Measurements of magnetic and electric dipole moments of hadrons

Nicola Neri
Università degli Studi di Milano & INFN
on behalf of the ALADDIN proto-collaboration

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Outline

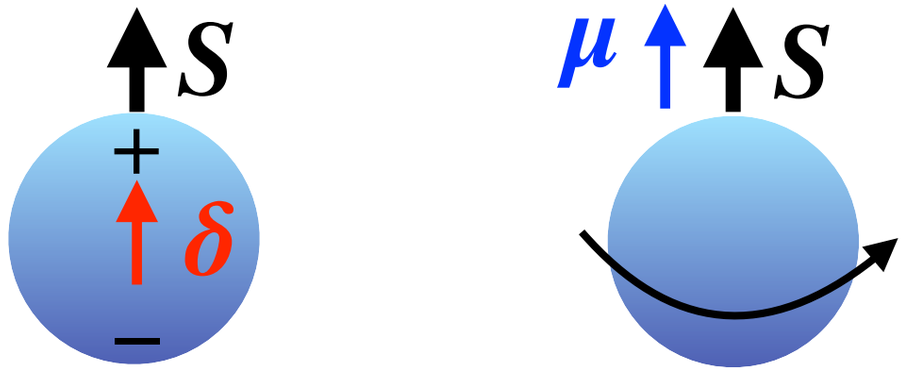
- Physics motivations
- Experimental technique for strange Λ baryons
  - feasibility studies and analysis in progress in LHCb
- Experimental technique for charm Λ_c^+, Ξ_c^+ baryons
  - TWOCRYST proof-of-principle
  - Proposed ALADDIN experiment
- Summary

τ lepton not discussed in this talk, see backup slides

Introduction

- Quantum systems

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



$\boldsymbol{\delta}$= electric dipole moment (EDM) d = gyroelectric factor

$\boldsymbol{\mu}$= magnetic dipole moment (MDM) g = gyromagnetic factor

MDM of spin-1/2 baryons $\mu_\Lambda = \frac{g_\Lambda}{2}\frac{e}{2m_\Lambda}$ and $\mu_{\Lambda_c^+} = \frac{g_{\Lambda_c^+}}{2}\frac{e}{2m_{\Lambda_c^+}}$

$g = 2$ for e, μ, τ (point-like), $g_p = 5.6$ for proton (substructure)

Discrete symmetries

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

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

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

	C	P	T
μ	−	+	−
δ	−	+	−
E	−	−	+
B	−	+	−
S	+	+	−

Hamiltonian

$$H = -\mu \cdot B - \delta \cdot E$$

Time reversal, Parity:

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

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

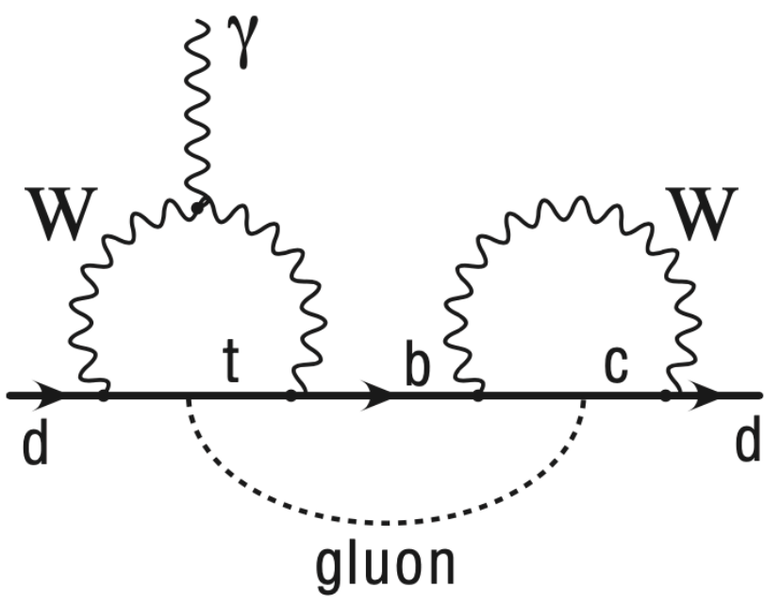
EDM: a probe for *CPV* beyond the SM

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

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

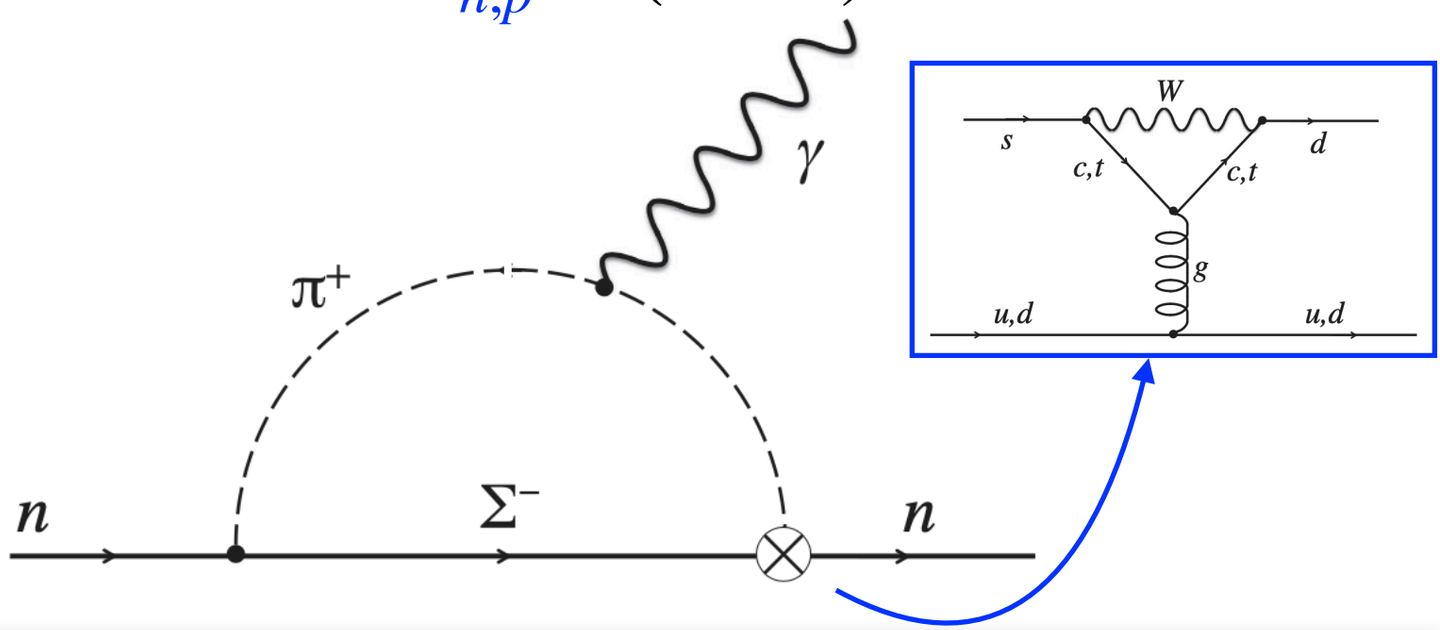
Example of SM CKM contributions

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



"Long distance" contribution

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



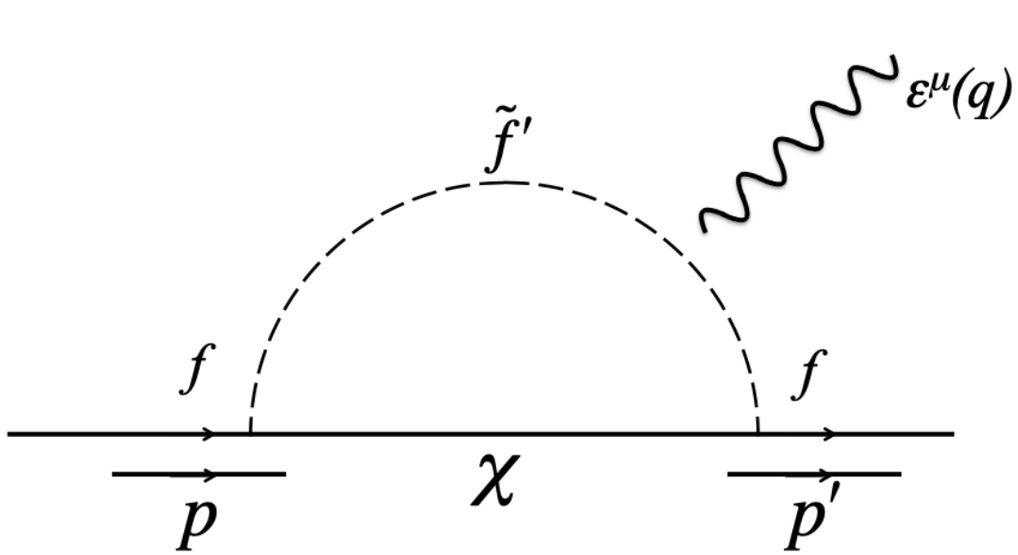
EDM: a probe for *CPV* beyond the SM

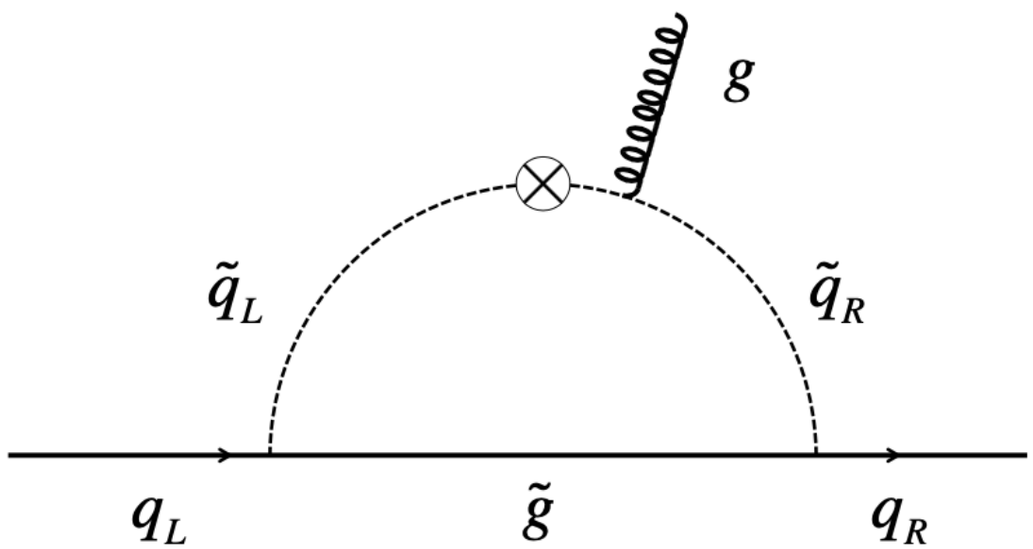
- $\mathscr{L}_{CPV} = \mathscr{L}_{CKM} + \mathscr{L}_{\bar{\theta}} + \mathscr{L}_{BSM}$
  - BSM: potential large contributions by new physics scale Λ_{NP} and CP-violating phase ϕ_{CPV}

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

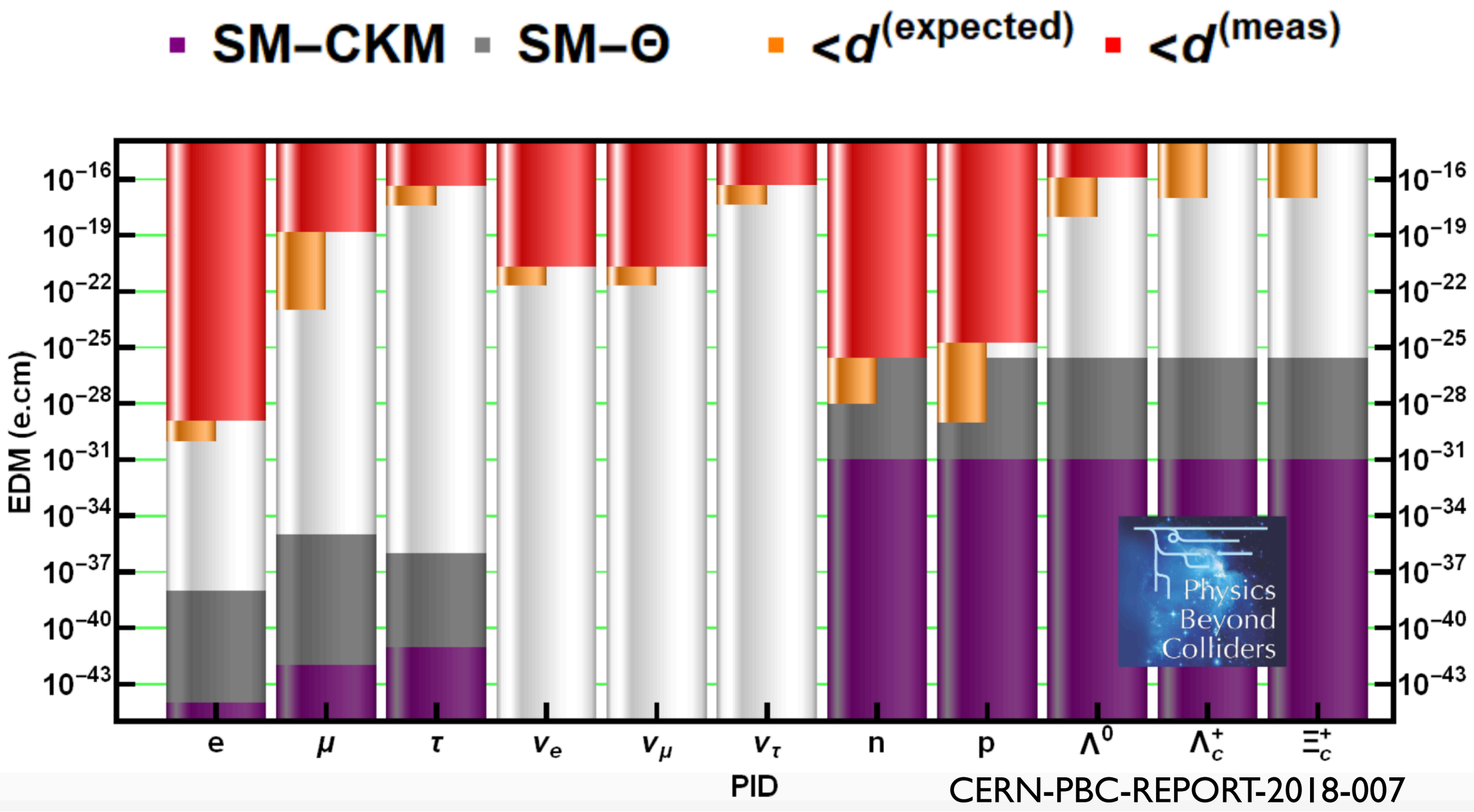
Examples of BSM contributions

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





Plans for EDM measurements



CERN-PBC-REPORT-2018-007

Baryon magnetic moments

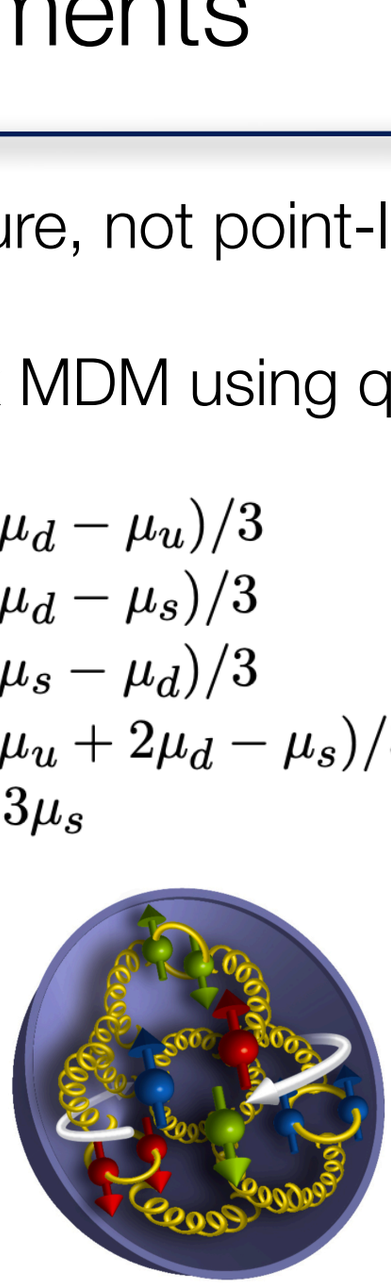
- $g \neq 2$ due to internal substructure, not point-like fermions
- From Λ baryon MDM to s quark MDM using quark model

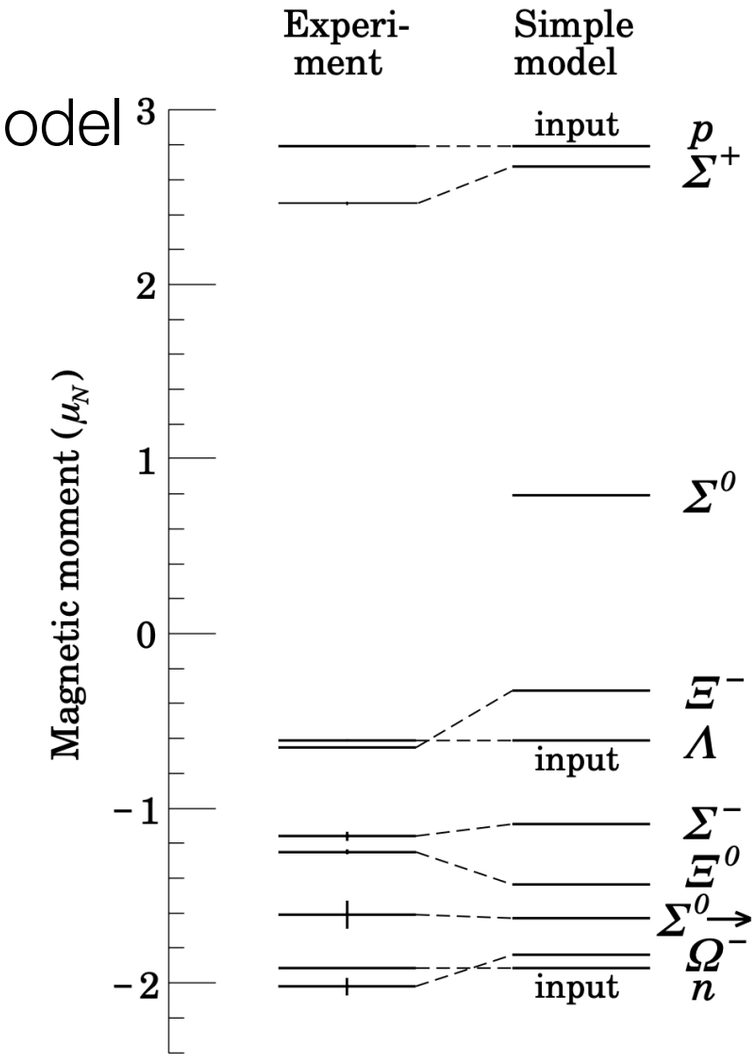
$$\mu_p = (4\mu_u - \mu_d)/3 \qquad \mu_n = (4\mu_d - \mu_u)/3$$
$$\mu_{\Sigma^+} = (4\mu_u - \mu_s)/3 \qquad \mu_{\Sigma^-} = (4\mu_d - \mu_s)/3$$
$$\mu_{\Xi^0} = (4\mu_s - \mu_u)/3 \qquad \mu_{\Xi^-} = (4\mu_s - \mu_d)/3$$
$$\mu_\Lambda = \mu_s \qquad \mu_{\Sigma^0} = (2\mu_u + 2\mu_d - \mu_s)/3$$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

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

From simple quark model

$$\mu_s = -0.613\mu_N$$
$$m_s = 510 \text{ MeV}$$





- Precise measurement of Λ MDM
- Test of *CPT* symmetry with $\overline{\Lambda}$ MDM

Corresponding proton measurements

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

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

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

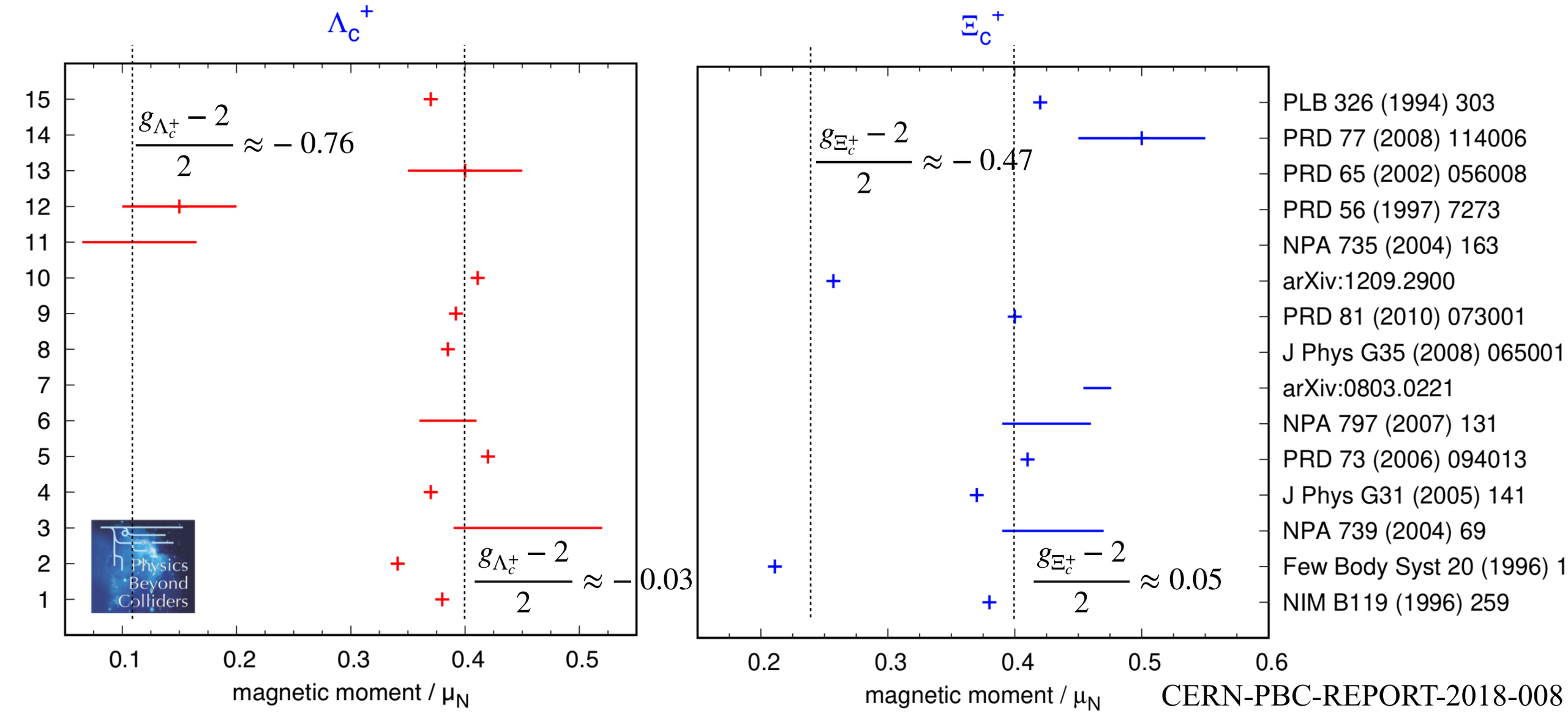
C. Smorra et al., *Nature* 550 (2017) 7676, 371-374

Charm baryon MDM: theory predictions

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

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

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

Status of art for Λ baryon EDM/MDM

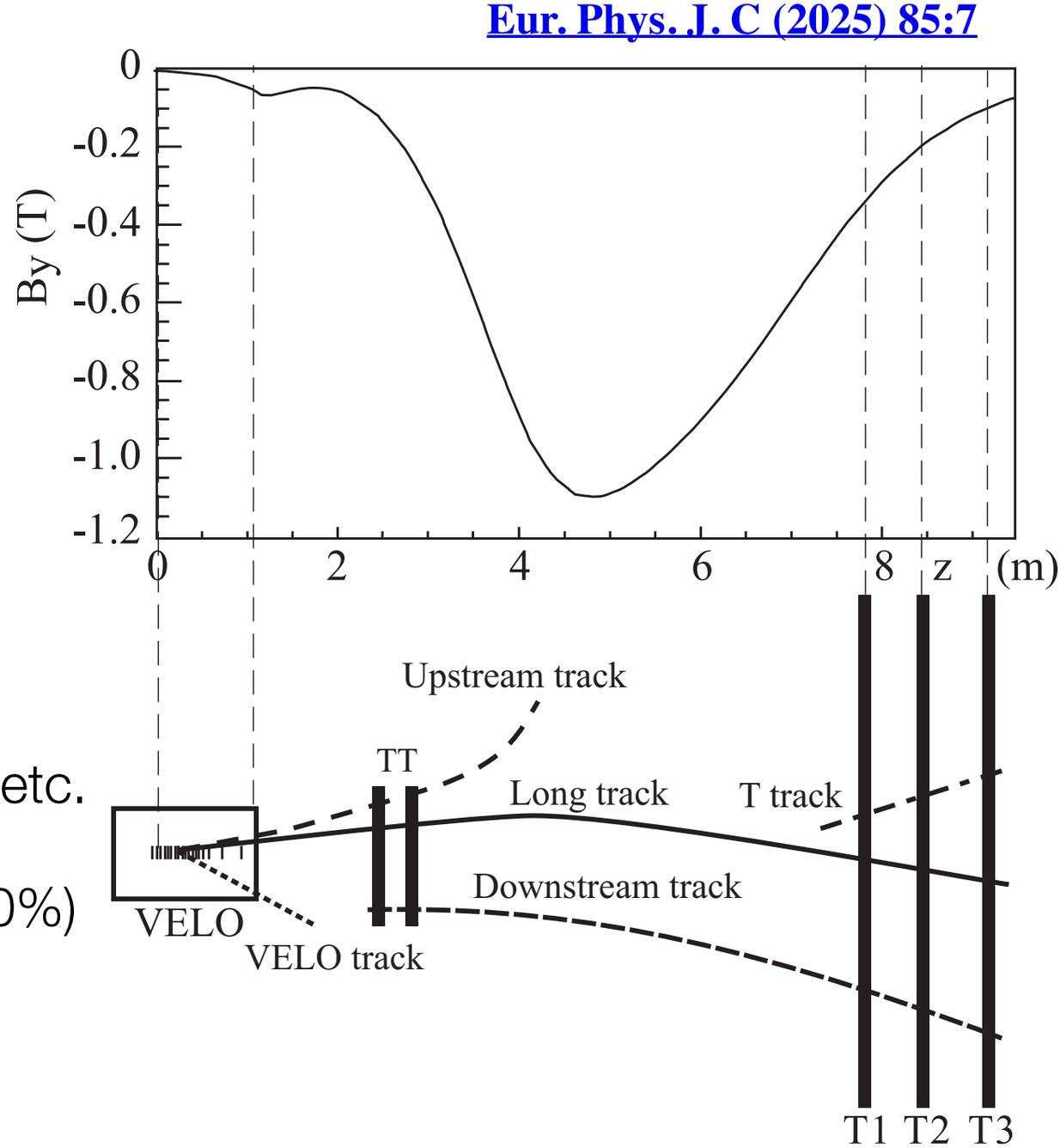
- Current direct limit on Λ baryon **EDM** $< 1.5 \times 10^{-16} e$ cm at 95% C.L. L. Pondrom et al., Phys. Rev. D **23**, 814 (**1981**)
- Measurement of **MDM** $\mu_\Lambda=(-0.6138\pm0.0047)\mu_N$ but no measurement for $\overline{\Lambda}$ exists. Phys.Rev.Lett. 41 (**1978**) 1348
- Measurement of MDM of $\overline{\Lambda}$ is needed for a **CPT** test
- 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 improve previous results, based on wrong α value
- BESIII recent result: indirect limit from $J/\psi \to \Lambda\overline{\Lambda}$ on $|\delta_\Lambda| < 6.5 \times 10^{-19} e$ cm at 95% C.L. arXiv:2506.19180

Λ baryon precession in the LHCb magnet

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

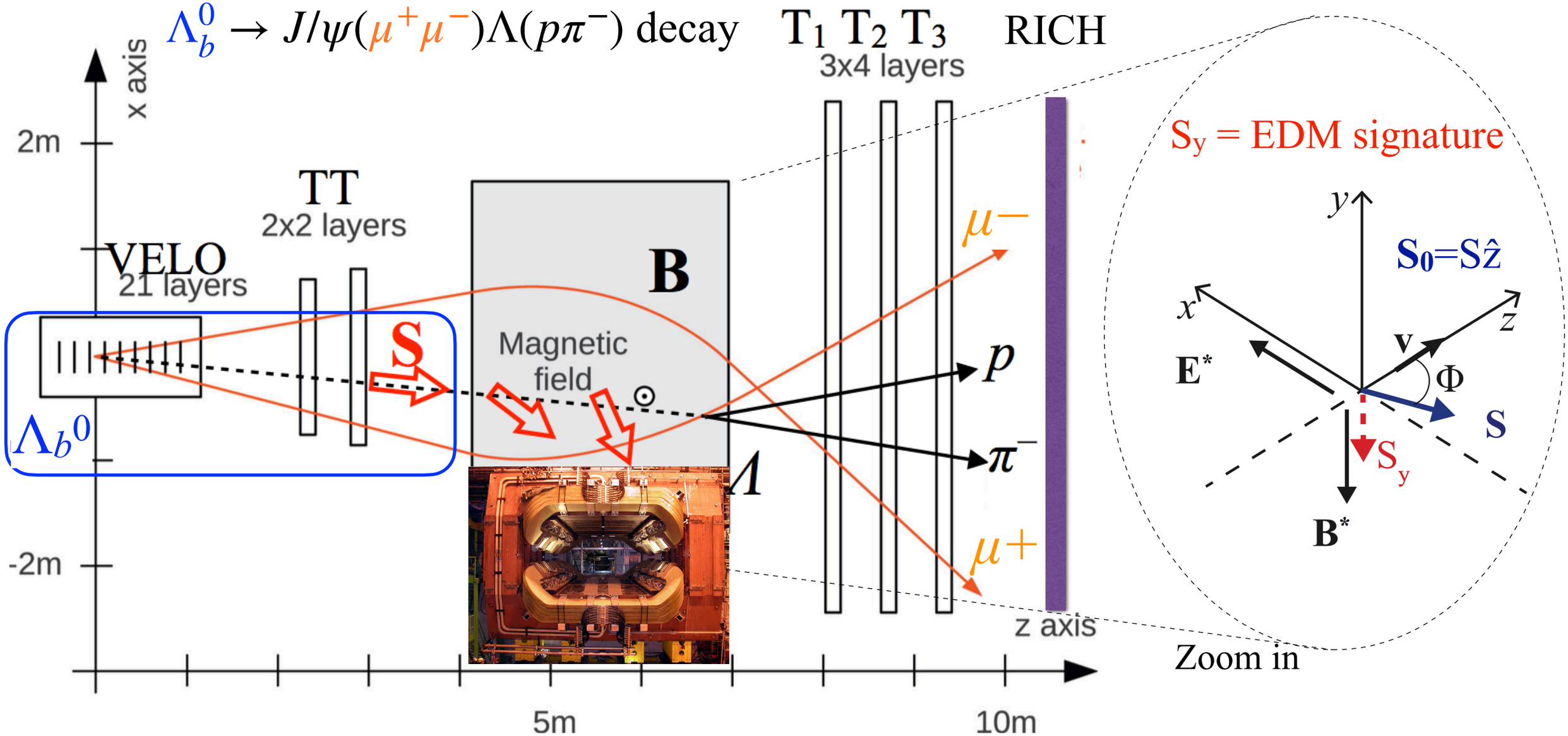
$$\frac{dS}{d\tau} = \boldsymbol{\mu} \times \boldsymbol{B^*} + \boldsymbol{\delta} \times \boldsymbol{E^*}$$

- 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**



Novel experimental technique for strange baryons

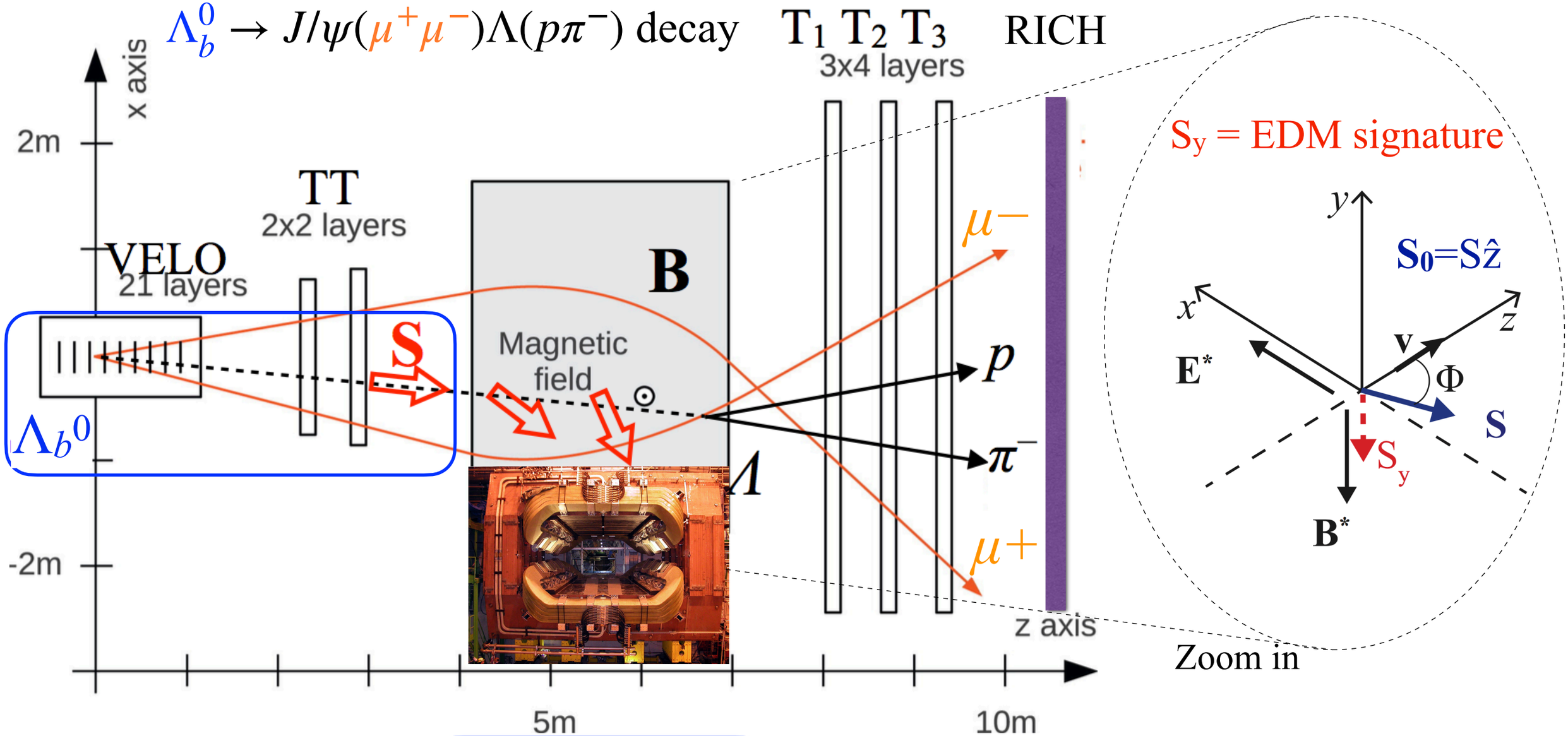
- EDM/MDM from spin precession of Λ baryon in LHCb **dipole magnet**



Λ polarised production

Novel experimental technique for strange baryons

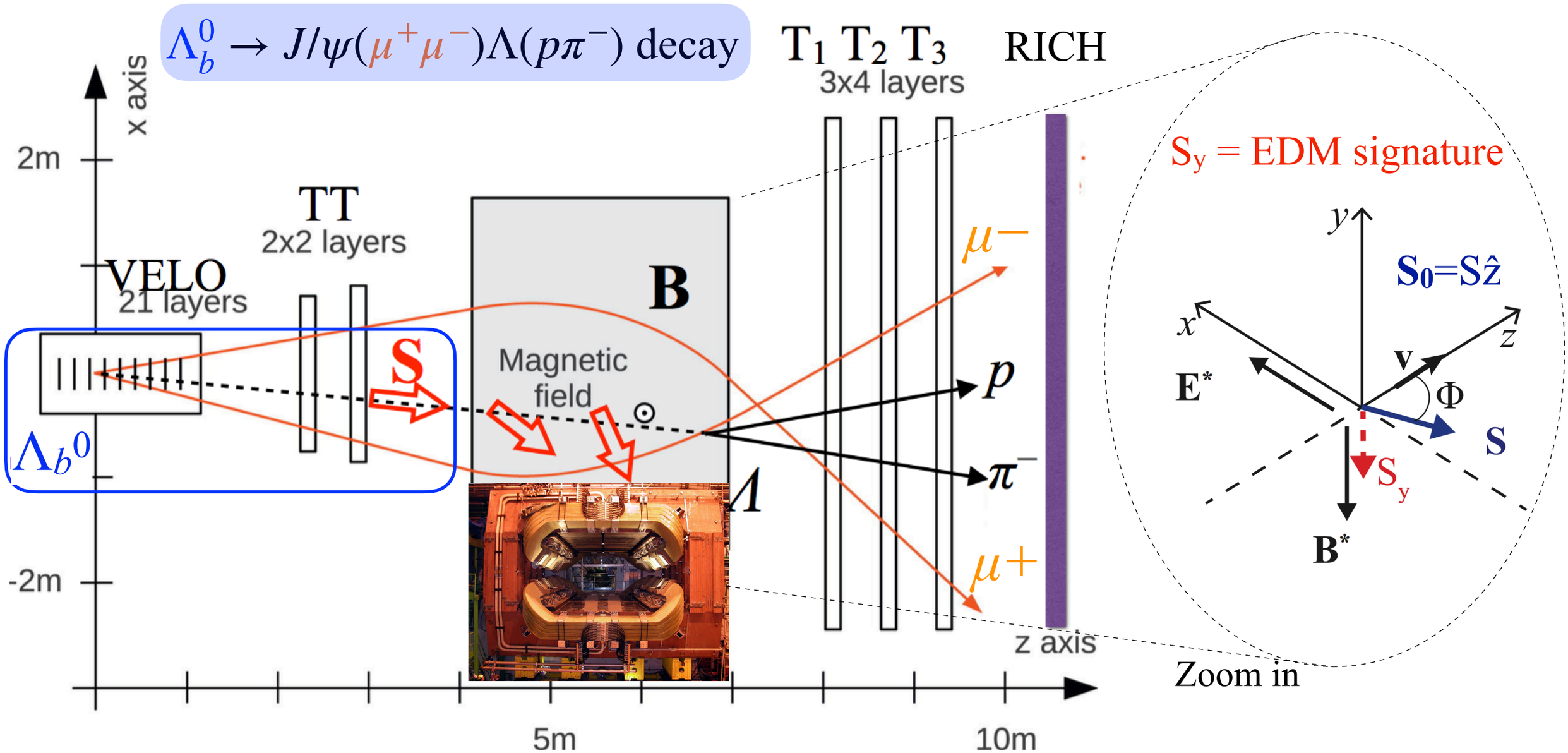
- EDM/MDM from spin precession of Λ baryon in LHCb **dipole magnet**



Λ polarised production spin precession

Novel experimental technique for strange baryons

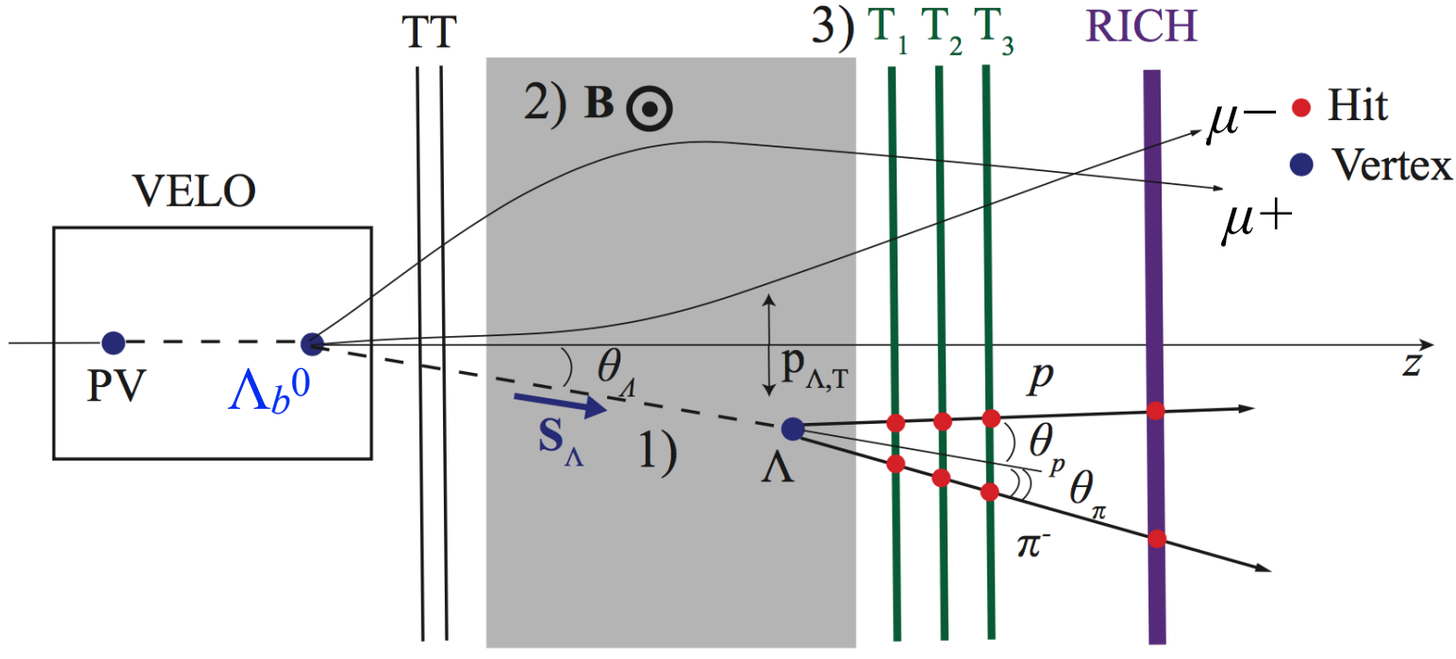
- EDM/MDM from spin precession of Λ baryon in LHCb **dipole magnet**



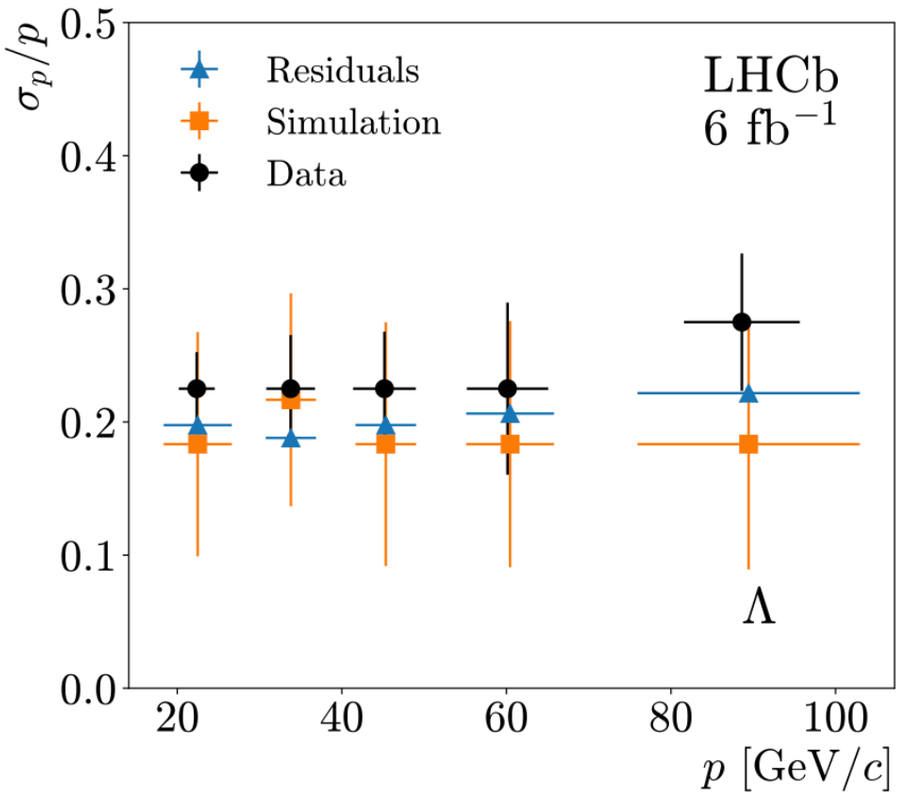
Λ polarised production spin precession event reconstruction

Λ baryon reconstruction downstream of the magnet

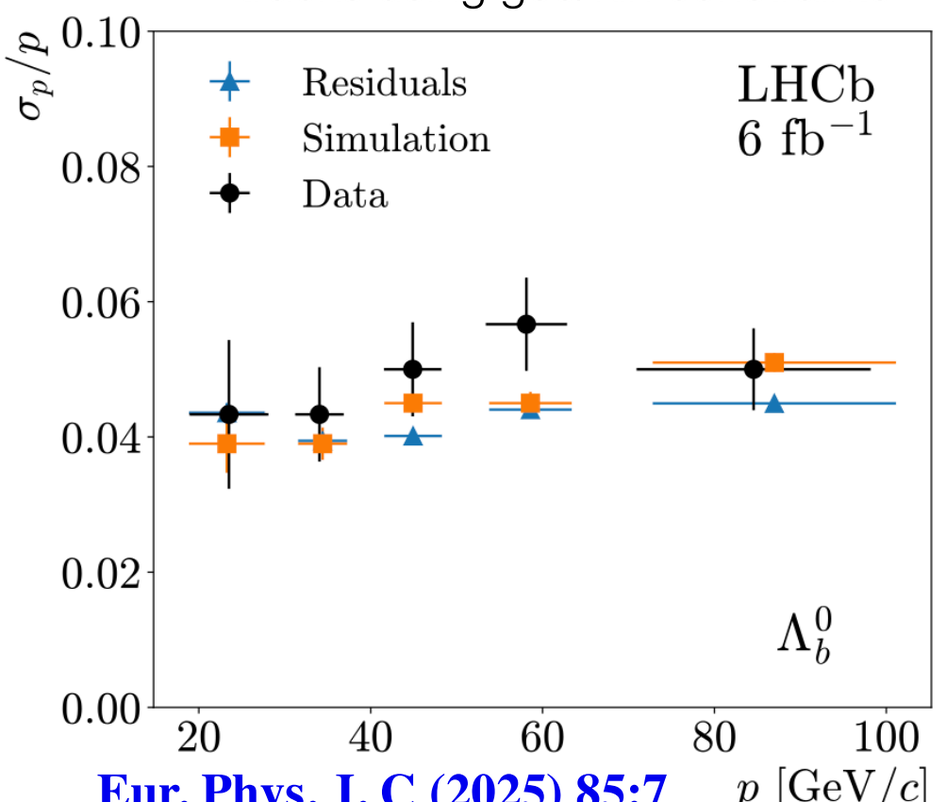
- Fit the entire decay chain $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$ imposing geometric and kinematic constraints



Momentum resolution on T tracks



Improved momentum resolution on T tracks using geo/kin constraints

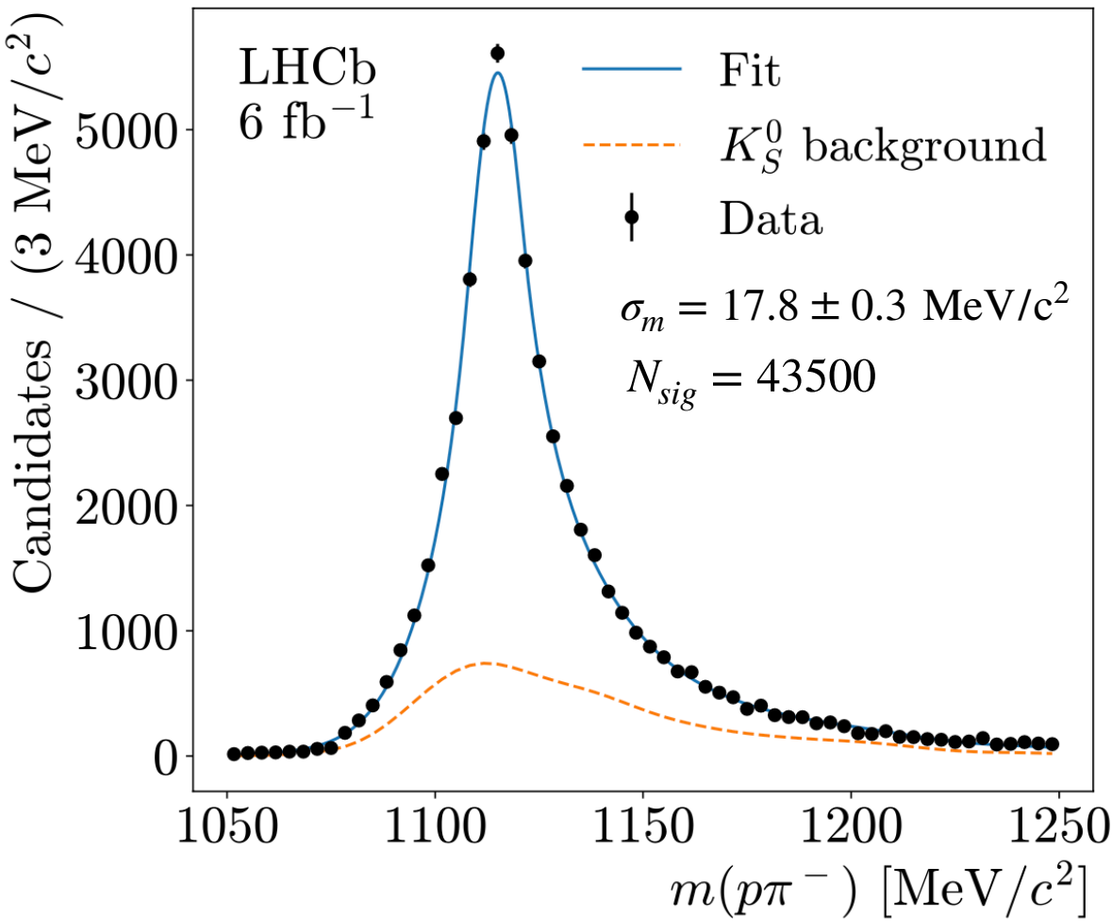


Eur. Phys. J. C (2025) 85:7

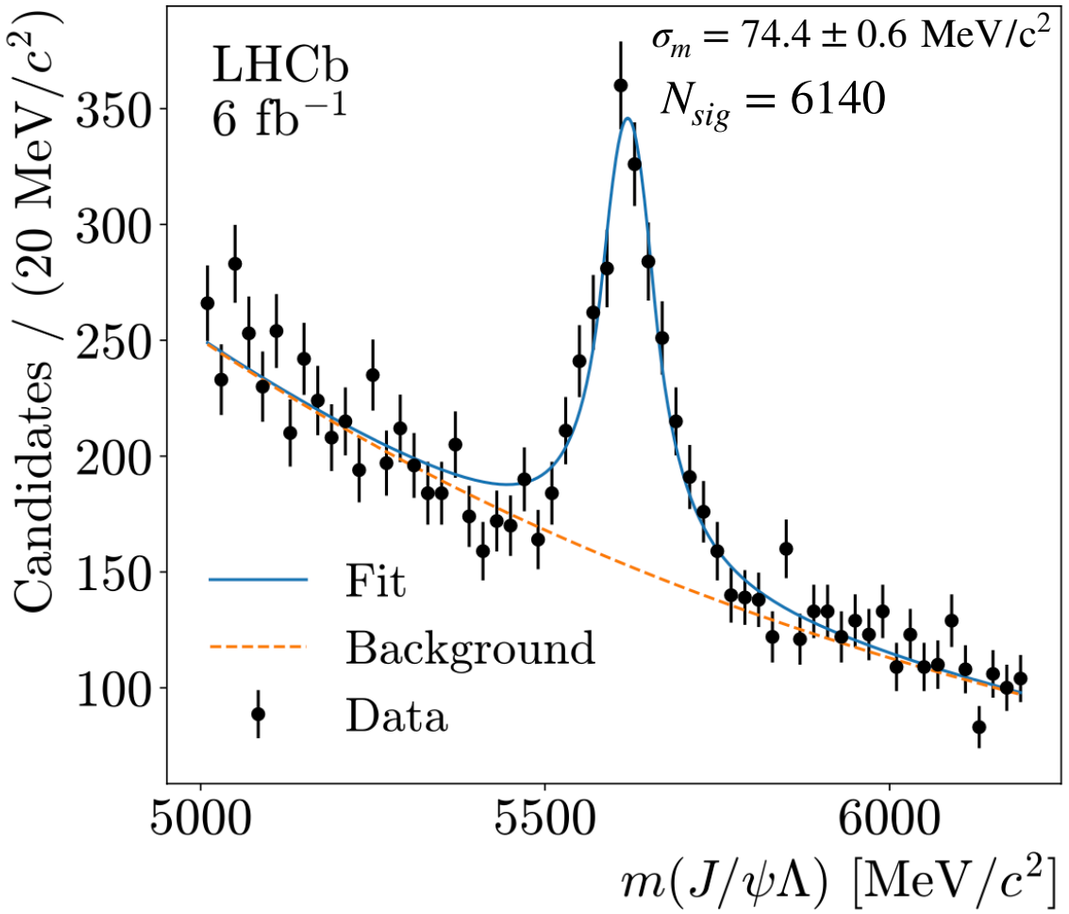
$\Lambda_b^0 \to J/\psi\Lambda$ reconstruction on data

- Reconstructed Λ decays between 6.0 - 7.6 m from the IP. Exploiting existing dimuon trigger on Run 1-2 data
- Λ baryon dipole moment measurement is in progress. G. Tonani PhD thesis

$\Lambda \to p\pi^-$



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



Eur. Phys. J. C (2025) 85:7

Plans for Run 3 (2022-2025, 50 fb^{-1})

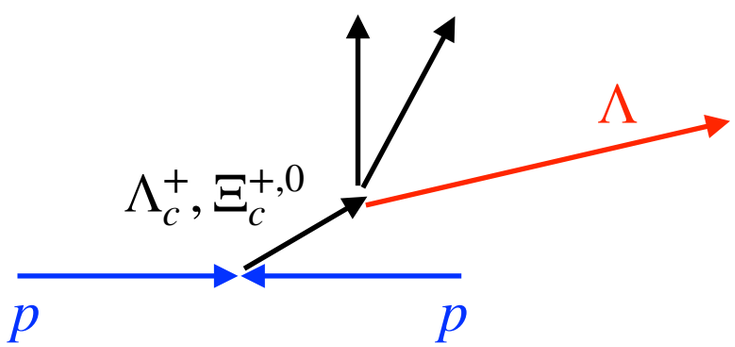
- New software trigger of Upgrade I detector allows to reconstruct Λ from charm decays. Expected several orders of magnitude increase in yield with respect to $\Lambda_b^0 \to J/\psi\Lambda$

- New charm (and beauty) hadron trigger lines for Λ decays in place

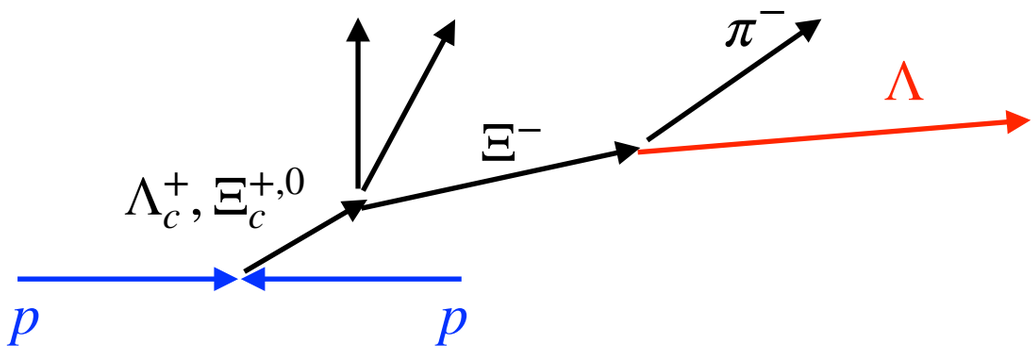
Eur. Phys. J. C **77** (2017) 181

SL events	N_Λ/fb^{-1} ($\times 10^{10}$)	LL events, $\Xi^- \to \Lambda\pi^-$	N_Λ/fb^{-1} ($\times 10^{10}$)
$\Xi_c^0 \to \Lambda K^-\pi^+$	7.7	$\Xi_c^0 \to \Xi^-\pi^+\pi^+\pi^-$	23.6
$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	3.3	$\Xi_c^0 \to \Xi^-\pi^+$	7.1
$\Xi_c^+ \to \Lambda K^-\pi^+\pi^+$	2.0	$\Xi_c^+ \to \Xi^-\pi^+\pi^+$	6.1
$\Lambda_c^+ \to \Lambda\pi^+$	1.3	$\Lambda_c^+ \to \Xi^- K^+\pi^+$	0.6
$\Xi_c^0 \to \Lambda K^+K^-$ (no ϕ)	0.2	$\Xi_c^0 \to \Xi^- K^+$	0.2
$\Xi_c^0 \to \Lambda\phi(K^+K^-)$	0.1	Prompt Ξ^-	$0.13 \times \sigma_{pp\to\Xi^-}$ [μb]

"Short-lived" category



"Long-lived" category



Sensitivity on MDM/EDM

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

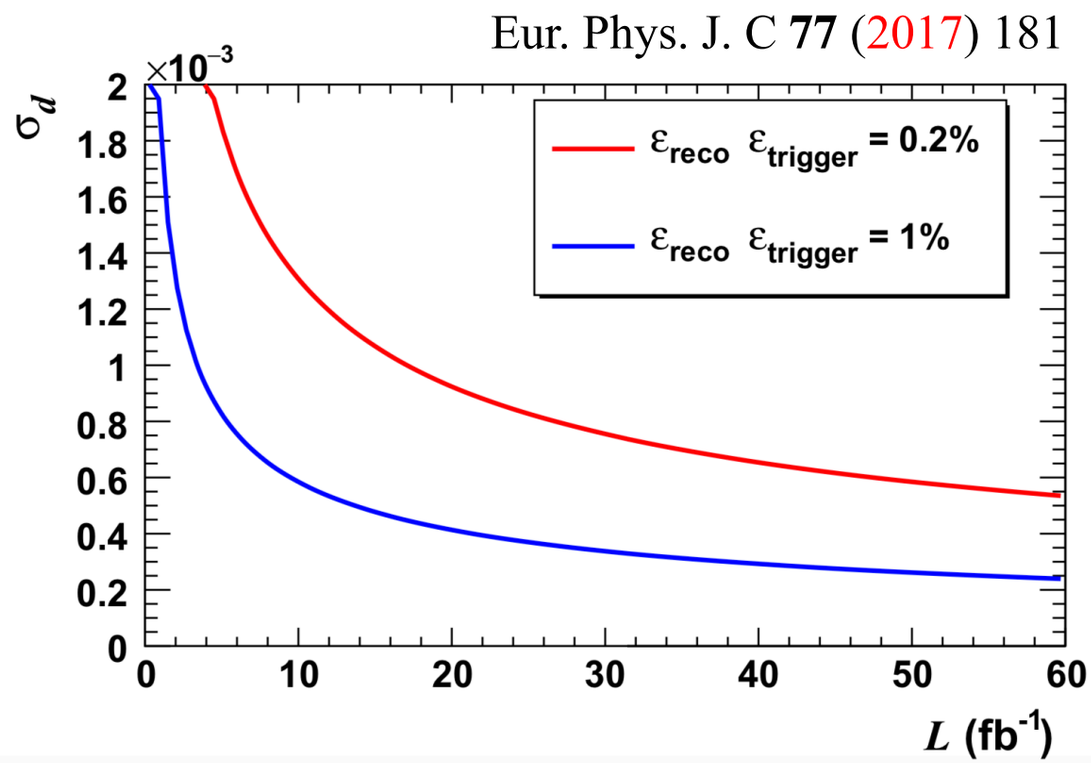
$$\mathbf{s} = \begin{cases} s_x = -s_0 \sin\Phi \\ s_y = -s_0 \dfrac{d\beta}{g} \sin\Phi \\ s_z = s_0 \cos\Phi \end{cases} \qquad \Phi \approx \frac{g\mu_B BL}{\beta\hbar c} \approx \frac{\pi}{4} \qquad BL \approx 4 \text{ T m}$$

Spin analyser in Λ helicity frame

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

CPT test at 10^{-4} via $\Lambda/\bar{\Lambda}$ MDM

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



Experimental method for charm baryons: Λ_c^+, Ξ_c^+

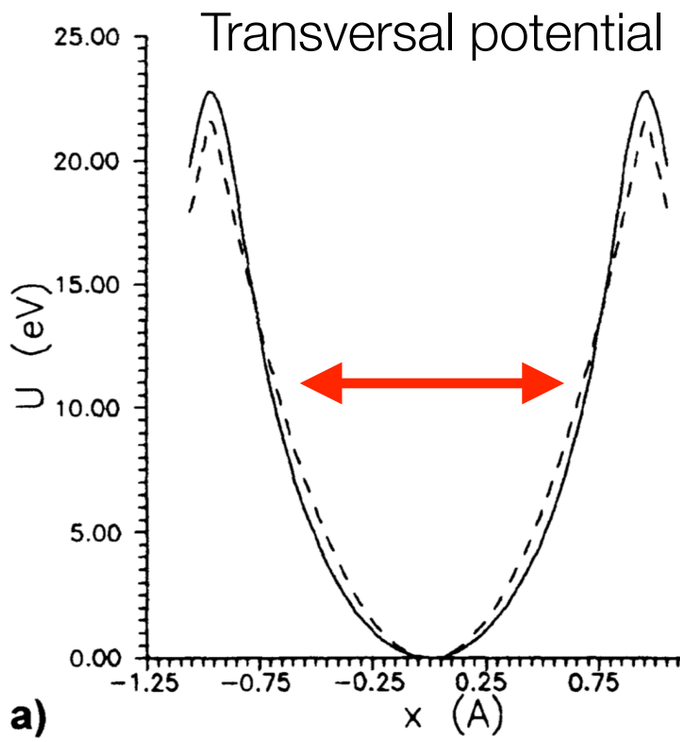
$\tau \approx 10^{-13}$ s

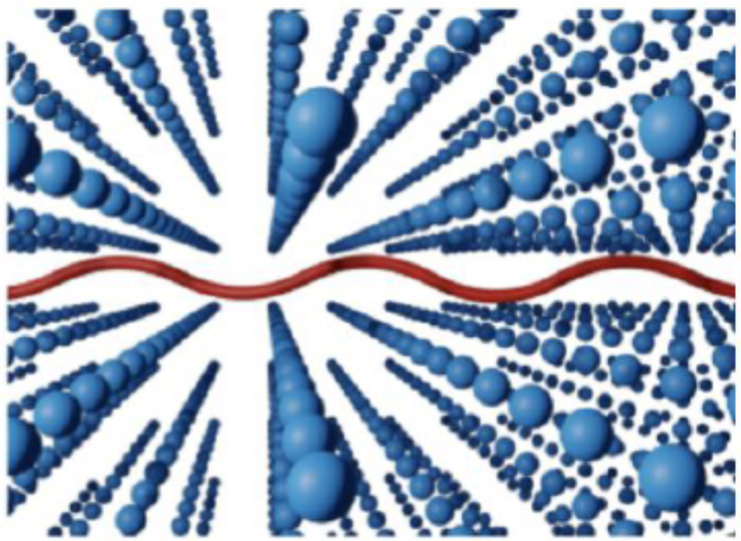
Channeling in bent crystals

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

- Predicted by **Baryshevsky** and **Pondrom**

V.G. Baryshevsky, Pis'ma Zh. Tekh. Fiz. 5 (1979) 182.
L. Pondrom, Proc. DPF Summer School on Elementary Particle Physics and Future Facilities, Snowmass, CO (1982).

- Determine particle gyromagnetic factor from BMT equation

V.L. Lyuboshits, Sov. J. Nucl. Phys. 31 (1980) 509.
I. J. Kim, Nucl. Phys. 8229. 251 (1983).

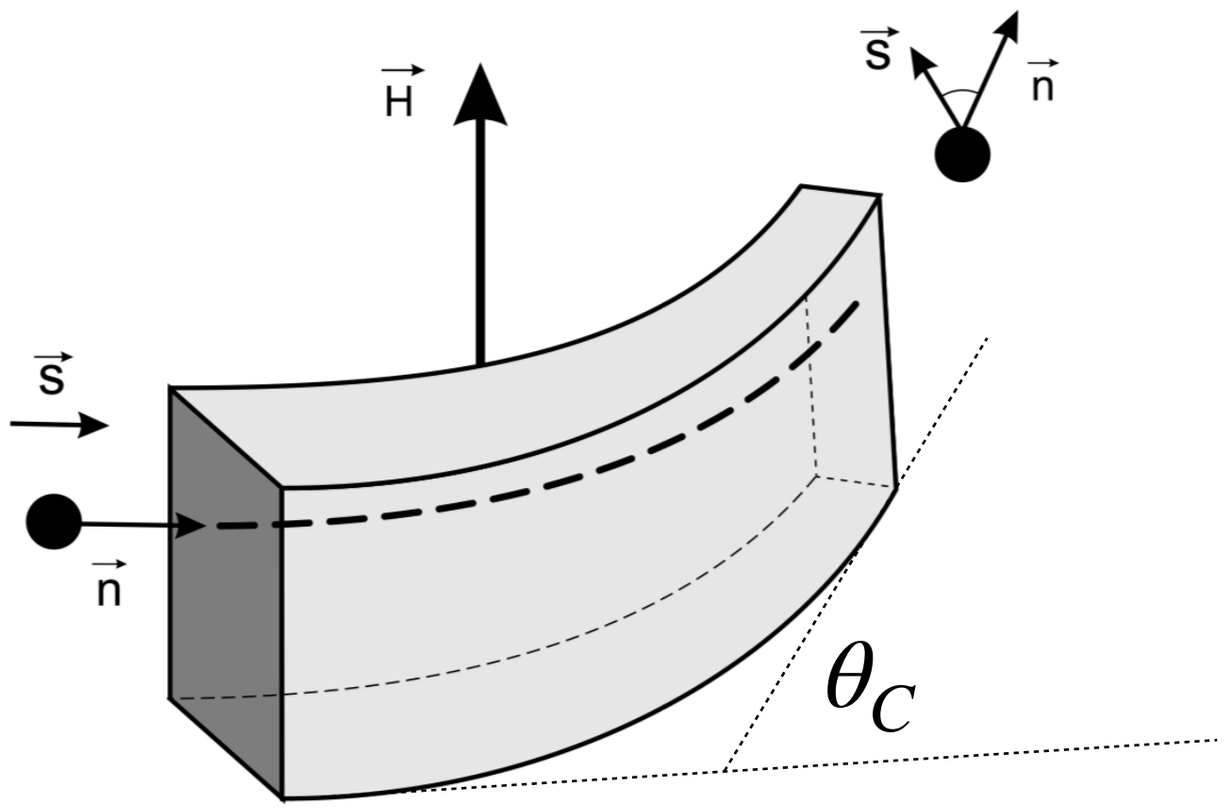


Fig. 1. Spin rotation in a bent crystal.

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

Φ = spin rotation angle

θ_C = crystal bending angle

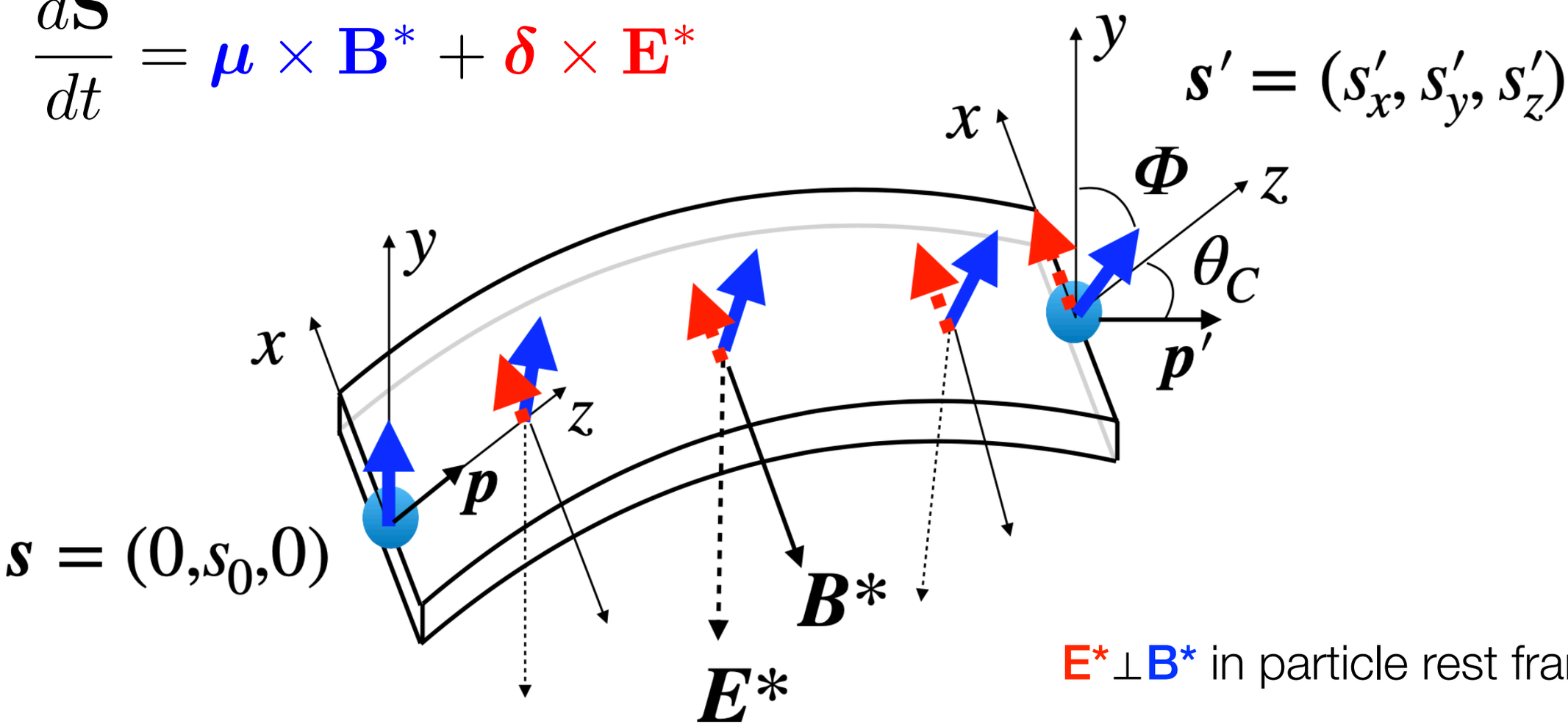
g = gyromagnetic factor

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

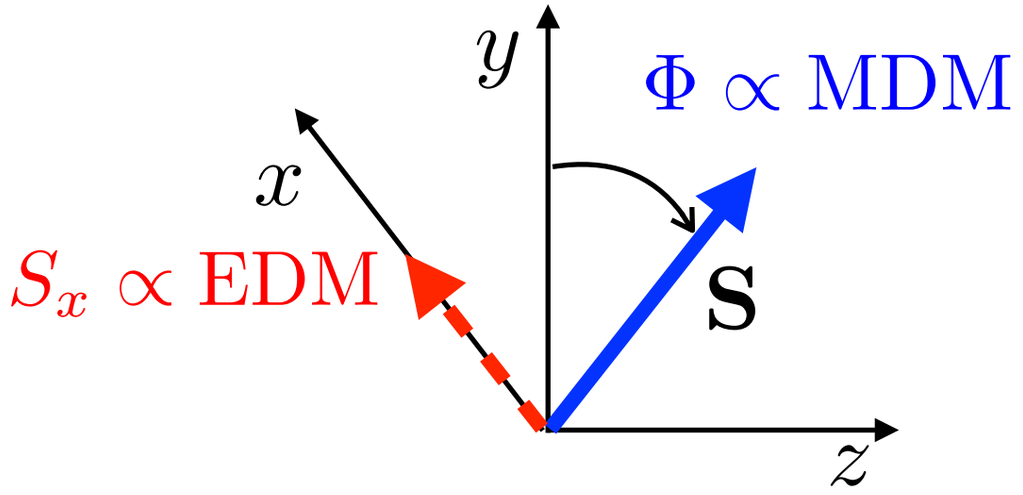
MDM/EDM with bent crystals

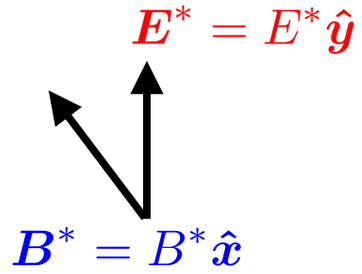
Fill the experimental gap in **heavy baryon electric dipole moment** searches. Method proposed in F. J. Botella et. al. EPJC (2017) 77:181

Spin-polarisation analyser: angular distribution of baryon decay products

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

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



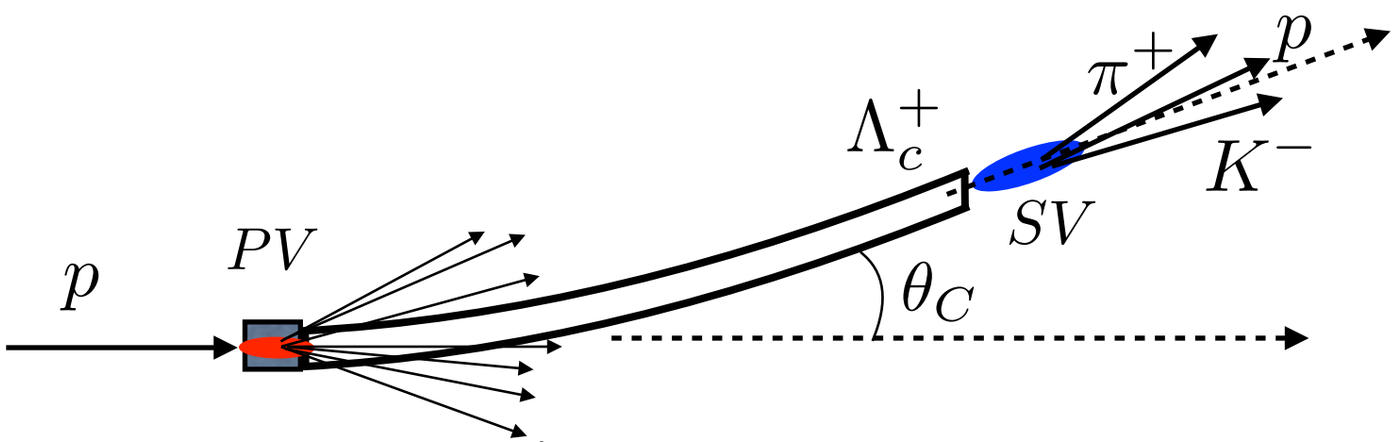


- MDM and EDM precession in the limit $\gamma \gg 1$, $d \ll g - 2$

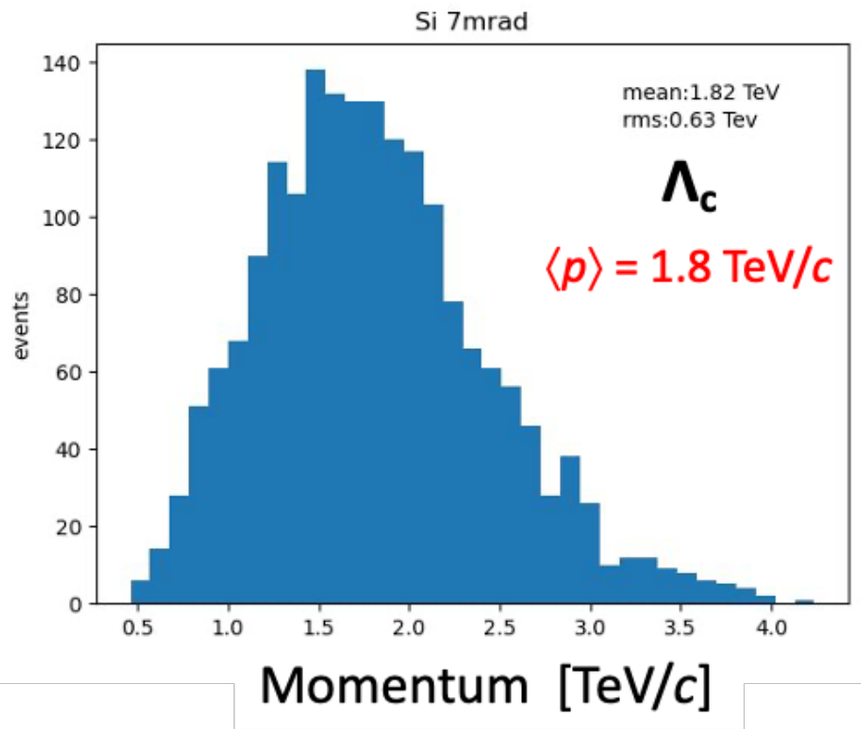
$$\Phi \approx \frac{g-2}{2}\gamma\theta_C \qquad S_x \approx S_0 \frac{d}{g-2}[\cos(\Phi) - 1]$$

Experimental technique at LHC

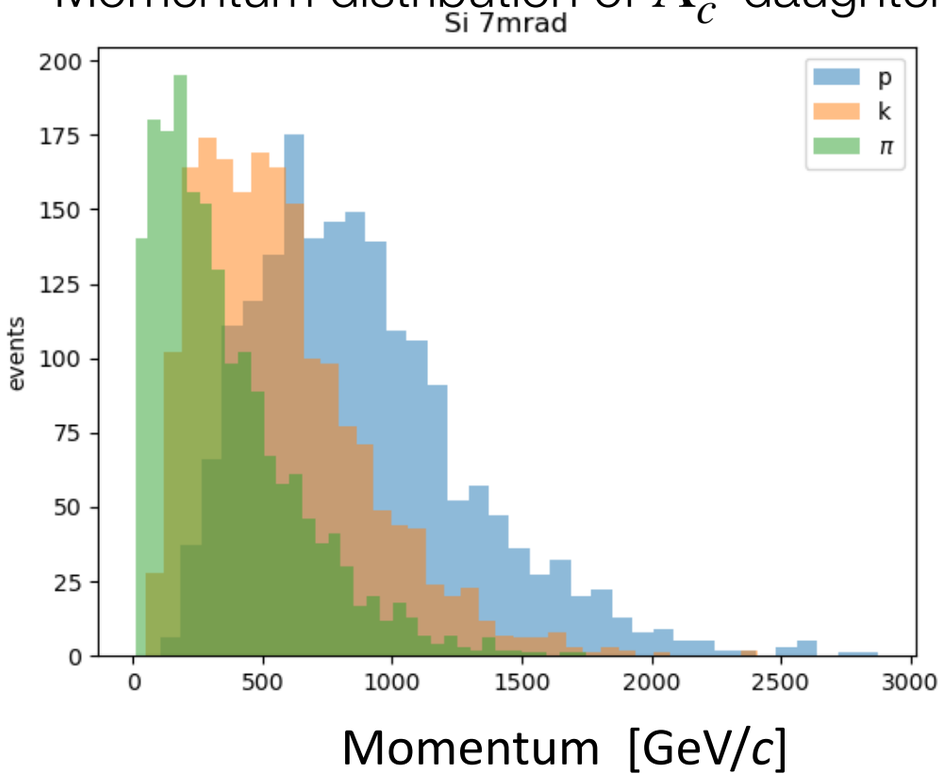
- Charm baryons from fixed-target *p*W collisions at LHC, $\sqrt{s} \approx 110$ GeV
- Average p=1.8 TeV/*c* for channeled Λ_c^+ with bending angle $\theta_C = 7$ mrad



Momentum distribution of channelled Λ_c^+



Momentum distribution of Λ_c^+ daughters



Sensitivities for charm MDM/EDM

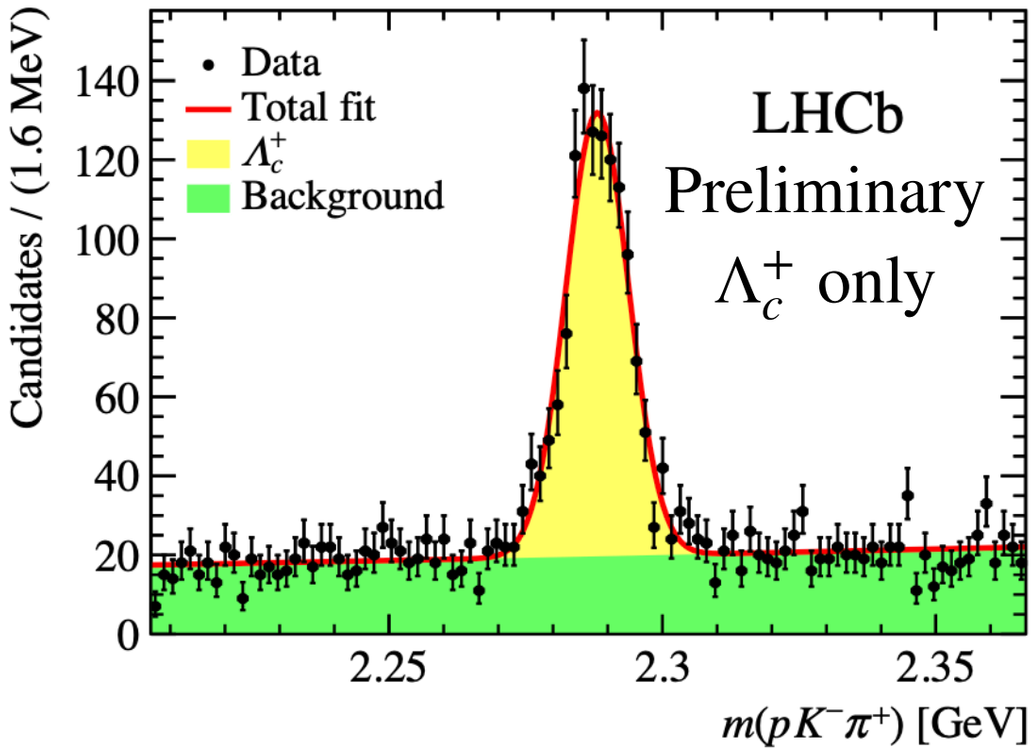
- Expected sensitivities in 2 years of data taking (1.37 · 10[13] PoT) and 2 cm W target
- Assumptions on initial polarisation $s_0 = 0.2 - 0.3$ and detector efficiency 20%

	IP8	IR3 Si		IP8	IR3 Ge
Deflection angle [mrad]	16	7	5	16	7
Length [cm]	10	7	7	10	7
	Λ_c^+ baryon				
a		$\approx -0.03[-0.76]$			
N_{tot} deflected per 10^{10} PoT	3.6	86	162	12	120
$\langle\gamma\rangle$	576	945	1036	717	886
$\langle p_T\rangle$ (GeV/c)	0.67	0.84	0.88	0.73	0.81
$\langle s_x\rangle$	0.09	0.20	0.23	0.13	0.20
$\langle s_y\rangle$	0.22	0.24	0.24	0.23	0.24
N_{rec} $pK^-\pi^+$ only	62	1474	2773	201	2066
N_{rec} all charged	109	2836	5409	367	3940
$\sigma_{\boldsymbol{\mu}}$ ($\times 10^{-2}$ μ_N) all charged	4.1	1.2	1.1	2.0	1.1
$\sigma_{\boldsymbol{\delta}}$ ($\times 10^{-16} e$ cm) all charged	6.9 [19]	1.5 [4.6]	1.2 [3.1]	3.1 [11]	1.4 [3.8]
	Ξ_c^+ baryon				
a		$\approx 0.05[-0.47]$			
N_{tot} deflected per 10^{10} PoT	19	135	215	40	98
$\langle\gamma\rangle$	437	596	641	520	602
$\langle p_T\rangle$ (GeV/c)	0.65	0.74	0.77	0.69	0.74
$\langle s_x\rangle$	0.08	0.16	0.17	0.10	0.14
$\langle s_y\rangle$	0.23	0.27	0.28	0.25	0.26
N_{rec} $\Xi^-\pi^+\pi^+$ only	89	735	1202	205	1096
N_{rec} all charged	227	1939	3198	531	2898
$\sigma_{\boldsymbol{\mu}}$ ($\times 10^{-2}$ μ_N) all charged	3.5	1.8	1.8	2.0	1.5
$\sigma_{\boldsymbol{\delta}}$ ($\times 10^{-16}$ e cm) all charged	7.2 [7.7]	3.1 [3.0]	3.0 [2.5]	3.6 [5.5]	2.9 [2.3]

Si = silicon
Ge = germanium

Polarisation in *p*-Ne collisions with LHCb SMOG

- Λ_c^+ polarisation in *p*W at $\sqrt{s} \approx 110\ \mathrm{GeV}$ is unknown. Measure Λ_c^+ polarisation in LHCb SMOG *p*-Ne collisions at $\sqrt{s} = 68.6\ \mathrm{GeV}$ (different kinematic region from ALADDIN)
- About 2k $\Lambda_c^+ + \overline{\Lambda}_c^-$signal yield with $\Lambda_c^+ \to pK^-\pi^+$. Analysis completed and in internal review. About 10% uncertainty on polarisation
- Large improvements expected with SMOG2 in Run3: x1000 increase in signal yield, separate interaction points *p*Gas from *pp* collisions LHCb-PUB-2018-015



Use decay amplitude model from PRD 108, 012023 (2023)

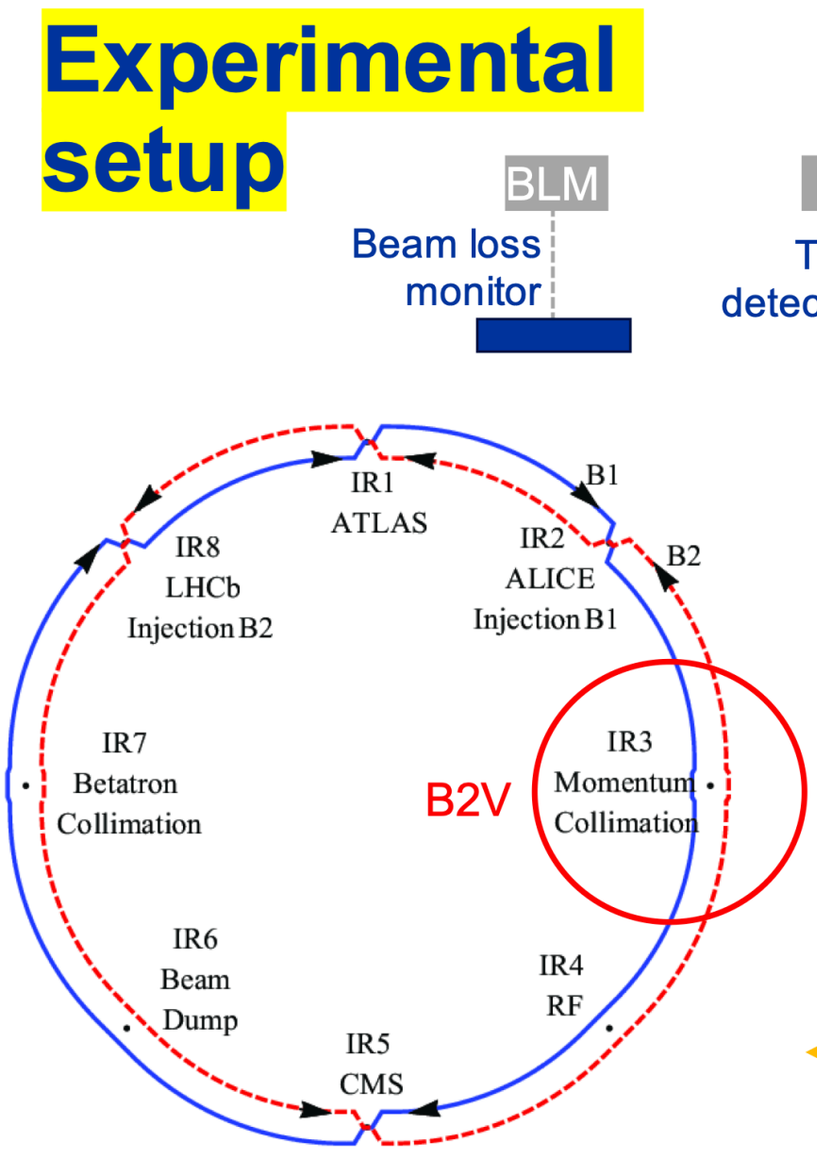
Fix decay model parameters from high statistics Λ_c^+sample and fit directly for polarisation

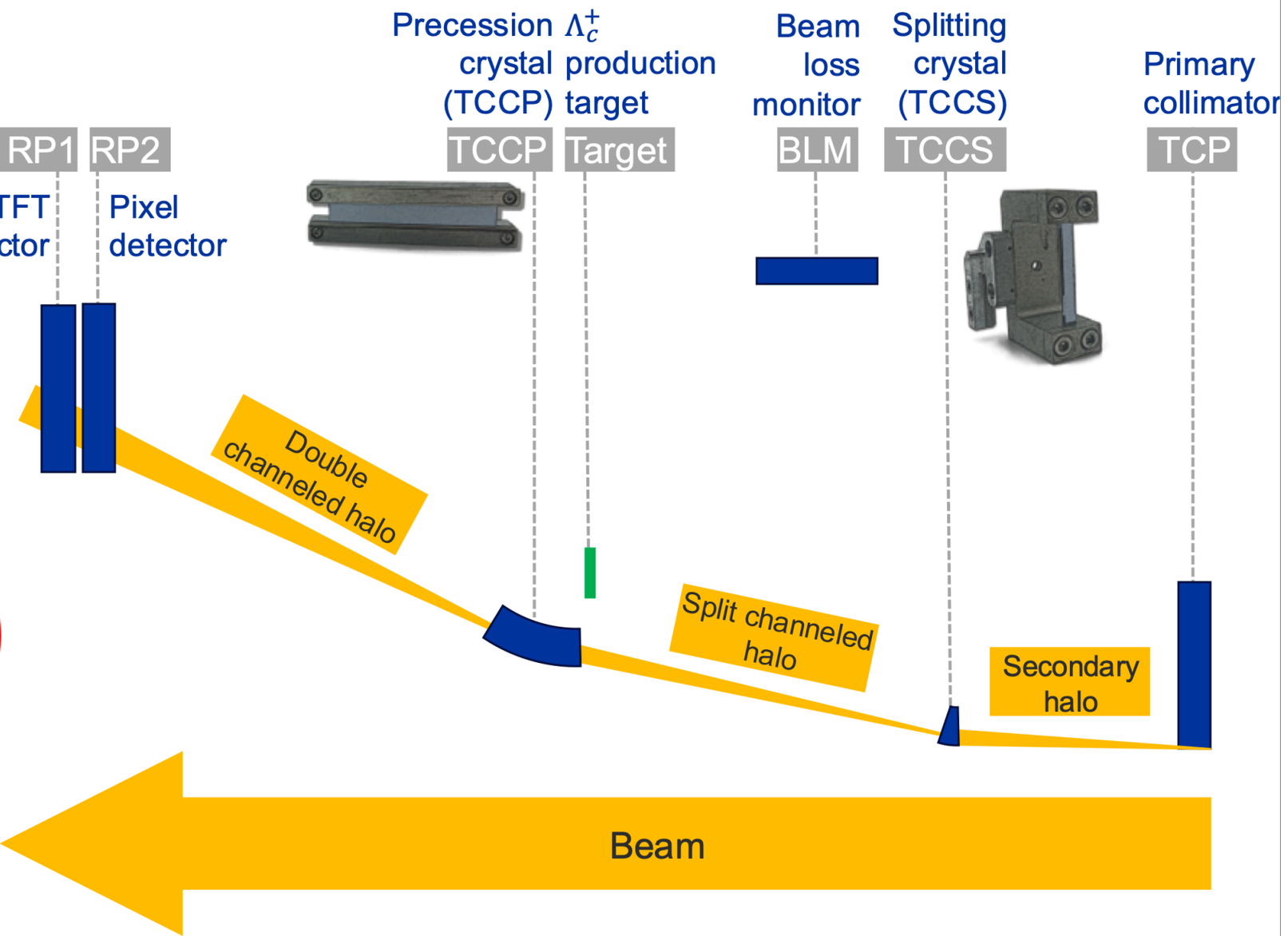
TWOCRYST proof-of-principle test in LHC

TWOCRYST setup at LHC

From R. Cai slides at EPS 2025 link

Experimental setup

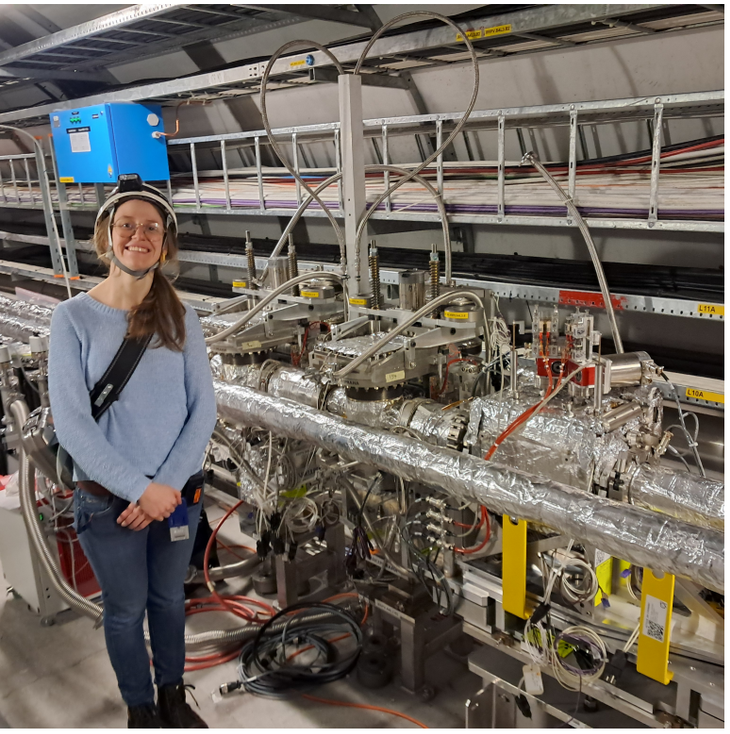


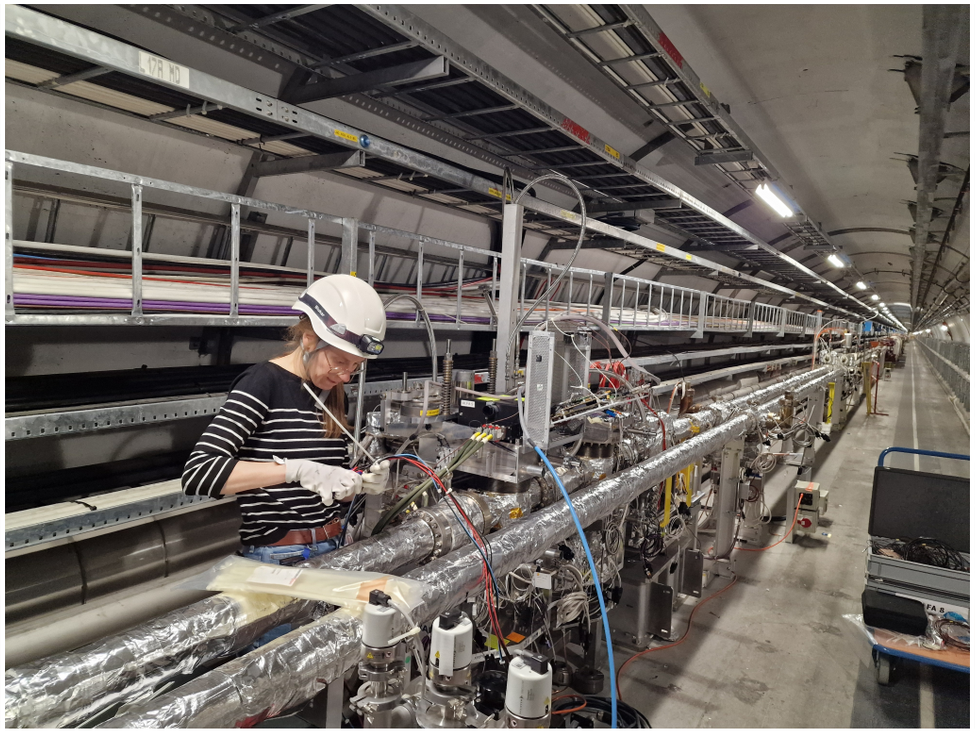


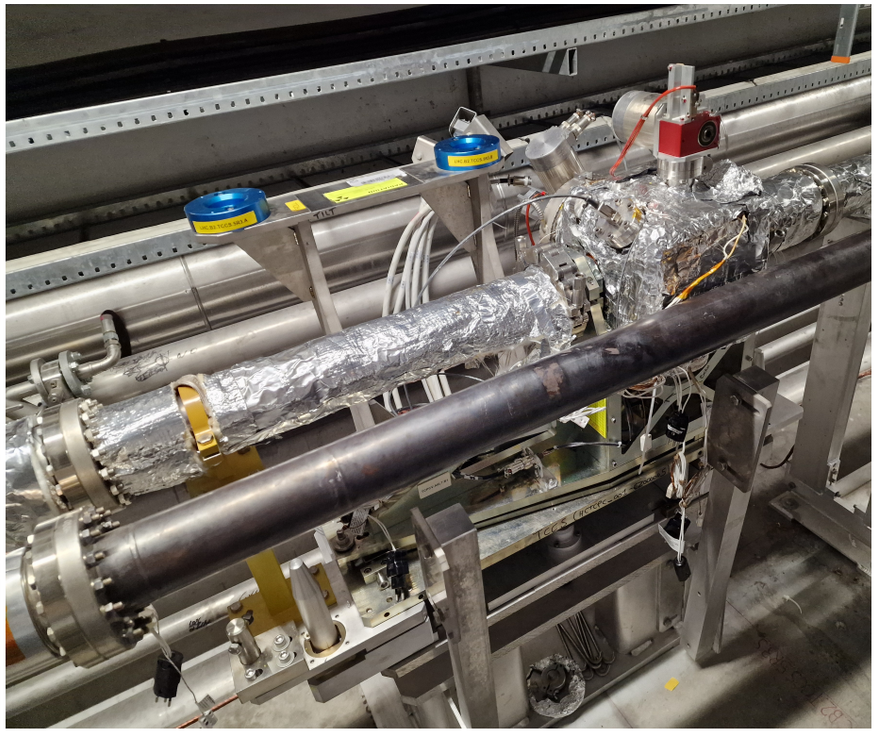
Installation of TWOCRYST

- Installation completed and successfully tested during YETS 2024/25:
  - goniometers equipped with bent crystals, Roman Pots, long cables, services
  - Pixel Detector, Fiber Tracker, secondary vacuum, long fibres, DAQ

2 Roman Pots + TCCP TCCS





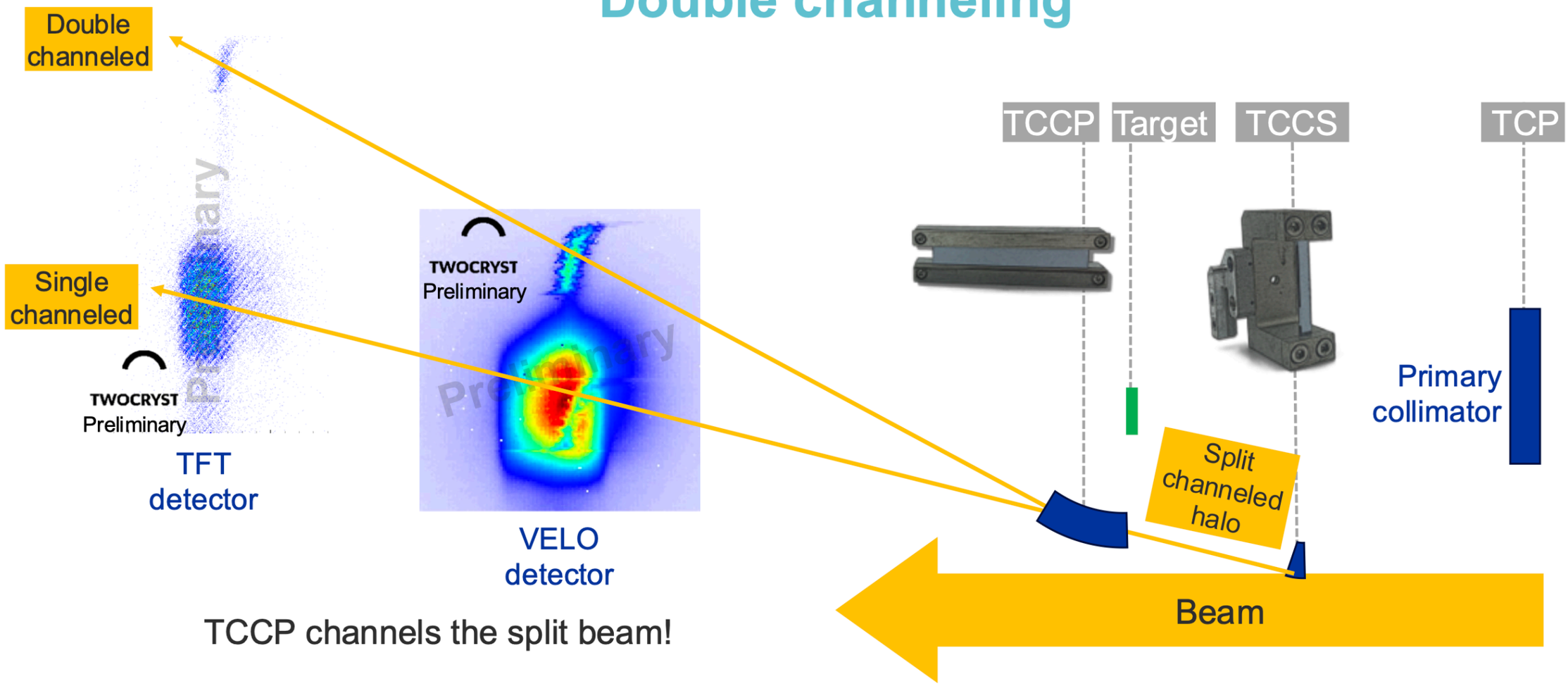


Courtesy of S. Jakobsen, P. Hermes (CERN)

From R. Cai slides at EPS 2025 link

First experience - Success!

Double channeling



TCCP channels the split beam!

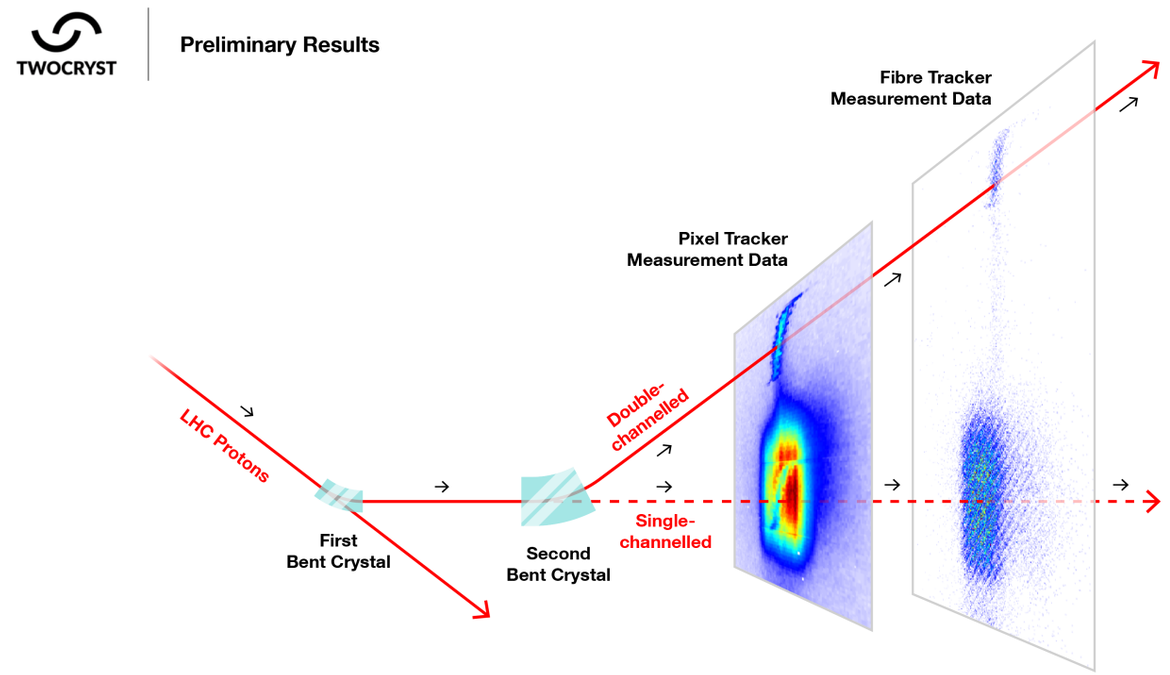
LHC MD June 2025: spectacular results

Recent CERN news link

Towards new physics with bent crystals

Double crystal channelling was observed for the first time at the LHC, a milestone for future short-lived particle research

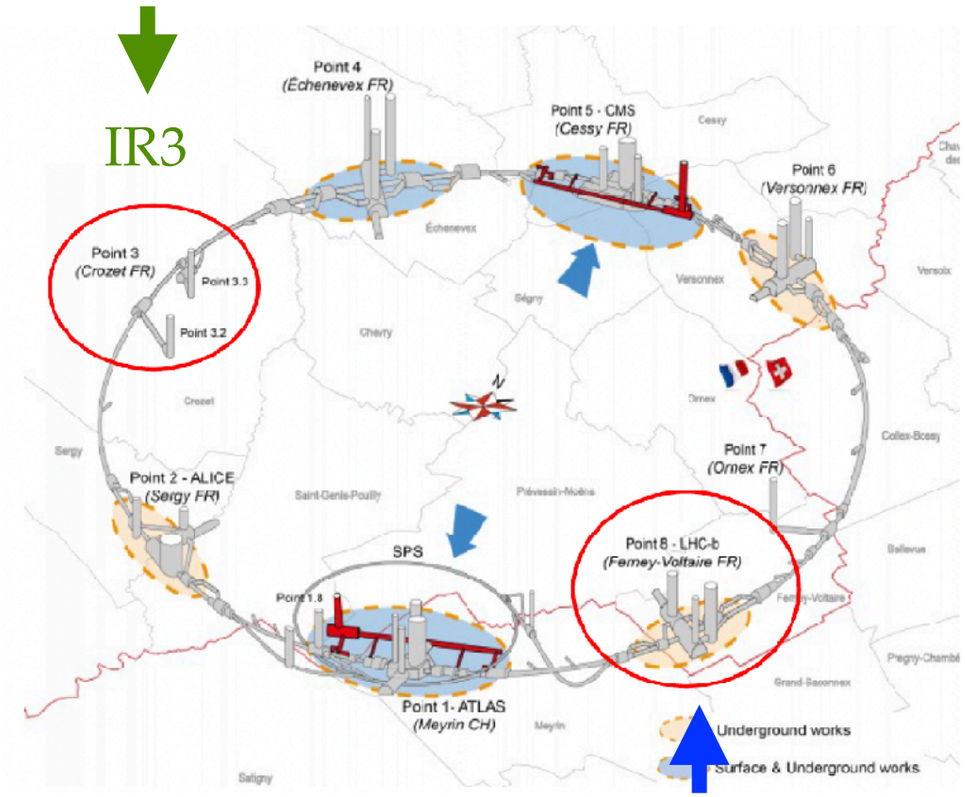
29 AUGUST, 2025 | By Insa Meinke



ALADDIN proposed experiment at the LHC

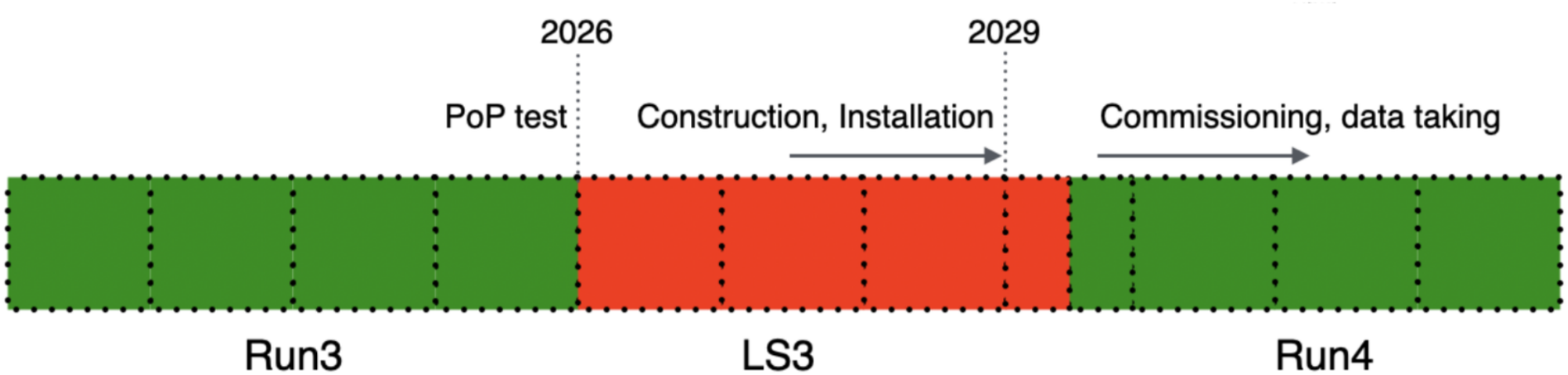
ALADDIN proposed experiment

- dedicated experiment at LHC IR3 region for measurement of charm baryon dipole moments
- data taking transparent to high intensity LHC operations



Letter of Intent (LOI) submitted in June 2024
CERN-LHCC-2024-011,LHCC-I-041

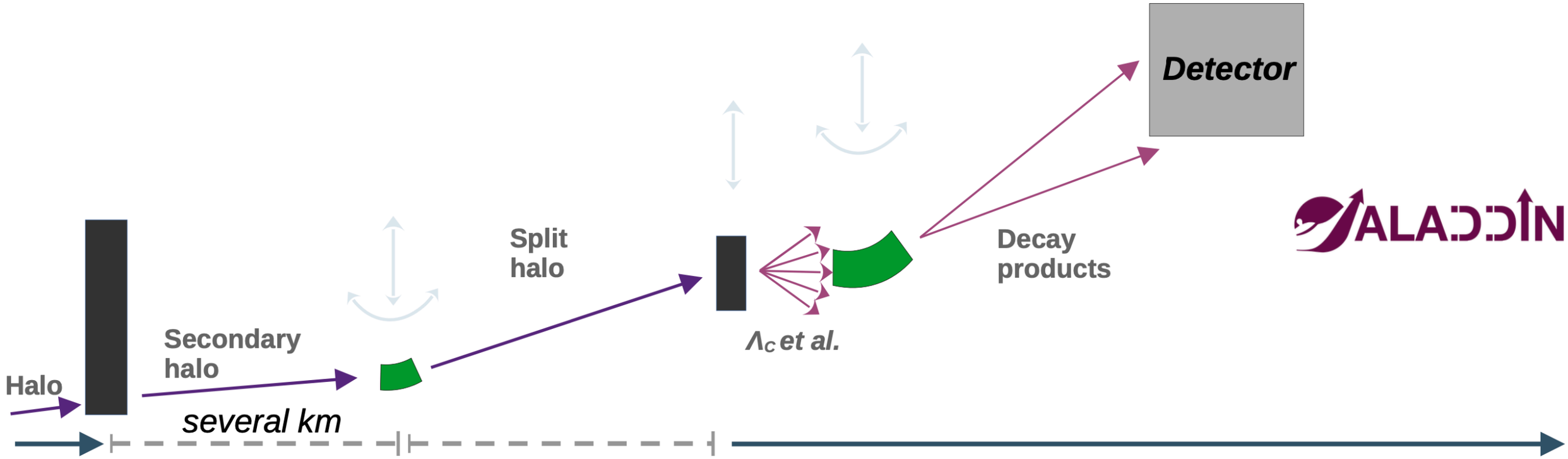
	Pro	Cons
IR3	Optimal experiment and detector PID information	Significant resources needed. New detector, services (long cables, cooling)



ALADDIN machine setup

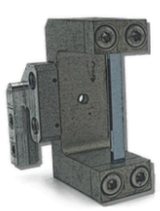
Courtesy of P. Hermes (CERN)

LHC Double Crystal FT Experiment – (Proposed 2029+)



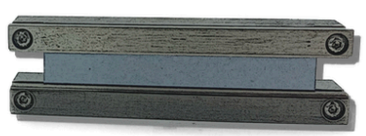
TCP — **Primary Collimator**

TCCS — **Splitting Crystal**

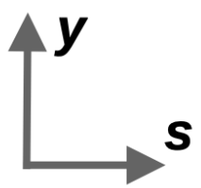


Target

TCCP — **Precession Crystal**



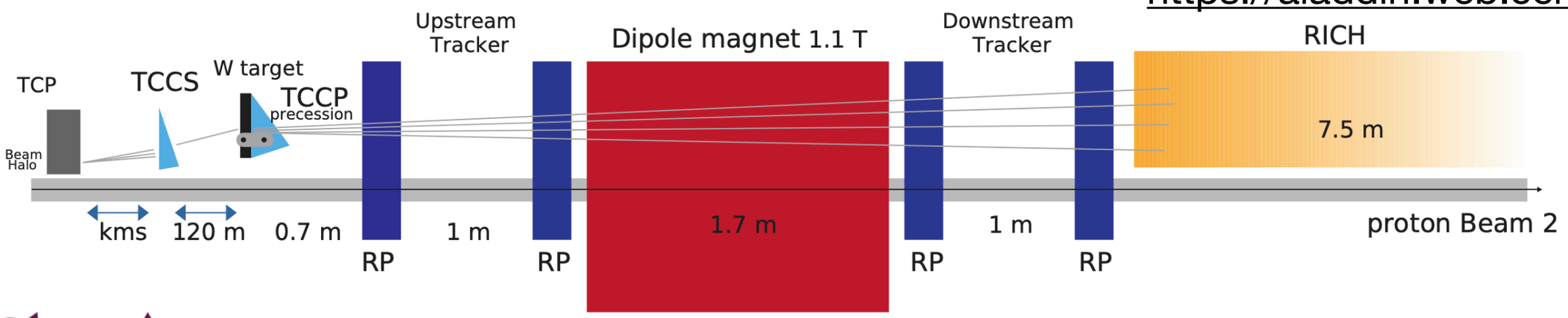
Detector



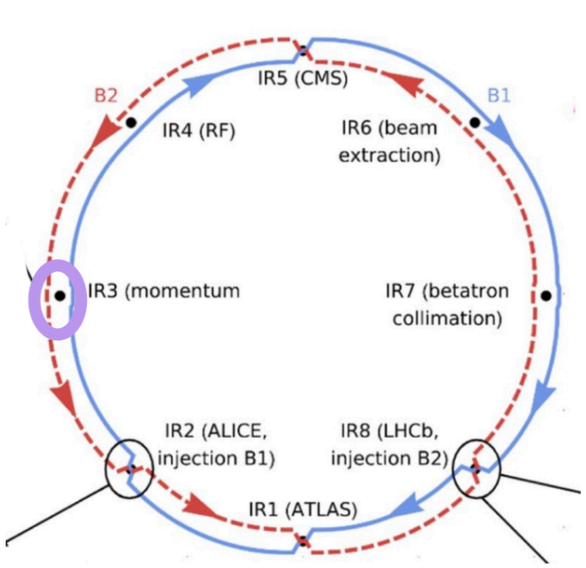
From S. Cesare slides at EPS 2025 link

The ALADDIN experiment

https://aladdin.web.cern.ch/



ALADDIN
An Lhc Apparatus for Direct Dipole moments INvestigation



Specifications of the fixed target experiment:

- Data-taking time: 10^{13} PoT = 10^{6} p/s × 2 years
- W target: 2 cm thickness
- Istantaneous luminosity L = 0.9 × 10^{31} $cm^{-2}s^{-1}$
- EDM – explorative measurement – sensitivity 3×10^{-16} e cm
- MDM – expected sensitivity ~10%

Possibility to extend the physics program:

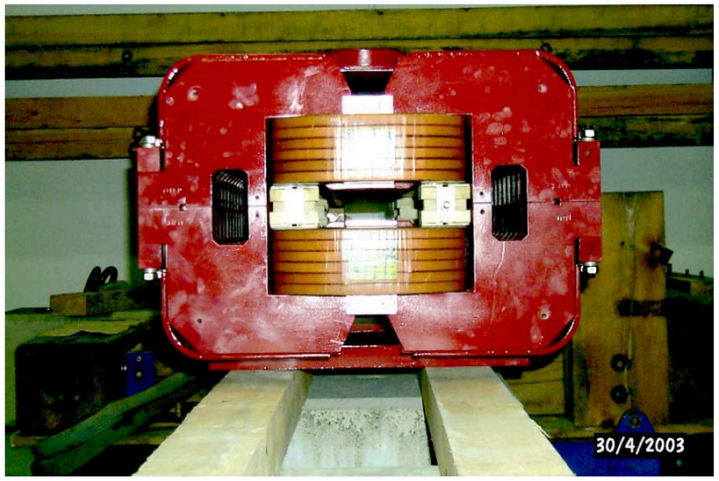
- Forward production of D mesons
- Photoproduction of J/ψ meson

Pseudorapidity $5 < \eta < 9$

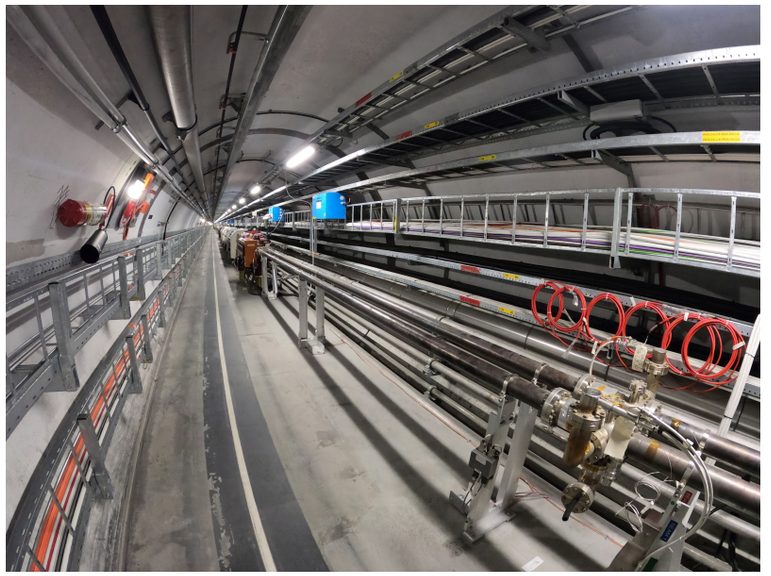
ALADDIN detector

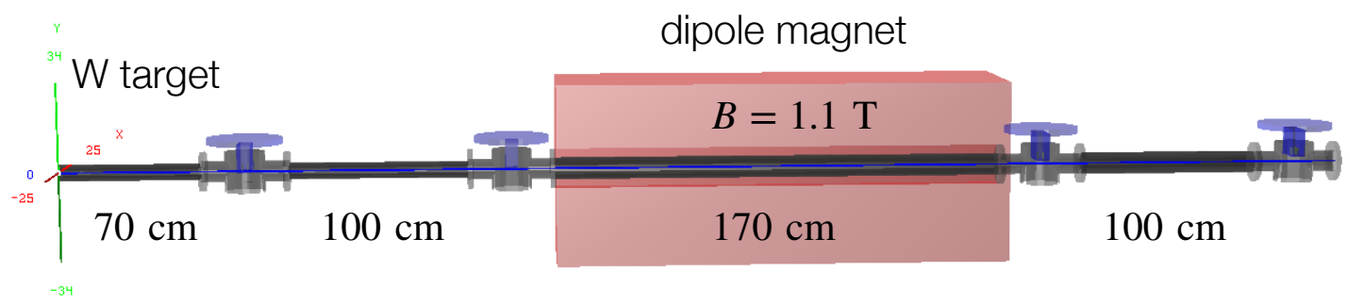
- Design of the detector based on spectrometer (left) and RICH (right)
- Tracking detectors placed inside Roman Pots (RP) close to the beam

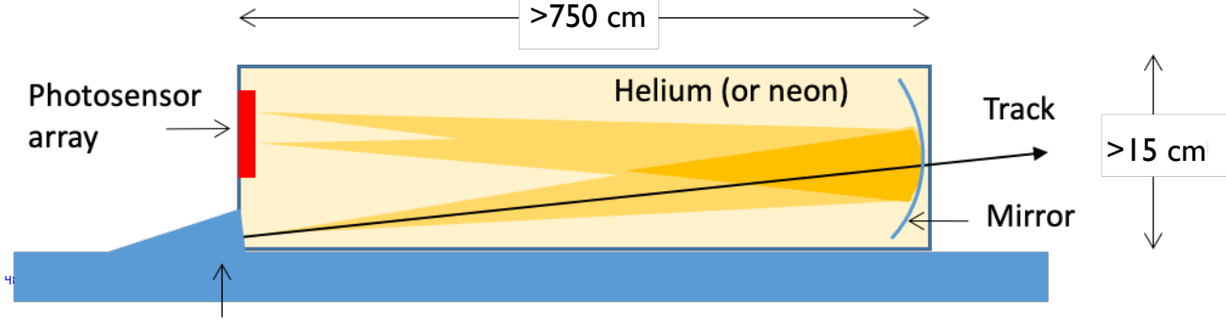
Dipole magnet available in situ (MCBW: 1.1 T x 1.7 m)



LHC IR3: space identified for ALADDIN





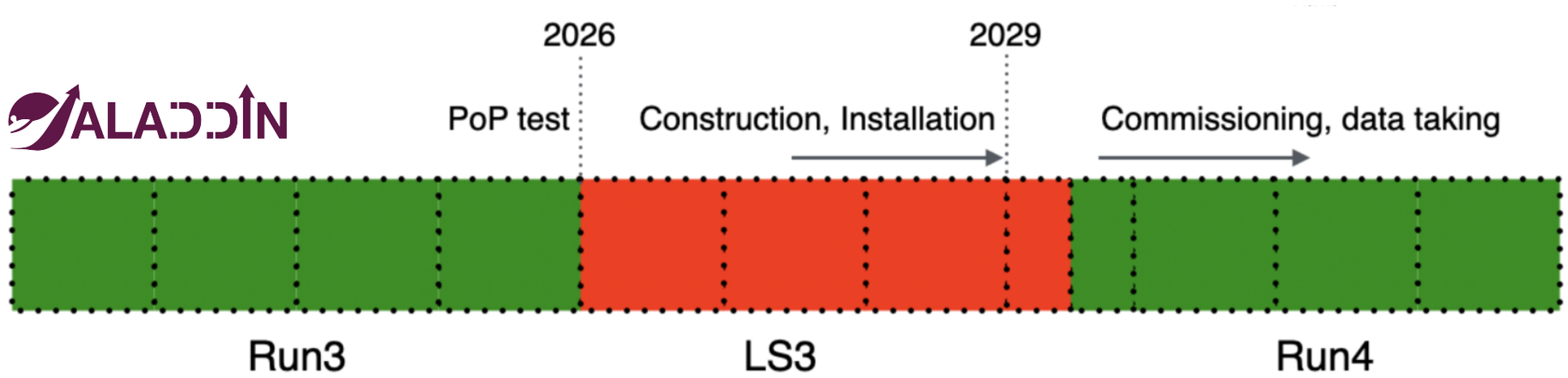


	pitch (μm)	hit rate (MHz/cm^2)	fluence (n$_{eq}$/cm^2)	area (cm^2)	tech. solution
Upstream	55	250	3.5×10^{15}	10	Si pixel
Downstream	100	30	9.0×10^{13}	30	Si pixel/strip

Specification for the tracking detectors positioned upstream and downstream of the dipole magnet. Hit rate estimated with full simulations

Summary

- Measurements of **MDM/EDM** of particles are sensitive to physics within and beyond the SM
- New experimental techniques for the measurement of strange Λ baryon and charm Λ_c^+, Ξ_c^+ baryons dipole moments have been developed and tested successfully
- **First measurement** at LHC of Λ **baryon MDM/EDM** is in progress, based on LHCb Run1-2 data (9 fb^{-1}) in $\Lambda_b^0 \to J/\psi\Lambda$ decays. Interesting perspective for Run3-4 (50 fb^{-1}) with additional decay modes
- **ALADDIN**, a dedicated fixed-target experiment at LHC IR3, is designed for Λ_c^+, Ξ_c^+ **charm baryon MDM/EDM**. Aims to start data taking in Run4 and continue beyond



ALADDIN Collaboration

https://aladdin.web.cern.ch/Collaboration.html

The ALADDIN collaboration

Authors as 22/07/2025

K. Akiba[1], F. Alessio [2], M. Benettoni [3], A. Bizzeti [23,24], F. Borgato [3,4], F. Bucci [23], R. Cardinale [5,6], S. Cesare [7,8], M. Citterio [8], V. Coco [2], S, Coelli [8], P. Collins [2], E. Dall'Occo [9], M. Ferro-Luzzi [2], A. Fomin [21], R. Forty [2], J. Fu [10], A. Gallas Torreira [25], P. Gandini [8], M. Giorgi [11,12], J. Grabowski [13], S. J. Jaimes Elles [14], S. Jakobsen [2], E. Kou [21], G. Lamanna [11,12], H. Li [10,16], S. Libralon [14], M. Lucio Martinez [14], D. Marangotto [7,8], F. Martinez Vidal [14], J. Mazorra de Cos [14], A. Merli [15], H. Miao [10,16], N. Neri [7,8], S. Neubert [13], I. Panichi [23,24], A. Petrolini [5,6], A. Pilloni [17], J. Pinzino [12], M. Prest [19], P. Robbe [21], L. Rossi [7,8], J. Ruiz-Vidal [14,22], I. Sanderswood [14], A. Sergi [5,6], G. Simi [3,4], M. Sorbi [7,8], M. Sozzi [11,12], E. Spadaro Norella [5,6], A. Stocchi [21], G. Tonani [7,8], T. Tork [7,8], A. Triossi [3,4], N. Turini [18,12], E. Vallazza [19,20], S. Vico Gil [14], Z. Wang [8], M. Wang [8], T. Xing [8], M. Zanetti [3,4], F. Zangari [7,8]

Institutes

1 Nikhef, National institute for subatomic physics, Amsterdam, Nederlands
2 CERN - Geneva, Switzerland
3 INFN Sezione di Padova, Padua, Italy
4 Università degli Studi di Padova, Padua, Italy
5 Università di Genova, Genoa, Italy
6 INFN Sezione di Genova, Genoa, Italy
7 Università degli Studi di Milano, Milan, Italy
8 INFN Sezione di Milano, Milan, Italy
9 Technische Universität Dortmund (TU), Dortmund, Germany
10 University of Chinese Academy of Sciences, Beijing, China
11 Università di Pisa, Pisa, Italy
12 INFN Sezione di Pisa, Pisa, Italy
13 University of Bonn, Bonn, Germany
14 IFIC - Universitat de Valencia-CSIC, Valencia, Spain
15 Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
16 Institute of High Energy Physics, Beijing, China
17 INFN Sezione di Catania, Università degli Studi di Messina, Messina, Italy
18 Università degli Studi di Siena, Siena, Italy
19 INFN Sezione di Milano Bicocca, Milan, Italy
20 INFN Sezione di Trieste, Trieste, Italy
21 IJCLab, Orsay, France
22 Lund University, Sweden
23 INFN Sezione di Firenze, Firenze, Italy
24 Università degli Studi di Modena e Reggio Emilia, Italy
25 Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade Santiago de Compostela, Spain

Machinist at CERN

In particular we would like to acknowledge the help of P. Hermes, K. Dewhurst, R. Cai, C. Maccani, D. Mirarchi, S. Redaelli and G.Arduini

Spokesperson: Nicola Neri

Physics Coordinator: Fernando Martinez Vidal

TWOCRYST Collaboration

CERN
O. Aberle, F. Alessio, C. Antuono, G. Arduini, M. Calviani, V. Coco, M. D'Andrea, Q. Demassieux, K. Dewhurst, M. Di Castro, L. Esposito, M. Ferro-Luzzi, H. Havlikova, P. Hermes, S. Jakobsen, C. Maccani, E. Matheson, D. Mirarchi, A. Perillo Marcone, S. Redaelli, B. Salvant, R. Seidenbinder, S. Solis Paiva, E. Soria, C. Zannini

IJCLab, Orsay, France
A. Fomin, P. Robbe, A. Stocchi

INFN Milano and University of Milano
S. Cesare, S. Coelli, P. Gandini,
D. Marangotto, A. Merli**, N. Neri, E. Spadaro Norella*, G. Tonani, F. Zangari

Warsaw University of Technology, Poland
M. Patecki

IFIC, University of Valencia-CSIC, Spain
S.J. Jaimes Elles, S. Libralon, F. Martinez Vidal, J. Mazorra de Cos, I. Sanderswood, S. Vico Gil

INFN Ferrara and University of Ferrara
L. Bandiera, V. Guidi, L. Malagutti, A. Mazzolari, R. Negrello, M. Romagnoni, M. Tamisari

INFN Padova and University of Padova
M. Benettoni, G. Simi, A. Triossi, M. Zanetti

INFN Legnaro Labs and University of Padova
D. De Salvador

INFN Pisa and Pisa University
G. Lamanna, J. Pinzino, M. Sozzi, N. Turini

UCAS, China
J. Fu, H. Miao, T. Xing

University of Malta
L. Grech, G. Valentino

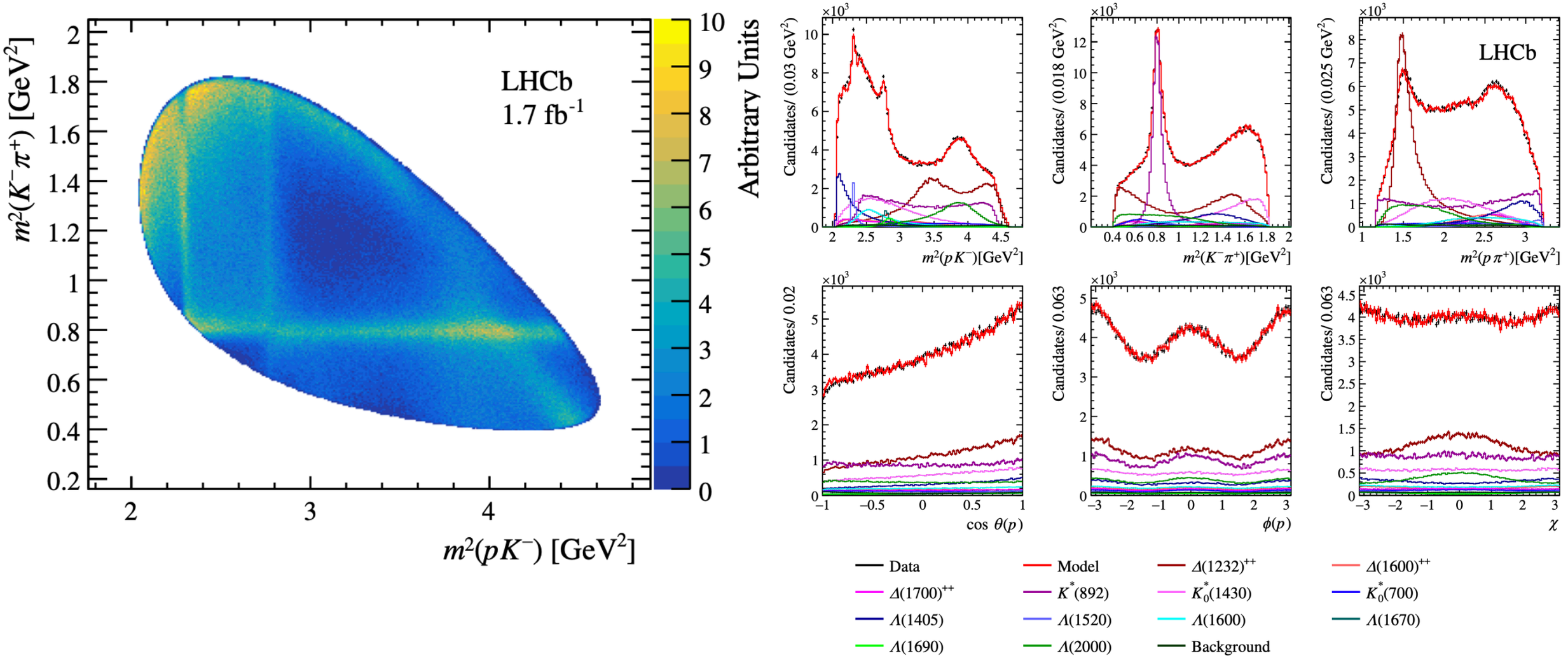
Institute of Nuclear Physics - Polish Academy of Sciences
K. Korcyl

Backup slides

Preparatory measurements with LHCb data

PHYS. REV. D 108, 012023 (2023)

- Use 400k $\Lambda_c^+ \to pK^-\pi^+$ signal events from semileptonic beauty hadron decays to determine the **amplitude model and Λ_c^+ polarisation**

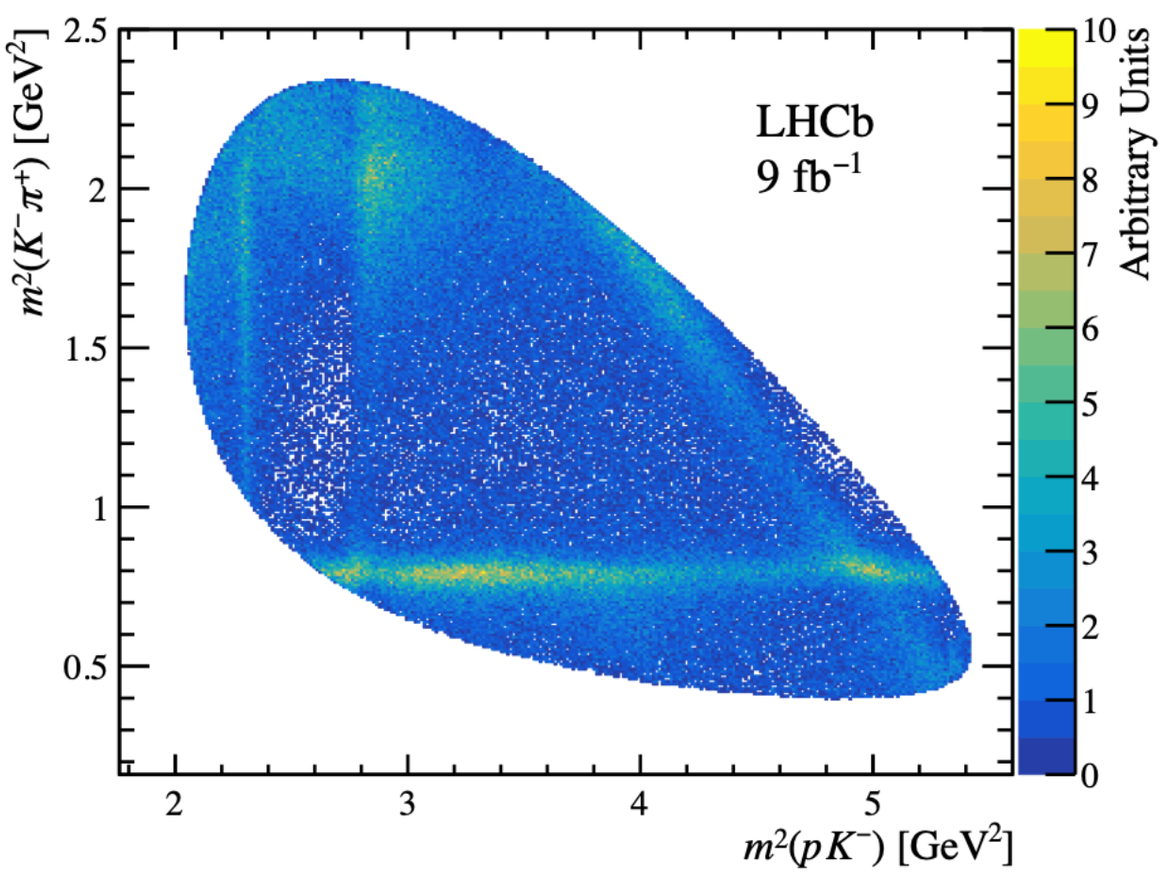


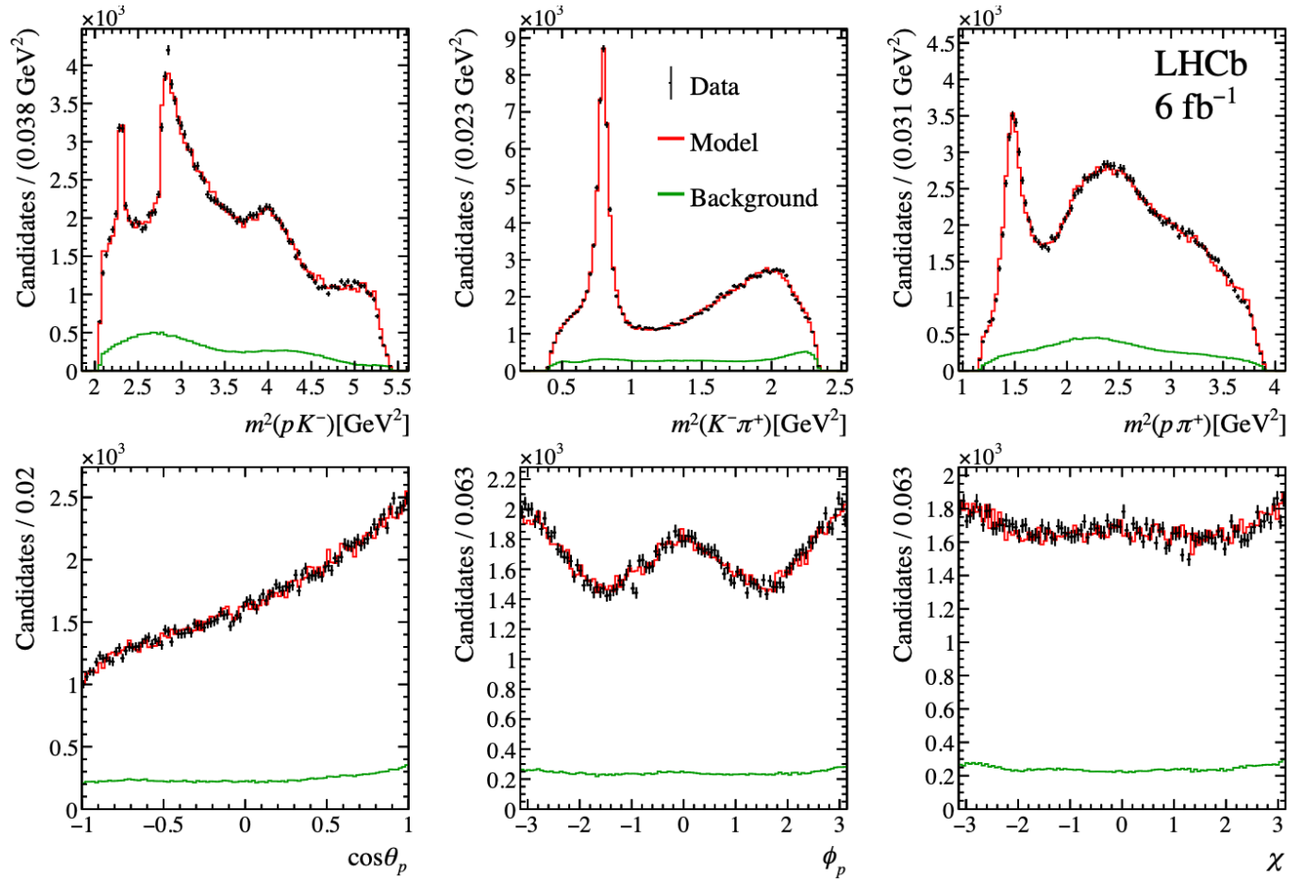
- Large sensitivity to polarisation (analysing power). $\Lambda_c^+ \to pK^-\pi^+$ **best probe for polarisation measurements** of Λ_c^+ produced in fixed-target collisions

Preparatory measurements with LHCb data

arXiv:2508.00492

- Use 187k $\Xi_c^+ \to pK^-\pi^+$ signal events from semileptonic beauty hadron decays to determine the **amplitude model and Ξ_c^+ polarisation**



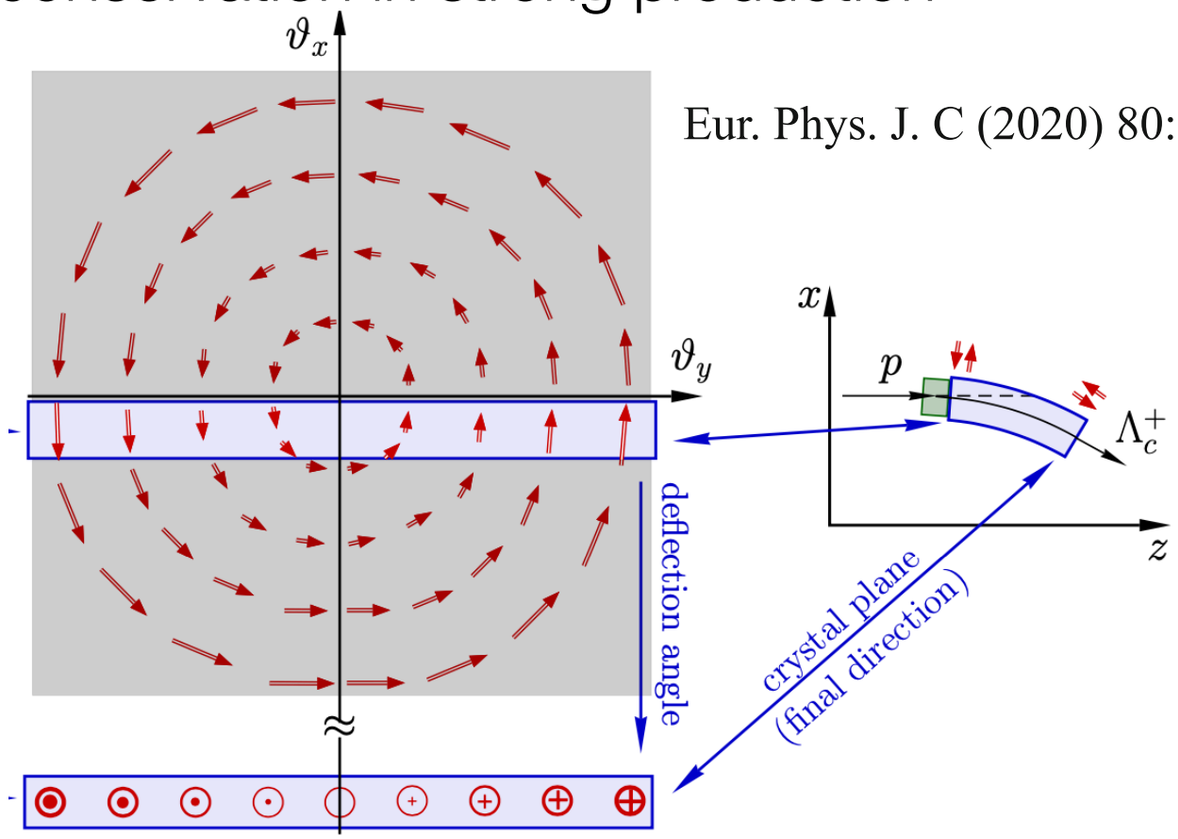


- Large sensitivity to polarisation (analysing power). $\Xi_c^+ \to pK^-\pi^+$ **suitable for polarisation measurements** of Ξ_c^+ produced in fixed-target collisions

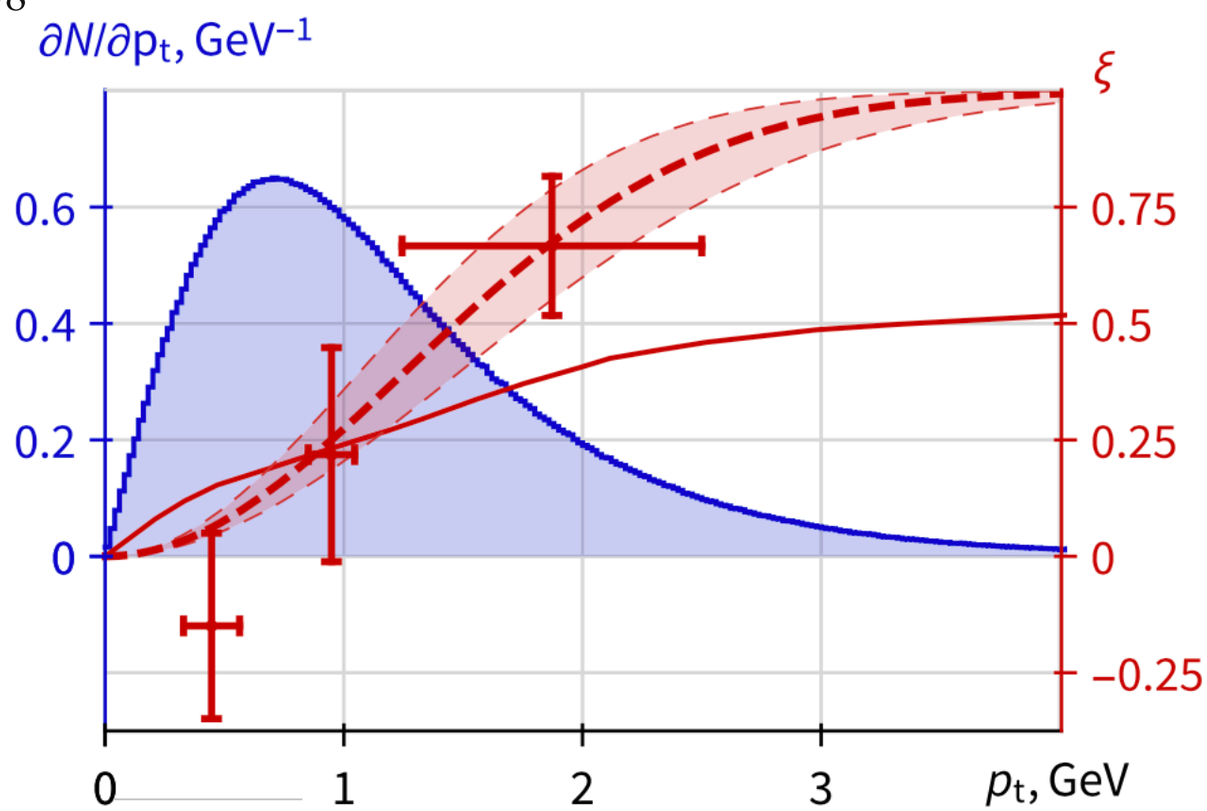
Polarisation of charm baryons

Polarisation perpendicular to production plane due to parity conservation in strong production

Sensitivity depends on baryon polarisation $\sigma_{d,g} \propto \frac{1}{s_0}$



Eur. Phys. J. C (2020) 80:358



Polarisation in crystal frame vs angle between p and crystal axis

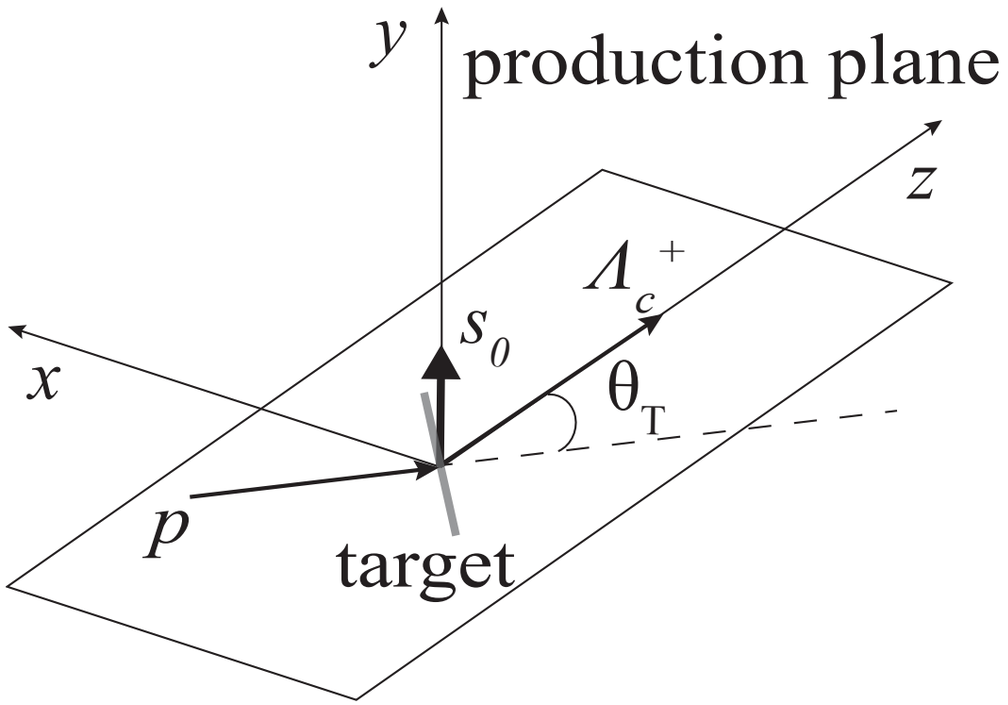
$$\boldsymbol{s}_0 = (s_{0x}, s_{0y}, s_{0z}) \approx \frac{s_0(p_T)}{p_T}(-p \sin\theta_{crys}, p_{xL}, 0)$$

PRD 103, 072003 (2021)

Polarisation of charm baryons

Polarisation perpendicular to production plane due to parity conservation in strong production

$$\sigma_{d,g} \propto \frac{1}{s_0}$$



Measure final polarisation vector $\mathbf{s}'$ with angular analysis of Λ_c^+ decay and extract d, g, s_0 with a fit to data

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

$$s'_y \approx s_0 \cos\Phi$$

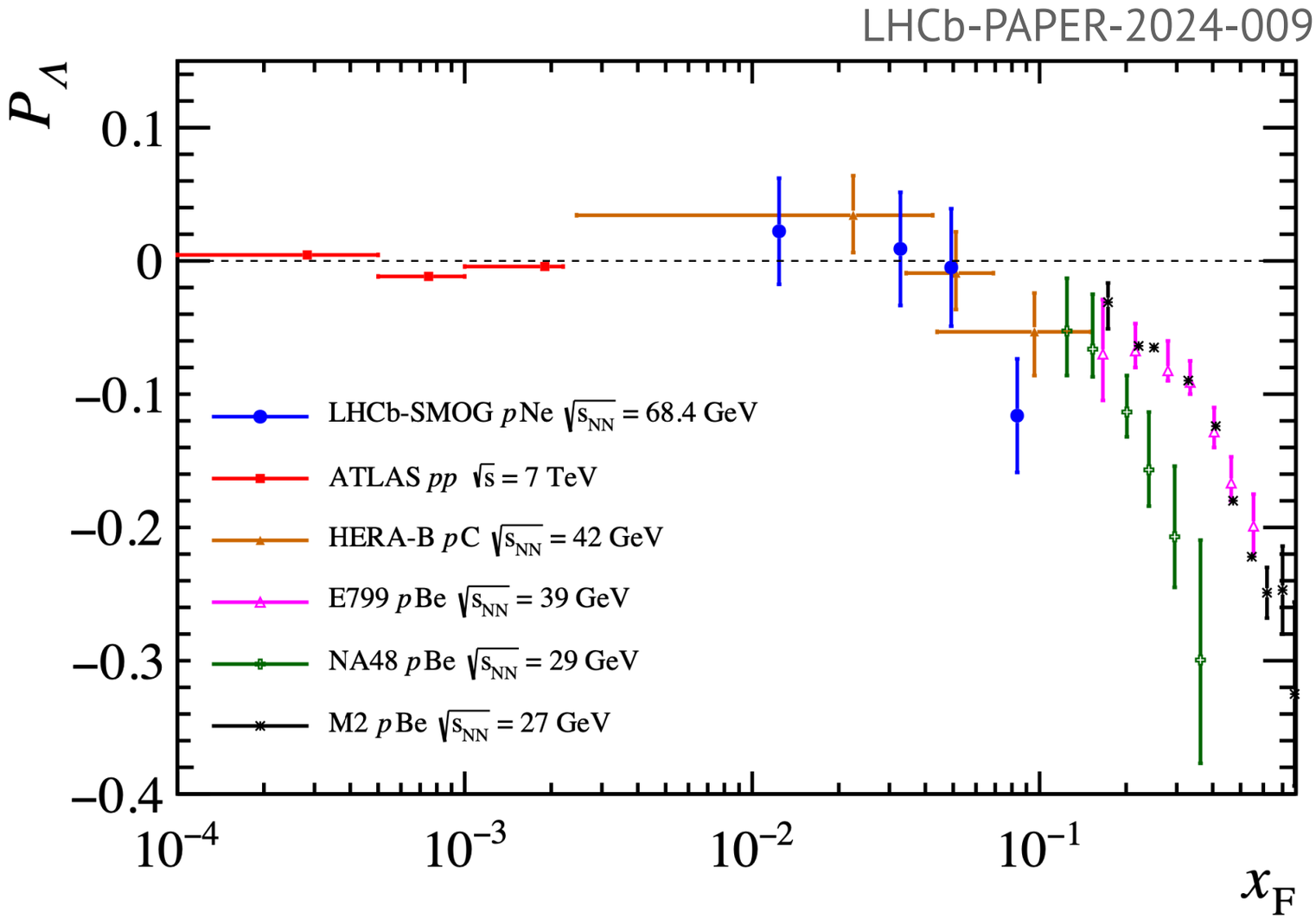
$$s'_z \approx s_0 \sin\Phi$$

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

Indications from Λ baryon polarisation

- Polarisation increases as a function of Feynman variable $x_F = \dfrac{p_L^*}{\max p_L^*}$
- For crystal experiment expect large positive x_F
- Work in progress to produce similar plot for Λ_c^+ with *pp* collisions and SMOG data at LHCb

LHCb-PAPER-2024-009



Charm baryons decays of interest

- List of Λ_c^+, Ξ_c^+ modes and corresponding branching fractions $\mathscr{B}$, reconstructibility $\epsilon_{3\mathrm{trk}}$ and effective branching fraction $\mathscr{B}_{\mathrm{eff}} = \mathscr{B} \cdot \epsilon_{3\mathrm{trk}}$
- Reconstructibility of $\Sigma^+, \Sigma^-, \Xi^-$ as charged stable particles throughout the detector taken into account in $\epsilon_{3\mathrm{trk}}$

$$\tau_{\Lambda_c} = 2.0 \cdot 10^{-13}\mathrm{s} \qquad \tau_{\Xi_c} = 4.5 \cdot 10^{-13}\mathrm{s}$$

Λ_c^+ decay	$\mathcal{B}$	$\epsilon_{3\mathrm{trk}}$	$\mathcal{B}_{\mathrm{eff}}$	Ξ_c^+ decay	$\mathcal{RB}$	$\mathcal{B}$	$\epsilon_{3\mathrm{trk}}$	$\mathcal{B}_{\mathrm{eff}}$
$pK^-\pi^+$	6.28 ± 0.32	1	6.26	$\Xi^-\pi^+\pi^+$	1	2.9 ± 1.3	0.70	1.99
$\Sigma^+\pi^-\pi^+$	4.50 ± 0.25	0.64	2.89	$\Sigma^+K^-\pi^+$	0.94 ± 0.10	2.7	0.50	1.34
$\Sigma^-\pi^+\pi^+$	1.87 ± 0.18	0.78	1.46	$\Sigma^+\pi^-\pi^+$	0.48 ± 0.20	1.4	0.50	0.69
$p\pi^-\pi^+$	0.461 ± 0.028	1	0.46	$pK^-\pi^+$	0.21 ± 0.04	0.6	0.99	0.60
$\Xi^-K^+\pi^+$	0.62 ± 0.06	0.79	0.49	$\Sigma^-\pi^+\pi^+$	0.18 ± 0.09	0.5	0.67	0.34
$\Sigma^+K^-K^+$	0.35 ± 0.04	0.63	0.22	$\Sigma^+K^-K^+$	0.15 ± 0.06	0.4	0.49	0.21
pK^-K^+	0.106 ± 0.006	0.99	0.11	$\Omega^-K^+\pi^+$	0.07 ± 0.04	0.2	0.49	0.10
$\Sigma^+\pi^-K^+$	0.21 ± 0.06	0.64	0.14					
all	-	-	12.02	all	-	-	-	5.3

New fixed-target experiment at LHC with unique forward acceptance

	ALADDIN	LHCb-SMOG
$\sqrt{s}$ (GeV)	115	115
Momentum p (GeV/c)	$\gtrsim 500$	$\lesssim 500$
Transverse momentum p_T (GeV/c)	$\lesssim 1.3$	0.2 to 1.8
Rapidity y^*	1 to 3.5 (very forward)	-3.5 to 0 (central/backward)
Pseudorapidity η	5 to 9	2 to 5
Four-momentum transfer Q (GeV/c)	4	15 to 115
$\log_{10} x_B$ (Bjorken)	Down to -3.2	Down to -3
x_F (Feynman)	0.1 to 0.5, max. at 0.3	-0.5 to 0, max. at -0.1

y^* is in the center-of-mass rest frame

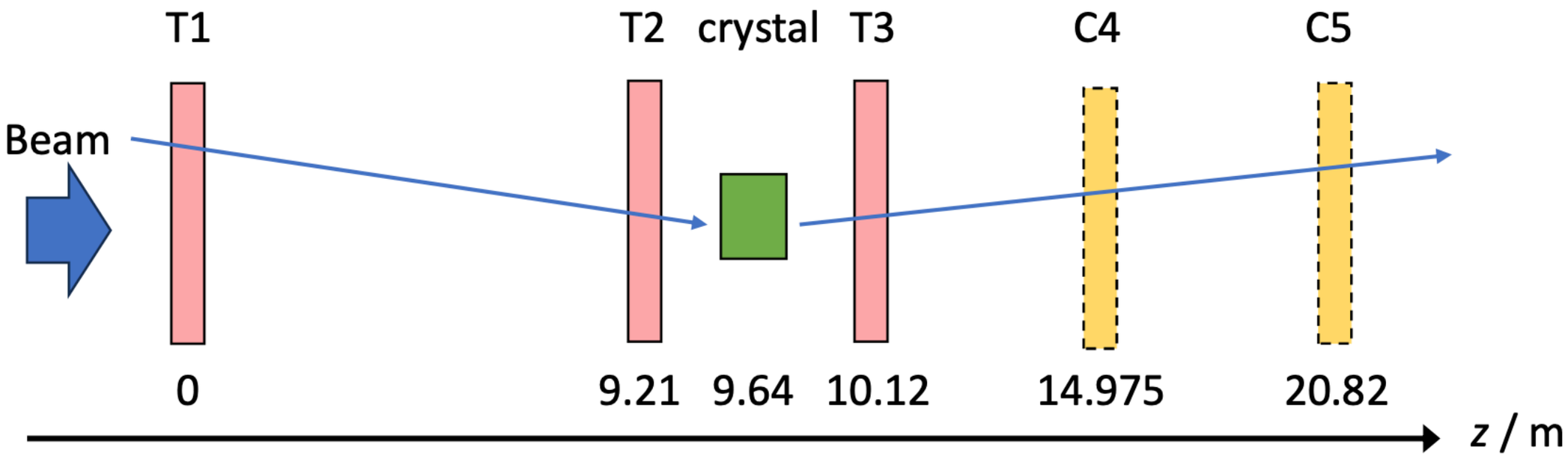
- Additional physics topics: charm hadron cross-section measurements, J/ψ photo production in the very forward region at pseudorapidity $5 < \eta < 9$
- Discussion ongoing between theorists/experimentalists to develop a program of new measurements with solid targets (W, Si, ….)

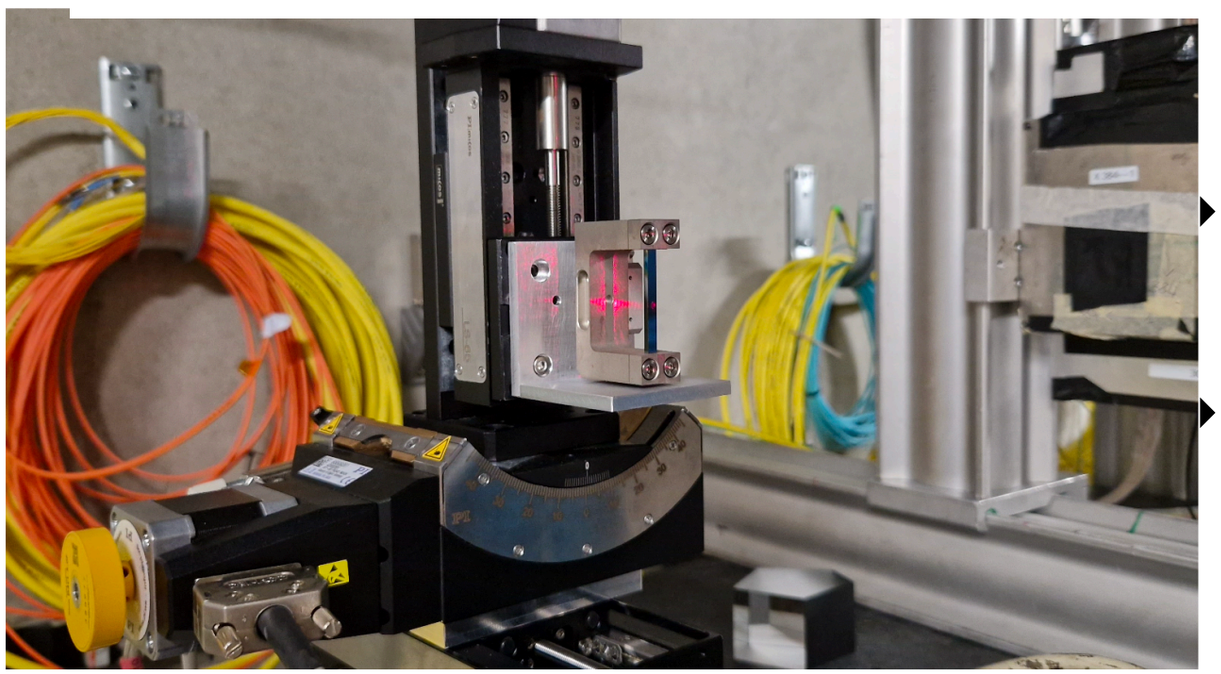
Bent crystal testbeam at SPS

European Research Council
Established by the European Commission

Acknowledgments: A. Mazzolari (INFN-Fe)

- Bent crystals produced at INFN Ferrara. Test at SPS H8 with INFN Milano Bicocca/Insubria telescope and **180 GeV/c positive hadron beam** (Aug 2023)





Acknowledgments: D. De Salvador (INFN-LNL)

- Silicon strip sensors T (C) with 50μm (242μm) pitch
- Goniometer with 1μm accuracy for precision crystal alignment

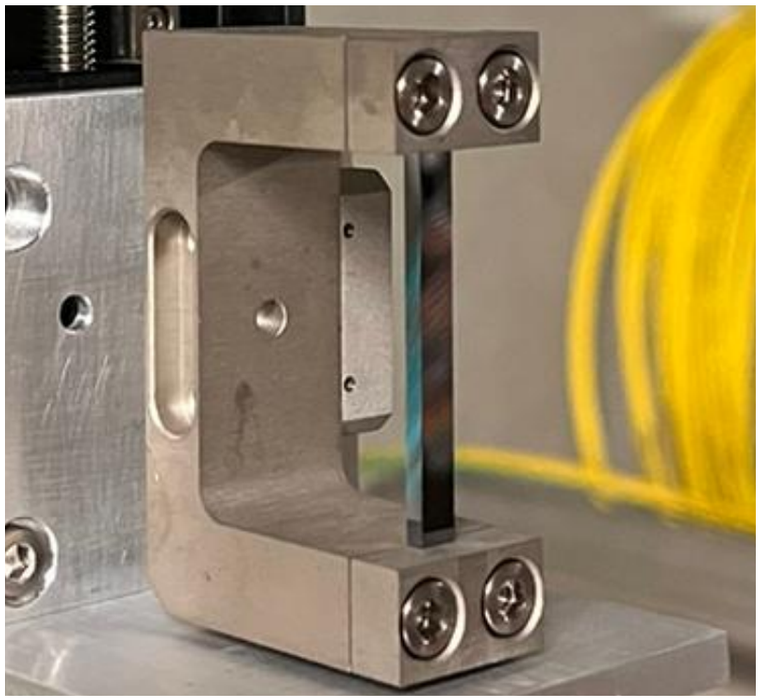
arXiv:2505.14365

Bent crystal testbeam at SPS

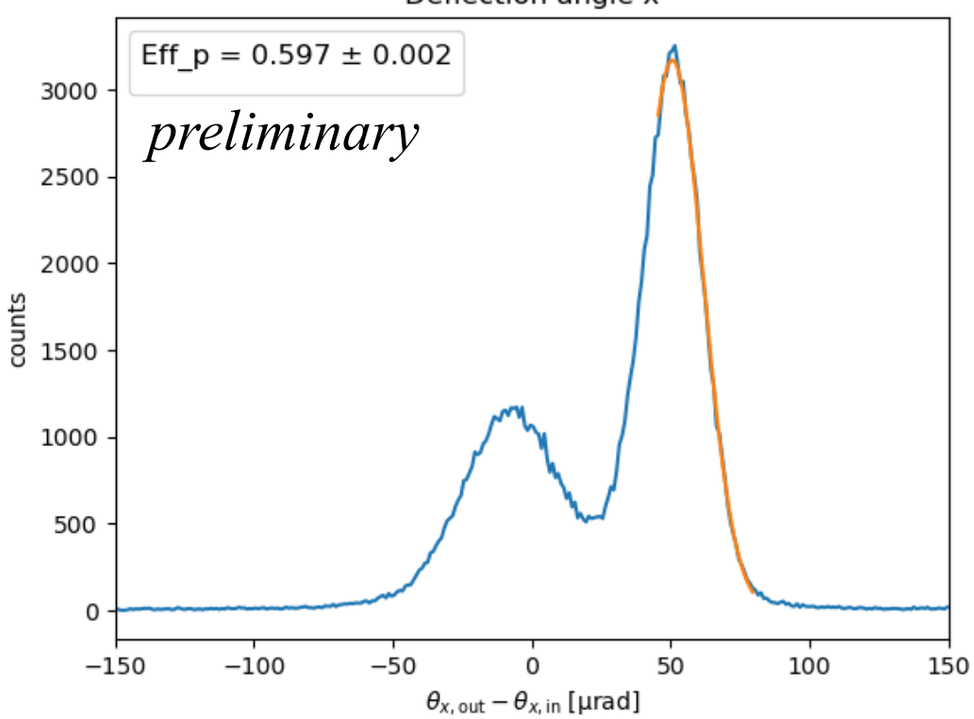
European Research Council
Established by the European Commission

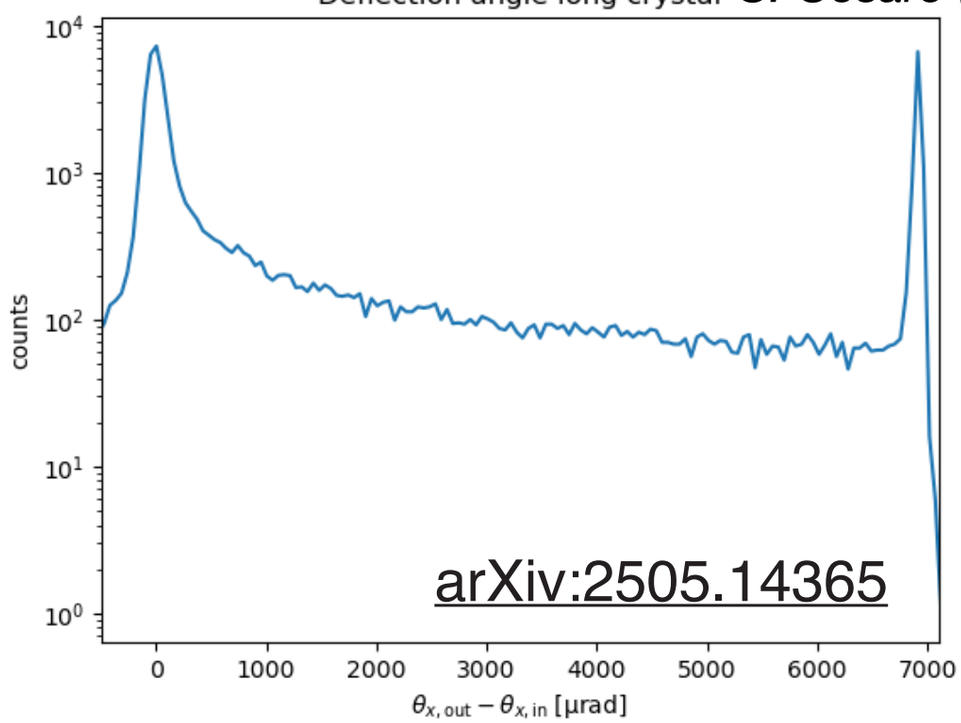
Acknowledgments: A. Mazzolari (INFN-Fe)

TCCS: Si, 50 μrad, 4 mm, chan. eff. 60%



TCCP: Si, 7 mrad, 70 mm, chan. eff. 16%





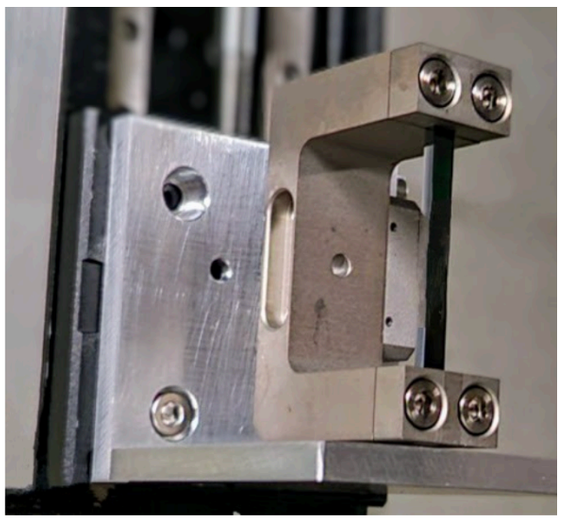
S. Cesare (Milano)

ERC SELDOM selected results

arXiv:2505.14365 (2025)

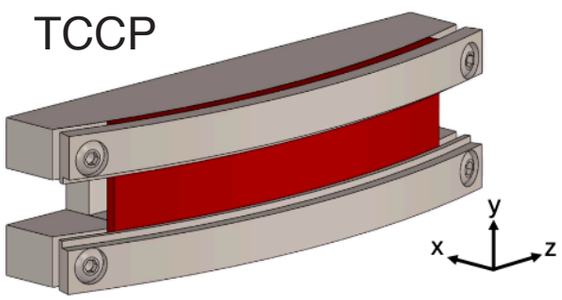
- Performance of short and long bent crystals for the TWOCRYST experiment measured on SPS 180 GeV/c hadron beam

Crystal		TCCS	TCCP	TCCPA
Crystal material		Si	Si	Si
Bending plane		(110)	(110)	(110)
Length	[mm]	4	70	70.5
Width	[mm]	35	8	22.5
Height	[mm]	2	2	2
Bend radius ρ	[m]	80	10	5.3
Bend angle θ_b	[mrad]	0.05	7.0	13.3
θ_L at 180 GeV/c	[µrad]	13.3	12.9	12.5

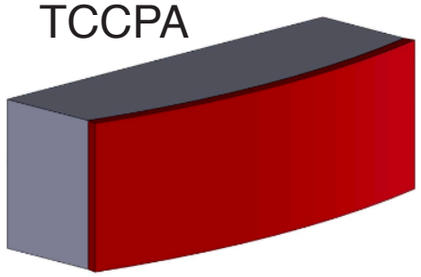


TCCS

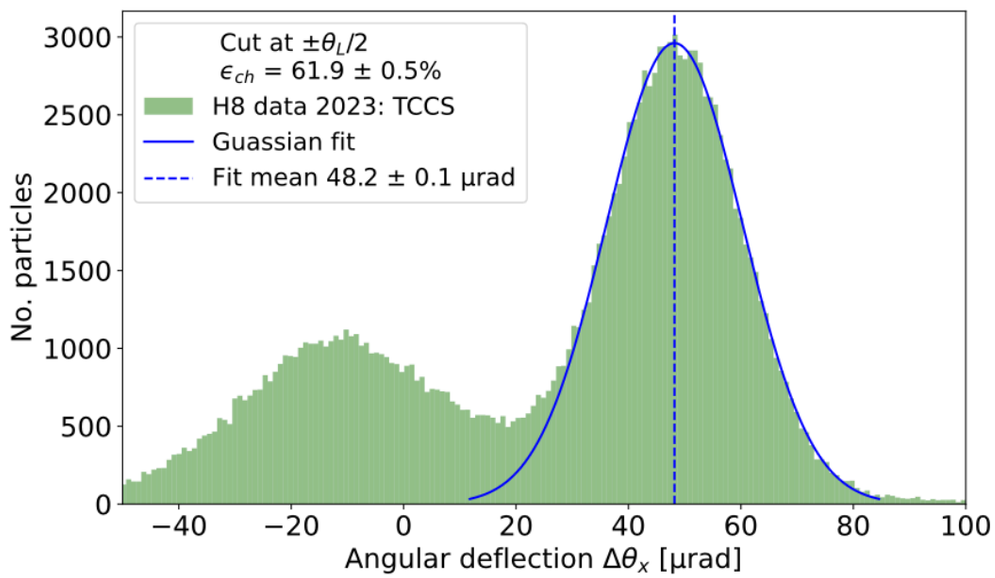
TCCP



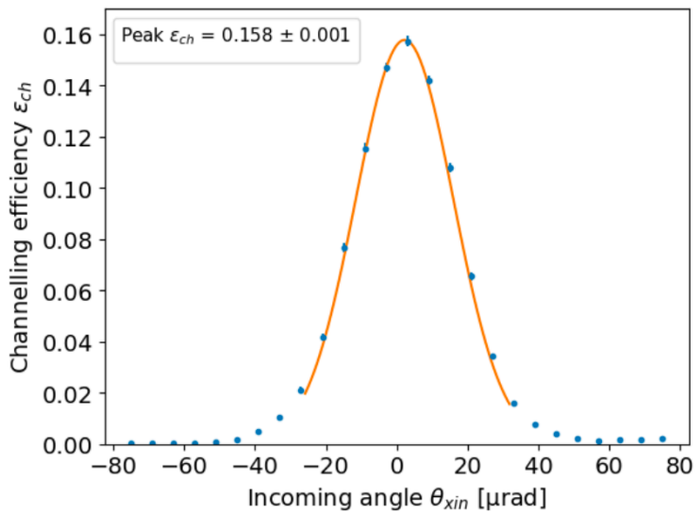
TCCPA



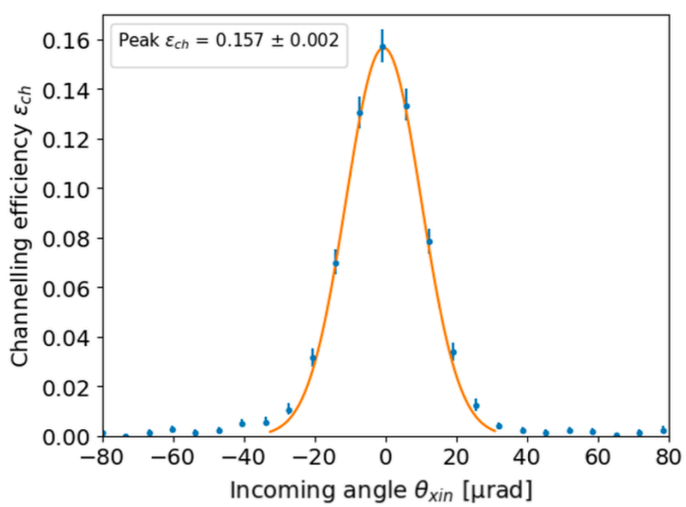
TCCS



TCCP



TCCPA



Additional physics opportunities to explore $(g-2)$ and EDM of the τ^+ lepton[1,2]

- Large statistics needed for interesting measurements, i.e. PoT≥ 10^{17} [2.5 cm W target]
- Many challenges: τ^+ reconstruction, background level, statistics
- Preparatory studies ongoing with LHCb SMOG data

[1] A.S. Fomin , A. Korchin, A. Stocchi, S. Barsuk, P. Robbe, *Feasibility of τ lepton electromagnetic dipole moments measurements using bent crystals at LHC*, *JHEP* 03 (2019) 156, arXiv:1810.06699

[2] 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 (2019) 1, 011801, arXiv:1901.04003

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

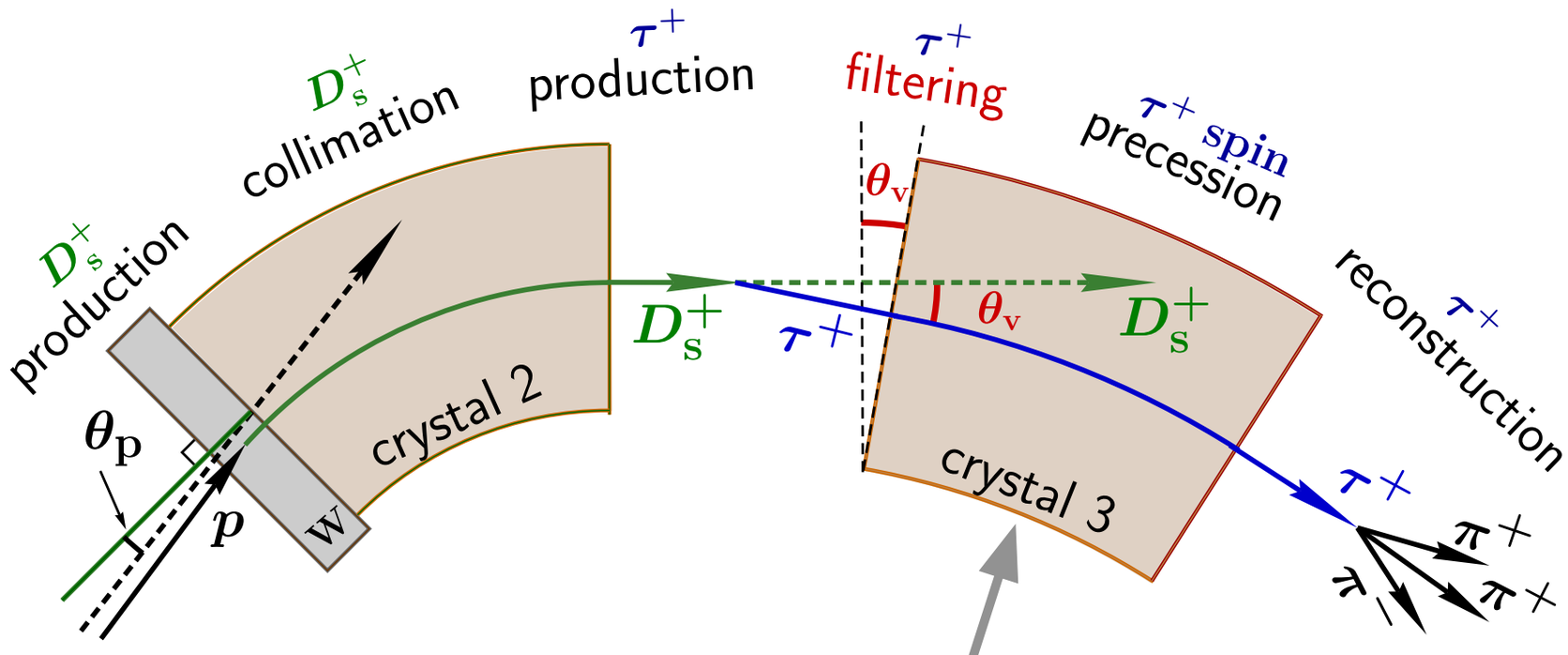
$$\tau^+ \rightarrow \pi^+\pi^-\pi^+\bar{\nu}_\tau$$

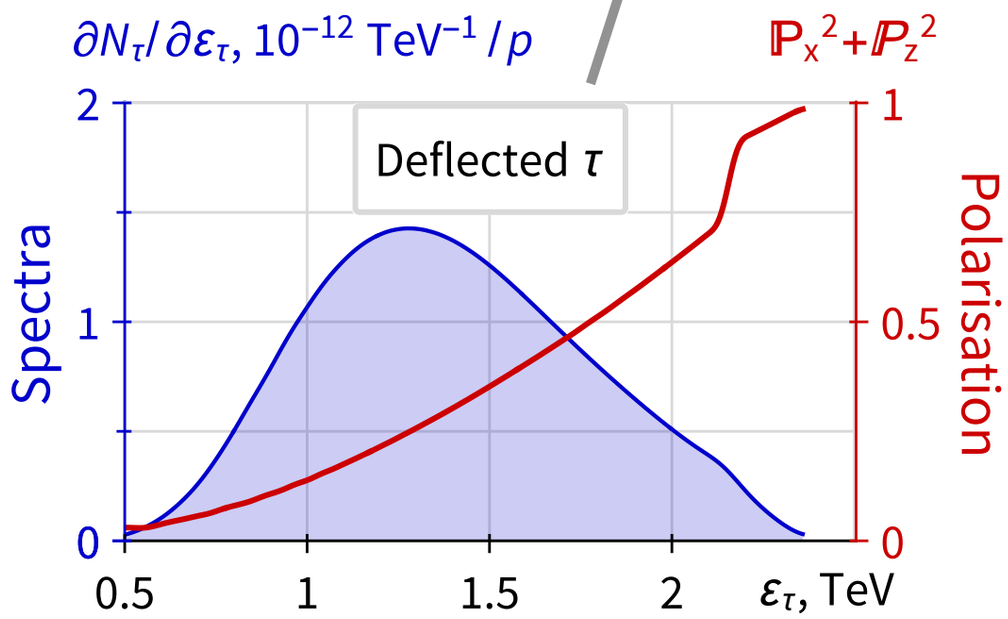
Crystal 2:

- deflection and “collimation” of D_s^+

Crystal 3:

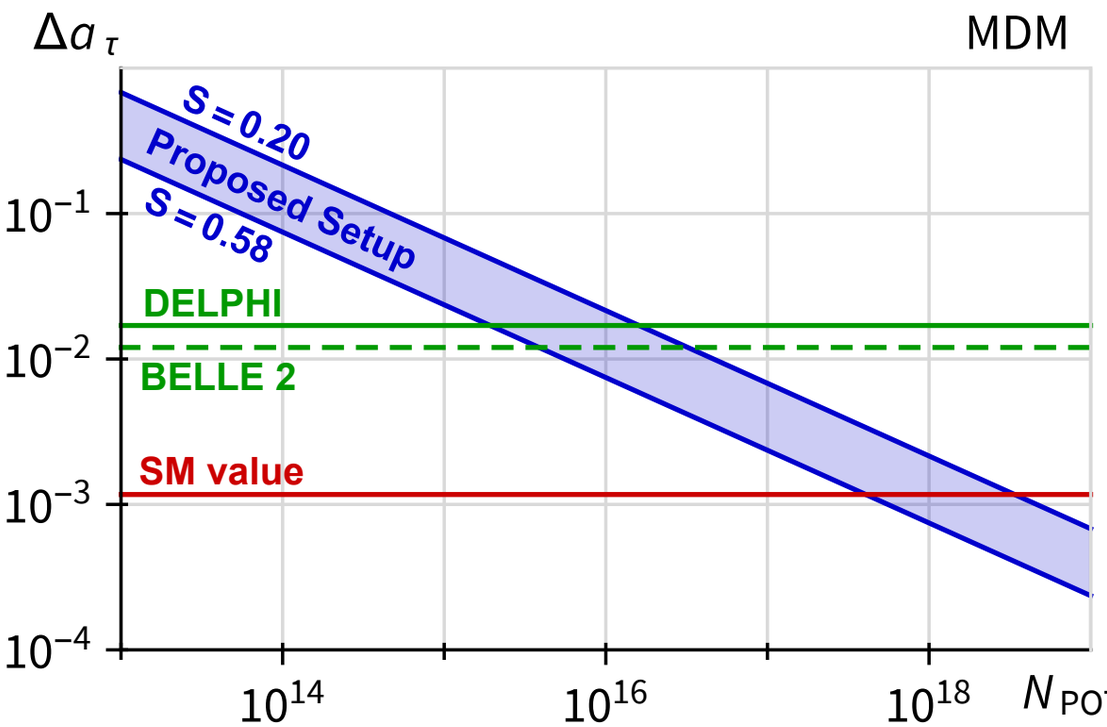
- selecting τ produced by D_s^+
- filtering τ initial polarisation
- τ spin precession

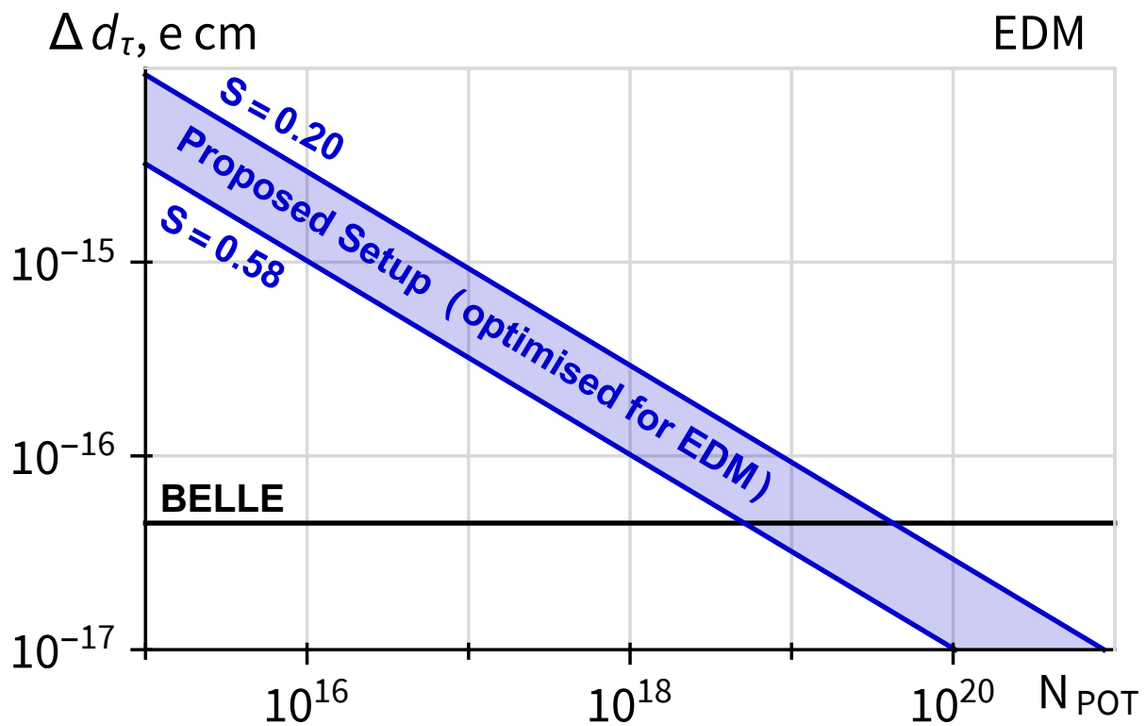




A. Fomin, A. Korchin, A. Stocchi, S. Barsuk, P. Robbe, JHEP (2019) 2019: 156, IC Channeling 2018.

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.

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

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)

Target:

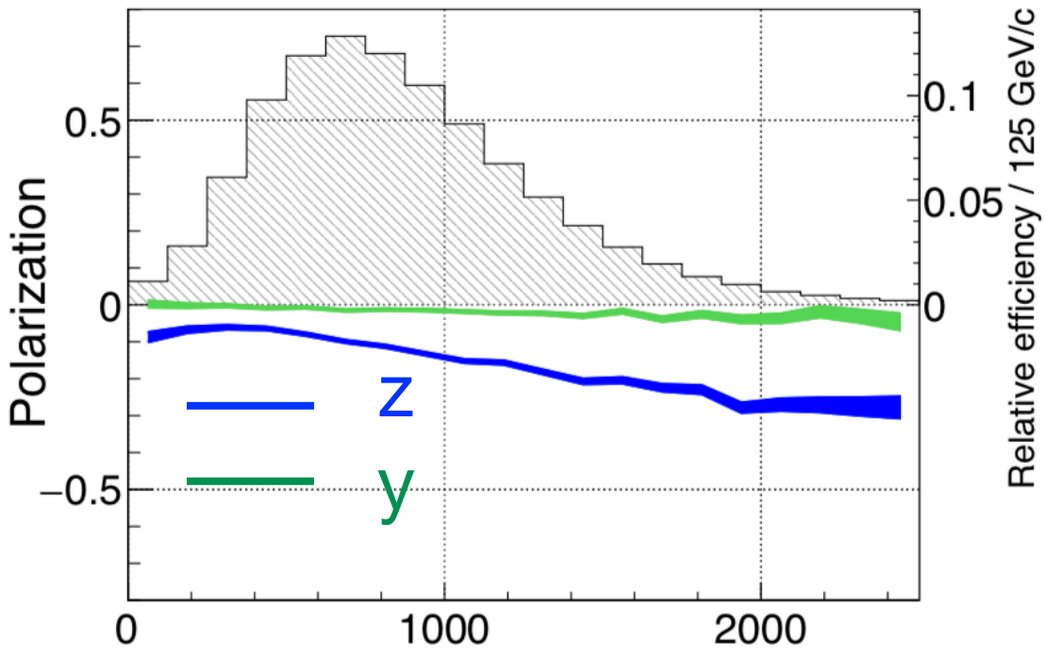
- production of $D_s^+(\to\tau^+\upsilon_\tau)$ with $\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$

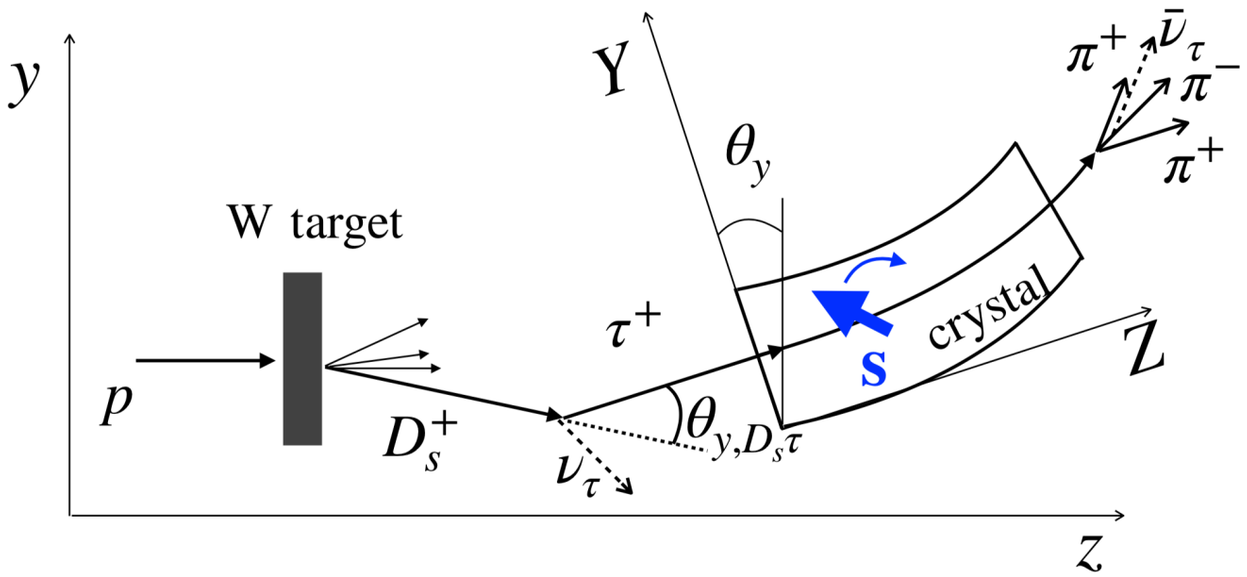
Single Crystal after target:

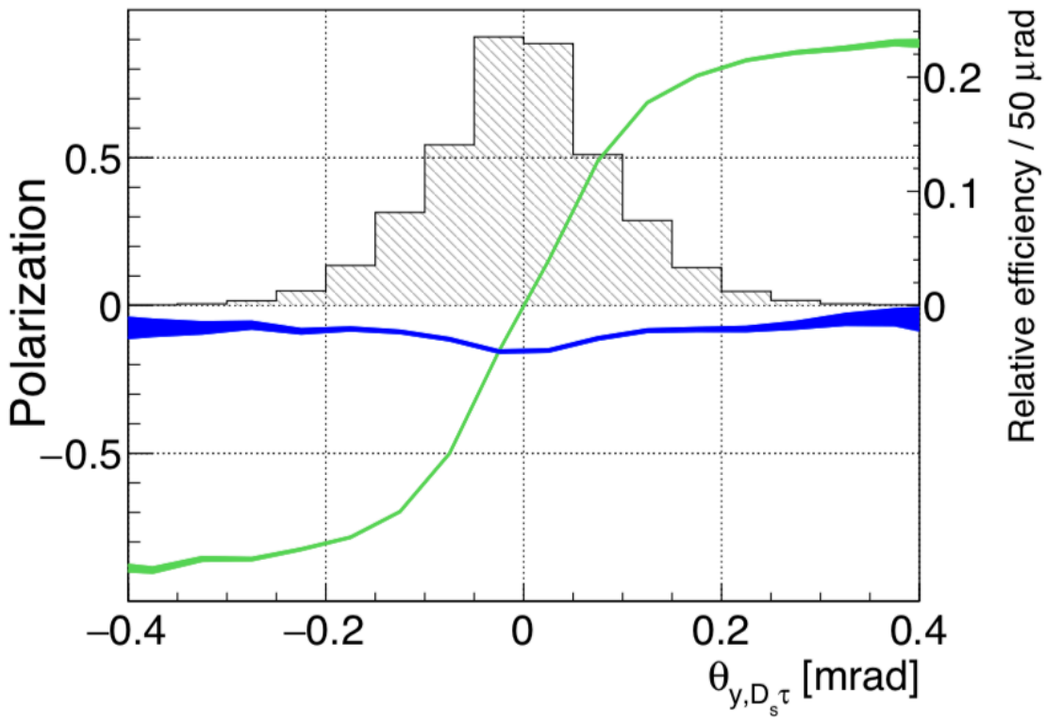
- τ spin precession

Spin polarisation:

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







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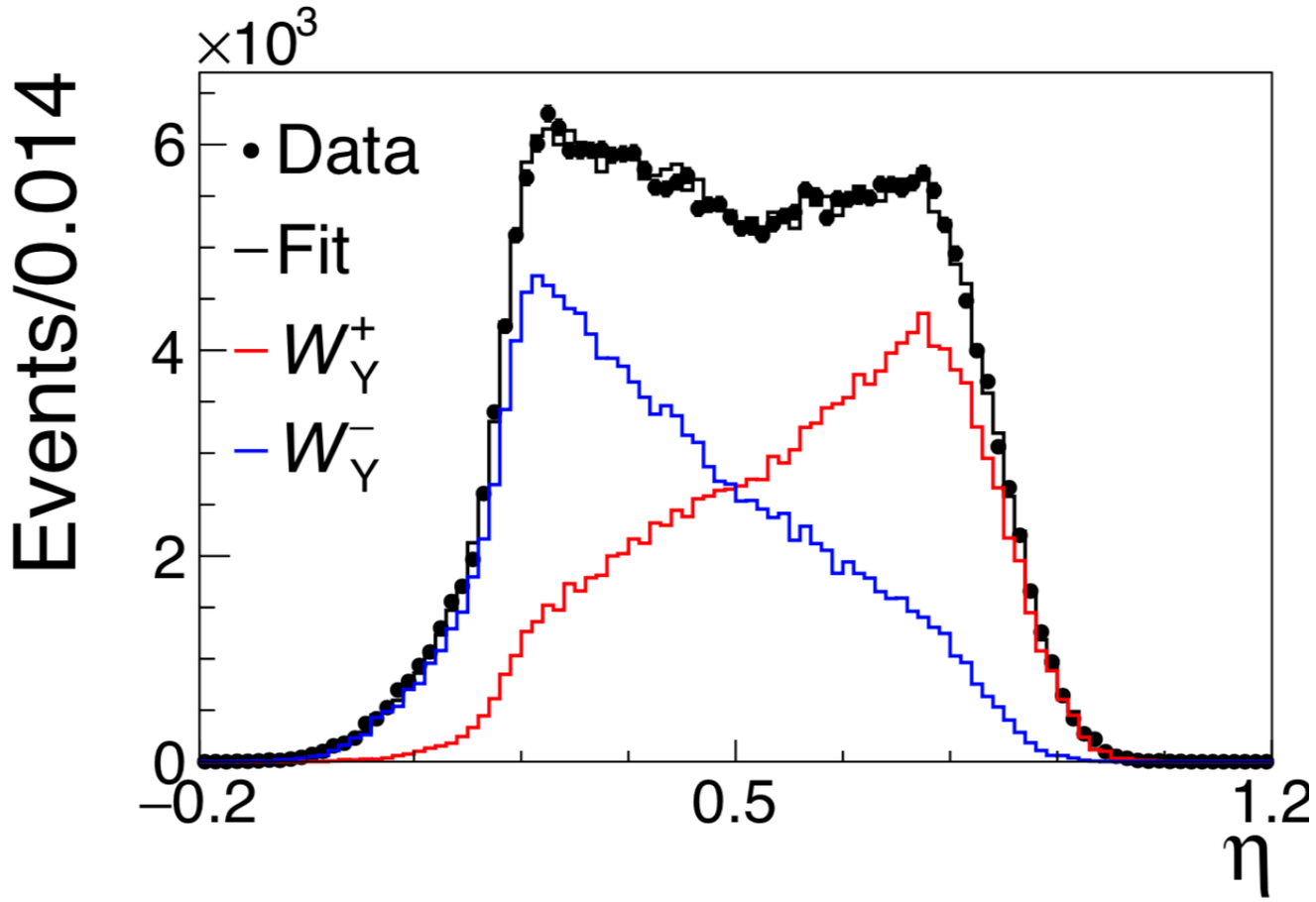

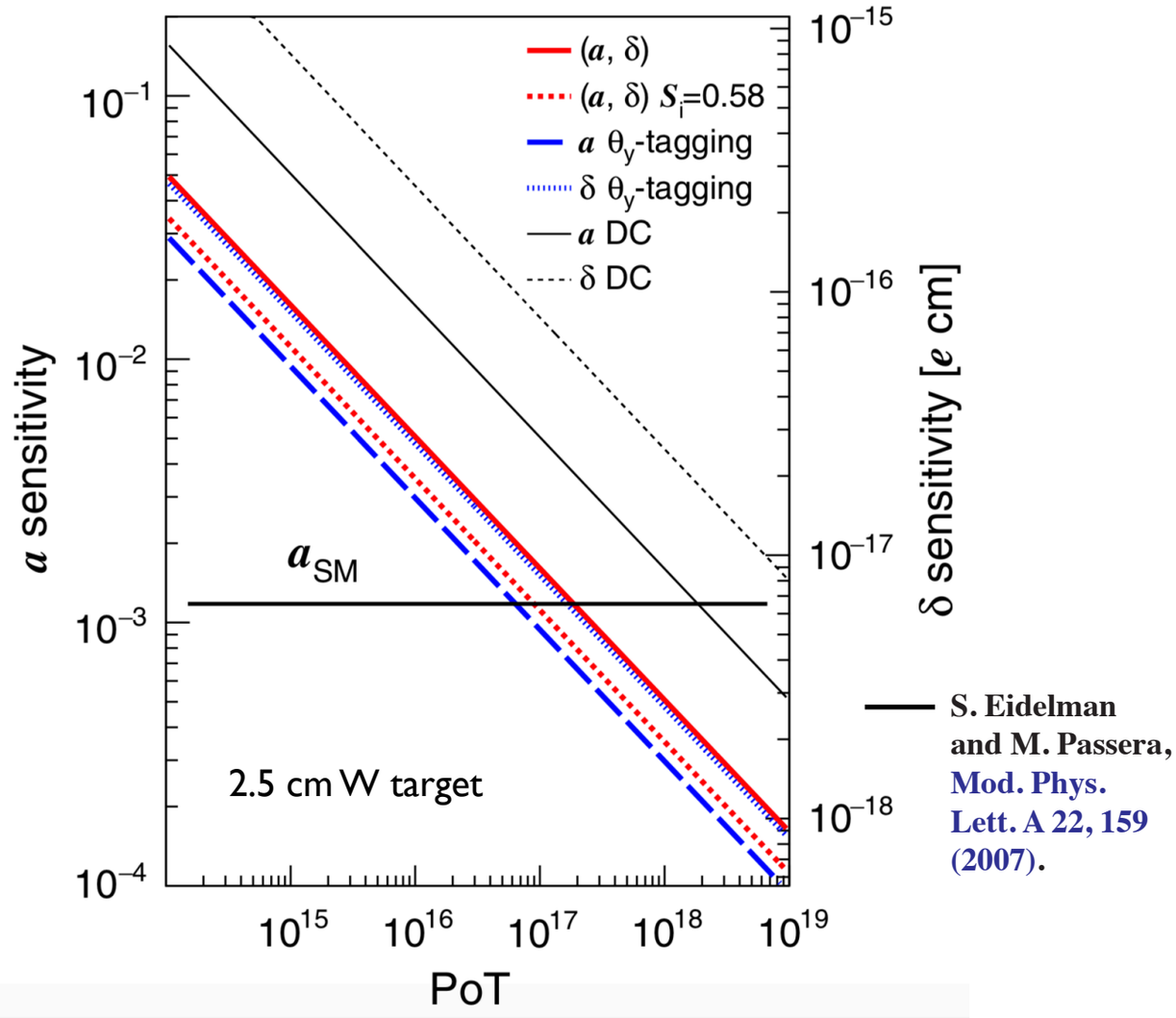

Multivariate classifier based on reconstructed τ variables to determine the polarisation and average event information S=0.42

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

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

EDM sensitivity ~10^{-17} e cm

Preparatory measurements in LHCb.

Explorative studies in ALADDIN

Beam dynamics simulations

Courtesy of C. Maccani (CERN, Padova)