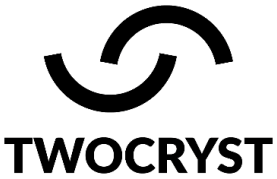
Direct measurement of dipole moments of short-lived particles at the LHC: advances and prospects



F. Martínez Vidal

IFIC, University of Valencia-CSIC

for the ALADDIN & TWOCRYST collaborations

ICHEP 2024, Prague

20.07.2024

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Plan de Recuperación, Transformación y Resiliencia
GENERALITAT VALENCIANA Conselleria de Educación, Universidades y Empleo
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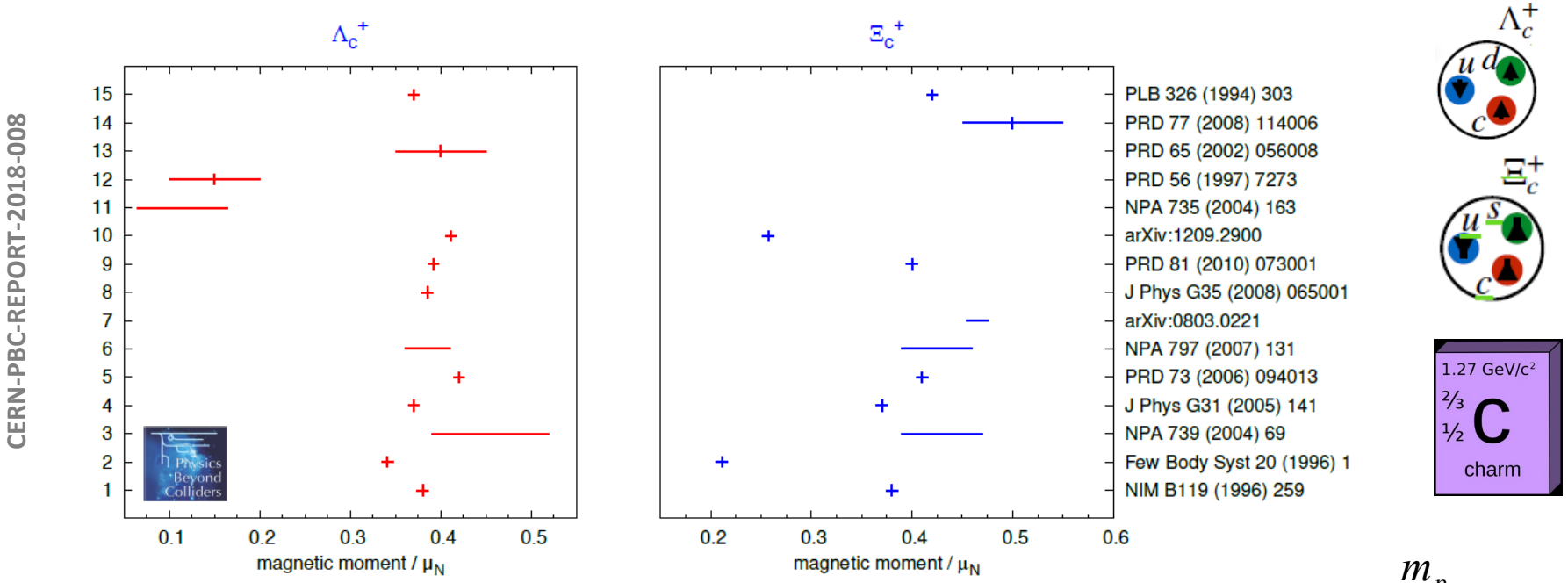
erc
SEL:DOM

Outline

- Physics goals
- Experimental technique
- Double crystal setup & proof-of-principle
- Proposed experiment & timeline
- Spectrometer & RICH detector
- Physics reach
- Summary

Physics goals

- **First** direct **measurements** of Λ_c^+, Ξ_c^+ magnetic (MDM, μ) and electric (EDM, δ) dipole moments. To date, out of experimental reach
- In the quark model, $\Lambda_c^+ = [ud]c$, $\Xi_c^+ = [us]c$ and naive MDM, $\mu_{\Lambda_c^+} = \mu_{\Xi_c^+} = \mu_c$. HQFT predictions require experimental values at least at **10%** precision



$\mu \approx 0.1\mu_N$ $\quad$ $\mu \approx 0.4\mu_N$ $\quad$ $\mu \approx 0.2\mu_N$ $\quad$ $\mu \approx 0.4\mu_N$

$g \approx 0.49$ $\quad$ $g \approx 1.95$ $\quad$ $g \approx 1.05$ $\quad$ $g \approx 2.10$

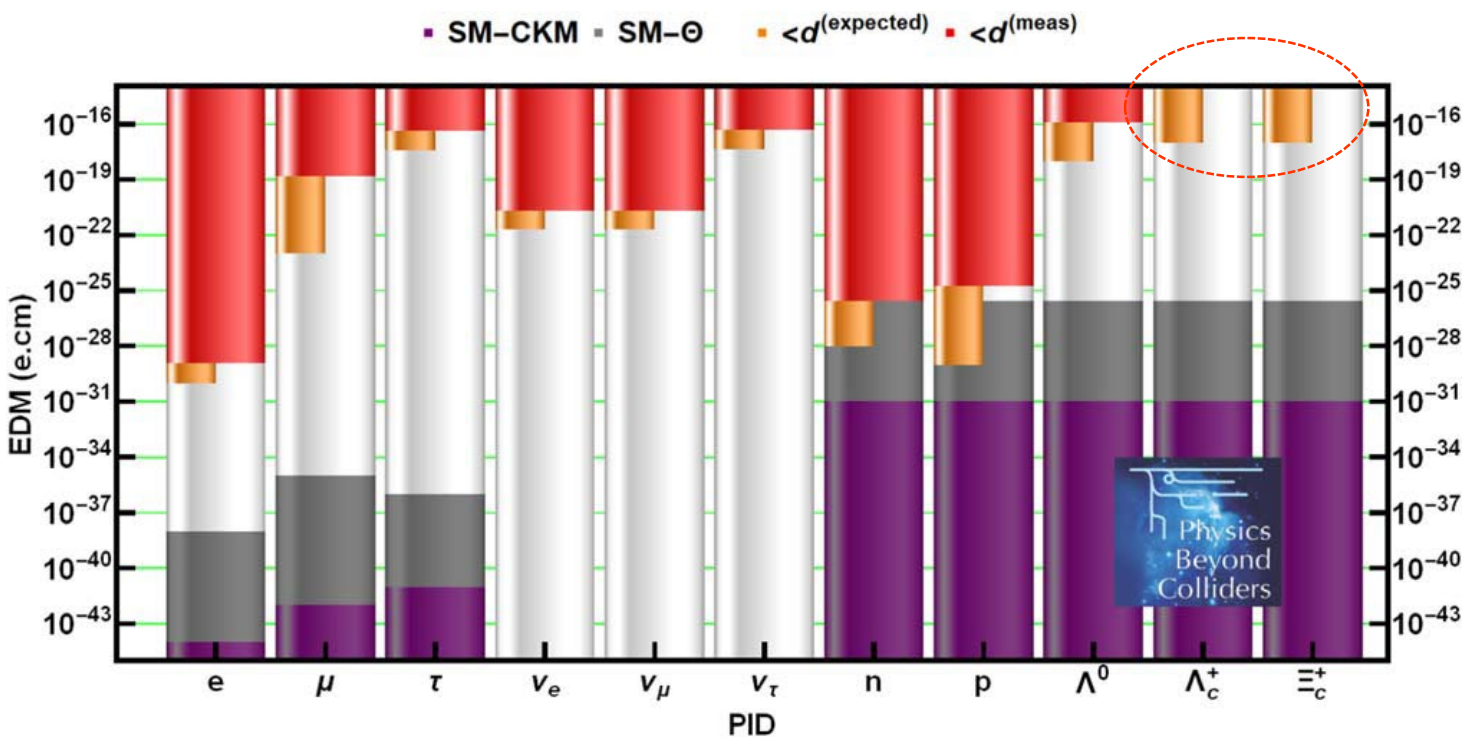
$a \approx -0.76$ $\quad$ $a \approx -0.03$ $\quad$ $a \approx -0.47$ $\quad$ $a \approx 0.05$

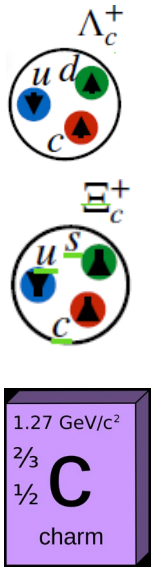
$$\mu = gJ\frac{m_p}{m}\mu_N$$

$$a = \frac{g-2}{2}$$

Physics goals

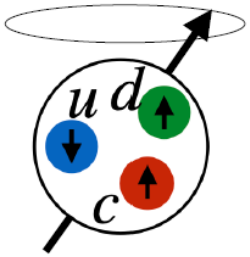
- Search for charm EDM, probe for BSM physics
- World-wide effort: charm quark might have special BSM couplings
  - ✓ Need global EDM analysis, experimental input from charm sector valuable





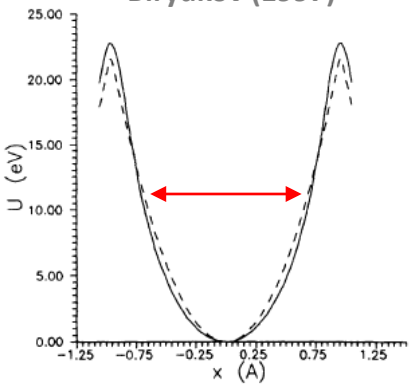
J. Phys. G: Nucl. Part. Phys. 47 (2020) 010501

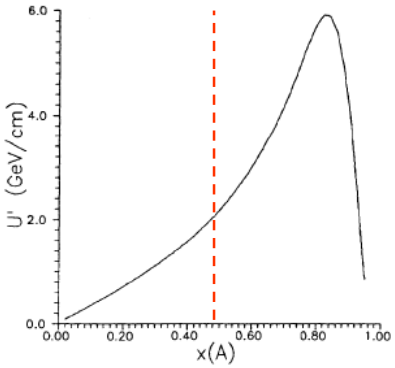
Experimental technique



- MDM and EDM accessed through spin precession in EM field
- Challenges:
  - ✓ Charm baryon lifetimes are very short, $\tau \approx 2\text{–}4\times10^{-13}$ s
    $\Rightarrow$ enough **flight length** and **strong EM field**
  - ✓ Sizeable **initial polarization**
  - ✓ **High intensity** charm baryon beam
  - ✓ **Excellent detector** for signal reconstruction, background rejection and angular analysis
- Charm baryons from fixed target-target **pW collisions** at the LHC, $\sqrt{s} \approx 115$ GeV
- Exploit **channelling in bent crystals**:
  - ✓ High boost $\gamma \approx 600\text{–}900 \Rightarrow$ flight length $\beta\gamma c\tau \approx 7\text{–}10$ cm
  - ✓ Strong electric field $E \approx 2$ GV/cm between atomic planes
    $\Rightarrow$ Effective magnetic field $B \approx 650$ T
    (≈ 0.5 MT in particle frame)

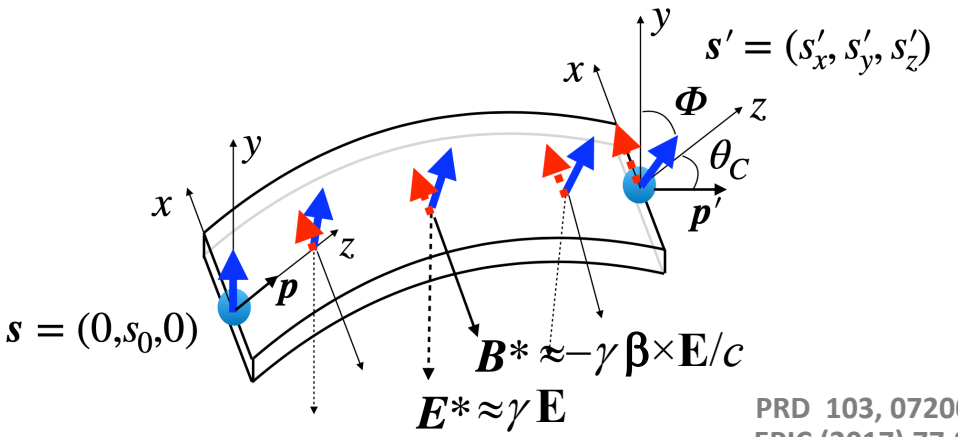
Lindhad (1965)
Biryukov (1997)





Experimental technique

- MDM and EDM precession in a bent crystal



PRD 103, 072003 (202
EPJC (2017) 77:828

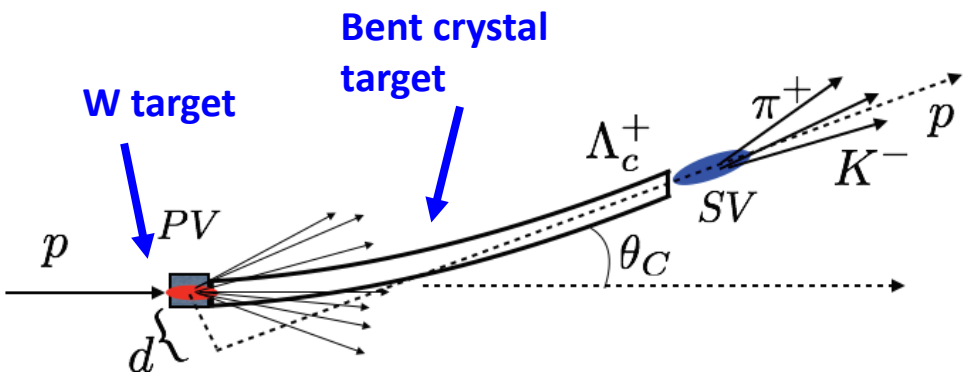
- Spin-polarisation analyser

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

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

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

- Signal signature



High momentum

- ✓ Average of 1.8 TeV/c for channelled Λ_c^+ baryons for 7 mrad bending angle
- ✓ Final-state particle momentum up to 2 TeV/c
- ✓ Track angular separation ≈0.5 mrad

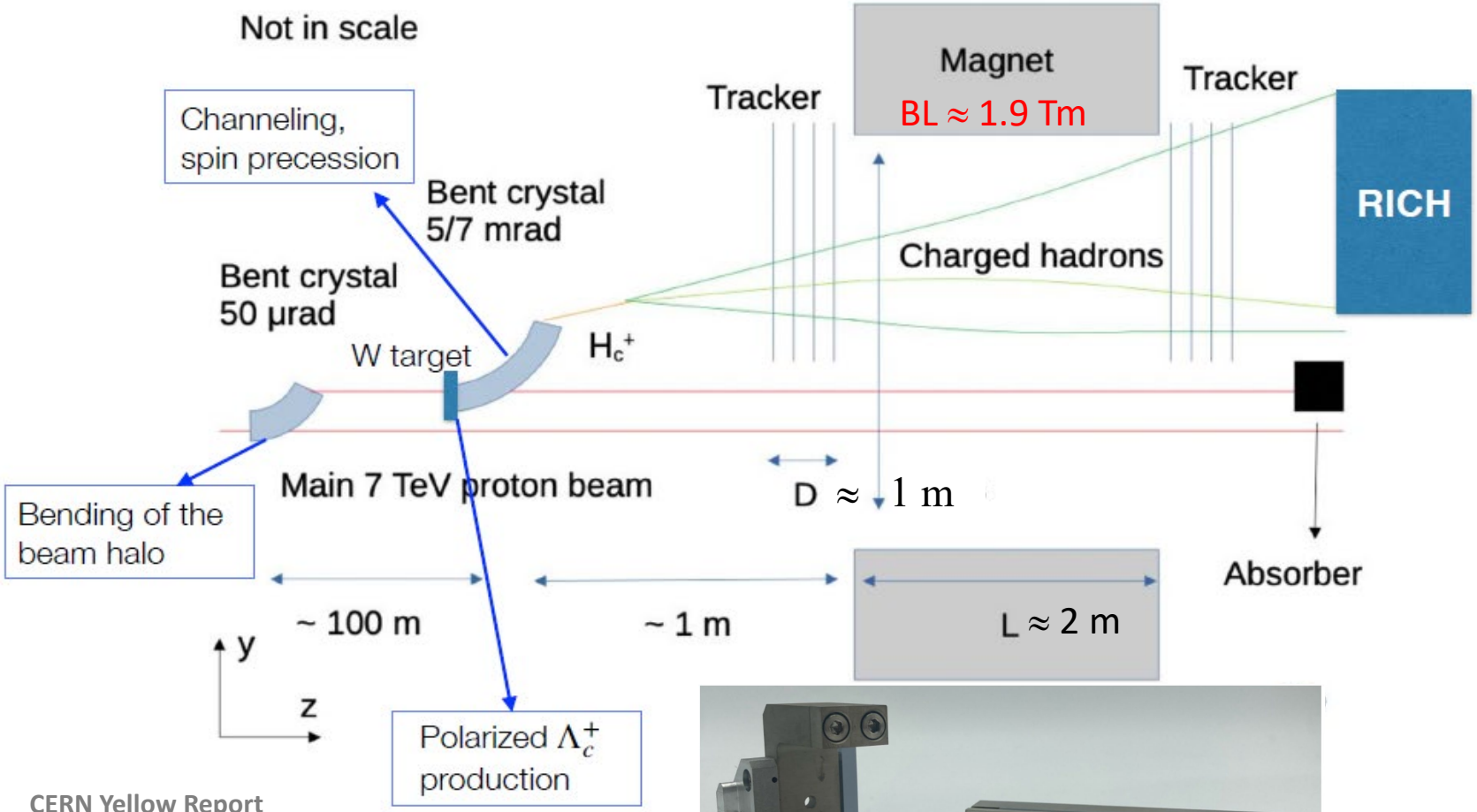
Angle at crystal angle

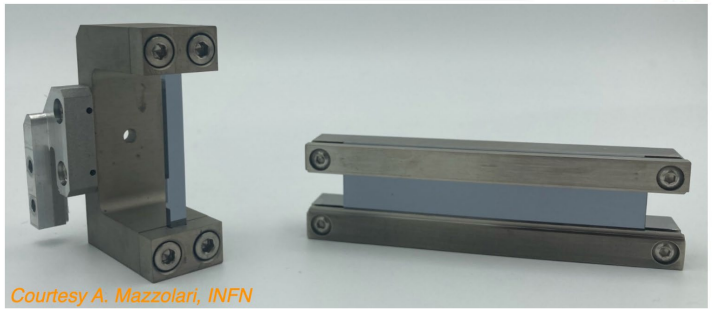
- ✓ Strongly collimated (within ≈10 μrad)

p/K/π PID above 500 GeV/c

Double-crystal setup: crystal based MDM/EDM measurement

See also P. Hermes talk



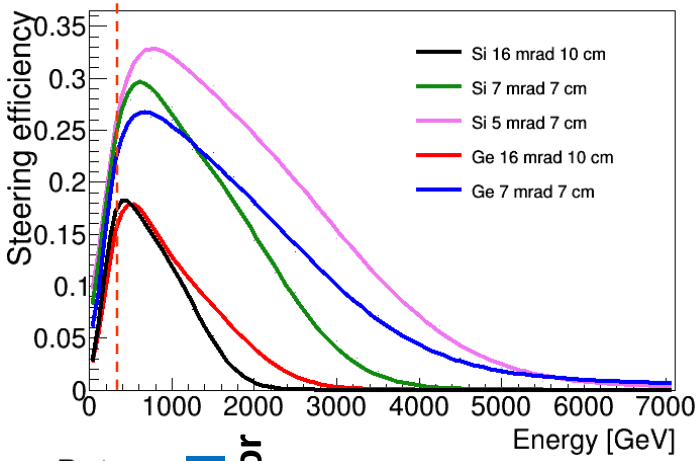


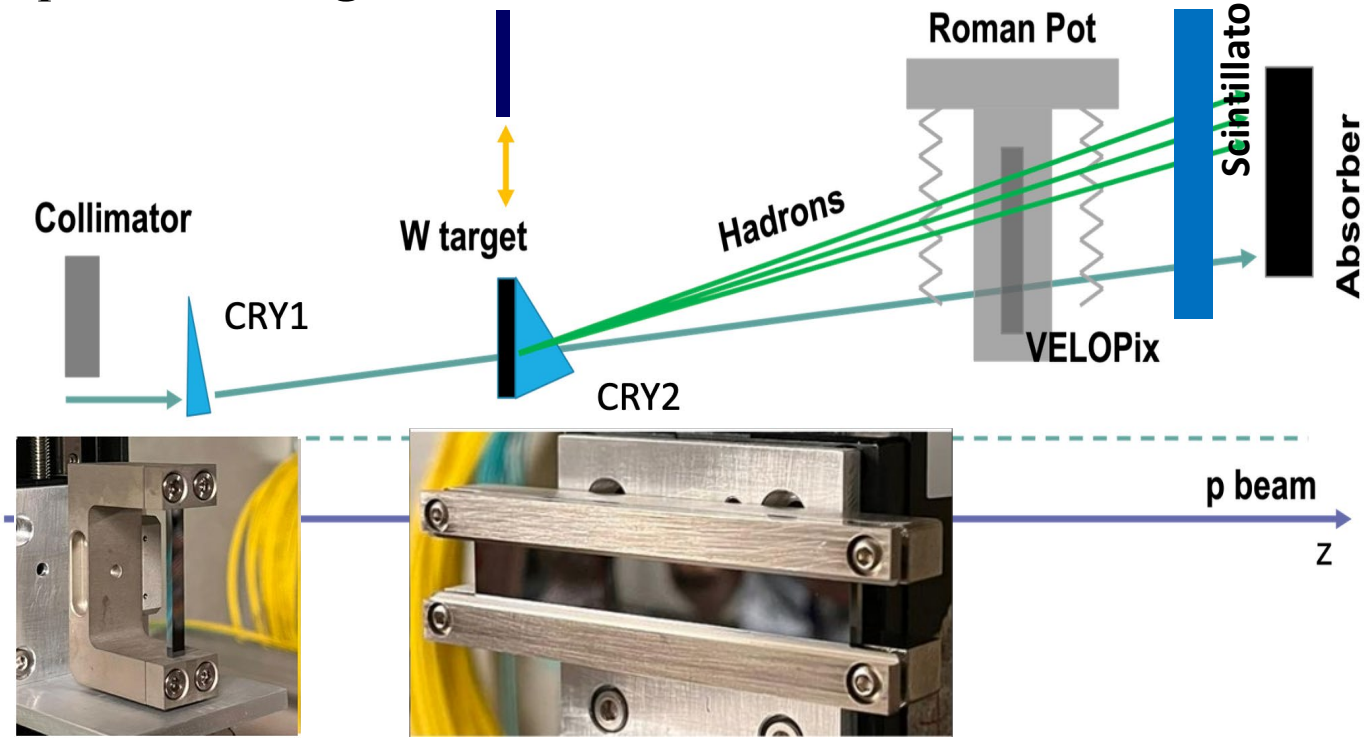
CERN Yellow Report
CERN-2020-004

See P. Hermes talk for details

TWOCRYST proof-of-principle at the LHC

- Foreseen in 2025 to:
  - ✓ assess **feasibility of machine operations**
  - ✓ assess achievable **proton flux**
  - ✓ measure **channelling efficiency at TeV** energies vs simulation
  - ✓ perform **background studies**





Si 50 μrad 4 mm, chan. eff. 60%

Si 7 mrad 7 cm, chan. eff. 16%

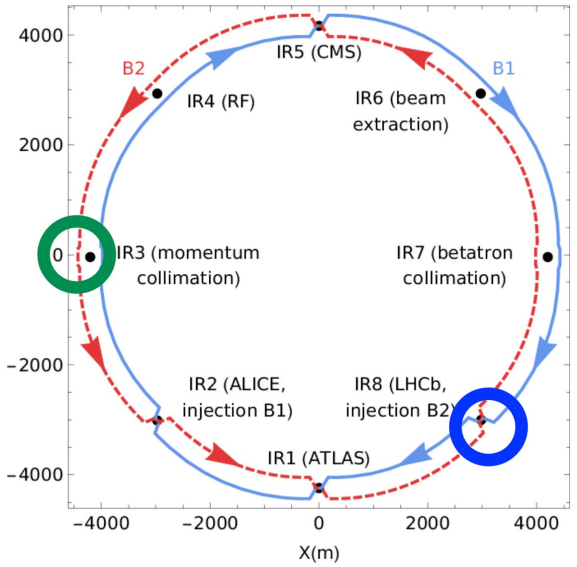
@ 180 GeV/c CERN SPS H8

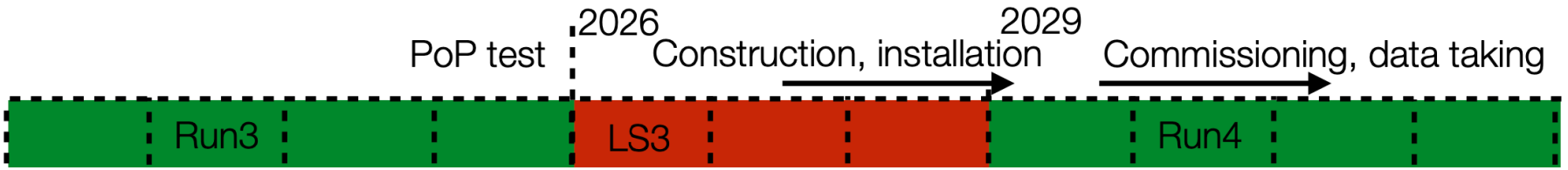
Acknowledgments:
A. Mazzolari

Proposed experiment at the LHC and timeline

- Two alternative proposals:
  - ✓ **Dedicated experiment at Insertion Region 3 (IR3) – baseline**
  - ✓ Use of LHCb detector at IP8 (fallback option)

	Pro	Cons
IR3	Optimal experiment and detector. PID information	More resources needed. New detector, services (long cables, cooling)
LHCb	Use existing tracking detector and infrastructure. Experimental area	No PID for p>100 GeV. Potential interference with LHCb core program





With current LS3 plans, some installations can only happen during the EYETS at the end of 2029. The commissioning line could start within 2029 for some ALADDIN components

ALADDIN LoI & proto-collaboration

Letter of Intent

ALADDIN: An Lhc Apparatus for Direct Dipole moments INvestigation

19 July 2024

K. Akiba [1], *F. Alessio* [2], *M. Benettoni* [3], *A. Bizzetti* [23,24], *F. Borgato* [3,4], *F. Bucci* [23], *R. Cardinale* [5,6], *S. Cesare* [7,8], *M. Citterio* [8], *V. Coco* [2], *P. Collins* [2], *E. Dall'Occo* [9], *M. Ferro-Luzzi* [2], *A. Fomin* [21], *R. Forty* [2], *J. Fu* [10], *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], *C. Maccani* [3,4], *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], *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]

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[24]Università degli Studi di Modena e Reggio Emilia, Italy

58 people, 19 groups from 8 countries

+ strong support from machine people:

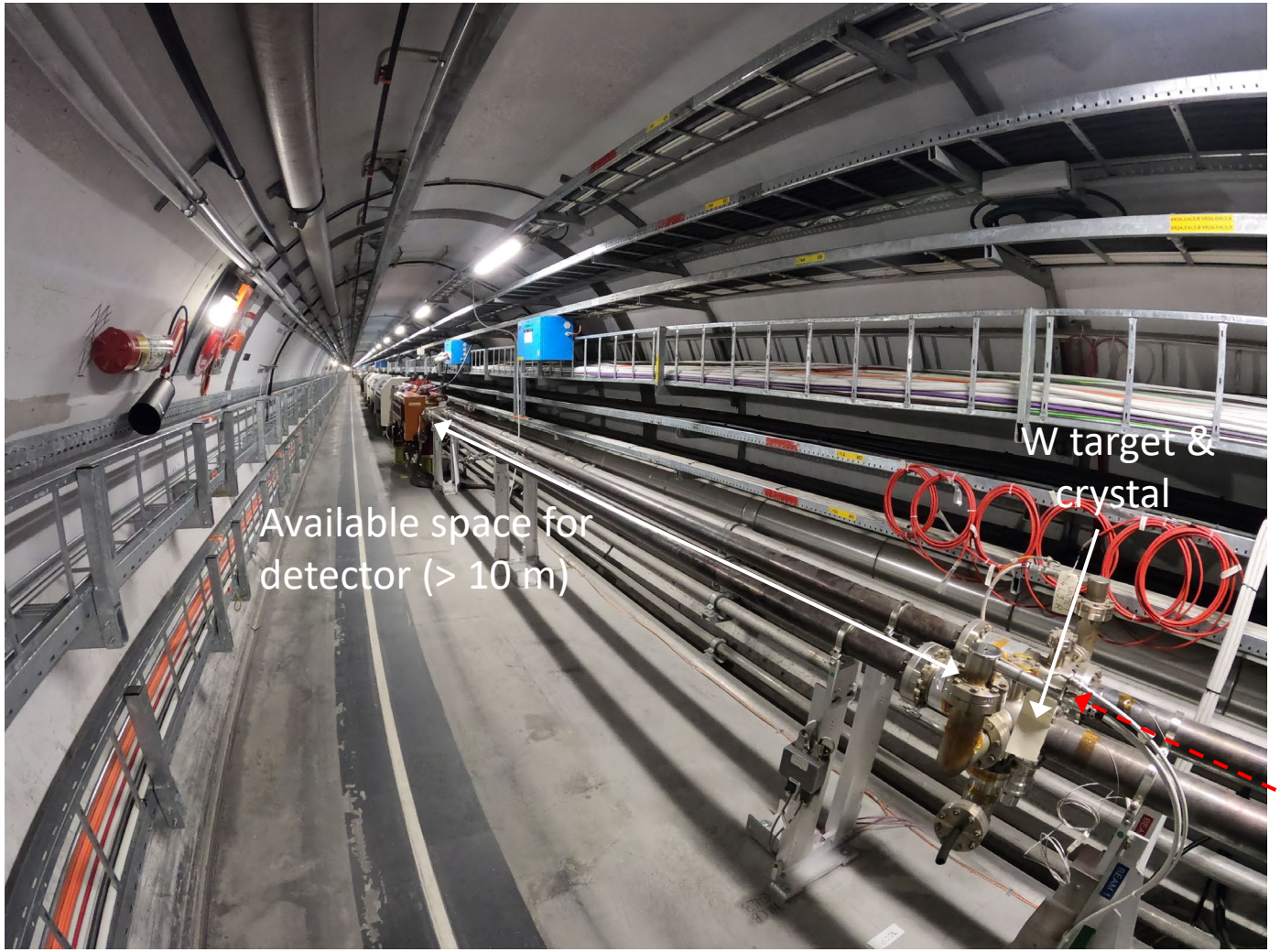
P. Hermes, K. Dewhurst, R. Cai, C. Maccani, D. Mirarchi, S. Redaelli, G. Arduini

+ TWOCRYST collaboration

Experiment site

See also P. Hermes talk

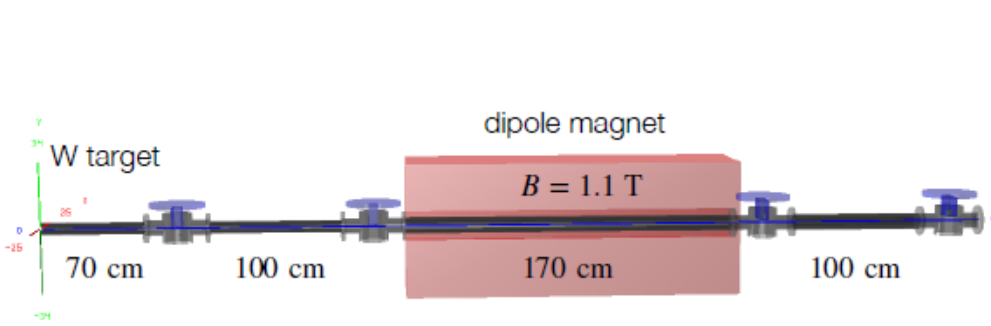
- Space identified for the PoP also suitable for the experiment at IR3 video

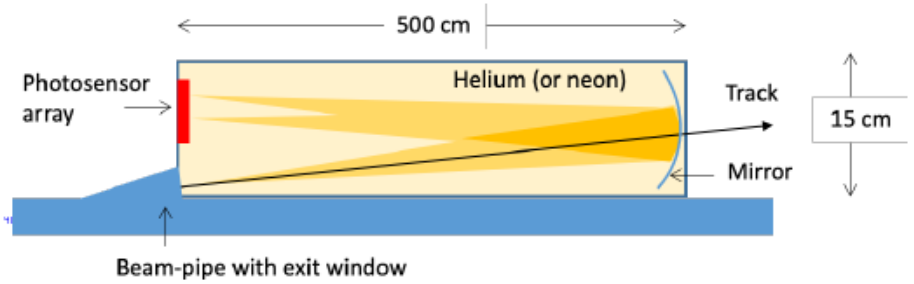


Detector layout

Spectrometer: 440 cm length

RICH: 500 cm length





Si detectors in 4 Roman Pot stations

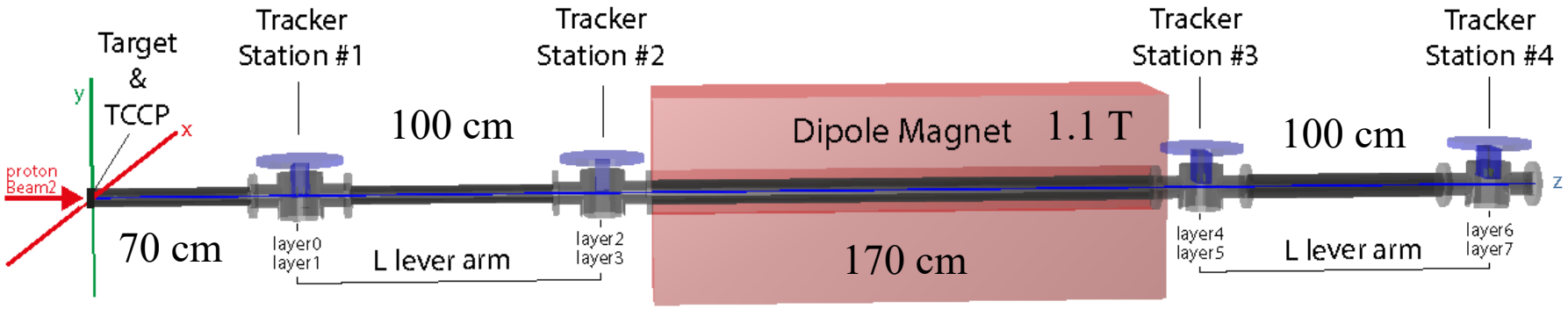
Helium radiator gas with SiPM array

Specifications for the tracking detectors positioned upstream and downstream of the (warm) dipole magnet. Hit rate estimated with full simulations

	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

Very forward spectrometer

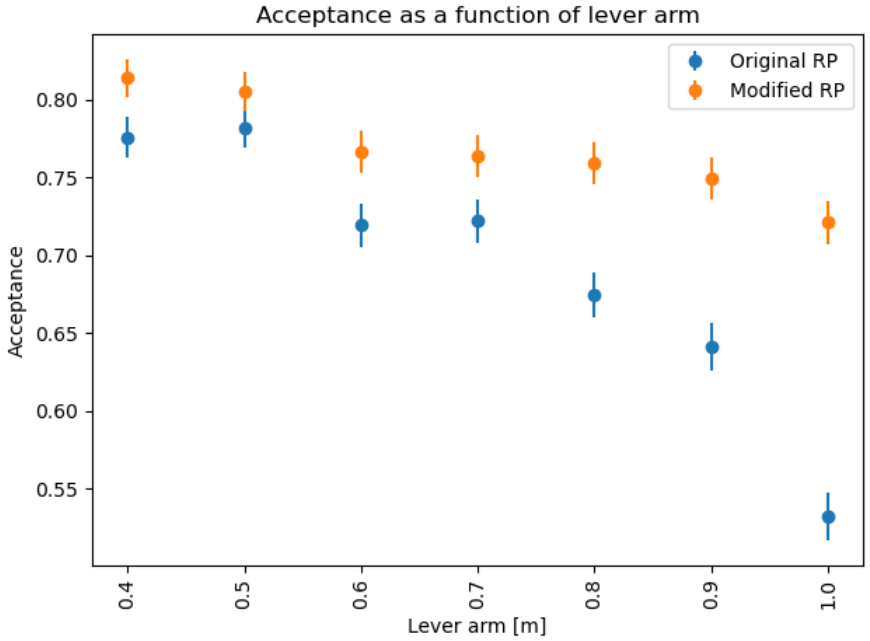
- Pseudorapidity acceptance **5 < η < 9**
- **4 tracking stations** (2 upstream + 2 downstream of the magnet) housed in Roman Pots (RPs)
- A local corrector **dipole magnet** MCBWV (1.1 T, 1.7 m) available in situ



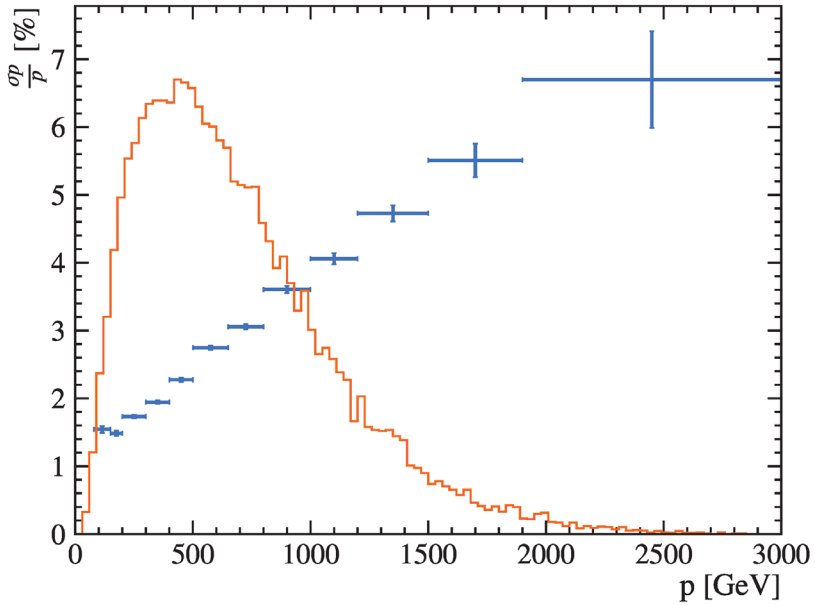
- **Momentum** resolution: $\frac{\sigma_p}{p} \approx \frac{2p}{0.3BLD}\sigma_x \approx 2\%$, with $p = 500\ \text{GeV}/c,\ BL = 1.9\ \text{Tm},$ $D = 1\ \text{m}, \sigma_x \approx 10\ \mu\text{m}$
- **Track angle** resolution: $\sigma_\theta \approx \sqrt{2}\sigma_x / D \approx 14\ \mu\text{rad}$
- **Impact parameter** resolution: $\sigma_{x,y} \approx 20\ \mu\text{m}$

Spectrometer performance (full simulations)

- **Acceptance** for Λ_c^+ signal decays 70% (with modifications to beam pipe geometry and current RP)



- Good **resolutions** for signal $\Lambda_c^+ \to pK^-\pi^+$ decays, very similar for other decays
  - ✓ Momentum resolution

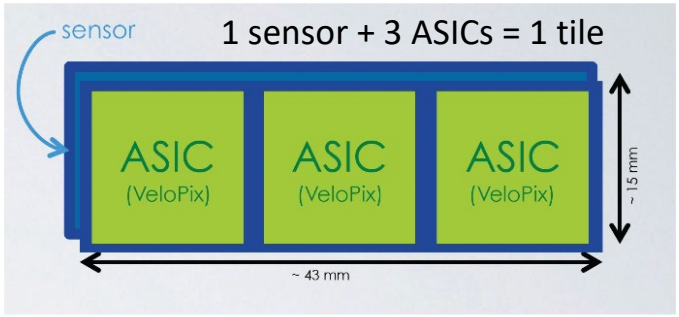


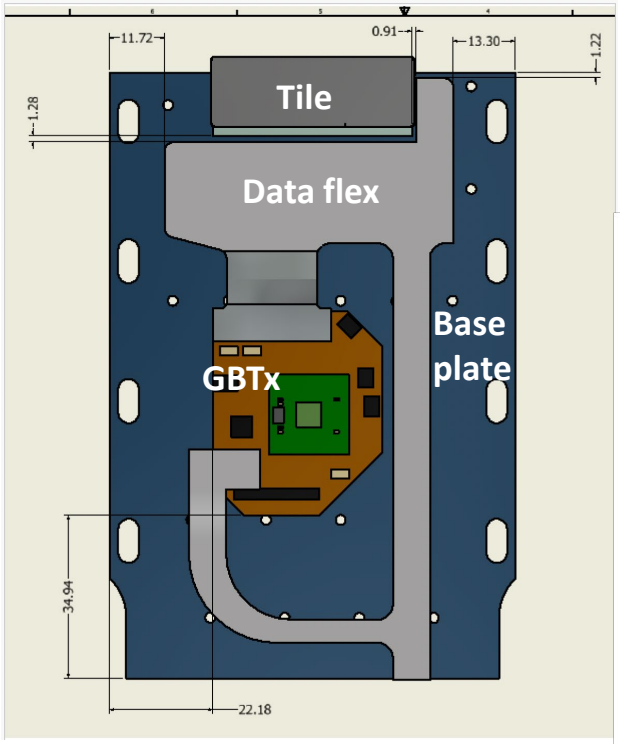
  - ✓ Mass resolution 27-18 MeV for 2-6 layers/tracking station

- Acceptance up to 90% and ×2 improvement in momentum resolution with dedicated compact magnet 4 T, L=1 m (future potential upgrade, 20K HTS)

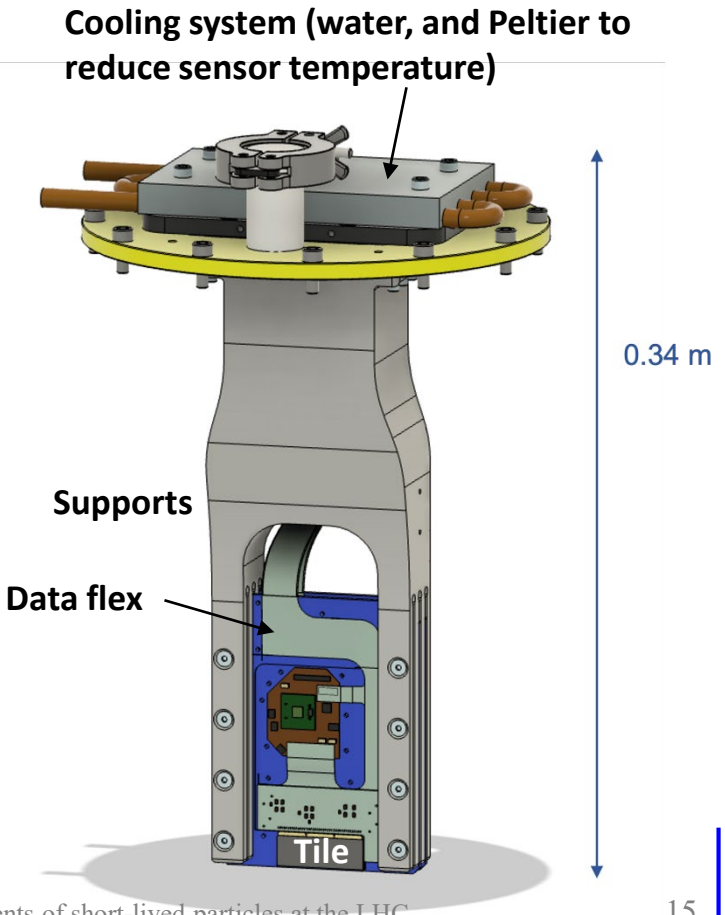
Pixel detector

- Based on **LHCb VELO pixel** sensors and VeloPix ASIC





Acknowledgments:
J.Buytaert, V. Coco, E. Lemos, P. Collins from LHCb VELO group

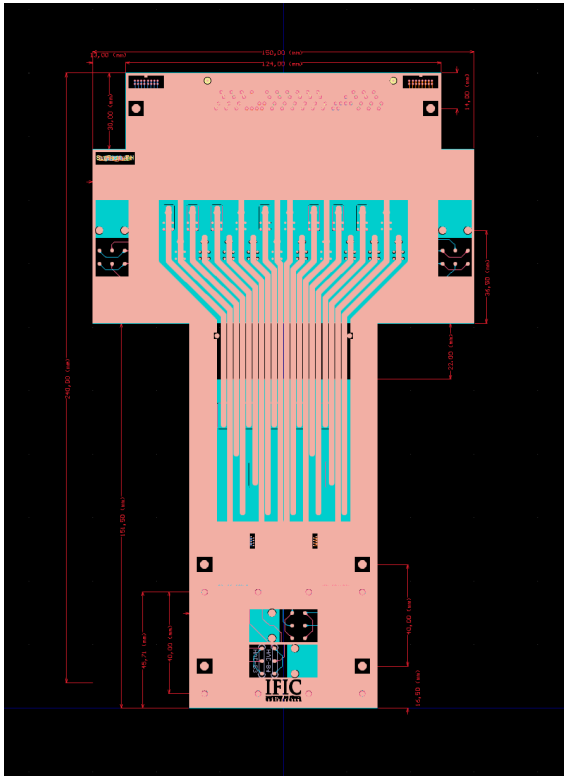


- CMS-TOTEM based design for detector package in the RP

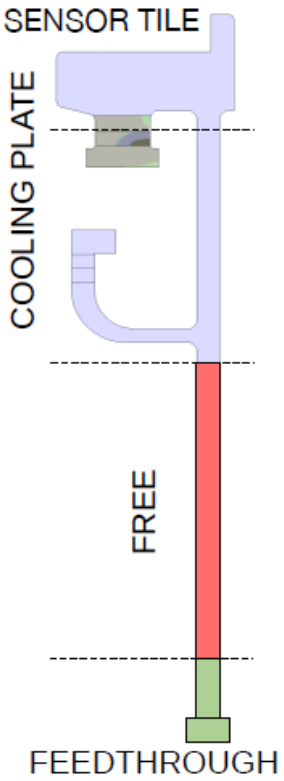
Pixel detector

- New design of **vacuum feed-through** board and **data flex** to accommodate control and data lines inside RP. In fabrication

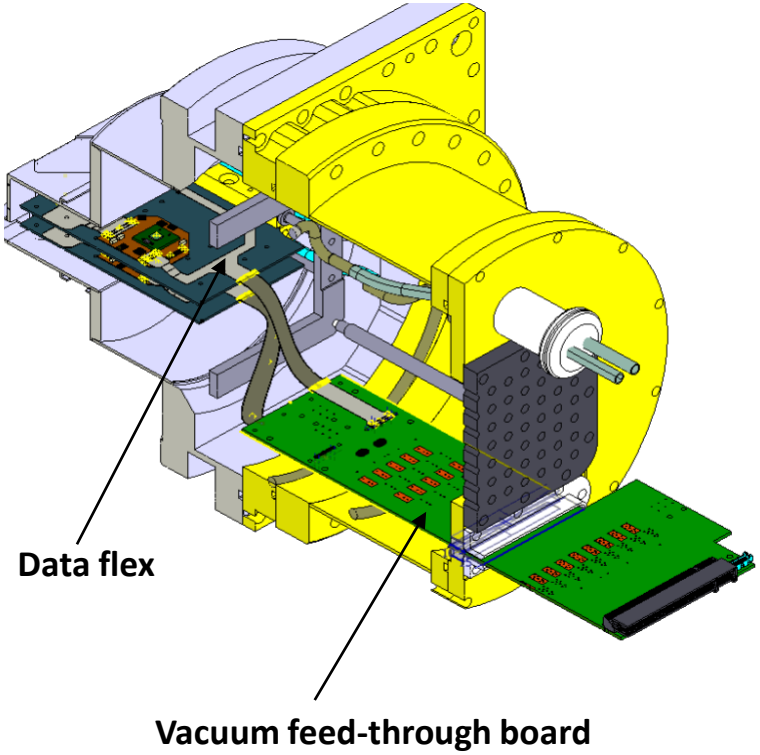
Vacuum feed-through board



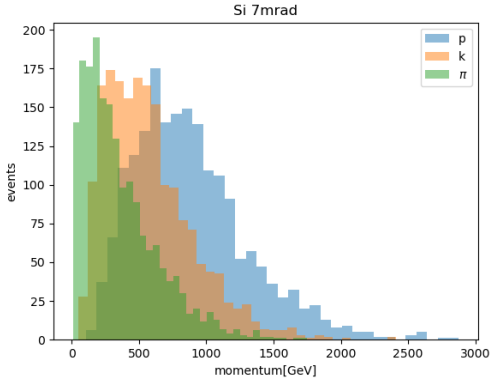
Rigid-flex data cable



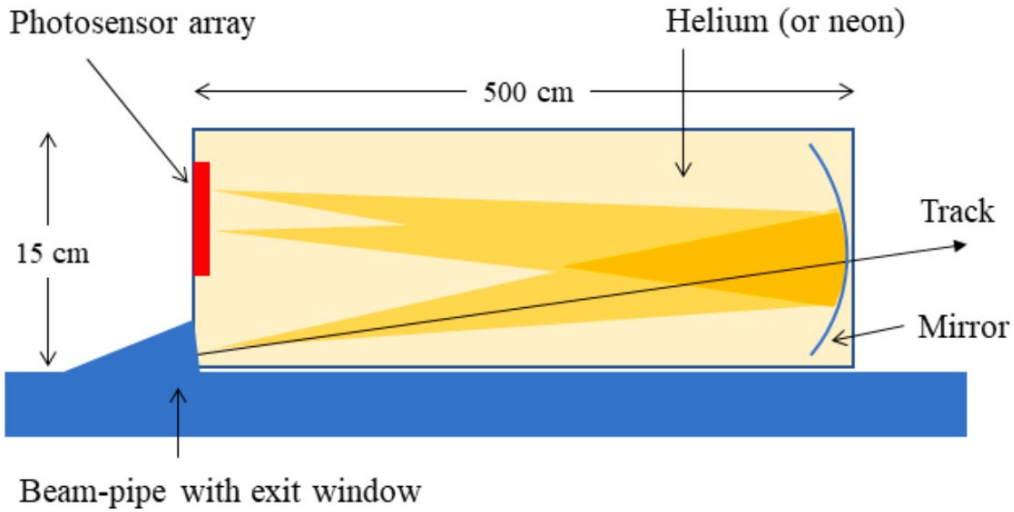
Integration inside the RP

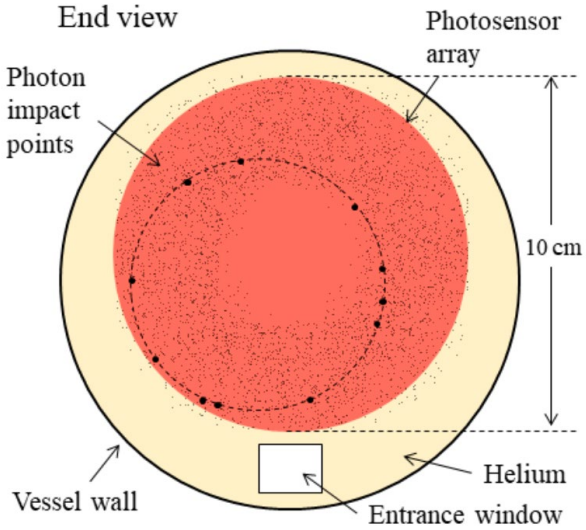


RICH detector



- Need charged particle identification **up to 1 TeV/*c***
- **Helium** radiator gas n=1.000035, length 500 cm, $N_{pe} \approx 12$
- **SiPM** as photosensor readout
  - ✓ SiPM area 100 cm^2, 0.5×0.5 mm^2 pixel
  - ✓ Synergy with DRD4 collaboration (**mm-scale** SiPM **pixelisation**)

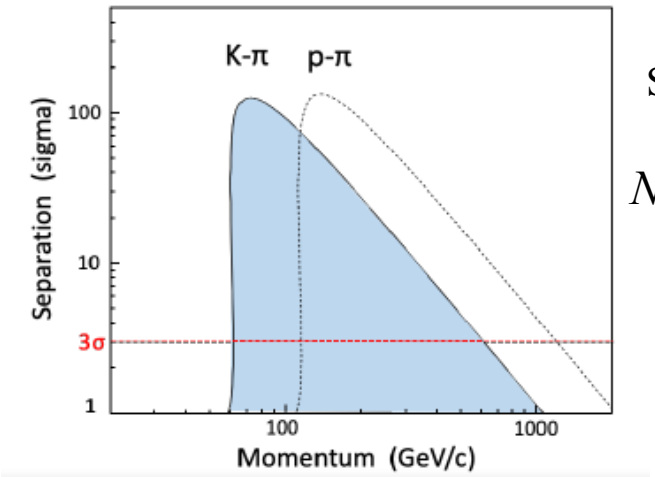




- **Angular** resolution: $\sigma_\theta \approx 42\ \mu$rad per photon

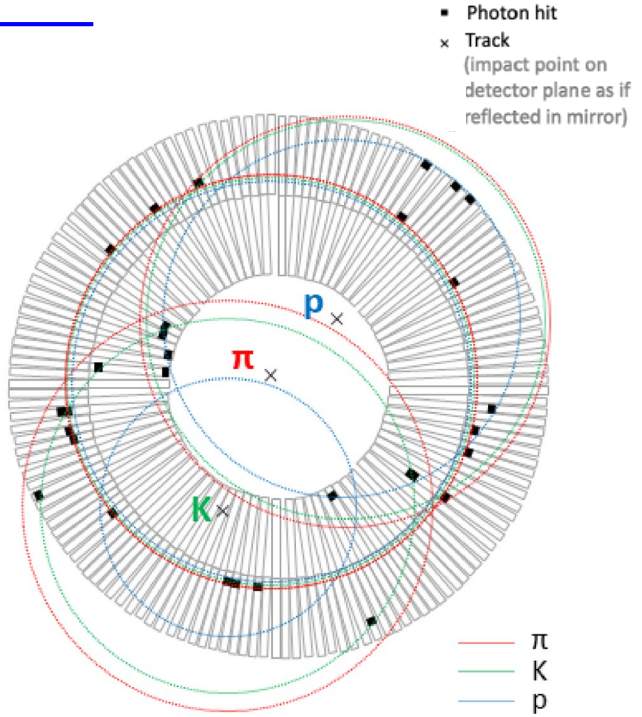
RICH detector

- **Pattern recognition**: relatively easy thanks to 38k channels, low occupancy 0.1% from signal tracks
- Upper limit for 3σ K-π (p-π) **separation** is 610 GeV/*c* (1.2 TeV/*c*)

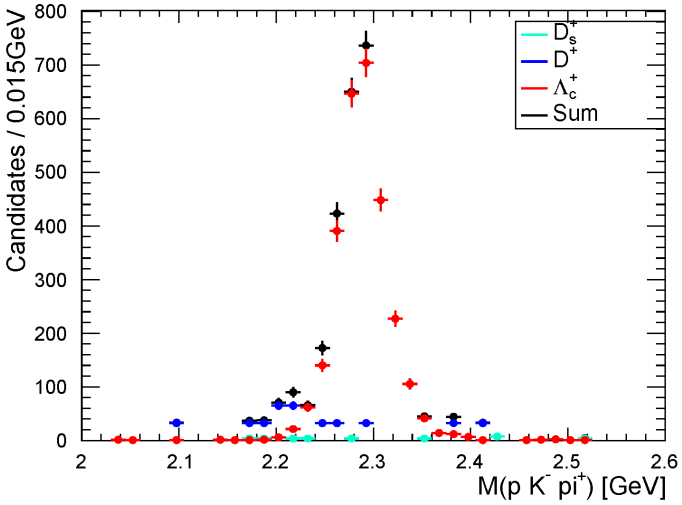


Separation power (sigma):

$$N_\sigma = \frac{|m_1^2 - m_2^2|}{2p^2(\sigma_\theta / \sqrt{N_{\text{pe}}})\sqrt{n^2 - 1}}$$



- Achieve 90% signal **efficiency** and 95% **bkg rejection** comparing $\Lambda_c^+ \to pK^-\pi^+$ (signal) and $D^+ \to K^-\pi^+\pi^+, D_s^+ \to K^+K^-\pi^+$ (bkg)

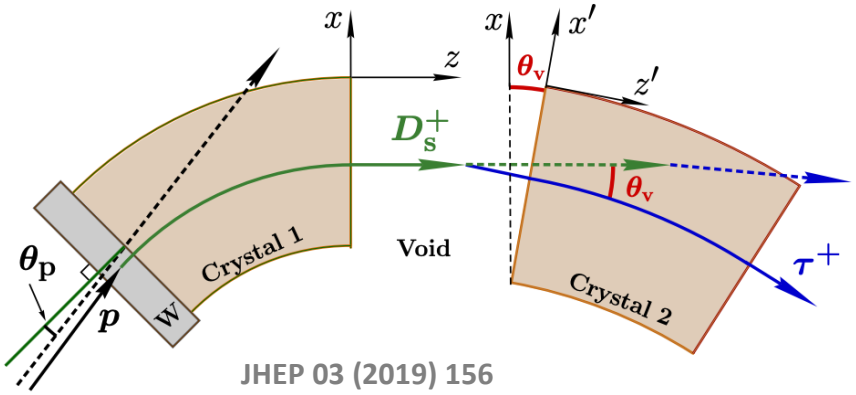


Physics reach

- **First measurements** of **charm baryon** MDM and EDM, for Λ_c^+ (Ξ_c^+), in 2 year data taking assuming 10^6 p/s (1.37×10^{13} PoT), 2 cm W, Si 7 mrad 7 cm, pol ≈ 30%
- **Sensitivity**: 1.2 (1.8)$\times10^{-2}$ μ_N, 1.5-4.6 (3) $\times10^{-16}$ $e$cm
- Λ_c^+ (Ξ_c^+) yields predicted by the recent fragmentation fractions from ALICE ×3 (×2) larger than from previous e^-p and e^+e^- data

PRD 105 (2022) L011103
JHEP 12 (2023) 086
arXiv:2405.14571

- Opportunity for **other measurements** in the **very forward region**, $5 < \eta < 9$, i.e. cross section of charm hadron production, QCD polarisation, J/ψ photoproduction
- **Explore** measurement of **τ** g-2 and EDM (require much larger #PoT, further R&D)



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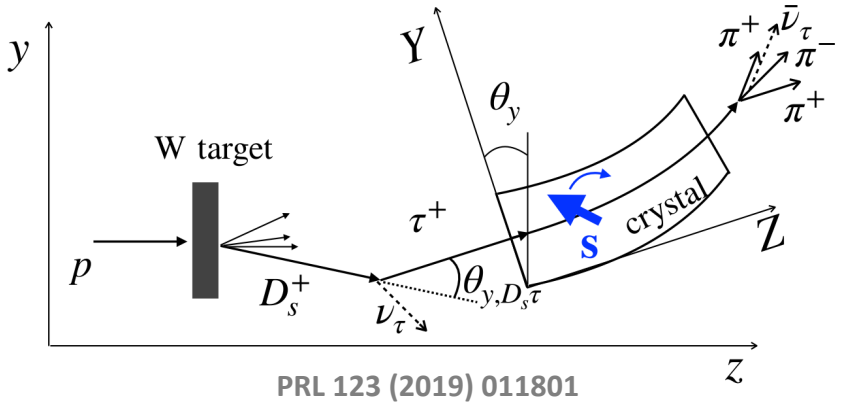

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Strong synergy with (SMOG) LHCb

- Dominant Λ_c^+, Ξ_c^+ final states are 3-body with protons and hyperons, e.g.

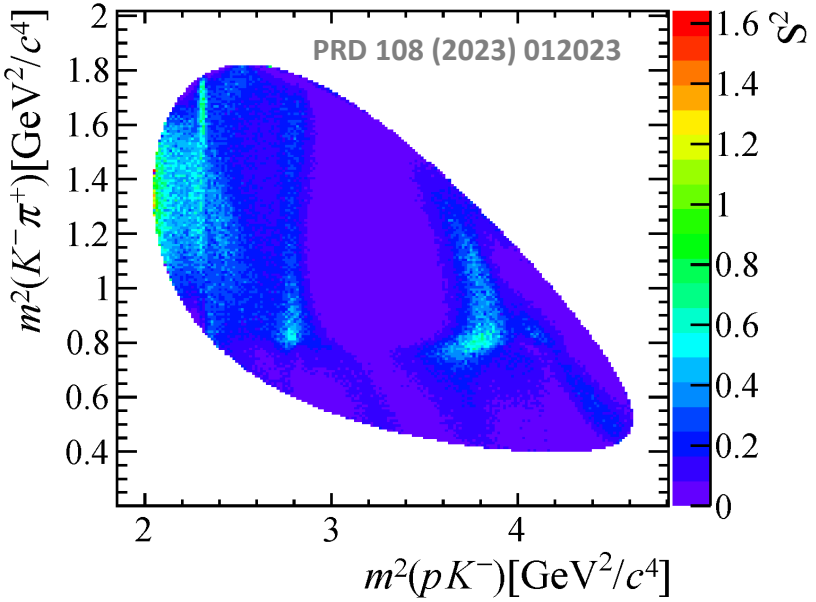
  $\Lambda_c^+ \to pK^-\pi^+,\ \Sigma^+\pi^-\pi^+, \Sigma^-\pi^+\pi^+$ $\qquad$ $\Xi_c^+ \to \Xi^-\pi^+\pi^+, \Sigma^+K^-\pi^+, \Sigma^+\pi^-\pi^+$

  $\Rightarrow$ **amplitude analyses** from pp data ongoing, ready for golden $\Lambda_c^+ \to pK^-\pi^+$

Event information S^2 (analysing power)

$$|\alpha_{\text{eff}}| = \sqrt{3}S$$

Average $S^2 \approx 0.145 \Rightarrow |\alpha_{\text{eff}}| \approx 66\%$



- + charm **cross sections**, QCD **polarisation**, **fragmentation fractions** from p-gas collisions (SMOG system)

Summary

- Developed **new experimental techniques** for the measurement of Λ_c^+, Ξ_c^+ magnetic and electric dipole moments
- Proposed a **dedicated fixed-target experiment at the LHC**,

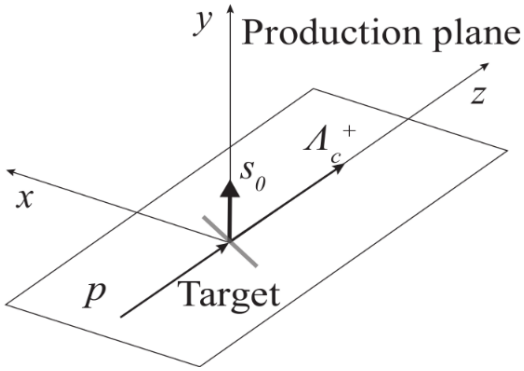
(An LHC Apparatus for Direct Dipole Moment INvestigation)

- Features a **spectrometer** for particles up to 2 TeV/c, a **RICH** detector for PID up to 1 TeV/c, and coverage $5 < \eta < 9$
- **TWOCRYST PoP** foreseen in 2025 to demonstrate the feasibility of ALADDIN, which aims to start taking data in LHC Run 4
- **LoI** for ALADDIN being submitted to the LHCC this coming week
- **TWOCRYST & ALADDIN** proto-collaboration **Workshop** will take place in Valencia (Spain), from 18 to 20 September, 2024 (indico, public on Tuesday), following a series of topical workshops (1st, 2nd, 3rd)

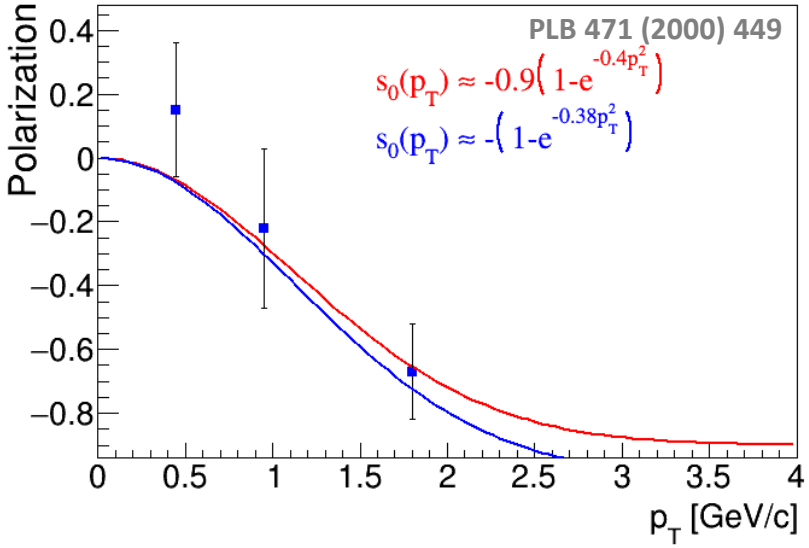
You are welcome to join!

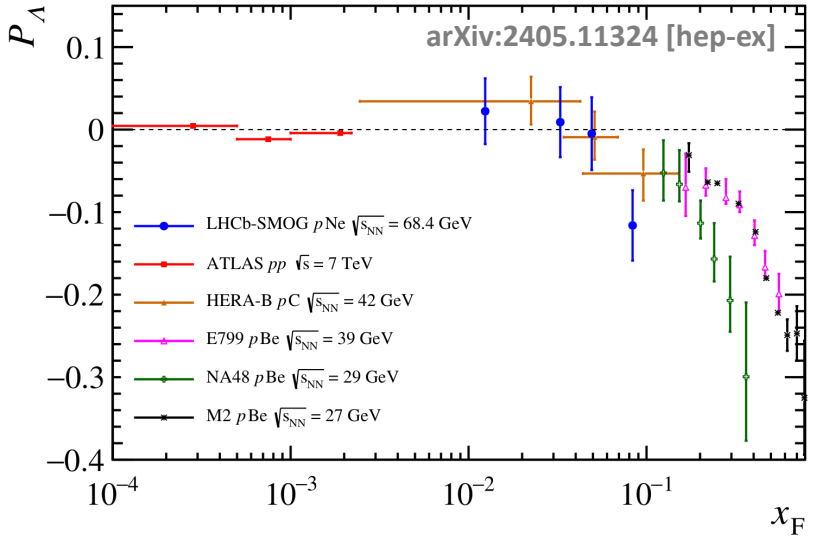
Backup

Polarisation



- Parity-conserving production, **polarization transverse** to the p-Λ_c^+ production plane
- Unknown for p-N at $\sqrt{s} \approx 115$ GeV
- Only existing Λ_c^+ polarization data is from E791 with 500 GeV/c π^- beam, covering $-0.1 < x_F < 0.4$
- Indications from Λ baryon





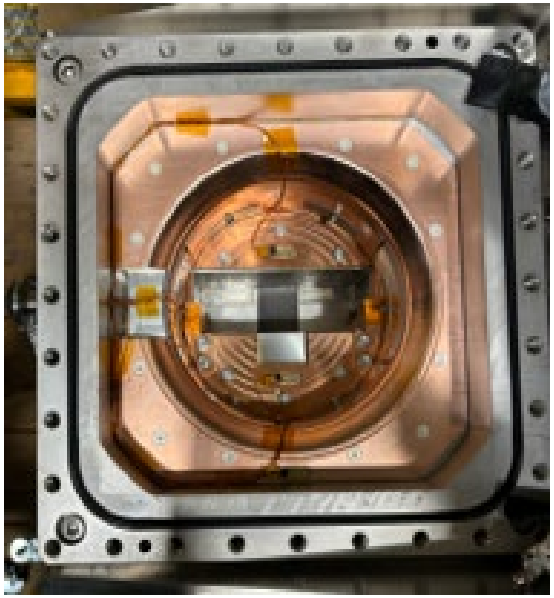
x_F region of the proposed experiment between 0.1 and 0.5 $\Rightarrow$ expected **polarisation at 30% level**

RP station for TWOCRYST

- ATLAS-ALFA RP extracted from LHC tunnel is available
- Pot rectangular section: 128×60×46 mm^3 (width × height × thickness)

ATLAS-ALFA RP station

Detector housing



CMS-TOTEM top part and new closing flange