The ALADDIN experiment at the LHC

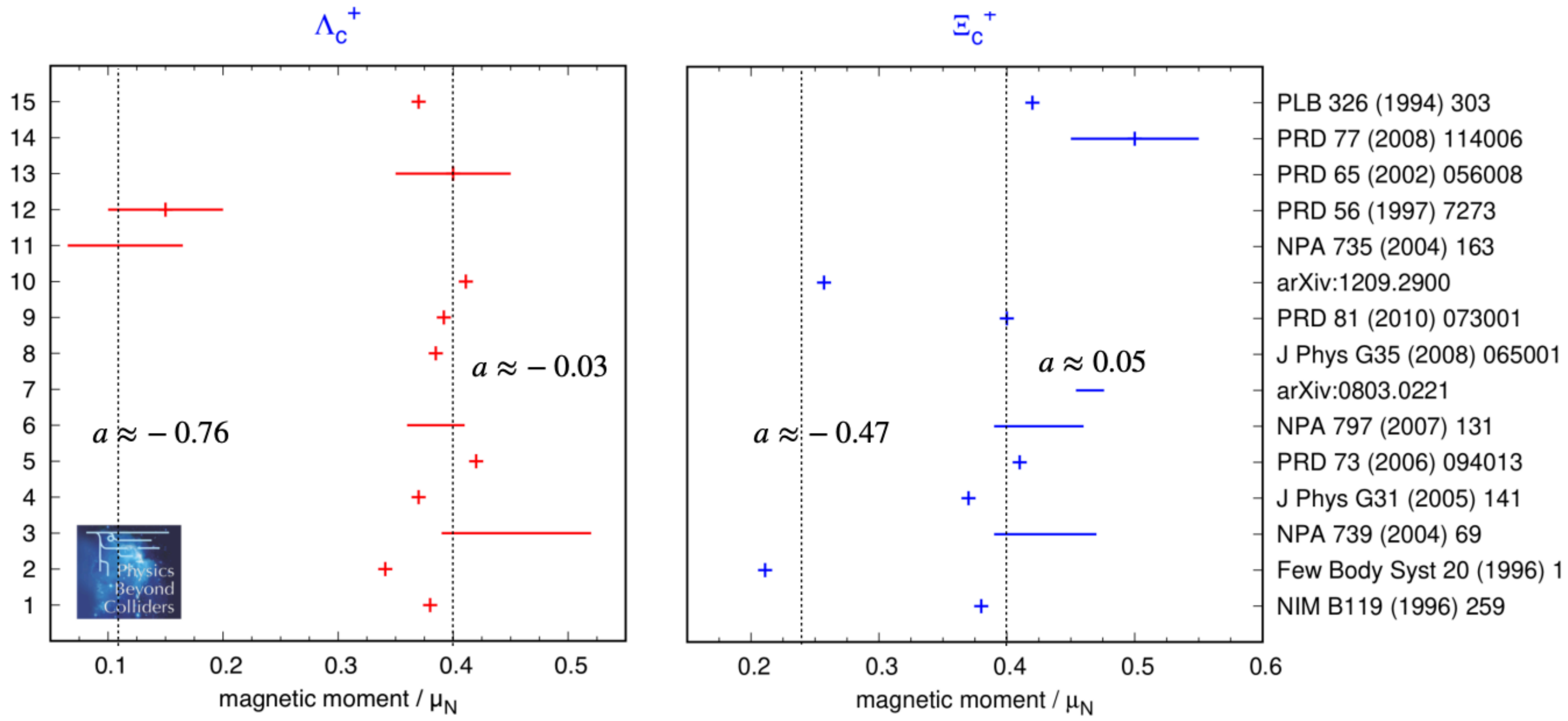
SARA CESARE – ON BEHALF OF THE ALADDIN COLLABORATION

EPS-HEP – MARSEILLE 6-11 JULY 2025

Magnetic Dipole Moments of charm baryons

Naive quark model MDM $\mu_{\Lambda_c^+} = \mu_c, \;\; \mu_{\Xi_c^+} = \mu_c$

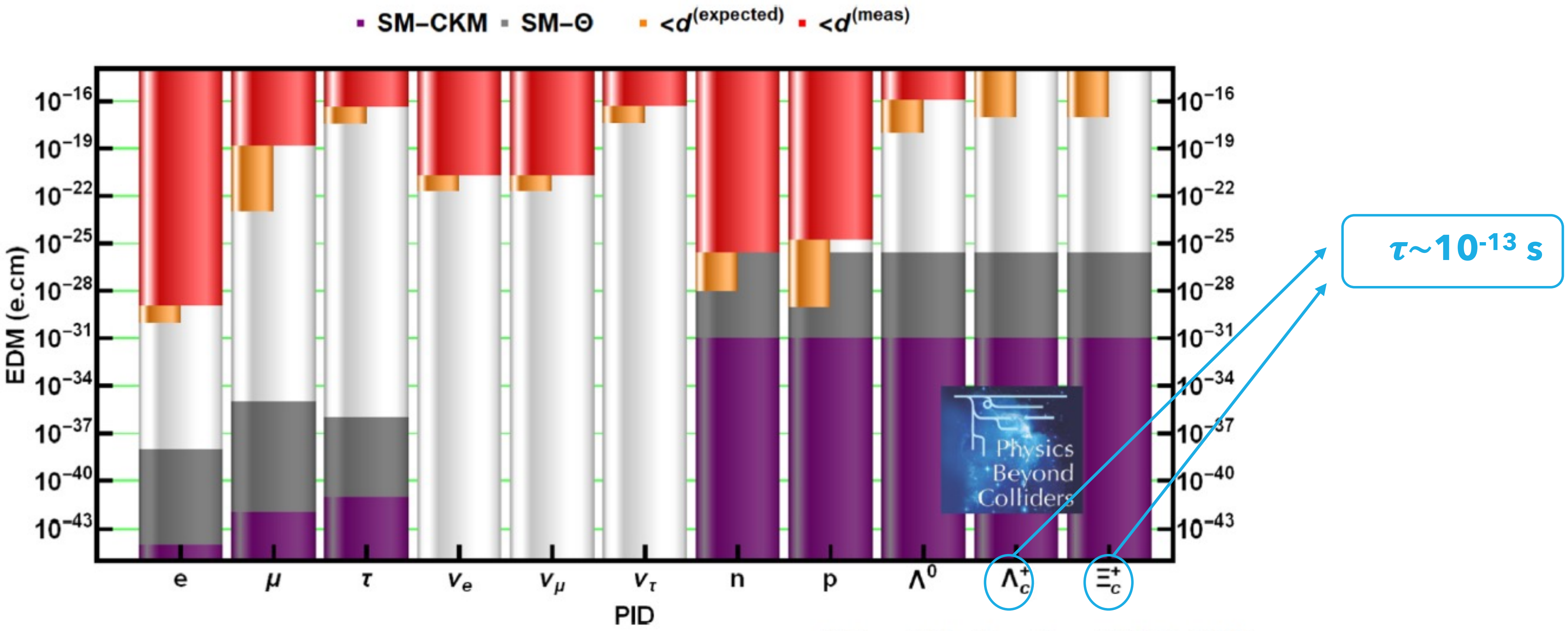
No measurements to date for short-lived **charm** baryons - will provide important anchor points for QCD calculations.



CERN-PBC-REPORT-2018-008

Direct measurements of EDM of charm baryons

No direct measurements of EDM for charmed baryons due to their short lifetime.



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

Experimental technique

Experimental method for EDM/MDM measurements of fundamental particles:

↓

Measurement of the spin precession angle induced by interaction with magnetic field

Requirements:

1. large samples of high energy polarized particles
2. intense electromagnetic field.
3. detector to measure the final polarization vector

Unstable particles: the precession has to take place before the decay (decay length ~ few cm for TeV energy particles at LHC).

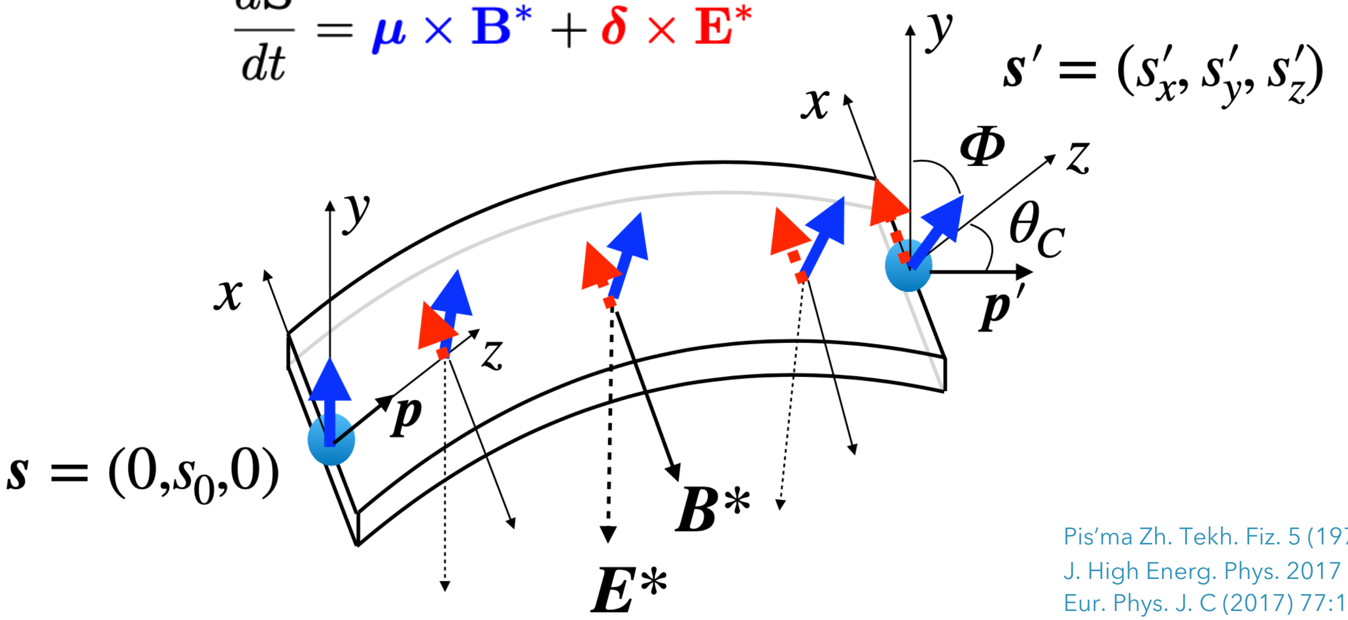
No experimental measurements exist for short-lived charm baryons since negligibly small spin precession would be induced by magnetic fields used in current particle detectors.

Spin precession in bent crystals

Firstly predicted by Baryshevsky (1979)

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

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



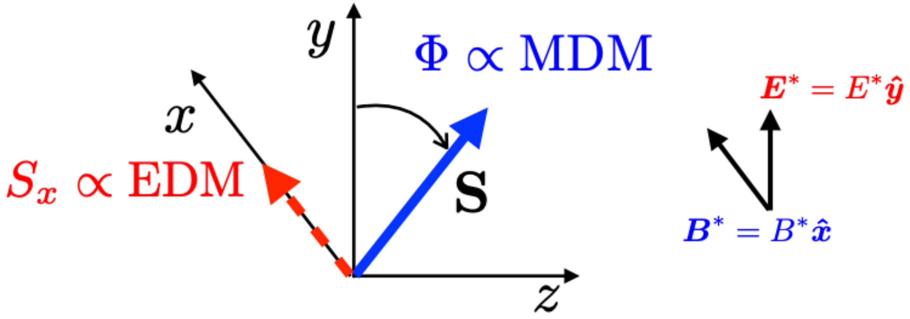
Pis'ma Zh. Tekh. Fiz. 5 (1979) 182
J. High Energ. Phys. 2017 (2017) 120
Eur. Phys. J. C (2017) 77:181
Eur. Phys. J. C (2017) 77:828

In bent crystal we obtain:

- Electric field E ≈ 1 GV/cm
- Effective magnetic field B ≈ 500 T

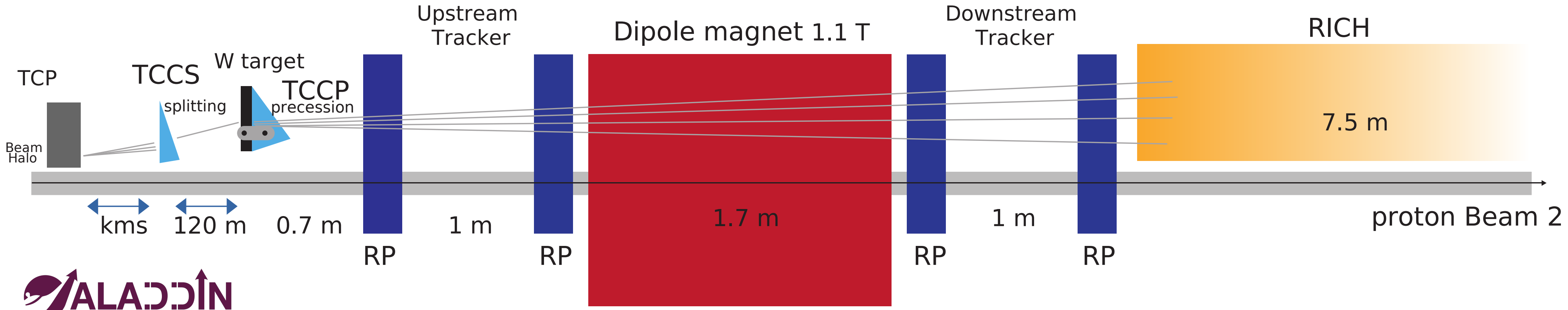
Induce a **spin precession** of the particles in a short distance

$$s_x \approx s_0 \frac{d}{g-2}(\cos\Phi - 1)$$



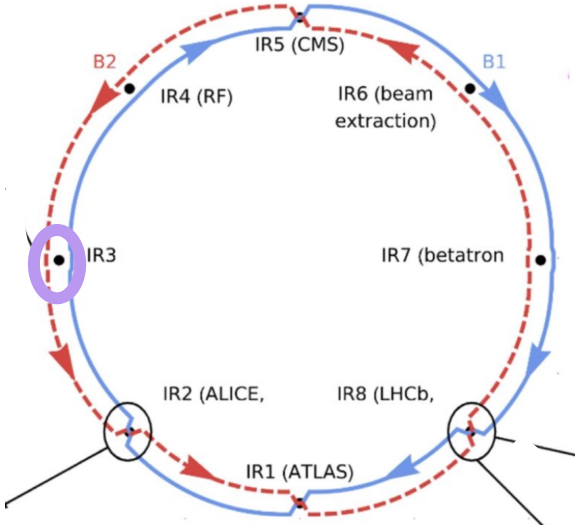
D. Chen et al. [E761 collaboration], Phys. Rev. Lett. 69, 3286 (1992).

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



ALADDIN

An Lhc Apparatus for Direct Dipole moments INvestigation



ALADDIN is a fixed-target eperiment proposed at LHC for EDM/MDM measurement of charm baryons

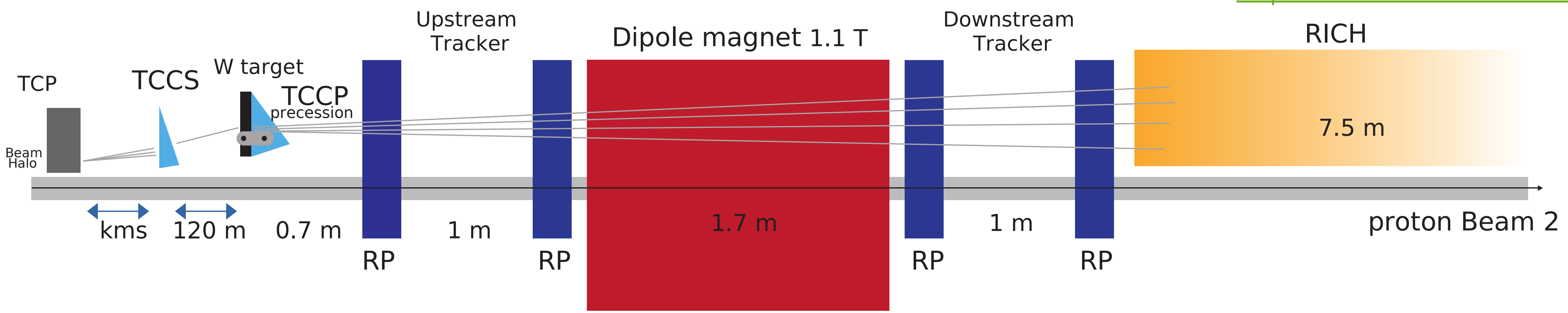
Pseudorapidity $5 < \eta < 9$

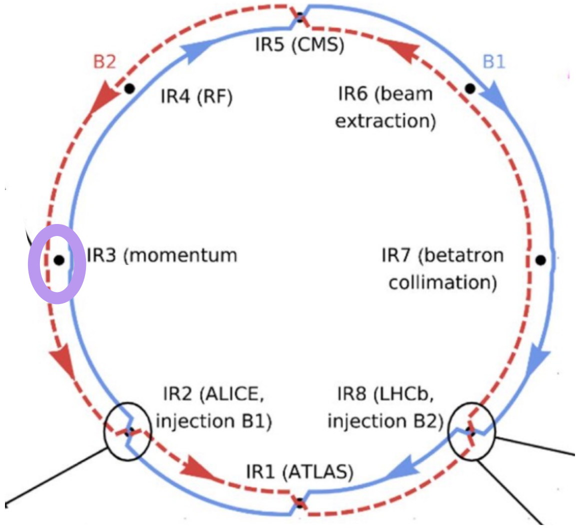
Experimental apparatus

- Crystal 1 (TCCS): halo extraction of the LHC beam
- Tungsten target - 2 cm
- Crystal 2 (TCCP): spin precession of baryons with charm
- Spectrometer: baryon reconstruction with a 1.9 Tm magnet
- Particle identification detector - RICH

The ALADDIN experiment

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





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} $\text{cm}^{-2}\text{s}^{-1}$
- EDM – explorative measurement – sensitivity 3×10^{-16} e cm
- MDM – expected sensitivity ~10%

Possibility to extend the physics program:

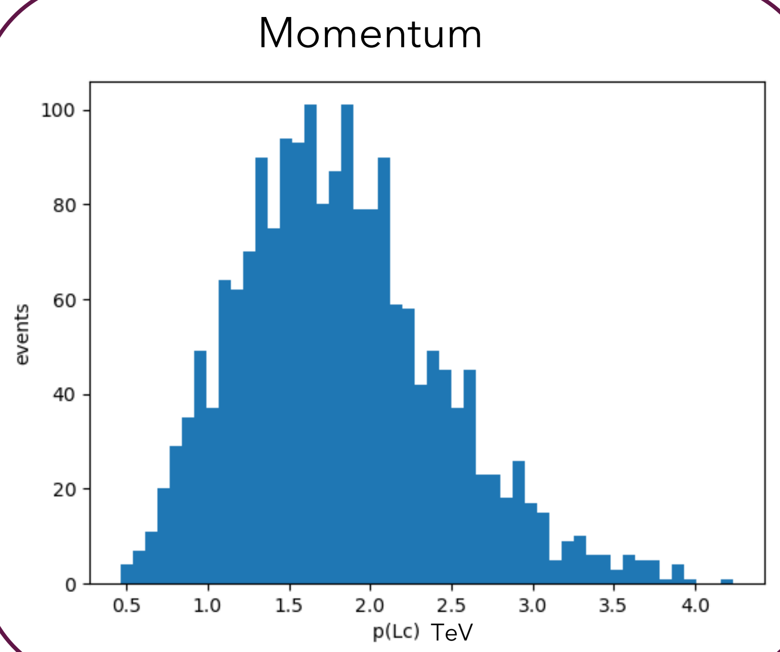
- Forward production of D mesons
- Photoproduction of J/ψ meson

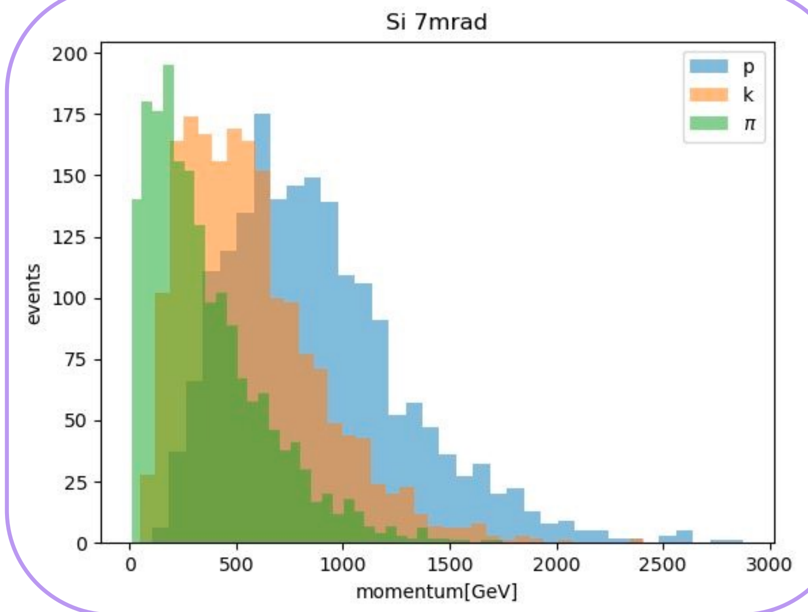
Pseudorapidity $5 < \eta < 9$

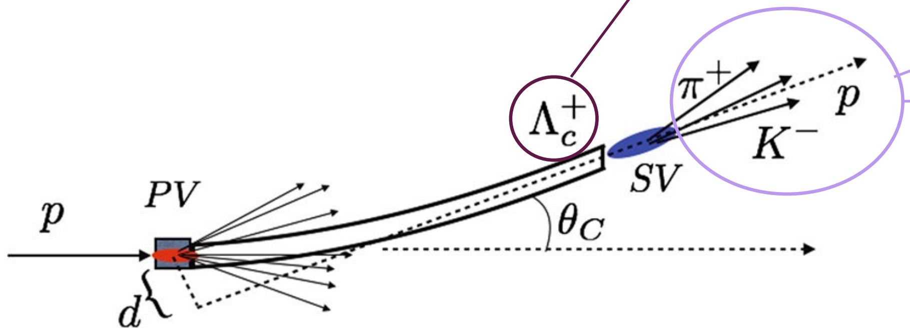
Signal kinematics

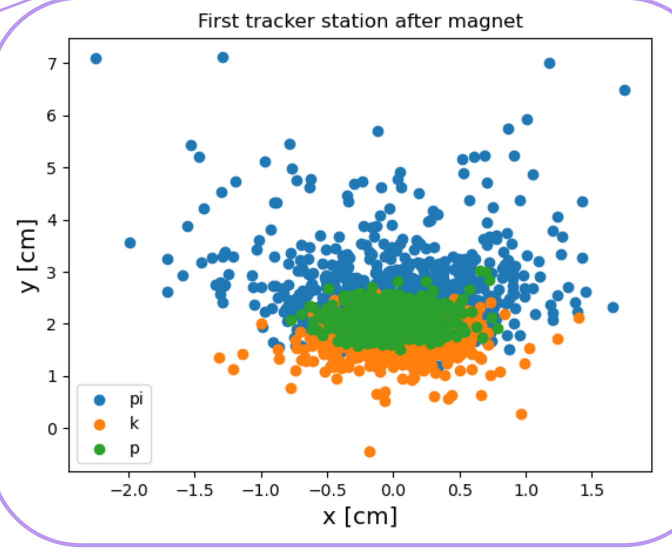
Starting from the 7 TeV protons of LHC:

- the charm baryons are produced in a **very forward** direction
- very high momentum, higher than **1 TeV.**







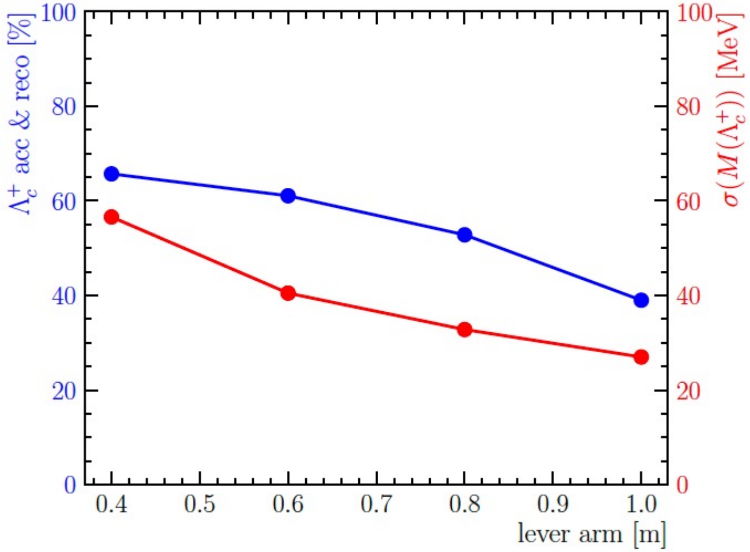


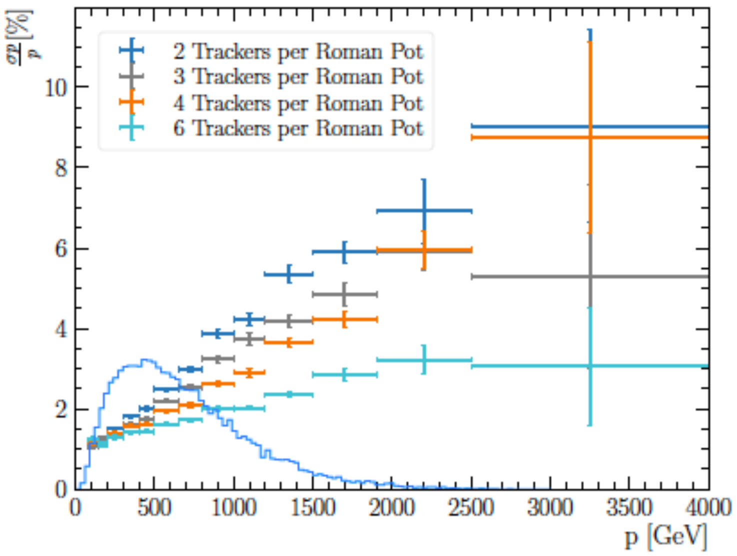
Forward Spectrometer

Designed as a forward spectrometer to give access to **zero angle production** of positive charged particles.

Pseudorapidity $5 < \eta < 9$

- Beam pipe: **Cu**, elliptical form
- Target: W, 2 cm long
- Cry 2: Si, 7 cm long, 7 mrad
- MCBW Magnet: Fe, at 2 m from crystal
  B=1.1 T, L =1.7 m
- Tracking stations: 4 before – 4 after magnet



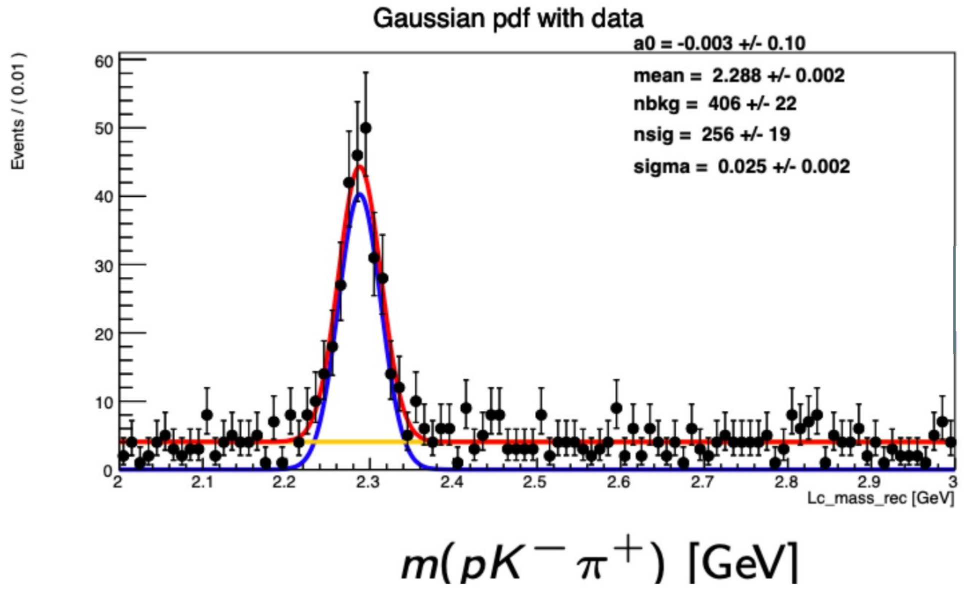


Mass resolution

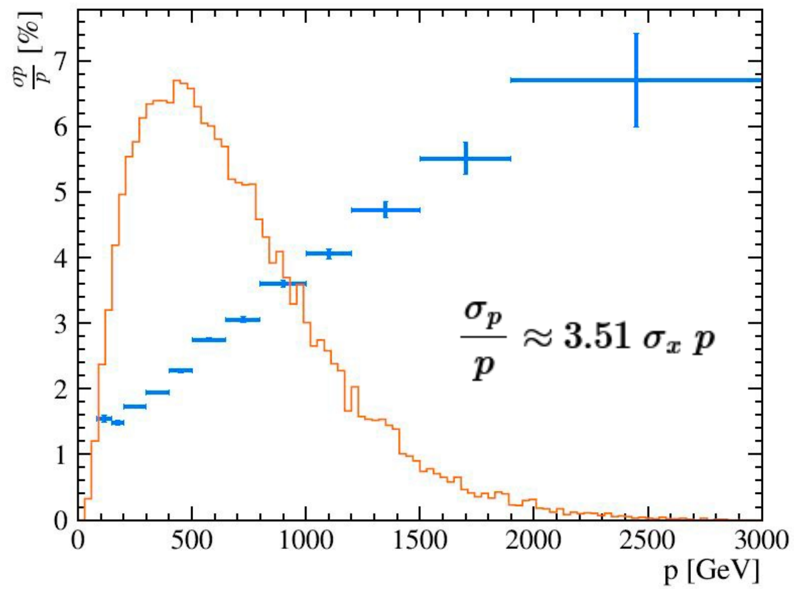
We need a good mass resolution (25 Mev) to separate the signal from misidentified background:

- $D^+ \to K^-\pi^+\pi^+$ one π^+ misidentified as p
- $D_s^+ \to K^+K^-\pi^+$ with K^+ misidentified as p

similar cross section, channelling probability, and lifetime as Λ_c^+



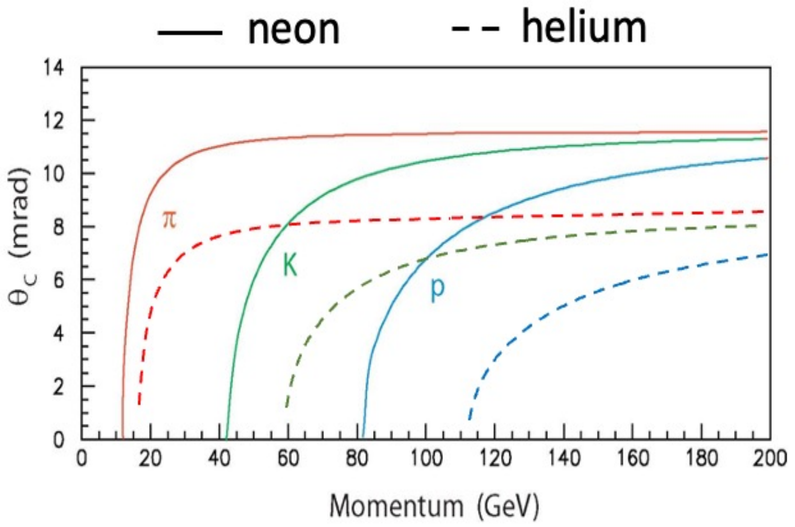
Mass resolution = 27(18) MeV for 2 (6) tracking layers



Particle Identification System

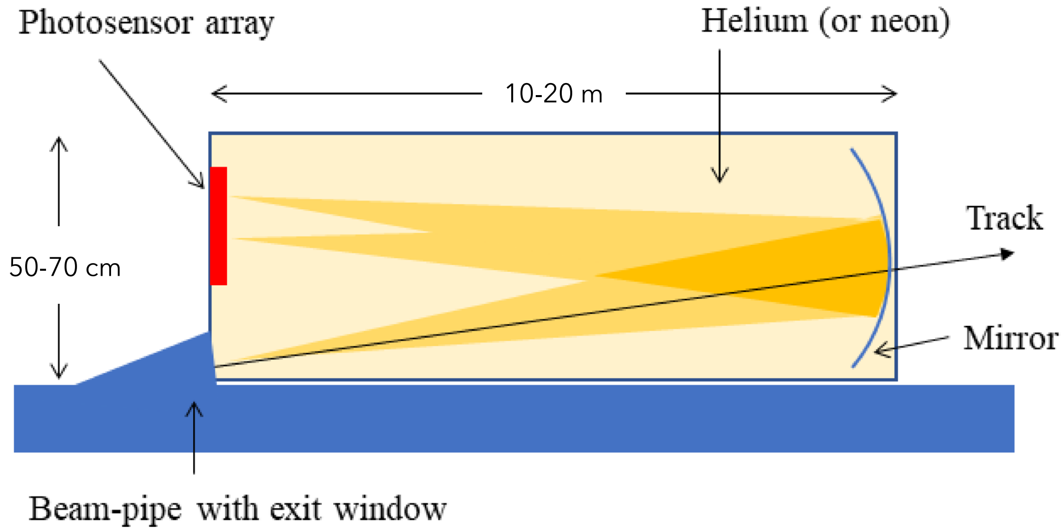
Adding a RICH detector would help separate the signal decay products and suppress background
The challenge is the high momenta involved, up to ~ **1 TeV** → excellent resolution is required

Aim for scaled-down RICH, using modern highly pixelated & efficient photosensors (e.g. SiPM or MCP-PMT) to compensate for reduced size



Spherical mirror at the end of the radiator volume,

- Gas: He/Ne.
- pixel size: $2\times2\ mm^2$
- Angular resolution: ~50 μrad/detector photon.

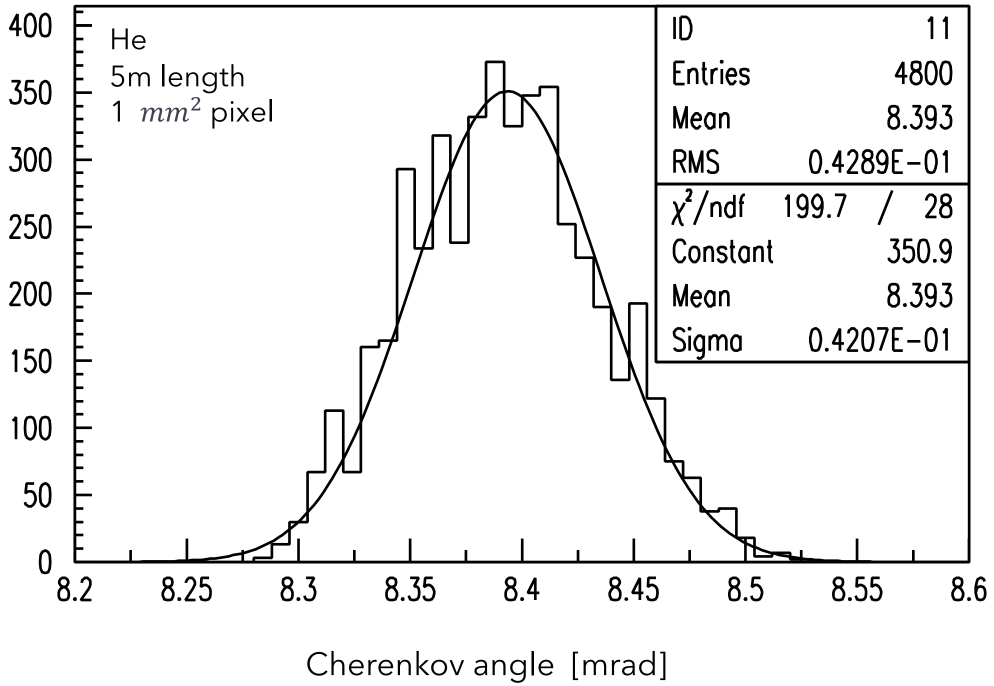


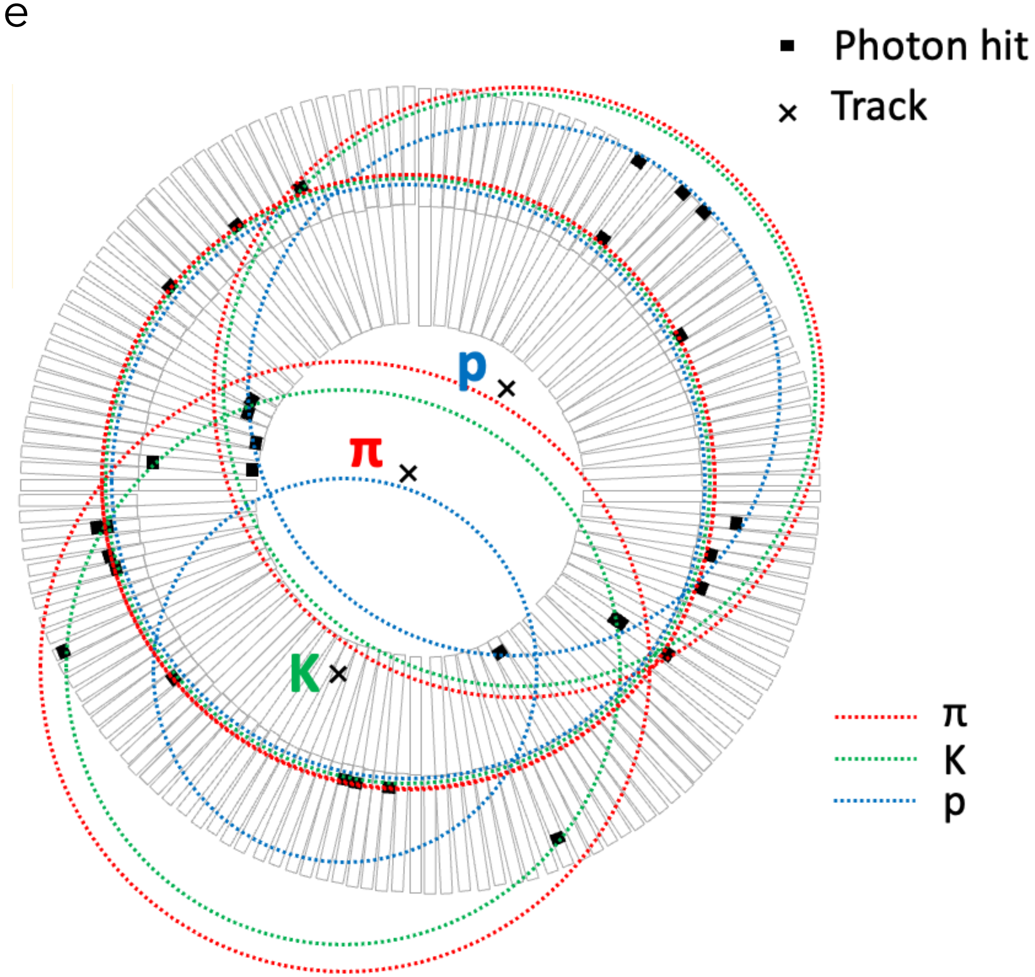
Angular resolution

Using the trajectory of the track and the position of the detected photon, the Cherenkov angle at emission can be reconstructed

σ_θ = 50 µrad per photon

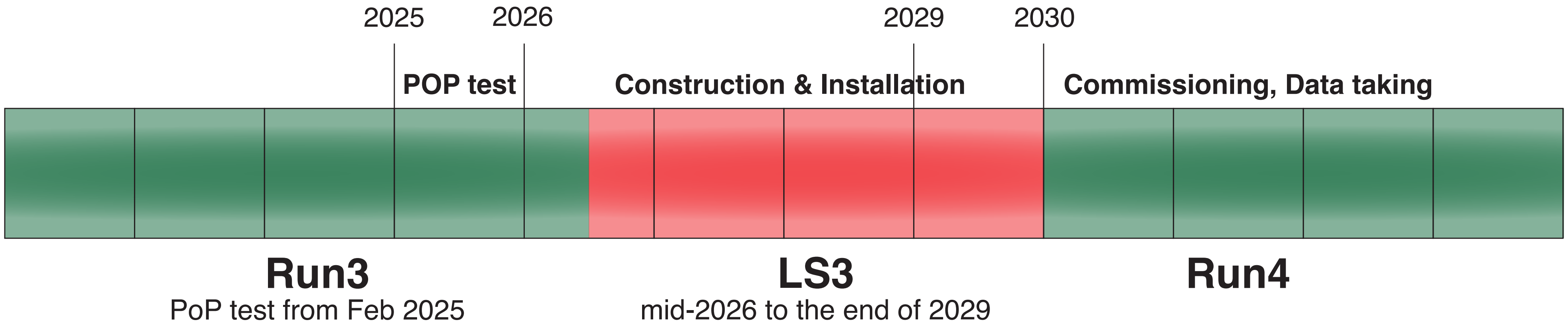
Combined resolution





Schedule of the experiment

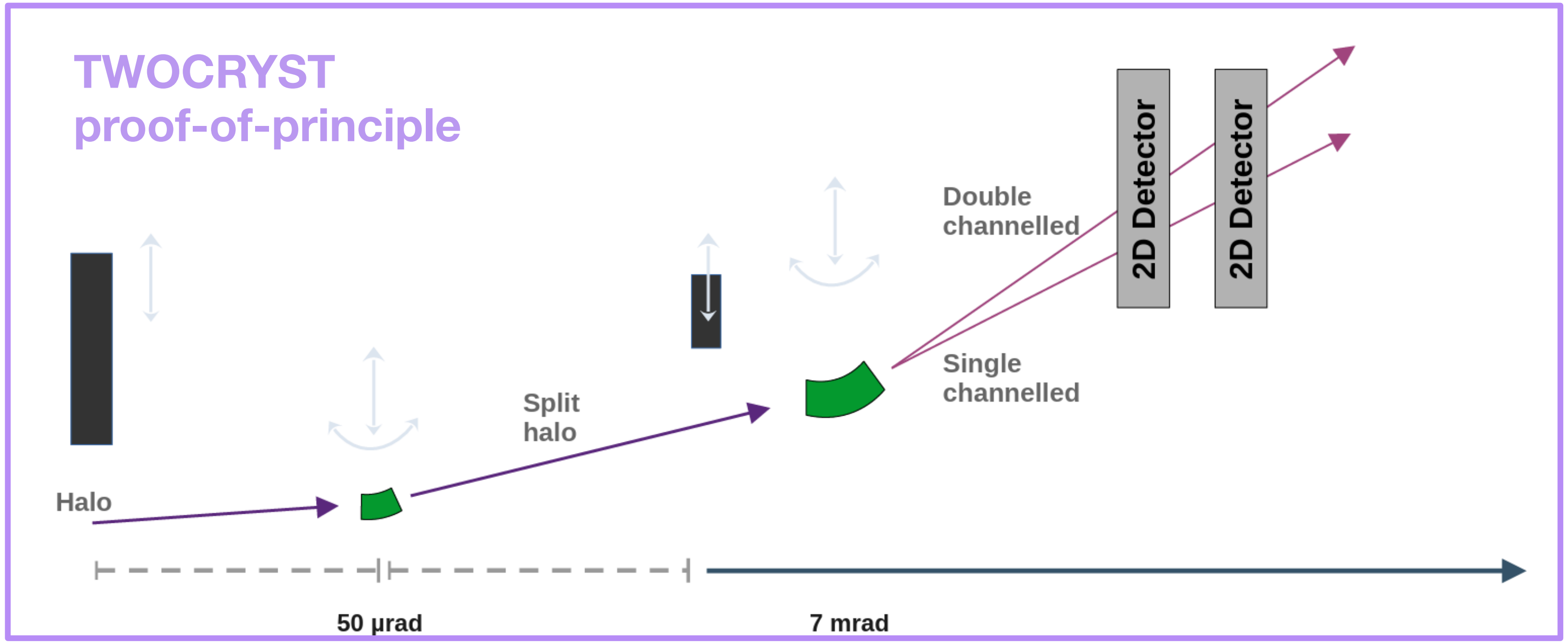
- **Letter of Intent (LOI)** was submitted in June 2024 - CERN-LHCC-2024-011,LHCC-I-041
- Very positive review by the LHCC scientific committee
- The **ALADDIN collaboration** has been created
  Spokesperson: N. Neri (Milano); Physics Coordinator: F. Martinez Vidal (Valencia); Collaboration Board Chair: Roberta Cardinale (Genova)
- A document with technical specifications will be published by the end of 2025
- The experiment is to be built and installed during LS3
- Data taking is planned during Run4
- Proof of Principle installed in 2025, first data taking took place in June 2025

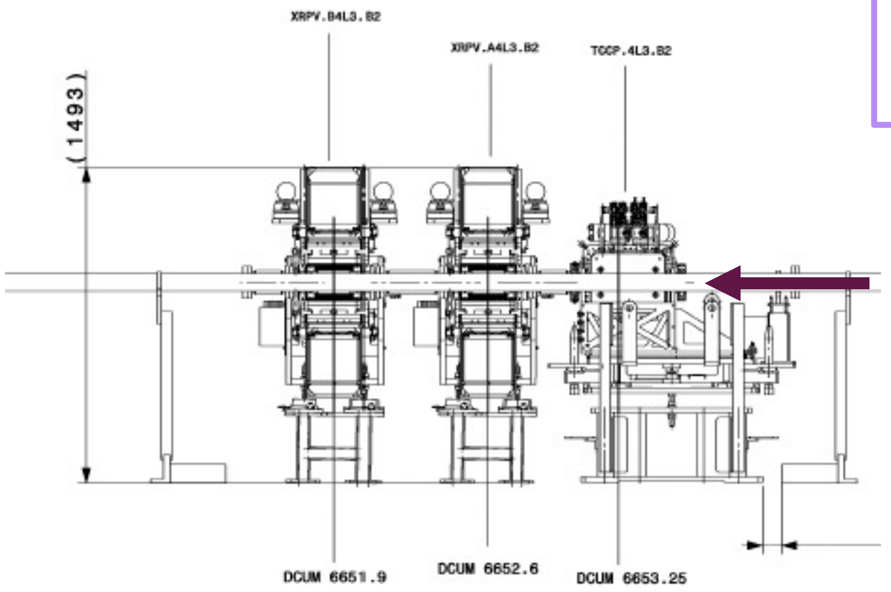


Proof-of-principle : the TWOCRYST project

See also R. Cai's talk on Thursday

A proof of principle (PoP), called TWOCRYST, was installed in 2025 at IR3, one of the two collimation regions of the LHC.





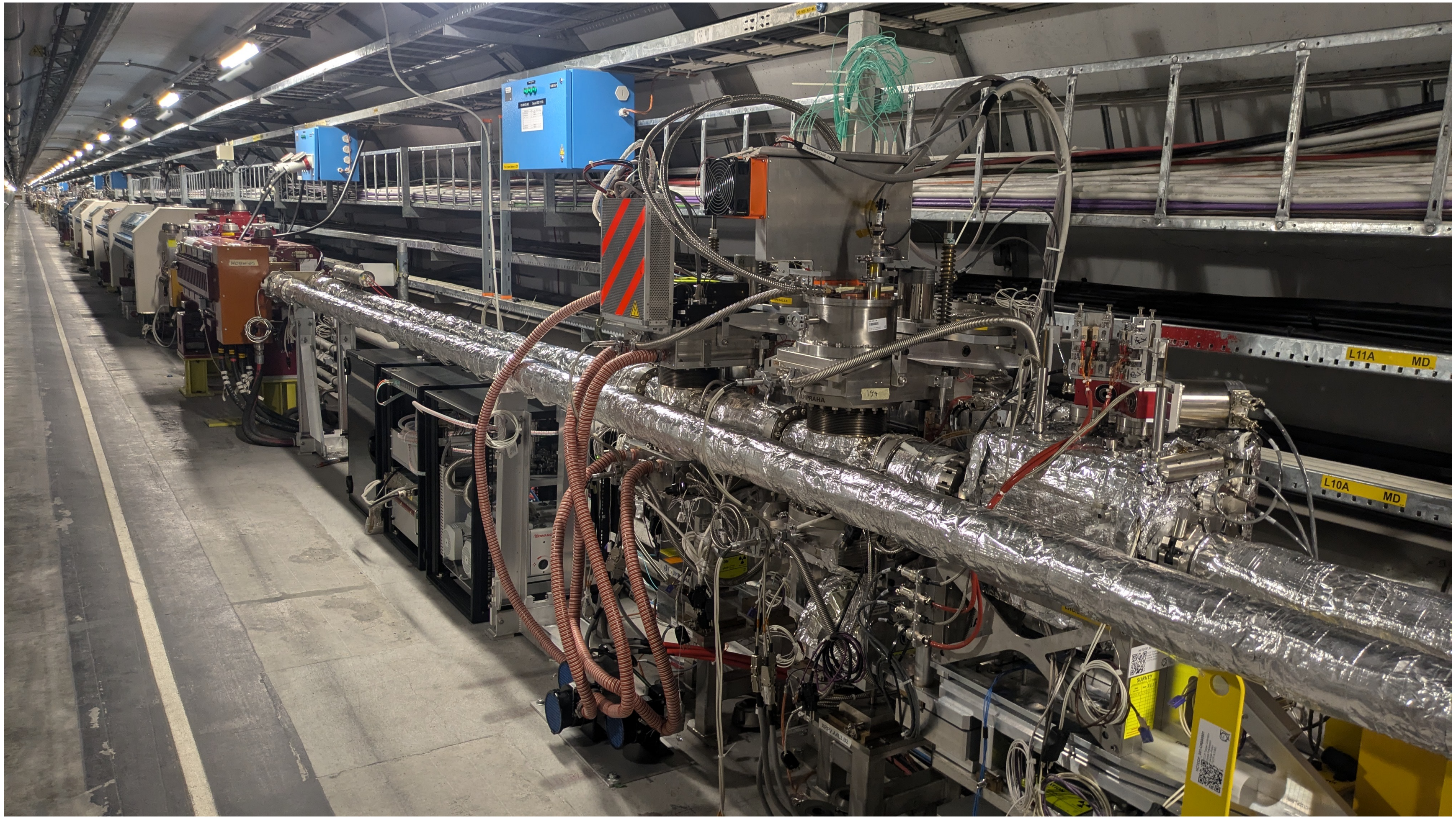
Goals of the PoP

- Demonstration of operational feasibility.
- Measurement of channeling efficiency for long crystals at TeV energies.
- Study of proton beam intensity on target and study of criticalities.

TWOCRYST was successfully installed in March 2025.

Roman Pots

- Allow the detector to be placed in a secondary vacuum within the accelerator tube without interfering with the beam
- Ability to achieve a distance d < 1 mm of the active area from the main beam

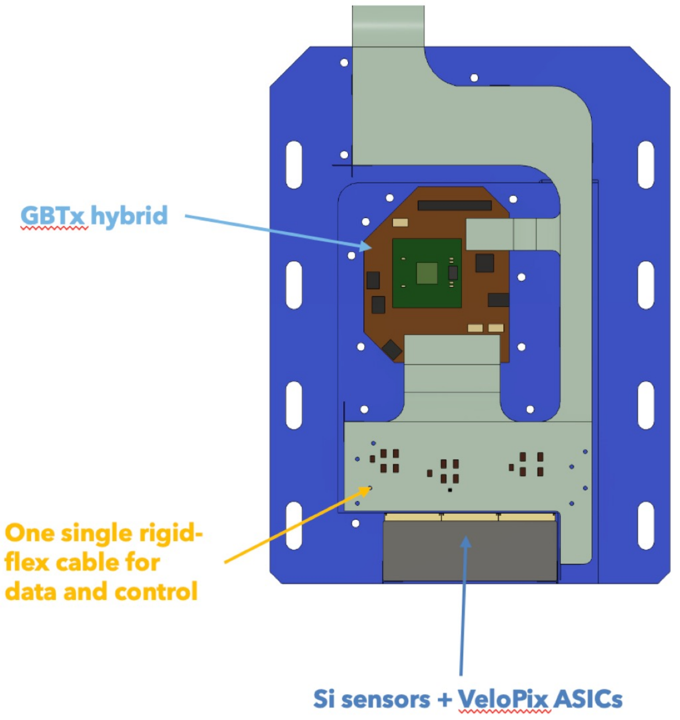


Data taking

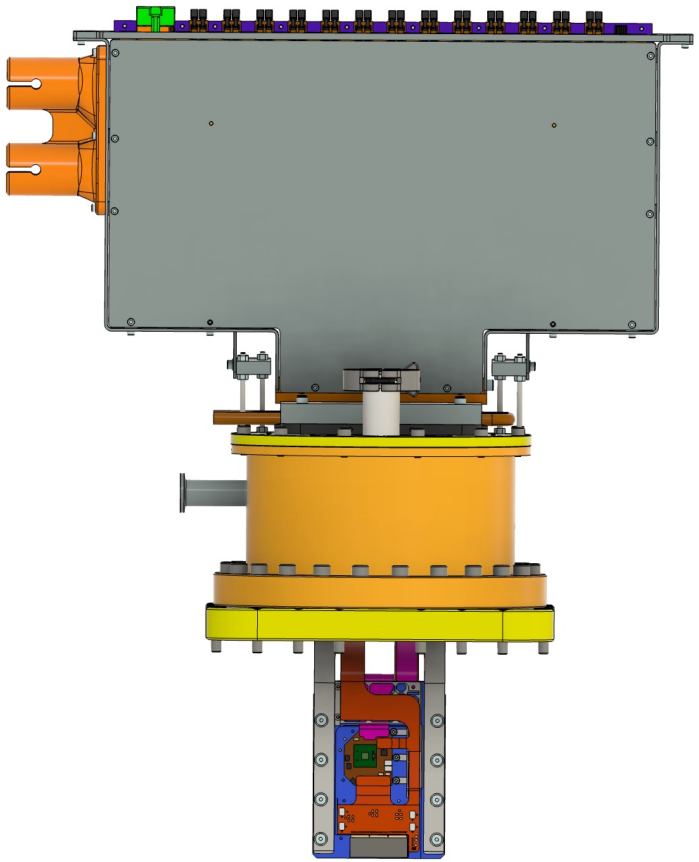
- Planned during 2025 with a special beam configuration
- Total duration of data approx. 30h

Pixel detector

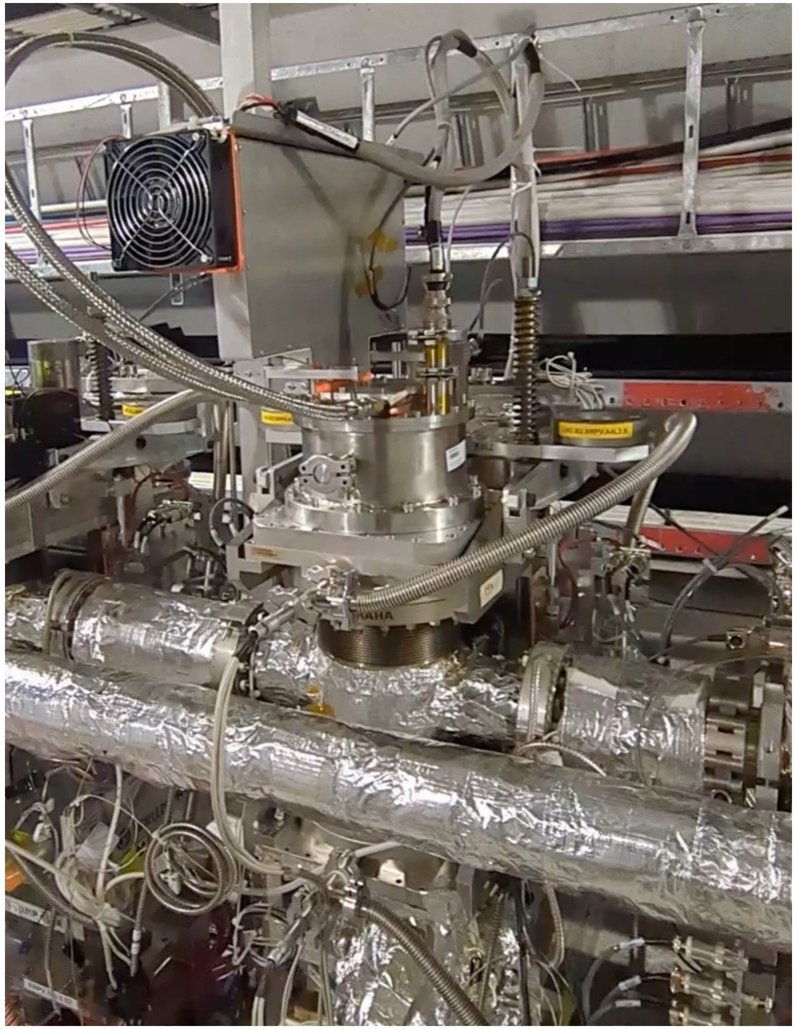
Tracking module



Detector package



Installed detector



First observation of double crystal channelling in the LHC

See also R. Cai's talk on thursday

Goals of the Machine Development tests

1. Multi-Turn crystal characterization

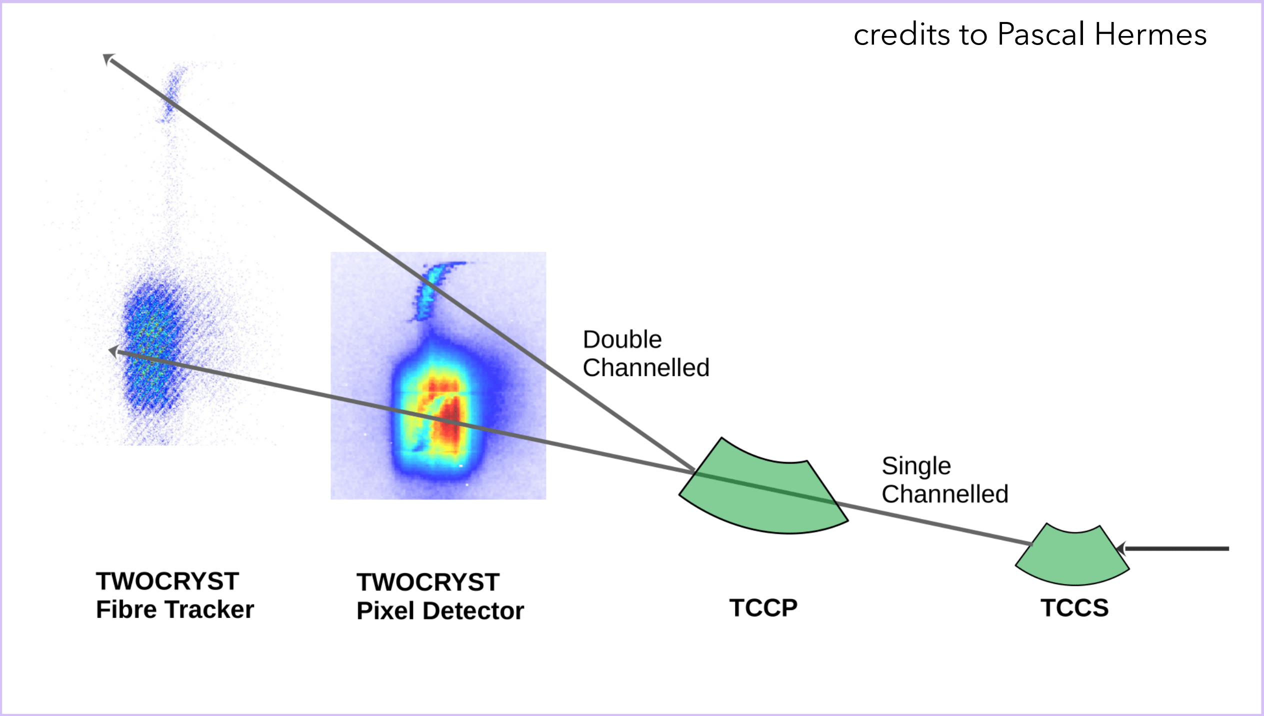
- Alignment and linear scans of both crystals + Roman Pots
- Channeling efficiency measurements for both TCCS and TCCP

2. TWOCRYST double channeling

- Vertical scan of the TCCP position to get into the double channeling configuration

Beam configuration

- Up to 30 pilot bunches, setup beam flag.
- Beam phase: injection



Snapshot of double-channelling signals as seen from both detectors

Conclusions

- ALADDIN is a fixed-target eperiment proposed at LHC for EDM/MDM measurement of charmed baryons.
- Expected sensitivity for MDM of $2{\times}10^{-2}\ \mu_N$ and EDM of $3{\times}10^{-16}\ e\ cm$ with 10^{13} PoT
- Successful Proof-of-principle took place in June 2025
- Letter of Intent was submitted in June 2024
- Very positive response from the LHCC committee
- A technical paper will be submitted by the end of 2025 to consider approval of the experiment and installation during LS3

Acknowledgments

TWOCRYST is carried out under the Physics Beyond Colliders (PBC) Fixed-Target Working Group and is a collaboration of the institutes CERN, INFN (Italy), IFIC (University of Valencia-CSIC, Spain), IJCLab (France), the University of Malta, the Institute of Nuclear Physics of the Polish Academy of Sciences, Warsaw University of Technology (Poland), and UCAS (China).

The project acknowledges support from the PBC project; the HL-LHC project; the ATLAS-ALFA collaboration; the ERC SELDOM Grant No. 771642; the INFN CSN5 project OREO; the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU under Project Title PRIN 202277EWLW; contributions from the AICRYSCON project funded by Xjenza Malta through the FUSION: R&I Research Excellence Programme; support from MICIU, AEI, and GVA (Spain) under projects PID2022-139842NB-C22, CIPROM/2022/36, ASFAE/2022/030, and NextGenerationEU; and funding from the National Science Centre, Poland (project No. 2021/43/D/ST2/02761).

The project acknowledges the work of a A. Mazzolari (UNIFE & INFN Ferrara) for the design and realization of TCCS and TCCP and A. Sytov (INFN Ferrara) for MC studies on channeling efficiency

Grazie per l'attenzione!

Backup

References for baryons

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Electromagnetic dipole moments

For particles with spin = $\frac{1}{2}$ we can define

$$\boldsymbol{\delta} = \frac{1}{2} d \mu_B \mathbf{P} \quad \text{EDM}$$

$$\boldsymbol{\mu} = \frac{1}{2} g \mu_B \mathbf{P} \quad \text{MDM}$$

Where P is the polarization vector

$$\mathbf{P} = 2 < \mathbf{S} > /\hbar$$

Hamiltonian of the system

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

T,P

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

The EDM violates T and P, therefore it violates CP through CPT theorem.

- **EDMs** are source of possible physics Beyond the Standard Model.

  (not measured yet for charm and beauty baryons and tau leptons)

- **MDMs** provide important anchor points for QCD calculations.

Phys. Lett. B291 (1992) 293

Spin precession in bent crystals

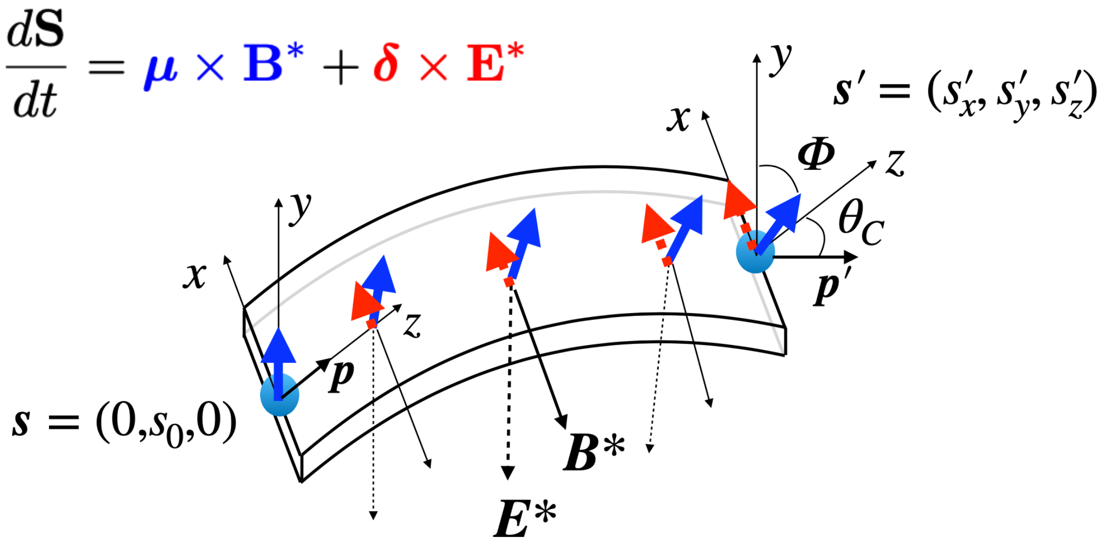
$$\boldsymbol{s} = (s_x, s_y, 0) \approx \frac{s_0(p_\mathrm{T})}{p_\mathrm{T}}(-p_{y_L}, p_{x_L}, 0)$$

$$s_0(p_\mathrm{T}) \approx A\left(1 - e^{-Bp_\mathrm{T}^2}\right)$$

$$s'_x \approx s_y \frac{a'd'}{a'^2_\mathrm{d}}(1-\cos\Phi) + s_x\left(\frac{a'^2}{a'^2_\mathrm{d}} + \frac{d'^2}{a'^2_\mathrm{d}}\cos\Phi\right),$$

$$s'_y \approx s_y\left(\frac{d'^2}{a'^2_\mathrm{d}} + \frac{a'^2}{a'^2_\mathrm{d}}\cos\Phi\right) + s_x\frac{a'd'}{a'^2_\mathrm{d}}(1-\cos\Phi),$$

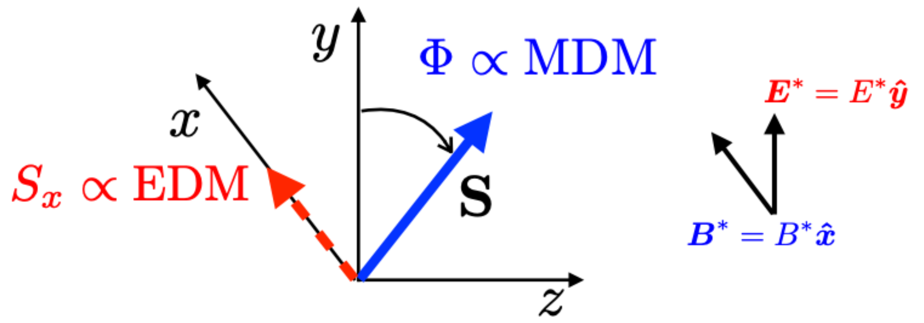
$$s'_z \approx -s_y\frac{a'}{a'_\mathrm{d}}\sin\Phi + s_x\frac{d'}{a'_\mathrm{d}}\sin\Phi,$$



Pis'ma Zh. Tekh. Fiz. 5 (1979) 182
J. High Energ. Phys. 2017 (2017) 120
Eur. Phys. J. C (2017) 77:181
Eur. Phys. J. C (2017) 77:828

Induce a **spin precession** of the particles in a short distance

$$\Phi \approx \frac{g-2}{2}\gamma\theta_C \qquad s_x \approx s_0\frac{d}{g-2}(\cos\Phi - 1)$$



D. Chen et al. [E761 collaboration], Phys. Rev. Lett. 69, 3286 (1992).

Polarization measurements and MDM/EDM extraction

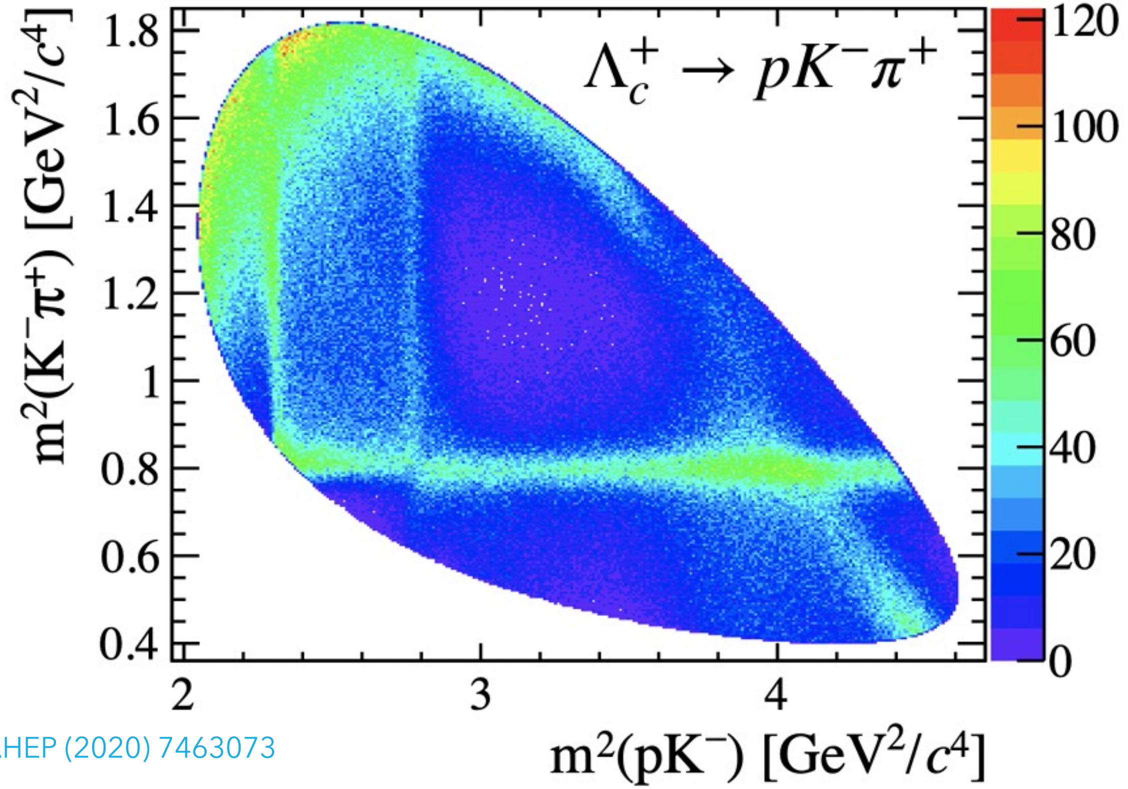
- Use many 3-body decays to increase the signal yield
- Extract maximum information via full amplitude analysis of the 3-body decays

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

The average event information S2 represents the sensitivity to the polarization s

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

where s0 is the best estimate for the polarization



D. Marangotto, AHEP (2020) 7463073

Background suppression

Compare efficiency for signal

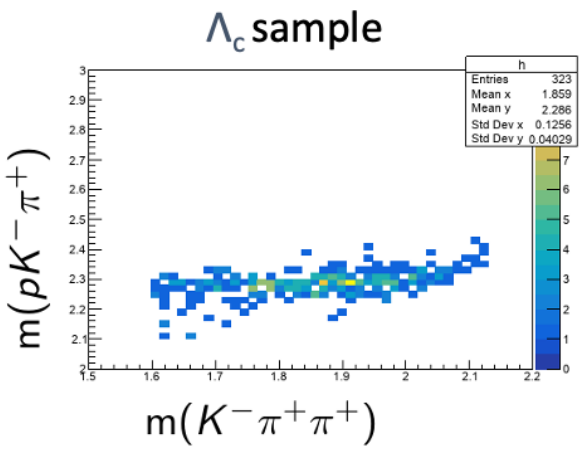
$\Lambda_c^+ \rightarrow p\, K^- \pi^+$

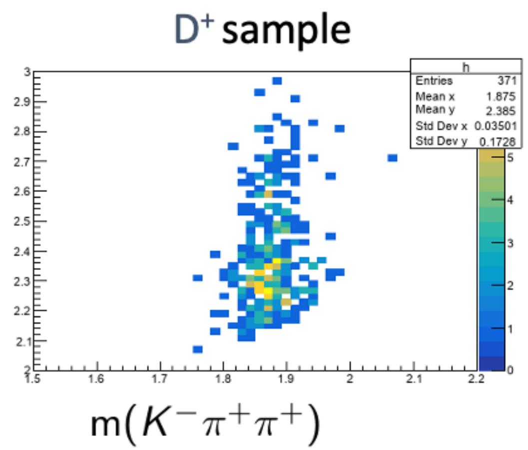
and suppression of background decays

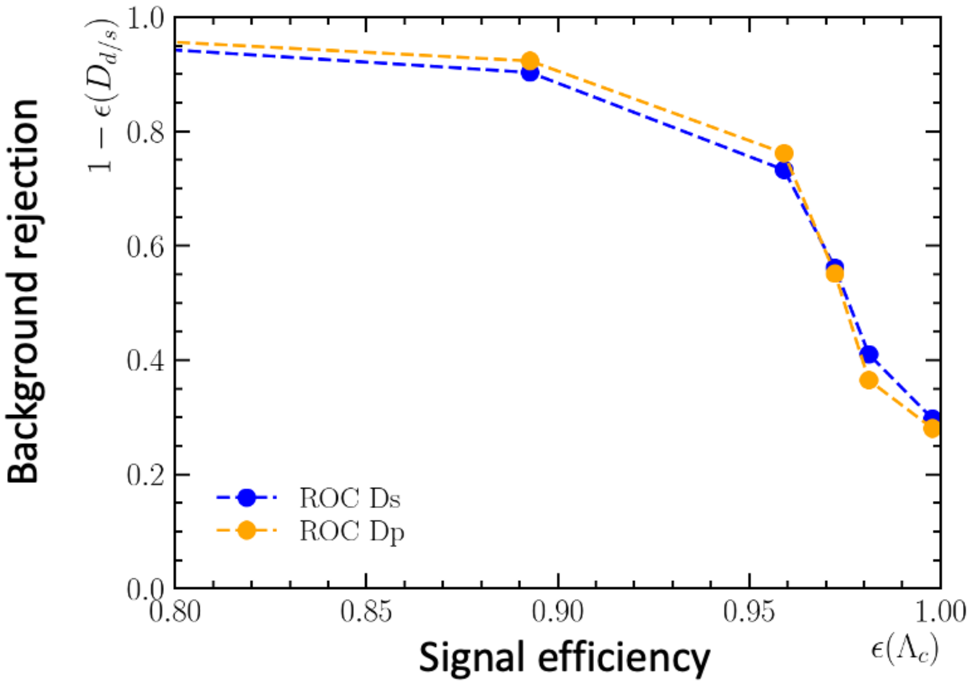
$D^+ \rightarrow K^- \pi^+ \pi^+$

$D_s^+ \rightarrow K^+ K^- \pi^+$

they would pollute peak in $m(\Lambda_c^+)$ when the decay products are misidentified







taken from slides of **Roger Forty**
https://indico.ijclab.in2p3.fr/event/9924/overview

Backup

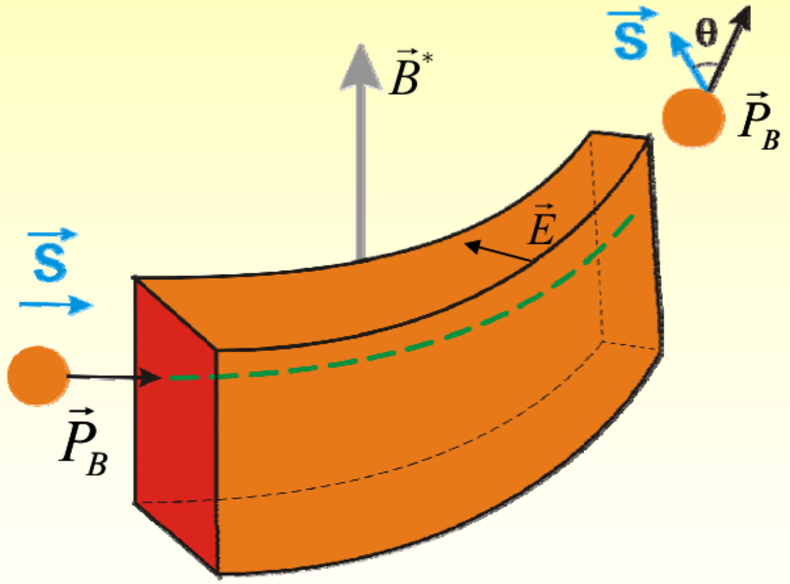
In particle rest frame

$$B^* \rightarrow \gamma E$$

$$\omega' = \frac{2\mu' B^*}{\hbar} = \frac{2\mu'\gamma E}{\hbar}$$

In laboratory frame

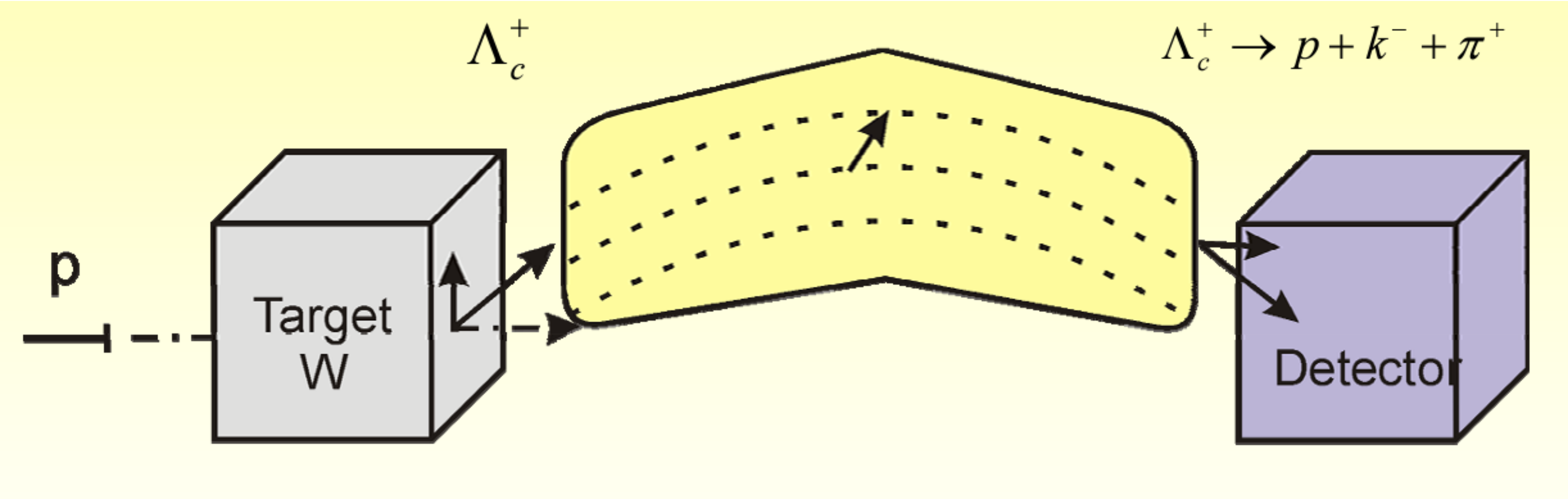
$$\omega = \frac{\omega'}{\gamma} = \frac{2\mu' E}{\hbar}$$



https://indico.cern.ch/event/598242/contributions/2433111/attachments/1394555/2128186/BARYSHEVSKY_2017-1.pdf

Backup

As a result of parity violation in weak decays asymmetry relative to baryon production plane exists.
The momentum direction of decay products follows the spin direction

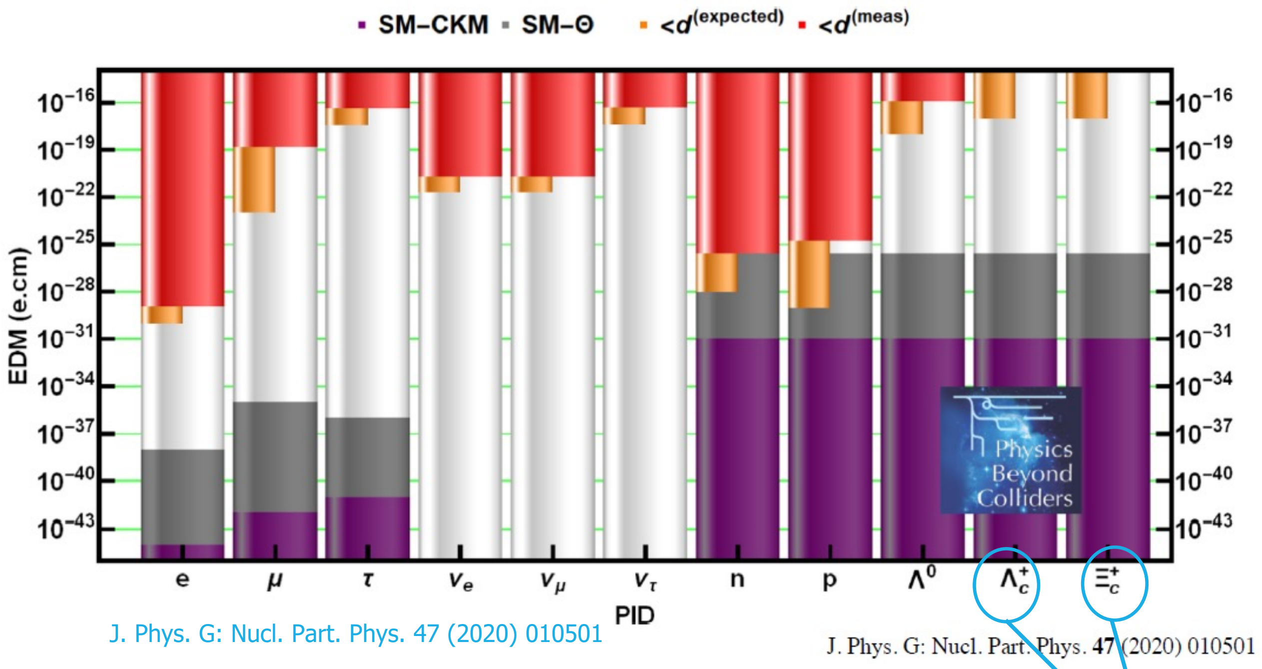


https://indico.cern.ch/event/598242/contributions/2433111/attachments/1394555/2128186/BARYSHEVSKY_2017-1.pdf

Direct measurements of EDM and MDM of charm baryons

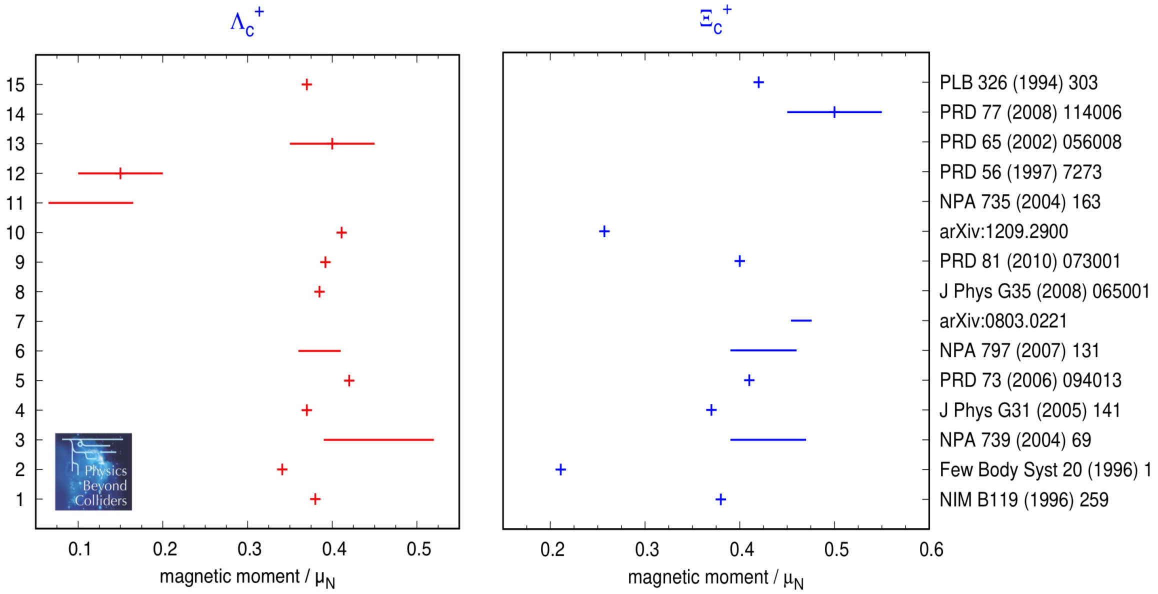
No direct measurements of EDM for charmed baryons due to their short lifetime.

We need experimental measurements to verify theoretical predictions.



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

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



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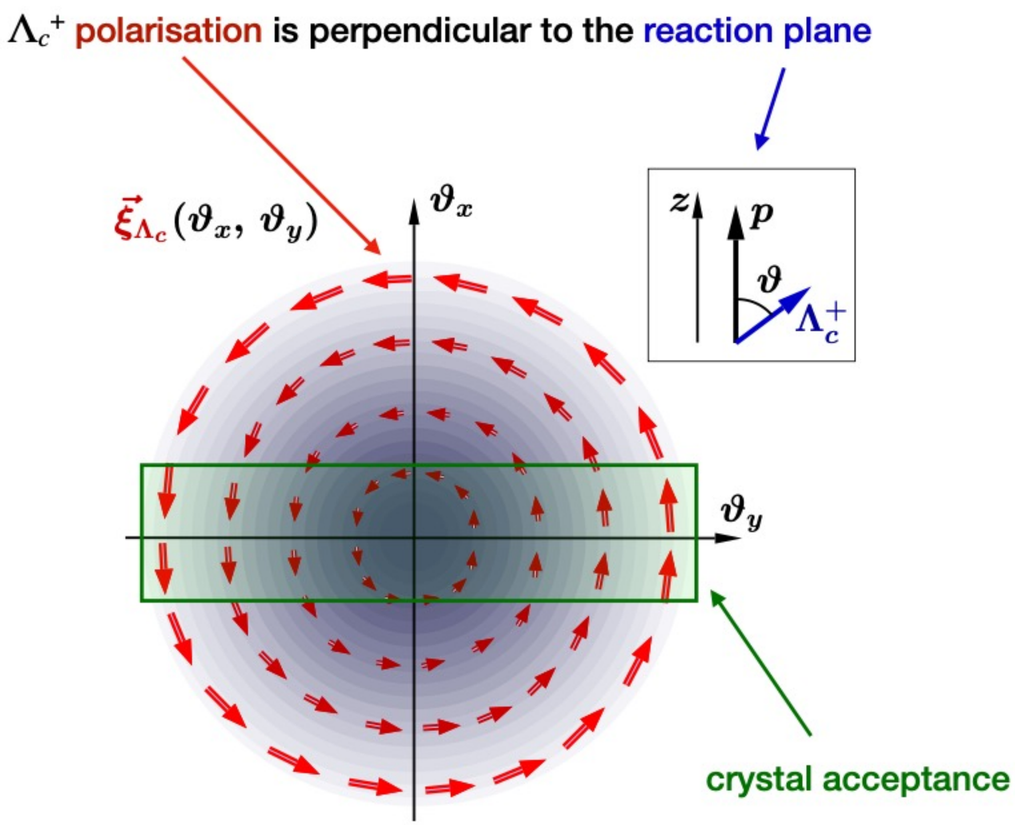
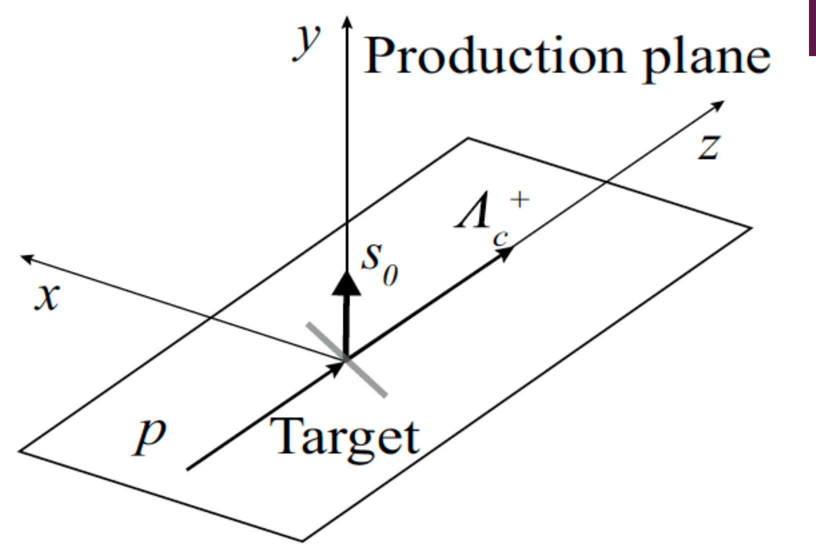
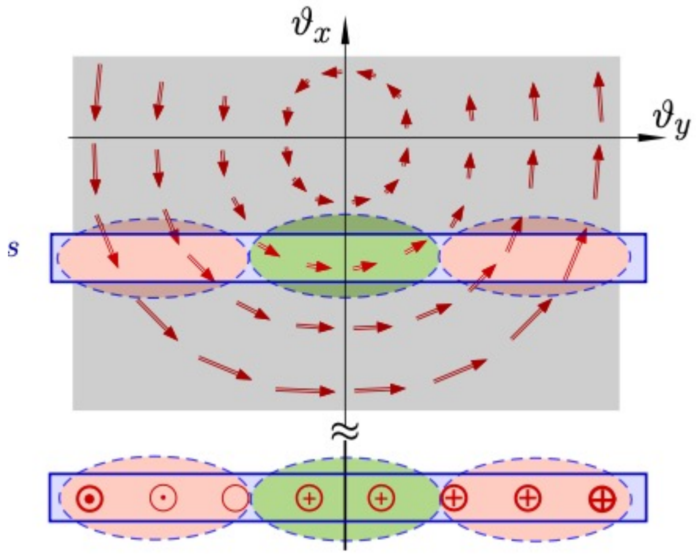
Transversal polarization





Simultaneous measurement



$$\Delta g = \frac{2}{\alpha \langle \xi_x \gamma \rangle \Theta} \sqrt{\frac{3}{N}}$$

$$\Delta f = \frac{2}{\alpha \langle \xi_y \gamma \rangle \Theta} \sqrt{\frac{3}{N}}$$