Proposed measurements of electromagnetic dipole moments of strange and charm baryons at LHC

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Outline

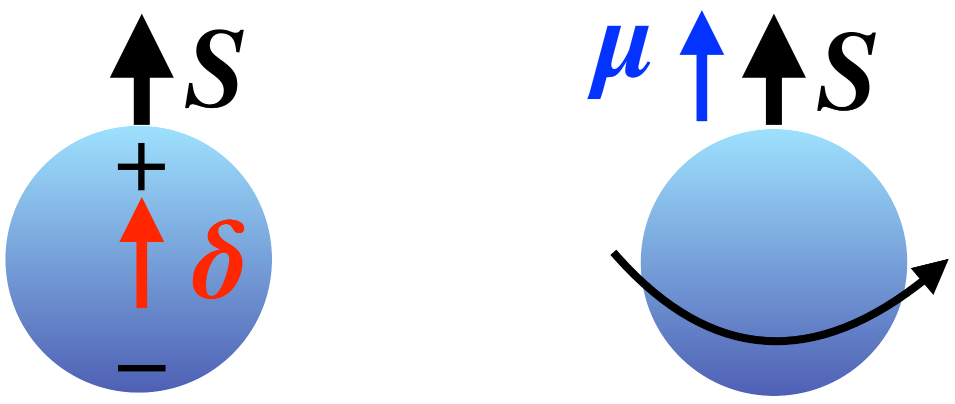
- Introduction and physics motivations
- Experimental method for strange baryons
  - feasibility studies and analyses in progress
- Experimental method for charm baryons
  - R&D and preparatory studies
- Summary

Introduction

- Quantum system

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

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



Hamiltonian

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

Time reversal, Parity:

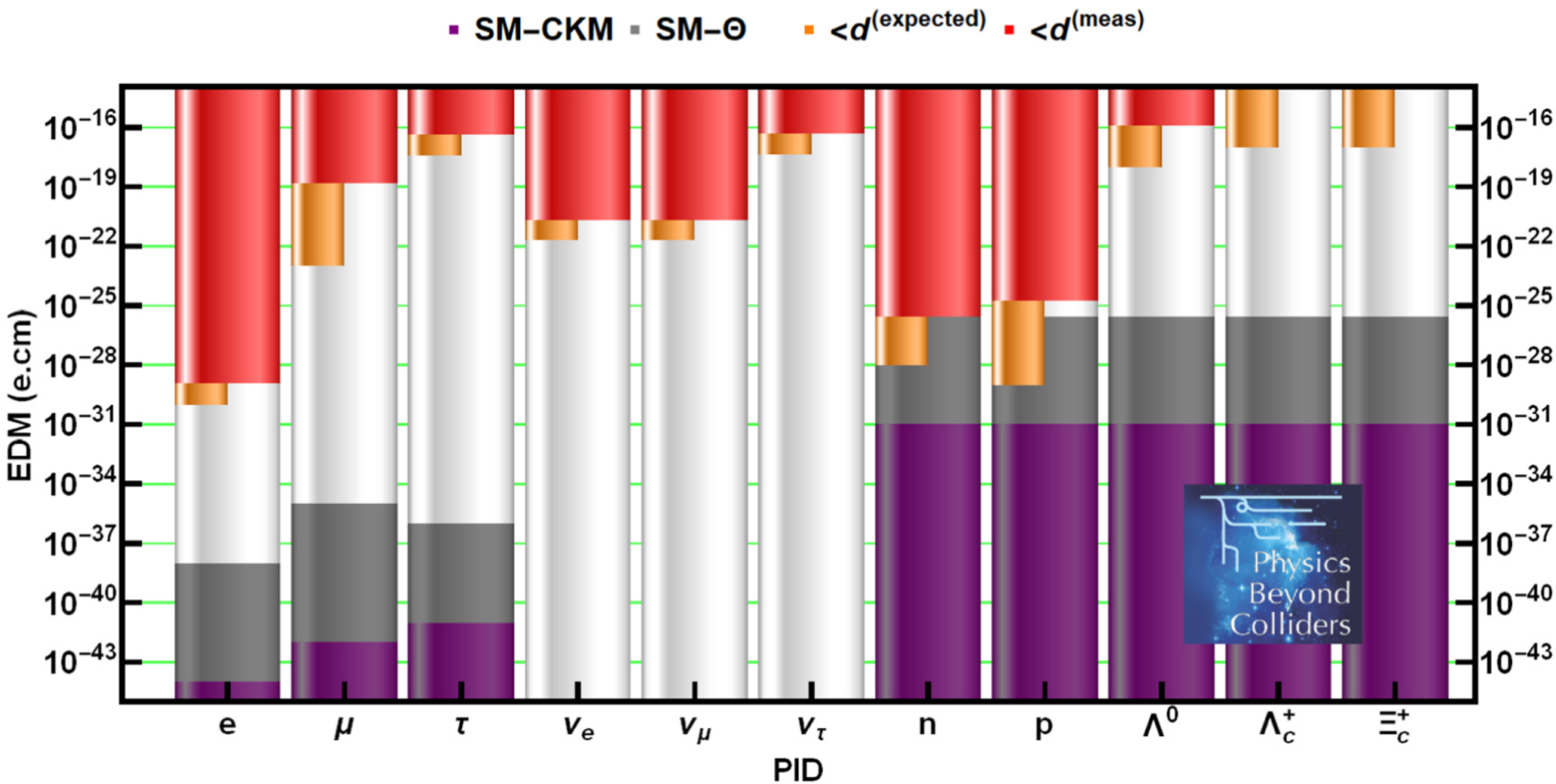
$$d\mu_N \boldsymbol{S}\cdot\boldsymbol{E} \xrightarrow{T,P} -d\mu_N \boldsymbol{S}\cdot\boldsymbol{E}$$

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

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

Status of EDM measurements

- Sensitive to New Physics: measure many systems to disentangle the underlying source of BSM physics



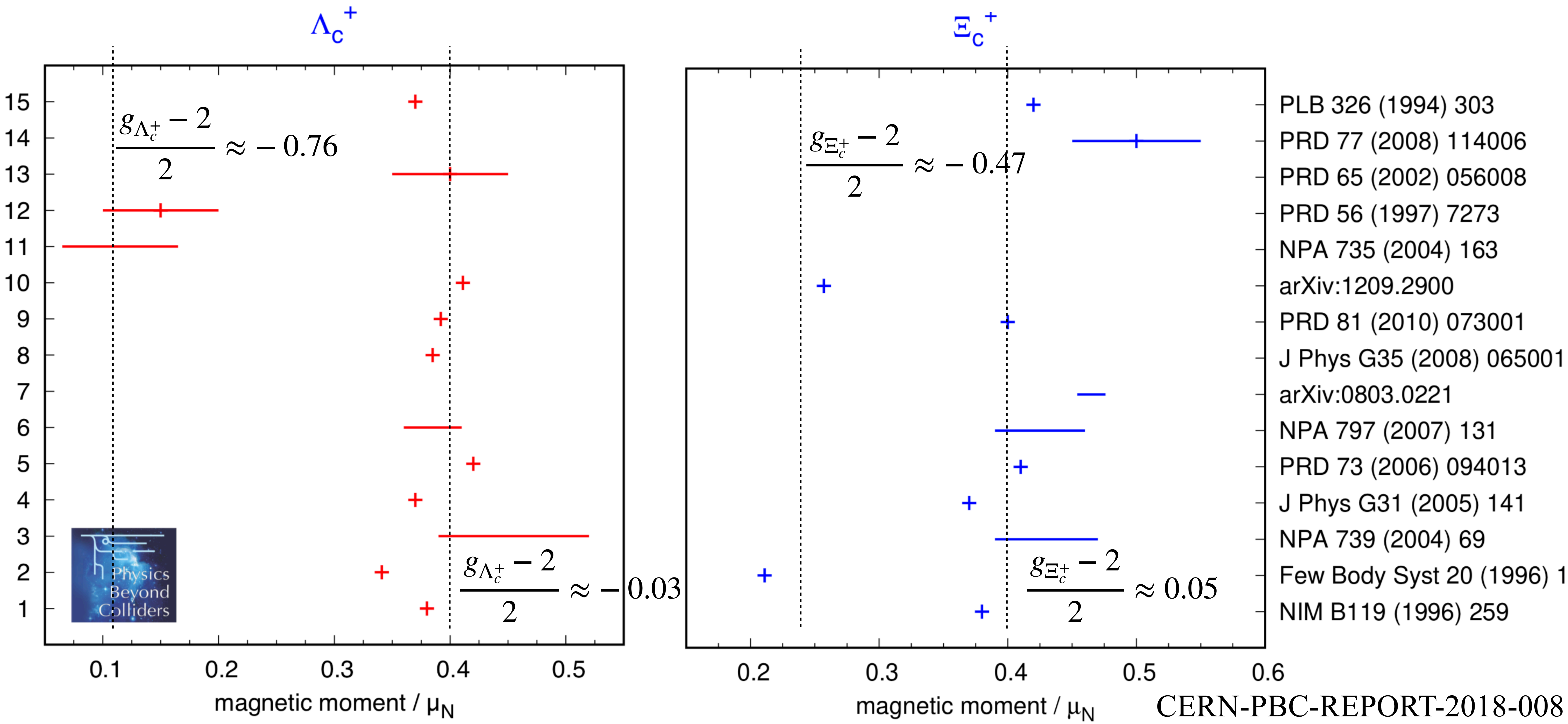
J. Phys. G: Nucl. Part. Phys. **47** (2020) 010501

MDM theoretical predictions

In the quark model $\Lambda_c^+ = [ud]c$ $\quad \Xi_c^+ = [us]c$ $\quad$ EPJC 80 (2020) 358

$\mu_{\Lambda_c^+} = \mu_c$ $\quad \mu_{\Xi_c^+} = \mu_c$ $\quad \mu_c = (0.48 \pm 0.03)\mu_N$

Beyond the quark model: e.g. heavy quark effective theories



CERN-PBC-REPORT-2018-008

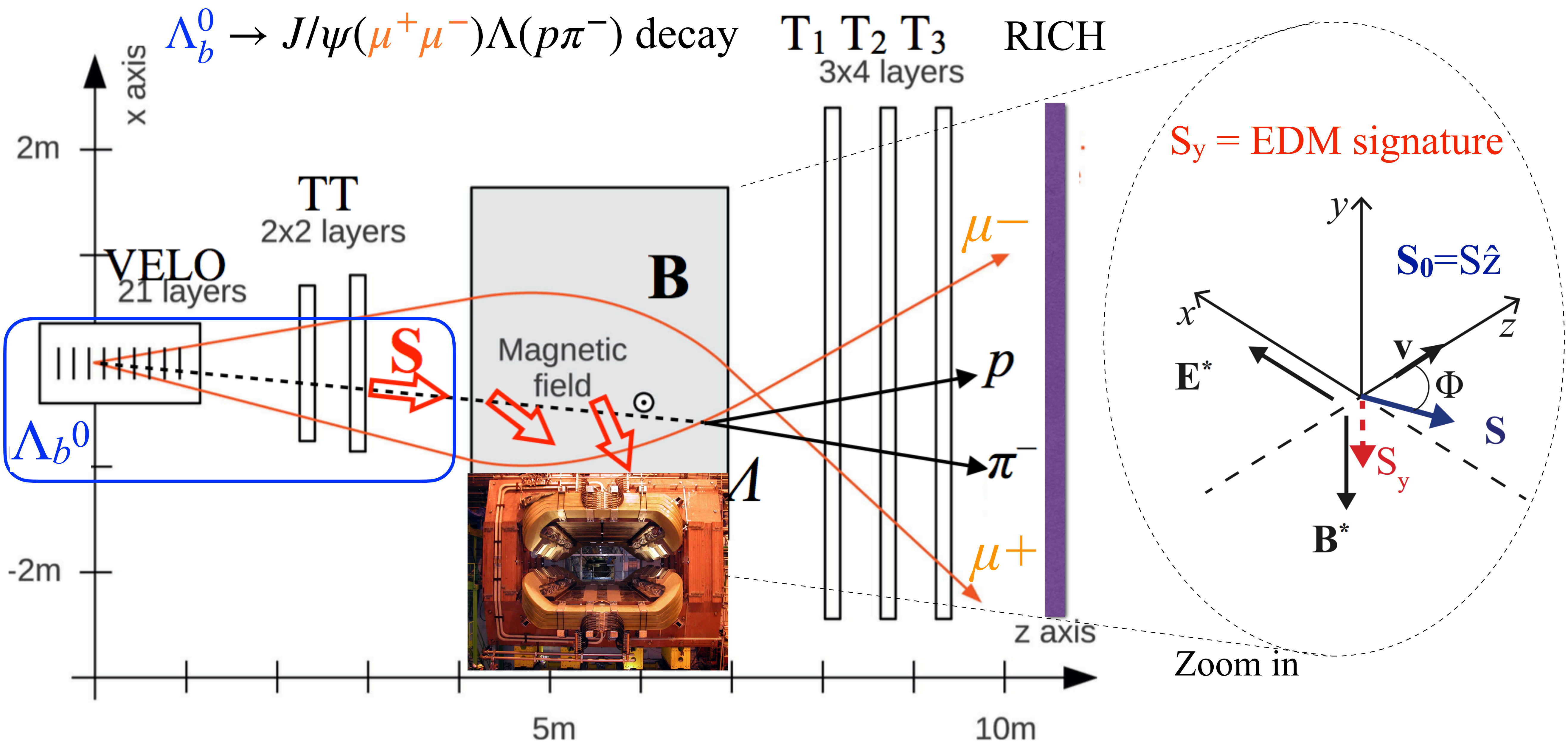
Proposed experimental method for neutral long-lived Λ baryons in LHCb

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

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

Experimental technique for strange baryons

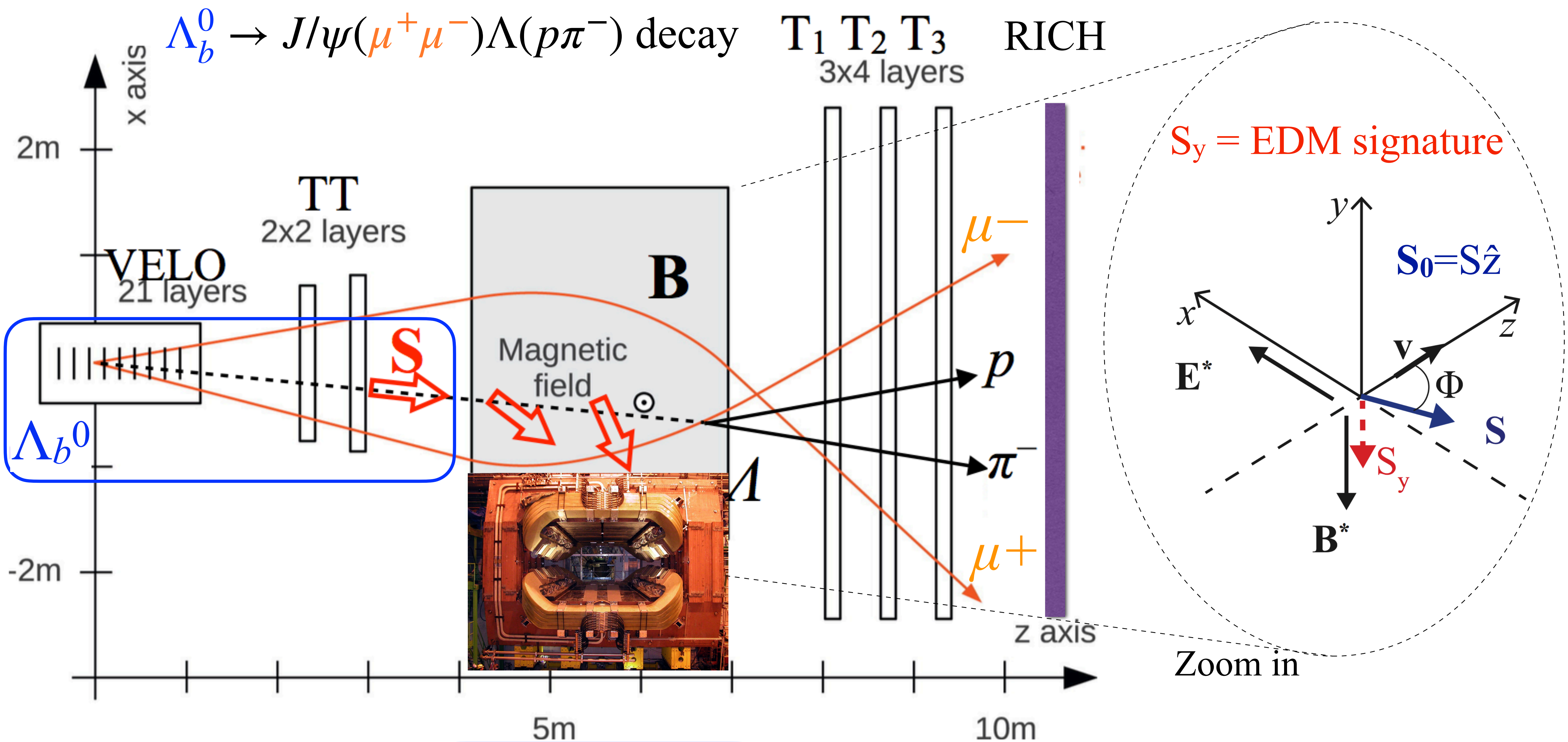
- EDM/MDM from spin precession of Λ baryon in LHCb **dipole magnet**



Λ polarised production

Experimental technique for strange baryons

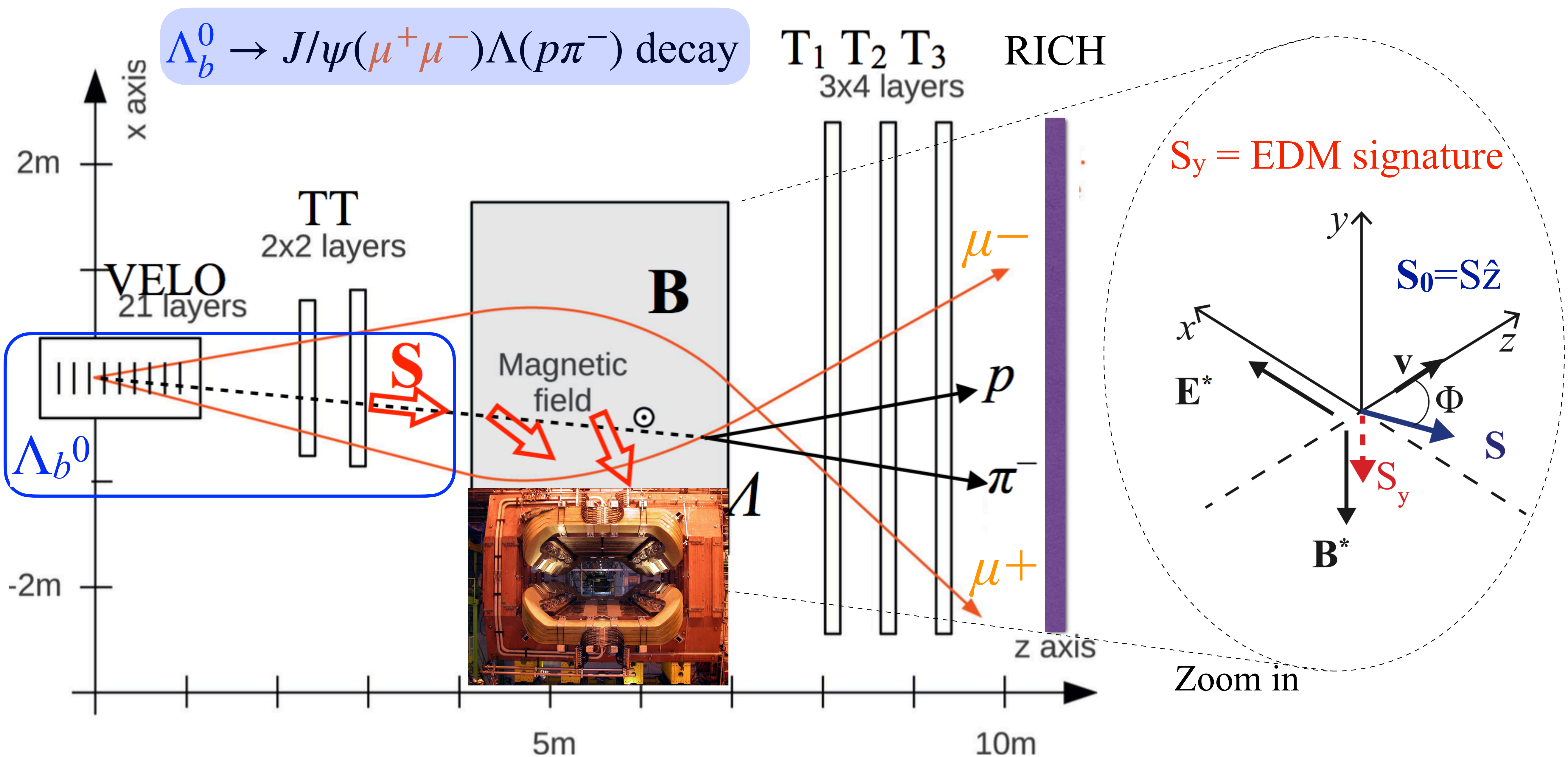
- EDM/MDM from spin precession of Λ baryon in LHCb **dipole magnet**



Λ polarised production spin precession

Experimental technique for strange baryons

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

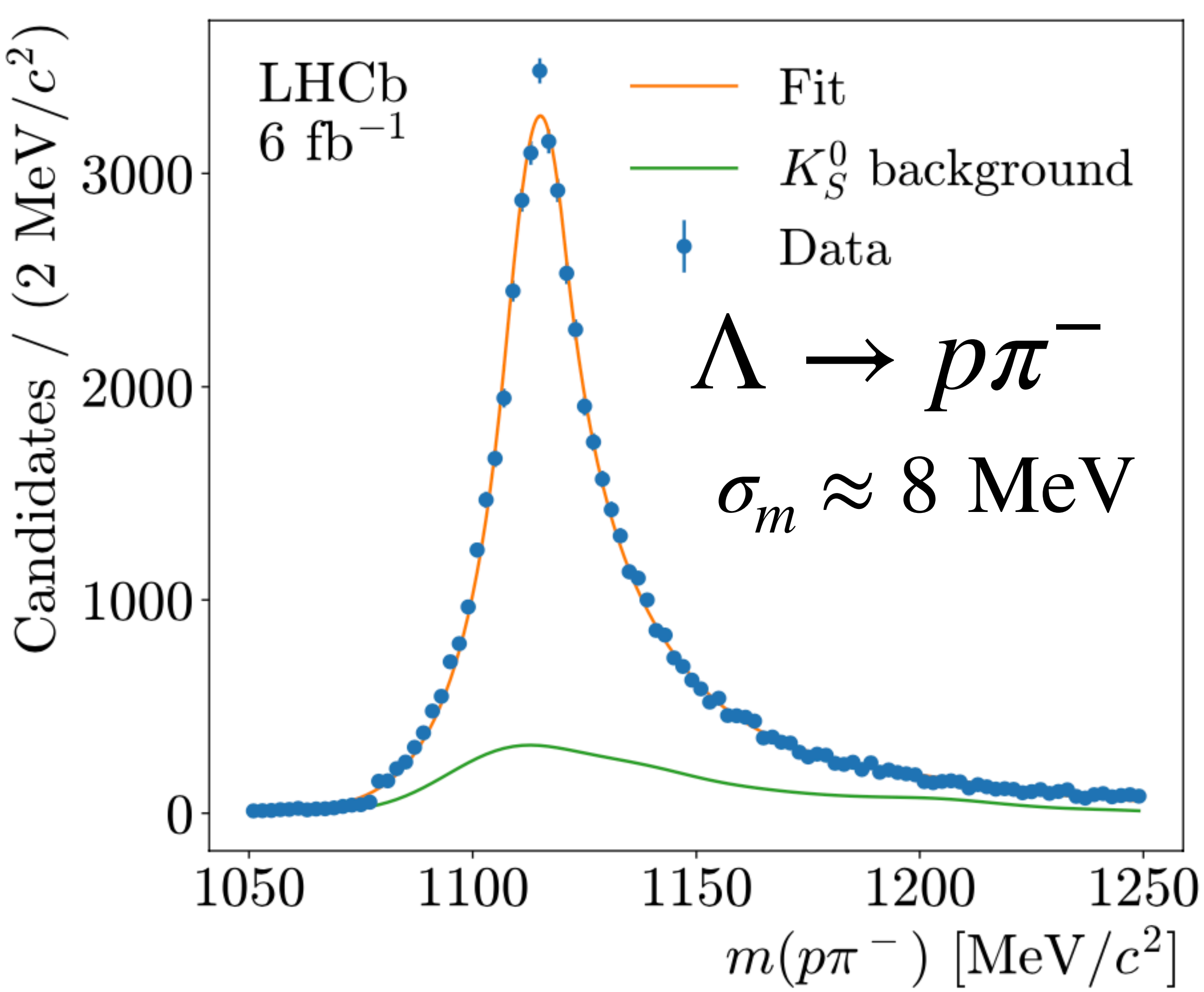


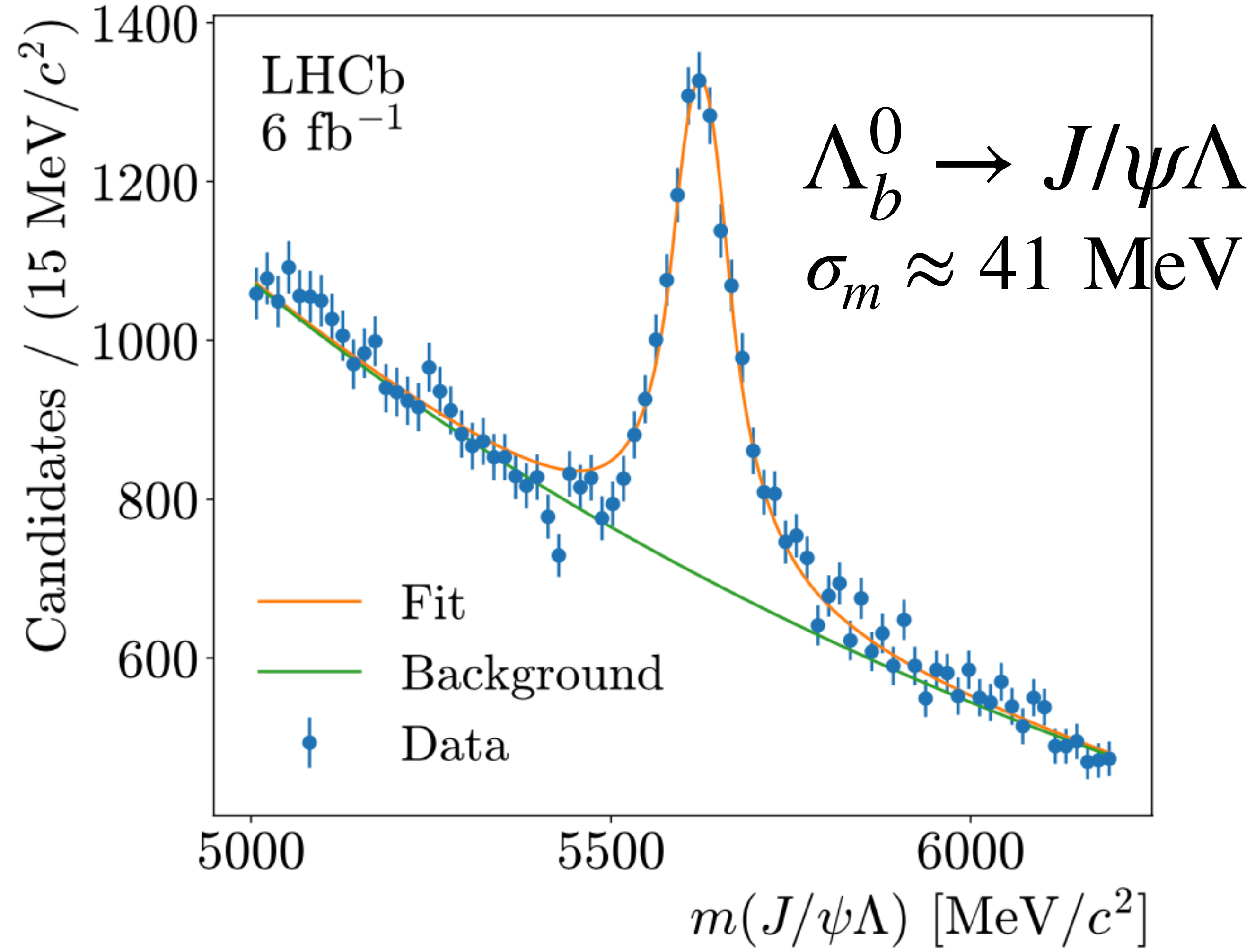
Λ polarised production spin precession event reconstruction

$\Lambda_b^0 \to J/\psi\Lambda$ reconstruction on Run 2 data

- Reconstruction of $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$ with Λ decay vertex z∈[6.0-7.6]m ✓
- No RICH2 info in Run2 for T tracks, T track fit and vertexing still to be optimised

LHCb-DP-2022-001
in review





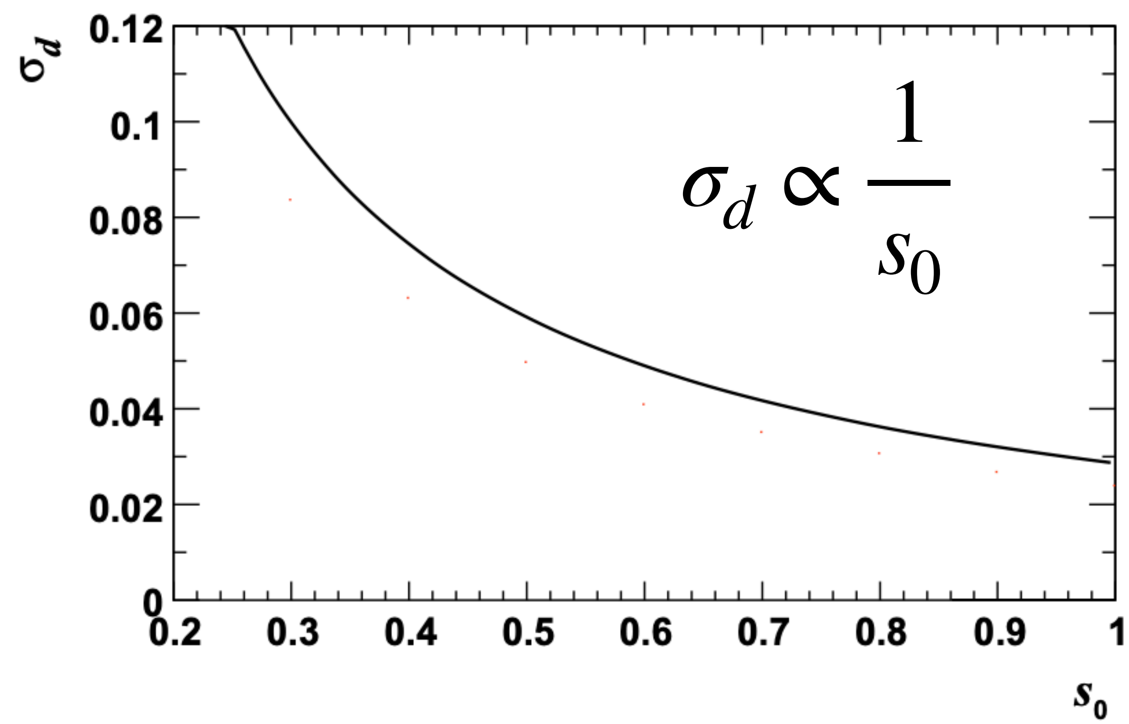
Sensitivity on MDM/EDM

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

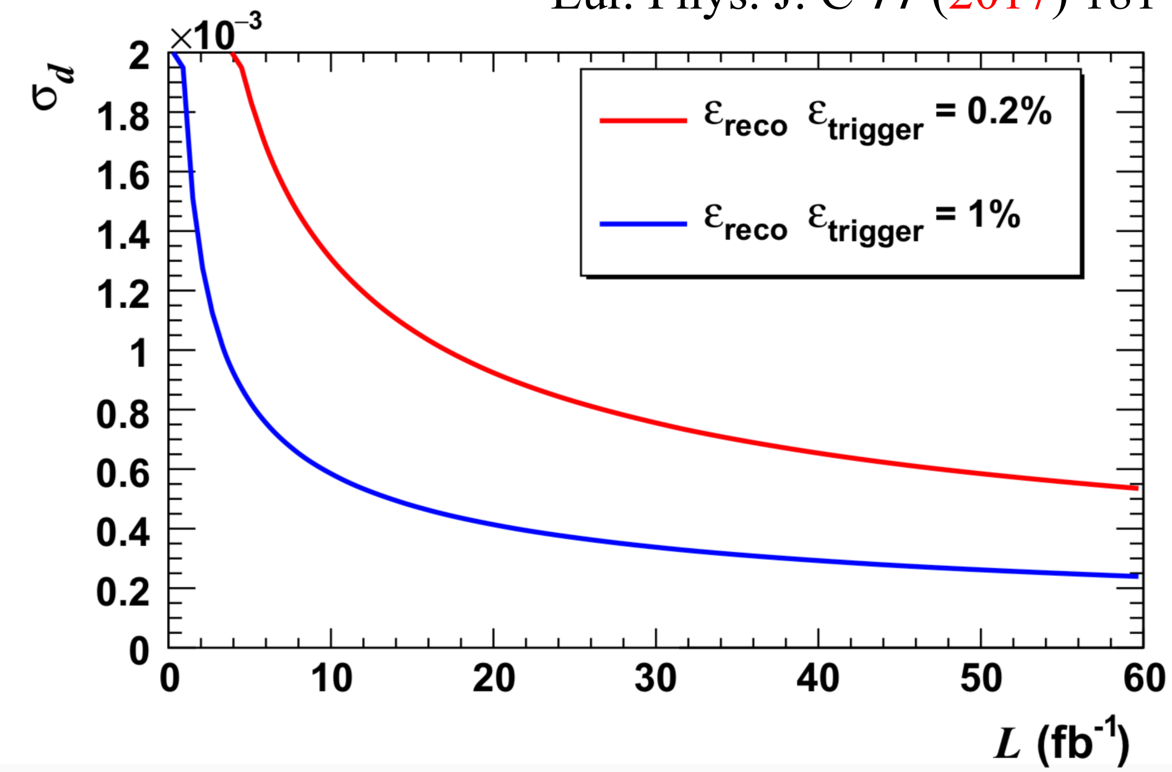
$$\mathbf{s} = \begin{cases} s_x = -s_0 \sin \Phi \\ s_y = -s_0 \frac{d\beta}{g} \sin \Phi \\ s_z = s_0 \cos \Phi \end{cases} \qquad \Phi \approx \frac{g \mu_B BL}{\beta \hbar c} \approx \frac{\pi}{4} \qquad BL \approx 4 \text{ T m}$$

Spin analyser in Λ rest frame

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



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



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

LHCb-INT-2017-011

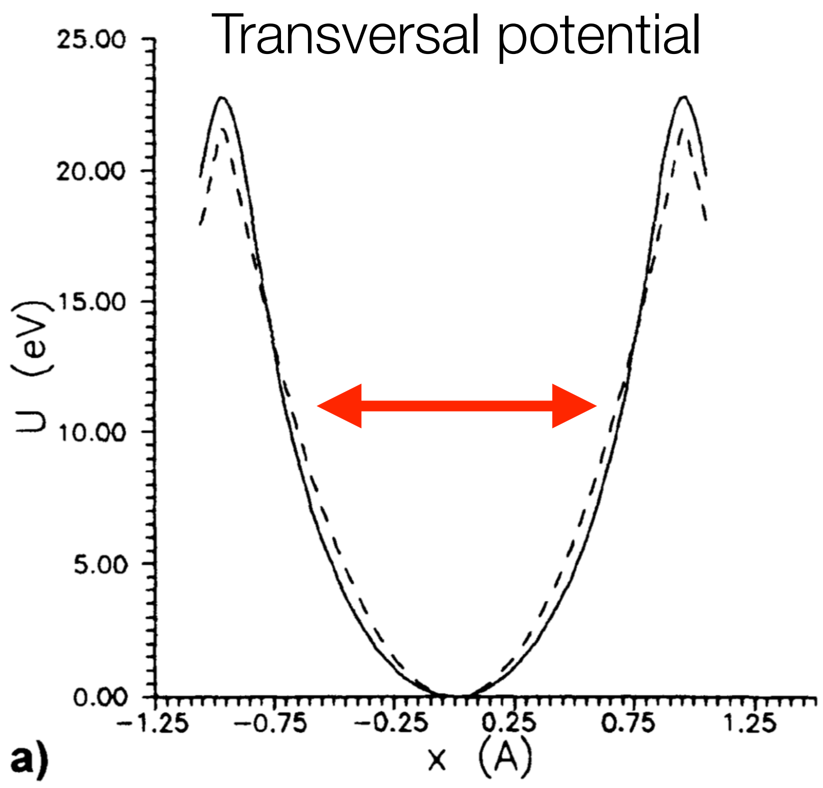
Channeling in bent crystals

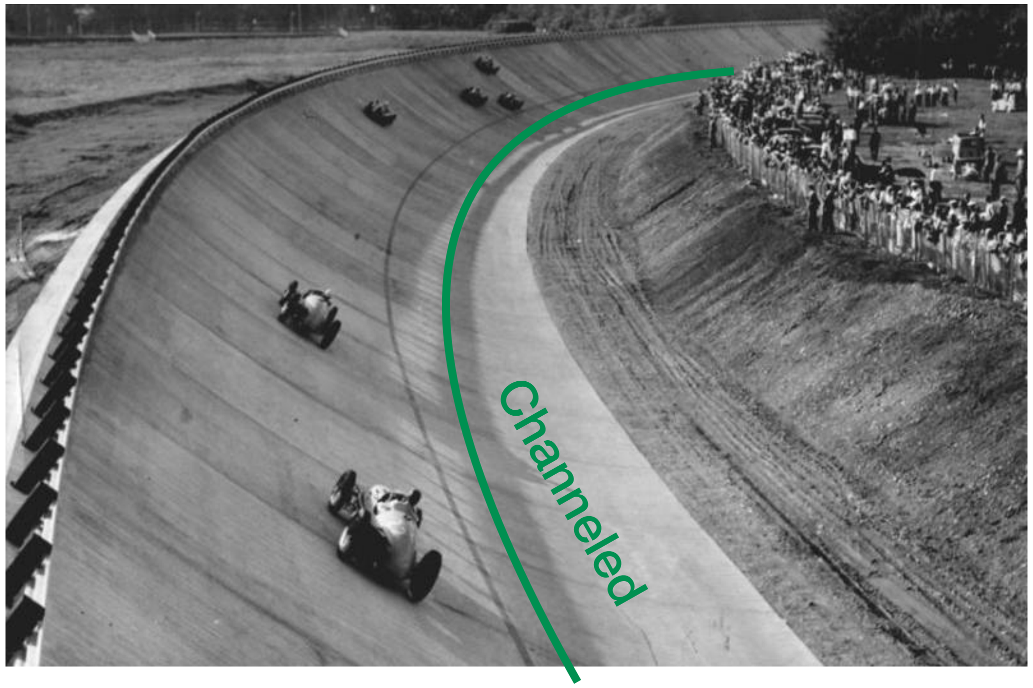
- Potential well between crystal planes $E \approx 1$ GV/cm

- 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



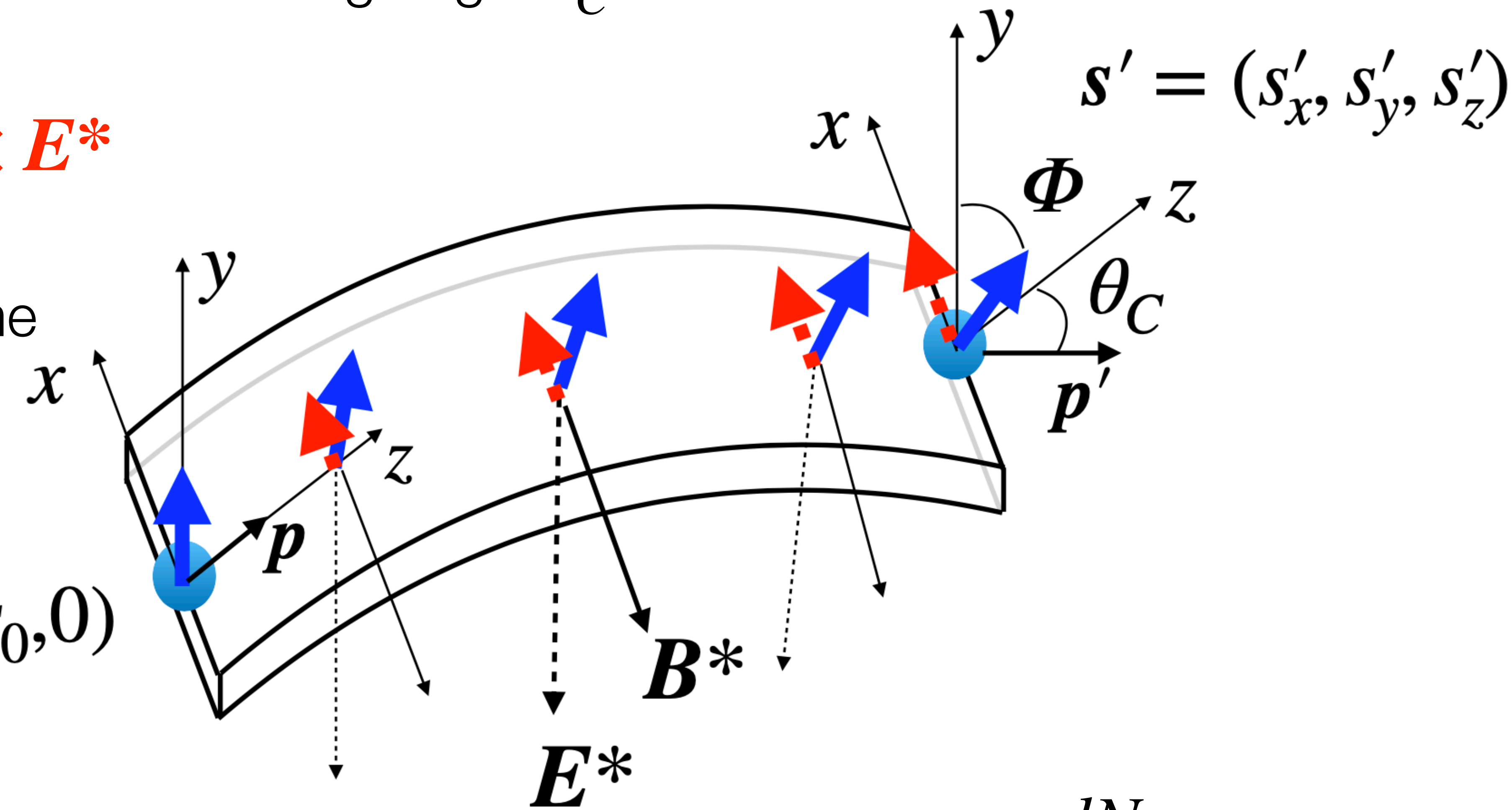


Λ_c^+, Ξ_c^+ spin precession in bent crystals at LHC

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

$$\frac{dS}{d\tau} = \mu \times B^* + \delta \times E^*$$

E*⊥B* in particle rest frame



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

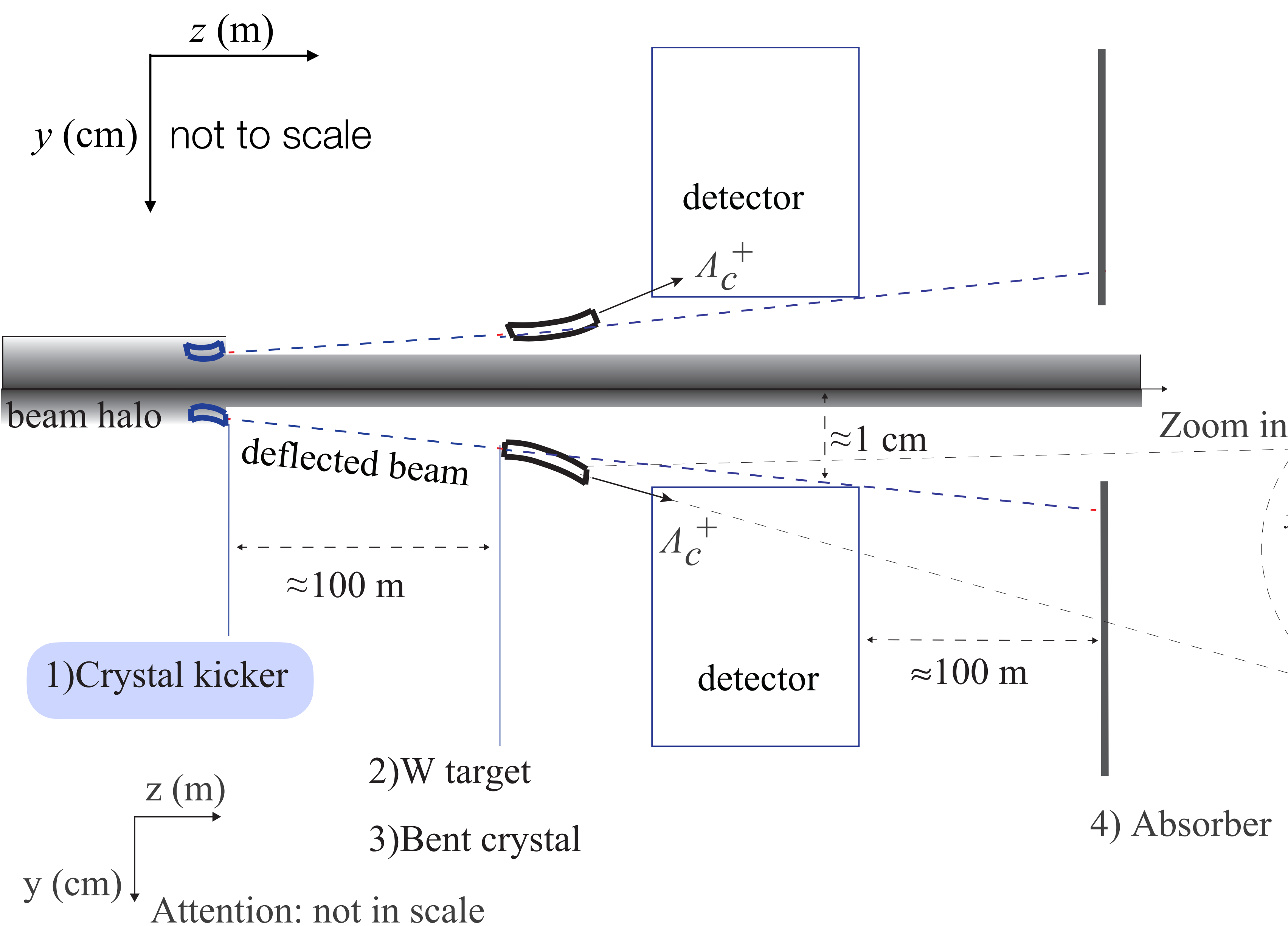
$$\Phi \approx \frac{g-2}{2}\gamma\theta_C$$

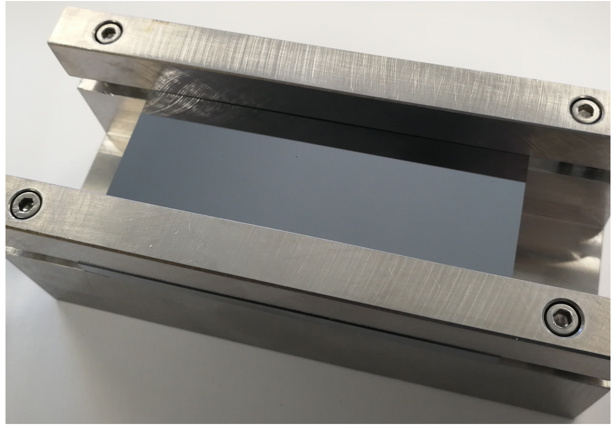
$$s'_x \approx s_0 \frac{d}{g-2}[\cos(\Phi) - 1]$$

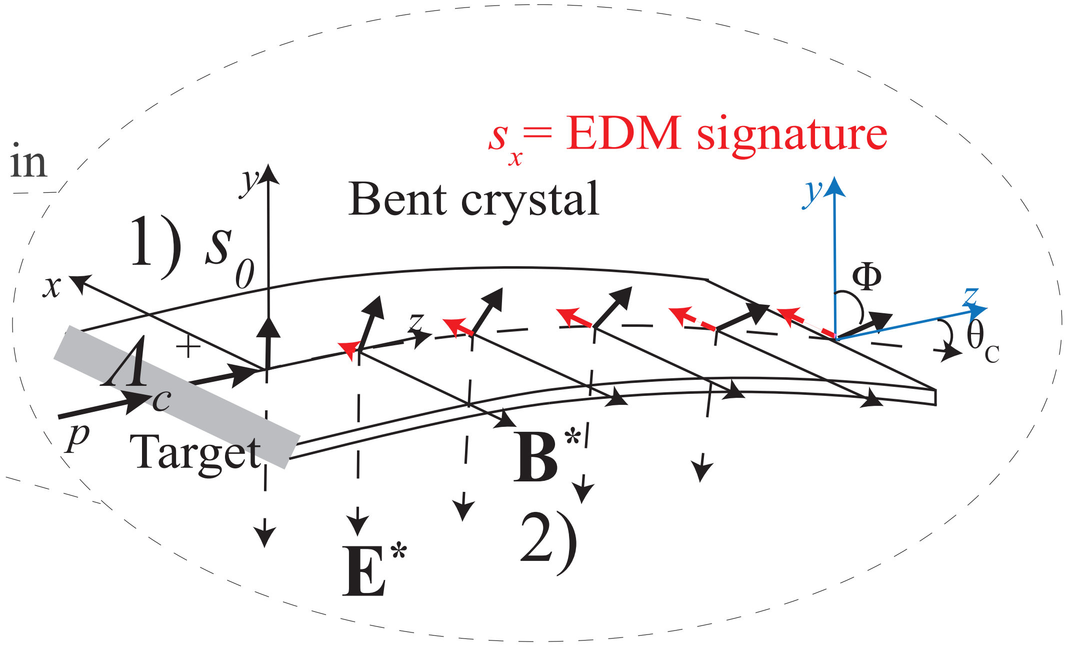
EPJC (2017) 77:181

Novel fixed-target experiment at LHC for charm baryons

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



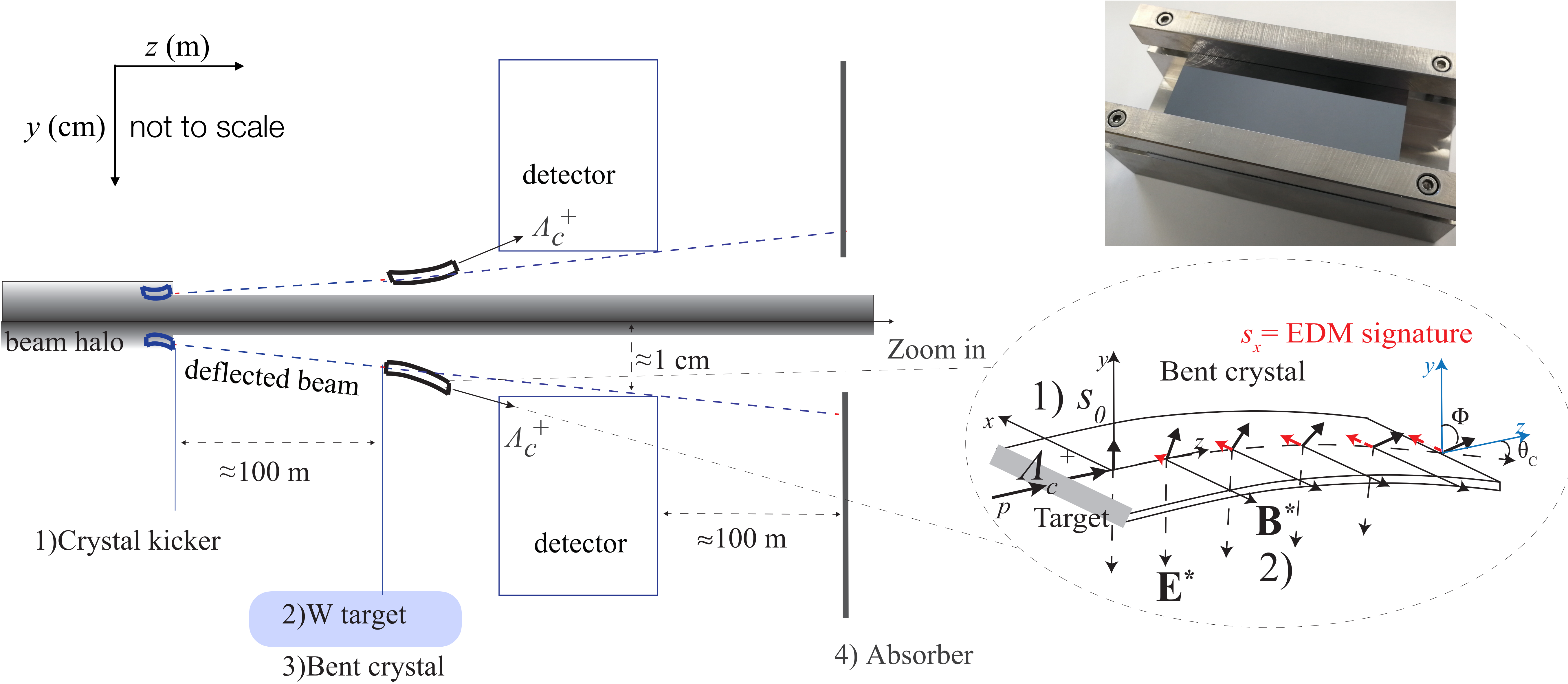




p extraction

Novel fixed-target experiment at LHC for charm baryons

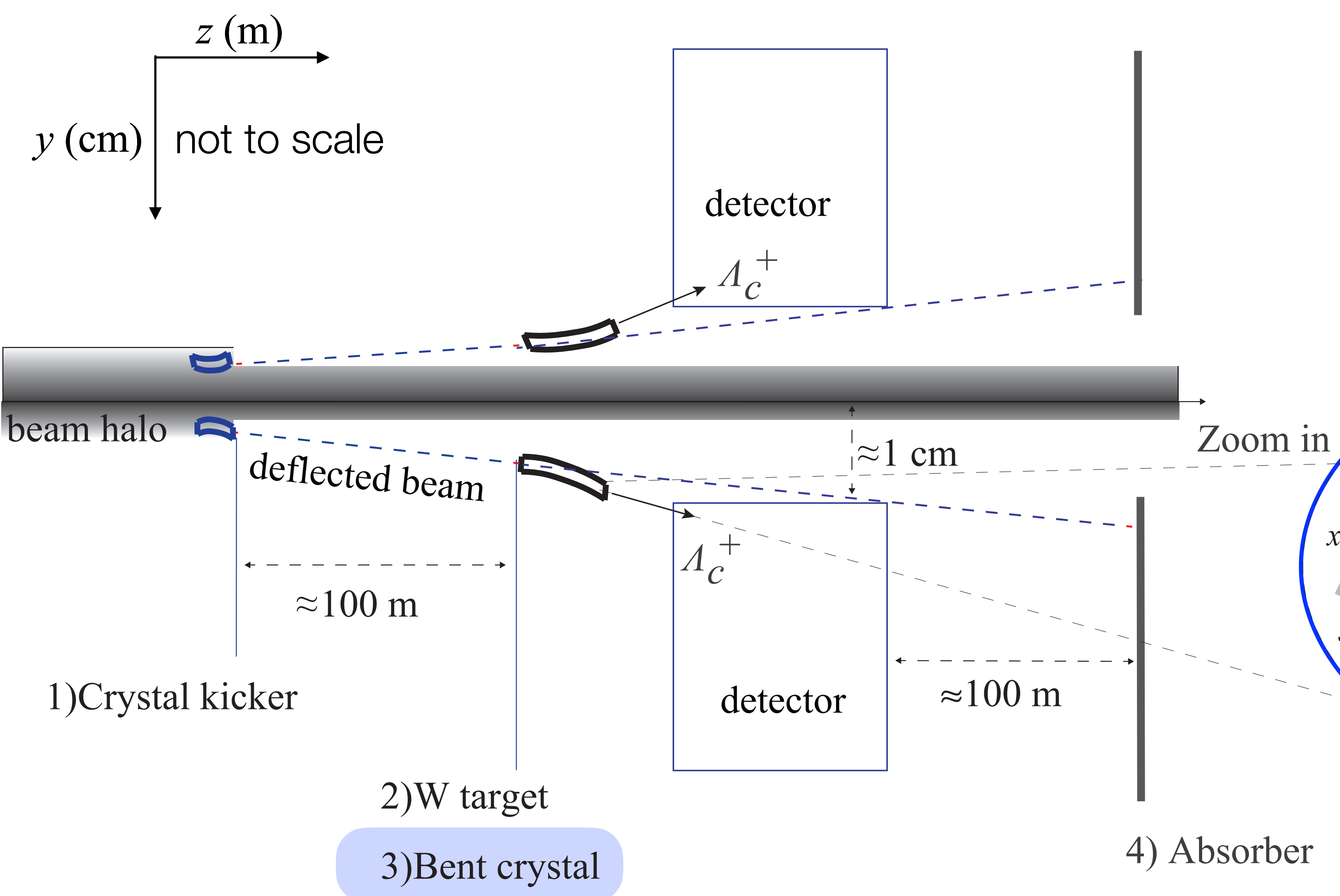
- EDM/MDM from spin precession of channeled baryons in **bent crystals**

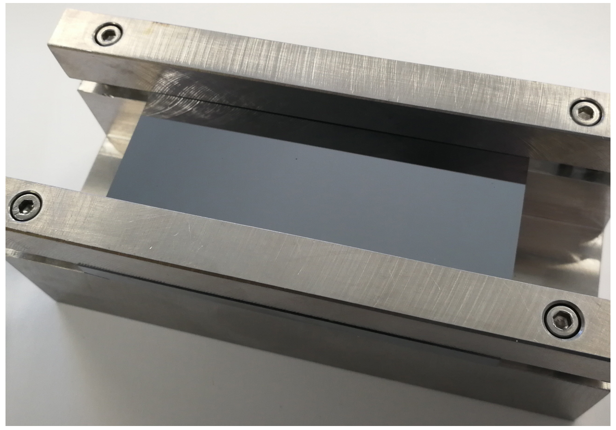


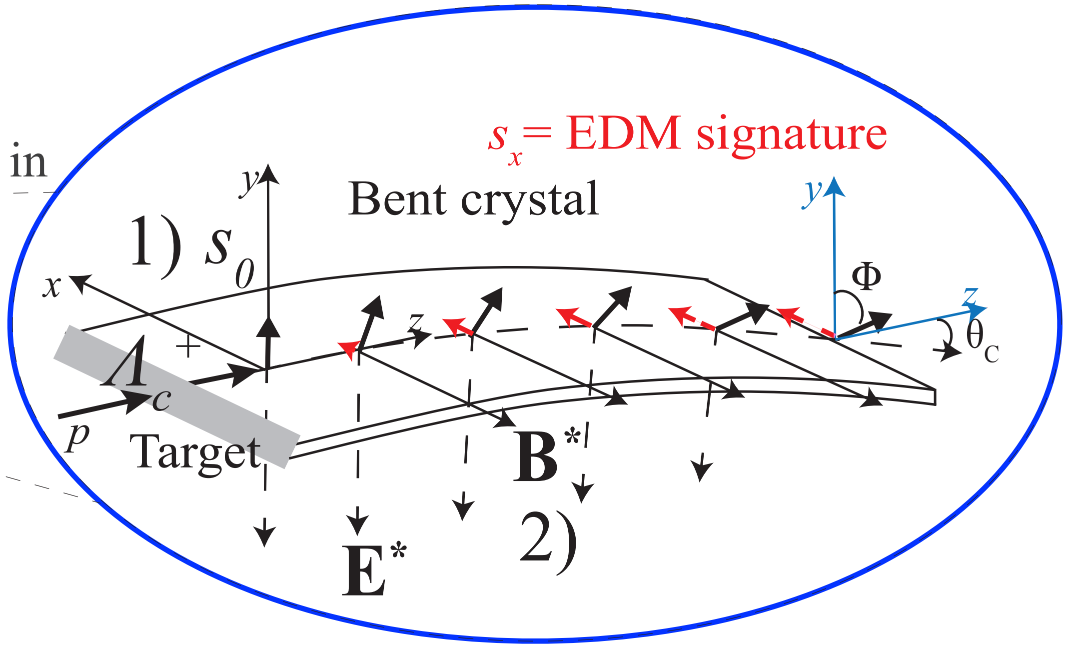
p extraction Λ_c^+ polarised production

Novel fixed-target experiment at LHC for charm baryons

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



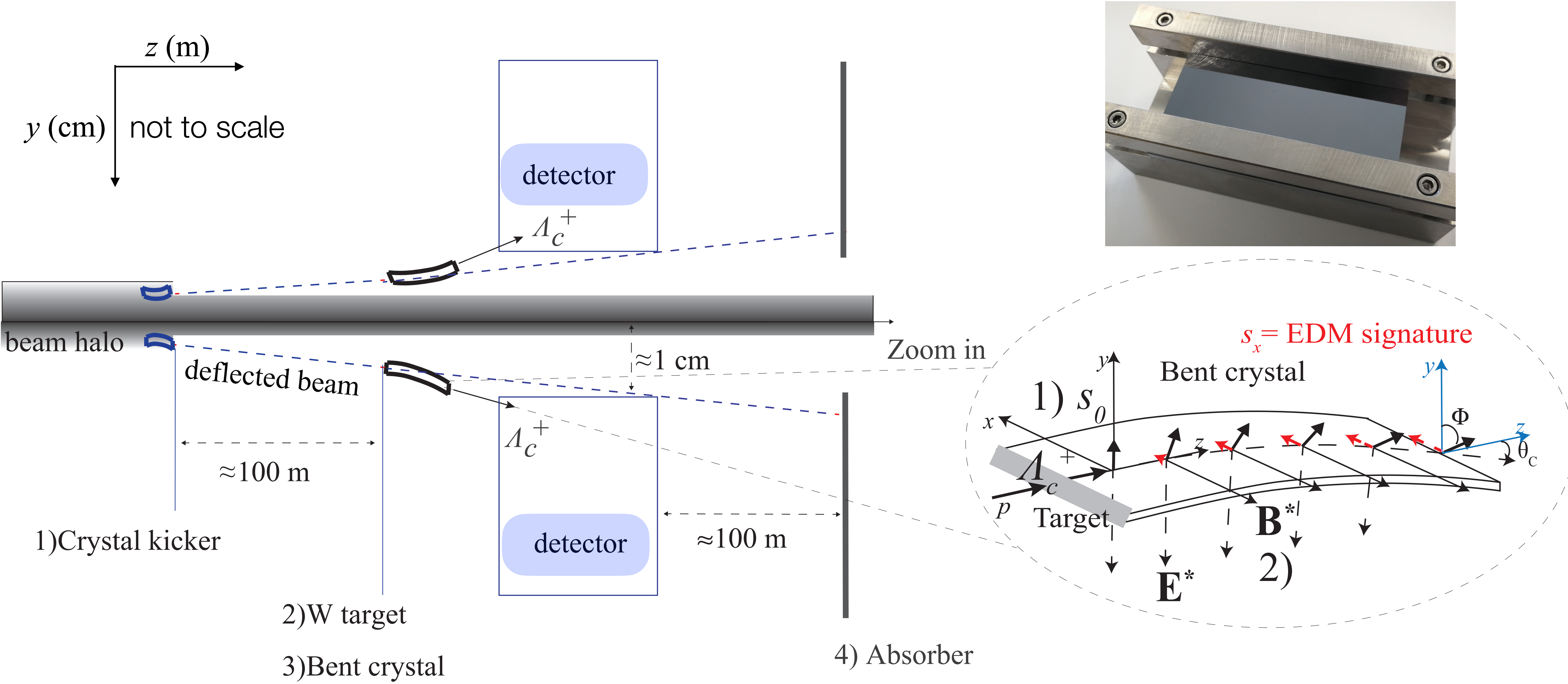




p extraction Λ_c^+ polarised production channeling spin precession

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

Sensitivity on MDM/EDM

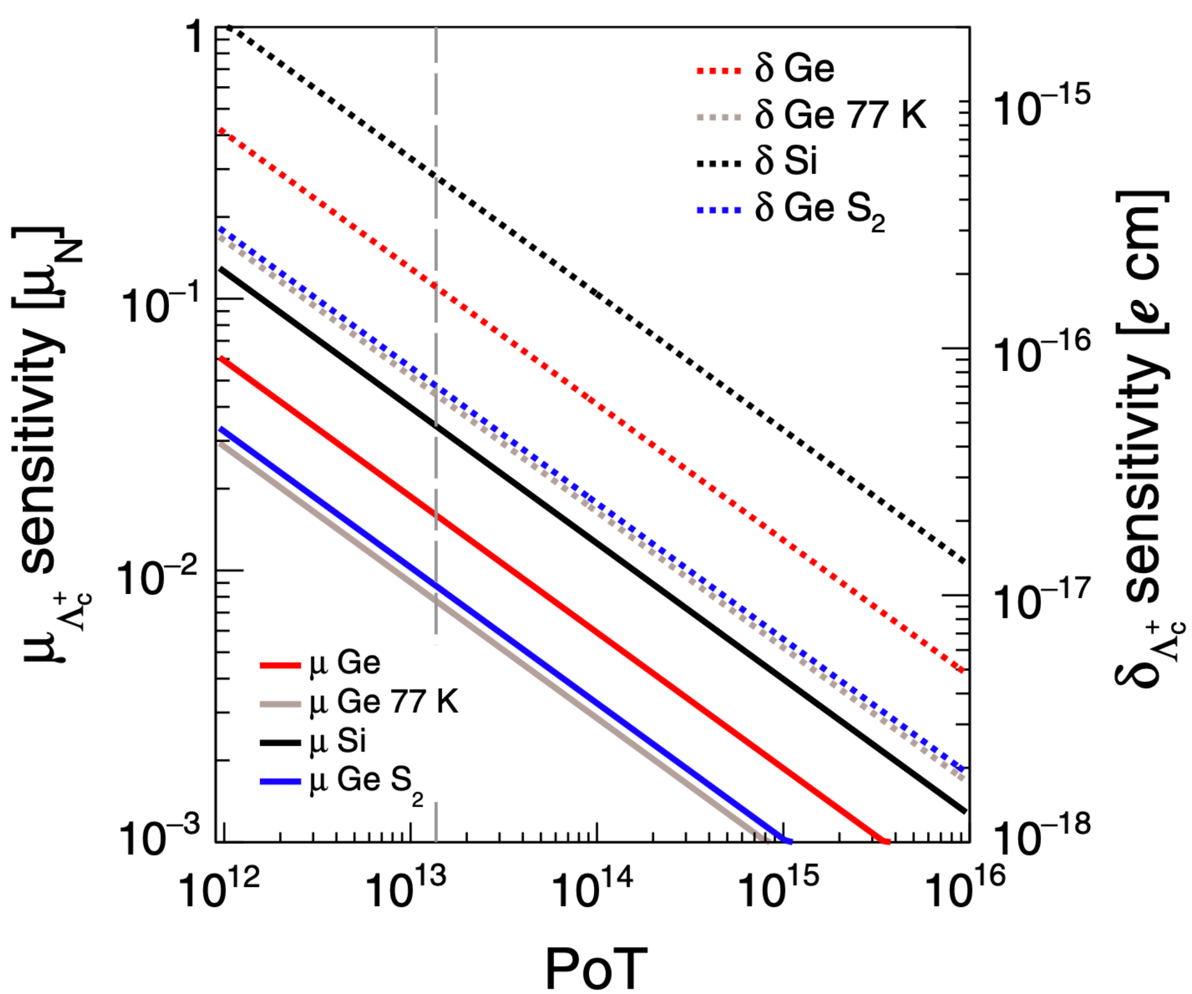
- S1 configuration: **LHCb detector, Ge (Si) 16 mrad, 10 cm**
- S2 configuration: **dedicated experiment, Ge 7 mrad, 7 cm**

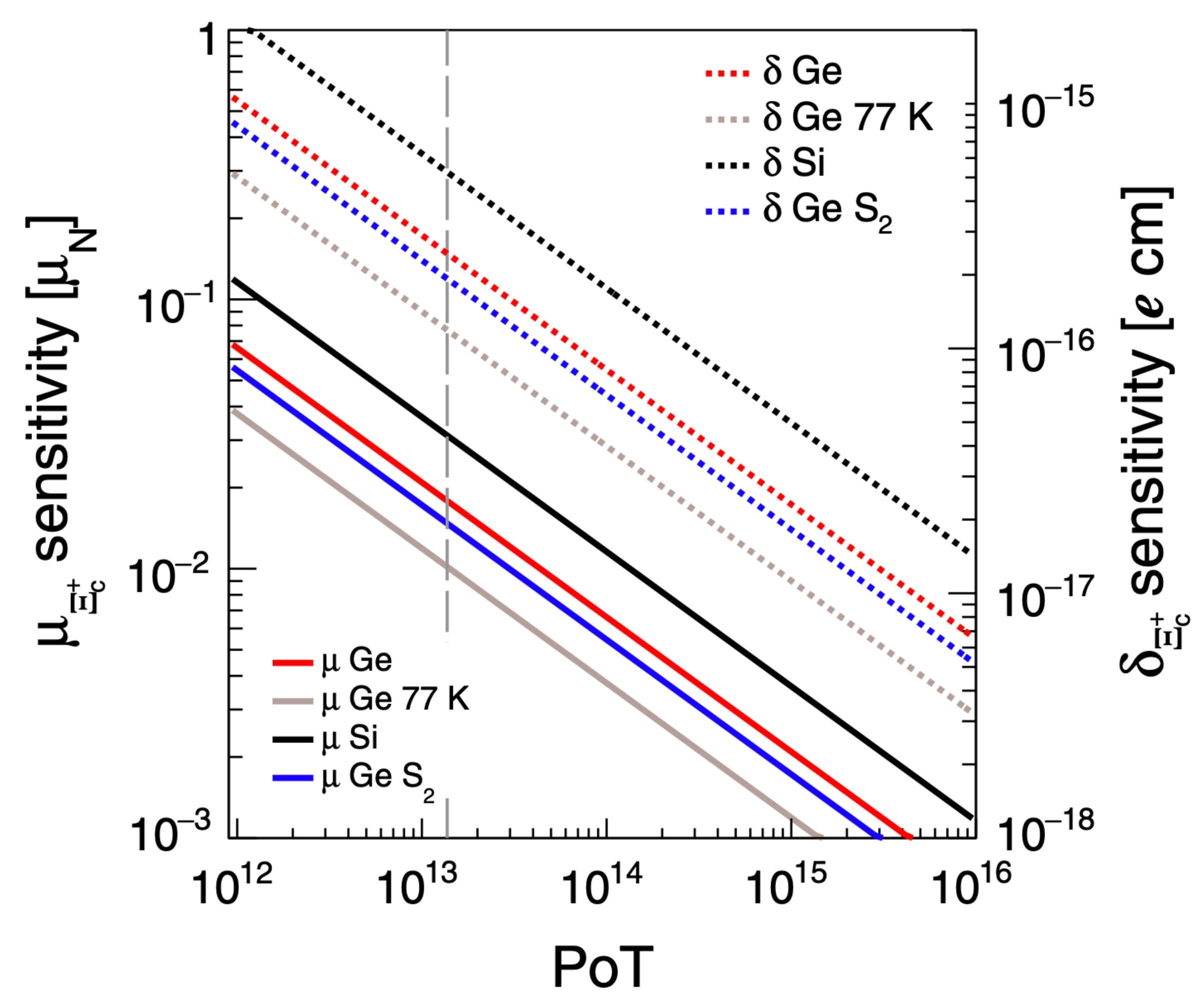
PoT = proton on target
W target 2 cm thick

Λ_c^+ baryon

PRD 103, 072003 (2021)

Ξ_c^+ baryon





- Measurements are **statistically limited**

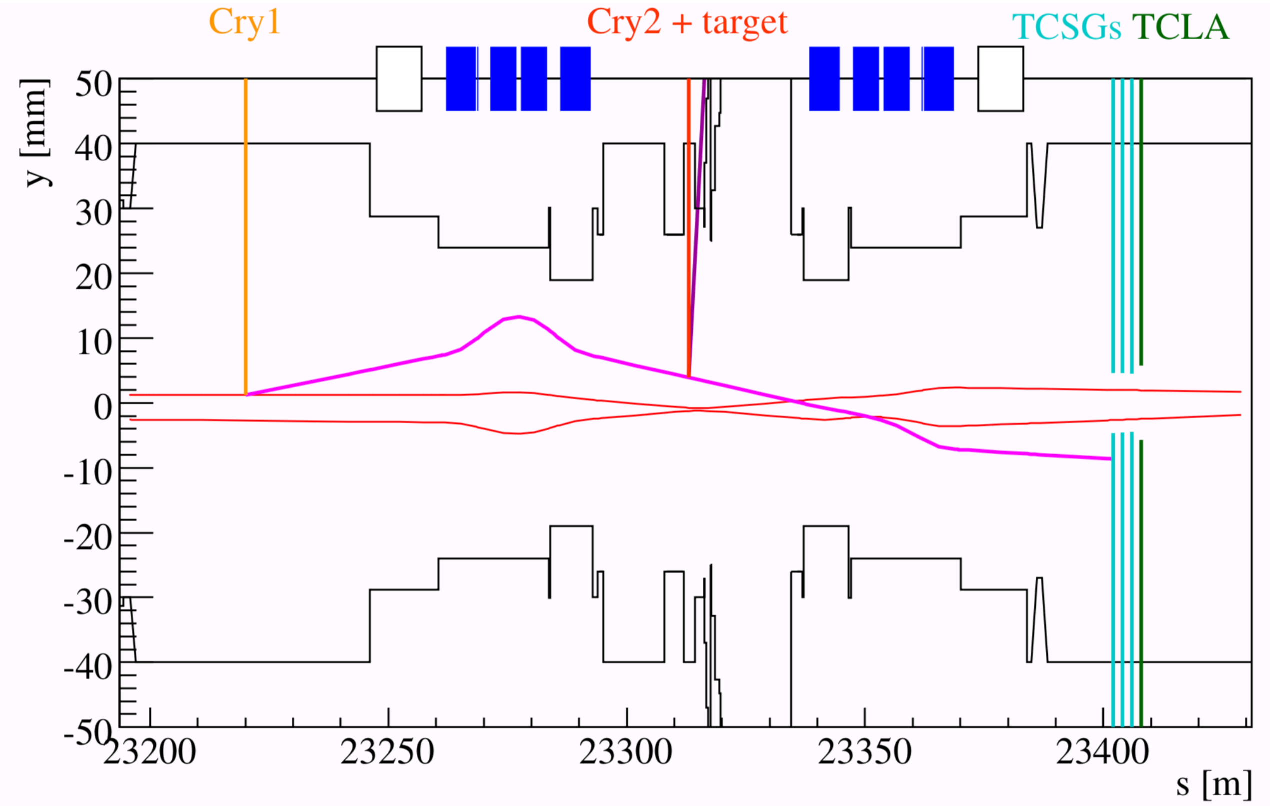
R&D and preparatory studies

LHC (SPS) machine studies

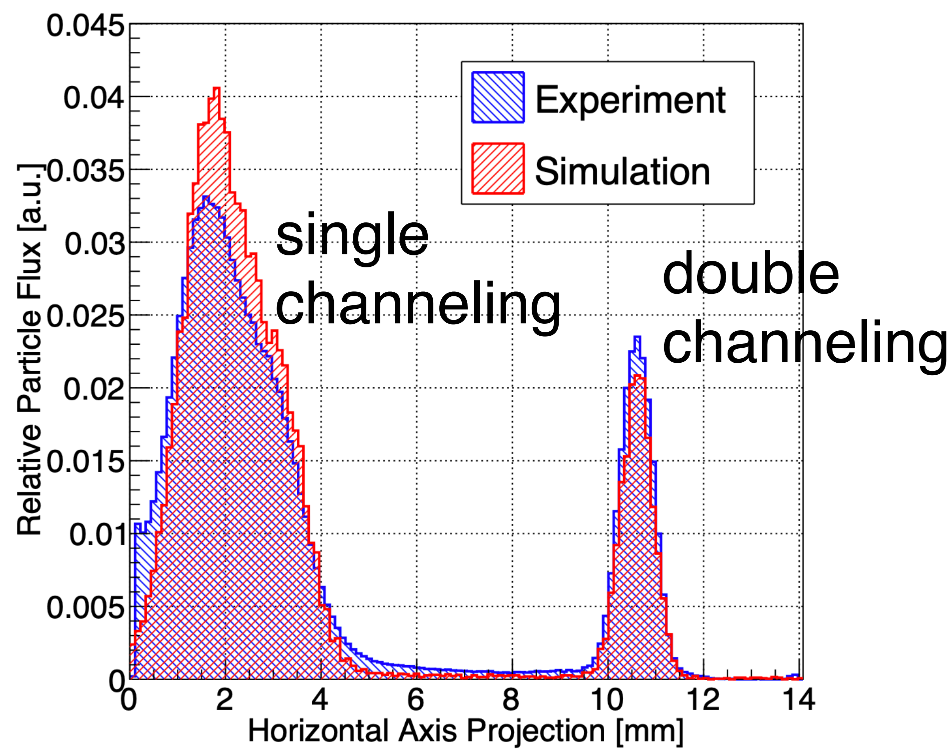
D. Mirarchi, A. S. Fomin, S. Redaelli, W. Scandale, EPJC 80 (2020) 10, 929

W. Scandale et al., NIM A 1015 (2021) 165747

LHC machine layout simulations



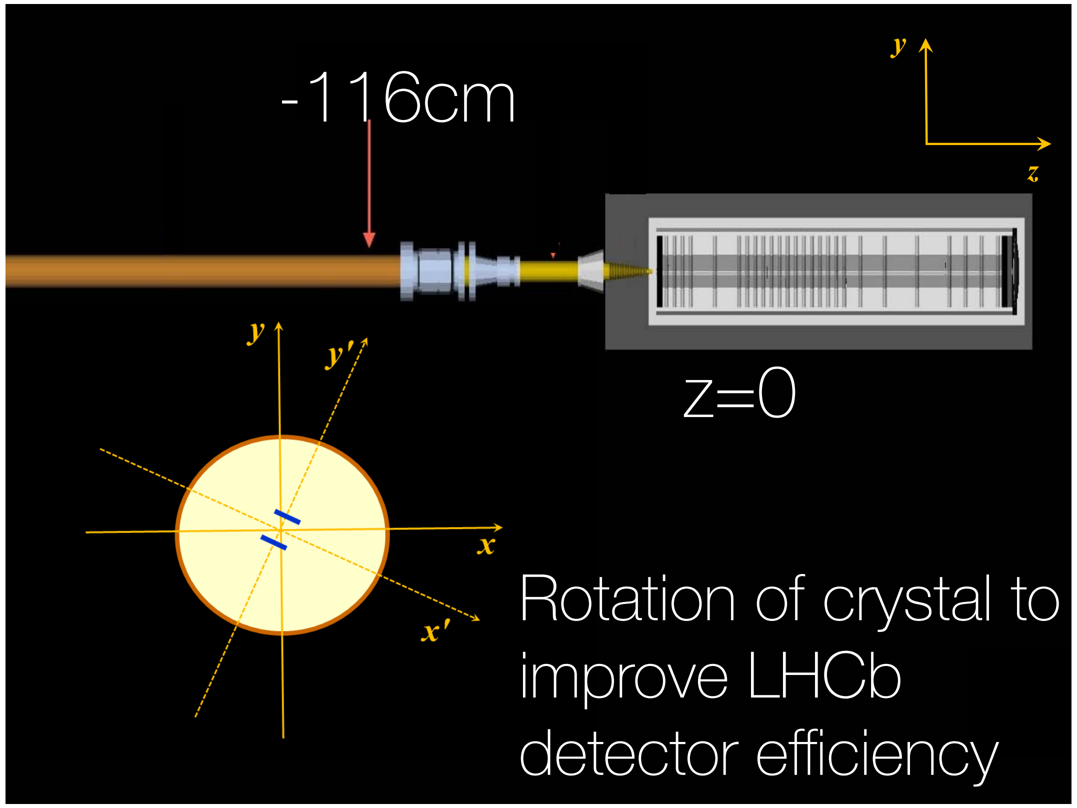
Experimental results at SPS



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

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

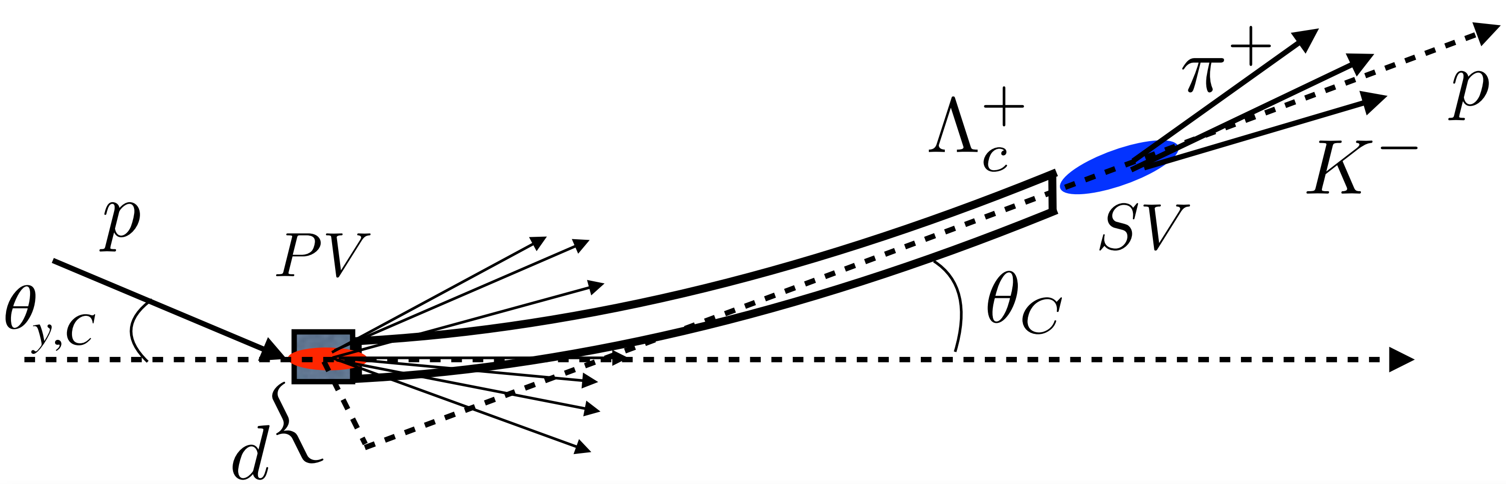
Simulation studies in LHCb

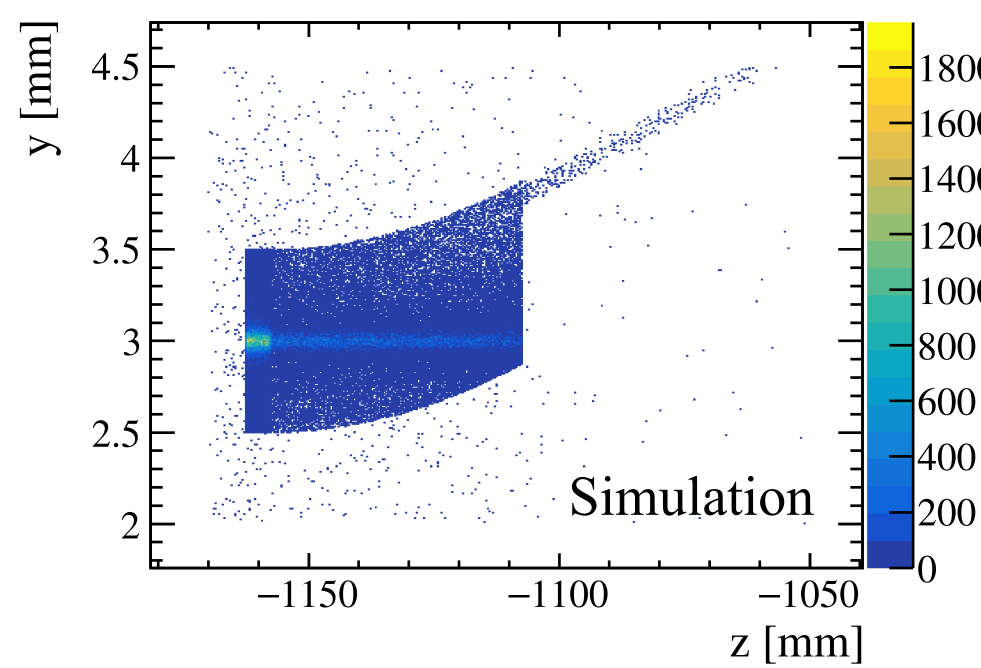


Andrea Merli PhD thesis CERN-THESIS-2019-108

- Good performance (signal and bkg) with LHCb detector. Full **simulation** of **fixed-target setup:** W target 0.5-2.0 cm and bent crystal
- $\nu_{target} \lesssim 0.01$ with 10^6 p/s on target
- About 10^{-4} Λ_c^+ are channeled and have **high momentum** ≳1 TeV

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

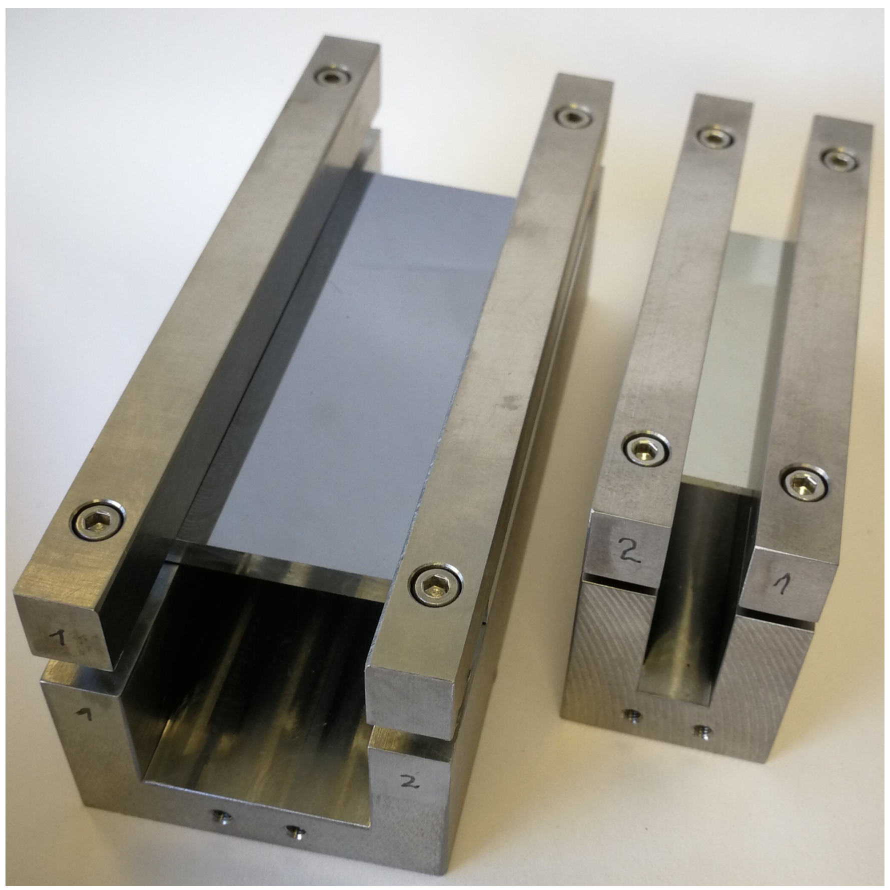




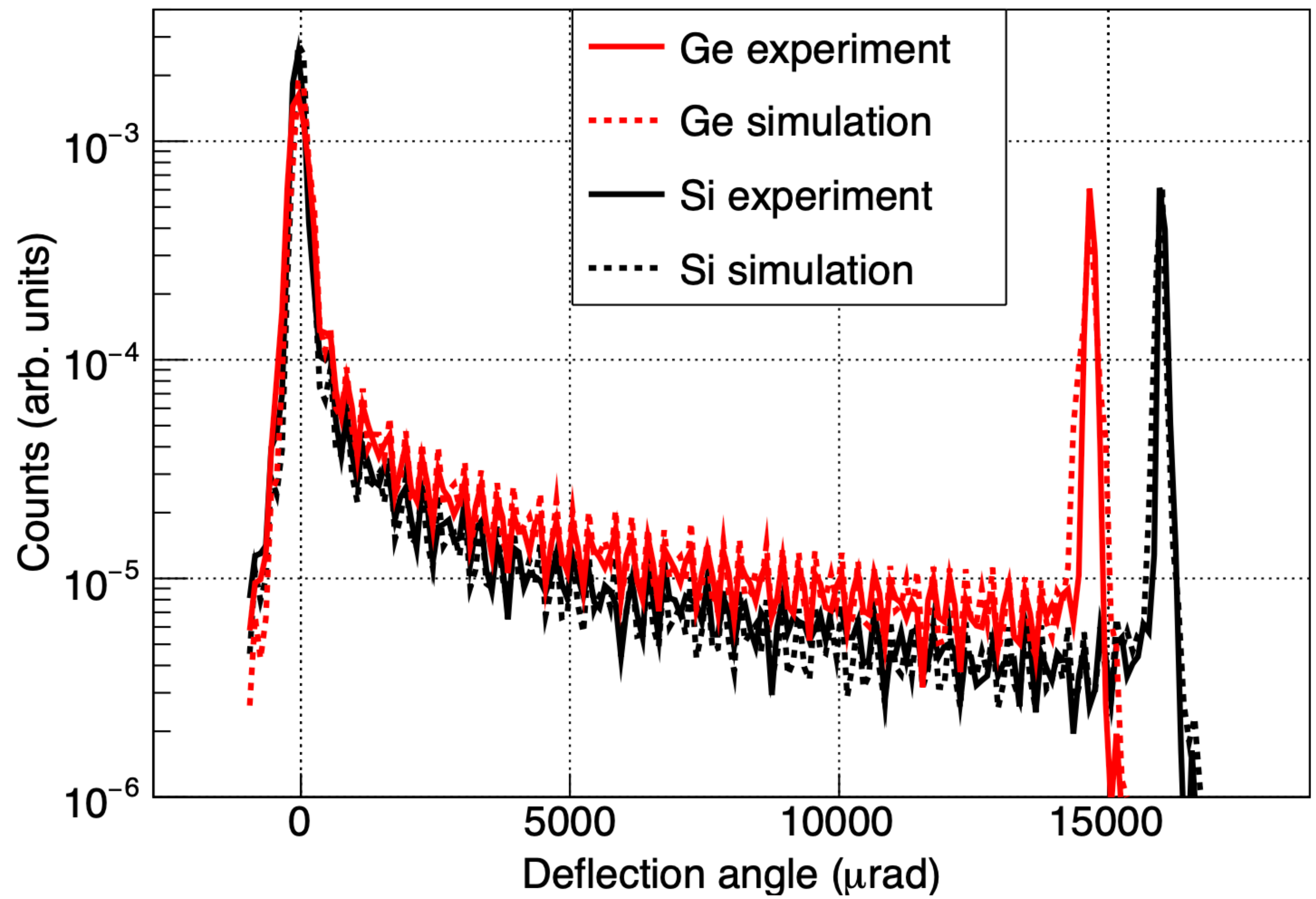
Long bent crystal prototypes

Si: 8 cm long, bent @16.0 mrad

Ge: 5 cm long, bent @14.5 mrad



PRD 103, 072003 (2021)



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

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

- Use 3-body decays to increase the signal yield
- Extract maximum information on polarisation via full amplitude analysis of the 3-body baryon decays

D. Marangotto, AHEP (2020) 7463073

D. Marangotto, AHEP (2020) 6674595

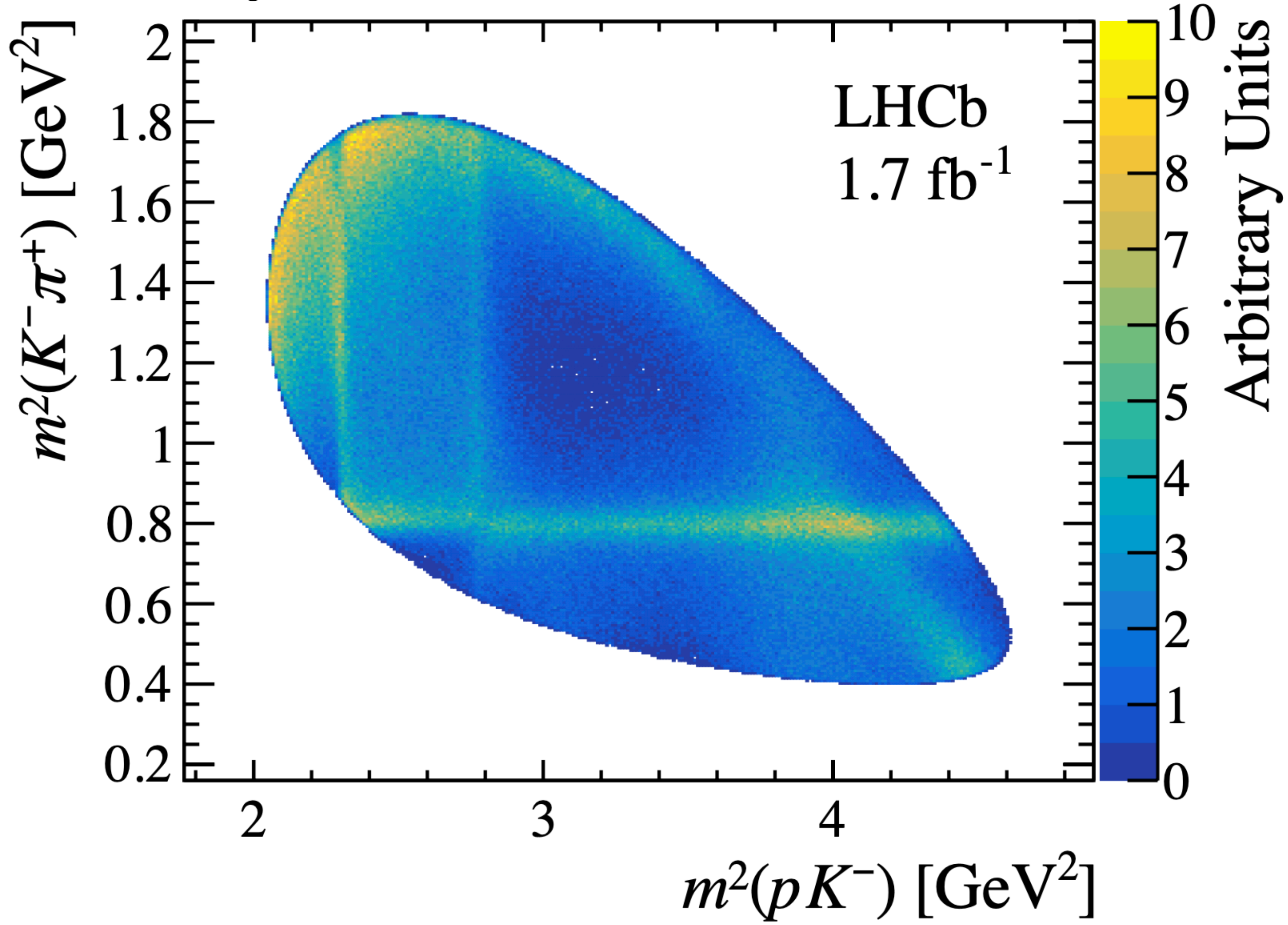
PRD 103, 072003 (2021)

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

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

LHCb-PAPER-2022-002

arXiv: 2208.03262

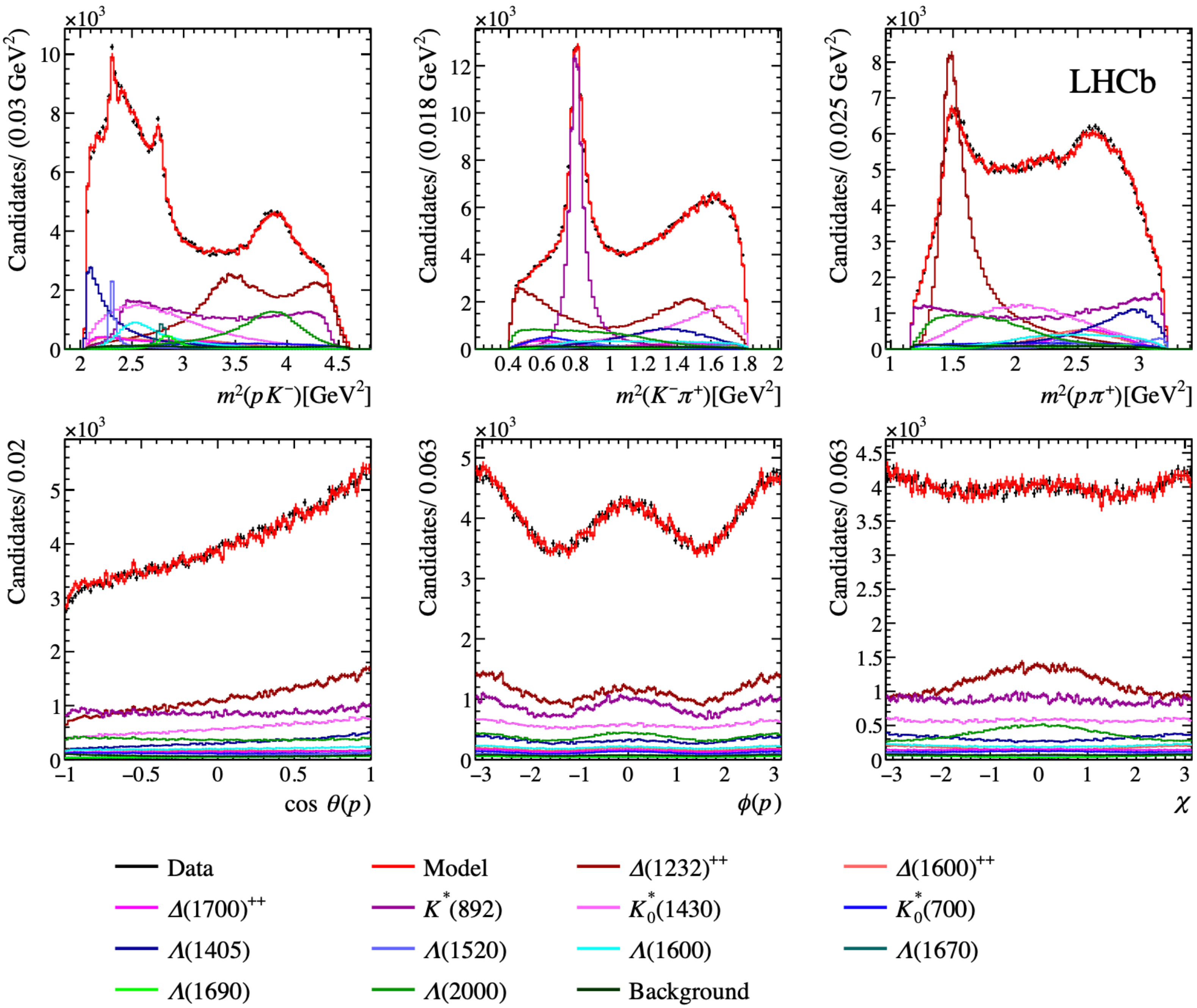


$\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis

LHCb-PAPER-2022-002
arXiv: 2208.03262

Λ_c^+ selected from semileptonic beauty decays

400k signal yield, 98% purity



Amplitude model

Resonance	J^P	Mass (MeV)	Width (MeV)	Fit Fraction (%)
$\Lambda(1405)$	$1/2^-$	1405.1	50.5	7.7
$\Lambda(1520)$	$3/2^-$	1515 – 1523	10 – 20	1.86
$\Lambda(1600)$	$1/2^+$	1630	250	5.2
$\Lambda(1670)$	$1/2^-$	1670	30	1.18
$\Lambda(1690)$	$3/2^-$	1690	70	1.19
$\Lambda(2000)$	$1/2^-$	1900 – 2100	20 – 400	9.58
$\Delta(1232)^{++}$	$3/2^+$	1232	117	28.60
$\Delta(1600)^{++}$	$3/2^+$	1640	300	4.5
$\Delta(1700)^{++}$	$3/2^-$	1690	380	3.90
$K_0^*(700)$	0^+	824	478	3.02
$K^*(892)$	1^-	895.5	47.3	22.14
$K_0^*(1430)$	0^+	1375	190	14.7

Polarisation measurement

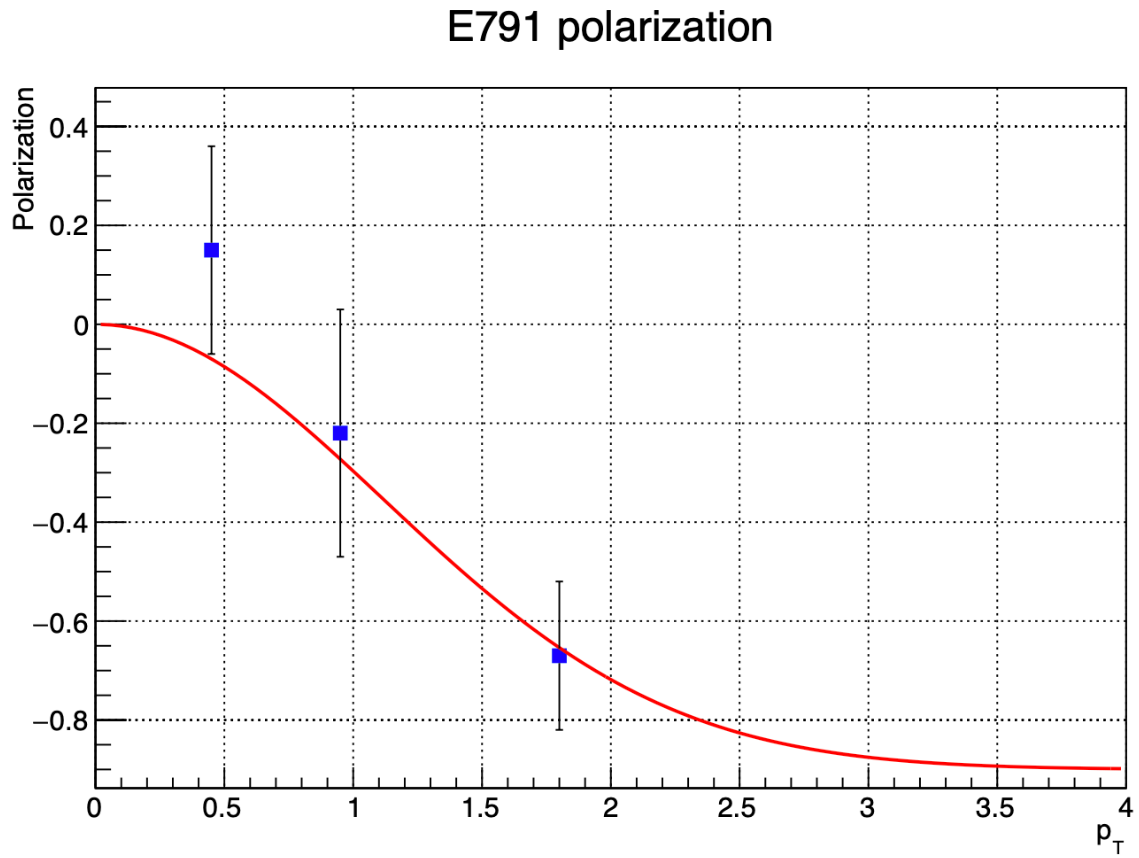
Component	Value (%)
P_x (lab)	$60.32 \pm 0.68 \pm 0.98 \pm 0.21$
P_y (lab)	$-0.41 \pm 0.61 \pm 0.16 \pm 0.07$
P_z (lab)	$-24.7 \pm 0.6 \pm 0.3 \pm 1.1$
P_x $(\tilde{B})$	$21.65 \pm 0.68 \pm 0.36 \pm 0.15$
P_y $(\tilde{B})$	$1.08 \pm 0.61 \pm 0.09 \pm 0.08$
P_z $(\tilde{B})$	$-66.5 \pm 0.6 \pm 1.1 \pm 0.1$

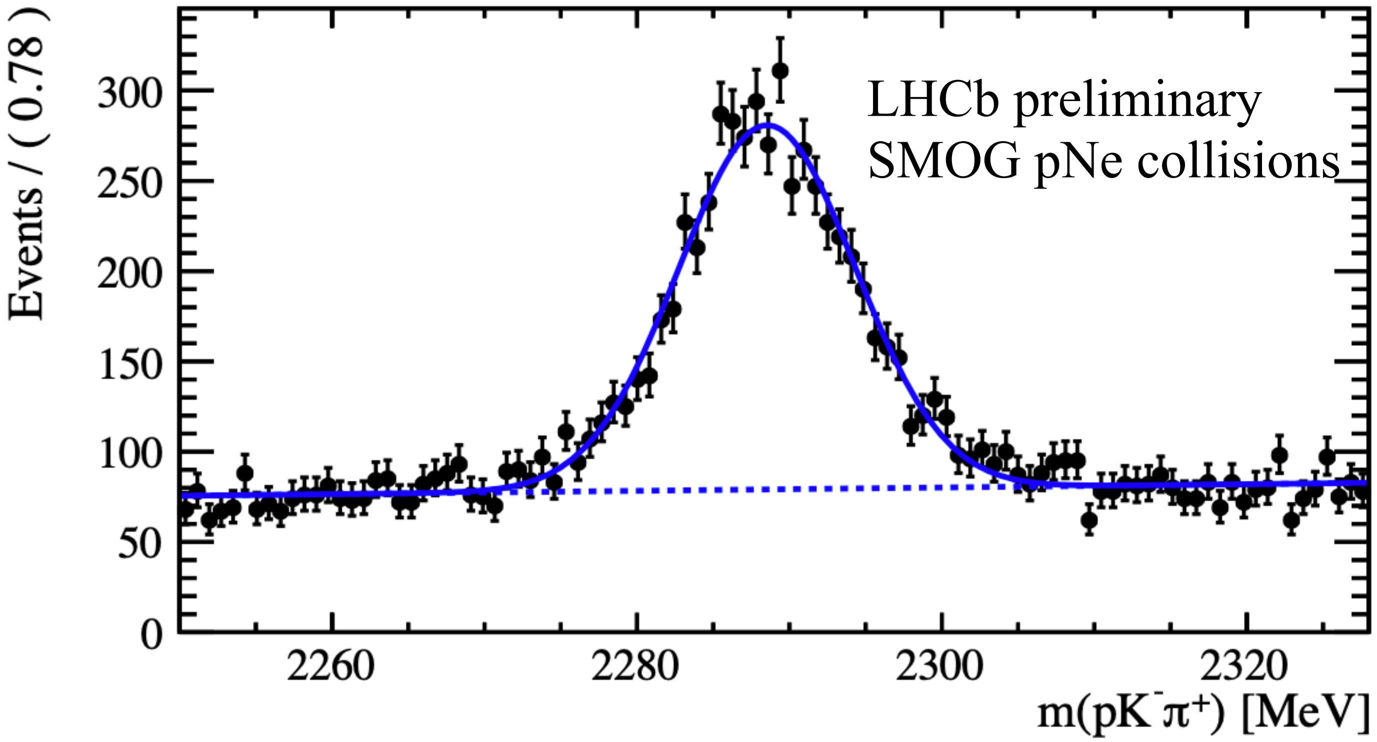
Λ_c^+ polarization in fixed-target collisions

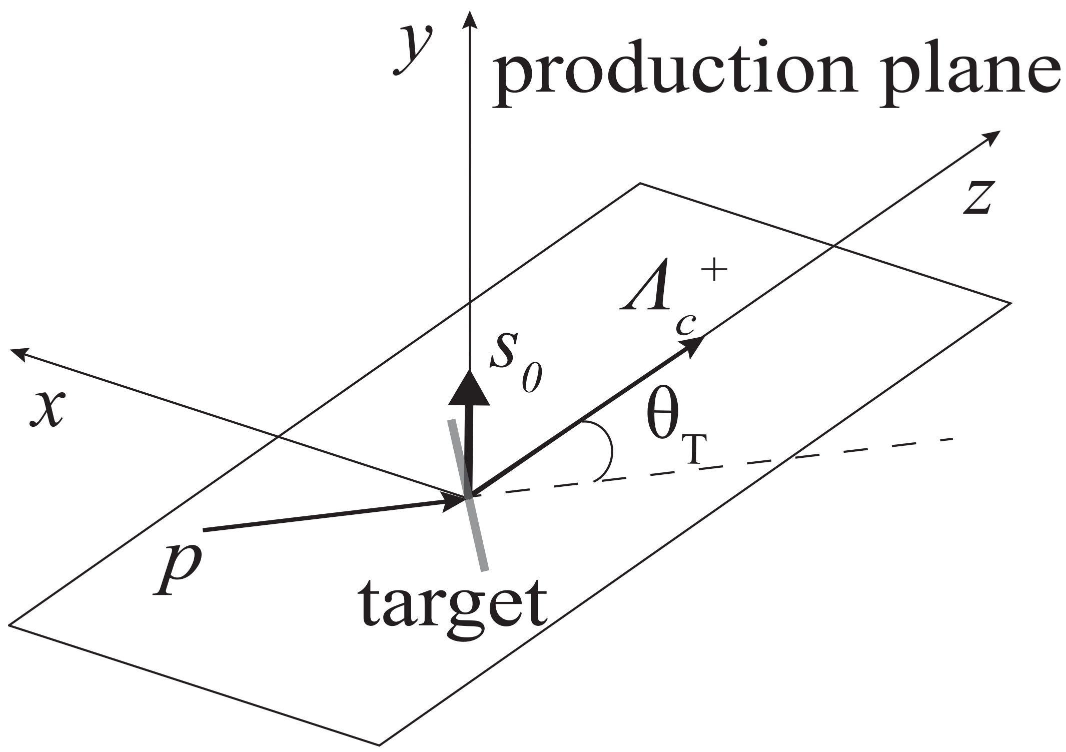
- Λ_c^+ polarization vs p_T measured in π^--N at $\sqrt{s}$=31 GeV by E791 experiment

  Physics Letters B 471 (2000), 449–459

- Λ_c^+ **polarization** and **cross-section** in SMOG p-Ne collisions $\sqrt{s}$=68.6 GeV at LHCb in progress (signal yield ≈2500)

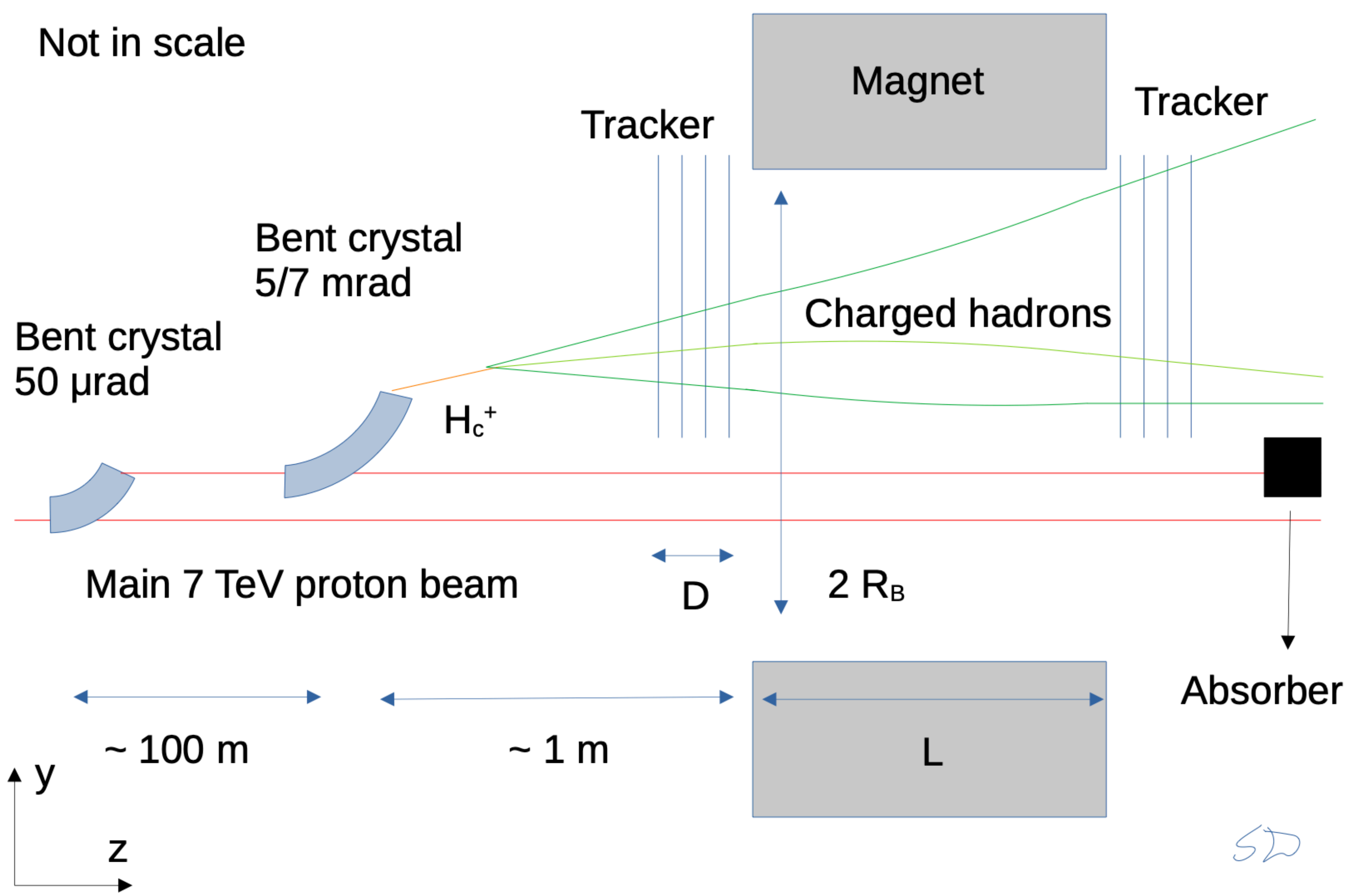






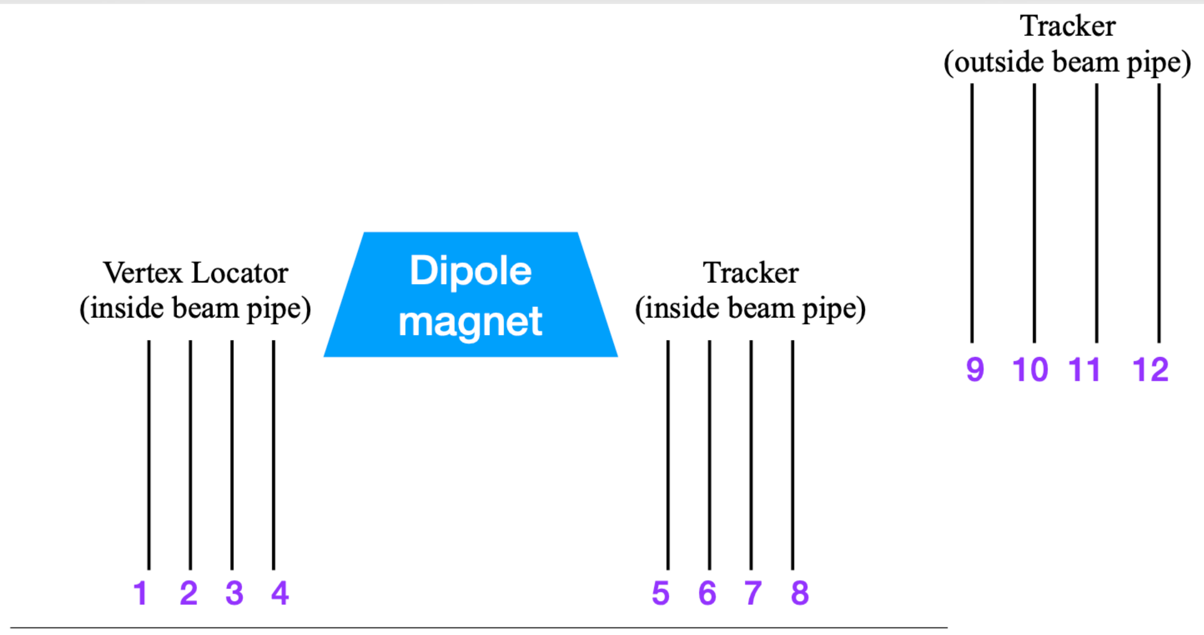
Test in LHC at IR3

- A **proof-of-principle** test at the insertion region 3 (IR3) is considered with LHC machine people
- Main goals of the test
  - test machine and operational aspects
  - measure channeling efficiency at TeV energies
  - study detector performance and background level

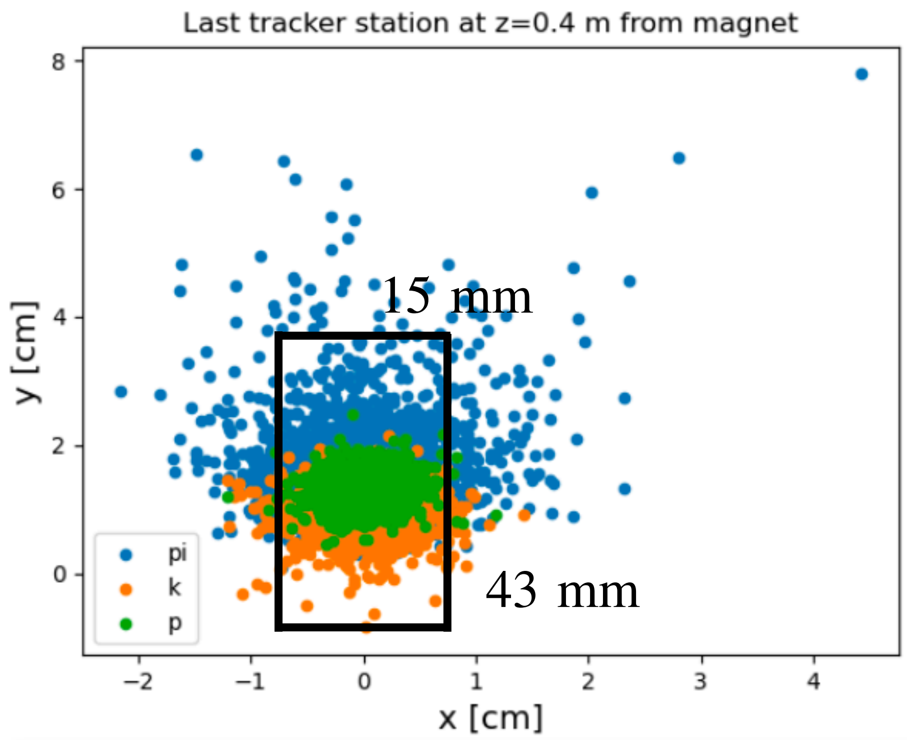


Studies for a dedicated experiment at IR3

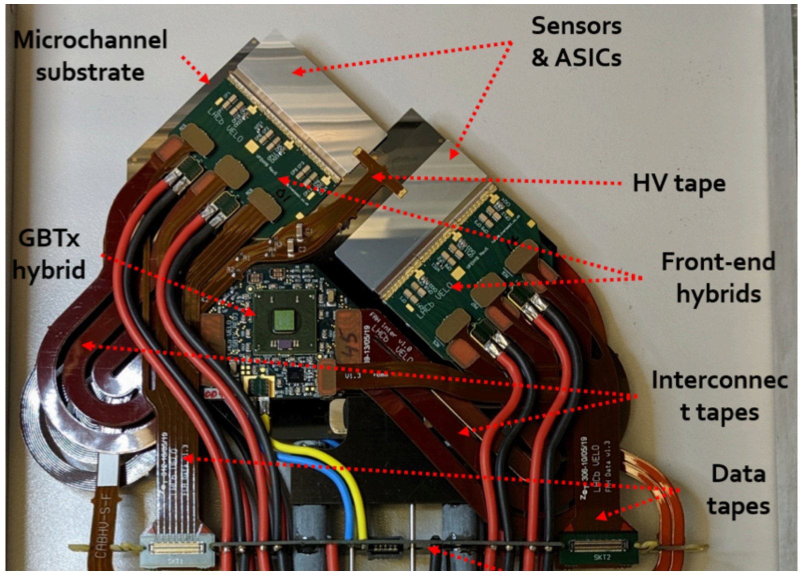
- Channeled Λ_c^+ in bent crystal are very focused in few cm²
- Preliminary simulations: with 8 **VELO tiles** + existing 1.9Tm dipole magnet in situ can build a spectrometer



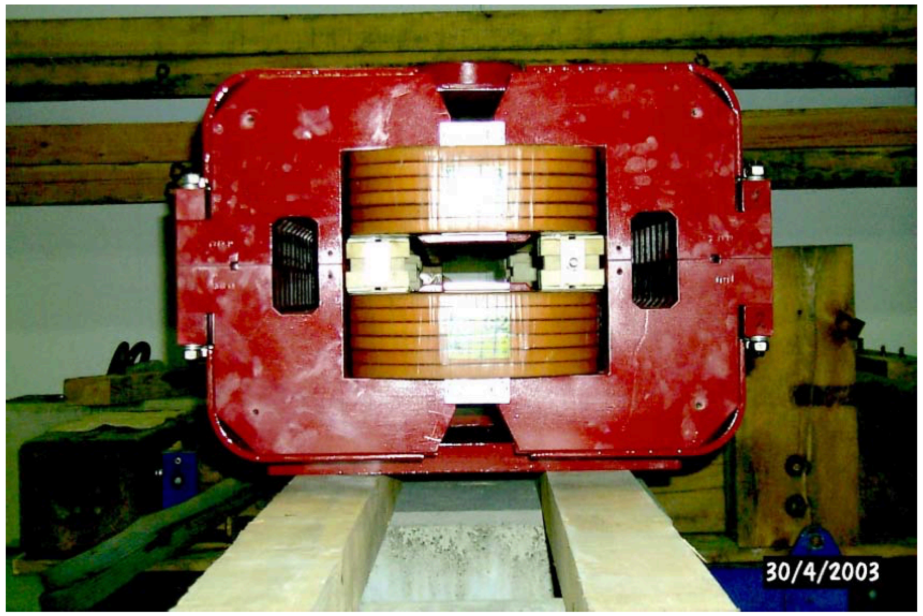
Hit distribution for $\Lambda_c^+ \rightarrow pK^-\pi^+$
Area ≈ few cm². rate ≈ 100 MHz/cm²



VeloPix modules in Roman Pots
for Vertex and Tracker stations
1 cm from the beam
55x55 μm² pixel,
pixel hit rate 600 MHz/cm²,
12 μm hit resolution



LHC orbit correction dipole MCBW (1.7 m, 1.1 T) is considered for the spectrometer (Credits: Pascal Hermes, CERN)

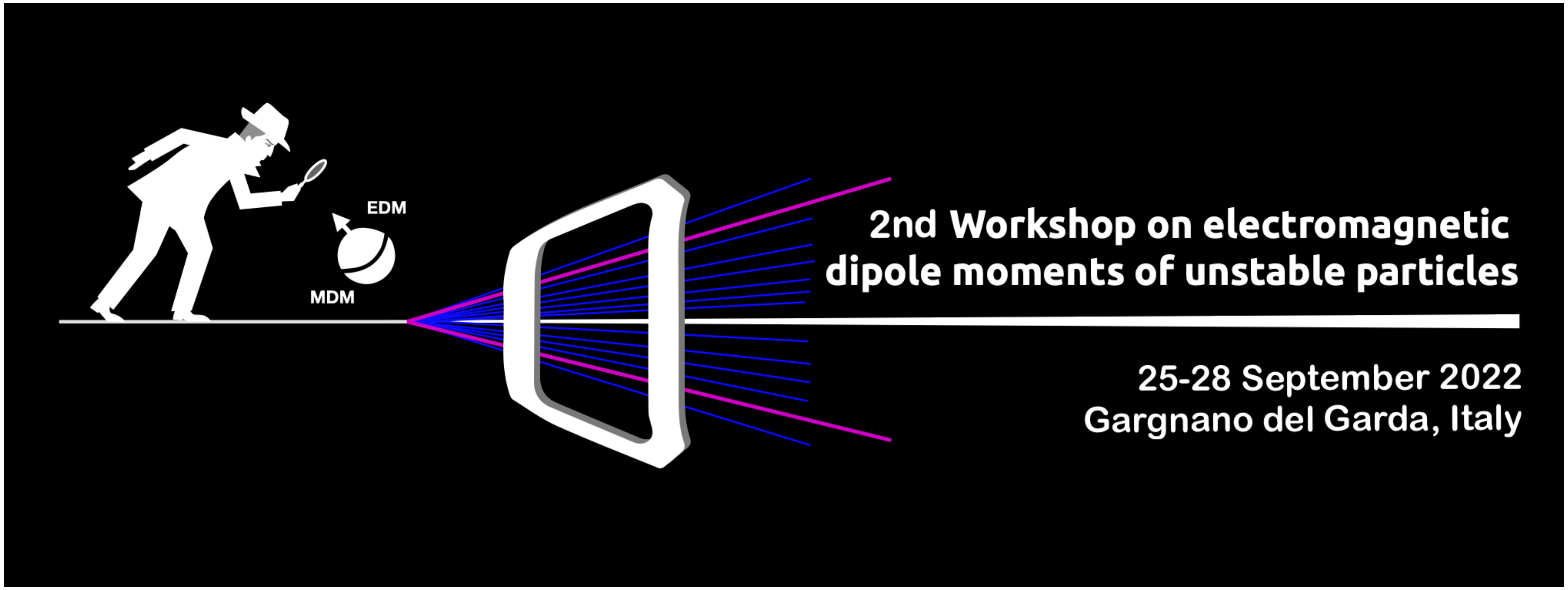


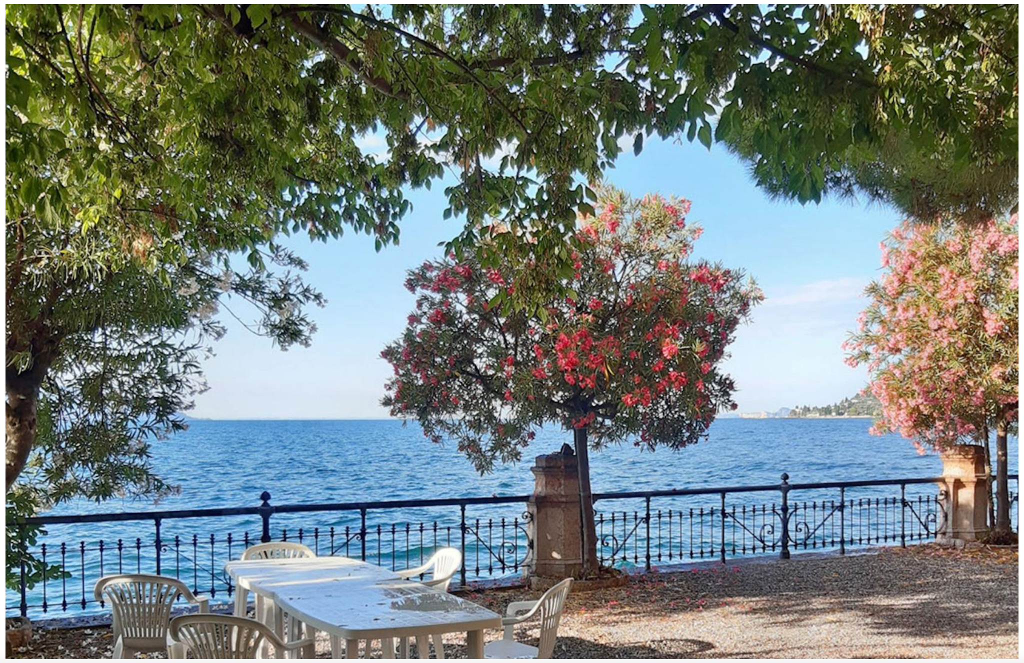
Summary

- **First measurements** of **strange** and **charm baryons** are possible in 2 year data taking using the LHCb detector
- **Milestones** achieved: feasibility detector studies, long bent crystal prototypes, preparatory studies in LHCb, machine layout, physics program extended
- Machine **test in LHC**, possibly during Run3
- Possibility to design a **dedicated fixed-target** experiment at LHC at high statistics for a more **ambitious physics program**

Recent topical workshop

- Agenda of the workshop at this link





Thanks for your attention!

Backup slides

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EDM: a probe for *CPV* beyond the SM

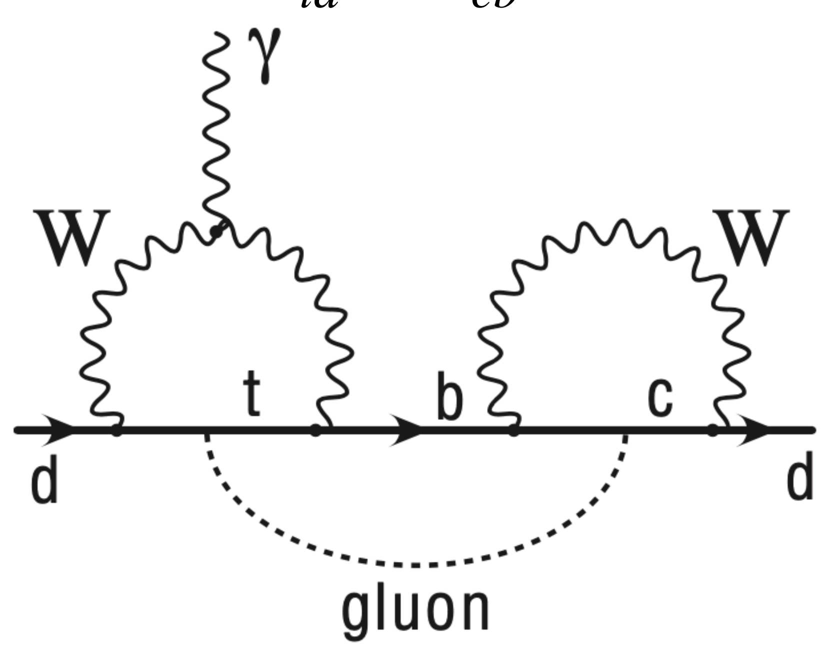
- $\mathscr{L}_{CPV} = \mathscr{L}_{CKM} + \mathscr{L}_{\bar{\theta}} + \mathscr{L}_{BSM}$
  - SM: negligible CKM contribution; $\bar{\theta}$-QCD for possible *CPV* in strong interaction, $\bar{\theta} \lesssim 10^{-10}$ from neutron EDM limit

$$\delta_n \approx (10^{-16} e \text{ cm})\bar{\theta}$$

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

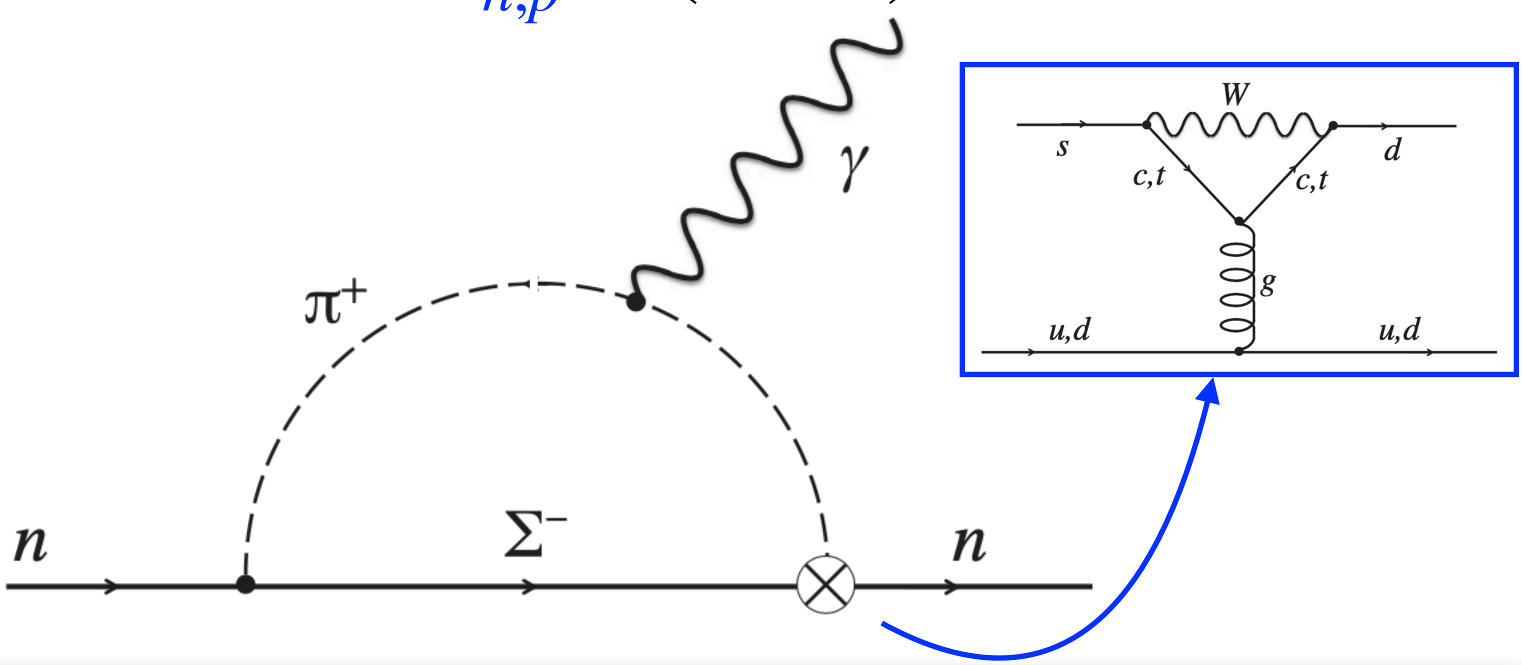
Example of SM CKM contributions

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



"Long distance" contribution

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



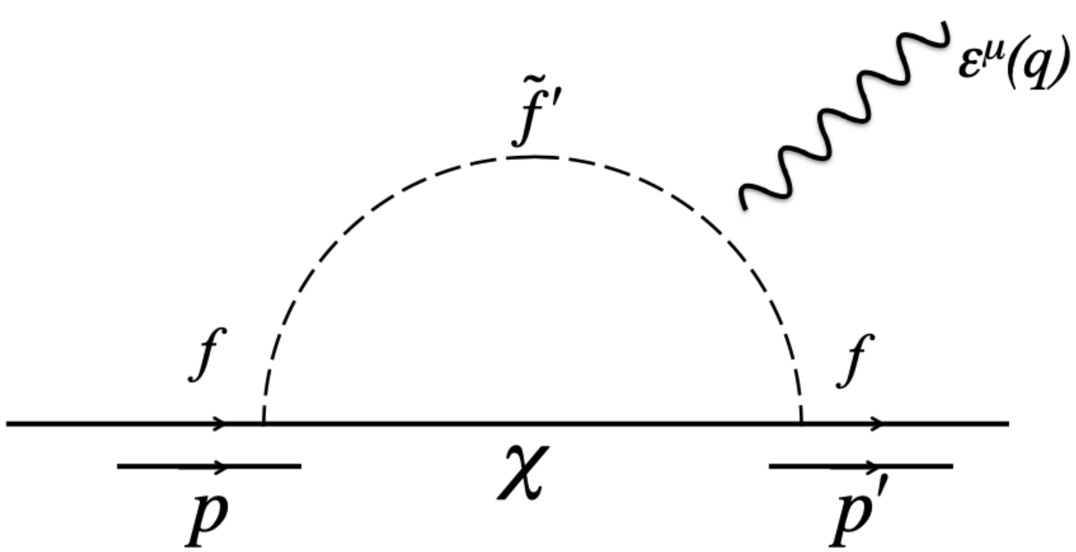
EDM: a probe for *CPV* beyond the SM

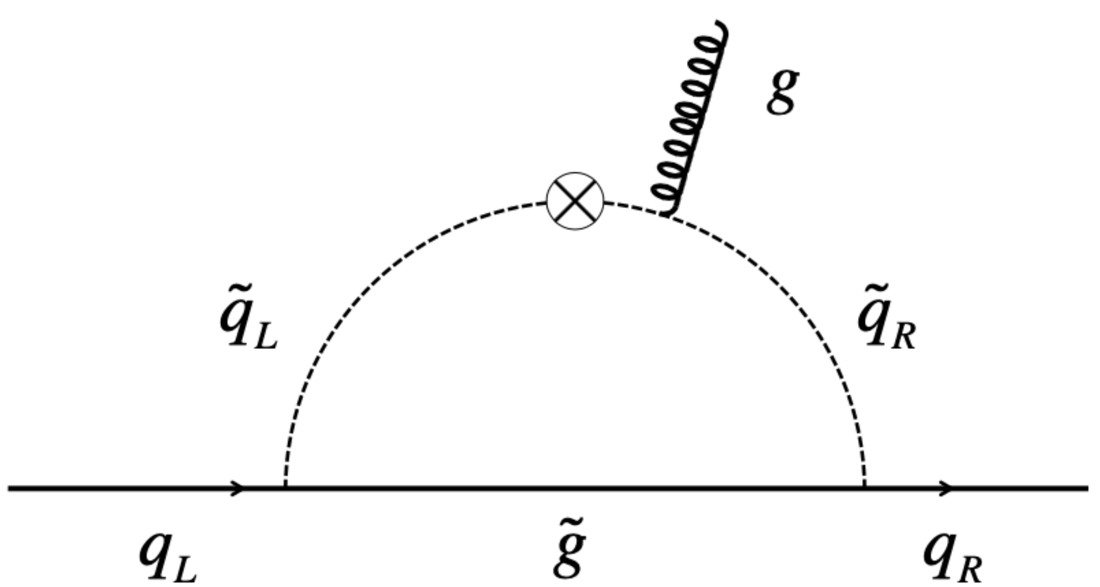
- $\mathscr{L}_{CPV} = \mathscr{L}_{CKM} + \mathscr{L}_{\bar{\theta}} + \mathscr{L}_{BSM}$
  - BSM: potential large contributions by new physics scale Λ_{NP} and CP-violating phase ϕ_{CPV}

$$\delta_{BSM} \approx (10^{-16} e\text{cm}) \left(\frac{246 \text{ GeV}}{\Lambda_{NP}} \right)^2 \sin \phi_{CPV} y_f F$$

Examples of BSM contributions

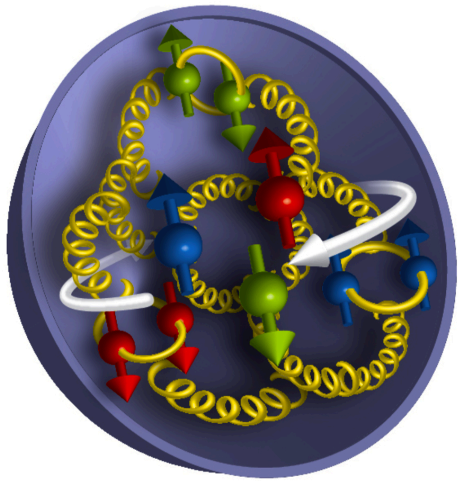
Rev. Mod. Phys. **91**, 015001 (2019)





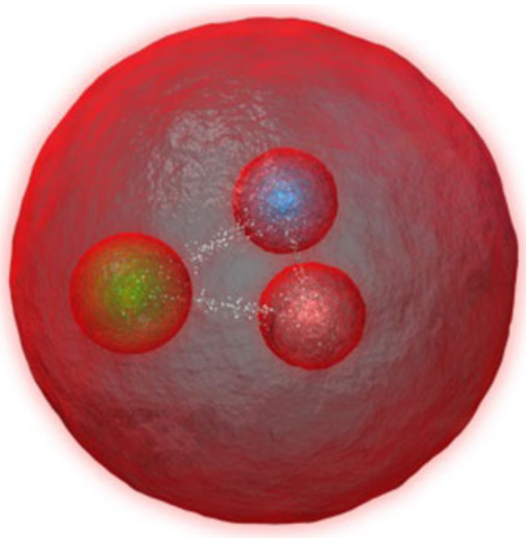
MDM of baryons

- No direct measurements for **charm** baryons
- Further information on **baryon substructure**



$$\mu_{\Lambda_c^+} = g_{\Lambda_c^+}\frac{e\hbar}{2m_{\Lambda_c^+}}$$ with $g_{\Lambda_c^+} \neq 2$ (not point-like fermion)

- Experimental anchor points for test of low-energy QCD models, **non-perturbative QCD** dynamics



- Measurement of MDM of Λ and $\overline{\Lambda}$ **strange** baryons and antibaryons for a **test of CPT symmetry**

Status of art for Λ baryon EDM/MDM

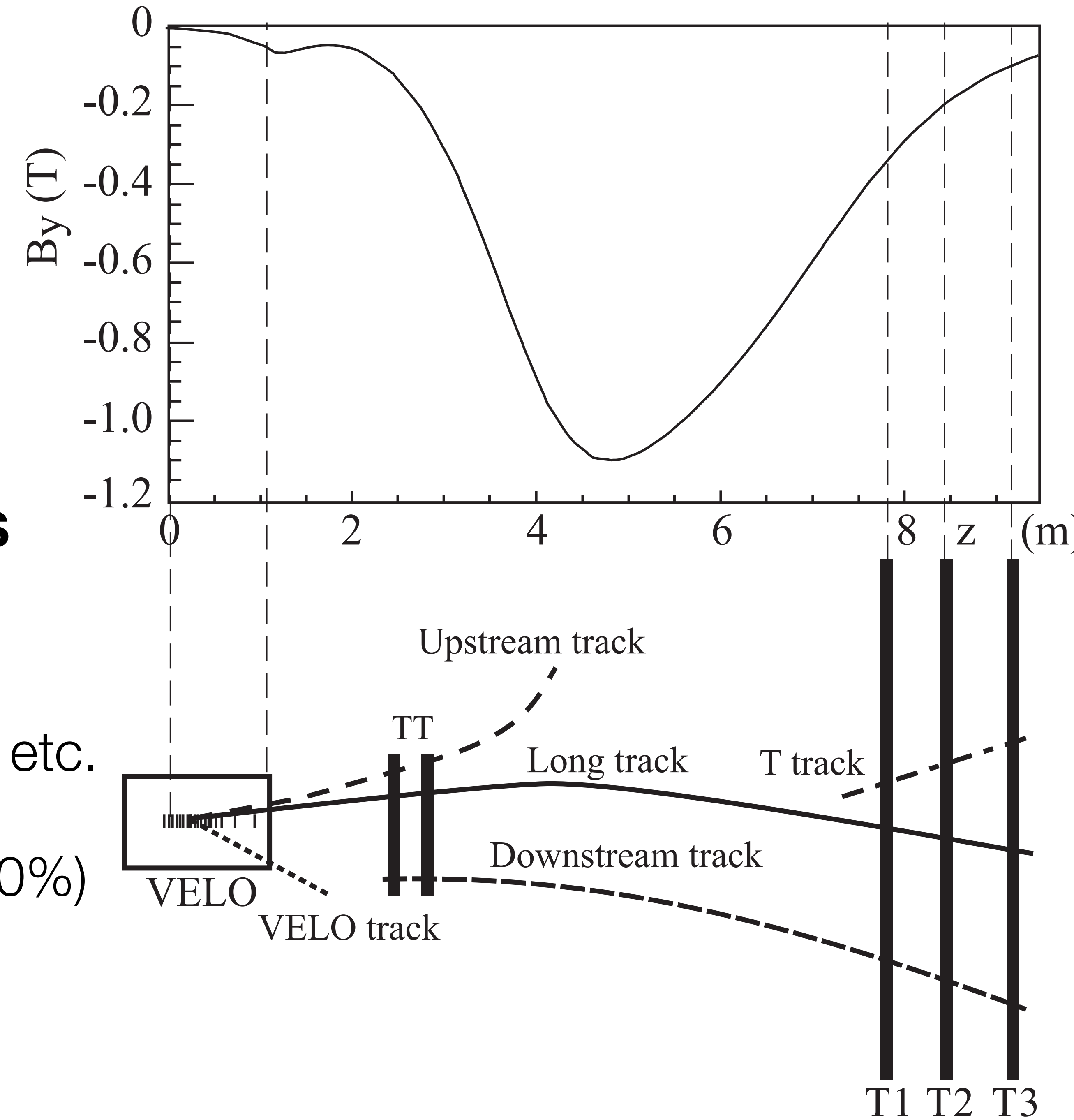
- Current limit on Λ baryon **EDM** $< 1.5 \times 10^{-16} e\text{cm}$ at 95% CL L. Pondrom et al., Phys. Rev. D **23**, 814 (**1981**)
- Measurement of **MDM** $\mu_\Lambda=(-0.6138\pm0.0047)\mu_N$ but no measurement for $\overline{\Lambda}$ exists Phys.Rev.Lett. 41 (**1978**) 1348
- Measurement of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

Λ baryon precession in the magnet

- Long-lived Λ baryons can travel through the LHCb **dipole magnet**
- **Spin precession** occurs in B field

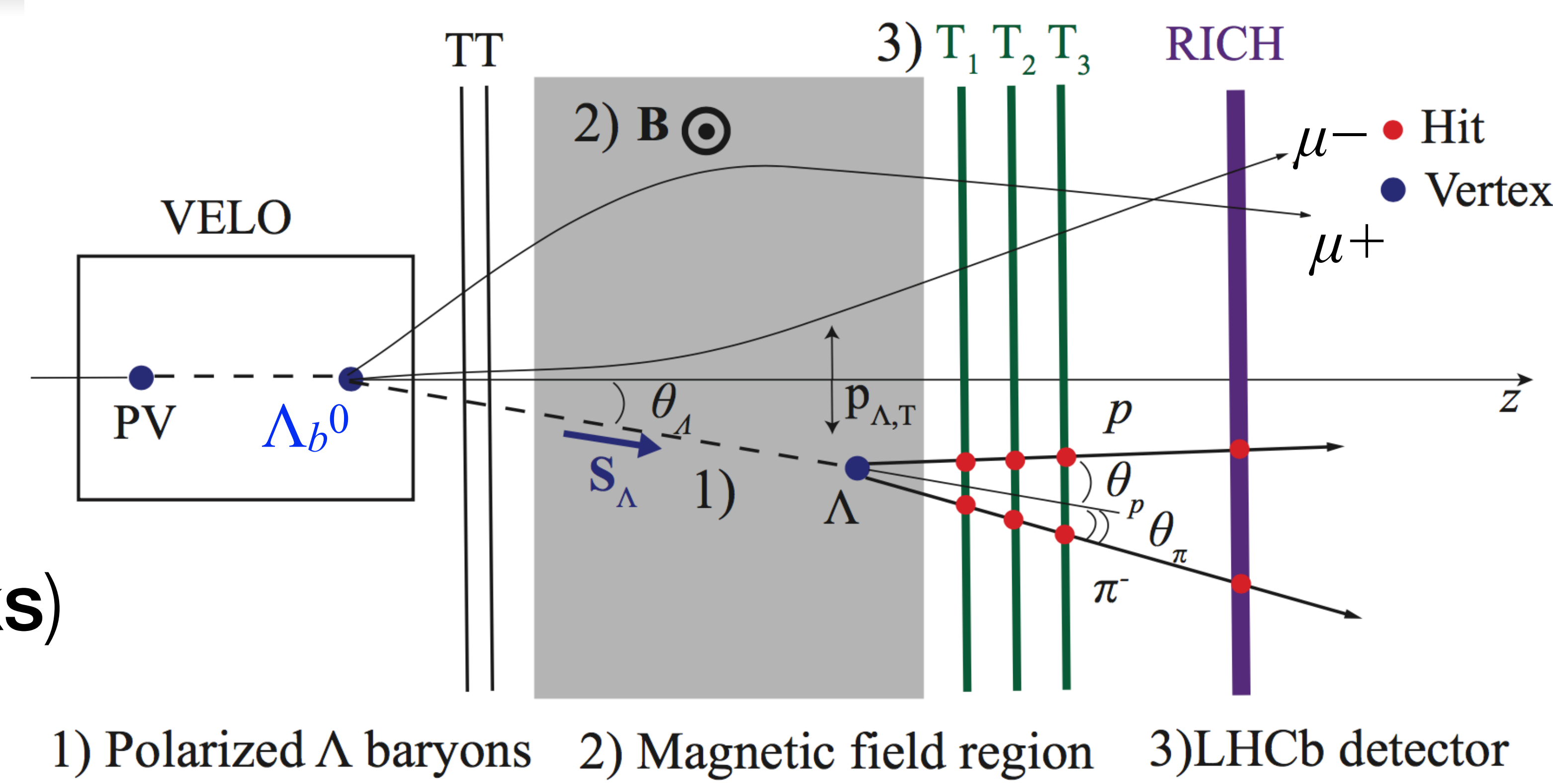
$$\frac{d\boldsymbol{S}}{d\tau} = \boldsymbol{\mu} \times \boldsymbol{B}^* + \boldsymbol{\delta} \times \boldsymbol{E}^*$$

- Select Λ (anti-Λ) from **weak decays**
  - $\Lambda_b^0 \to J/\psi\Lambda$, $\Xi_c^0 \to \Lambda K^-\pi^+$, $\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$, $\Xi_c^0 \to \Xi^-(\Lambda\pi^-)\pi^+$, etc.
  - Large longitudinal **polarisation** (up to 100%) due to parity violation in the weak decay
- Challenge: reconstruct Λ baryon decays after the magnet using **T tracks**

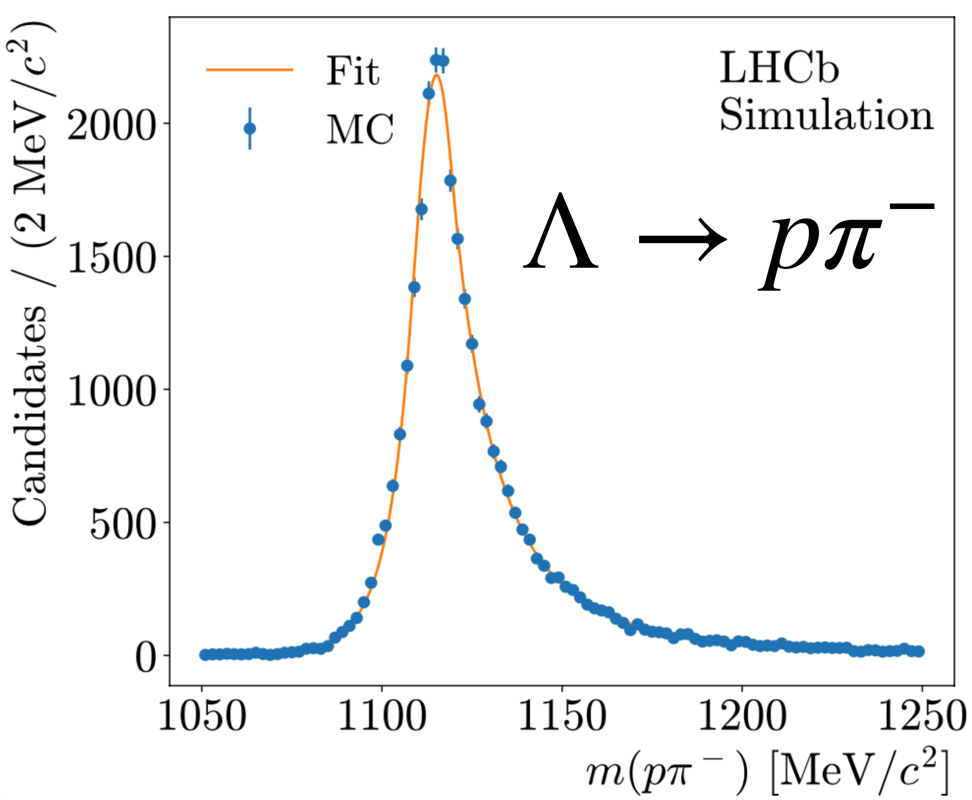


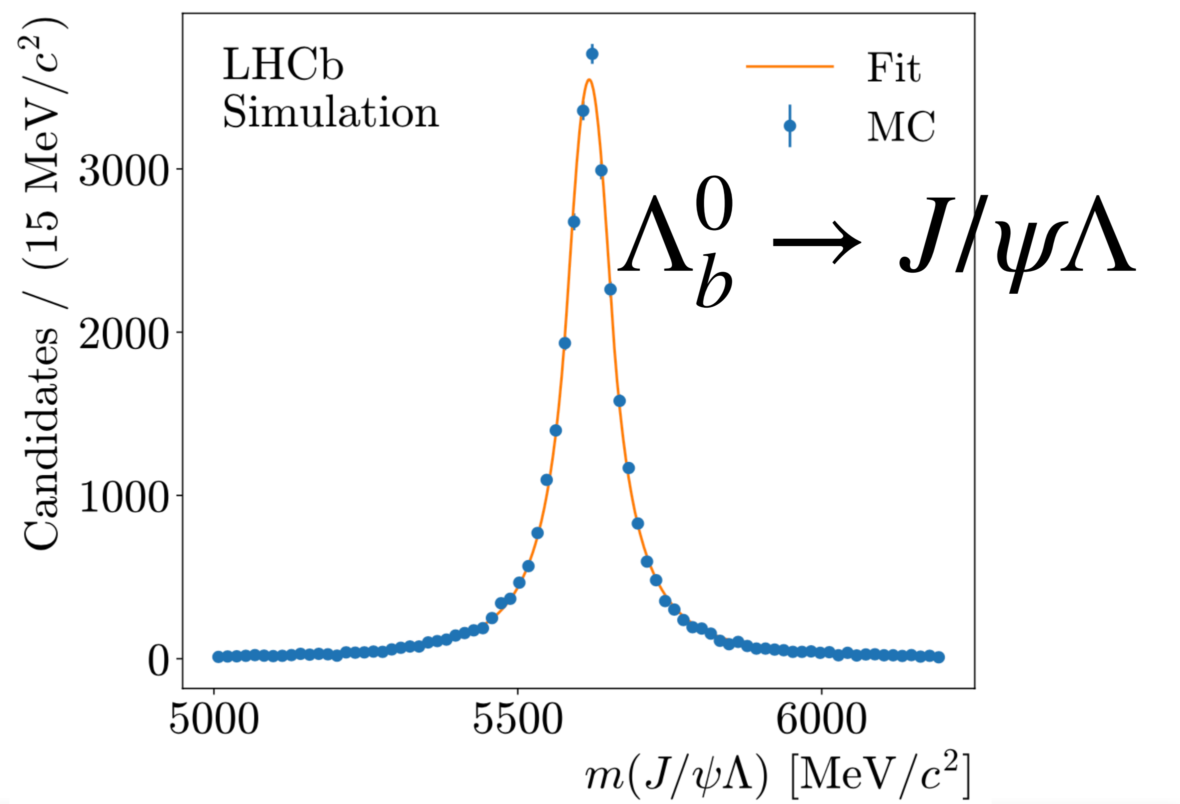
Simulations studies for Λ reconstruction

- Fit full decay chain $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$ with geom. and kin. constraints
- Λ decays after the magnet $z \in [6.0\text{-}7.6]$m from IP (**T tracks**)



LHCb-DP-2022-001
in review

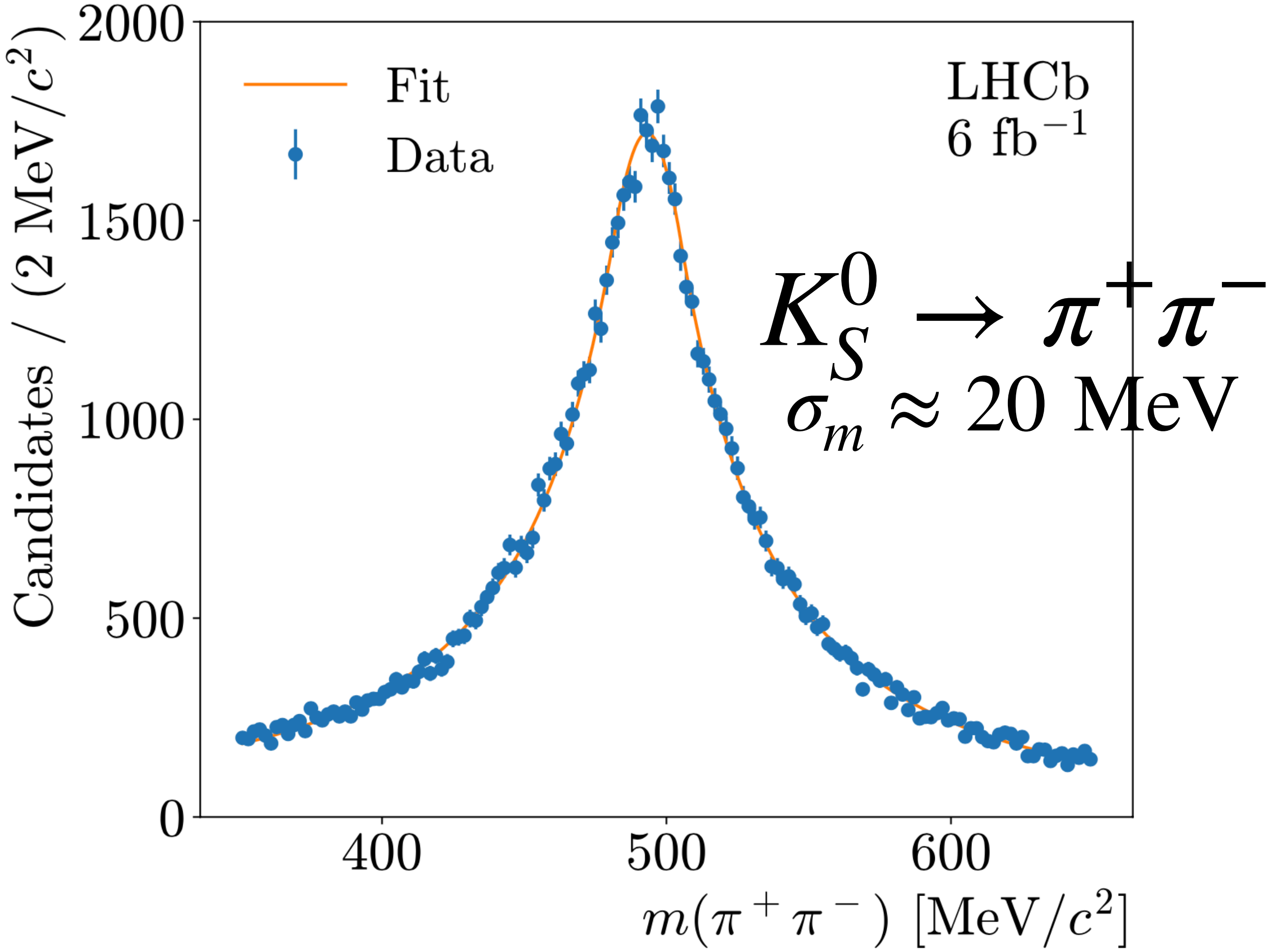


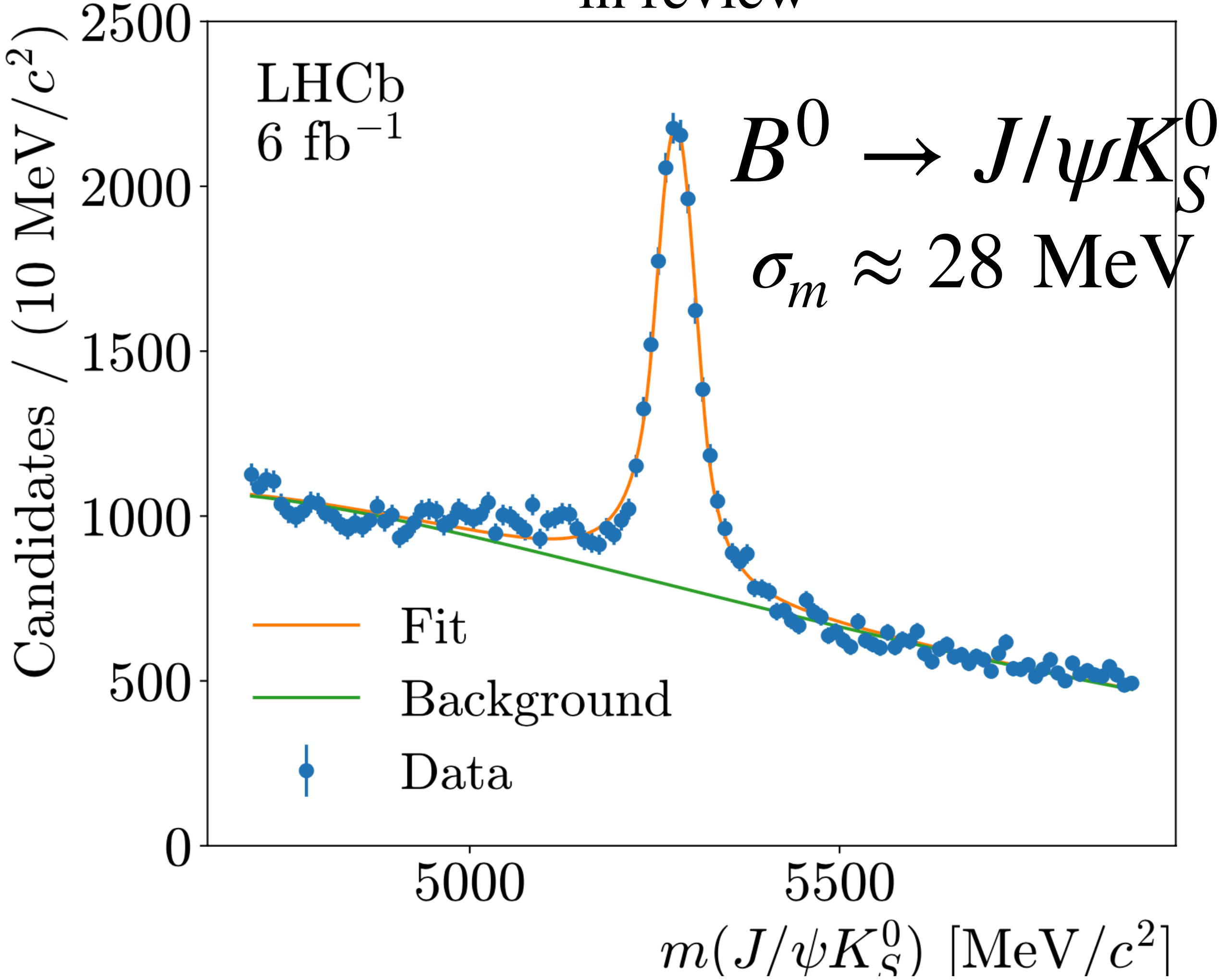


$B^0 \to J/\psi K_S^0$ reconstruction on Run 2 data

- Reconstruction of $B^0 \to J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$ with K_S^0 decay vertex z∈[6.0-7.6]m ✓
- Useful **control sample**

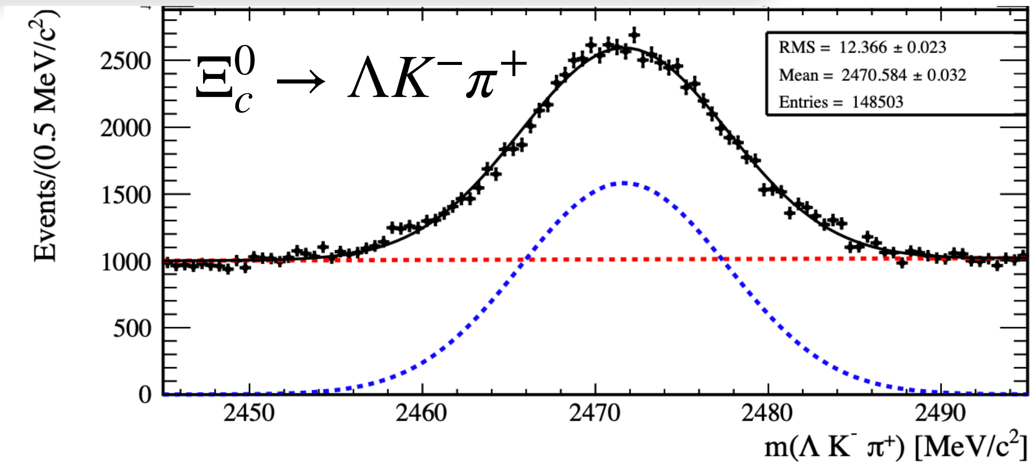
LHCb-DP-2022-001
in review

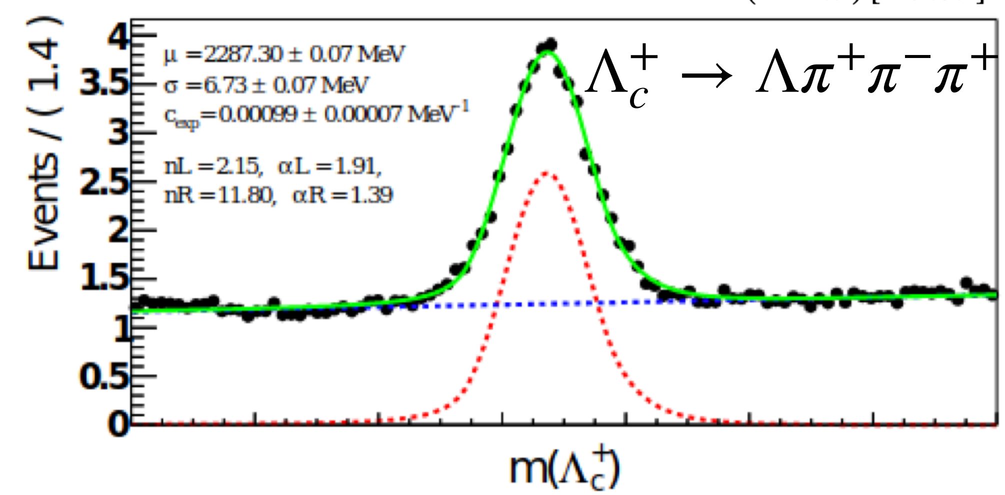


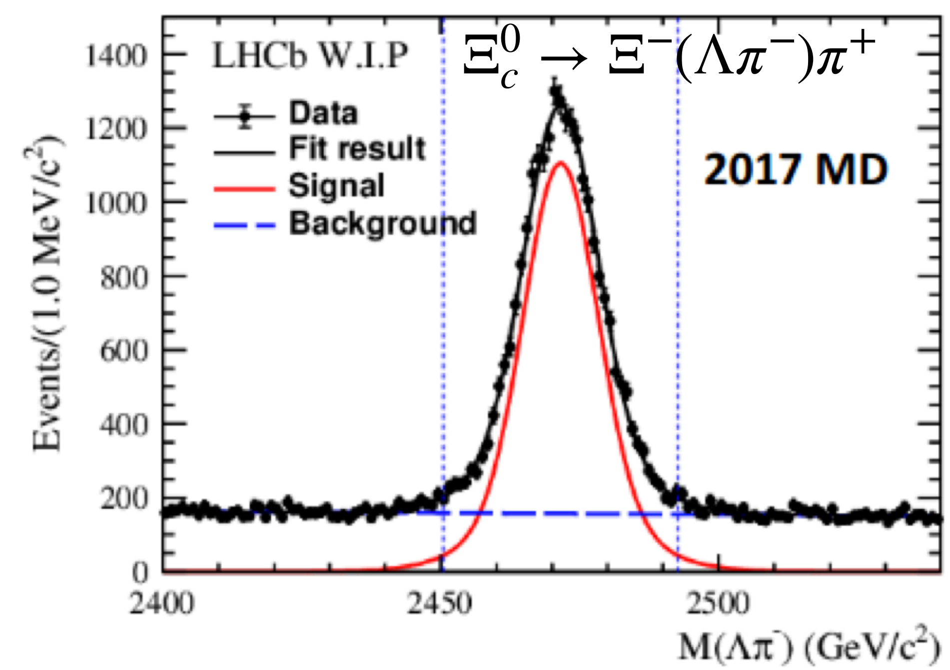


Λ baryon polarisation

- Λ polarisation close to **maximal** in $\Lambda_b^0 \to J/\psi\Lambda$ decays, JHEP 2020, 110 (2020)
- Measurements of Λ polarisation in progress for $\Xi_c^0 \to \Lambda K^-\pi^+$, $\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$, $\Xi_c^0 \to \Xi^-(\Lambda\pi^-)\pi^+$ decays using **Run2 data**
- Polarisation is significantly higher for Λ generated in 2-body **weak decays** wrt multi-body decays







Status and plans for Run3

- Reconstructed Λ and K_S^0 decays after the magnet using Run2 data. Also opportunity to extend BSM **LLP searches** in LHCb. LHCb-DP-2022-001

- Improve reconstruction based on T tracks
  - track fit, vertexing, use PID info
  - preparing trigger lines for Run3, exploit the new flexible software trigger, improved HybridSeeding

S. Aiola et al., Computer Physics Communications, 2020, 107713

- Unique opportunity at LHCb to perform Λ EDM/MDM **measurement** using Run1+Run2 (started) and Run3 data

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

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

Channeling in bent crystals

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

Spin precession in bent crystals

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

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

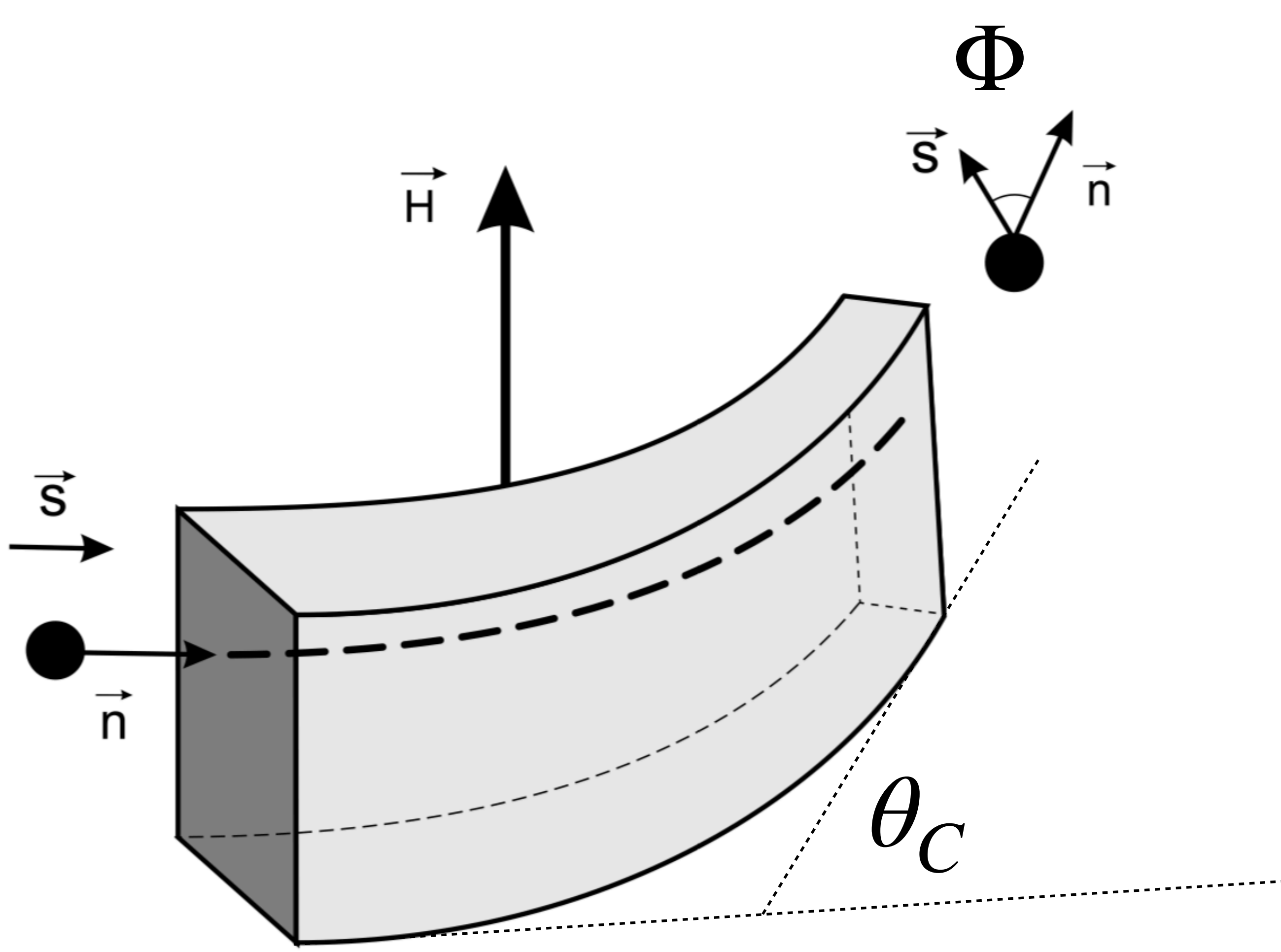


Fig. 1. Spin rotation in a bent crystal.

- 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

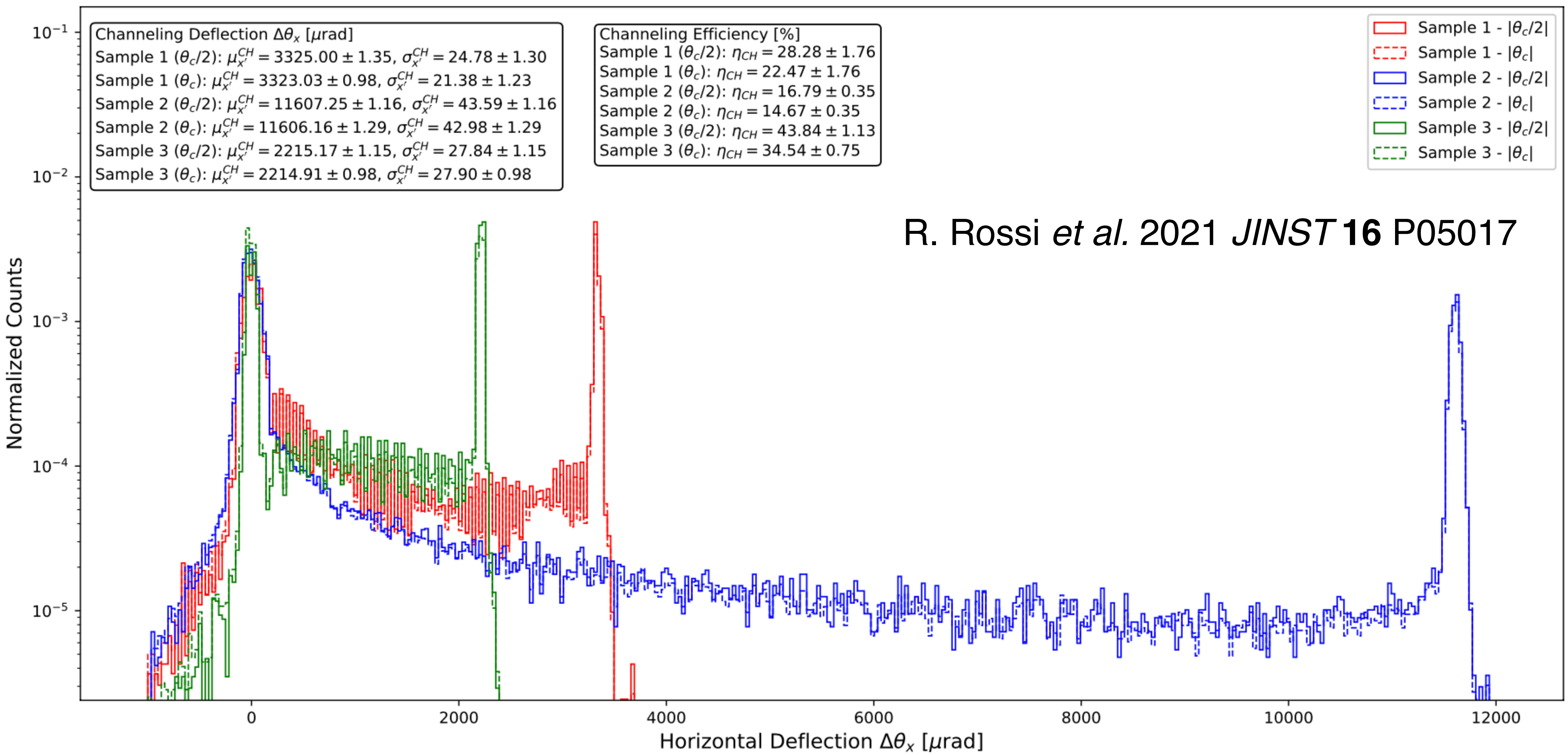
g = gyromagnetic factor

γ = Lorentz boost

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

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

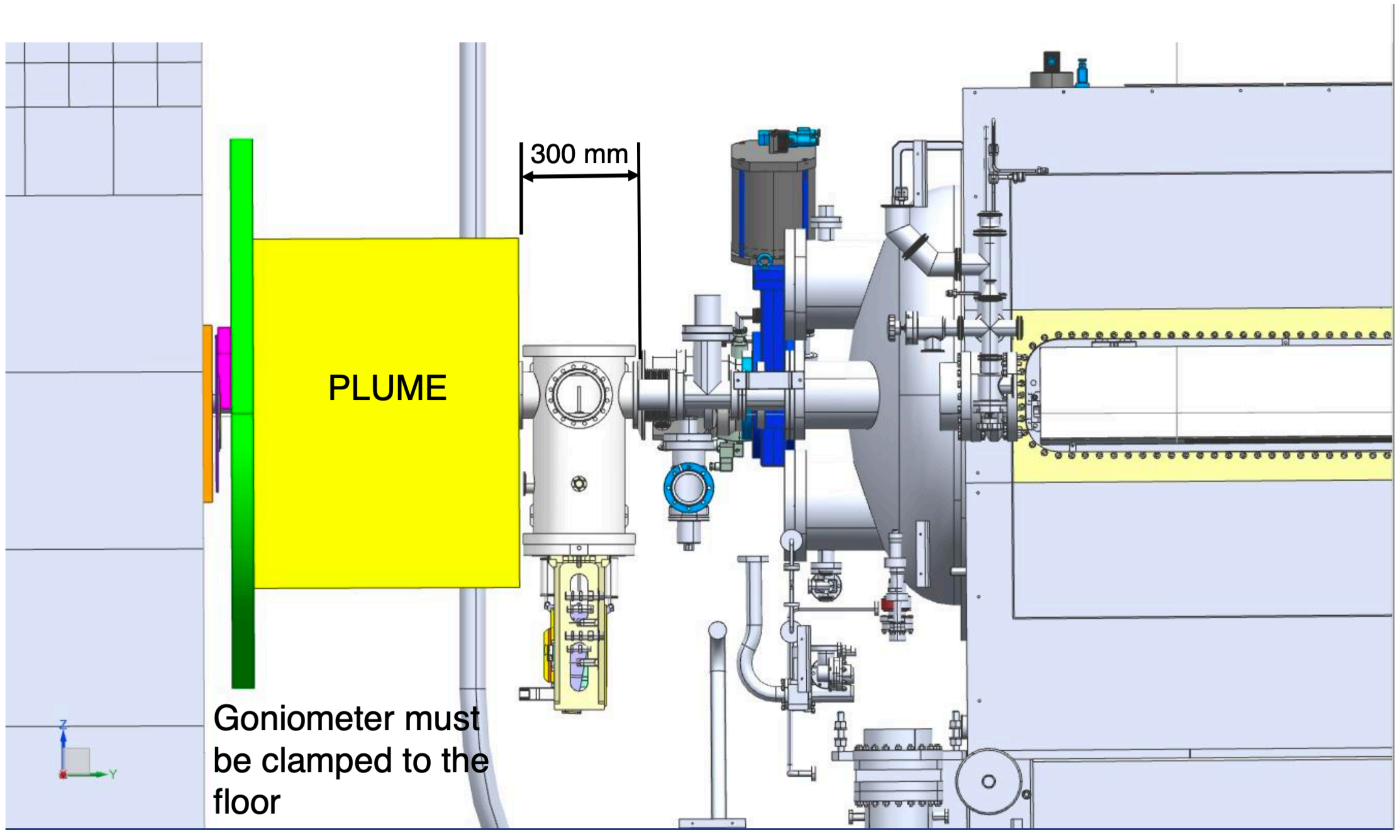
Long bent crystal prototypes



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

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

Fixed-target setup upstream of LHCb



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

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

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