Direct measurements of charm baryons dipole moments at LHC

SARA CESARE – ON BEHALF OF THE TWOCRYST COLLABORATION

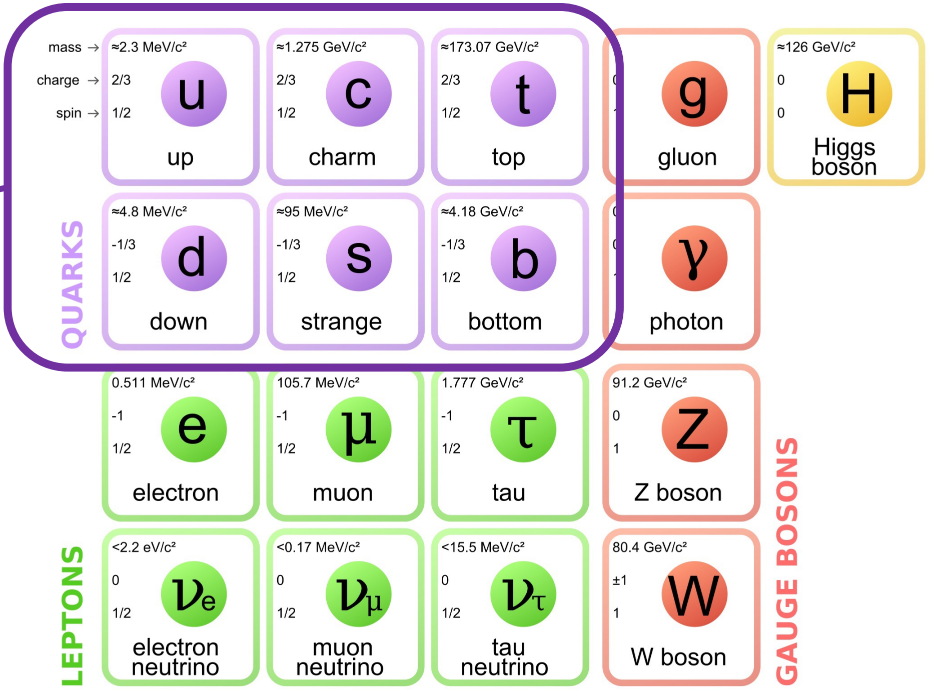
EDMS: COMPLEMENTARY EXPERIMENTS AND THEORY CONNECTIONS – 05/02/2024

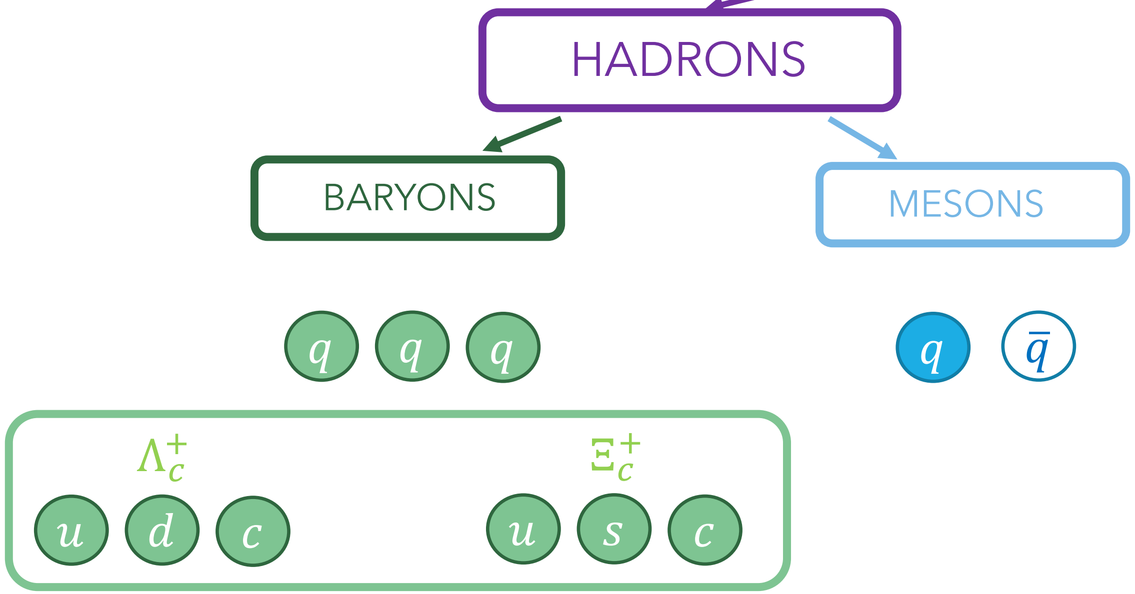
Outline

- Introduction
- Dipole Moments of unstable particles
- Fixed-target experiment with bent crystal
- Expected sensitivities
- Detector for proof-of-principle (PoP) test
- Summary

Charm baryons

Standard model of particle physics





m = 2286.46±0.14 MeV
τ = (2.015 ±0.027)×10^{-13} s
S = 1/2 +

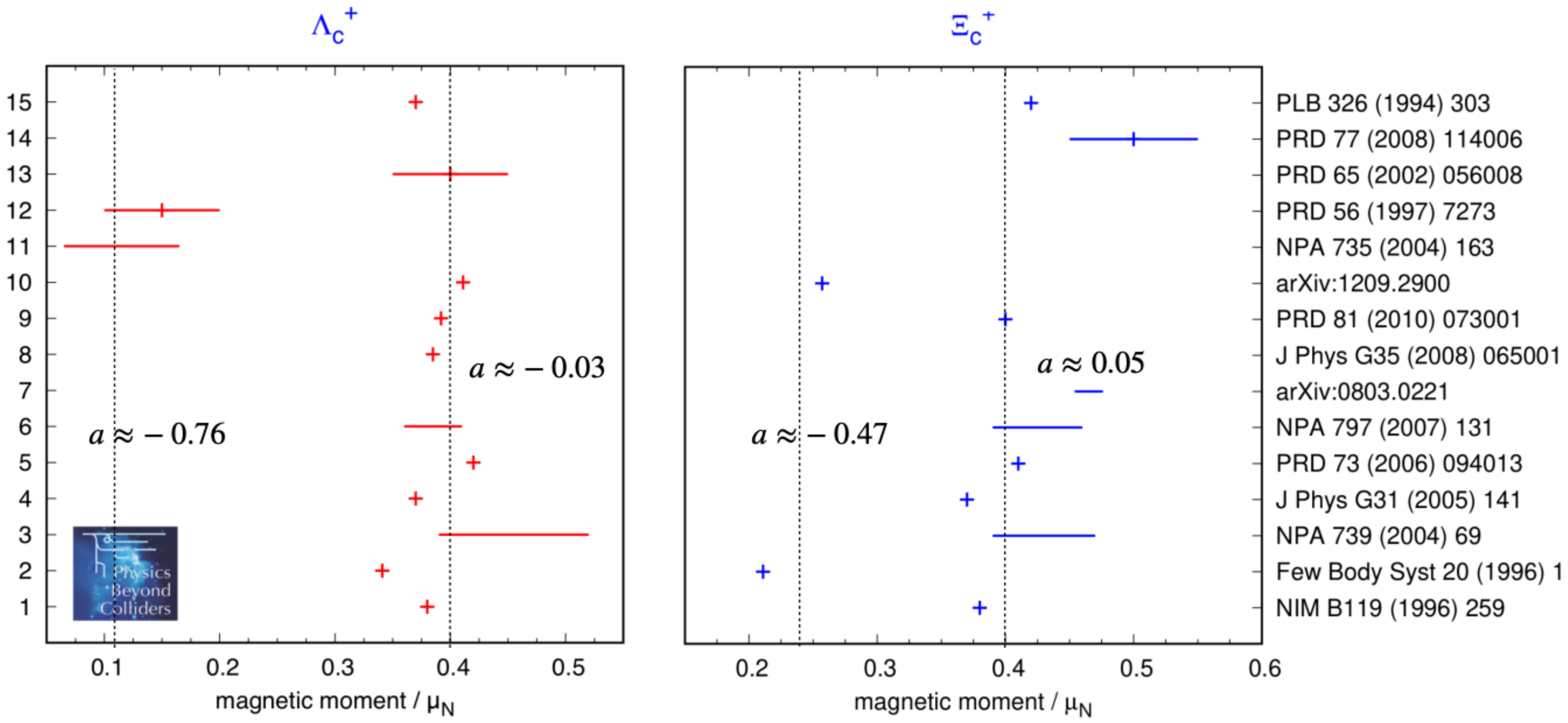
m = 2467.71±0.23 MeV
τ = (4.53 ±0.05))×10^{-13} s
S = 1/2 +

Baryons are composite particles made of three quarks, as opposed to mesons, which are composite particles made of one quark and one antiquark

Magnetic Dipole Moments of charm baryons

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

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

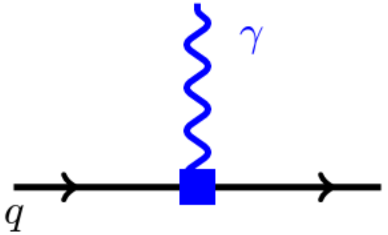


CERN-PBC-REPORT-2018-008

Electric Dipole Moments of charm baryons

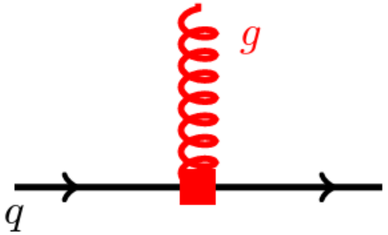
charm EDM

$d_q \, \bar{q} i \sigma^{\mu\nu} \gamma_5 q \, F_{\mu\nu}$



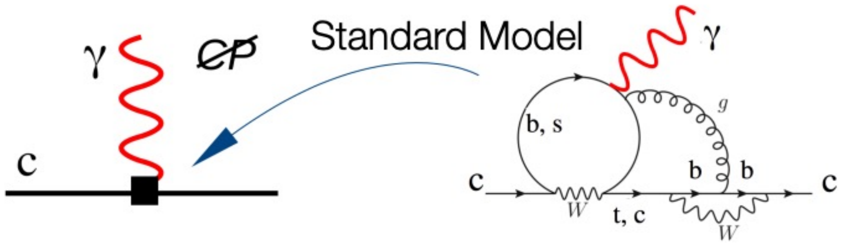
charm chromo-EDM

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



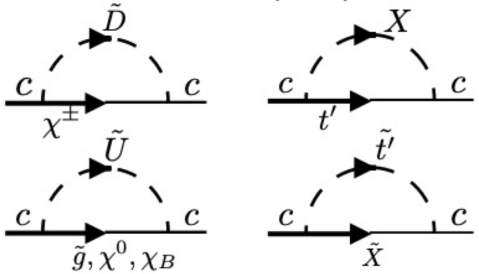
Charm EDM in SM-CKM ~10^{-32} e cm

Khriplovich, Lamoreaux (1997)



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

EPJC 77 (2017), 102



Indirect limit on the Charm EDM

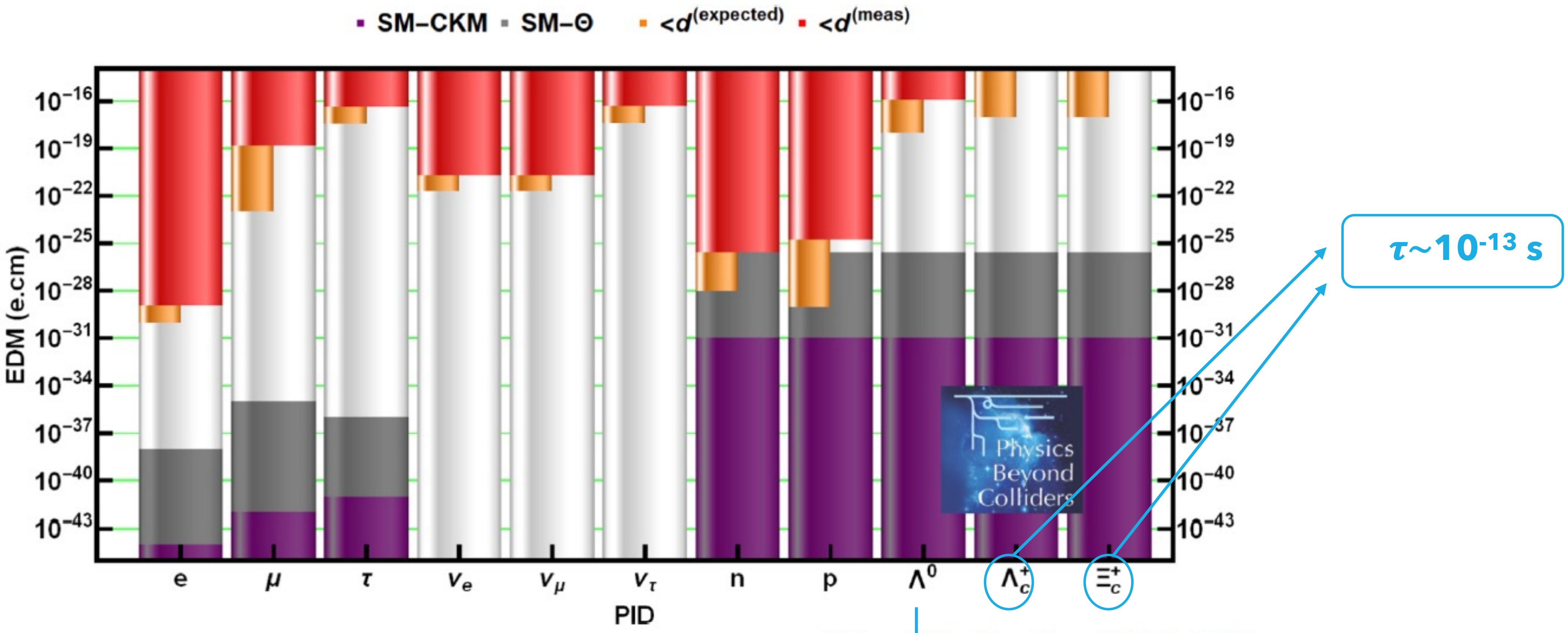
What is the maximum d_c allowed regardless of NP models?

Bound	Ref.	Measurement	Method
$\|d_c\| < 8.9 \times 10^{-17}$ ecm	[Escribano:1993xr]	$\Gamma(Z \to c\bar{c})$	Measurement at the Z peak (LEP). Weights electic (d_c) and weak (d_c^w) dipole moments through model-dependent relations.
$\|d_c\| < 5 \times 10^{-17}$ ecm	[Blinov:2008mu]	$e^+e^- \to c\bar{c}$	The total cross section (from the LEP combination [ALEPH:2006bhb]) is enhanced by the charm EDM vertex $c\bar{c}\gamma$.
$\|d_c\| < 3 \times 10^{-16}$ ecm	[Grozin:2009jq]	electron EDM	Considers contribution of d_c into d_e through light-by-light scattering (three-loop) diagrams.
$\|d_c\| < 1 \times 10^{-15}$ ecm	[Grozin:2009jq]	neutron EDM	Similar approach than Ref. [Sala:2013osa] with different treatment of diverging integrals and more conservative assumptions.
$\|d_c\| < 4.4 \times 10^{-17}$ ecm	[Sala:2013osa]	neutron EDM	Considers contribution of d_c into d_d via $W^\pm$ loops. Expressions from Ref. [CorderoCid:2007uc].
$\|d_c\| < 3.4 \times 10^{-16}$ ecm	[Sala:2013osa]	$BR(B \to X_s\gamma)$	Considers contributions of d_c into the Wilson coefficient C_7.
$\|d_c\| < 1.5 \times 10^{-21}$ ecm	[Gisbert:2019ftm]	neutron EDM	Renormalization group mixing of d_c into $\tilde{d}_c$.
$\|d_c\| < 6 \times 10^{-22}$ ecm	[Ema:2022pmo]	neutron EDM	Contribution of d_c to $3g$-1γ operators, to light-quark, to neutron EDM
$\|d_c\| < 1.3 \times 10^{-20}$ ecm	[Ema:2022pmo]	electron EDM	Contribution of d_c to 2γ-$2g$ operators, to electron-nucleon, to paramagnetic molecule ThO

Courtesy of Joan Ruiz Vidal

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

See Giorgia's talk on Thursday!

Search for Dipole moments of Charm baryons

Experimental method for EDM/MDM measurements of fundamental particles:

↓

Measurement of the spin precession angle induce 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).

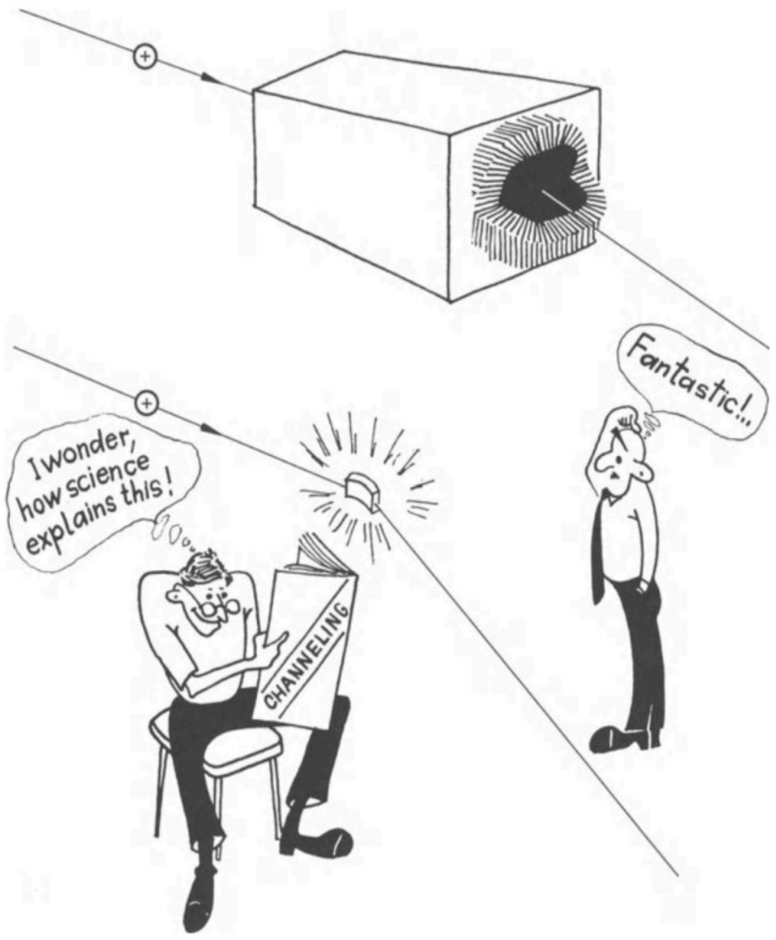
No experimental measurements exist for short-lived charm baryons since negligibly small spin precession would be induced by magnetic fields used in current particle detectors.

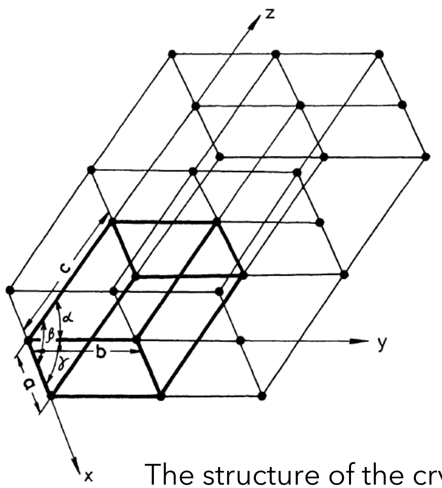
Channeling in bent crystals

- 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)

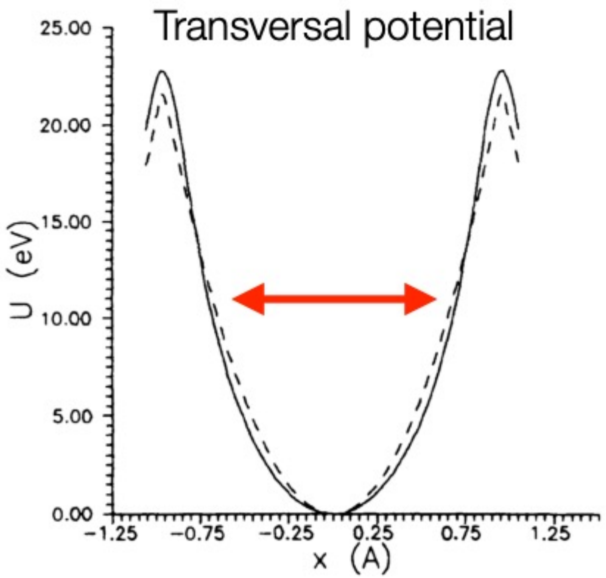
- Bent crystals used to:
  1. Steer high-energy particle beams
  2. Induce spin precession

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





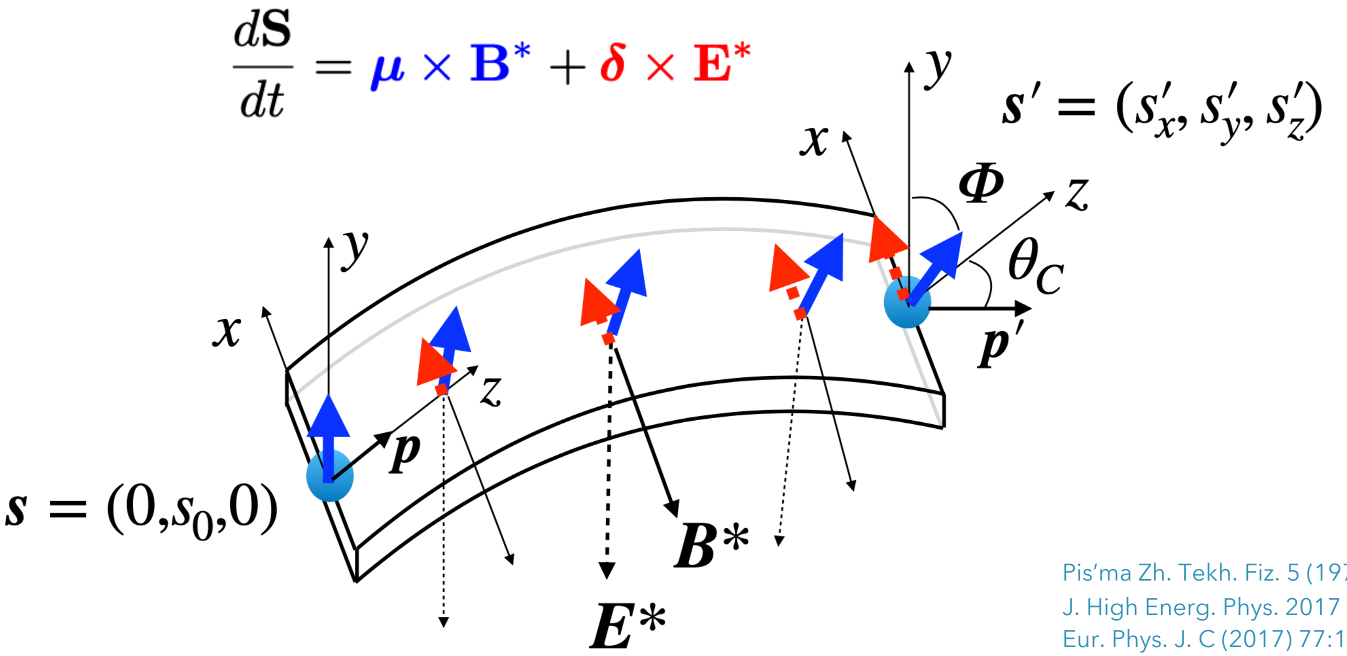
The structure of the crystal lattice and its primitive cell.



Spin precession in bent crystals

Firstly predicted by Baryshevsky (1979)

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



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

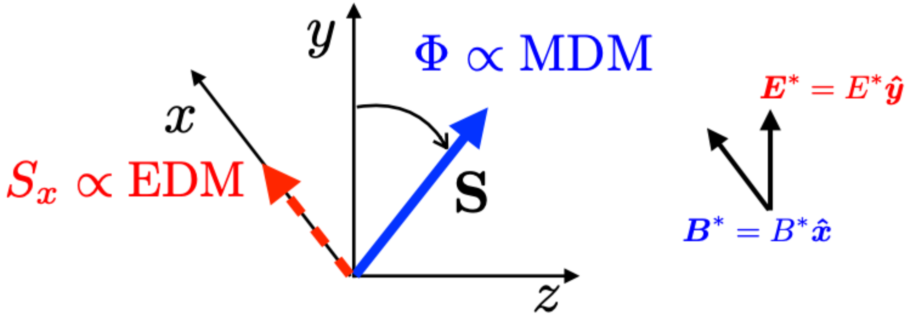
In bent crystal we obtain:

- Electric field E ≈ 1 GV/cm

- Effective magnetic field B ≈ 500 T

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

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

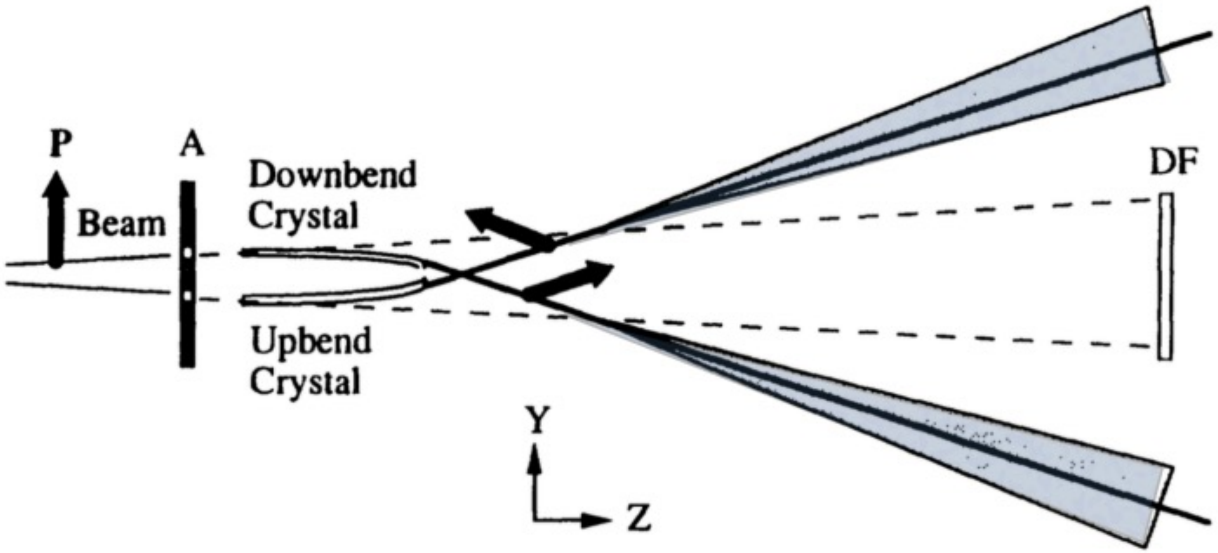


D. Chen et al. [E761 collaboration], Phys. Rev. Lett. 69, 3286 (1992).

Proof of principle in E761 - FERMILAB

- E761 Fermilab experiment firstly observed spin precession in bent crystals and measured MDM of Σ^+
- **350 GeV/c** Σ^+ produced from interaction of 800 GeV/c proton beam on Cu target
- Used upbent and downbent silicon crystals L= 4.5 cm, θ_c=1.6 mrad for opposite spin precession, reduced systematics

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



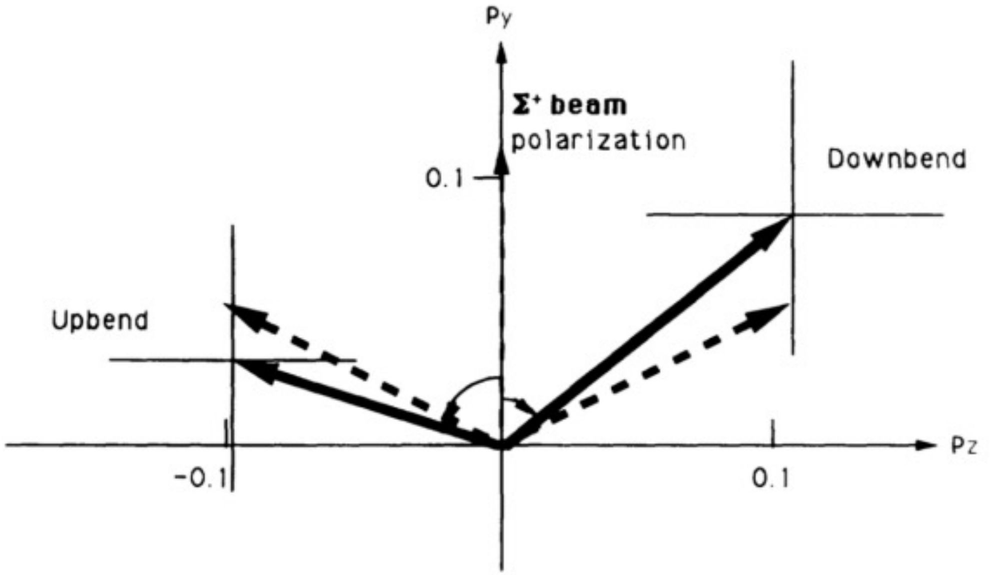
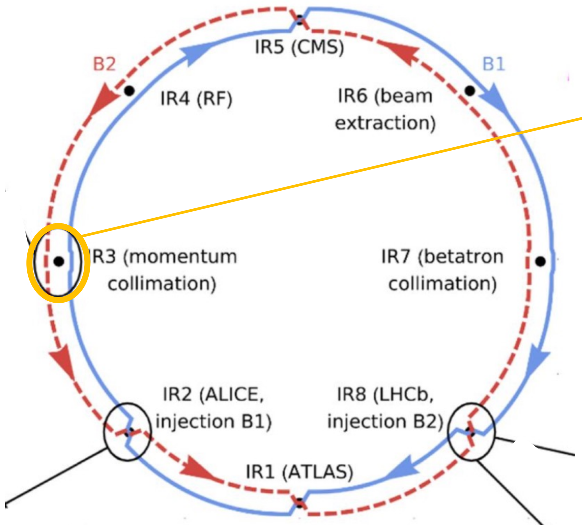


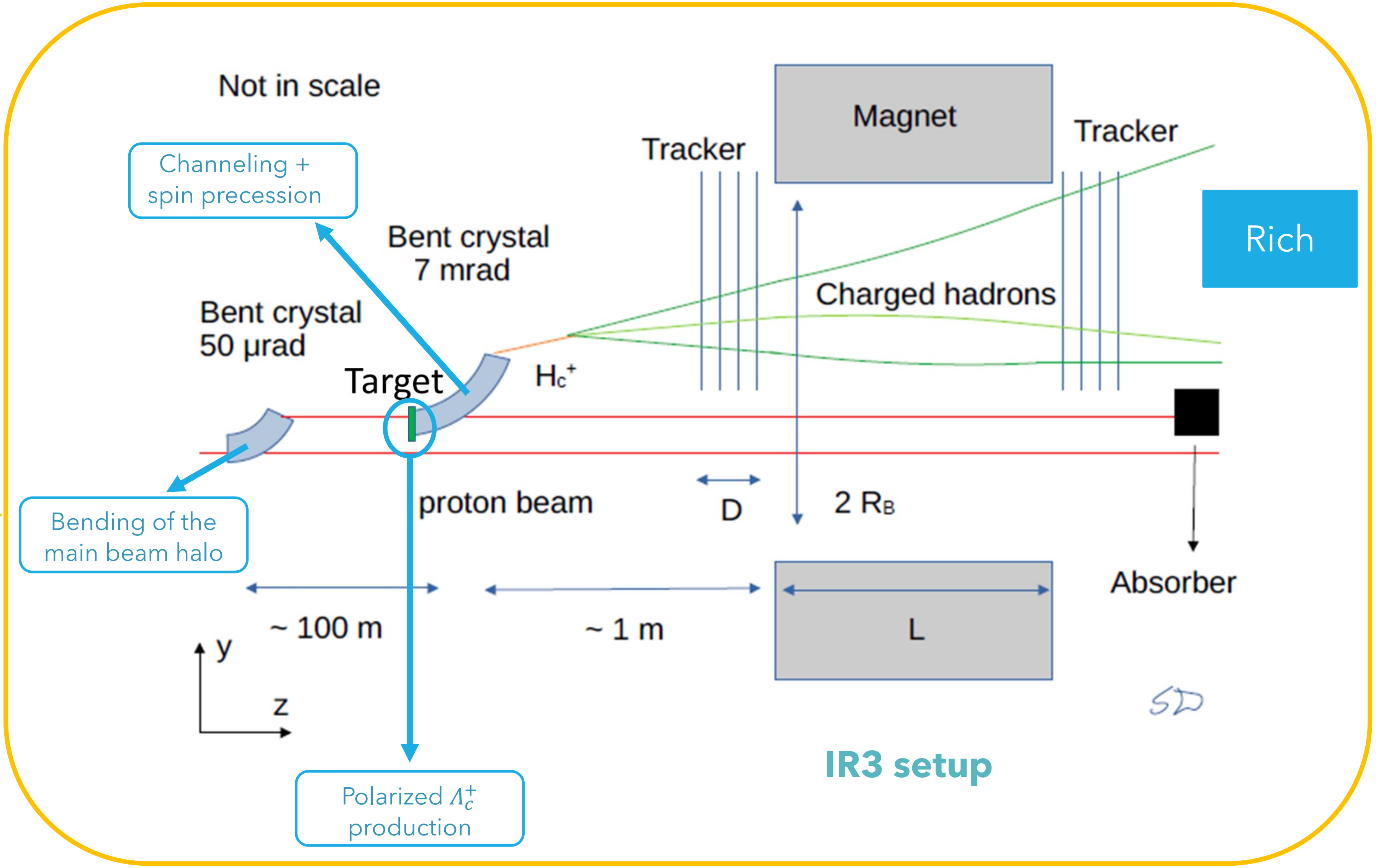
FIG. 3. Measured polarizations and uncertainties (1σ statistical errors) after spins have been precessed by the two crystals. The dashed arrows show the expected precessions.

Fixed target experiment with bent crystals at the LHC

Two alternative scenarios:

1. New independent experiment at LHC IR3 (nominal).
2. Target placed in front of the LHCb detector.



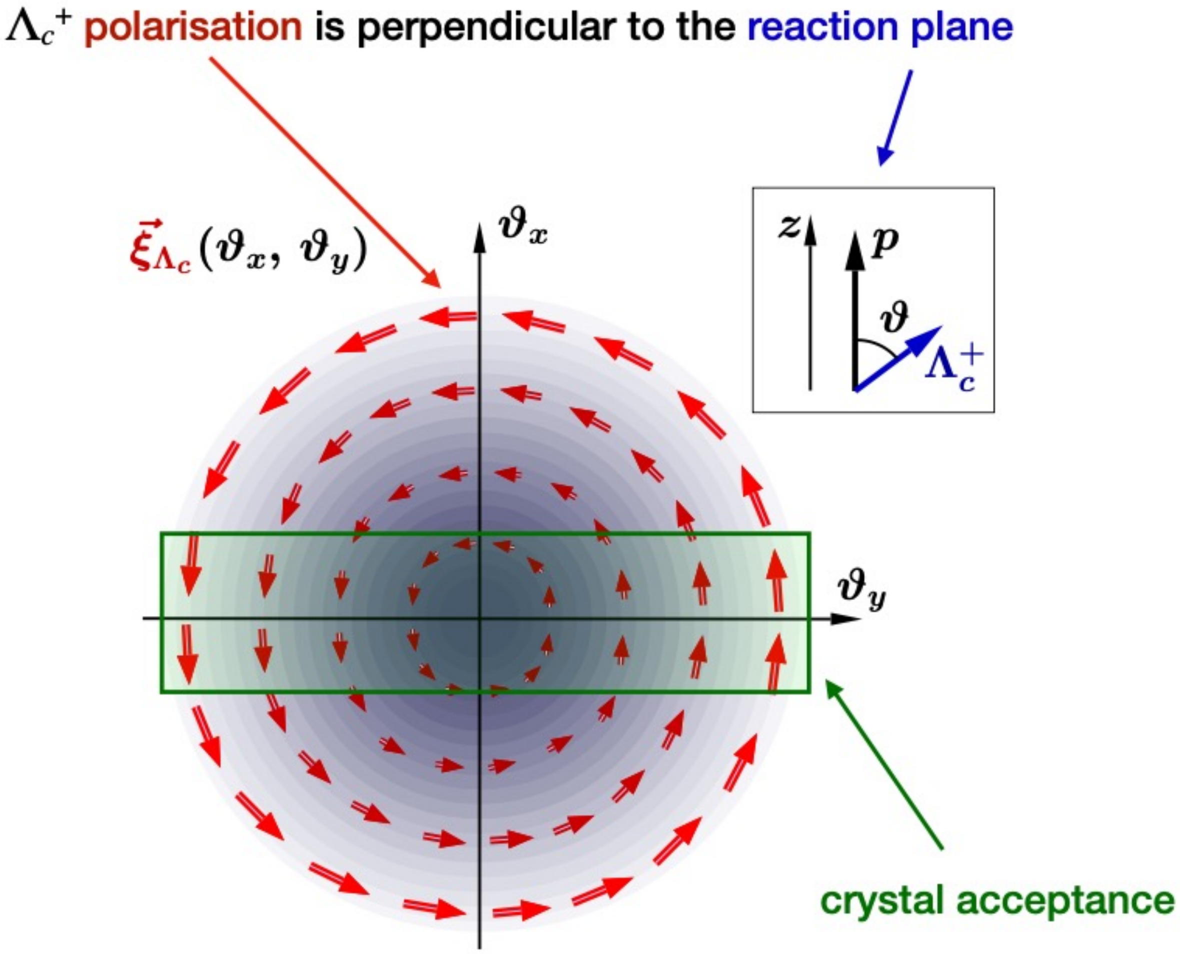


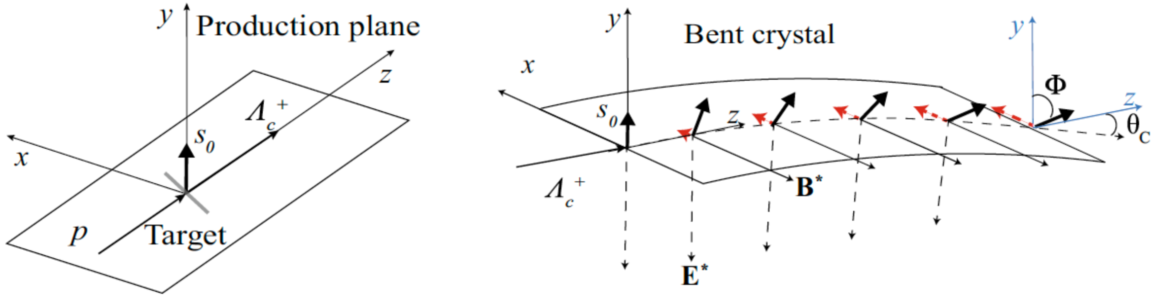
IR3 setup

Transversal polarization and spin precession

A. Fomin et al. Eur. Phys. J. C (2020) 80:358 [1909.04654]

Due to the parity conservation in the strong interactions





- In the instantaneous rest frame of the particle the electromagnetic field causes the spin rotation.
- The signature of the EDM is a polarization component perpendicular to the initial baryon momentum and polarization vector

Polarization measurements and MDM/EDM extraction

2-body decay approach $\Lambda_c^+ \to pK^{*0}$

We can define the angular distribution as

$$\mathcal{W} \propto 1 + \alpha_{\text{eff}}\, \boldsymbol{s}' \cdot \hat{\boldsymbol{k}},$$

$\boldsymbol{\alpha_{eff}}$ parity violating coefficient
$\hat{\boldsymbol{k}}$ direction of the final state baryon
$\boldsymbol{s}'$ Λ_c^+ polarization vector after precession

3-body decay approach $\Lambda_c^+ \to p^+ K^- \pi^+$

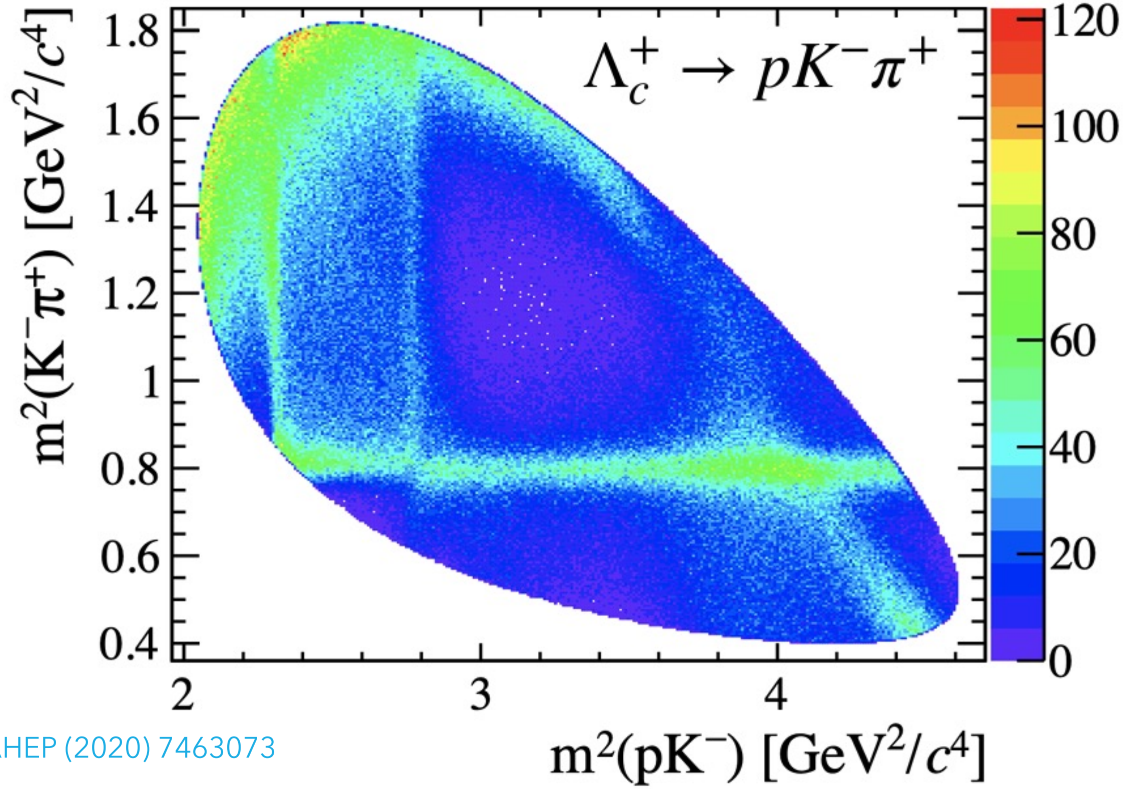
Use 3-body decays to increase the signal yield

Extract maximum information via full amplitude analysis of the 3-body decays

The average event information S^2 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 s_0 is the best estimate for the polarization

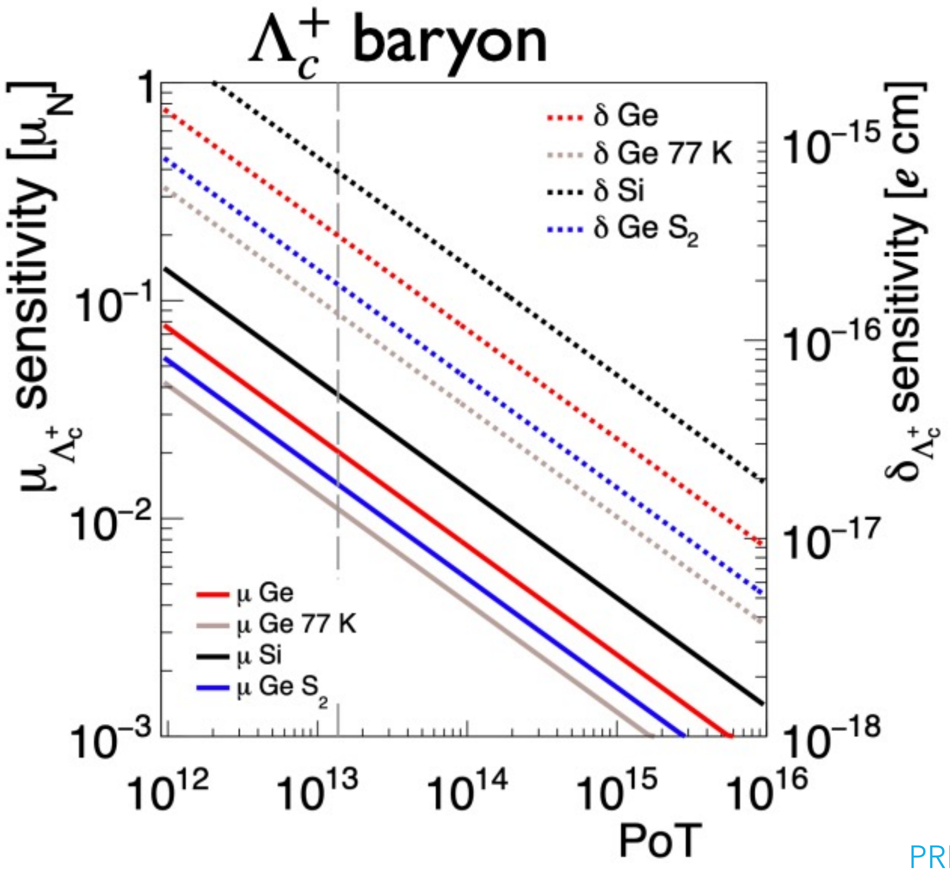


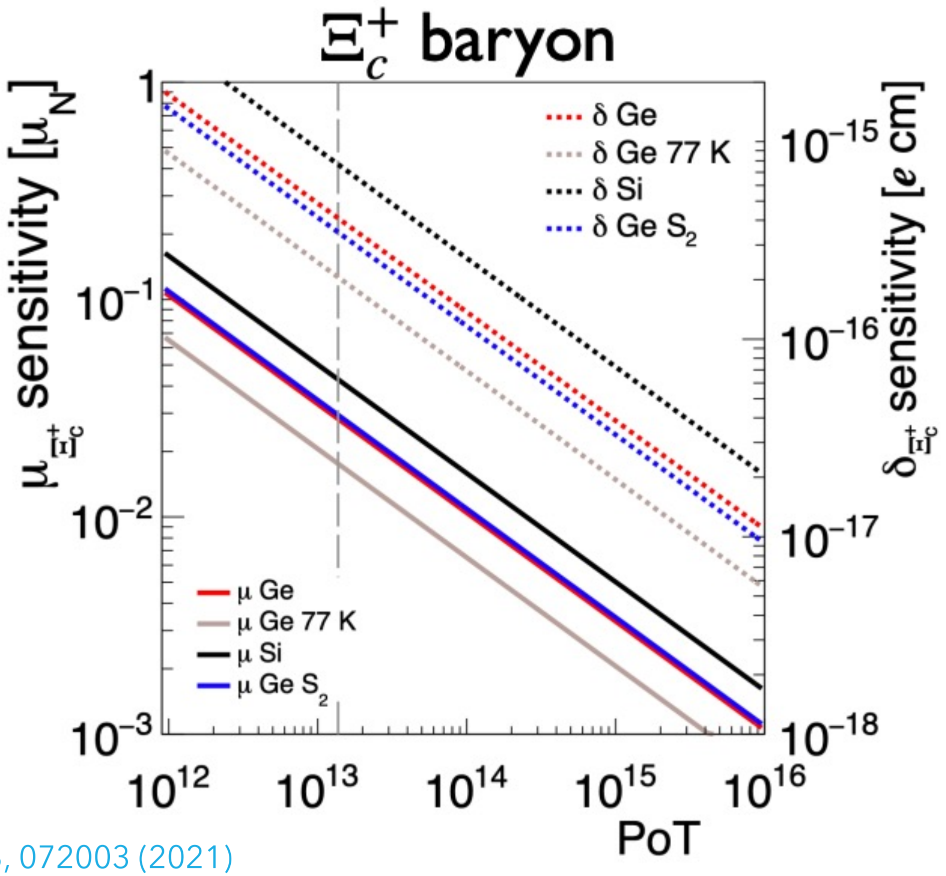
D. Marangotto, AHEP (2020) 7463073

Sensitivity on MDM/EDM

- S1: LHCb detector
- S2: IR3 dedicated experiment

- Data-taking time: 10^{13} PoT = $10^{6}\ p/s \times 2$ years
- W target: 2 cm thickness
- Expected Yields Λ_c^+ : 5900 events Ξ_c^+ : 3200 events





PRD 103, 072003 (2021)

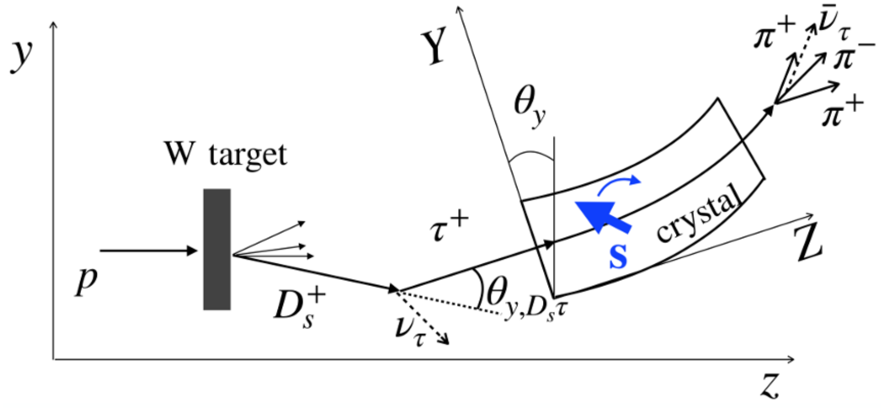
Direct measurement of τ lepton dipole moments

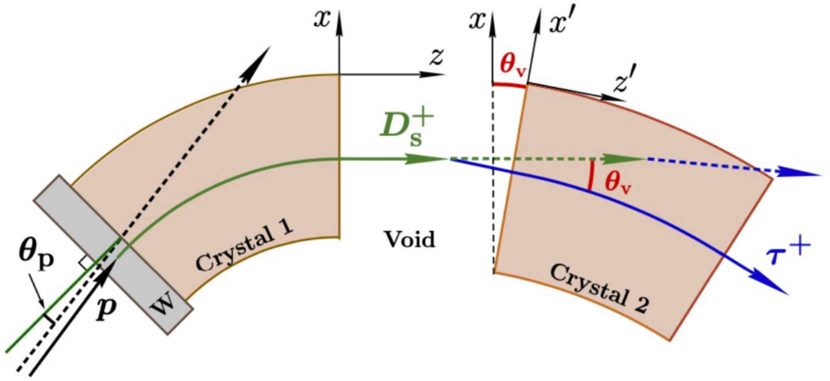
Proposal for the measurement of the τ lepton dipole moments

- Based on the spin precession
- 2 possible setup
- Challenges due to the decay of the D_s^+ and channeling of the produced τ lepton - need for more statistic!

Exploration of g-2 and EDM of τ is limited by the available PoT at the LHC.

PRL 123, 011801 (2019)

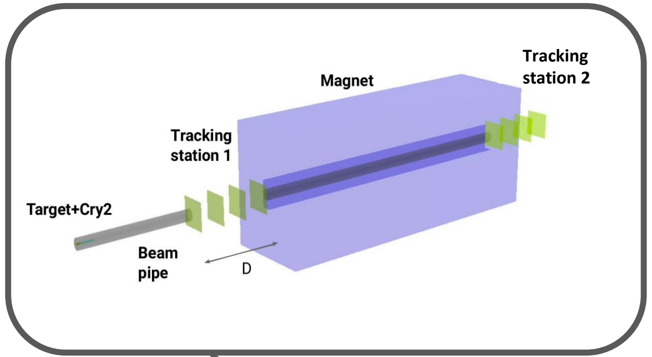


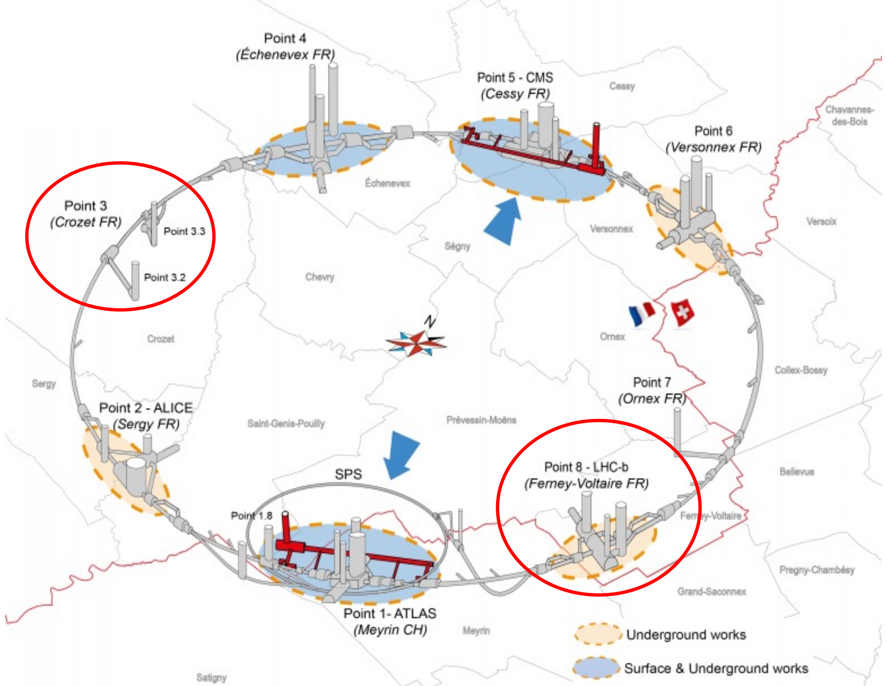


JHEP 03 (2019) 156

Timeline of the experiment

- The PoP test is called TWOCRYST and was approved by the LMC (LHC Machine Committee) to take data in 2025.
- Ongoing review of the experiment at the LHC Committee.
- Letter of Interest will be presented in June 2024.



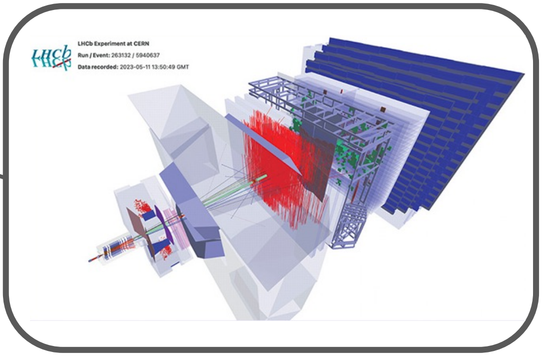


Start of my Phd
Crystal Test Beam
Integration of the sensors in the Roman Pot + Installation in the tunnel
End of my Phd
Experiment

2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030

Production and test of the sensors

Proof of Principle Test



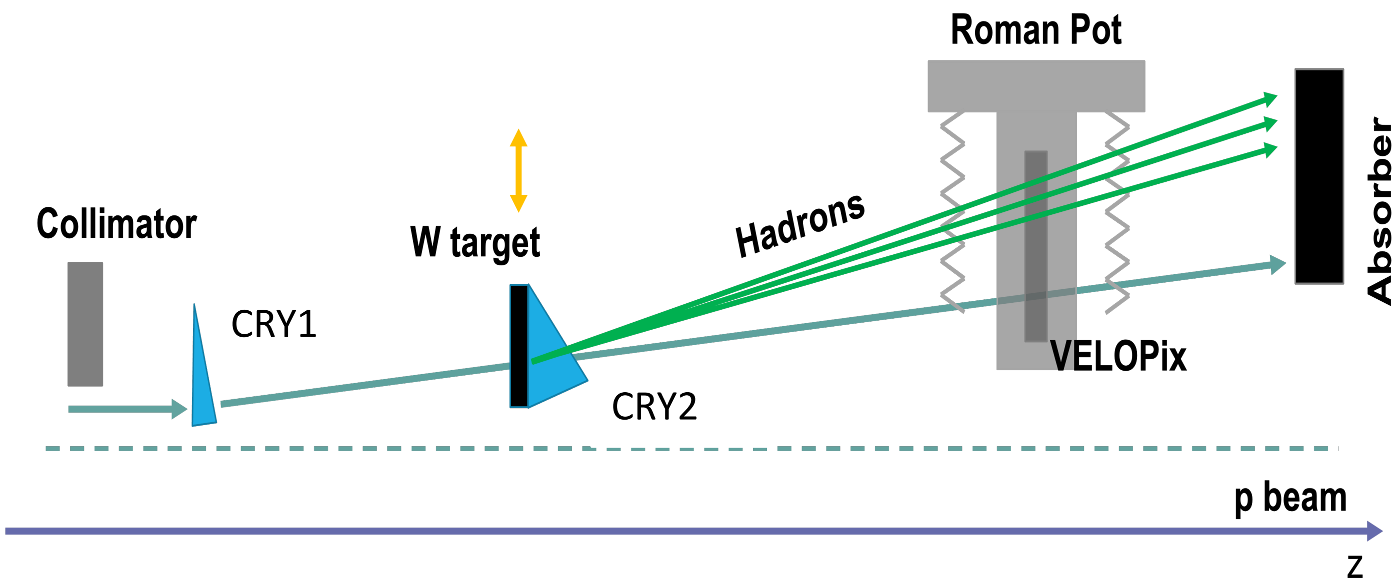
Proof-of-principle test (PoP)

Goals of the test

1. Demonstrate the operational feasibility of the double crystal and tracking detector setup at the LHC
2. Confirm the estimated achievable rates of proton on target
3. Measure channeling efficiency of long crystals at TeV energies
4. Background studies

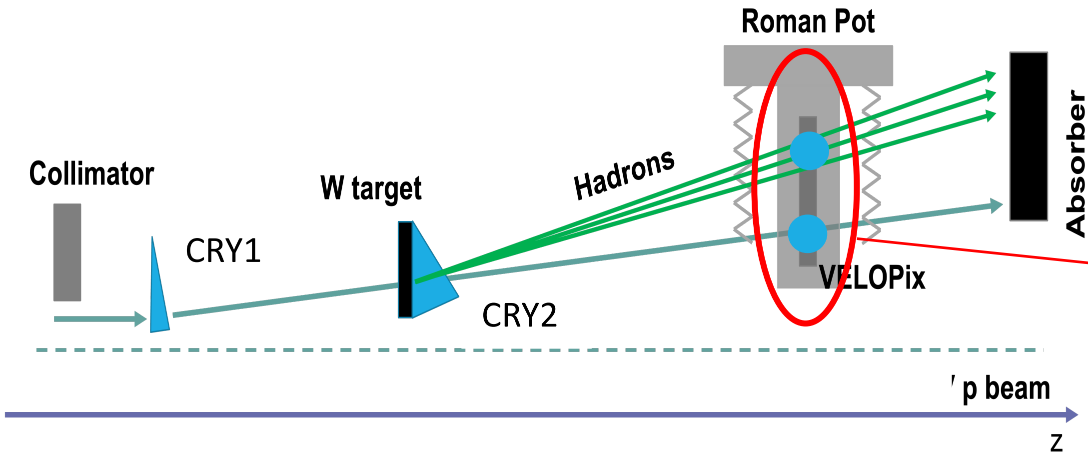
Experimental set-up

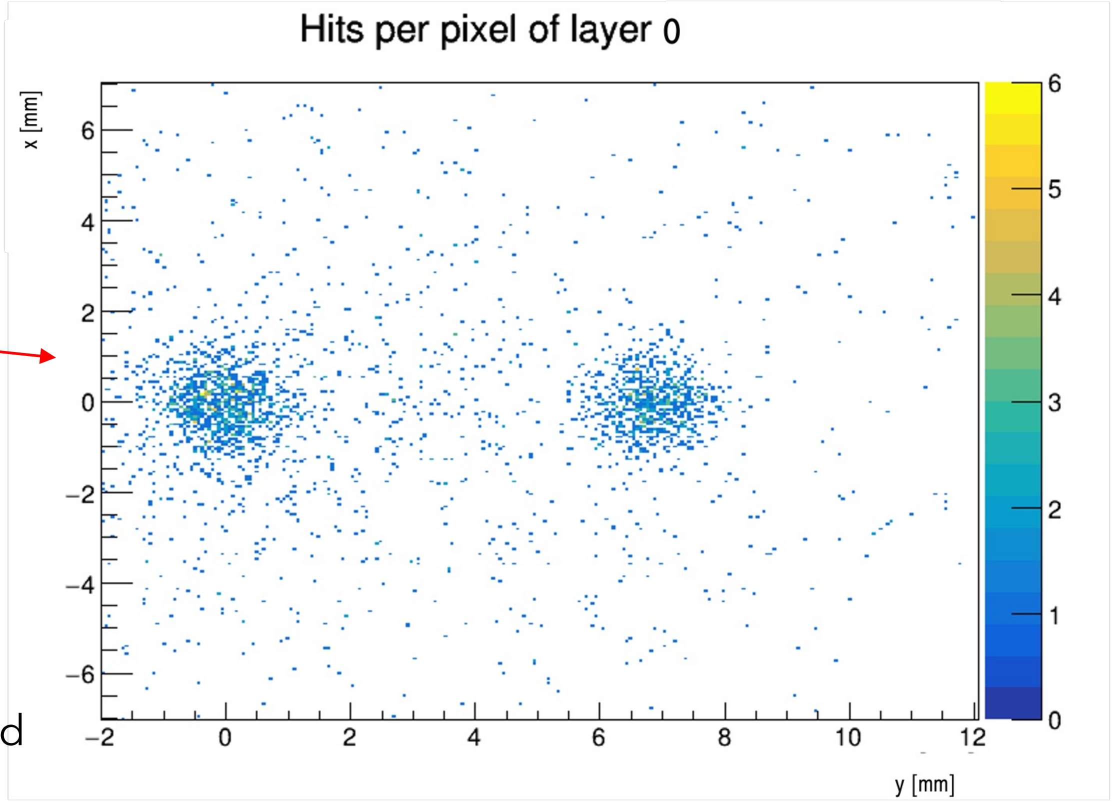
- Short crystal for beam-halo deflection
- W target
- Long crystal for Λ_c^+ channeling
- One tracking station in a Roman Pot
- Absorber



Measurement of the channeling efficiency

- Simulation studies of 1 TeV protons channeled with the double crystal setup
- Second crystal – tracker layer distance **d=1m**
- Need to measure both the channelled and unchanneled protons from the second crystal.





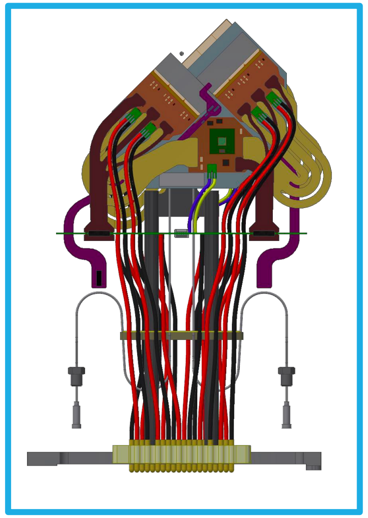
Background studies

- High granularity is needed to resolve between tracks in pW and pSi collisions (with target in place) in the future experiment

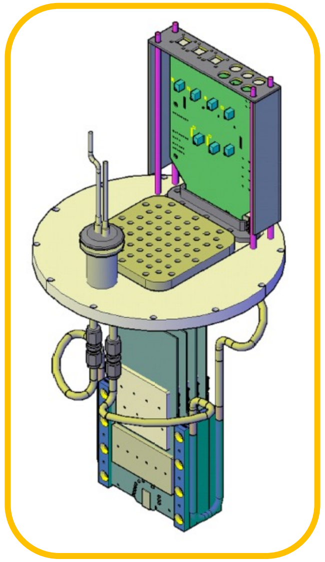
2D Pixel detector proposal

Modular tracking detector based on:

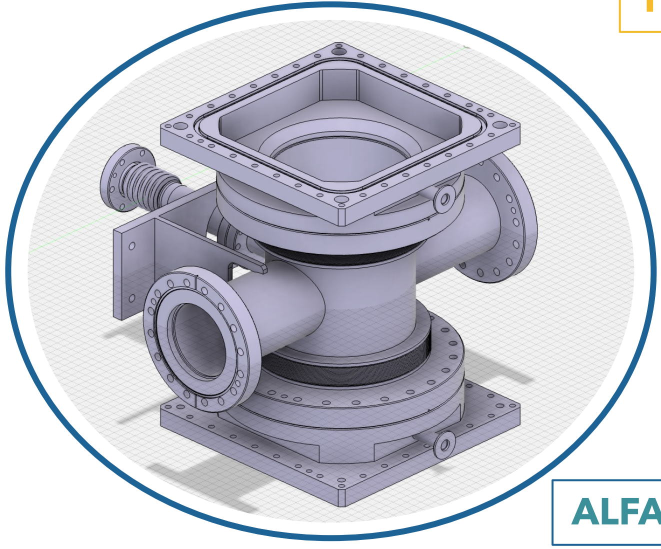
- LHCb Vertex Locator (VELO) silicon pixel sensors + ASIC and readout chain
- CMS TOTEM experiment mechanical support and cooling
- ATLAS ALFA experiment Roman Pot



VELO module



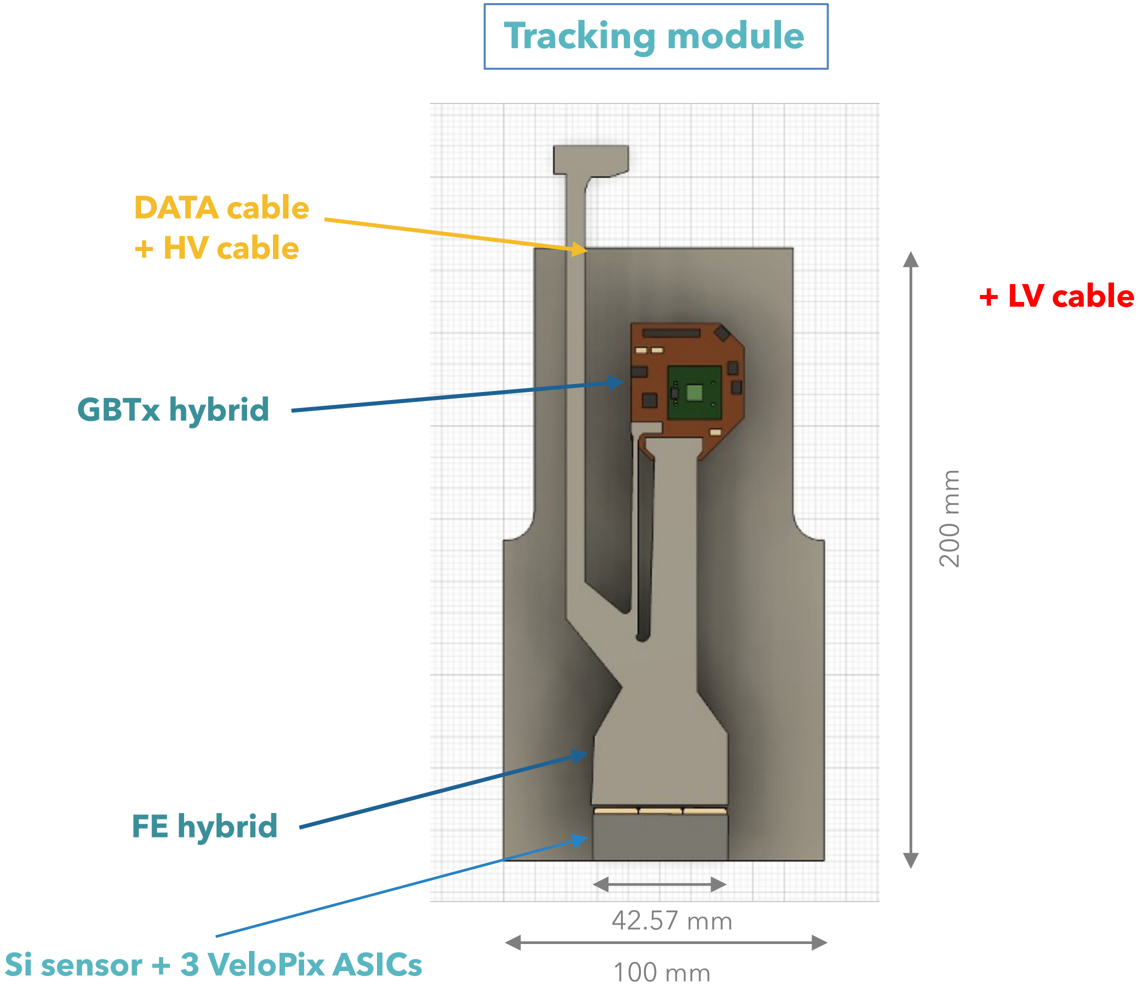
TOTEM support

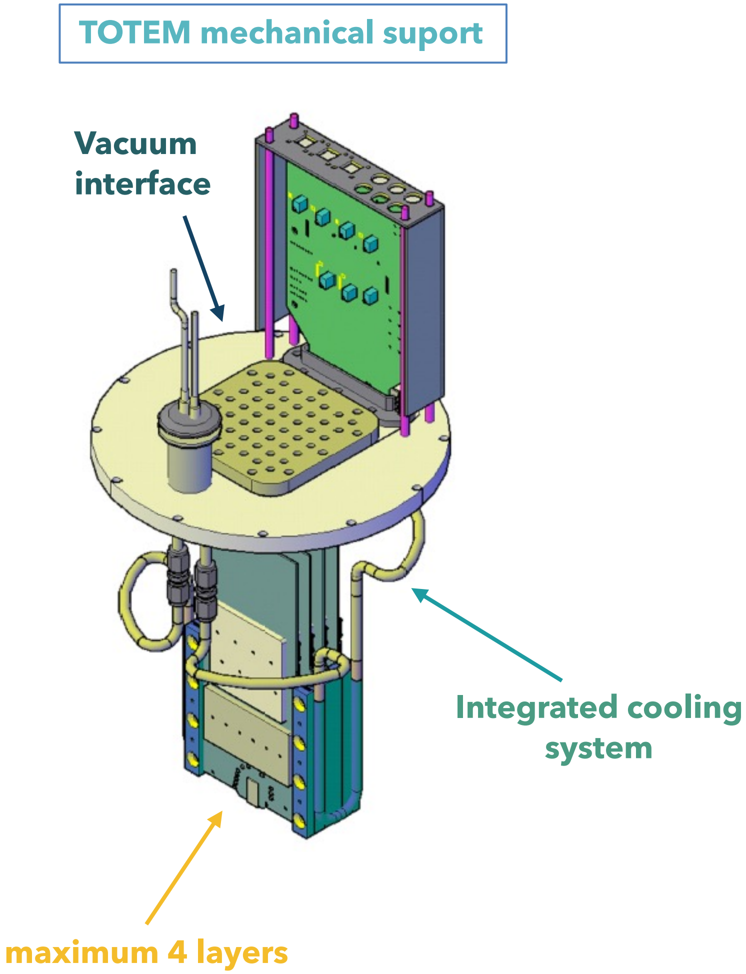


ALFA Roman Pot

https://cds.cern.ch/record/1624070/files/LHCB-TDR-013.pdf
https://cds.cern.ch/record/2017378/files/ATLAS-TDR-024.pdf
https://iopscience.iop.org/article/10.1088/1748-0221/3/08/S08007/pdf

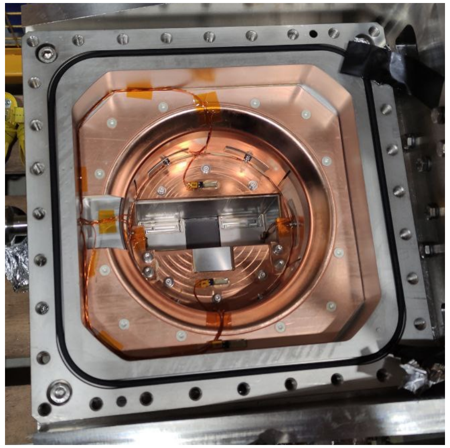
Tracking module





Roman pot box and cooling system

Roman Pot



Roman Pot station

ALFA roman pot

- Two ATLAS ALFA Roman Pot stations have already been extracted from the LHC tunnel
- Control system for vertical movement
- Possibility to use both ATLAS ALFA and CMS TOTEM detector package and cooling system
- Diameter of the outer cylinder of the pot ~ 15 cm

Cooling system

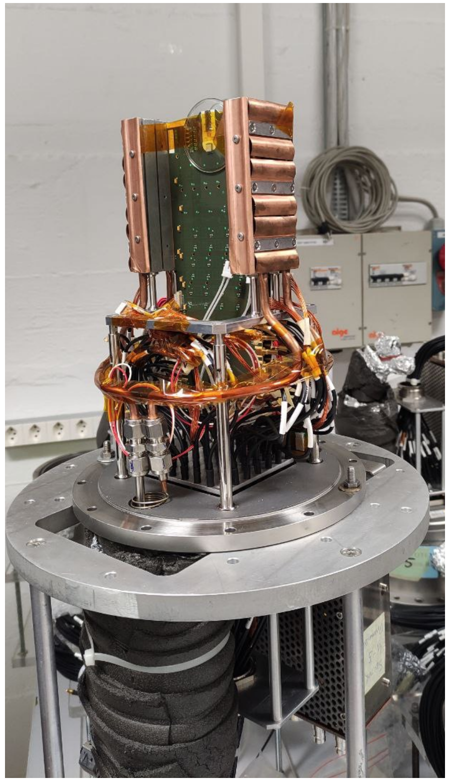
- Each VeloPix generate up to 3W
- Each ASIC additional 5 W

- Maximum 4 module/rp ~ 30 W

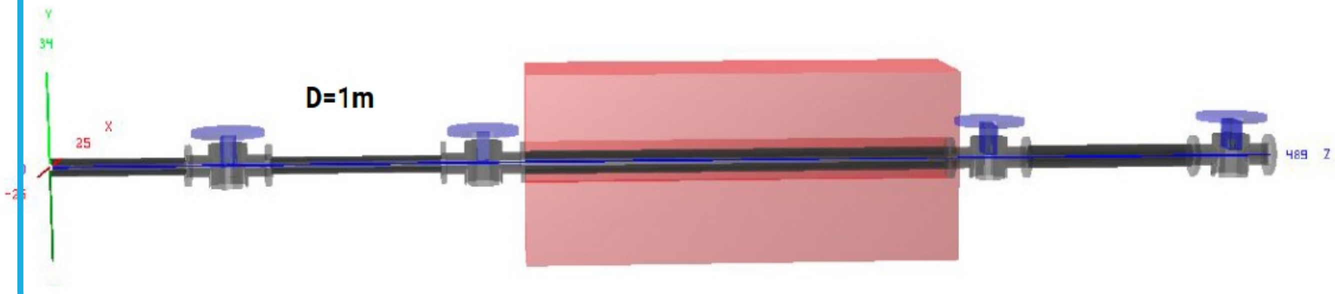
- Proof of principle operational temperature ~ 20 ° C

- Water cooling system + thermally conductive support board

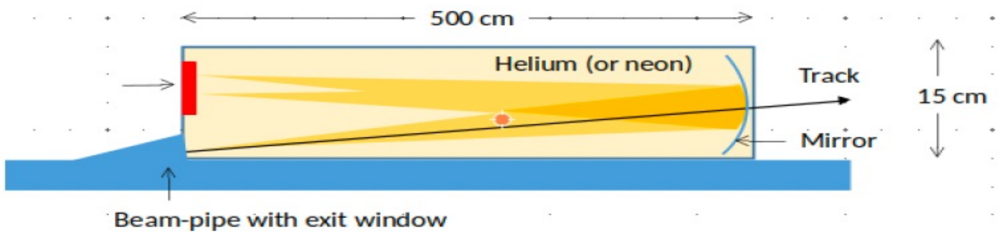
- External chiller with local water circuit
- Interlock system



Forward Spectrometer



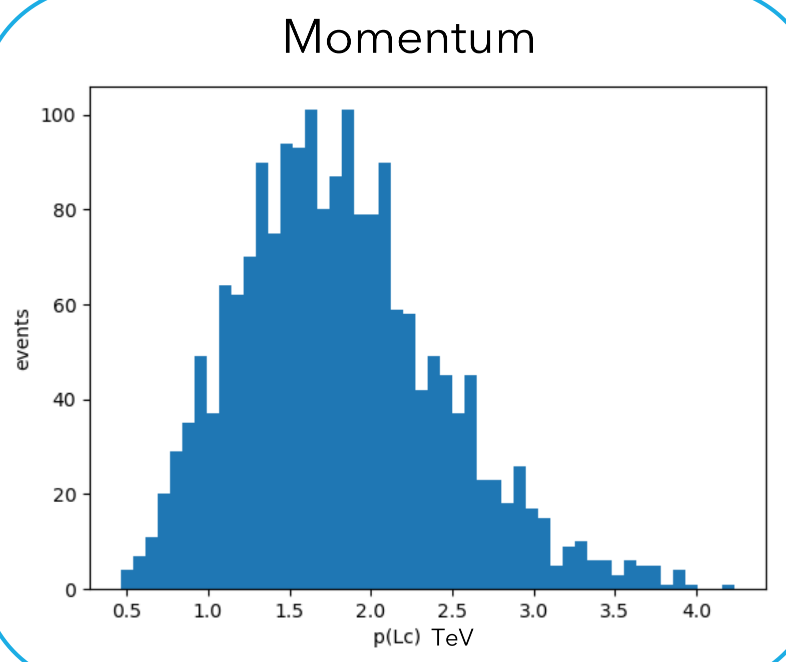
Rich detector

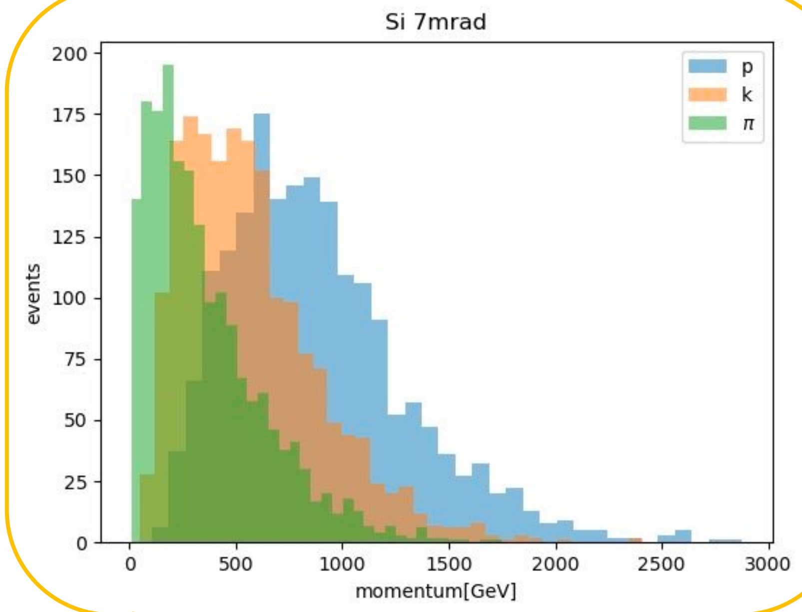


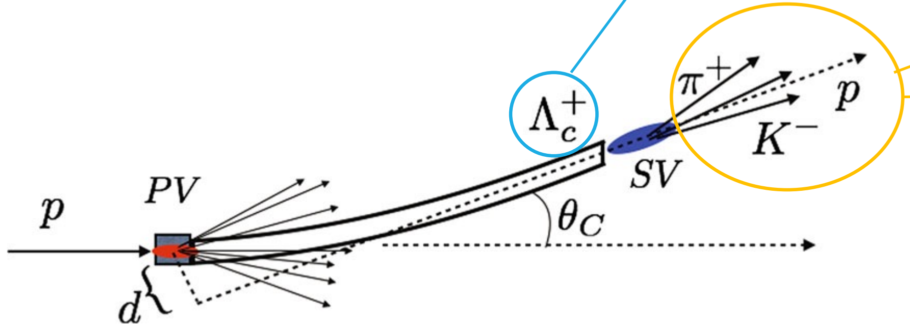
Signal kinematics

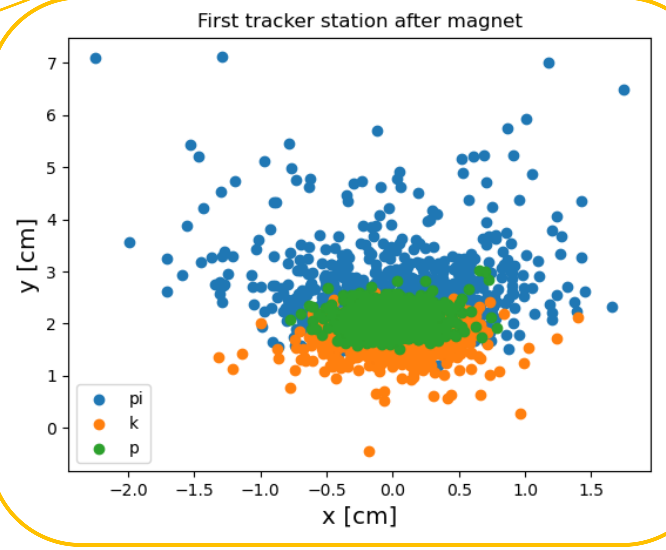
Starting from the 7 TeV protons of LHC:

- 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.

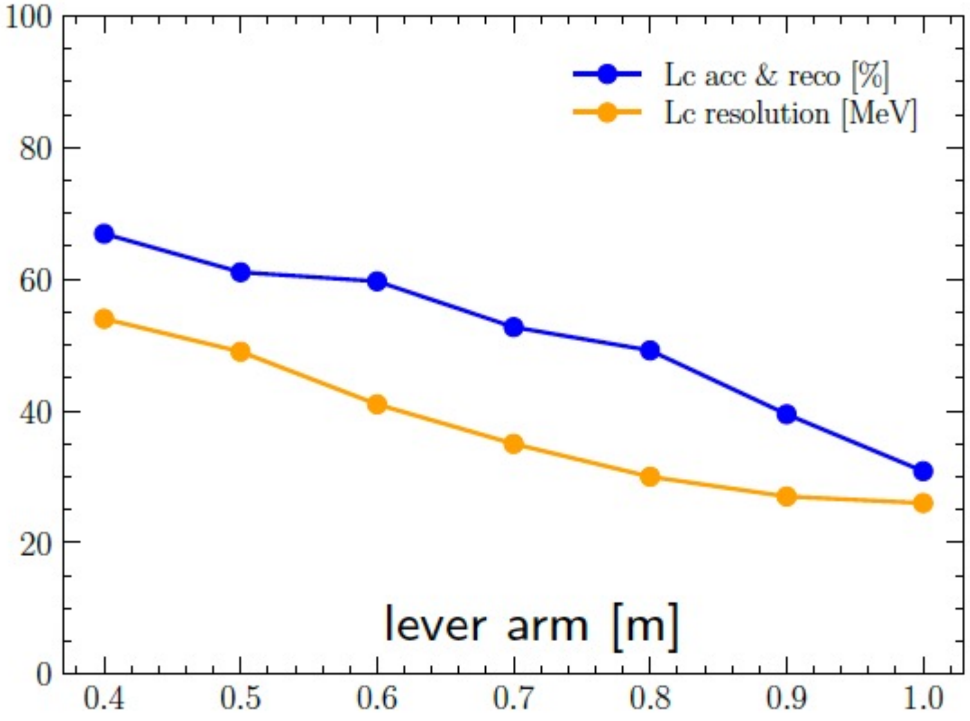
Pseudorapidity $5 < \eta < 10$

- Beam pipe: Cu OFE, elliptical form
- Target: W, 2 cm long
- Cry 2: Si, 7 cm long, 7 mrad
- MCBW Magnet: Fe, at 1m from crystal

  B=1.1 T, L =1.7 m
- Tracking stations: 8 modules:

  4 before – 4 after magnet

current setup



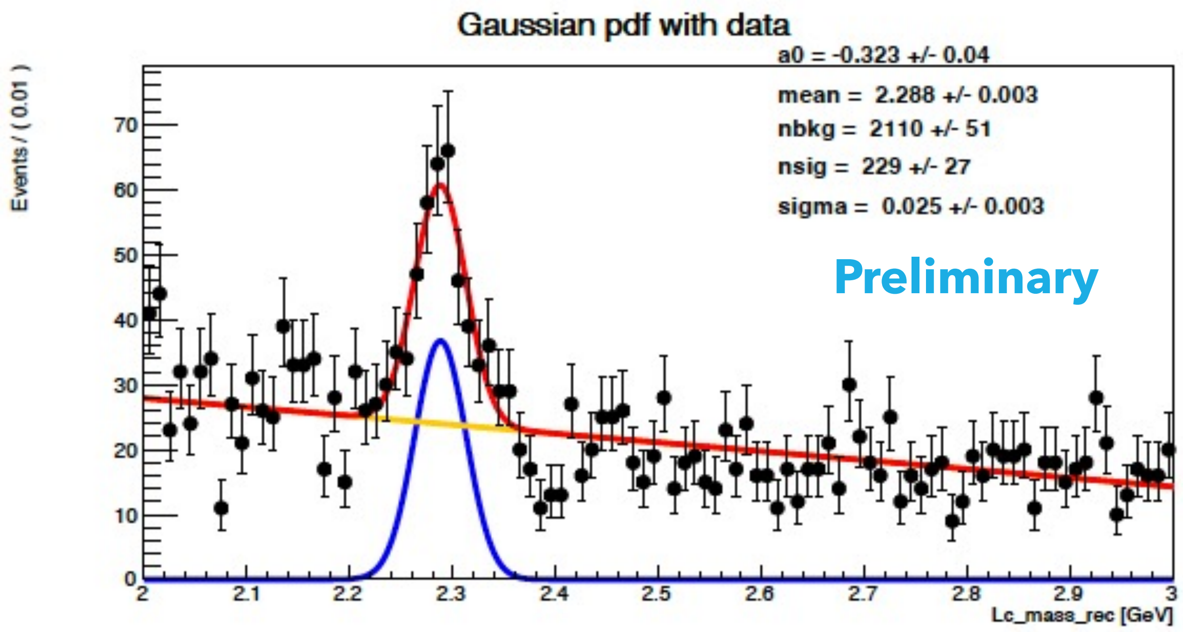
taken from slides of **Jascha Grabowsky**
https://indico.ijclab.in2p3.fr/event/9924/overview

Mass resolution

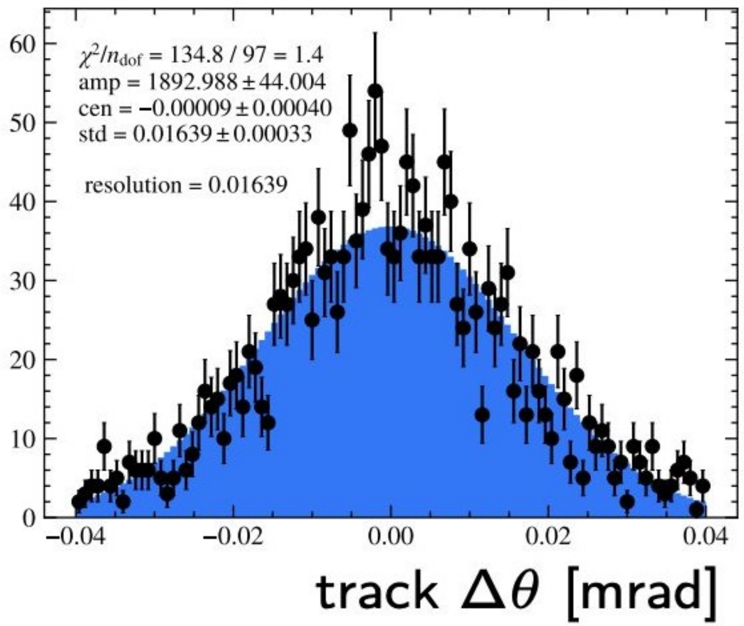
We need a good mass resolution (25 Mev) to separate the signal from misidentified background:

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

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



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



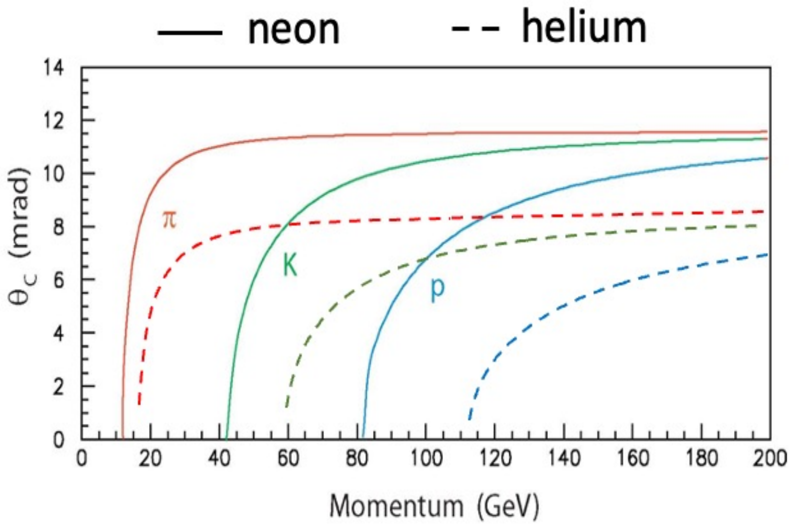
Particle Identification System

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

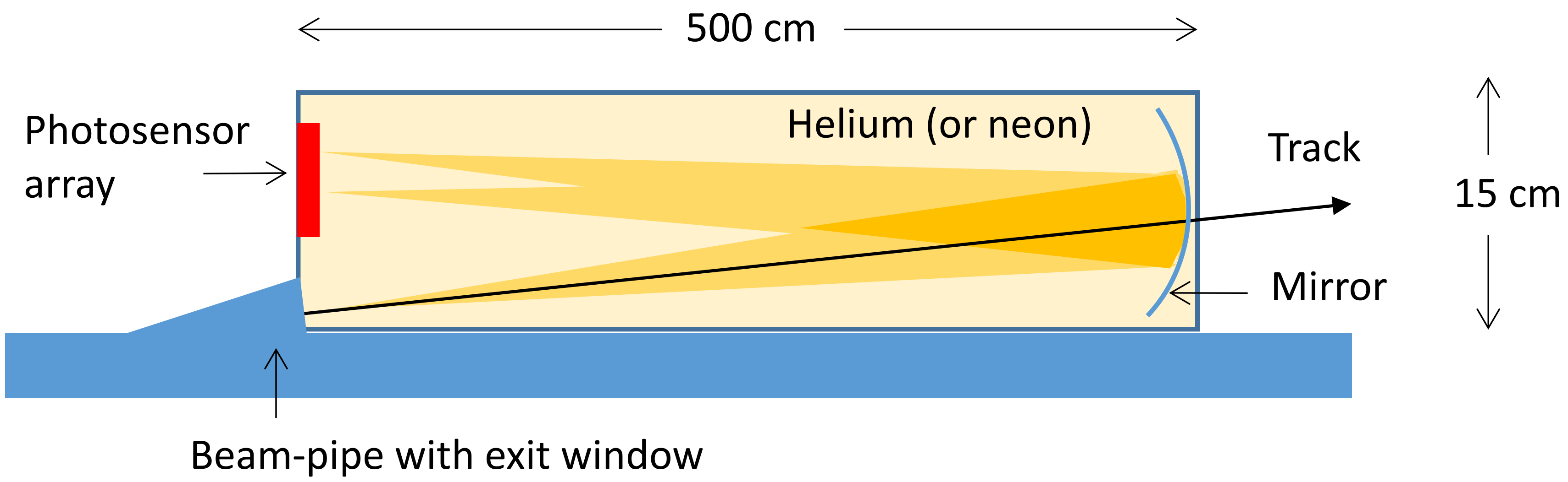
Aim for scaled-down RICH, using modern highly pixelated & efficient photosensors (e.g. **SiPM**) to compensate for reduced size

Spherical mirror at the end of the radiator volume,

- Radius of curvature $R = 2L = 10$ m
- Cherenkov angle = 8.4 mrad for helium
  → ring images are quite small: diameter $d = R\,\theta_C = 8.4$ cm



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



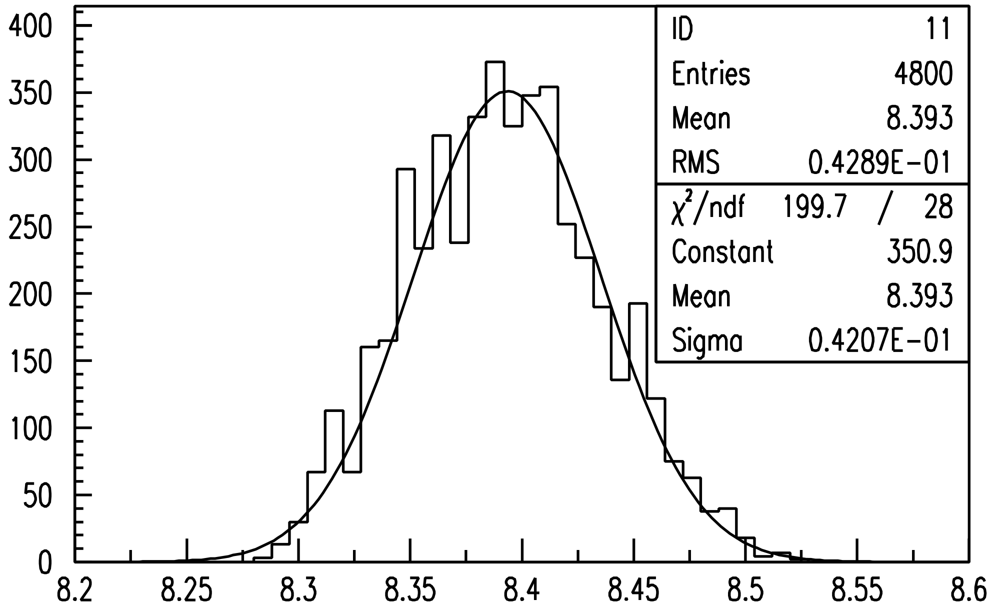
Angular resolution

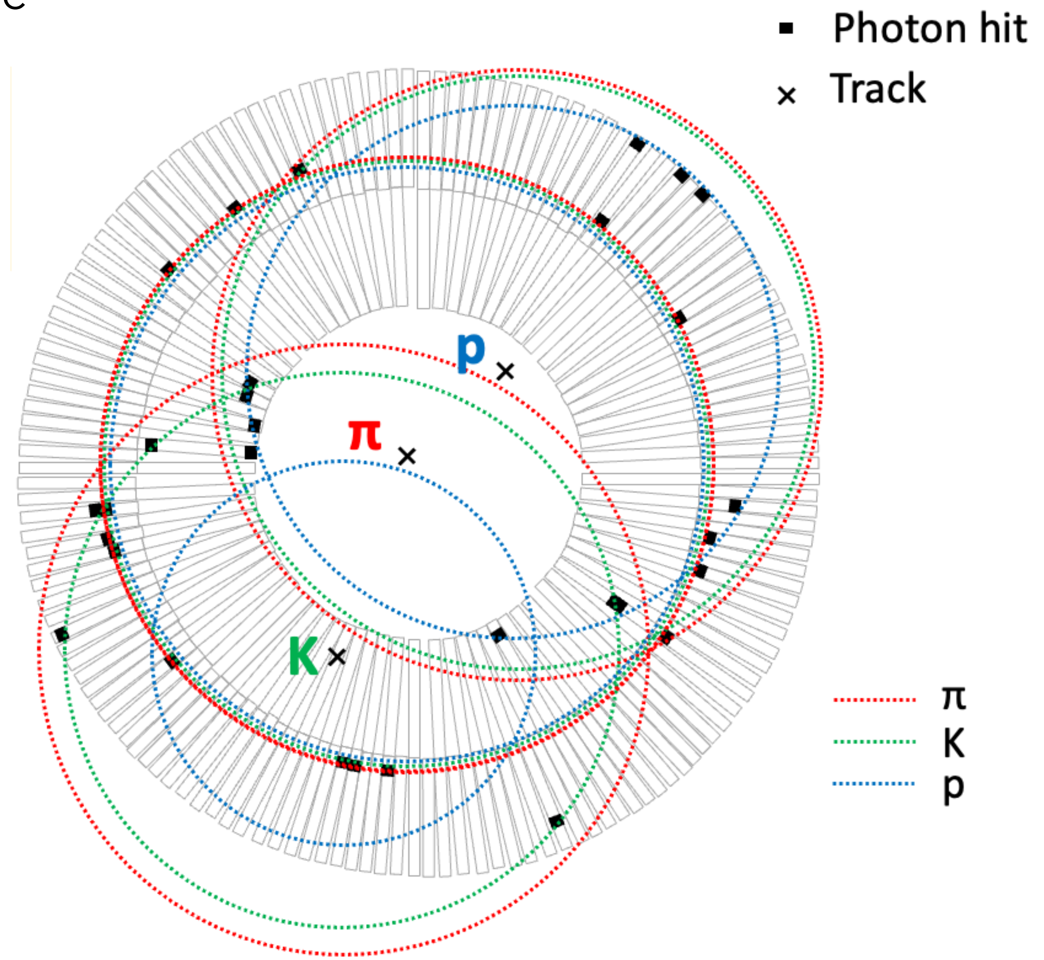
taken from slides of **Roger Forty**
https://indico.ijclab.in2p3.fr/event/9924/overview

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

σ_θ = 42 µrad per photon

Combined resolution





Background suppression

Compare efficiency for signal

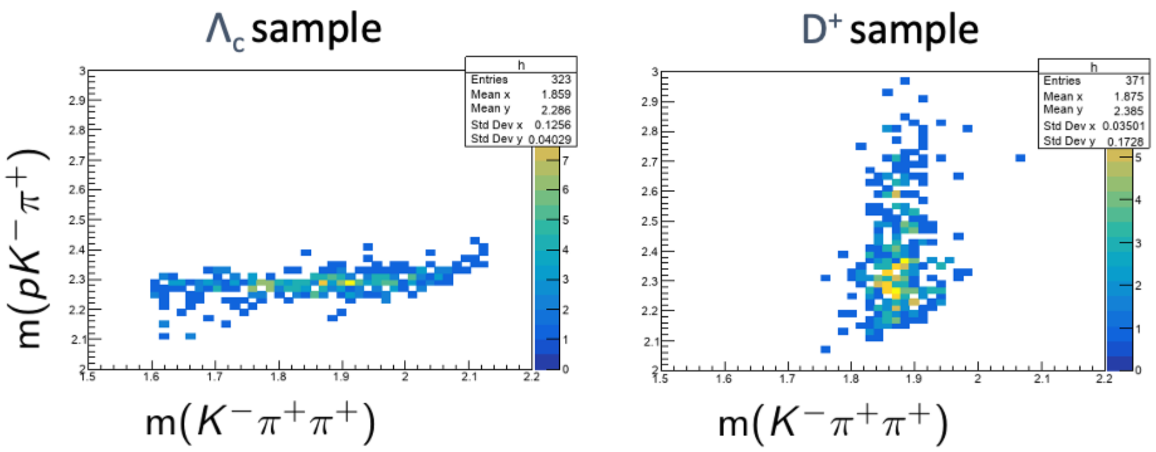
$\Lambda_c^+ \rightarrow p\, K^- \pi^+$

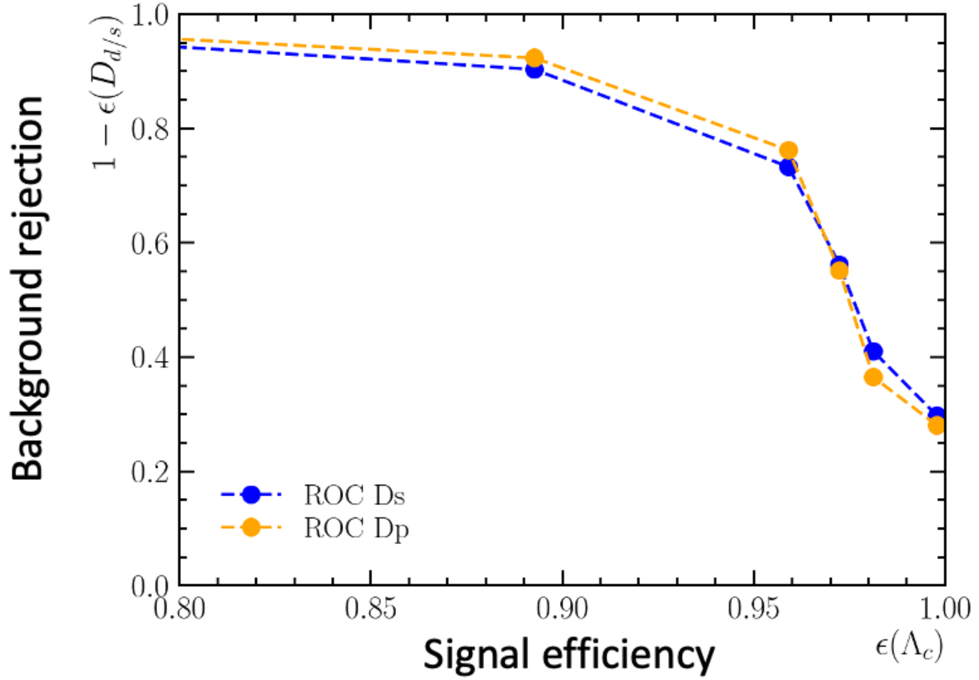
and suppression of background decays

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

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

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

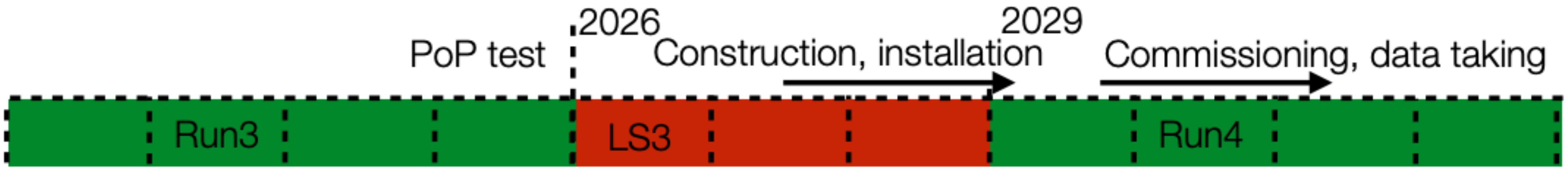




taken from slides of **Roger Forty**
https://indico.ijclab.in2p3.fr/event/9924/overview

Conclusions

- Proposed fixed target experiment at LHC to measure direct EDM/MDM of charm baryons
- Expected sensitivities on MDM of $2{\times}10^{-2}\mu_N$ and EDM of $3{\times}10^{-16}$ e cm with 10^{13} PoT
- Proof-of-principle test approved by the LMC committee scheduled for 2025
- Ongoing LHCC review of the project
- Letter of Interest to be presented in June 2024



Thank you for your attention!

Backup

Backup

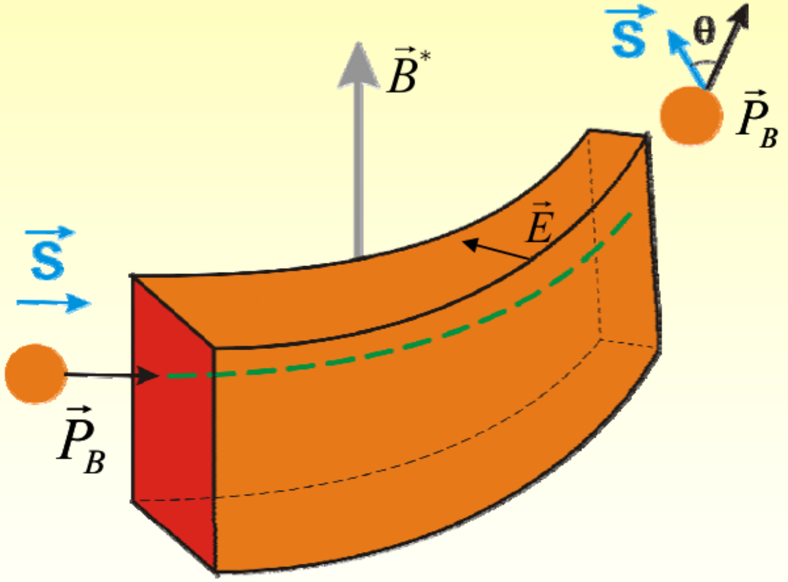
In particle rest frame

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

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

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

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

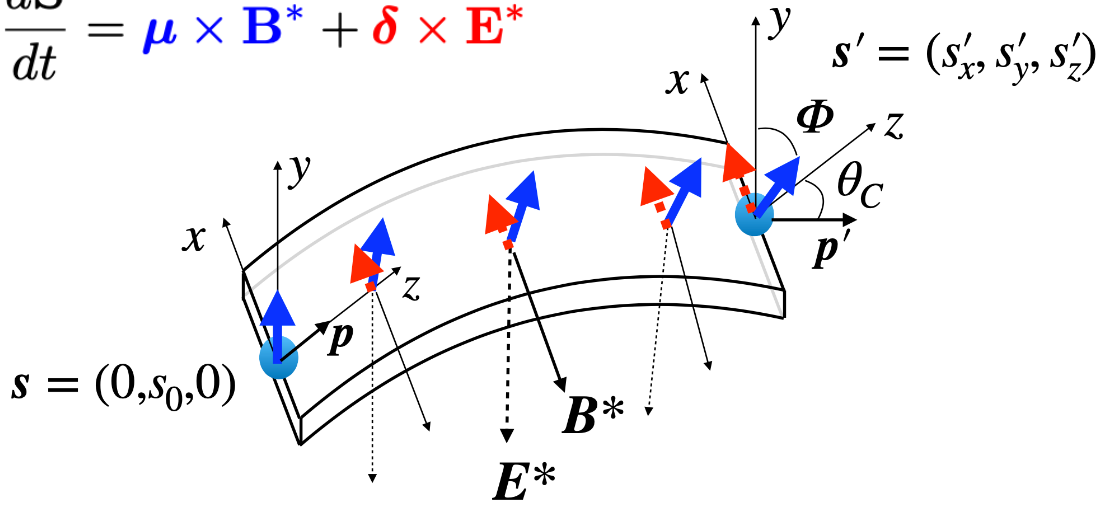
$$s_0(p_\mathrm{T}) \approx A\left(1 - e^{-Bp_\mathrm{T}^2}\right)$$

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

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

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

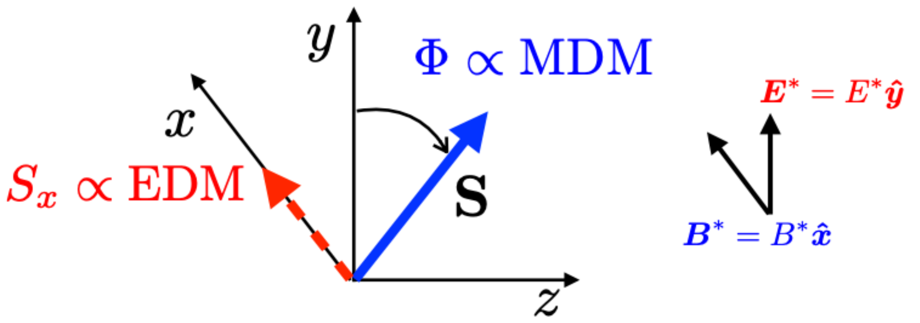
$$\frac{d\mathbf{S}}{dt} = \boldsymbol{\mu} \times \mathbf{B}^* + \boldsymbol{\delta} \times \mathbf{E}^*$$



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

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

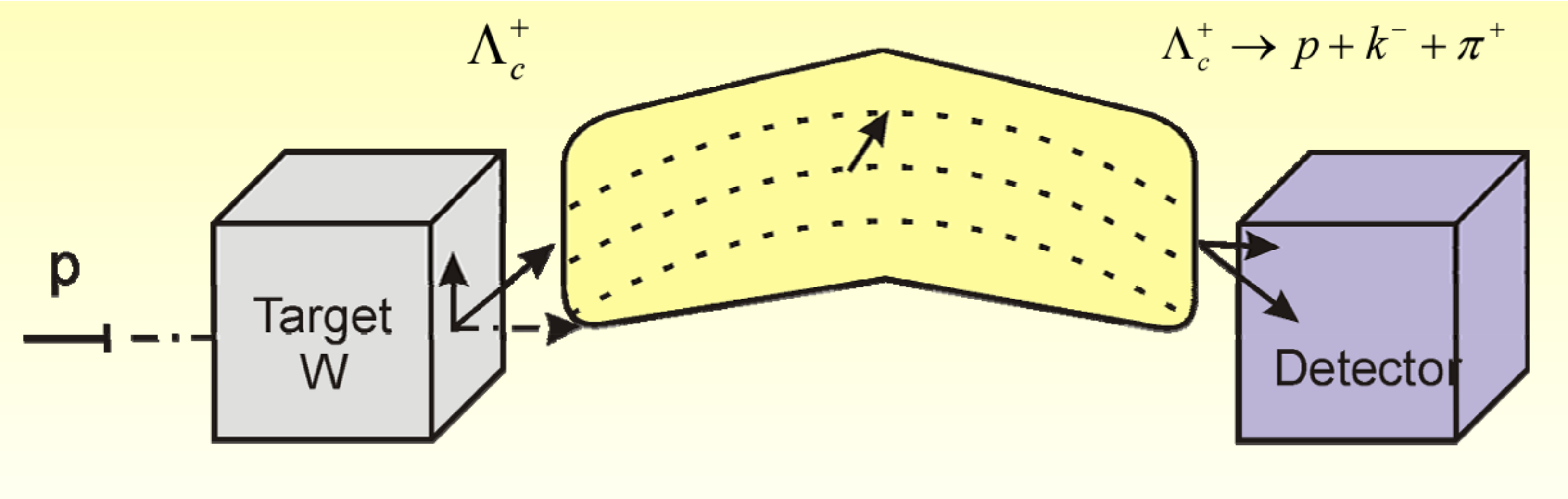
$$\Phi \approx \frac{g-2}{2}\gamma\theta_C \qquad s_x \approx s_0 \frac{d}{g-2}(\cos\Phi - 1)$$



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

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

Polarization measurements and MDM/EDM extraction

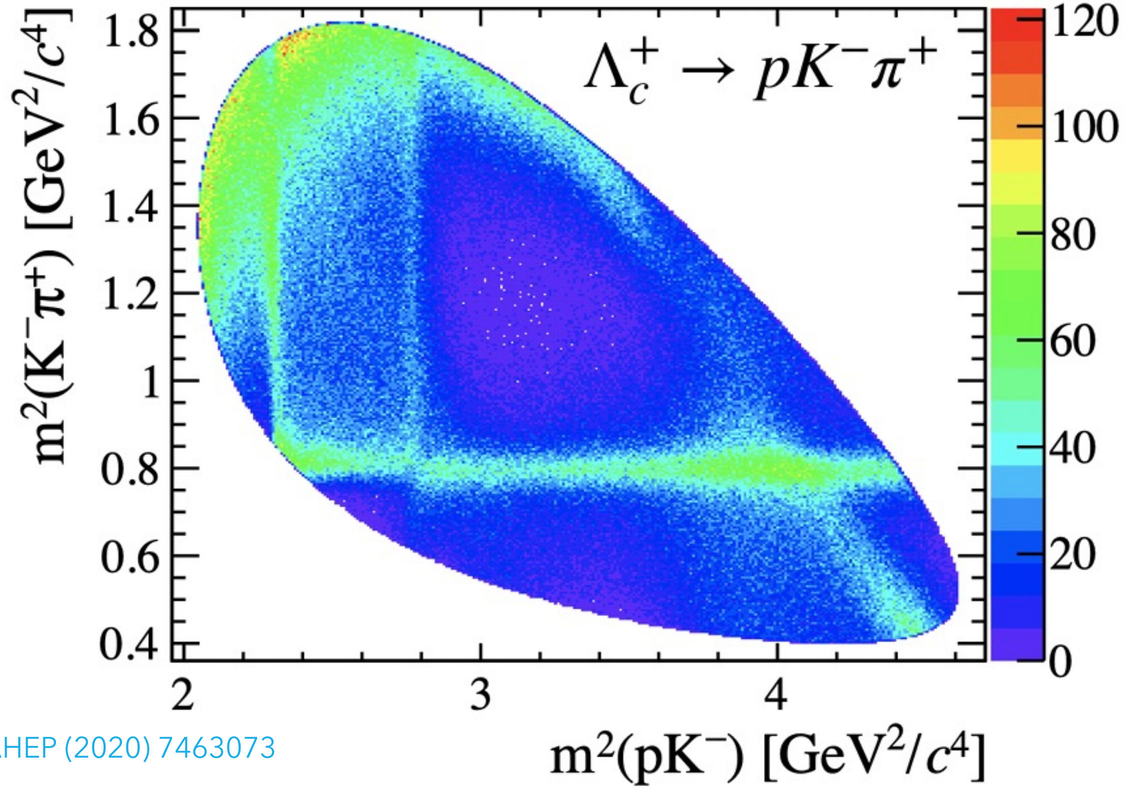
- Use many 3-body decays to increase the signal yield
- Extract maximum information via full amplitude analysis of the 3-body decays

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

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

where s0 is the best estimate for the polarization



D. Marangotto, AHEP (2020) 7463073

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

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

$\downarrow$ 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)

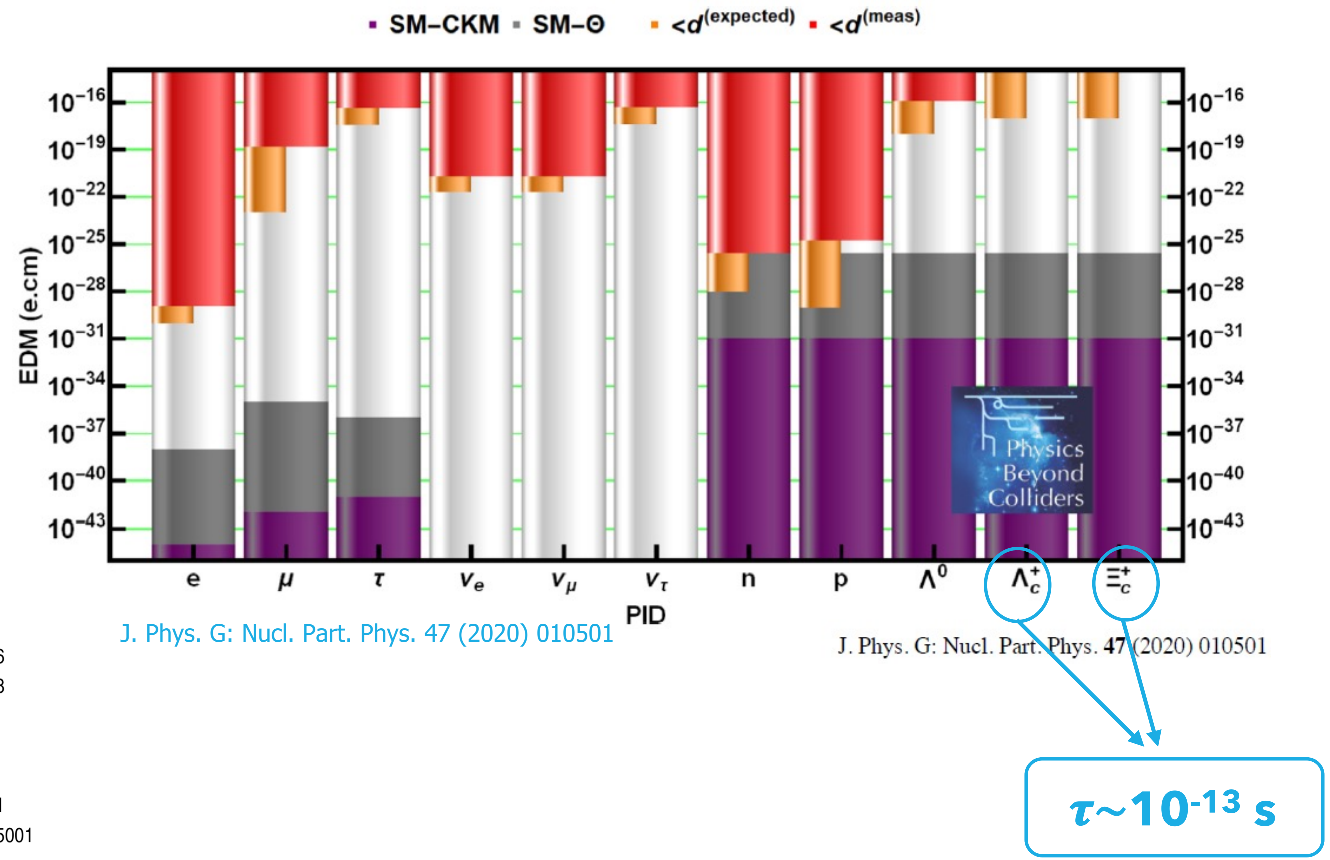
- **MDMs** provide important anchor points for QCD calculations.

Phys. Lett. B291 (1992) 293

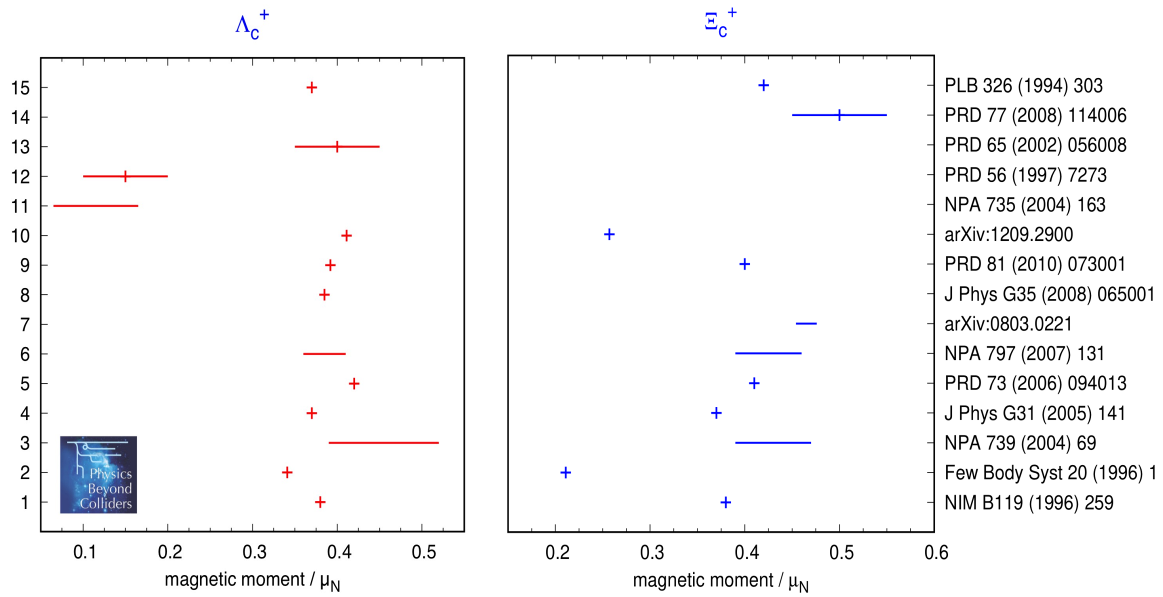
Direct measurements of EDM and MDM of charm baryons

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

We need experimental measurements to verify theoretical predictions.

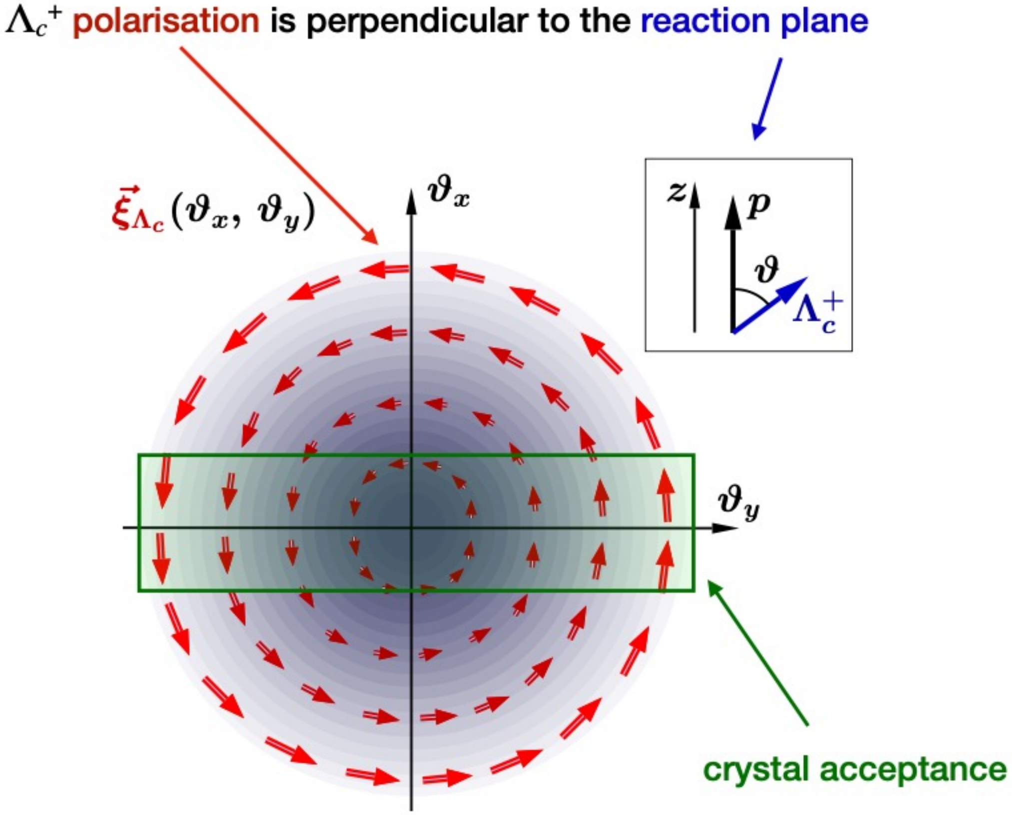


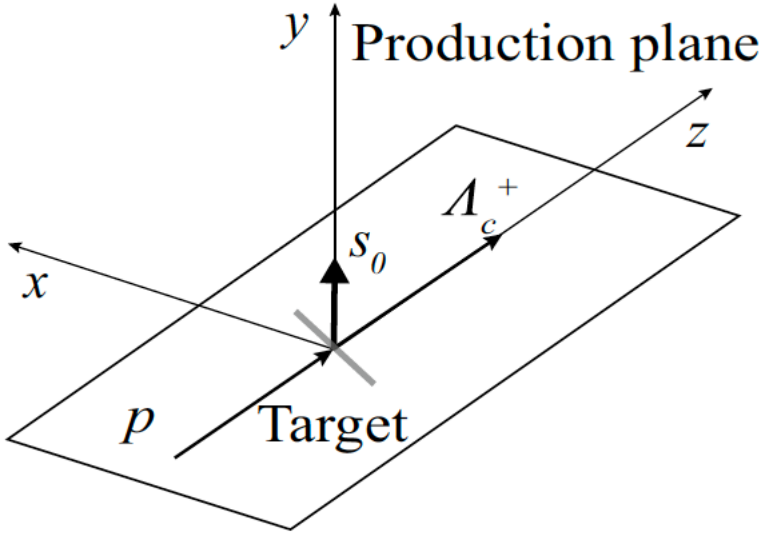
J. Phys. G: Nucl. Part. Phys. 47 (2020) 010501



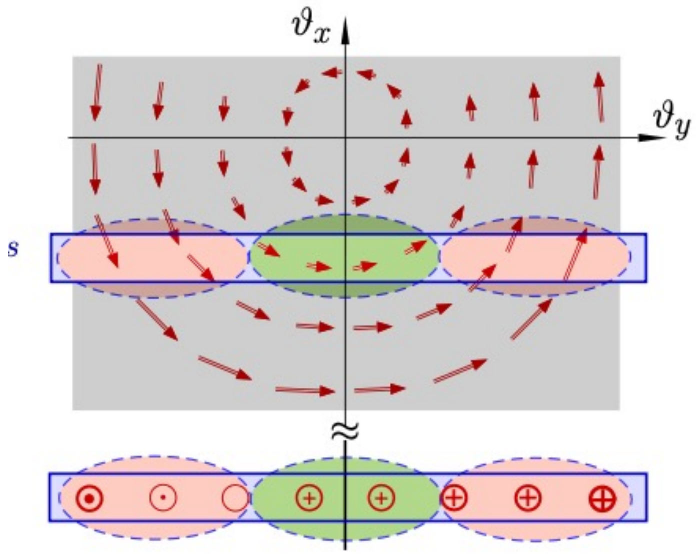
CERN-PBC-REPORT-2018-008

Transversal polarization





Simultaneous measurement



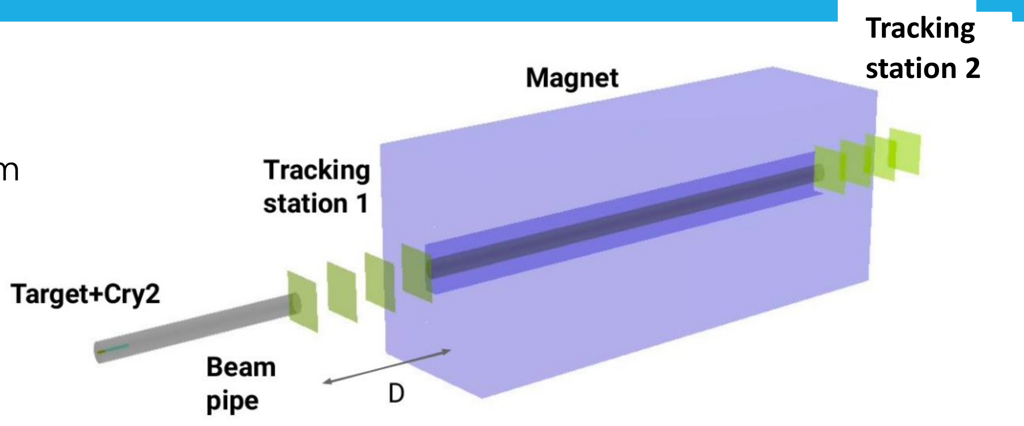
$$\Delta g = \frac{2}{\alpha \langle \xi_x \gamma \rangle \Theta} \sqrt{\frac{3}{N}}$$

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

Simulation for the future experiment

Optimization of the detector setup for the EDM/MDMs and Λ_c^+ measurements.

- Beam pipe: Cu OFE, elliptical form
- Target: W, 2 cm long
- Cry 2: Si, 7 cm long, 7 mrad
- MCBW Magnet: Fe, at 1m from crystal B=1.1 T, L =1.7 m
- Tracking stations: 8 modules. 4 before – 4 after magnet



Simulation framework:

- Geometry based on DD4Hep
- Generators: Phythia/Angantyr model, particle gun, general particle source
- Visualisation: geoDisplay
- Event model: DDG4
- Channeling: Geant4
- Tracking: GenFit

Parametric simulations to study magnet acceptance and $\mathbf{m(pK^-\pi^+)}$ resolution vs detector geometry

Invariant mass resolution versus tracker lenght

$\sigma_M < 50$ MeV for tracker lenght D > 40 cm