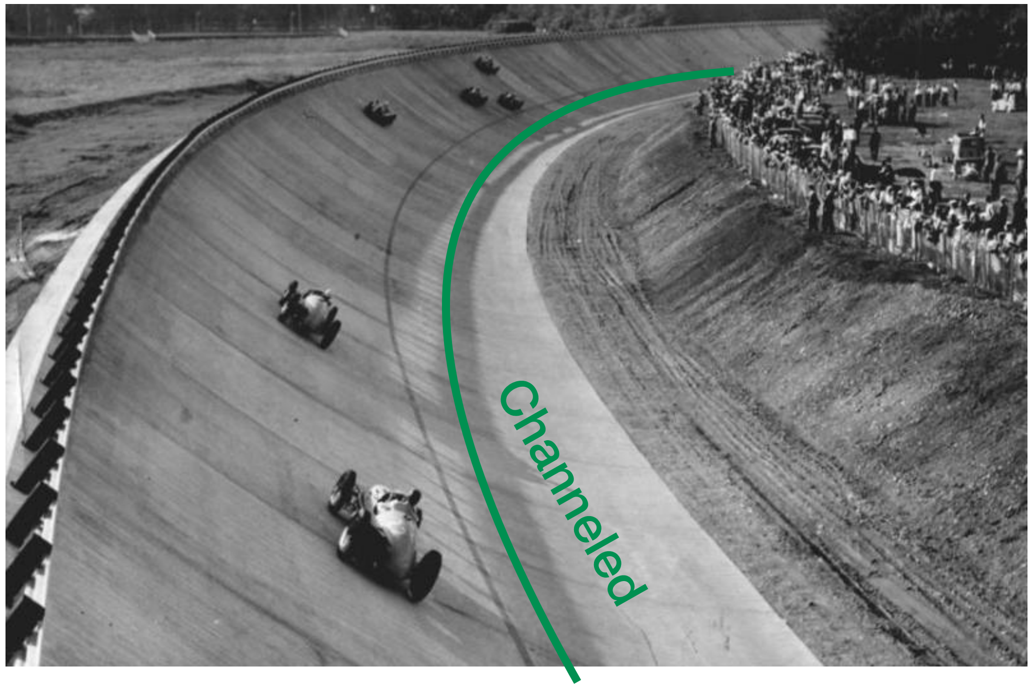
Channeling in bent crystals

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

Channeling in bent crystals

- Potential well between crystal planes
- 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.

- Determine particle gyromagnetic factor from BMT equation

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

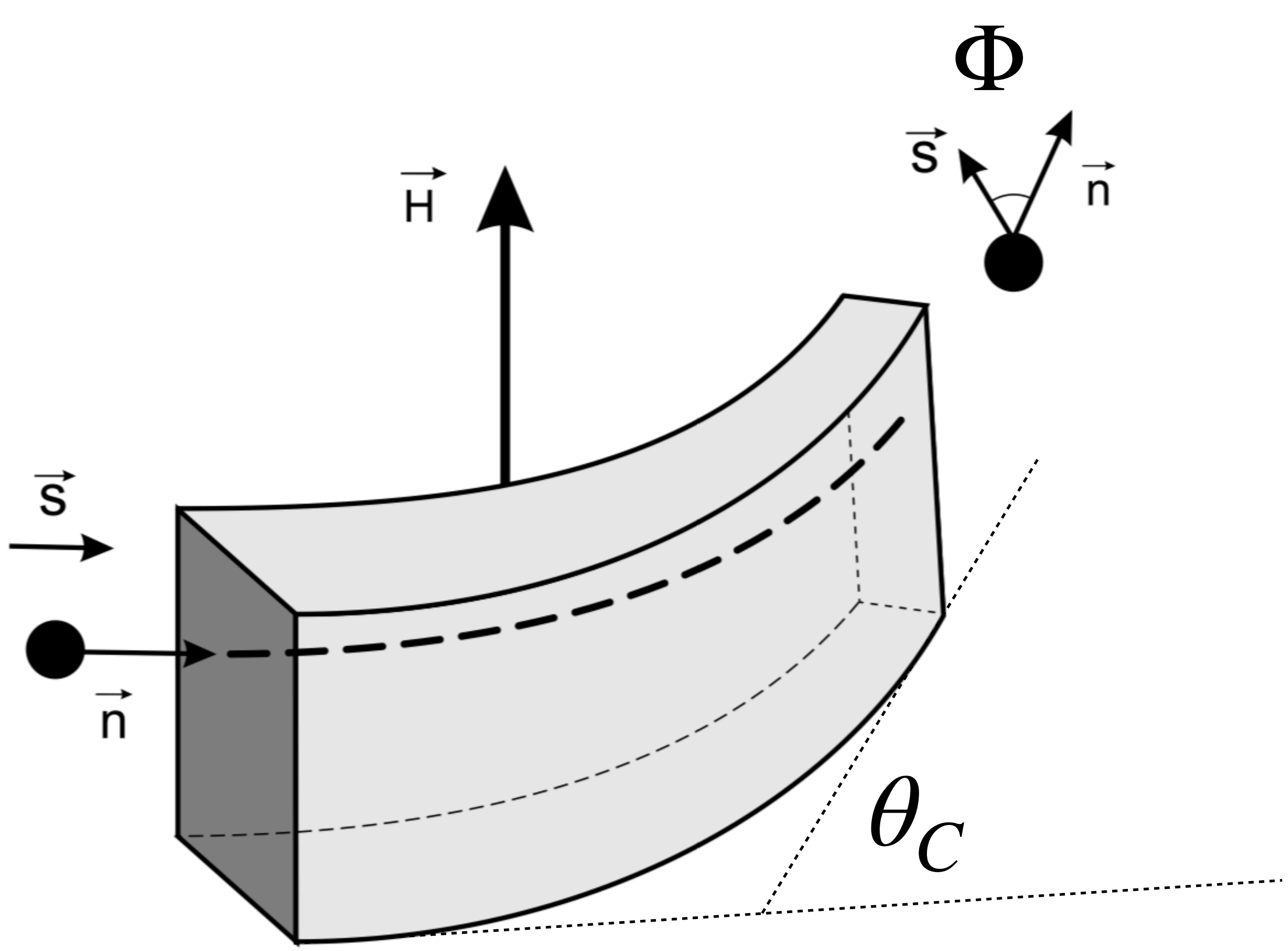


Fig. 1. Spin rotation in a bent crystal.

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

Φ = spin rotation angle

θ_C = crystal bending angle

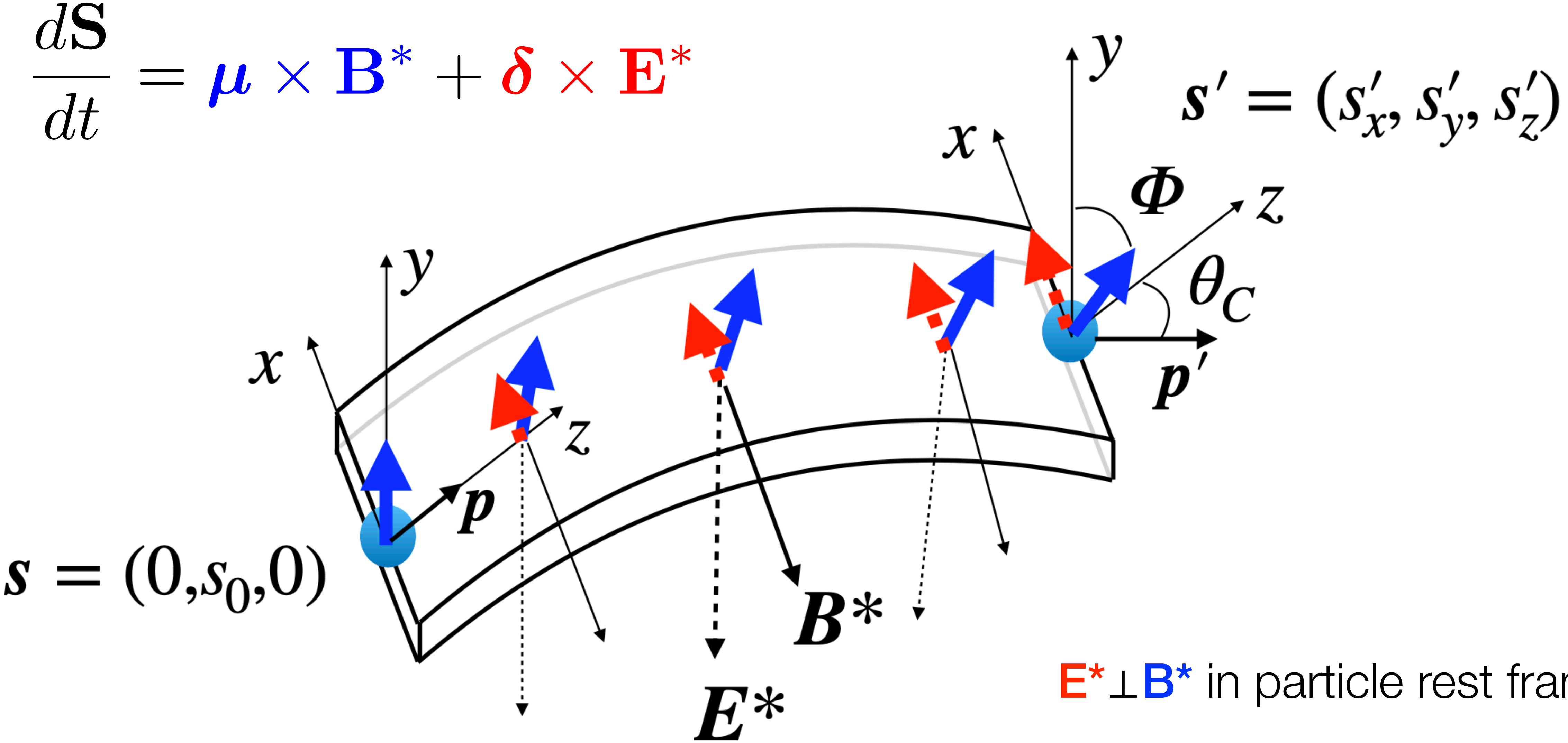
g = gyromagnetic factor

γ = Lorentz boost

Spin precession in bent crystals

- Crystal electric field $E \approx 1$ GV/cm, $\gamma \approx 500$, $\theta_C \approx 10$ mrad
- In particle rest frame $E^*_\perp \approx \gamma E_\perp$, $B^*_\perp \approx \gamma E_\perp$

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



E* ⊥ B* in particle rest frame

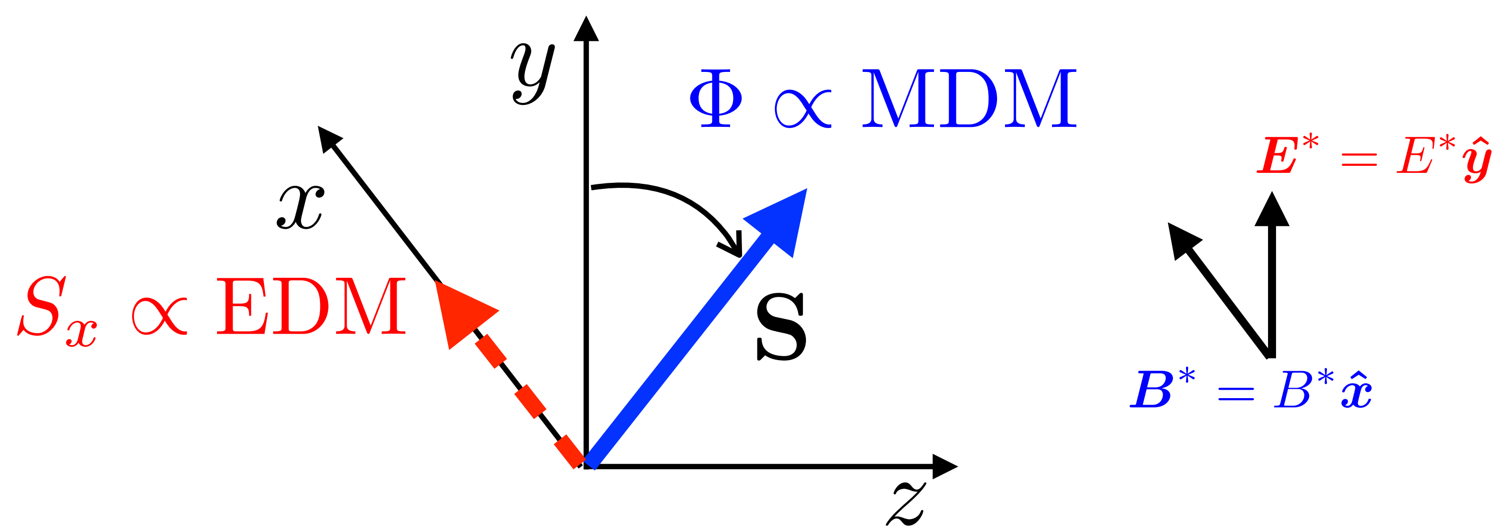
MDM/EDM with bent crystals

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

Spin-polarisation analyser: angular distribution of baryon decay products

For a 2-body decay: $\frac{dN}{d\Omega'} \propto 1 + \alpha \boldsymbol{S} \cdot \hat{\boldsymbol{k}}$

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



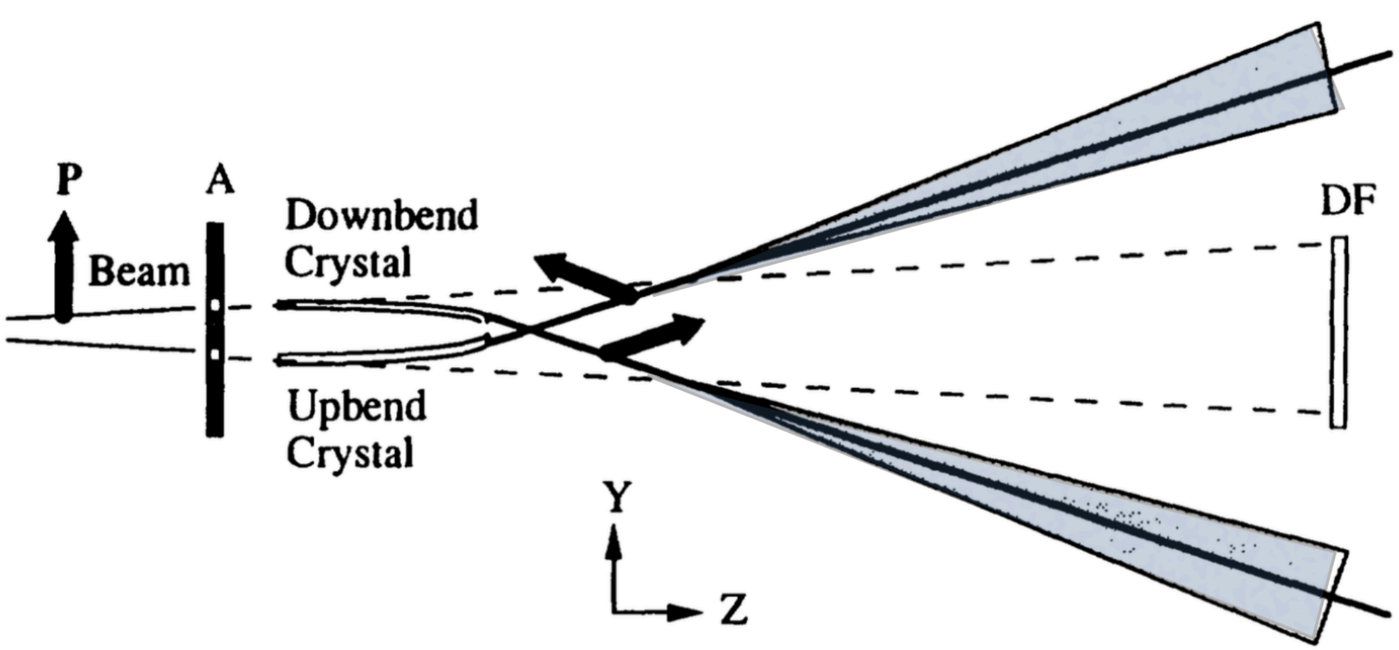
- MDM and EDM precession in the limit $\gamma \gg 1$, $d \ll g - 2$

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

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



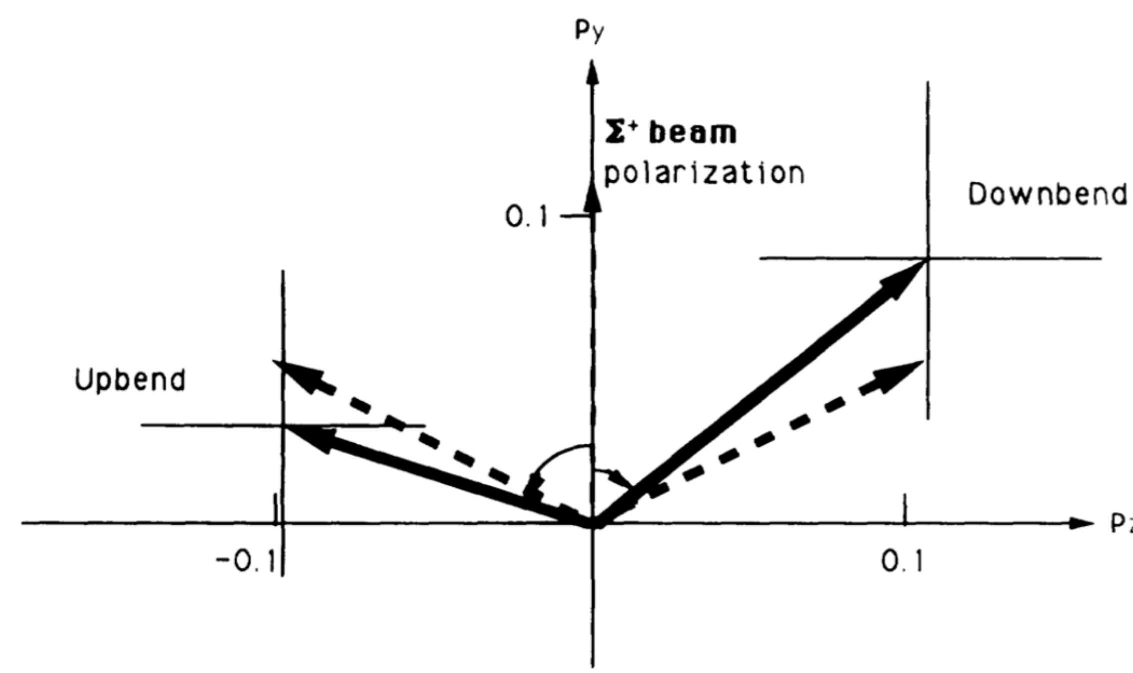
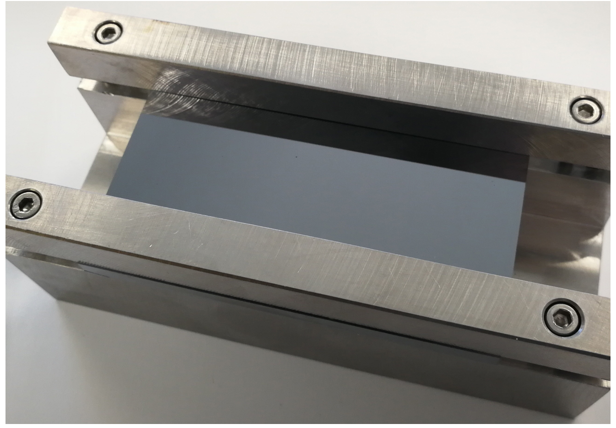
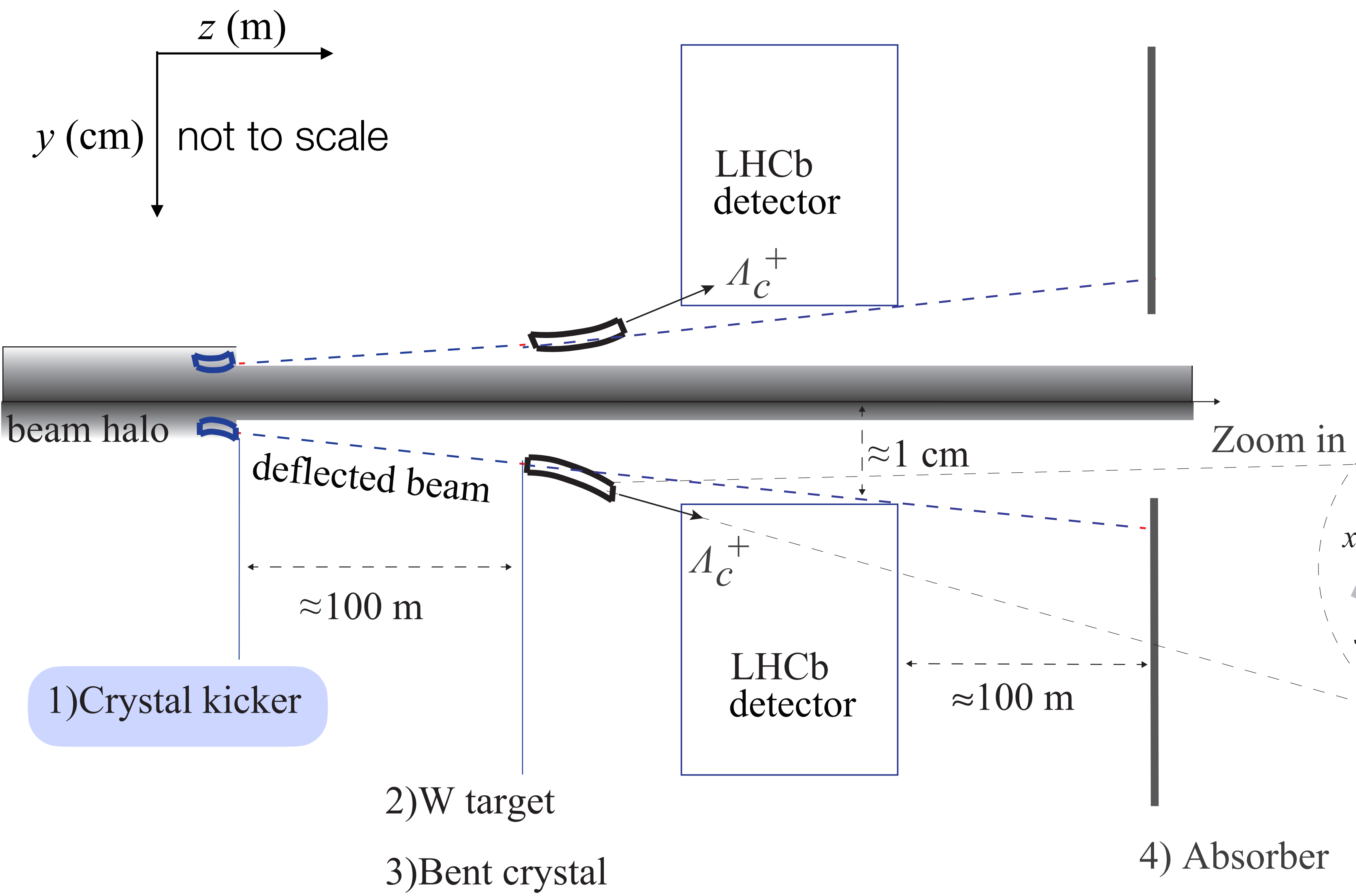


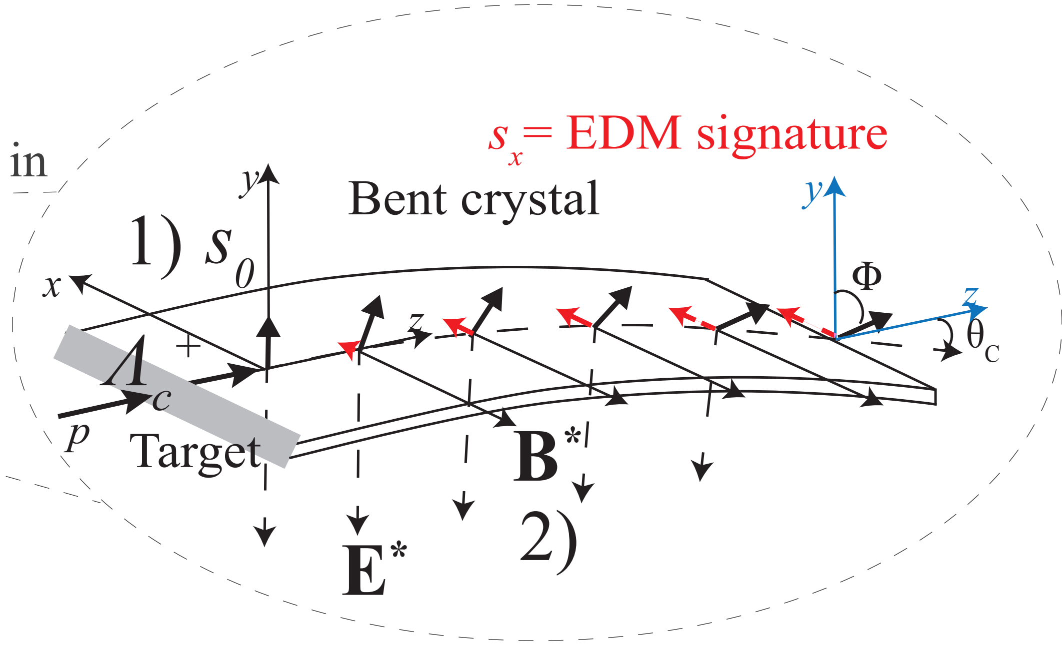
FIG. 3. Measured polarizations and uncertainties (1σ statistical errors) after spins have been processed by the two crystals. The dashed arrows show the expected precessions.

Novel fixed-target experiment at LHC for charm baryons

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



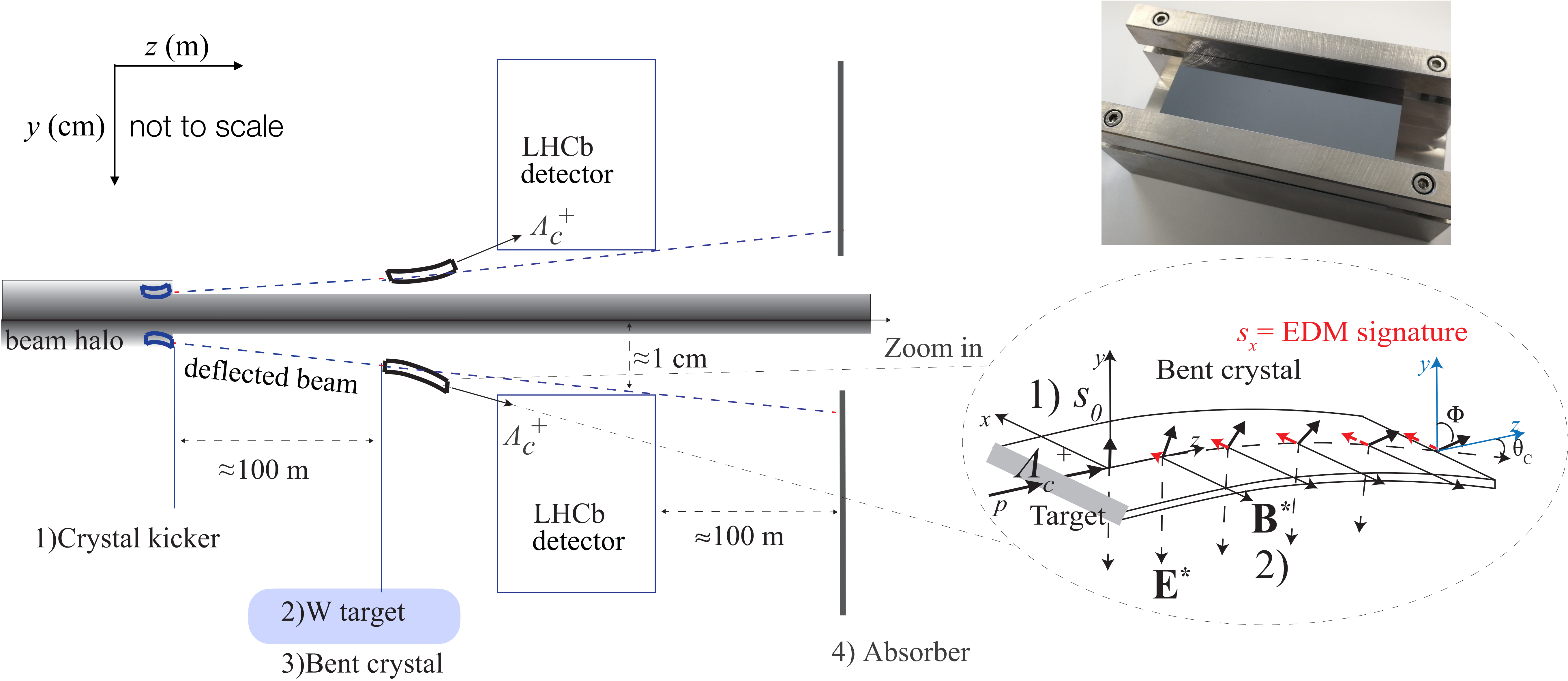




p extraction

Novel fixed-target experiment at LHC for charm baryons

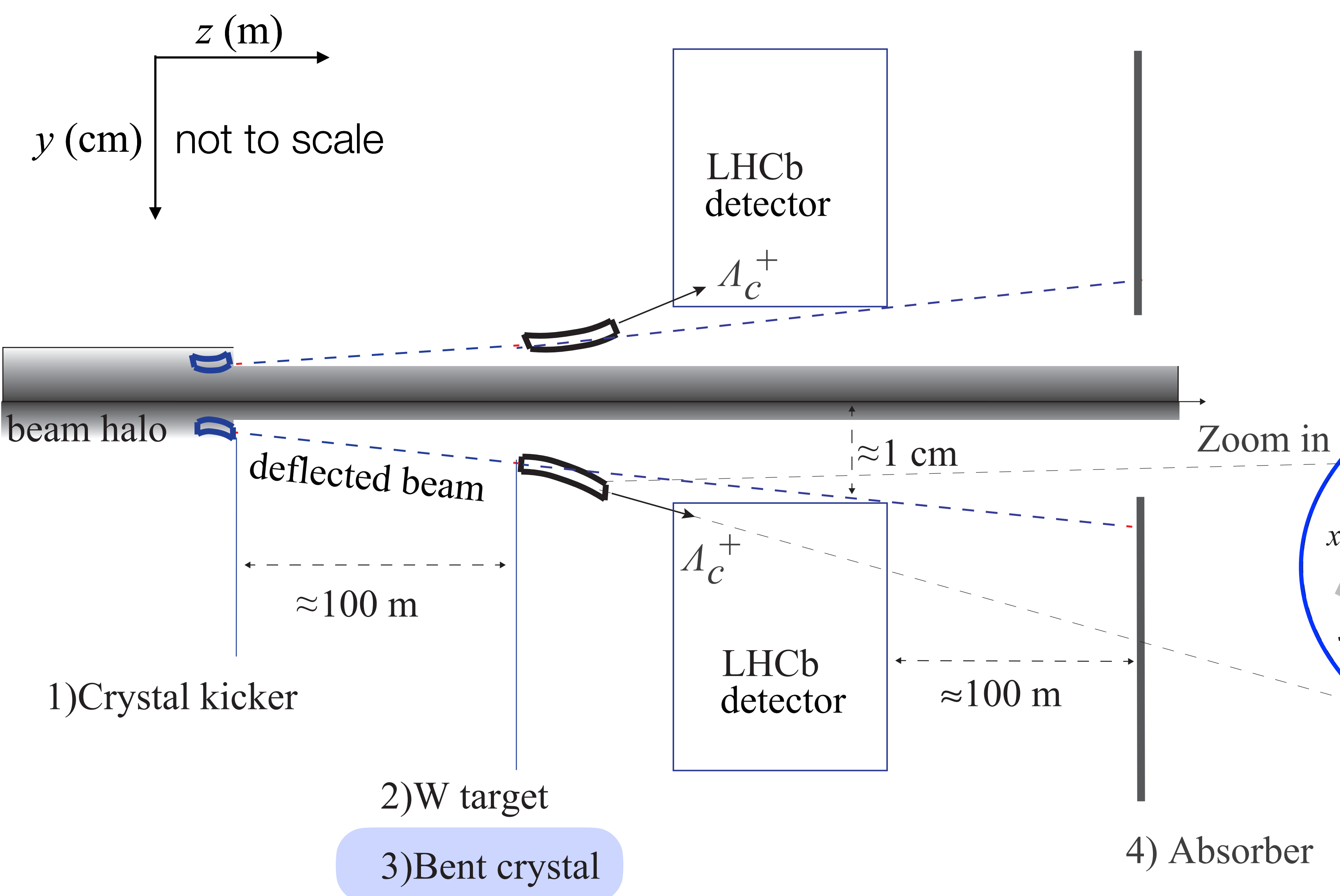
- EDM/MDM from spin precession of channeled baryons in **bent crystals**

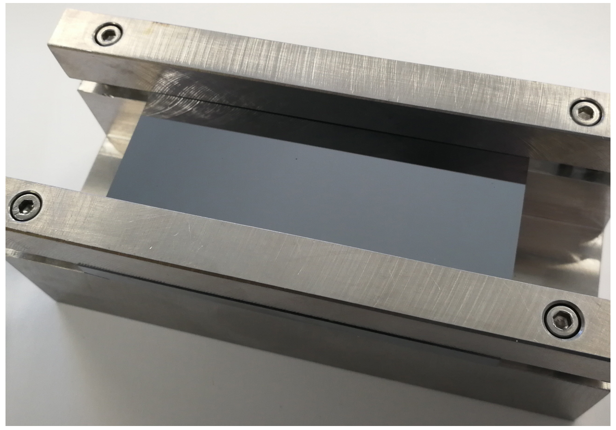


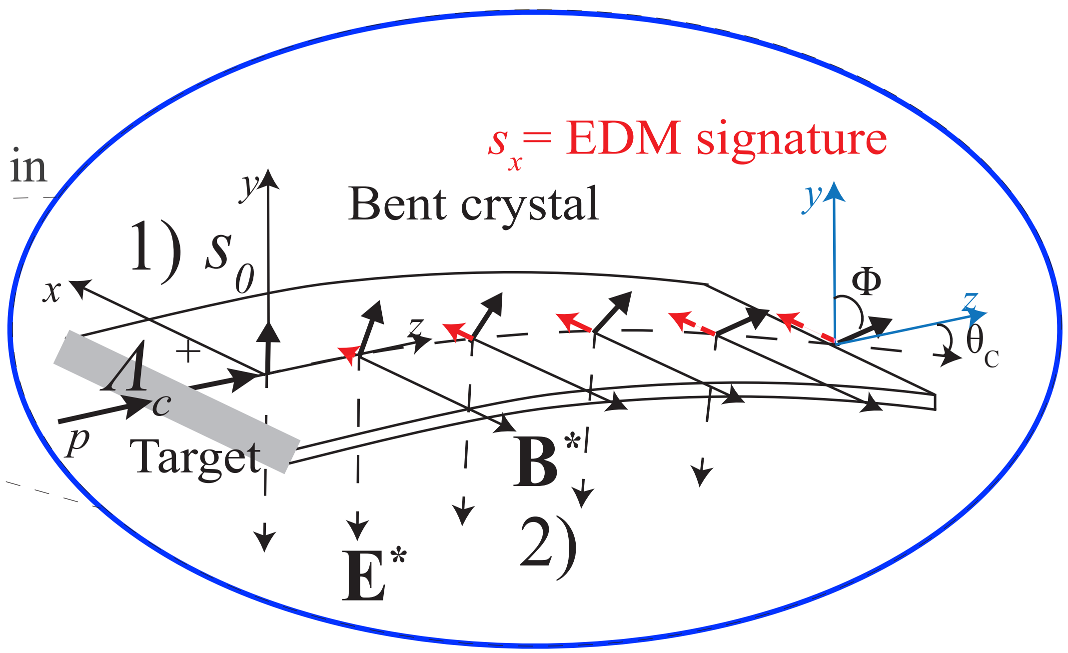
p extraction Λ_c^+ polarised production

Novel fixed-target experiment at LHC for charm baryons

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



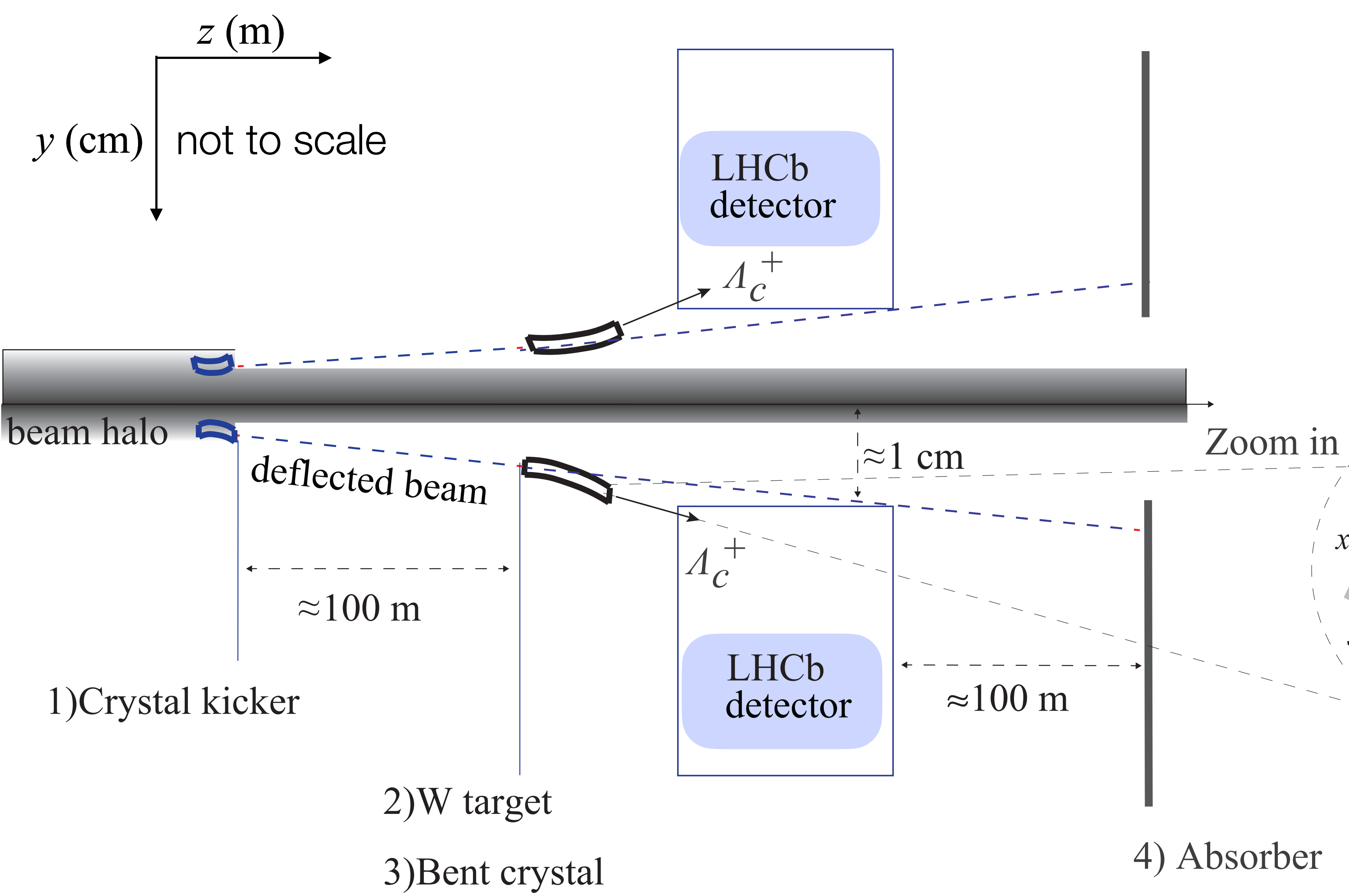


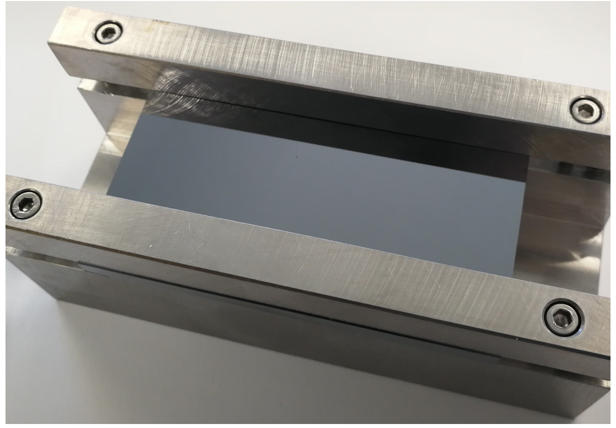


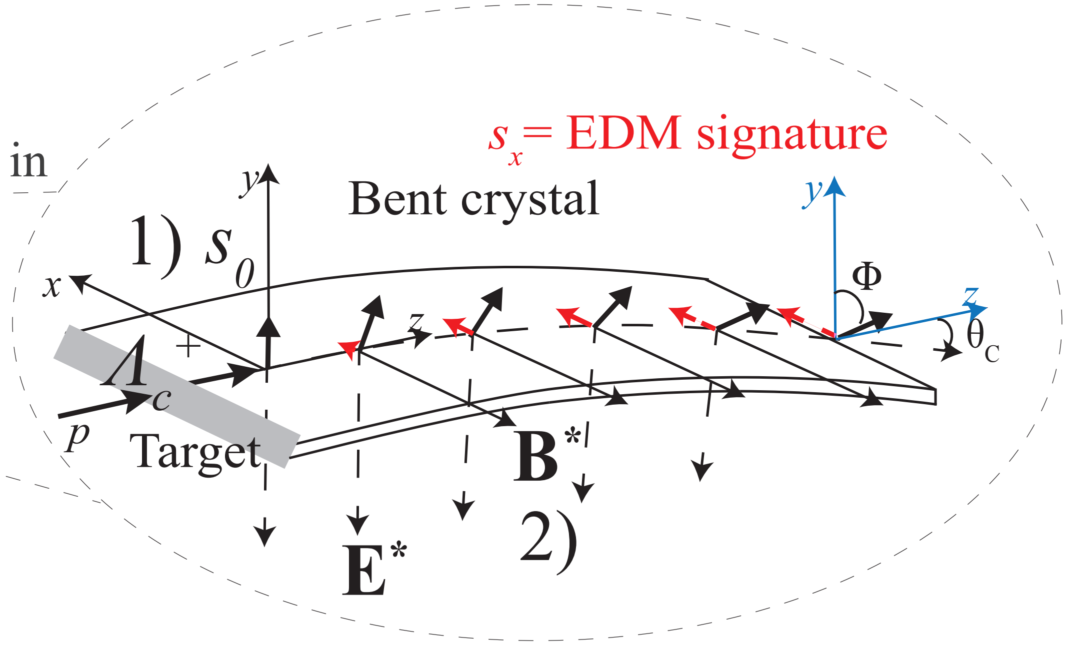
p extraction Λ_c^+ polarised production channeling spin precession

Novel fixed-target experiment at LHC for charm baryons

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



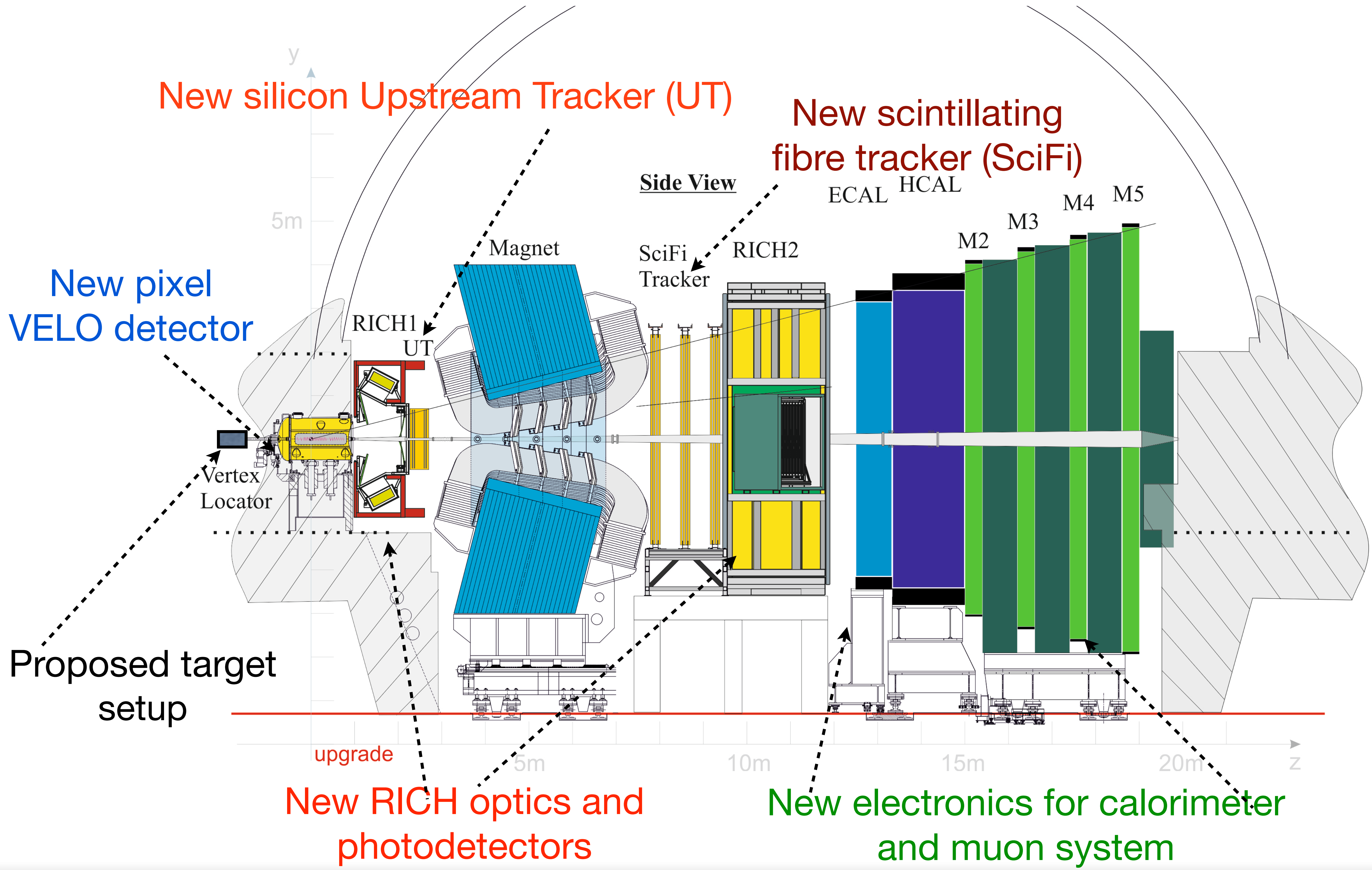




p extraction Λ_c^+ polarised production channeling spin precession event reconstruction

LHCb Upgraded detector

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



Sensitivity on MDM/EDM

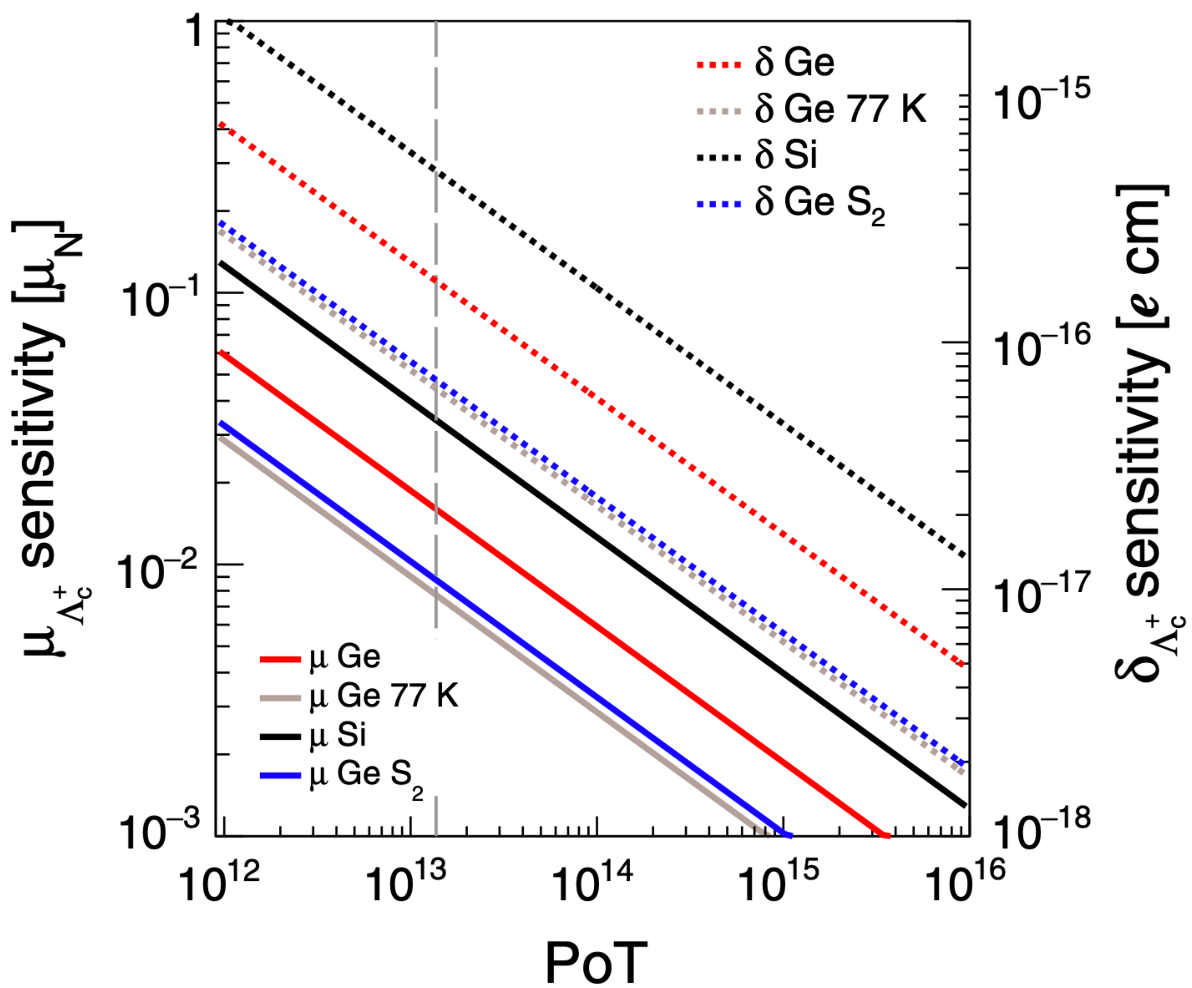
- S1 configuration: **LHCb detector, Ge (Si) 16 mrad, 10 cm**
- S2 configuration: **dedicated experiment, Ge 7 mrad, 7 cm**

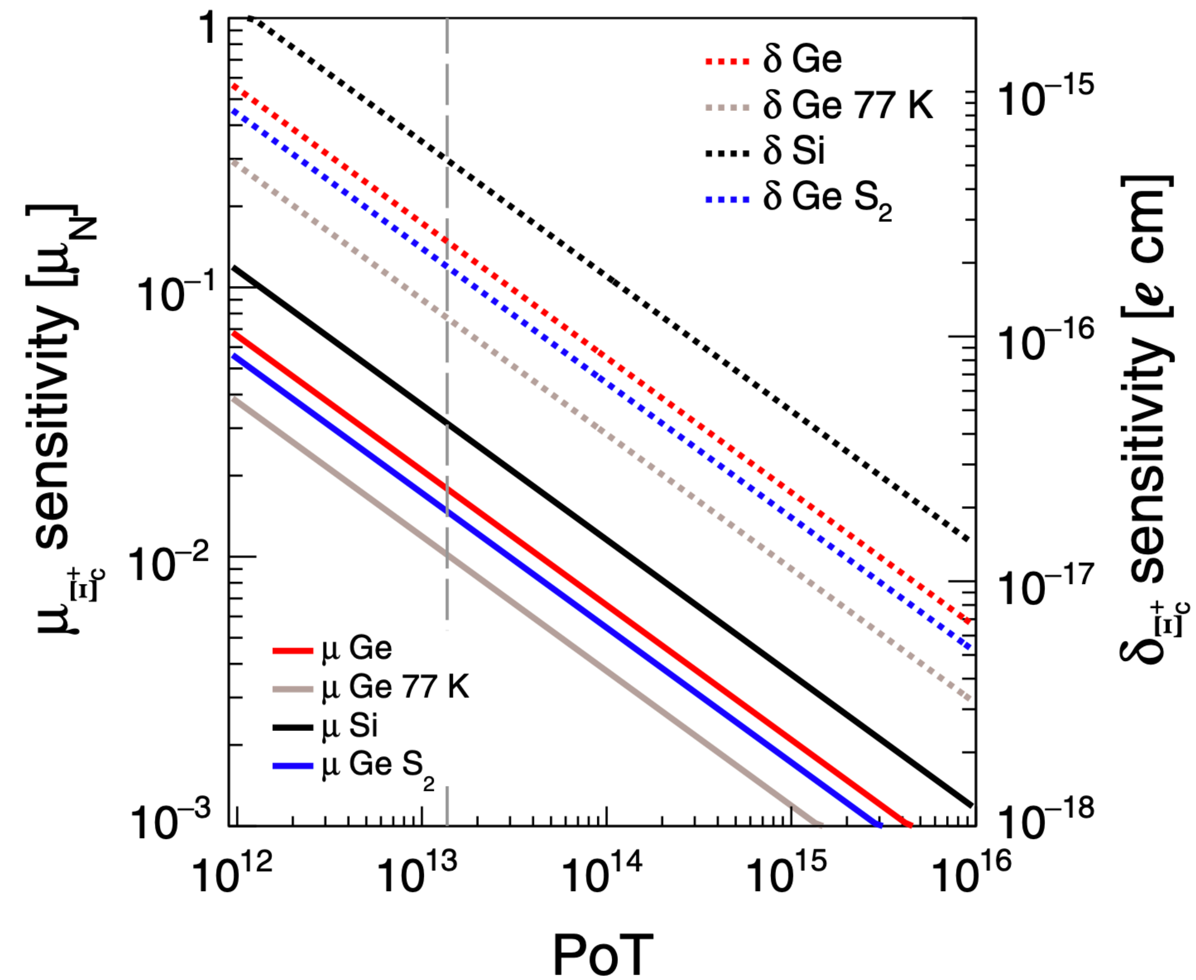
PoT = proton on target
W target 2 cm thick

Λ_c^+ baryon

PRD 103, 072003 (2021)

Ξ_c^+ baryon



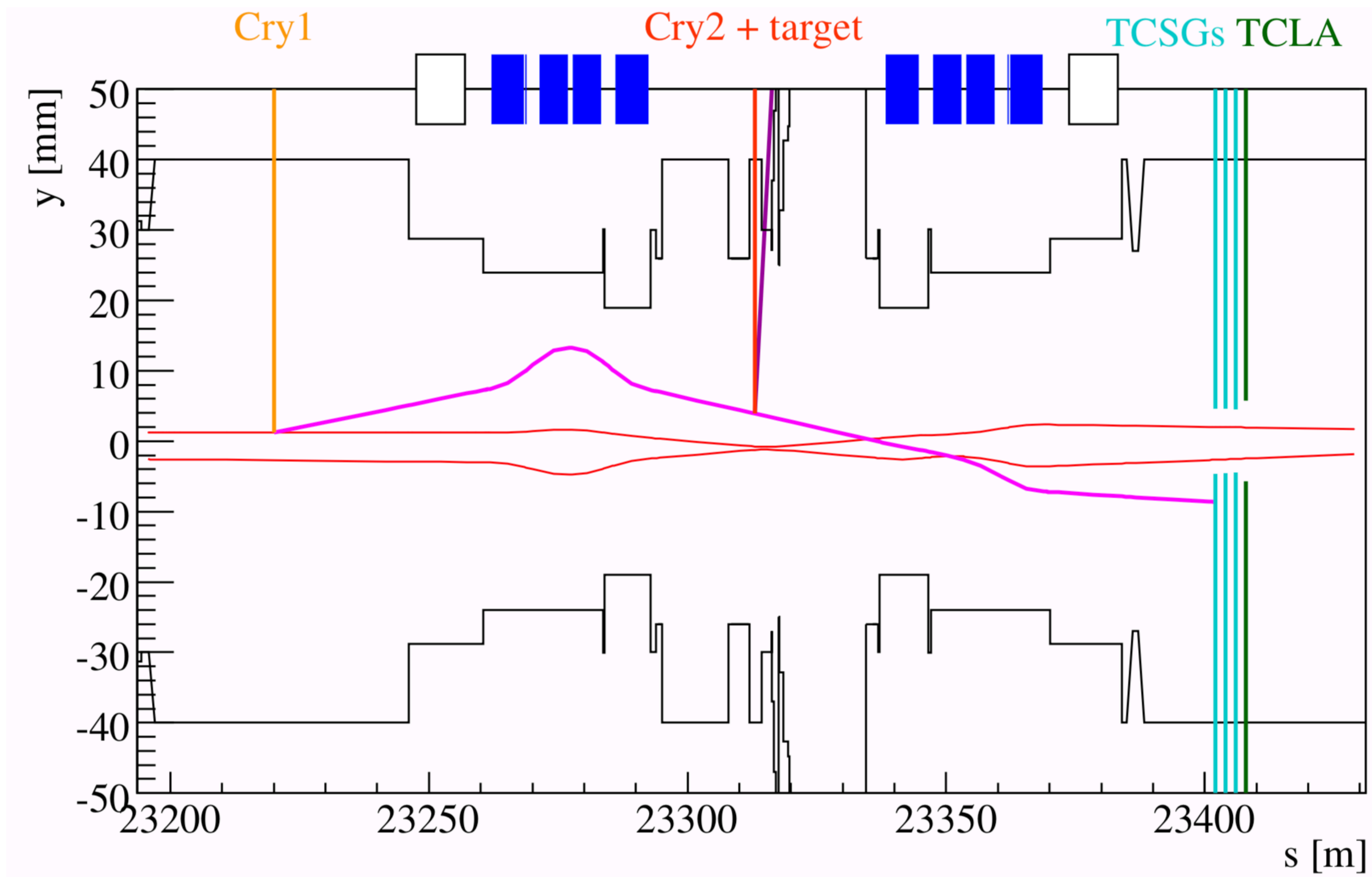


- Measurements are **statistically limited**

R&D and preparatory studies

LHC machine studies

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



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

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

Long bent crystal prototypes

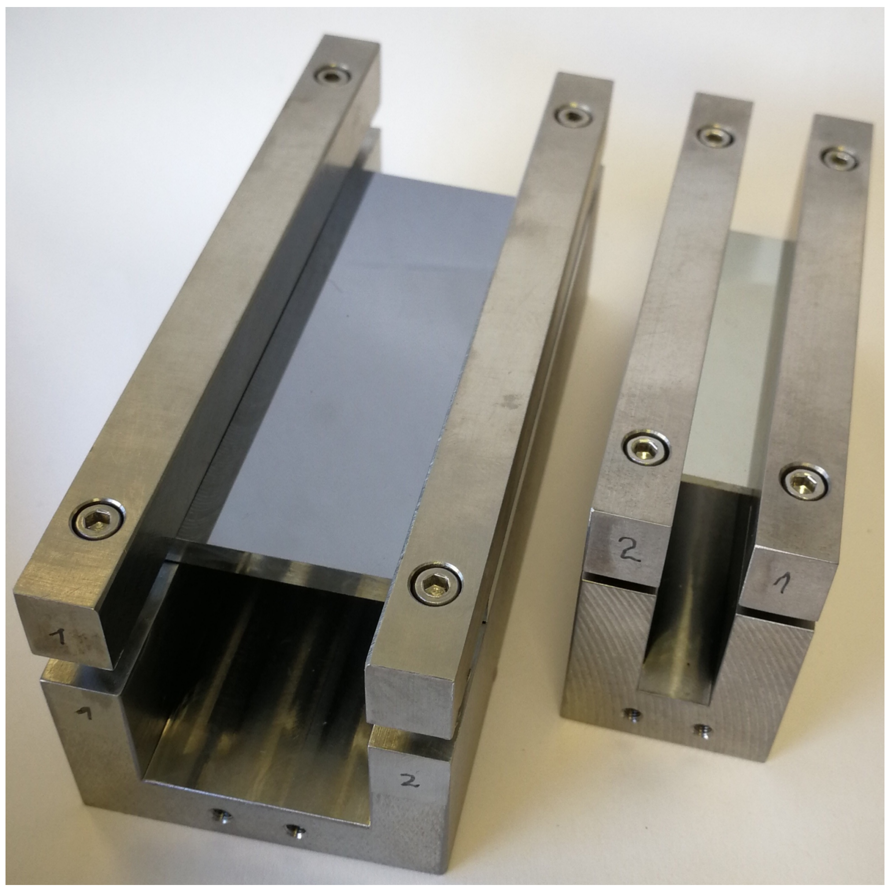
Si: 8 cm long, bent @16.0 mrad

Ge: 5 cm long, bent @14.5 mrad

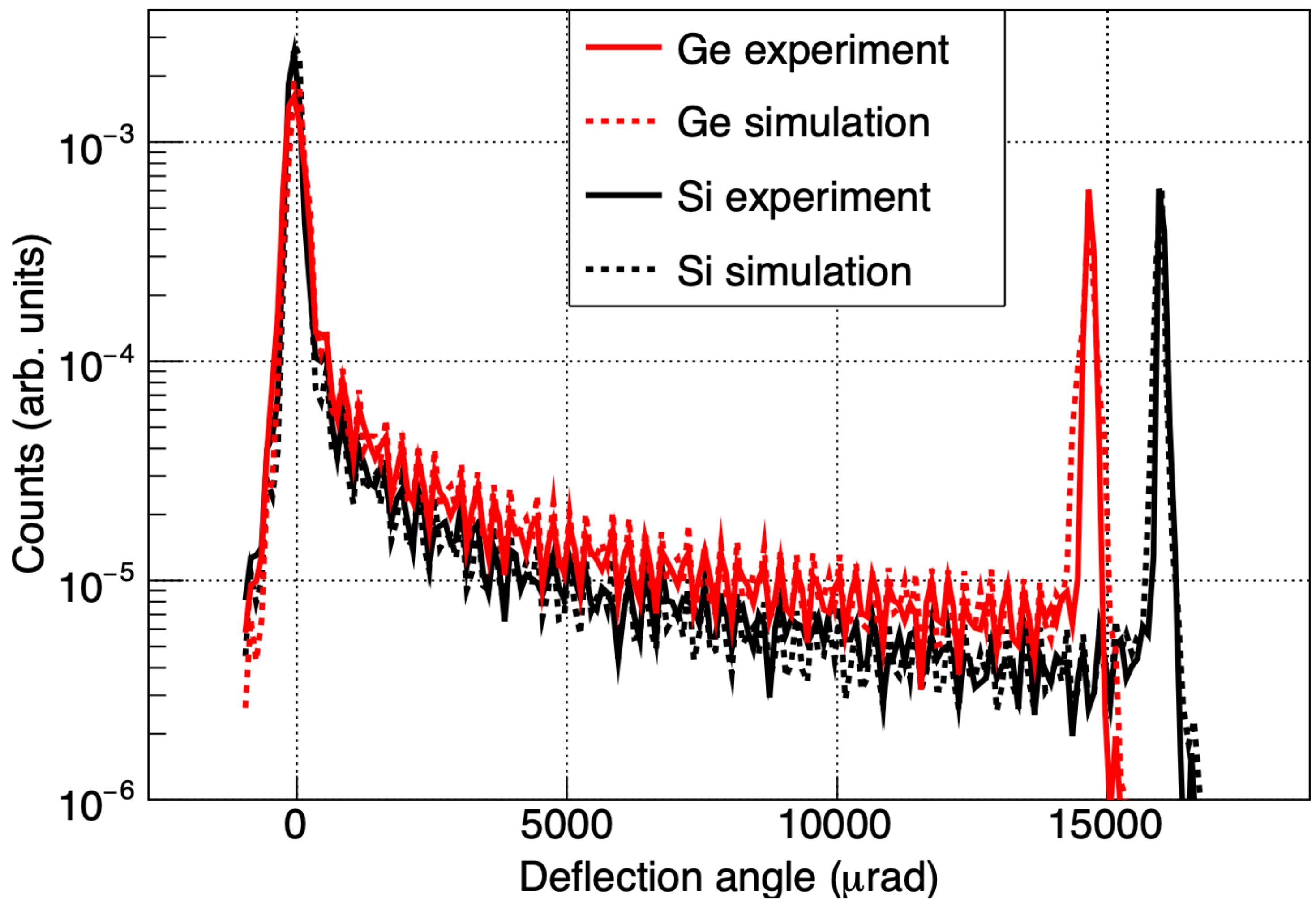
Silicon crystal 8 cm long

Bending angle 16 mrad

PRD 103, 072003 (2021)



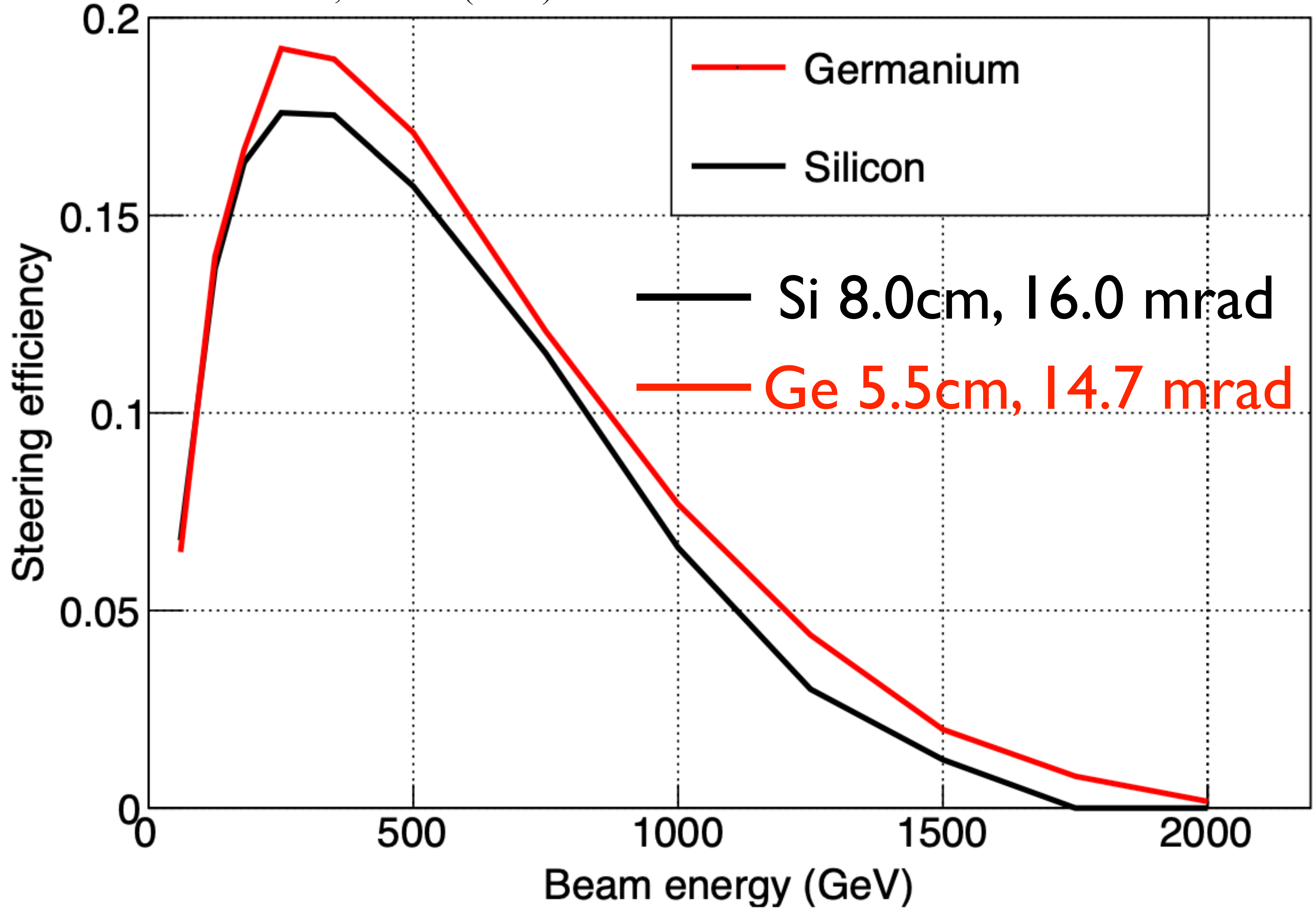
Courtesy of A. Mazzolari



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

Channeling efficiency vs energy

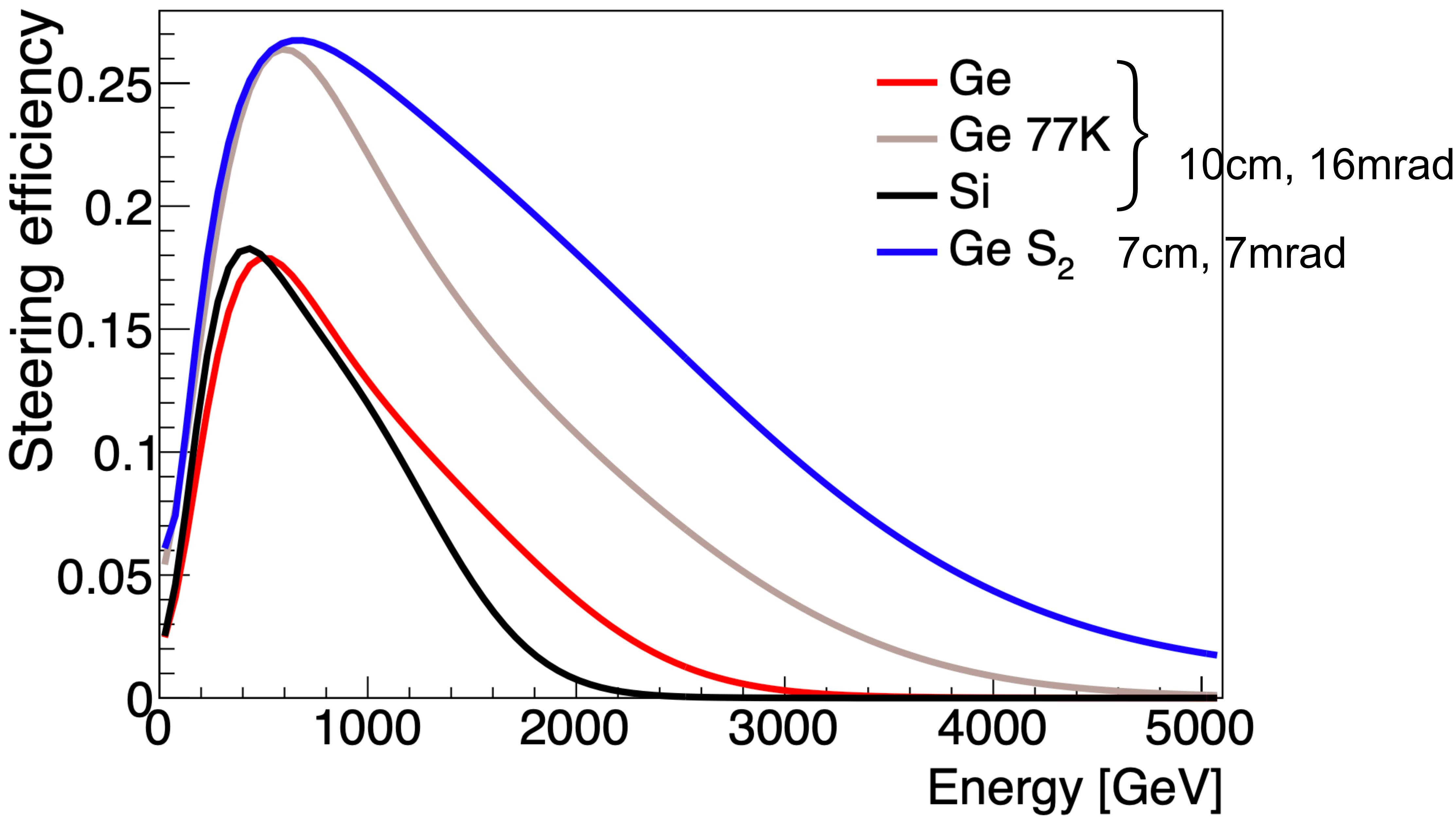
PRD 103, 072003 (2021)



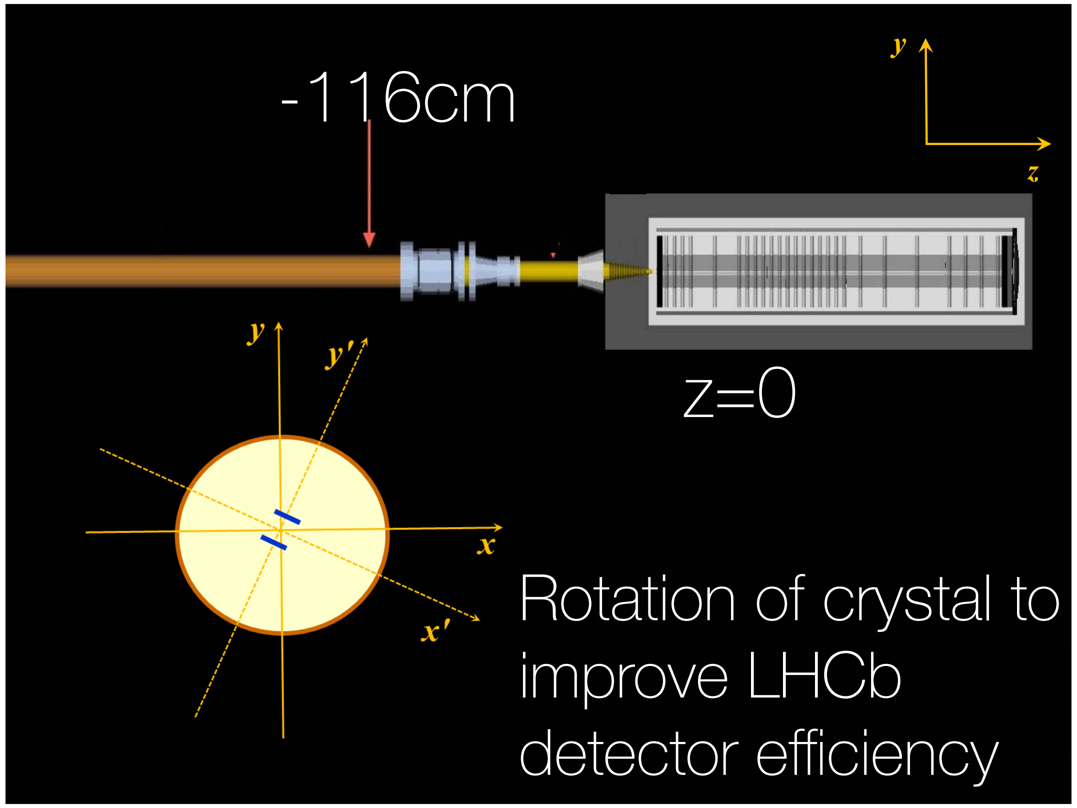
Channeling efficiency vs energy

Channeling simulations: for cooled Ge at T=77 K significant increase in efficiency.

PRD 103, 072003 (2021)

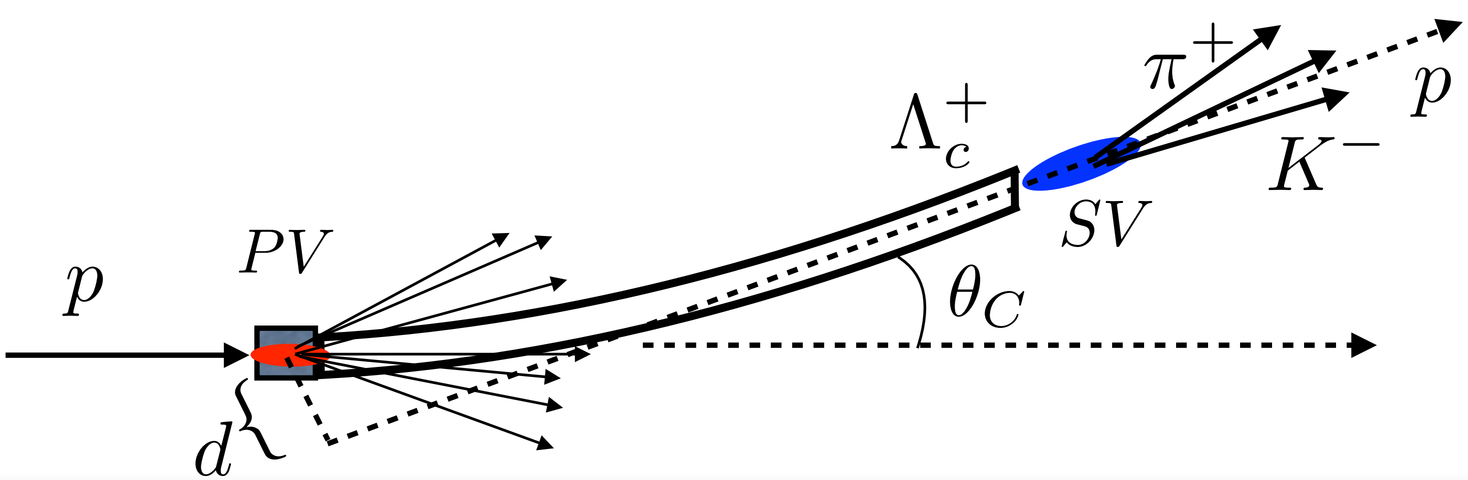


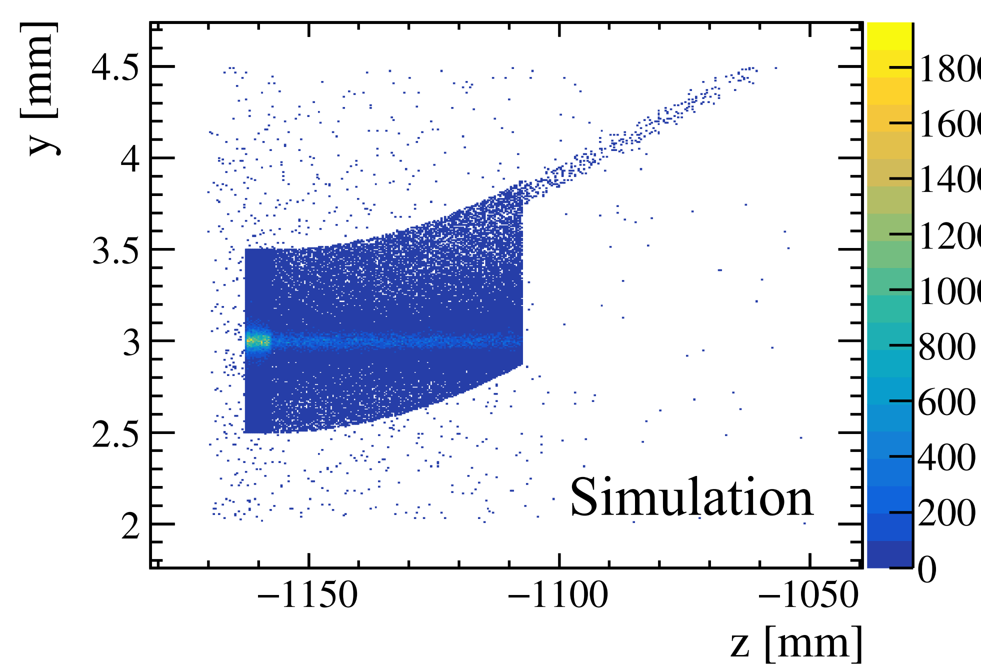
Preparatory studies in LHCb



- 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)





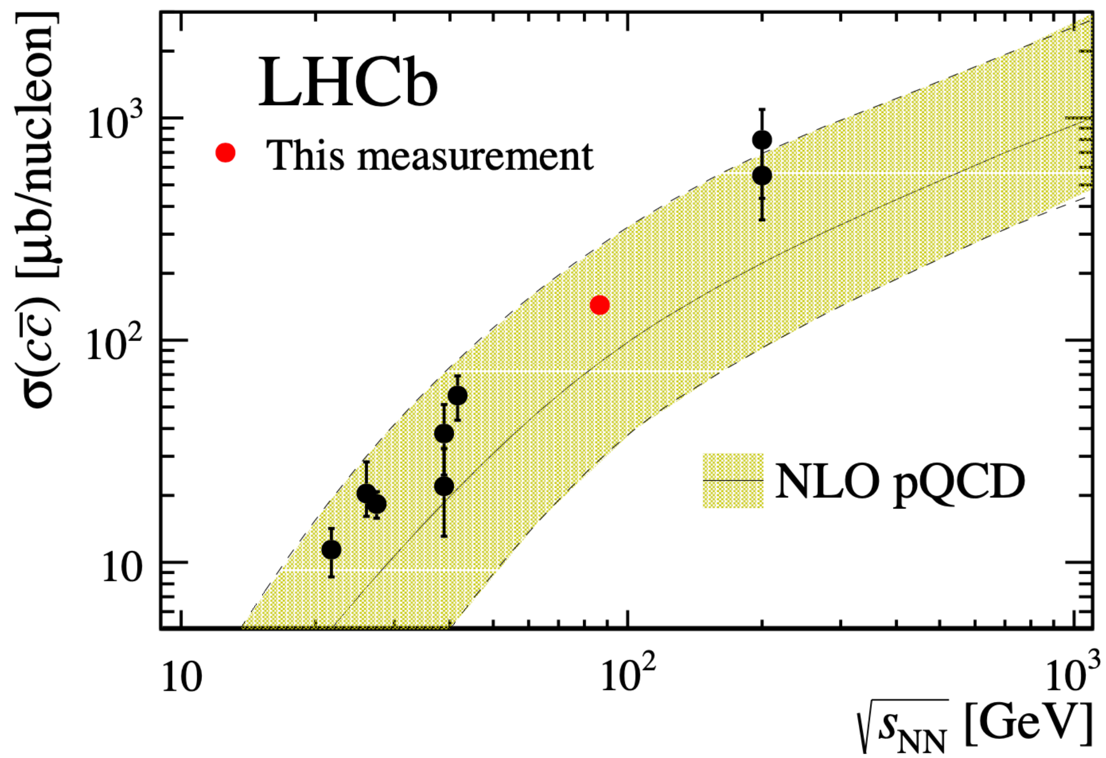
Production of Λ_c^+ baryons

Measured $c\bar{c}$ cross-section at $\sqrt{s_{NN}}$ = 86.6 GeV - PRL 122, 132002 (2019), Erratum

$\sigma_{c\bar{c}}$ = 144 ± 12.1 ± 3.5 μb/nucleon

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

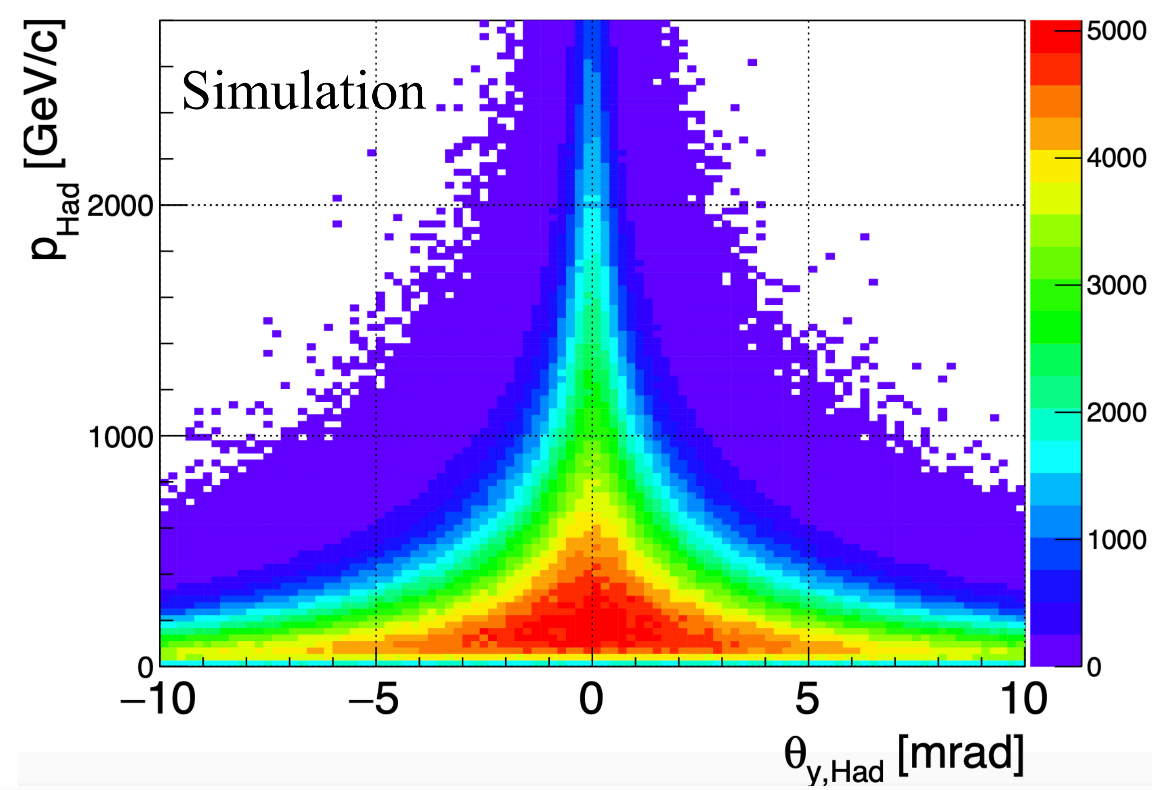
Λ_c^+ **polarization** measurement ongoing using p-Gas collisions



Polar angle vs momentum for Λ_c^+ baryons produced in fixed-target

Production peaked at zero angle

Select forward-produced Λ_c^+ baryons: <p>≈1 TeV

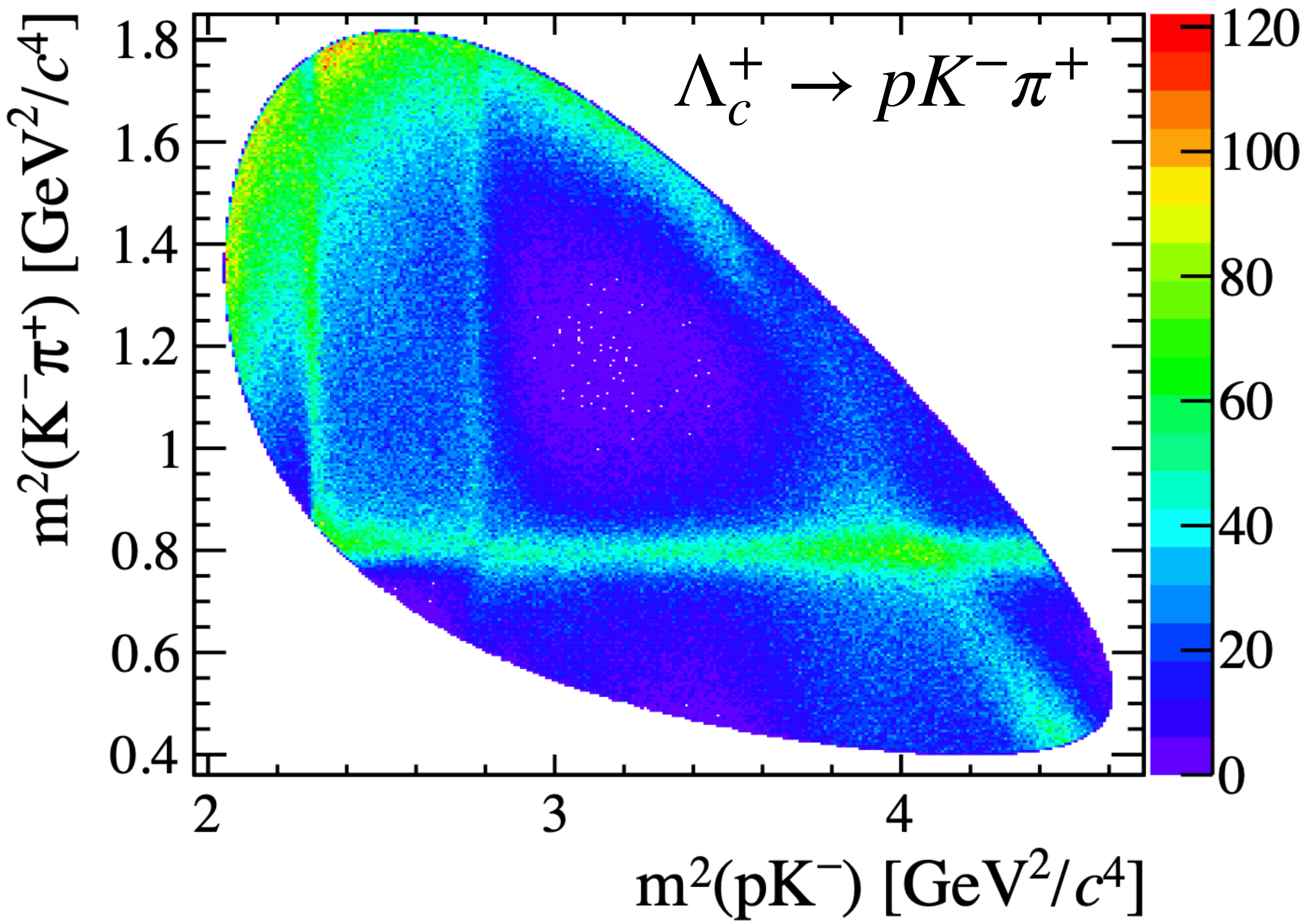


Use copious Λ_c^+, Ξ_c^+ 3-body decays

- Use many 3-body decays to increase the signal yield
  - Ξ^-, $\Sigma^\pm$ strange baryons with very high momentum can be reconstructed as stable charged particles in the detector

PRD 103, 072003 (2021)

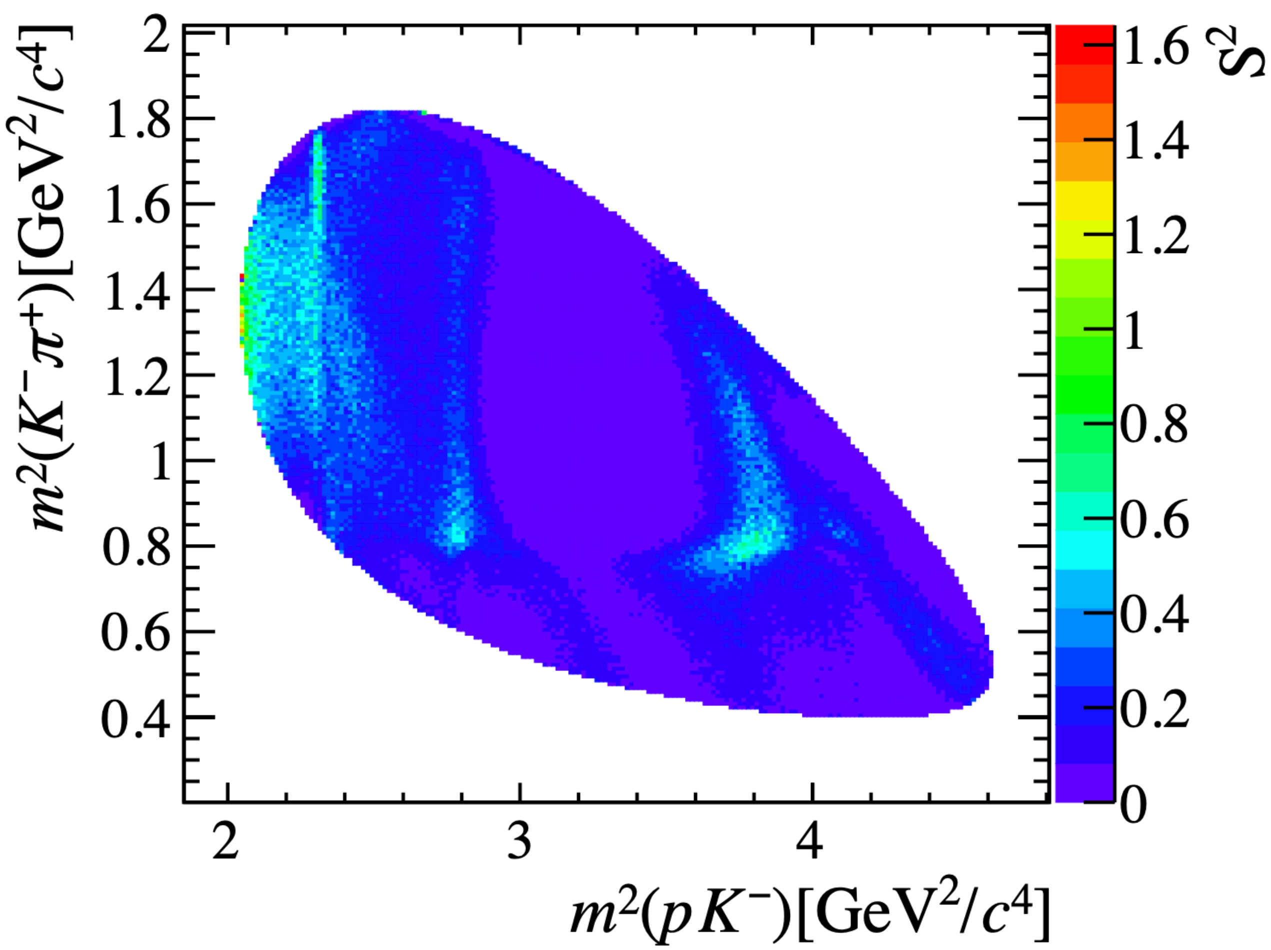
Λ_c^+ final state	$\mathcal{B}$ (%)	$\epsilon_{3\text{trk}}$	$\mathcal{B}_{\text{eff}}$ (%)
$pK^-\pi^+$	6.28 ± 0.32	0.99	6.25
$\Sigma^+\pi^-\pi^+$	4.50 ± 0.25	0.54	2.43
$\Sigma^-\pi^+\pi^+$	1.87 ± 0.18	0.71	1.33
$p\pi^-\pi^+$	0.461 ± 0.028	1.00	0.46
$\Xi^-K^+\pi^+$	0.62 ± 0.06	0.73	0.45
$\Sigma^+K^-K^+$	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



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

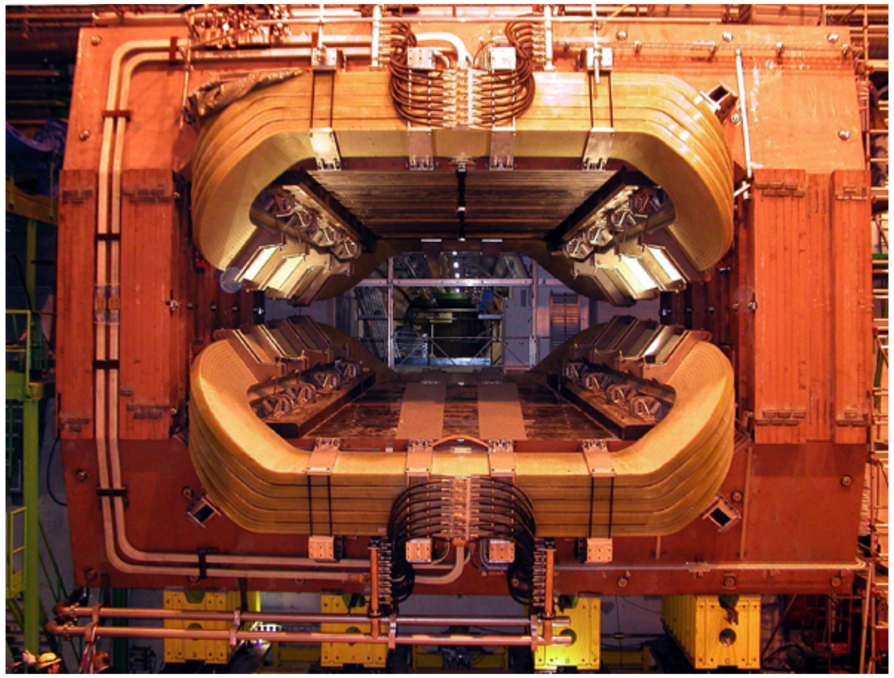
Sensitivity: average event information

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

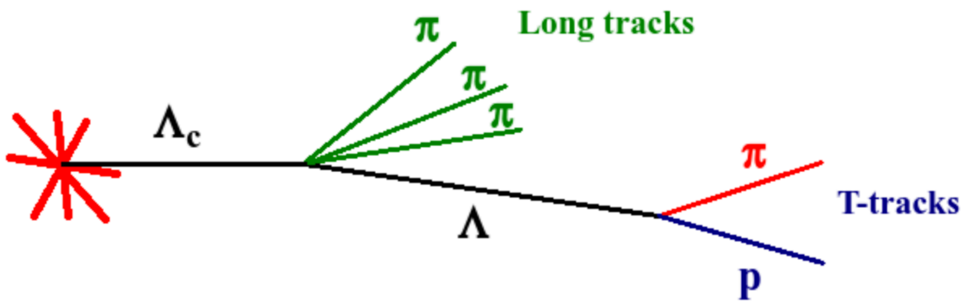
Experimental method for neutral long-lived Λ baryon $\tau \approx 10^{-10}$ s

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. $\Xi_c^0 \to \Lambda K^- \pi^+$, $\Lambda_c^+ \to \Lambda \pi^+ \pi^- \pi^+$
  - 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

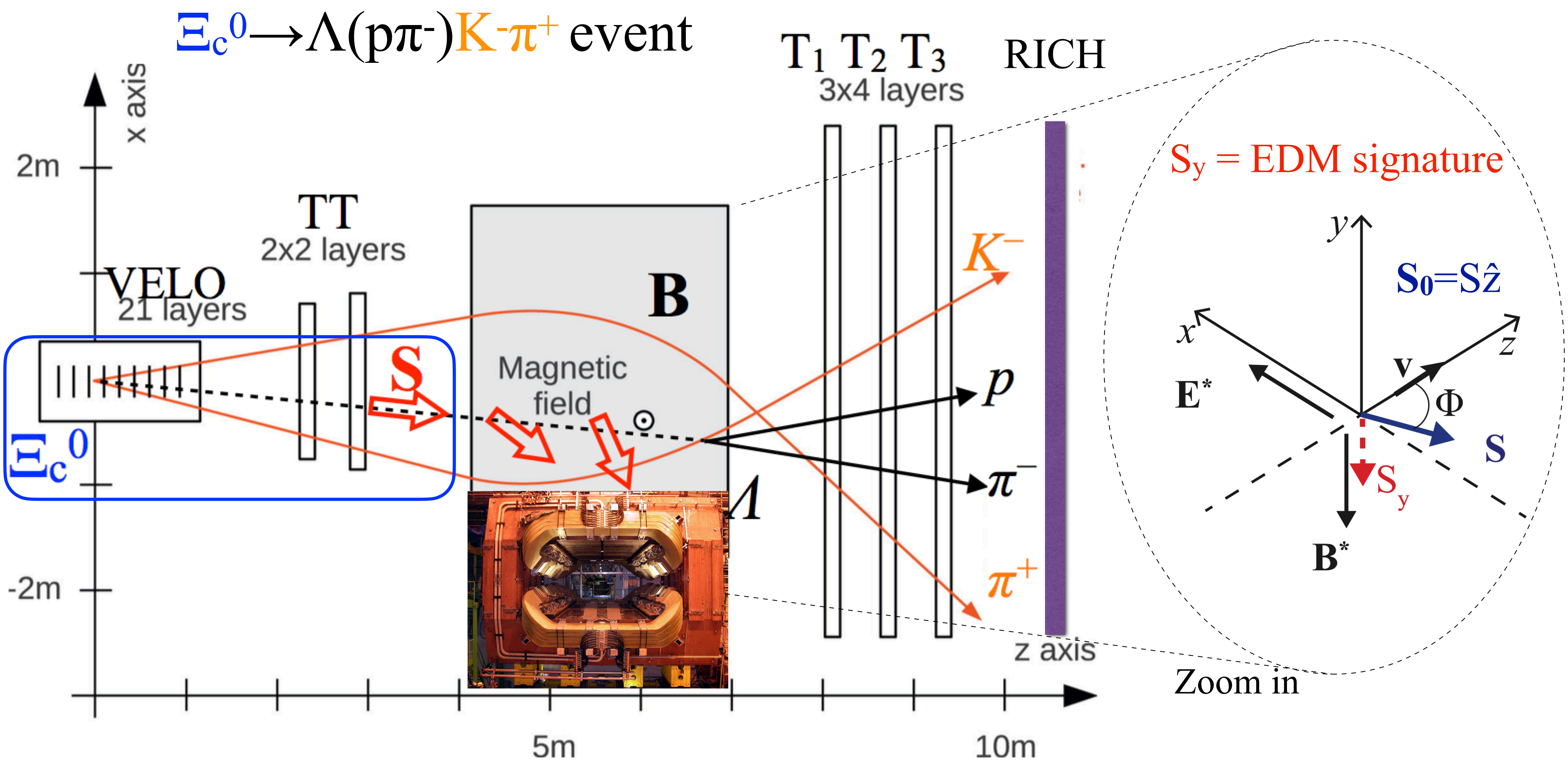


$$\Lambda_c^+ \to \Lambda \pi^+ \pi^+ \pi^-$$



Novel experimental technique for strange baryons

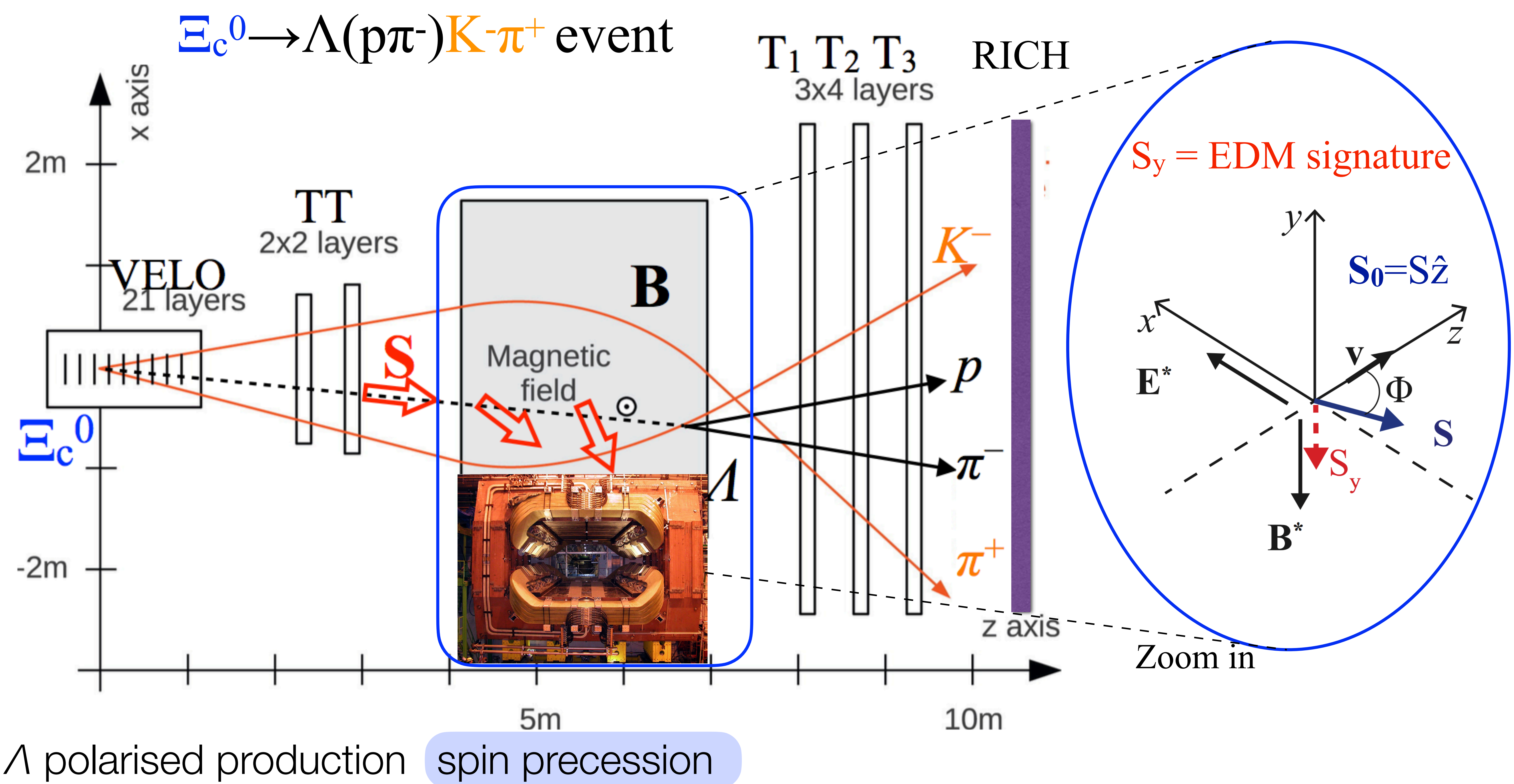
- EDM/MDM from spin precession of Λ baryon in LHCb **dipole magnet**



Λ polarised production

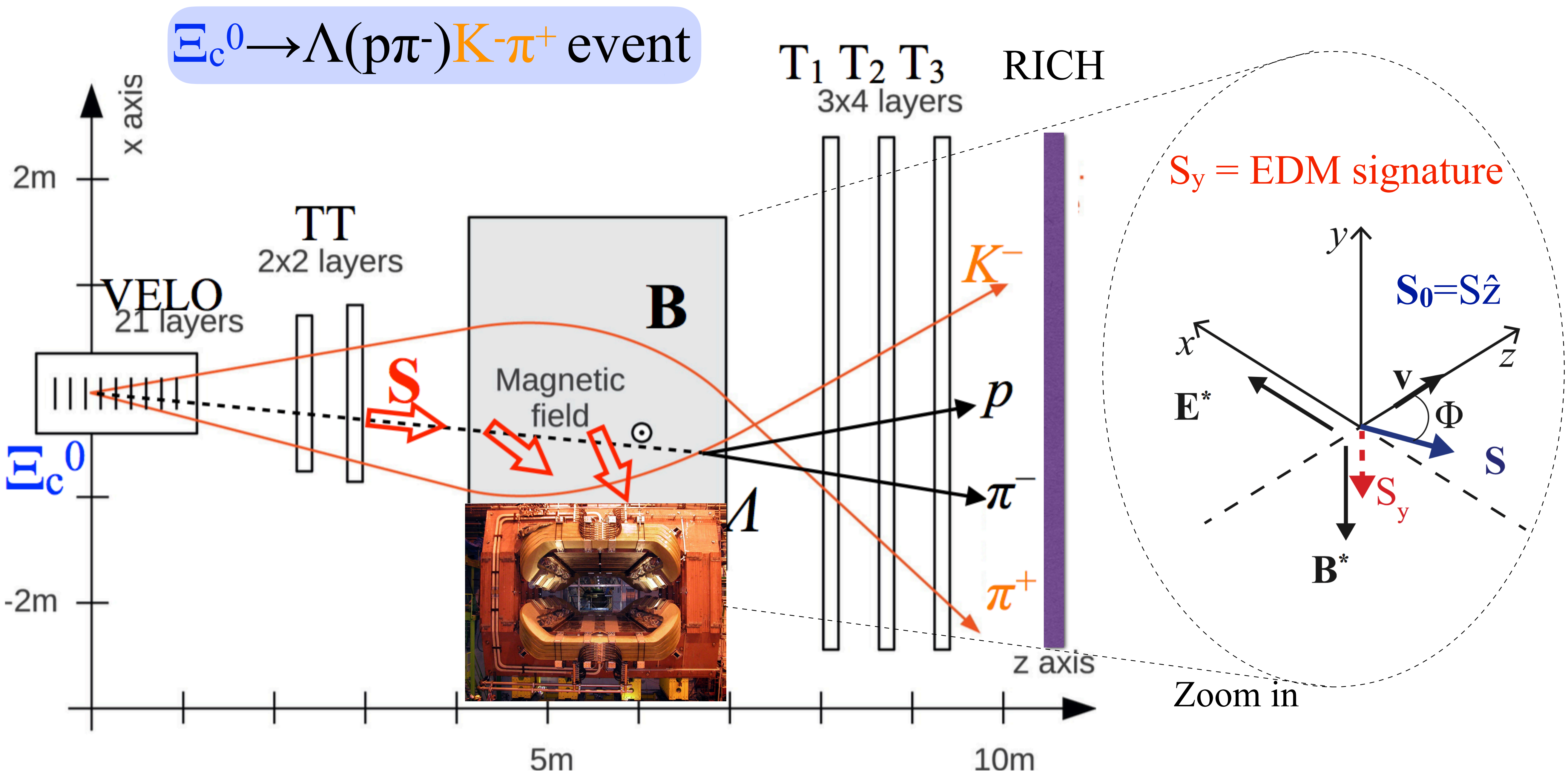
Novel experimental technique for strange baryons

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



Novel experimental technique for strange baryons

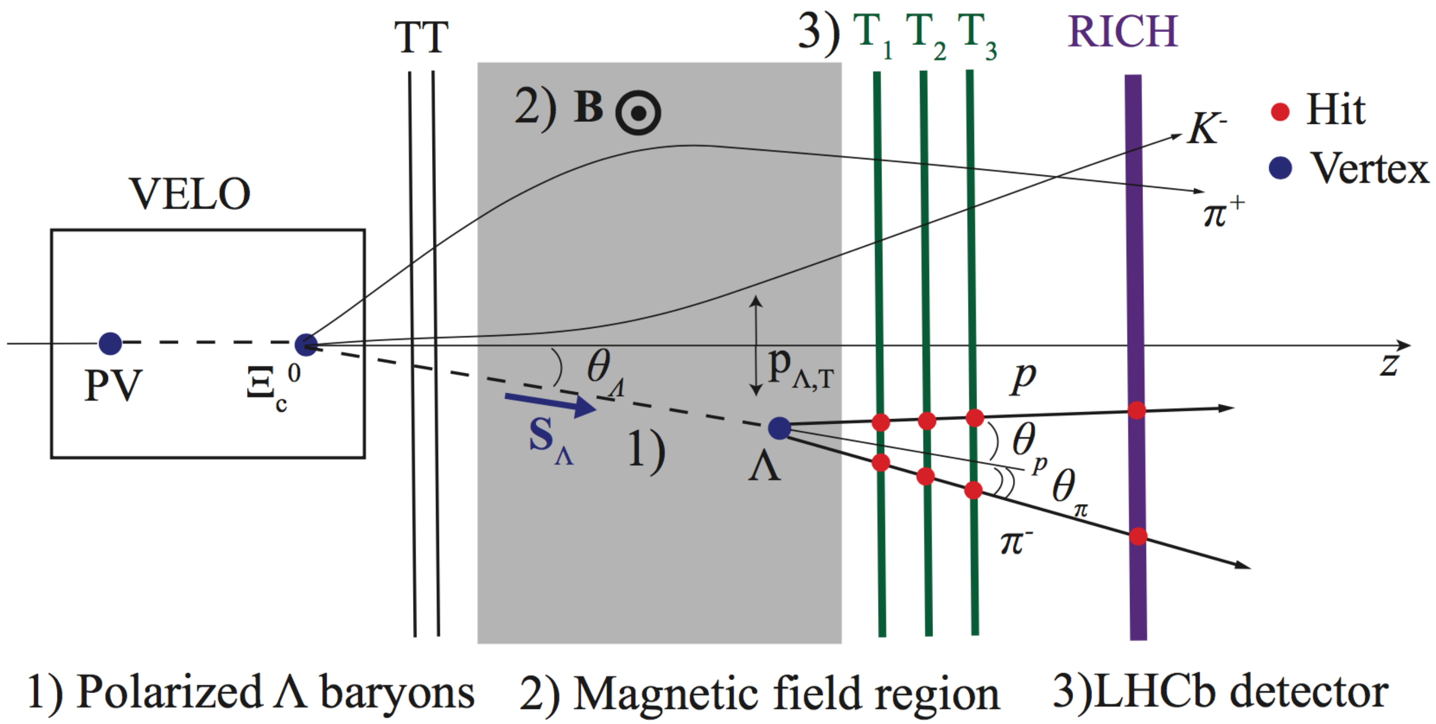
- $\color{red}{\text{EDM}}$/$\color{blue}{\text{MDM}}$ from spin precession of Λ baryon in LHCb **dipole magnet**

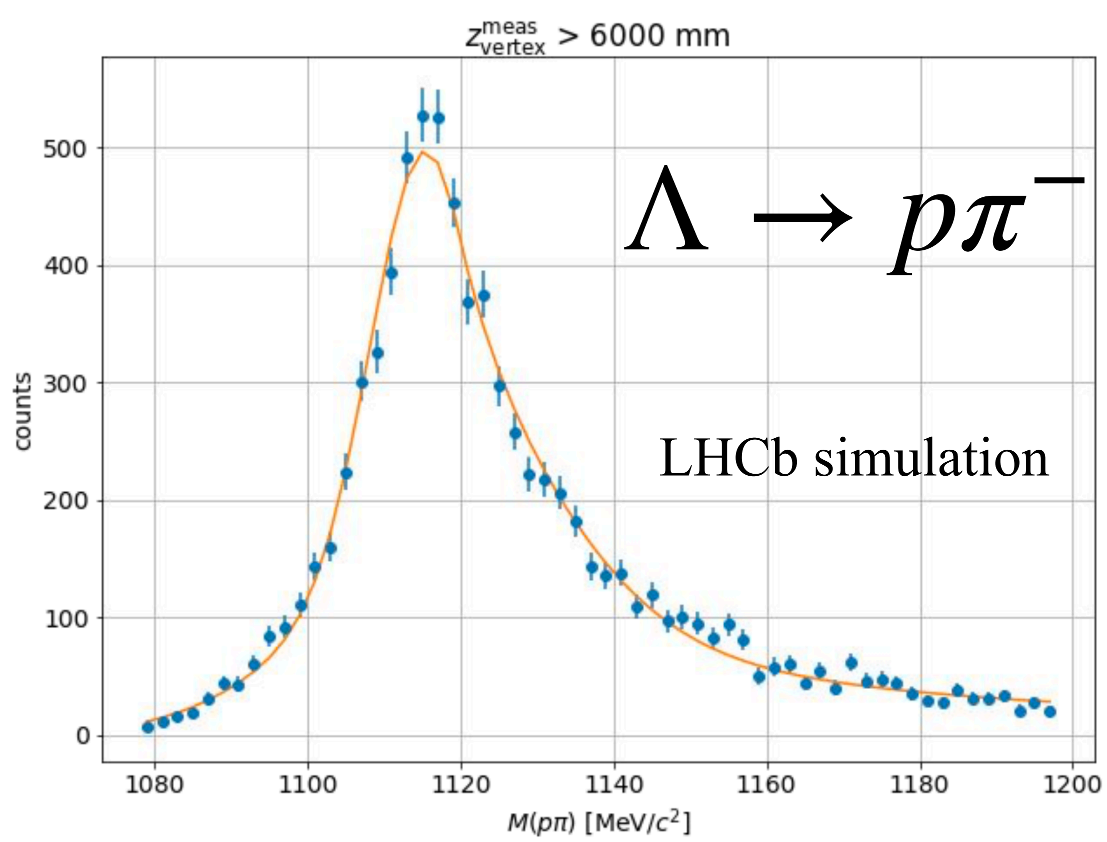


Λ polarised production spin precession event reconstruction

Simulations studies for Λ reconstruction

- Fit the entire decay chain $\Xi_c^0 \to \Lambda(p\pi^-)K^-\pi^+$ imposing geometric and kinematic constraints





- Reconstructed m(pπ-) invariant mass for Λ candidates decaying at the end of the magnet
- Trigger and selection strategy for Run3 data taking in progress

Sensitivity on MDM/EDM

- Initial longitudinal polarisation $\mathbf{s}_0 = s_0 \hat{z}$
- Rotation after interaction with B field

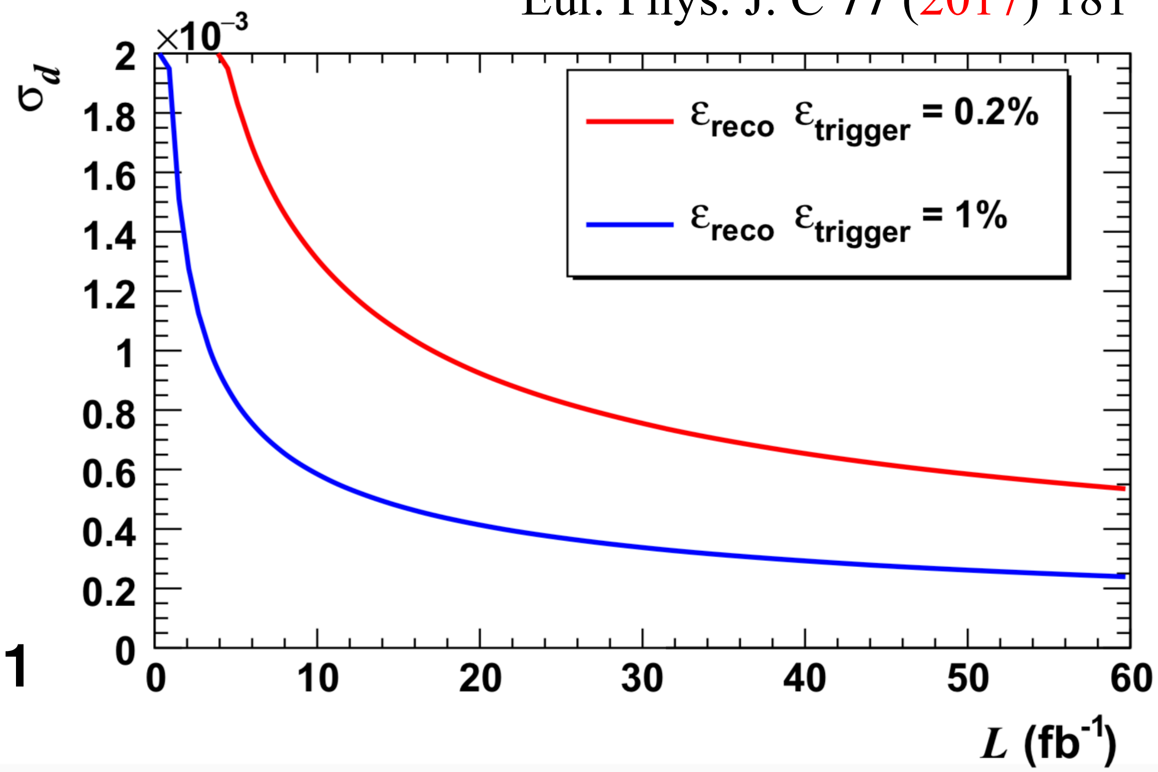
$$\mathbf{s} = \begin{cases} s_x = -s_0 \sin \Phi \\ s_y = -s_0 \frac{d\beta}{g} \sin \Phi \\ s_z = s_0 \cos \Phi \end{cases}$$

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

Spin analyser in Λ helicity frame

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

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



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

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

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

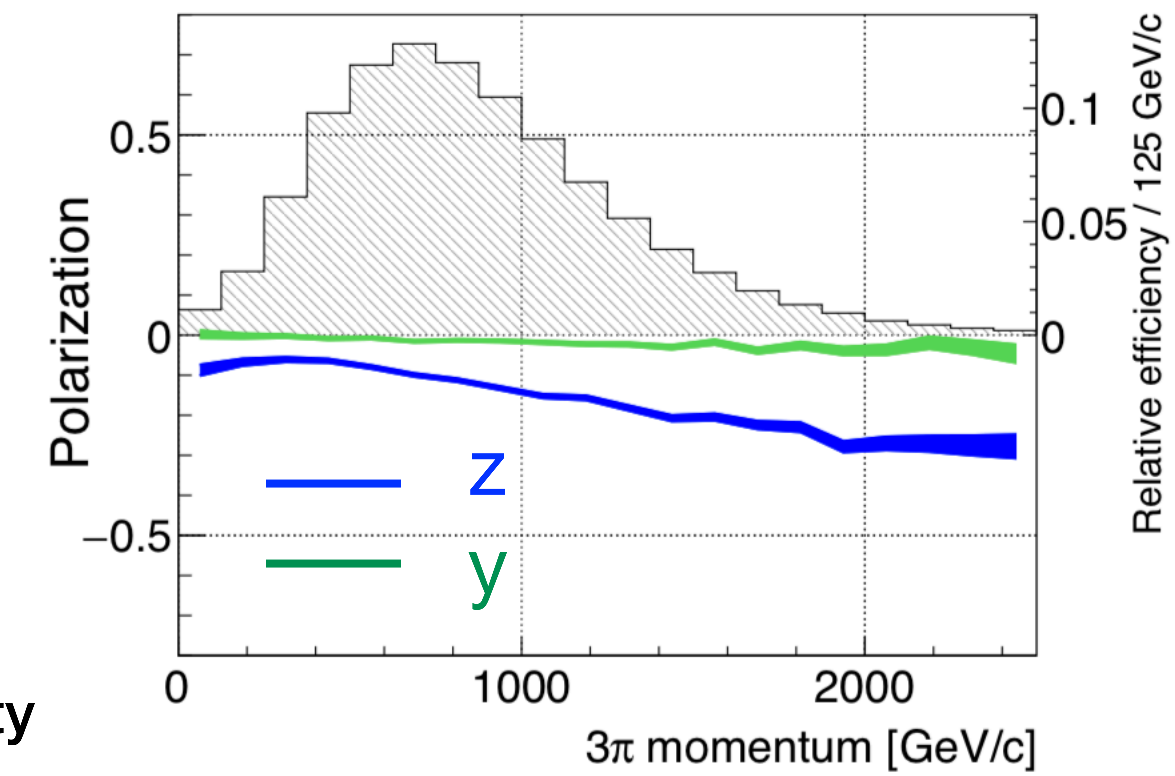
$$\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$$

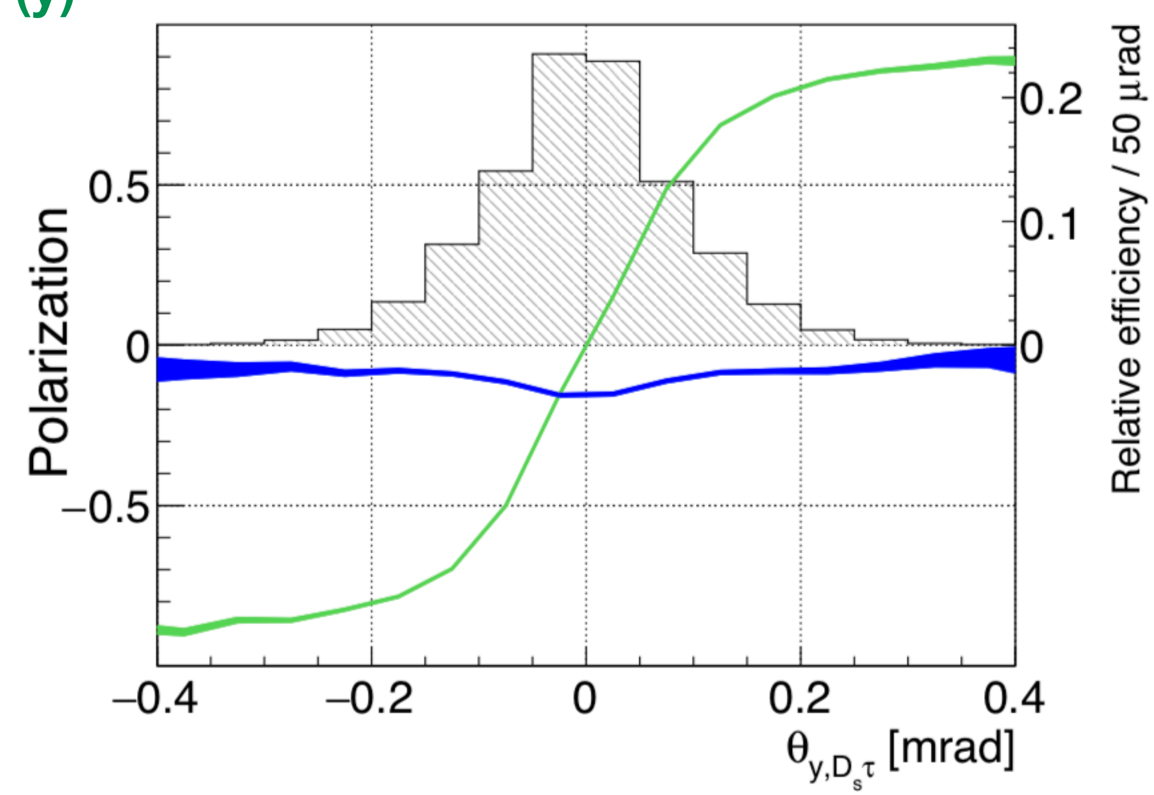
Single Crystal after target:

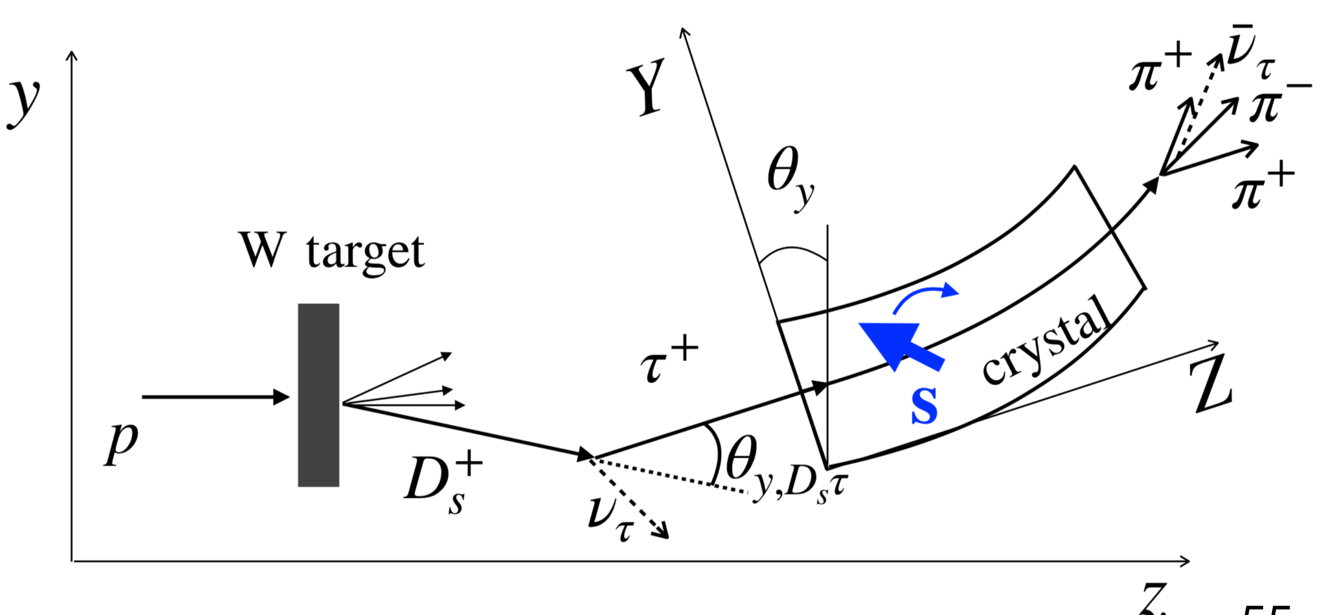
- τ spin precession

Spin polarisation:

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

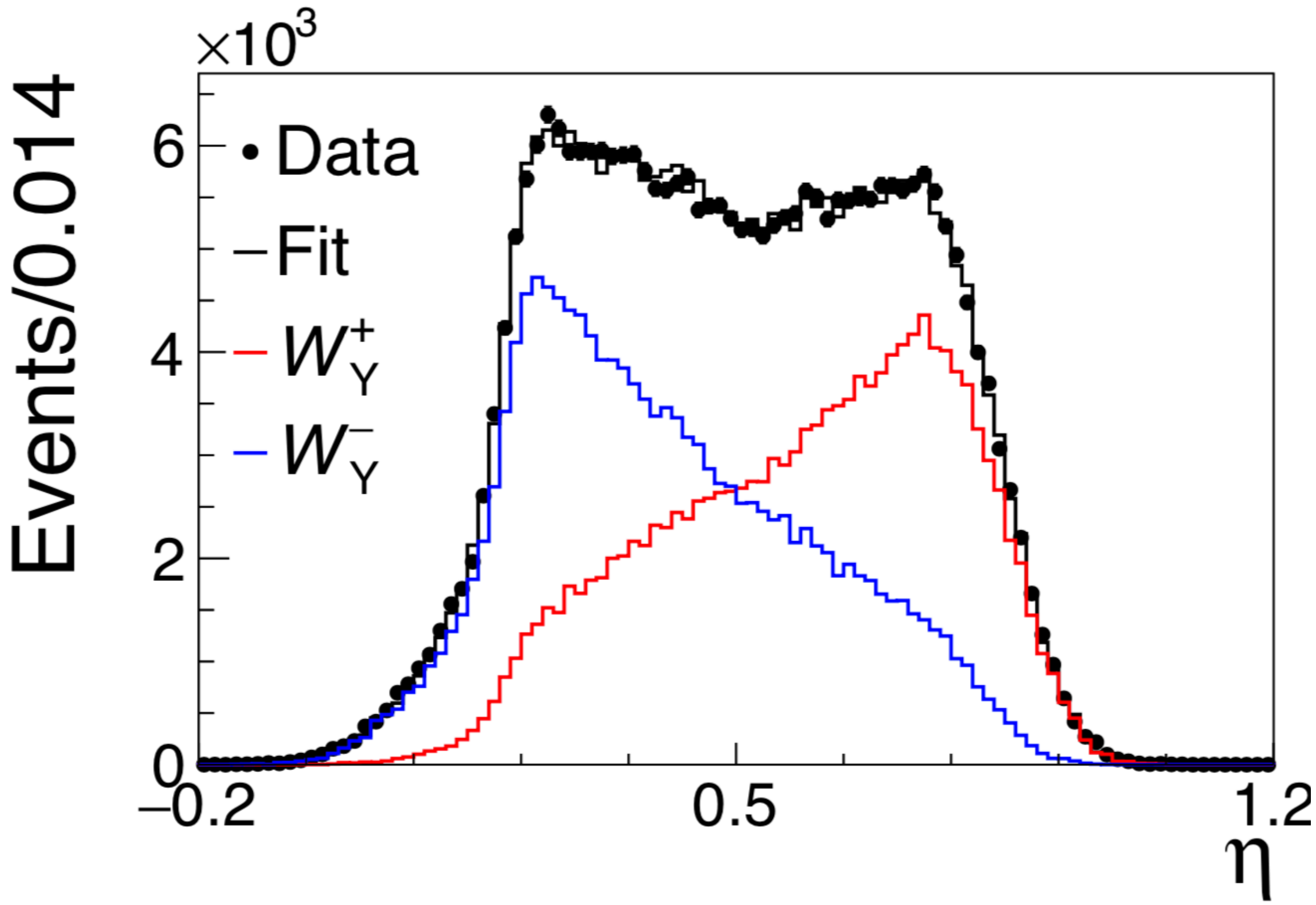


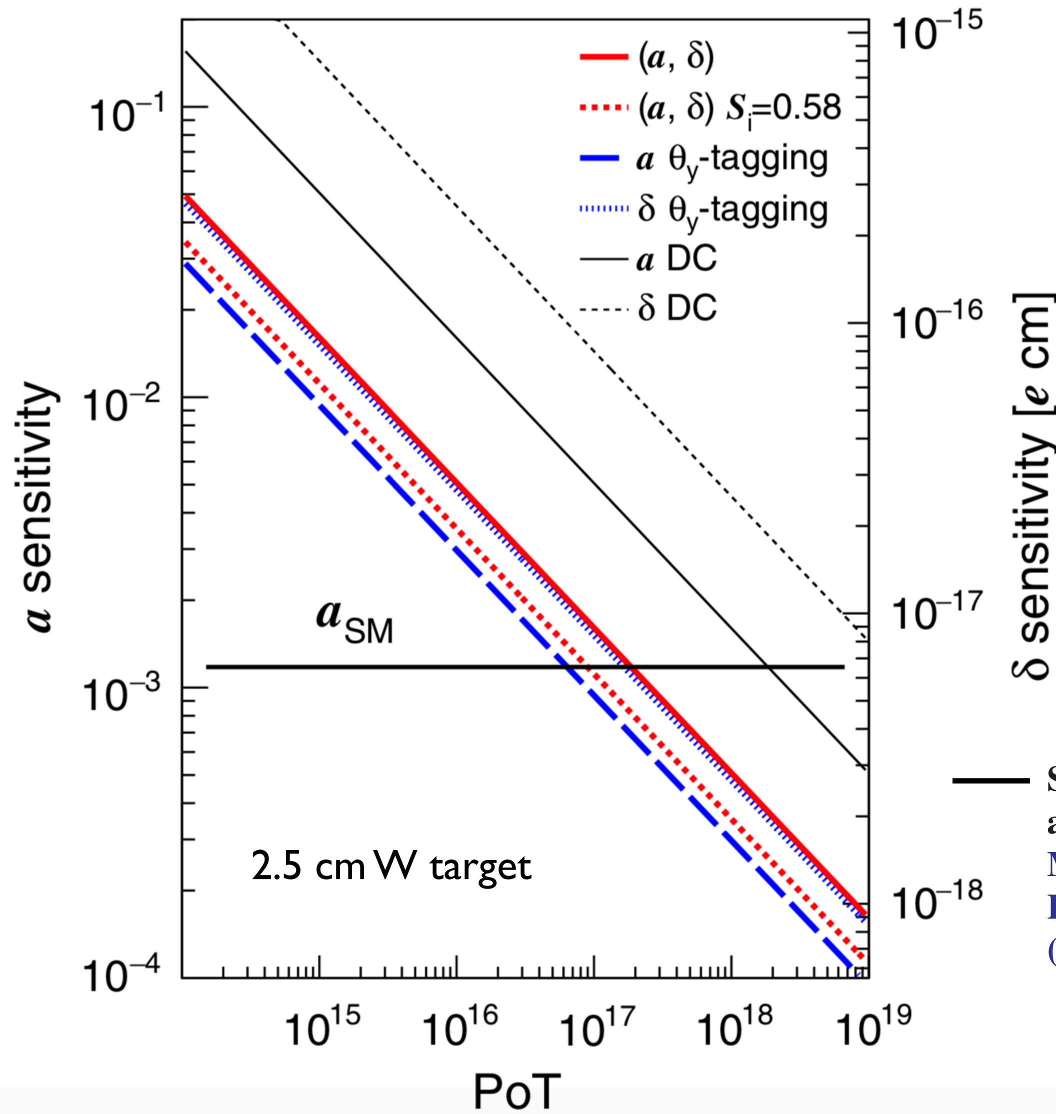




J. Fu, M. A. Giorgi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N.N., J. Ruiz Vidal, Phys. Rev. Lett. 123, 011801 (2019)

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

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

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

EDM sensitivity ~10^{-17} *e* cm

Challenging: dedicated experiment needed

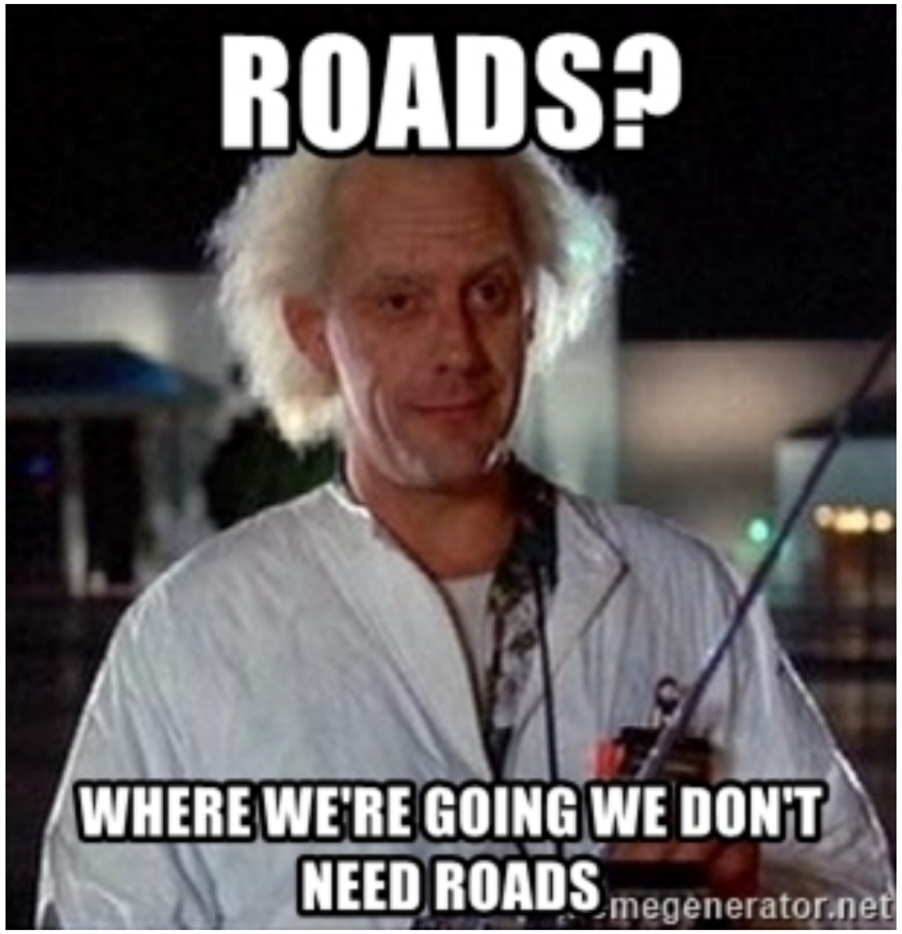
J. Fu, M. A. Giorgi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N.N., J. Ruiz Vidal, Phys. Rev. Lett. 123, 011801 (2019)

Summary

- Measurements of **MDM/EDM** of particles are sensitive to physics within and beyond the SM
- A **proposal** to measure MDM/EDM of short-lived particles at LHC, i.e. strange and charm baryons and tau lepton, has ben present
- Feasibility studies show that **first measurements** are possibile
  - strange baryons, using the **LHCb** detector
  - charm baryons, require a **fixed-target** setup to be installed upstream of the LHCb detector
  - 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
- Produce a **technical design report** and, if approved, proceed with installation and data taking in LHCb during Run3
- If successful, 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!

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- 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, E. Vallazza
- **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. Giacomo, R. Kurt, R. Lindner, C. Parkes, G. Passaleva, M. Pepe-Altarelli, V. Vagnoni, G. Wilkinson

SELDOM webpage

@SeldomTeam

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.
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- 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.

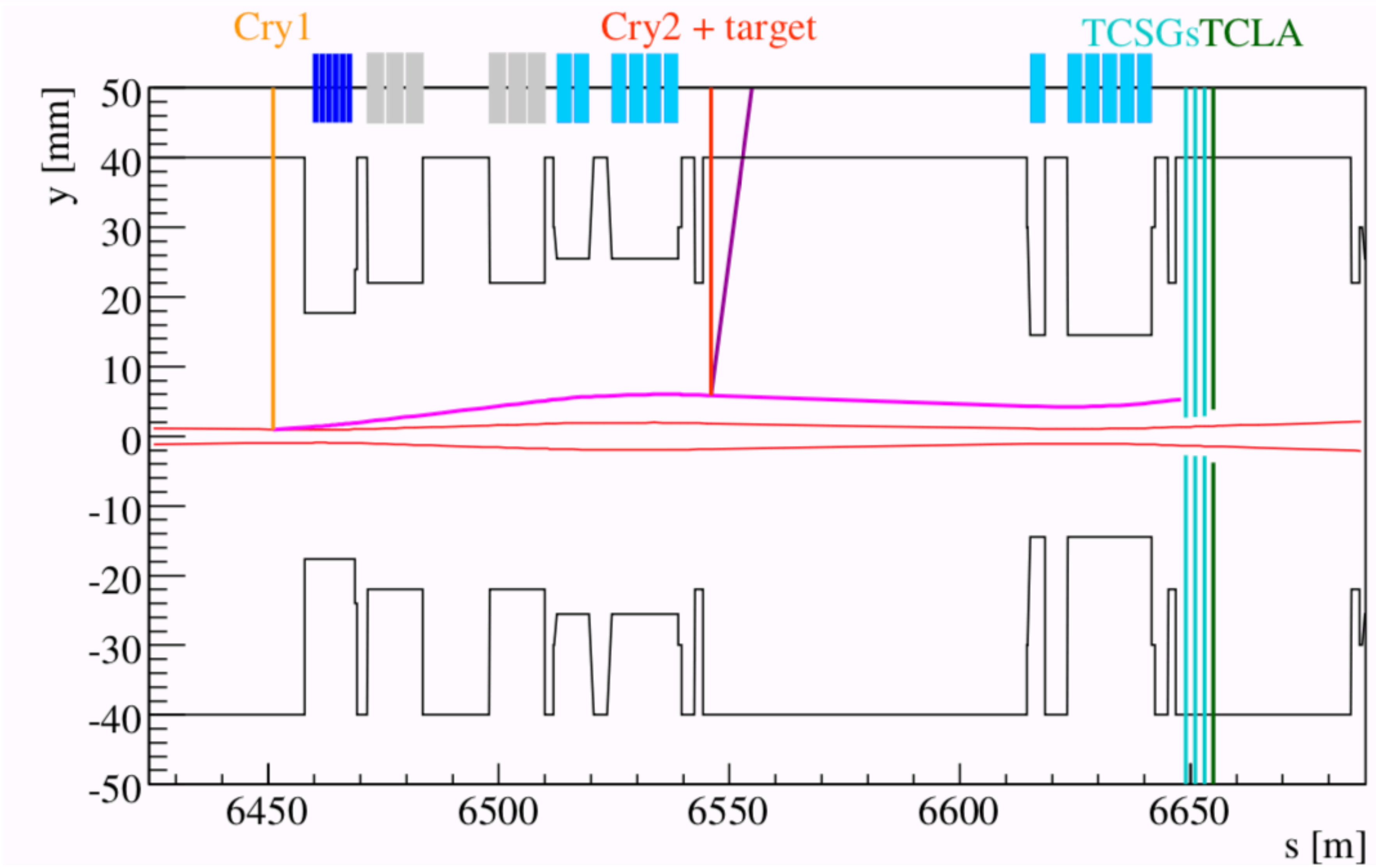
References for τ lepton

- 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

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
- 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)

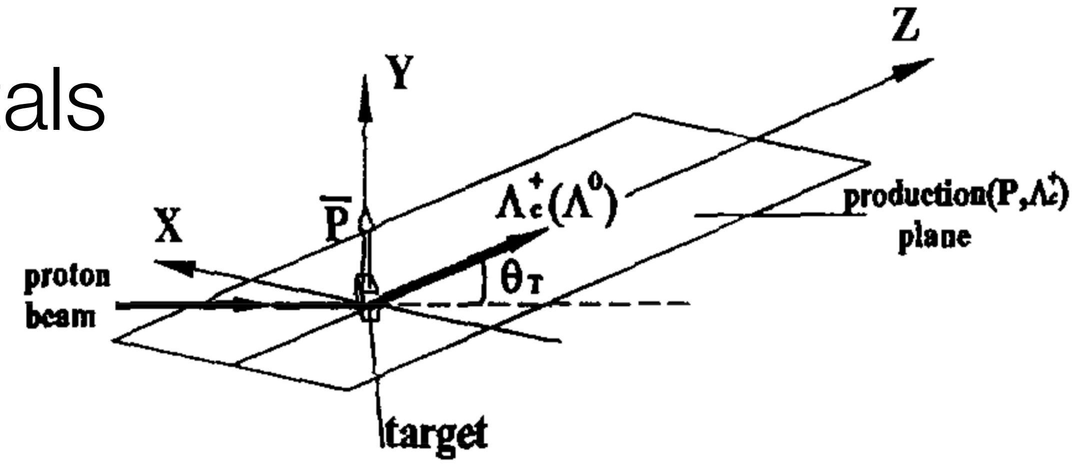


Fig. 3. Schematic diagram of the Λ_c^+ (Λ^0) polarization production.

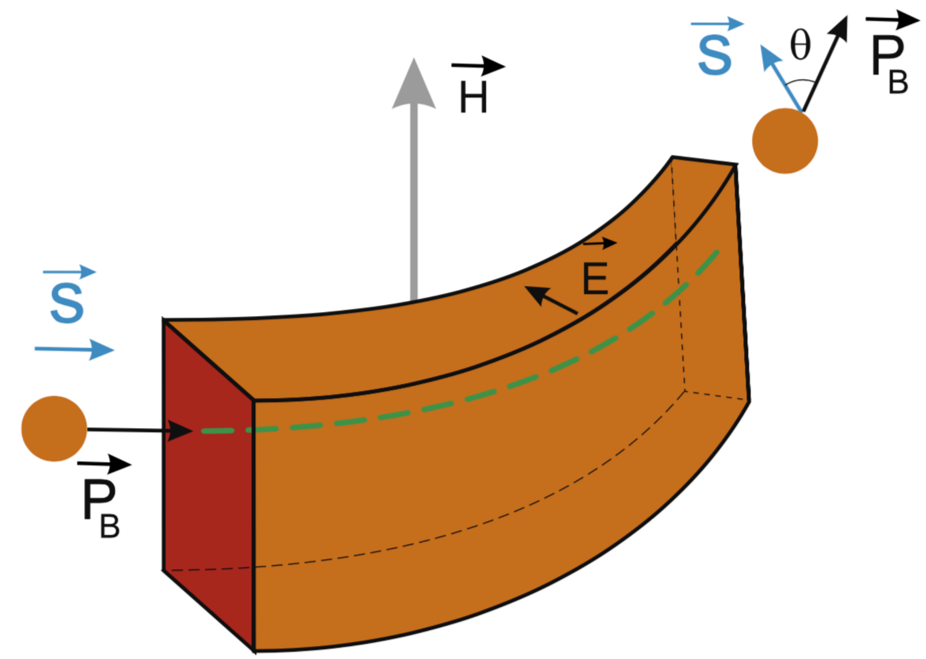
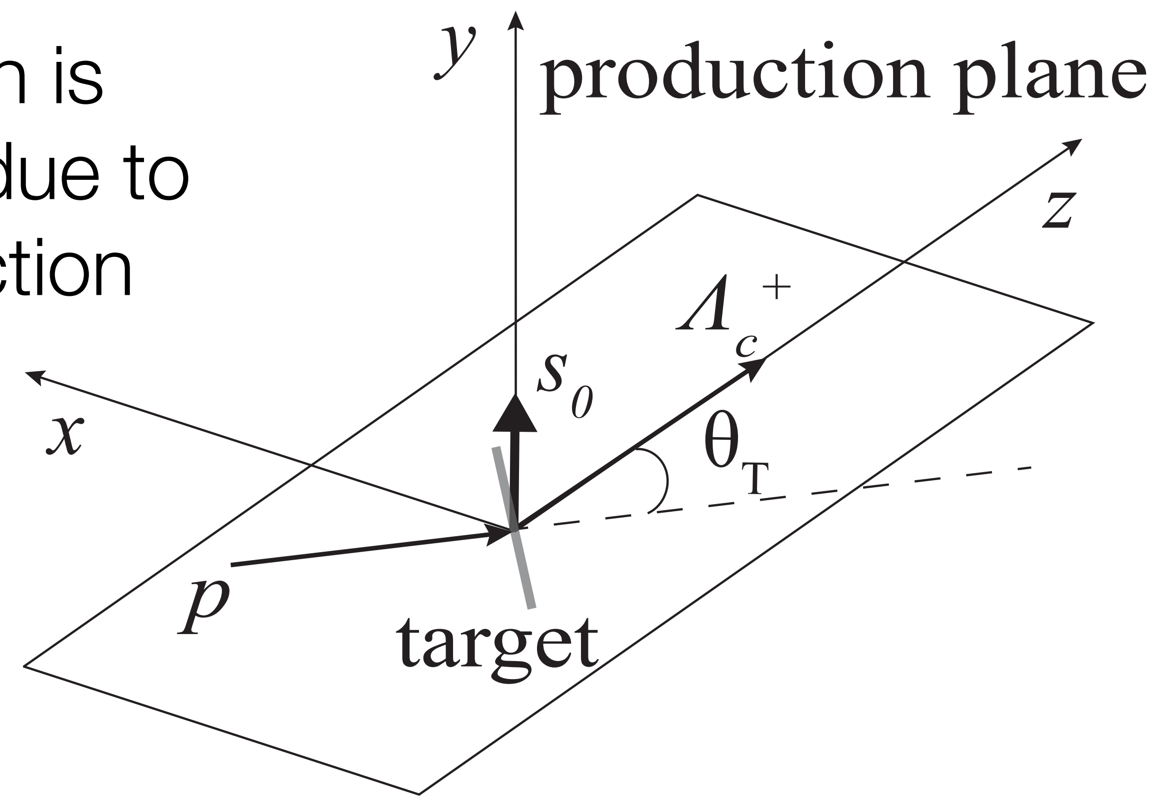
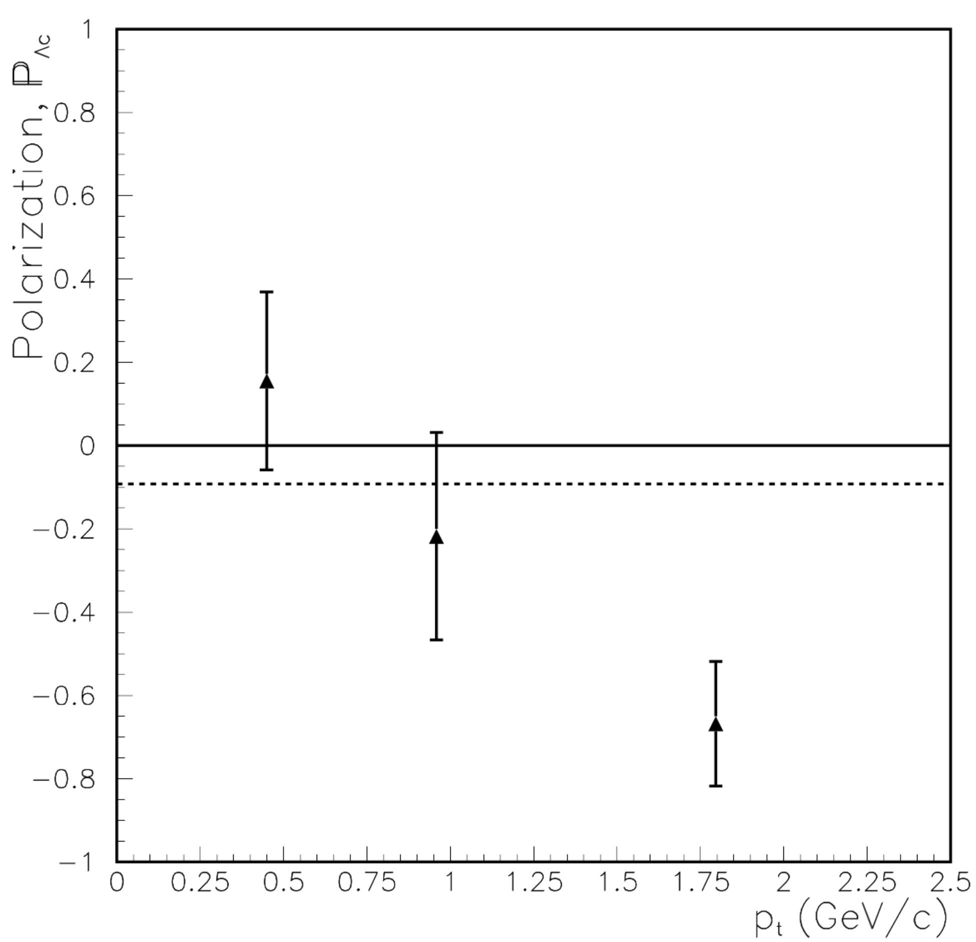


Fig. 1. Spin rotation in a bent crystal.

Charm baryon polarisation

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





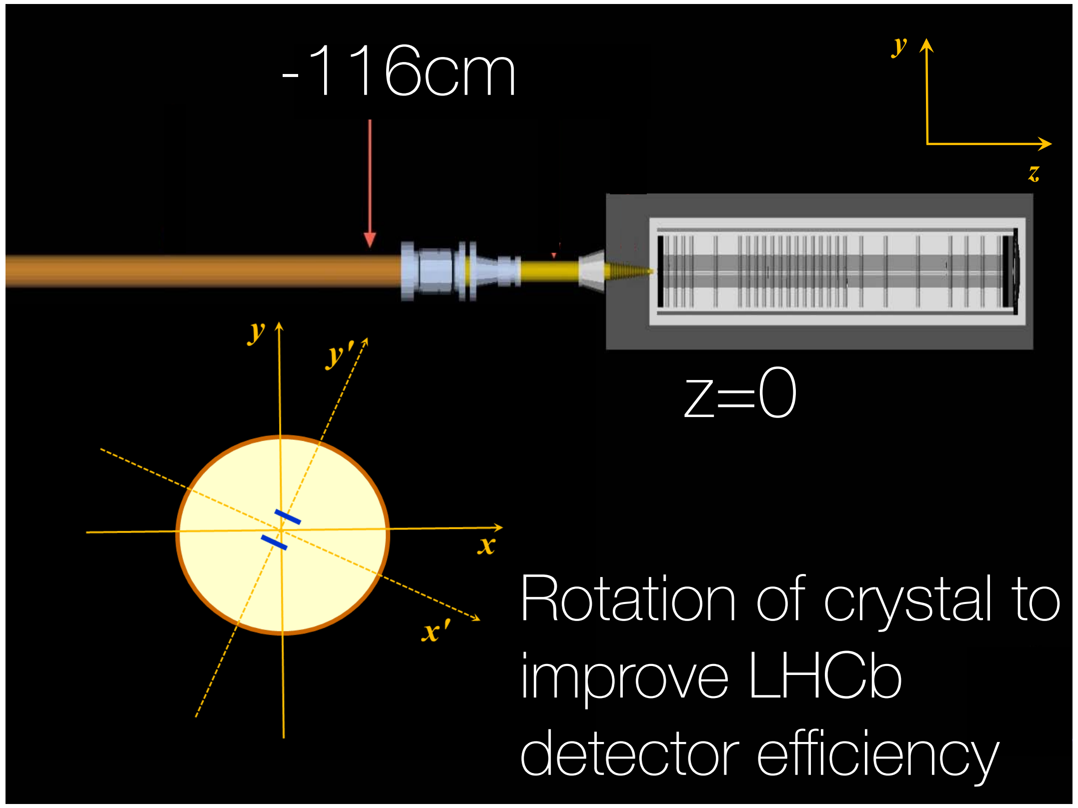
- Λ_c^+ polarisation vs transverse momentum measured by E791 experiment in 500 GeV/c π^--N reactions

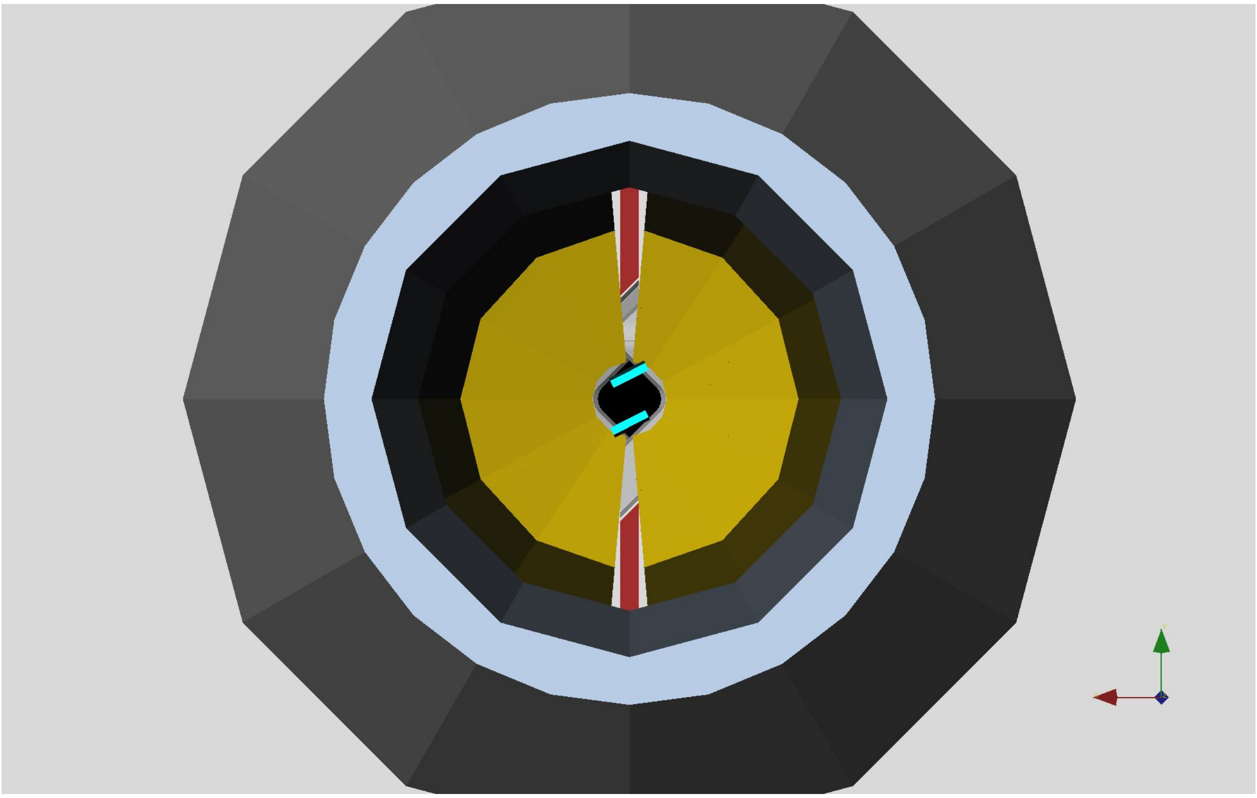
- Increases with Λ_c^+ transverse momentum

Detector simulation studies

Simulation studies

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



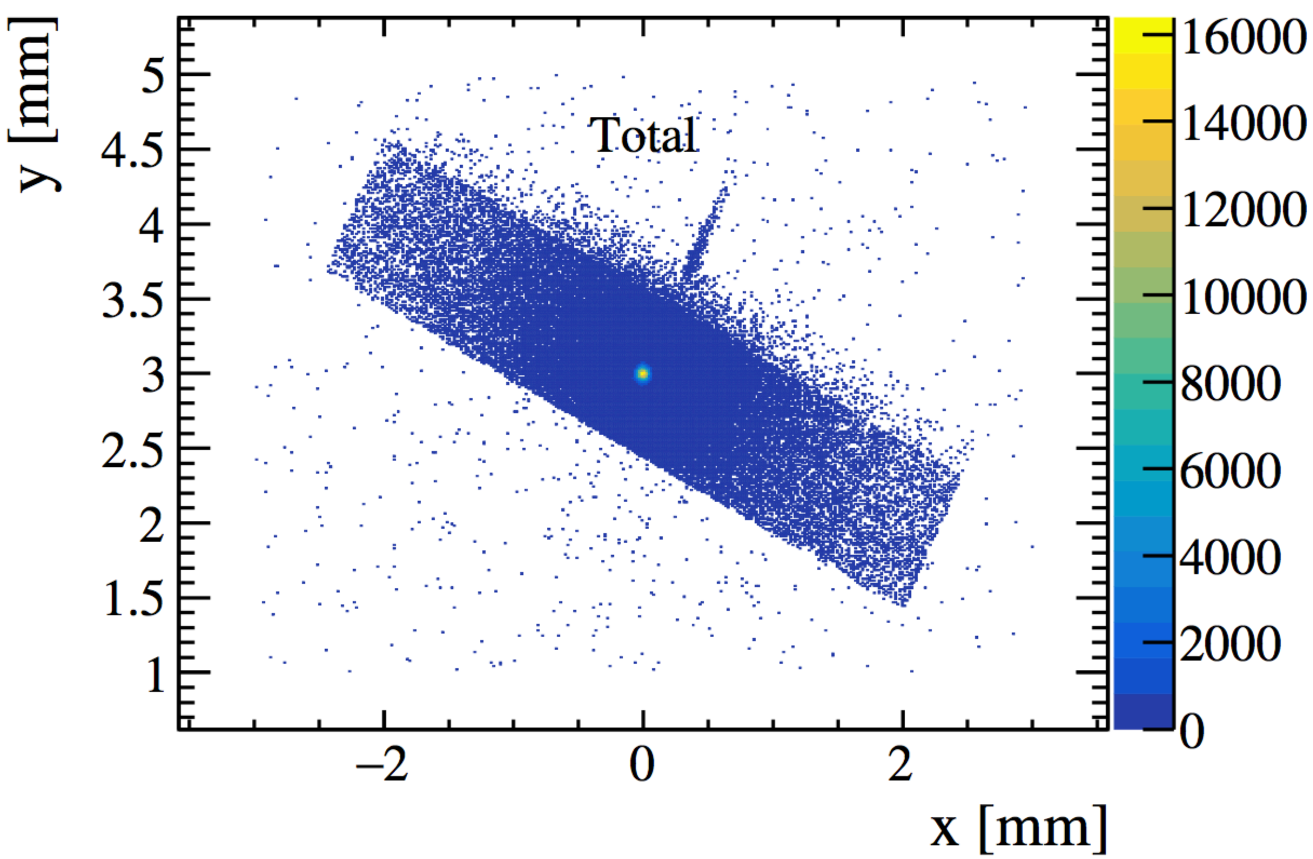


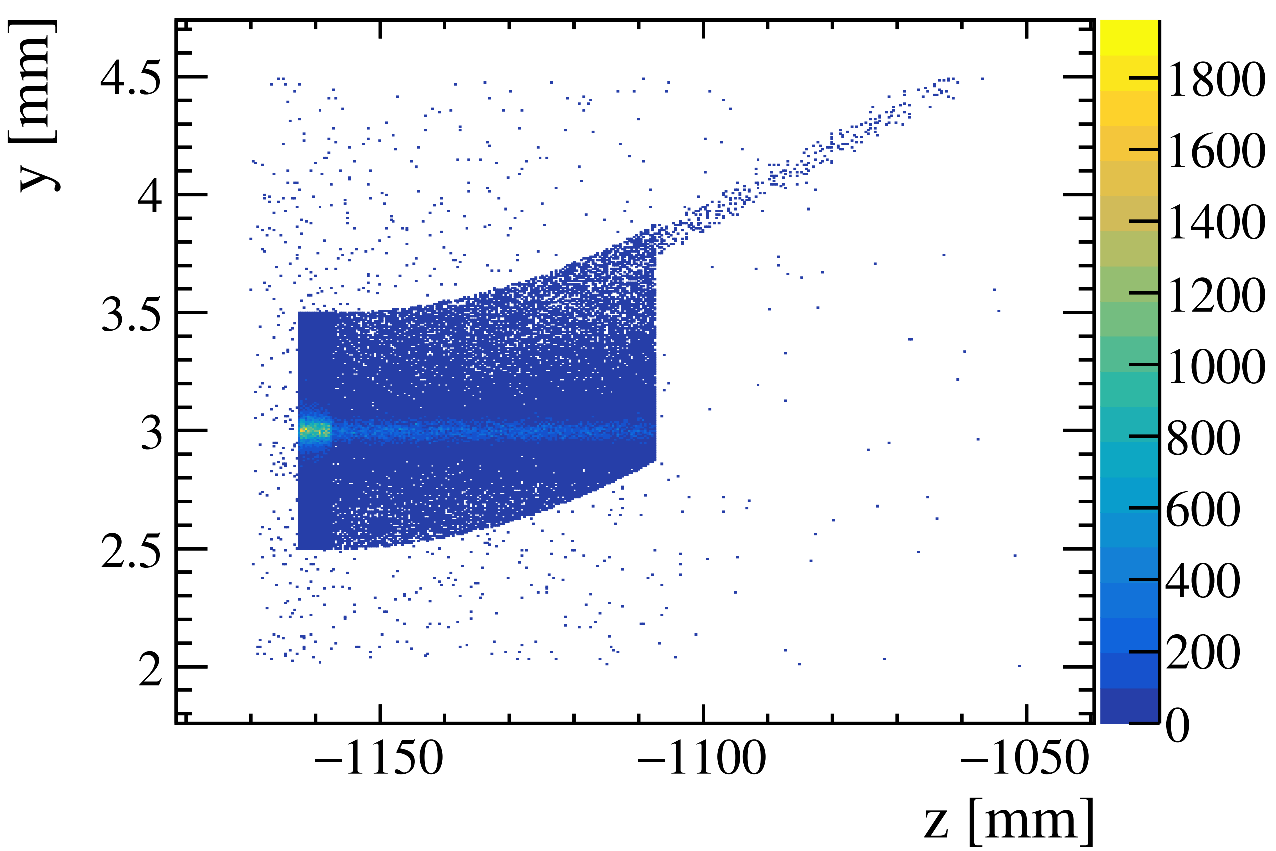
- Use EPOS for fixed-target minimum bias events, PYTHIA for baryons produced in pW hard collisions

- Signal reconstruction and background rejection studied using LHCb full simulation

Fixed-target simulation

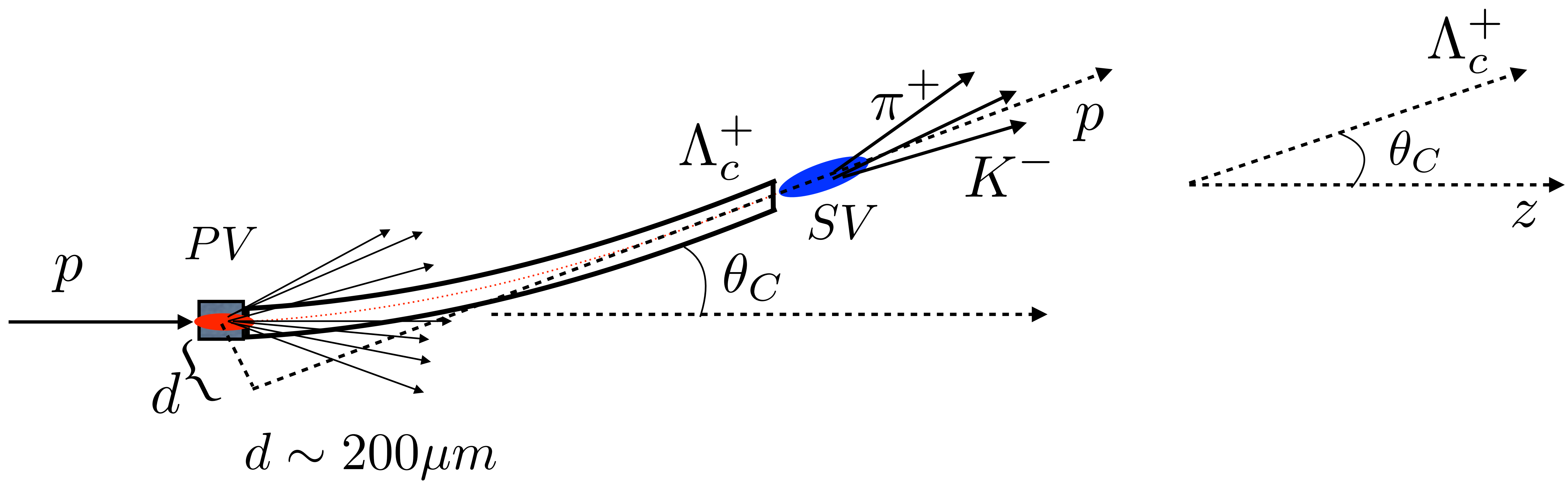
- Radiography of the target in (0, 0.3, -116) cm
- Distribution of origin vertex of stable charged particles in simulated events
- Simulated processes include: hadronic interactions, pair production, Bremsstrahlung, Compton, δ rays





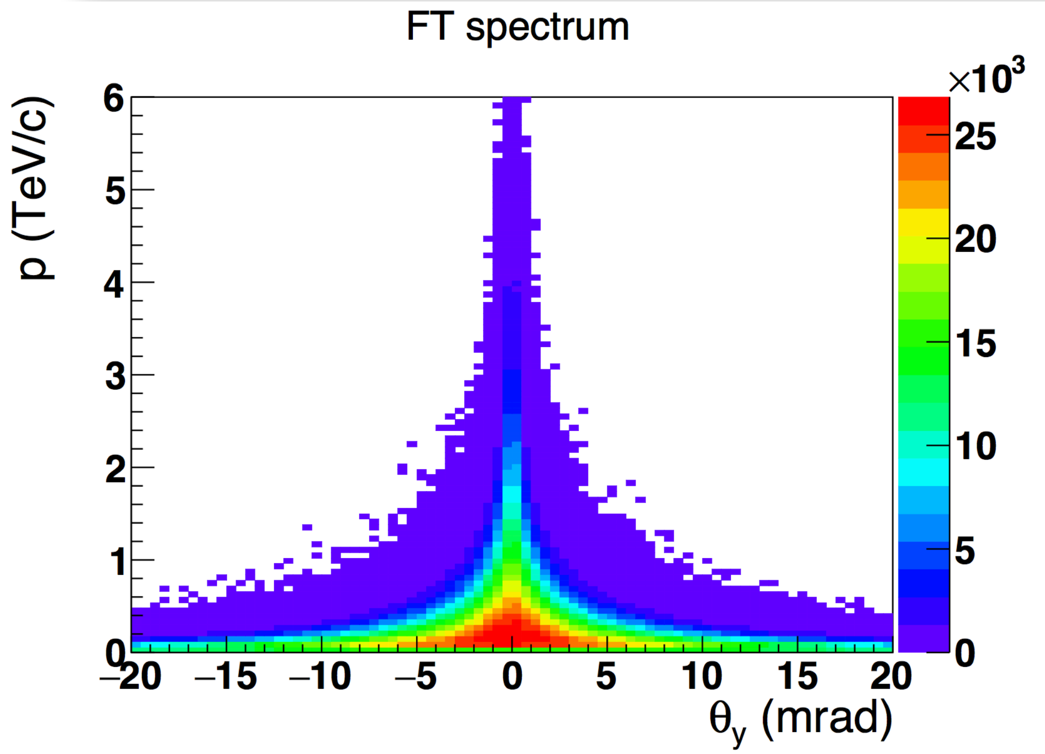
Identification of signal events

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



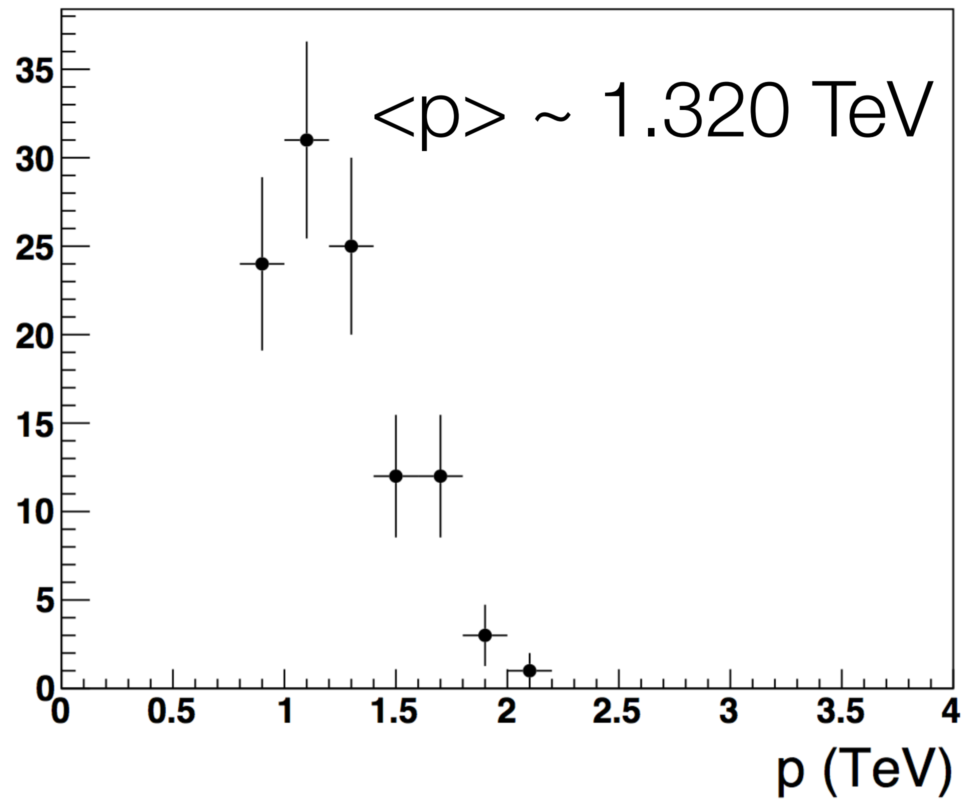
- Use PV to identify Λ_c^+ produced in W target, and Λ_c^+ vertex helps to identify decays outside of the crystal (max spin precession)
- Λ_c^+ angle determined by crystal bending angle, e.g. θ_C=15 mrad
- Channeled baryons have high momentum ≳1 TeV/c

Λ_c^+ momentum distribution

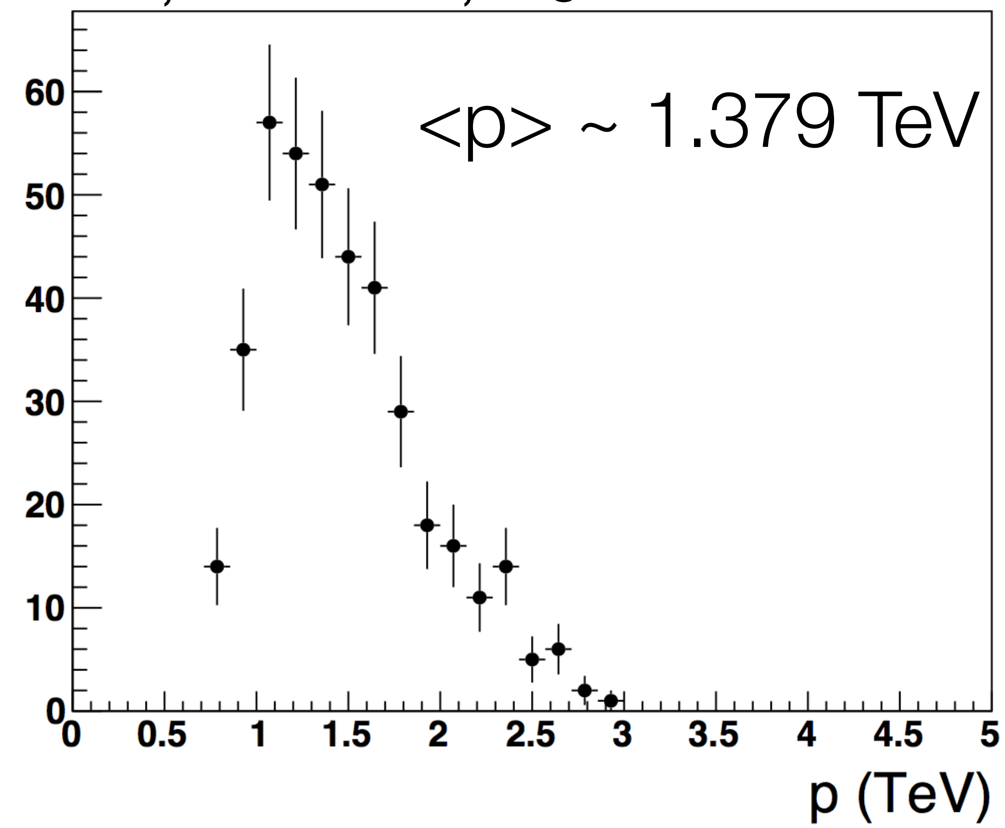


- At production (top)
- After channeling and p>800 GeV/c (bottom)

Si, L~7 cm, θ_C~14 mrad

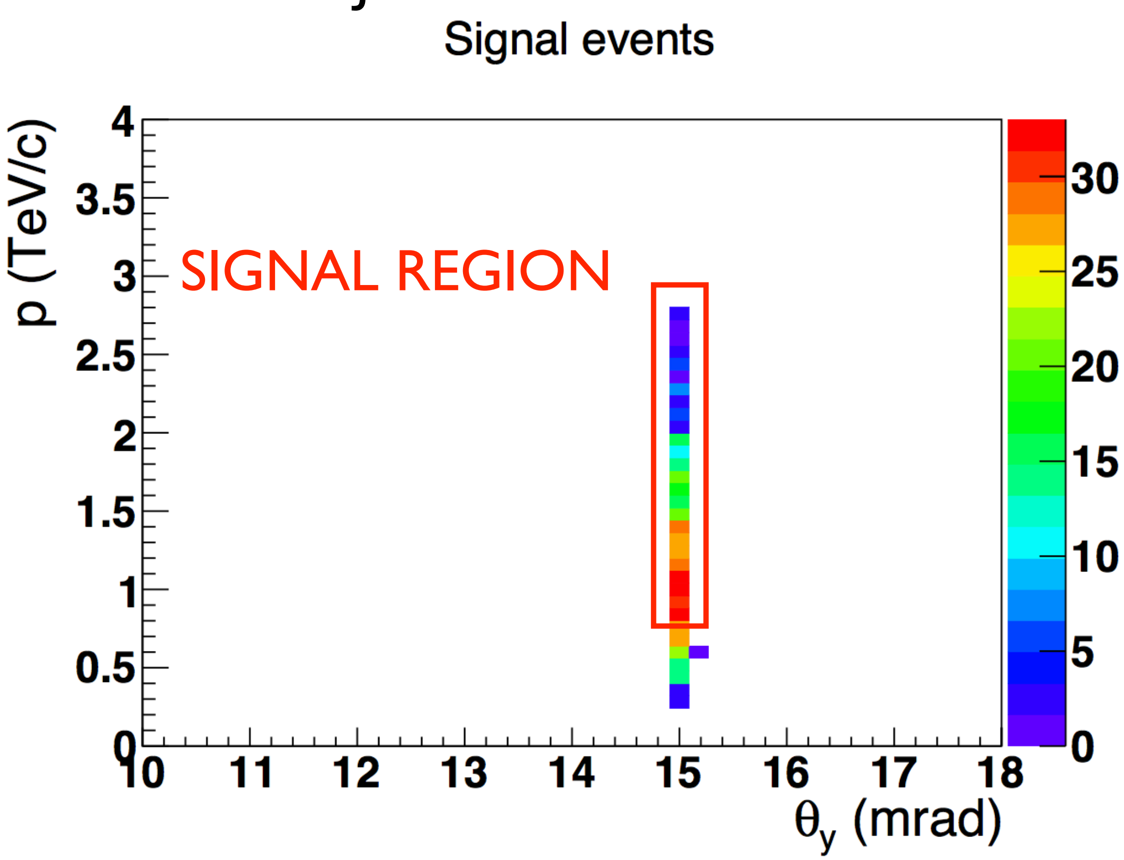


Ge, L~5 cm, θ_C~15 mrad

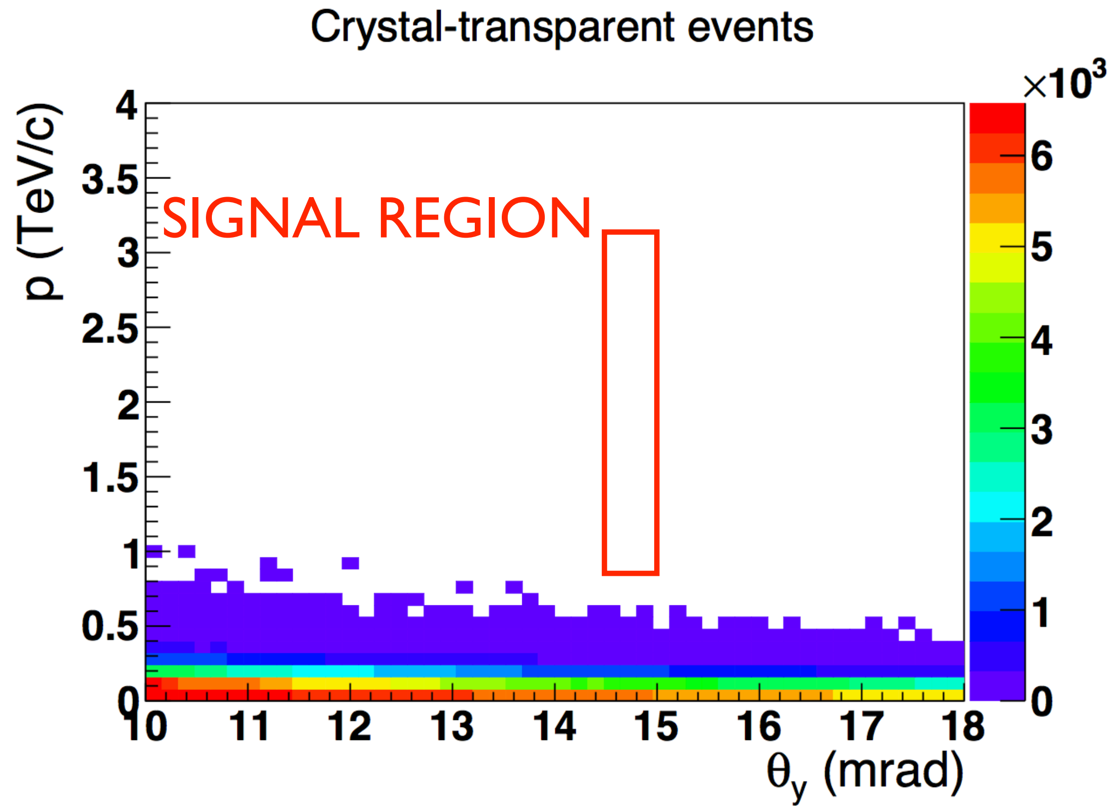


Background rejection

- 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)

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

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

$$|S_0| \approx 0.6$$

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

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

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

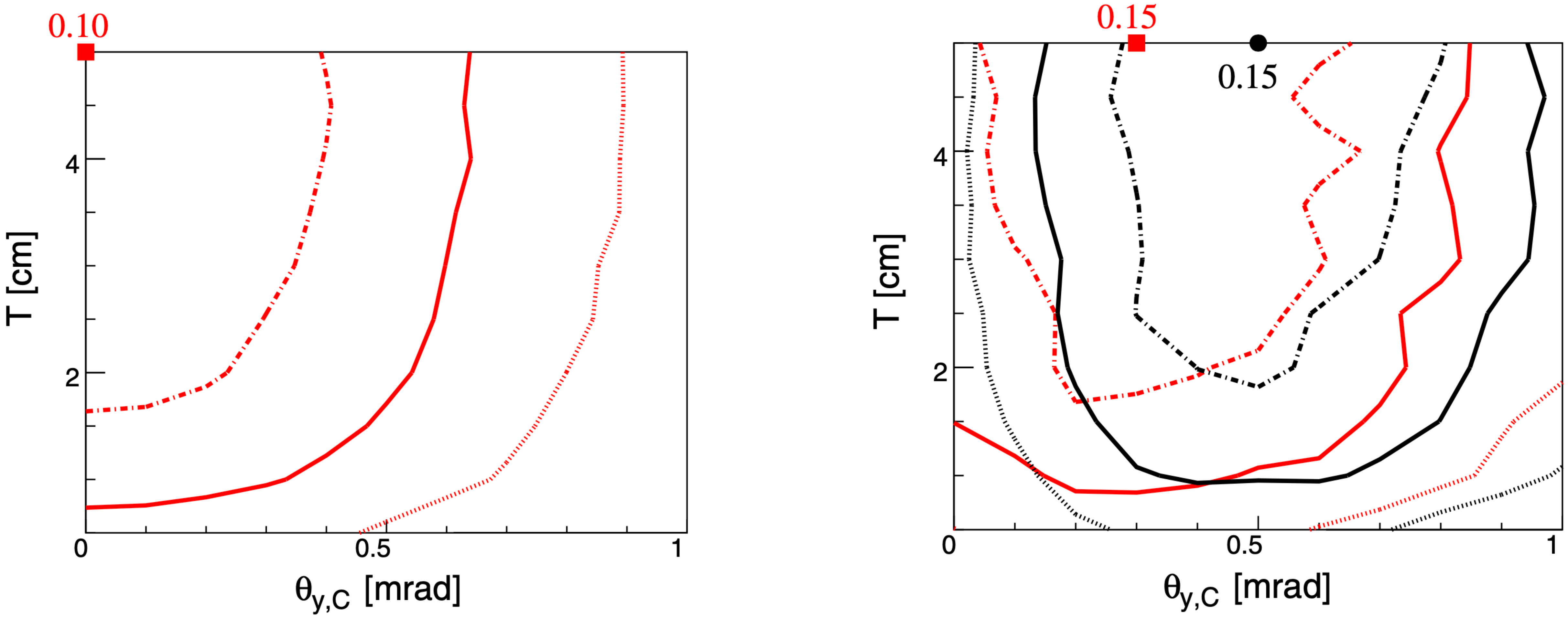
$$\alpha_{\Delta^{++}K^-} \approx -0.67$$

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

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

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

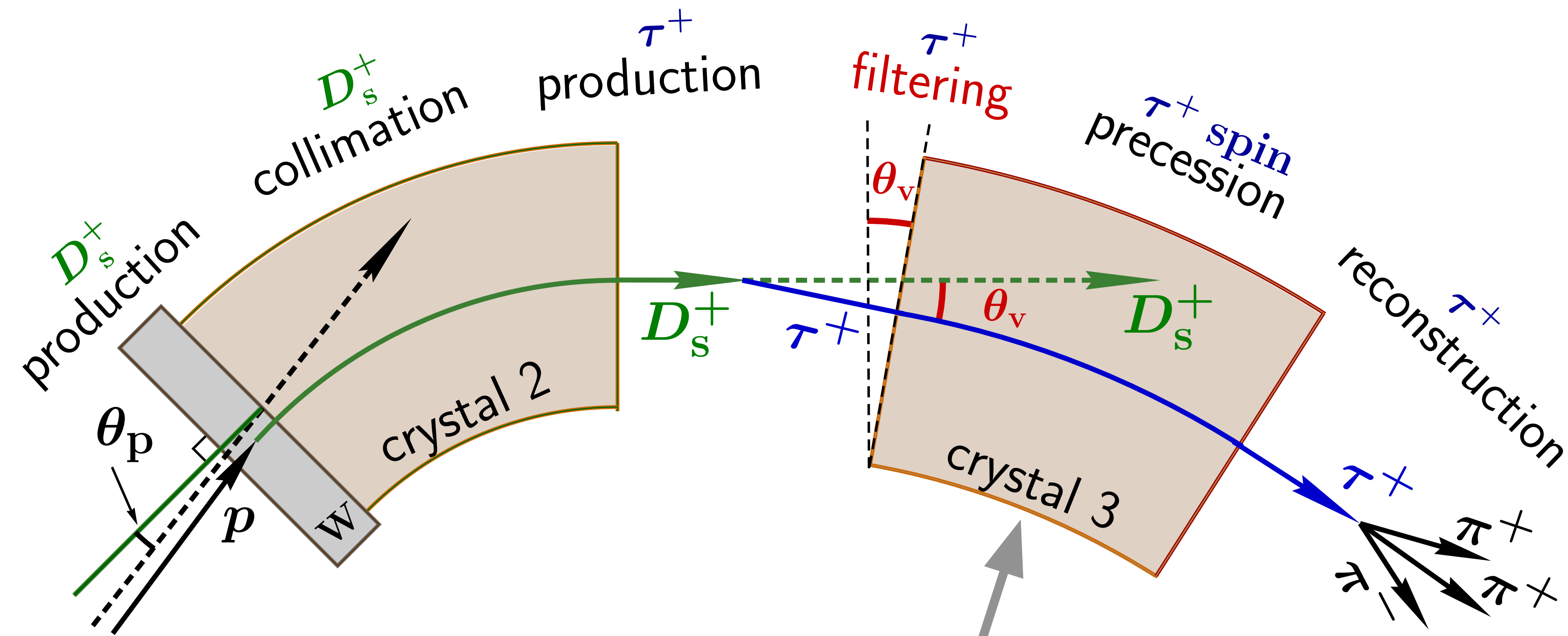
$$\tau^+ \to \pi^+ \pi^- \pi^+ \bar{\nu}_\tau$$

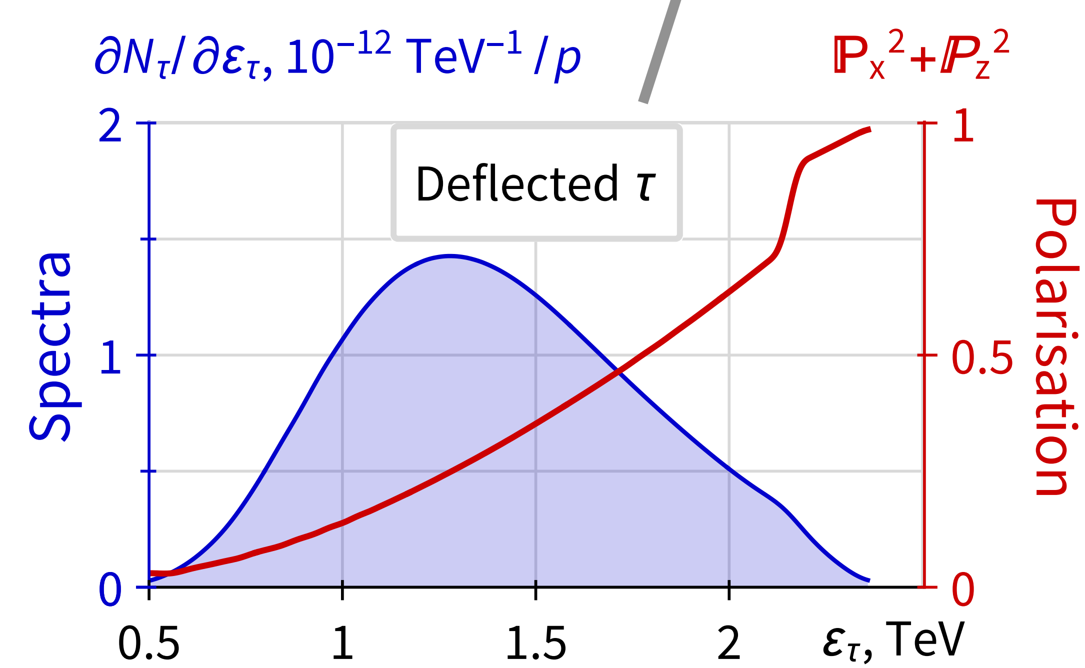
Crystal 2:

- deflection and "collimation" of D_s^+

Crystal 3:

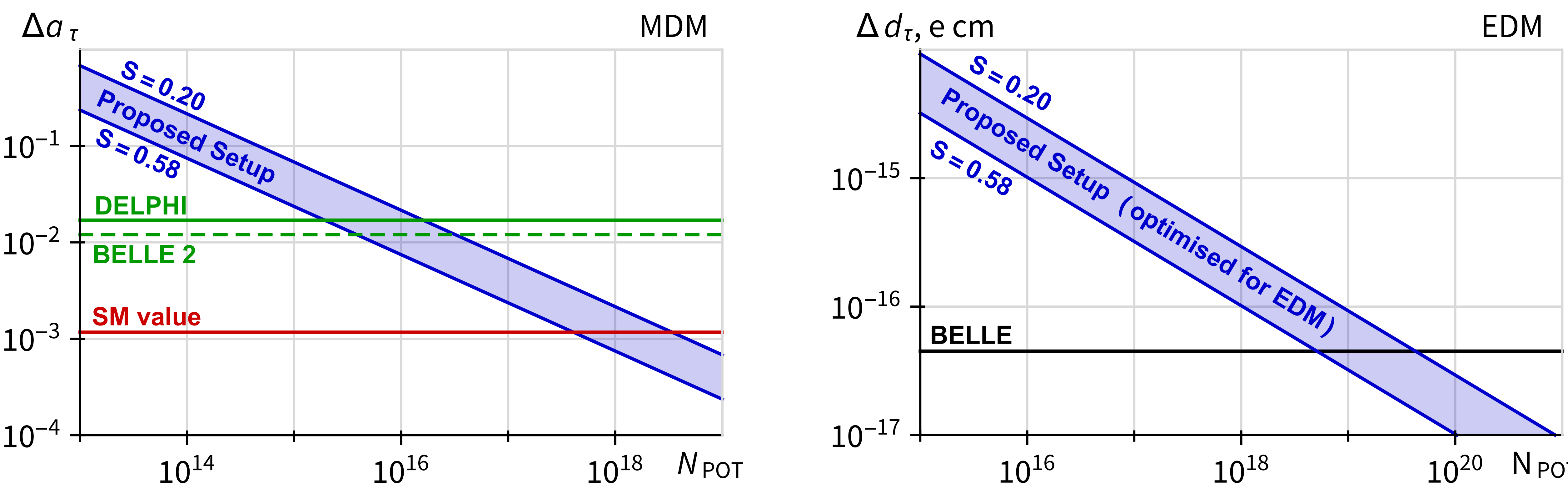
- selecting τ produced by D_s^+
- filtering τ initial polarisation
- τ spin precession





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

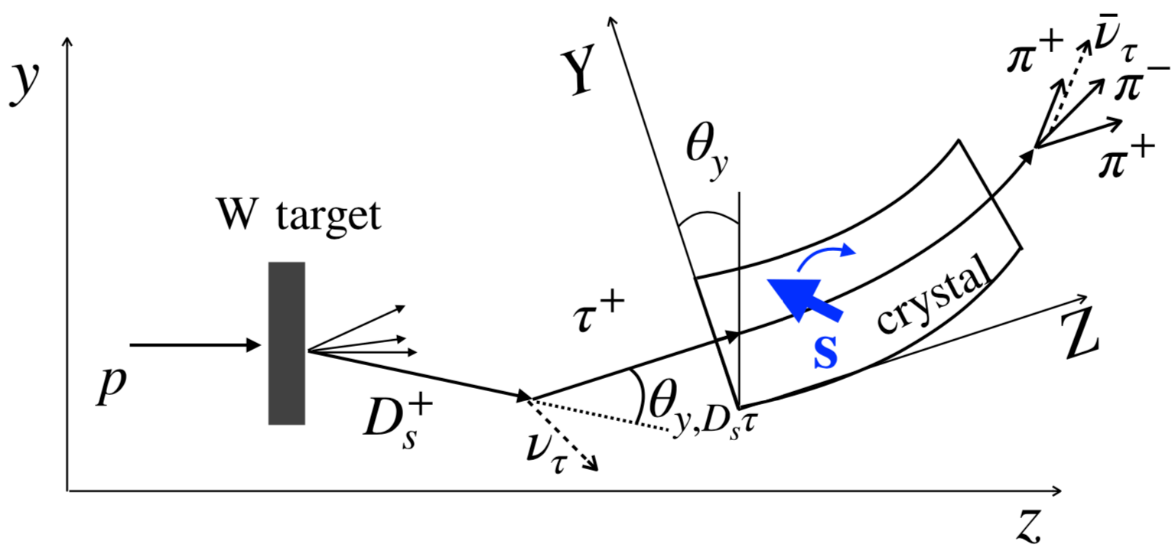
EDM: 10^{19} PoT — to reach the present accuracy [BELLE: K. Inami et al. PLB 551:16–26, 2003]

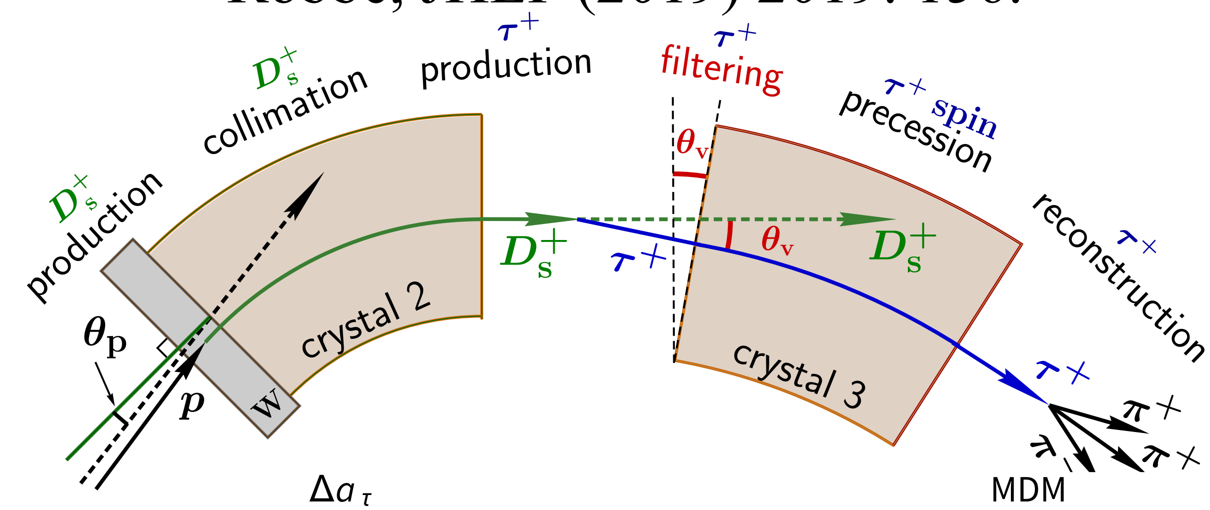
A. Fomin, A. Korchin, A. Stocchi, S. Barsuk, P. Robbe, JHEP (2019) 2019: 156, IC Channeling 2018.

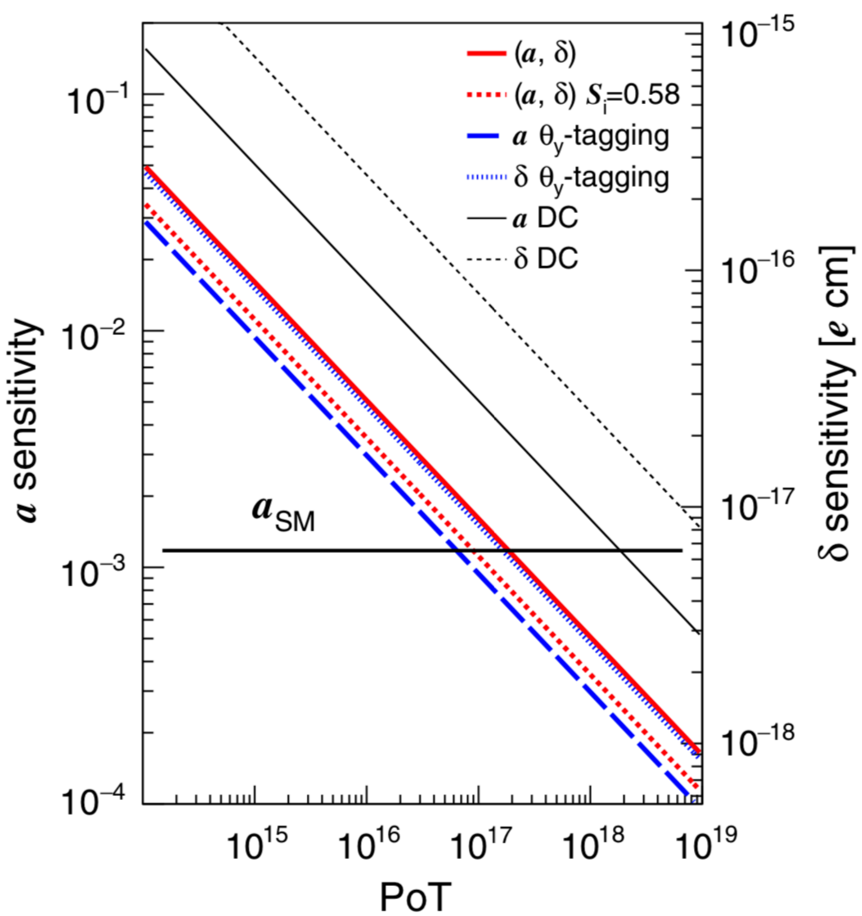
Future plans for τ MDM/EDM

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