A RICH detector for the ALADDIN experiment

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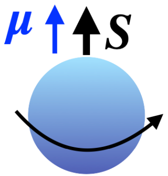
On behalf of ALADDIN Collaboration

RICH25 - 18/09/25

Electromagnetic dipole moments of charm baryons

MDM: $\boldsymbol{\mu} = g\frac{q\hbar}{2m}\frac{\boldsymbol{S}}{\hbar}$

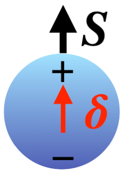


Naive quark model prediction:

$\mu_{\Lambda_c^+} = \mu_c, \quad \mu_{\Xi_c^+} = \mu_c$

Anchor point for low-energy QCD models

EDM: $\boldsymbol{\delta} = d\frac{q\hbar}{2m}\frac{\boldsymbol{S}}{\hbar}$



If EDM ≠ 0: source of **CPV beyond SM**
(EDM violates T, P and CP)

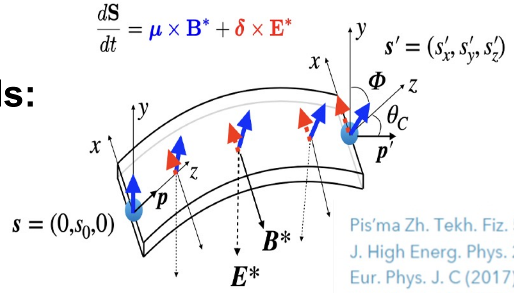
$\Lambda_c^+ = [ud]c \qquad \Xi_c^+ = [us]c$

No measurement to date for short-lived charm baryons because of

- Short lifetime: $c\tau \approx 100\ \mu m$
- Decay length: $\gamma \approx 500 \quad \gamma c\tau \approx 5\ cm$

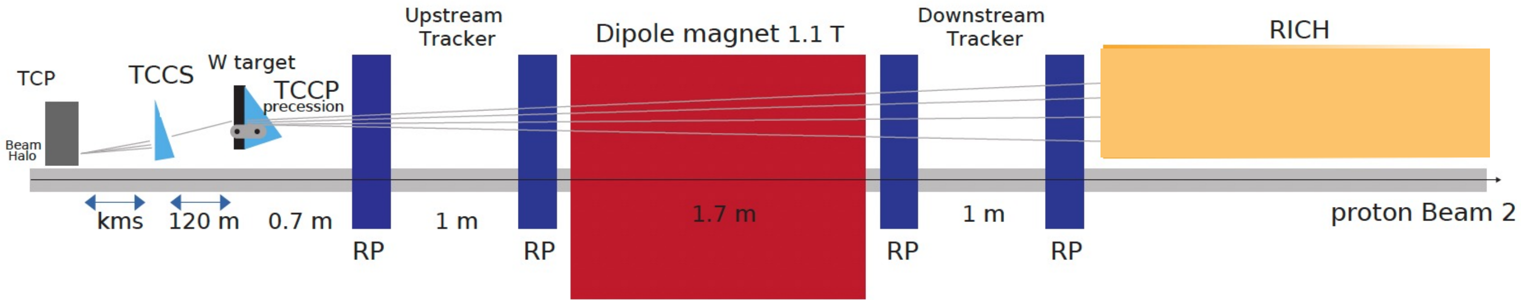
EDM/MDM measurement = spin precession induced by interaction with intense electromagnetic field

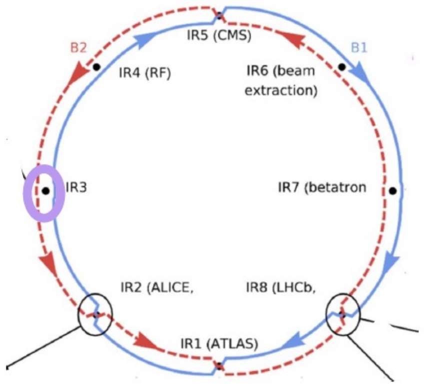
Channeling in Bent crystals:
Spin precession
thanks to intense fields
(E ~1 GeV/cm, B ~500 T)



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

ALADDIN experiment





ALADDIN (**A**n **L**hc **A**pparatus for **D**irect **D**ipole moments **IN**vestigation) is a fixed-target experiment proposed for EDM/MDM measurement of charm baryons

Experimental apparatus

Pseudorapidity 5<y<10

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

Expected sensitivity for MDM of $2{\times}10^{-2}\mu_N$ and EDM of $3{\times}10^{-16}ecm$ with 10^{13} PoT

The ALADDIN Collaboration

Spokeperson: Nicola Neri
Physics Coordinator: Fernando Martinez Vidal
CB Chair: Roberta Cardinale

~70 members from 24 institutes in 8 countries

<u>Website</u>: https://aladdin.web.cern.ch/

Authors as 05/02/2025.

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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

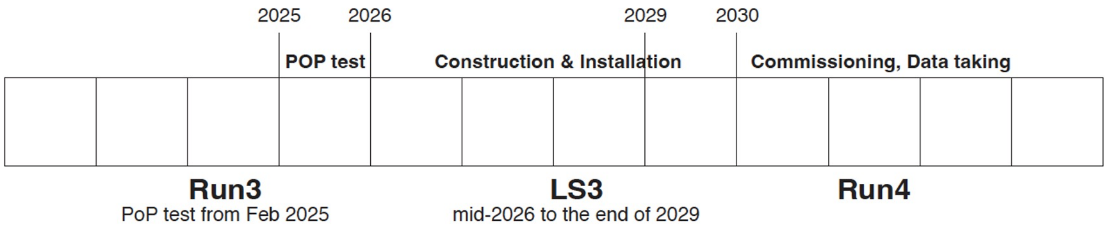
Machinist at CERN

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

ALADDIN schedule and TWOCRYST

ALADDIN schedule:

- Letter of Intent (**LoI**) was submitted in June 2024 → Very positive response from the LHCC committee
- **TDR** is in preparation
- Installation during a YETS in Run4
- Data-taking in **Run4**

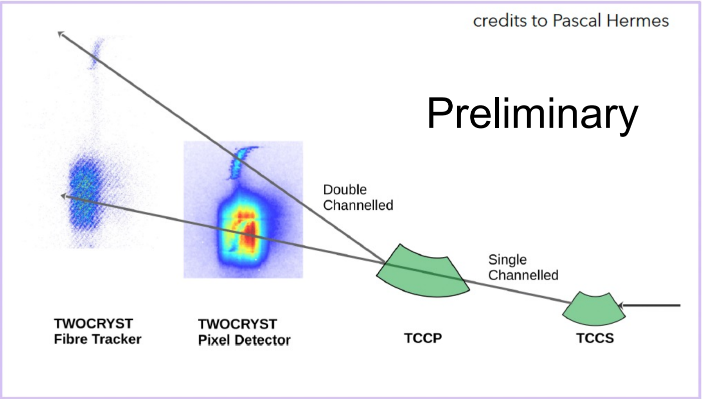


TWOCRYST is a proof-of-principle (PoP) test approved by the LMC committee and installed in March 2025

- to demonstrate feasibility of double channeling at TeV energy
- Preliminary results of double channeling: observed at 450 GeV, 1 and 2 TeV in MD tests but analyses are still in progress, especially at higher energies

See CERN bulletin

Result of June MD run

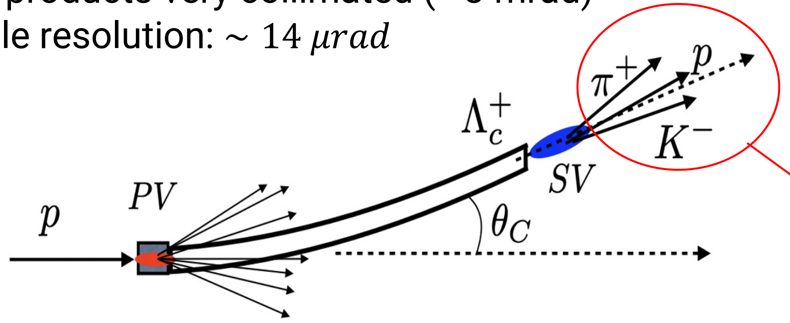


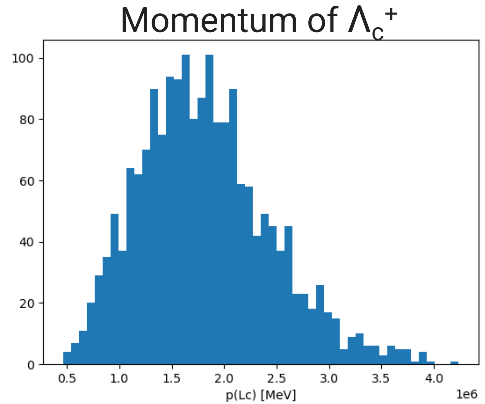
Snapshot of double-channelling signals as seen from both detectors

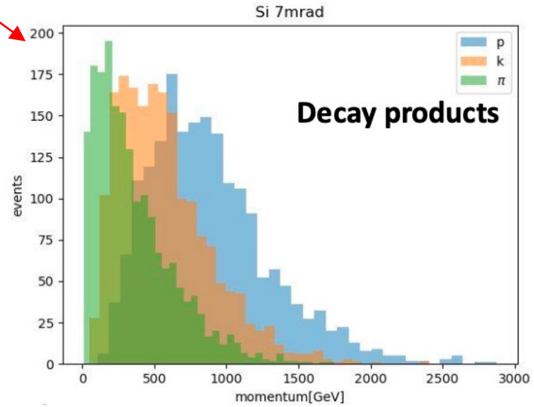
Λ_c^+ signal and identification

Charm baryons are produced

- with very high momentum O(1 TeV)
- in forward direction at 7 mrad
- Λ_c^+ decay products very collimated (< 3 mrad)
- Track angle resolution: $\sim 14\ \mu rad$



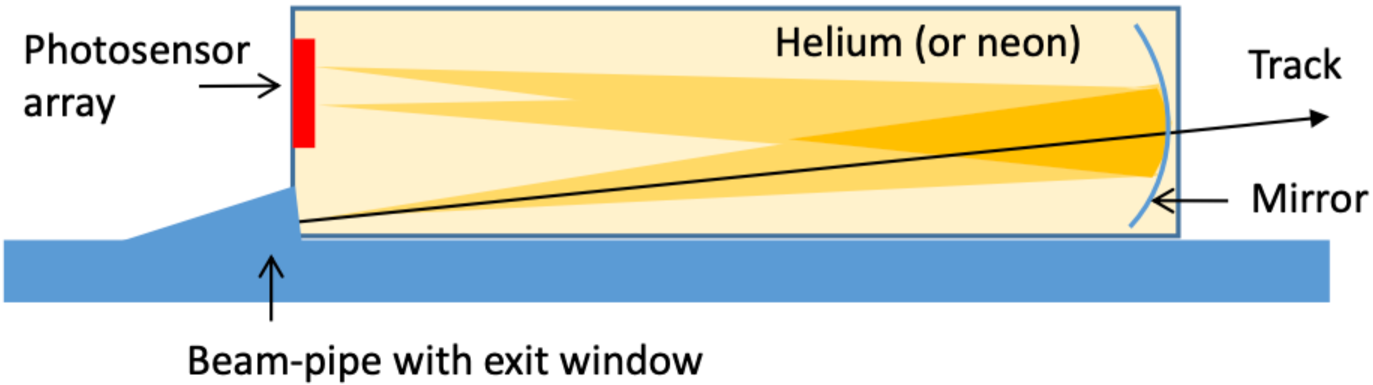




RICH detector is essential to distinguish signal from **background** decays (channeled $D^+ \rightarrow K^+\pi^+\pi^-, D_s \rightarrow K^+K\pi^-$)

The ALADDIN RICH detector

Long vessel RICH radiator filled with **He or Ne**, originally proposed in LoI by R. Forty



RICH requirements

The RICH layout is chosen in order to achieve:

- **Good separation** for particles at **O(1 TeV)**
- Maximum **photon yield ➔** increasing the vessel length *L*

$$N_{pe} = \alpha L \int \epsilon \sin^2 \theta_C dE,$$
$$\alpha = 370 cm^{-1} eV^{-1}$$

ε = quantum efficiency (PDE)
+ geom acceptance
+ mirror reflectivity
+ front-end efficiency

- Small **Cherenkov resolutions**, currently limited by chromatic and pixel size error

Chromatic error: variation of refractive index with wavelength

Emission point error: quality of focusing; excellent due to long focal length and on-axis photons

Pixel error: $\sigma = {}^{2p}/_{R\sqrt{12}}$, p = pitch; to be below chromatic error we need mm-pixel size

$\sigma_{tot} \sim 50\ \mu rad$

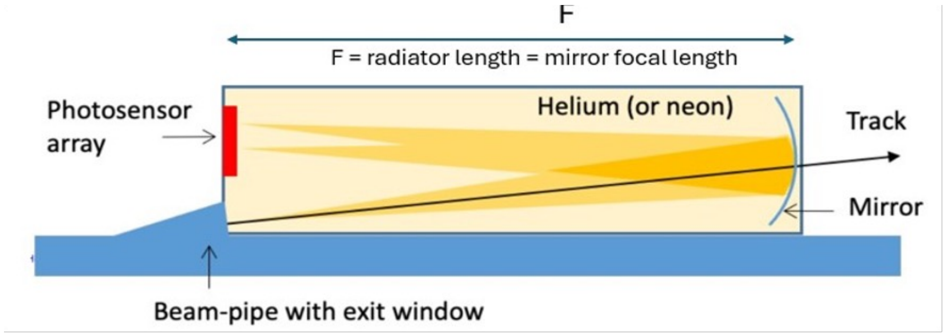
- Keep system compact: vertical direction (~70 cm) and along beam (**~29 m max**) ⟶ New space request under consideration

Detector options

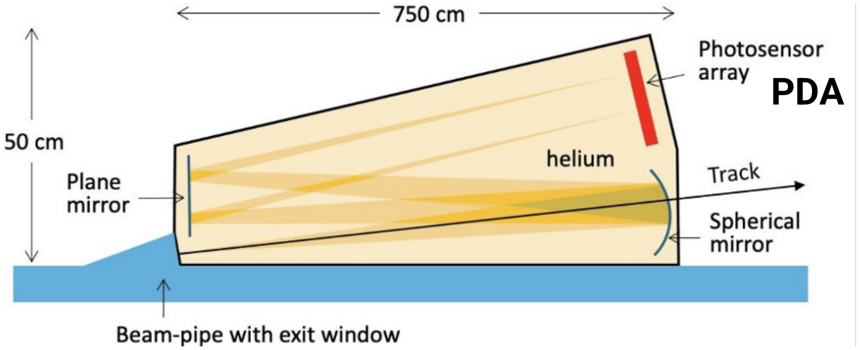
Different geometries and gas options are under investigation:

1. Single reflection, 12-20 m long vessel
2. Double reflection, 7.5-12 m long vessel

Helium ($(n-1) = 3.1 \cdot 10^{-5}$): better high-momentum separation and lower chromatic error
Neon ($(n-1) = 5.9 \cdot 10^{-5}$): higher yield
$@\lambda = 309\ nm$, P=980 mbar/T=300 K



$f \sim L$
→ Optimal solution if sufficient space is available



$f \sim 2L$
→ Increase focal length to accommodate larger pixel size

Photodetector technology: SiPM or MCP of mm-pixel size

Layout studies & methods

1. **OpticaEM** [1], a customizable framework for optics (geometrical and wave) calculations, built on top of WOLFRAM Mathematica©; to define layout and performances.
2. **Geant4 simulation** to include realistic event generation, Cherenkov photon emission and detection, and background studies.

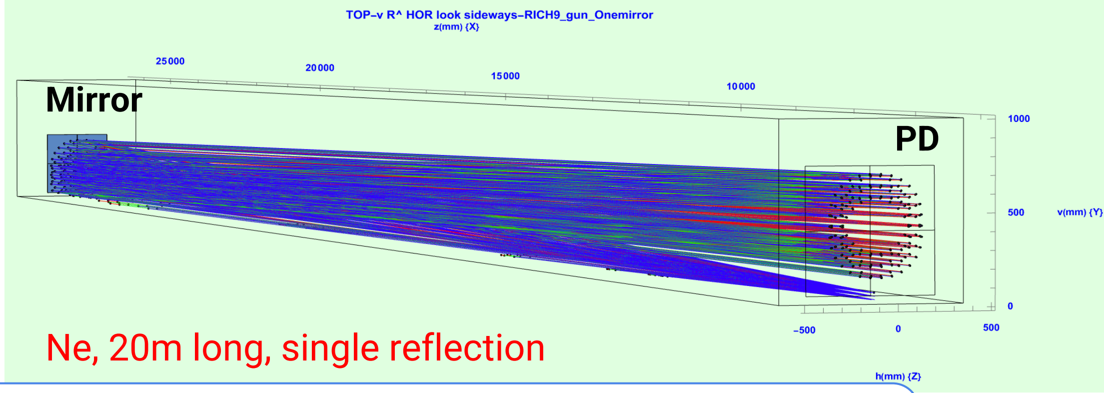
[1] https://www.opticasoft.com/support

Layout definition with OpticaEM

Geometrical layout with Optica

The geometrical layout (position/area/tilt of mirror and PD) is optimized with OpticaEM in order to **minimize focusing** or emission point error

Source: cone of photons emitted from tracks in a grid of +/-3 mrad around 7 mrad at $\lambda = 309\ nm$

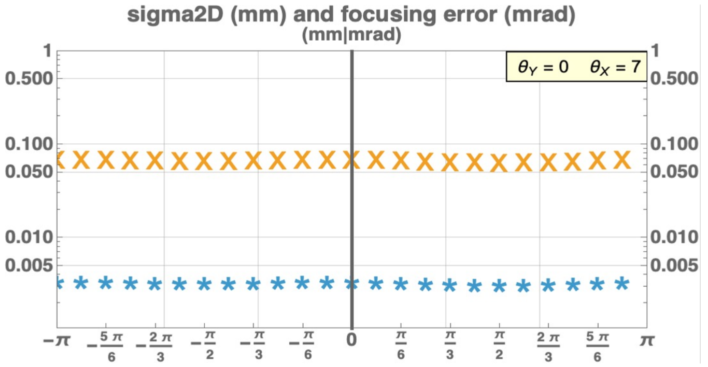


Focusing/Emission point error:

Definition:= radial distance between first-last emitted photon on the PD $\cdot\ 1/\sqrt{12}$(sigma2D)$/f_{eff}$, where f_{eff}= track path length

→ Focusing is flat in ϕ and small (~3 μrad)
→ PD position can be further optimized to reduce focusing to 0, but already negligible

For a given track, as a function of ϕ



Results and PID separation

Performance for different layout comparisons @ P=980 mbar/ T=300 K
and SiPM as photosensor

Geometry: Gas & L	He – 20 m	Ne – 20 m	He – 7.5 m	Ne – 7.5 m
	Single reflection		Double reflection	
PE yield	**25**	**47**	**10.8**	**17.7**
Chromatic error	23	41	23	41
Emission error	3	3	10	10
Pixel error, 2 mm^2	28	28	38	38
Total error (μrad)	**36**	**50**	**45**	**57**

Geometry:

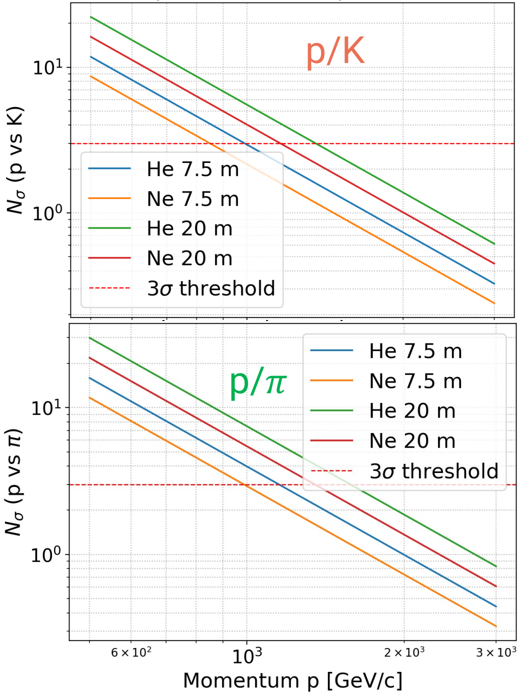
- Single reflection with 20 m long radiator is preferable to increase photon yield
- Double reflection as a **backup** solution in case space is not enough (up to results of beam dynamics simulations)

Gas: **Ne** = best gas radiator to increase photon yield

➔ **3σ separation** for Ne - 20m up to ~1.4/1.2 TeV for p/π and p/K

Preliminary PID Separation:

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



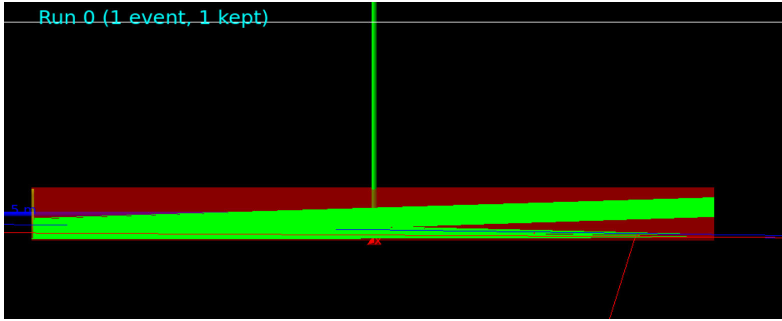
Geant4 simulation

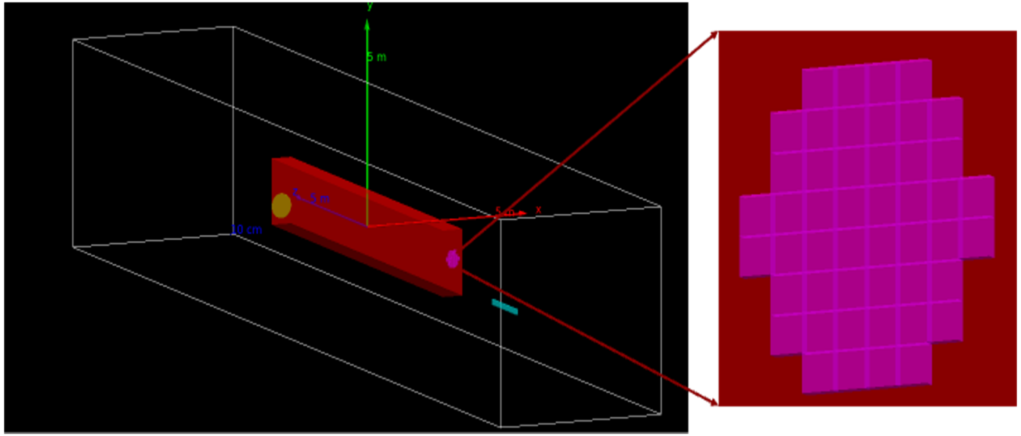
Full simulation with Geant4

Geometry: single reflection with length **L=20 m**,
RICH-TCCP distances varing assuming up to (29 m – L) available space

- Origin: center of the RICH radiator
- **Mirror**: R = 2L = 40 m
- **Photodetector**: array of **53x53 mm^2 pixels**
- Ideal scenario: inefficiencies are not considered, i.e. QE/PDE, mirror reflectivity and gas absorption.

Event display





Optimization studies:
- Position/dimensions of entrance window
- RICH position to reduce photon losses
- Choice of pixel granularity
- Separation between signal & background tracks

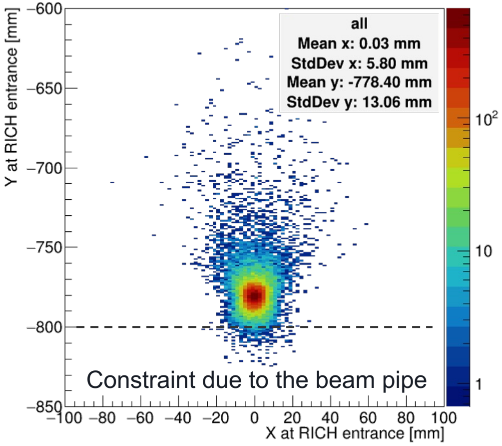
RICH position and photon losses

20 m long vessel

Full simulation is used to optimize Δz - the best RICH position wrt TCCP, in order to obtain:

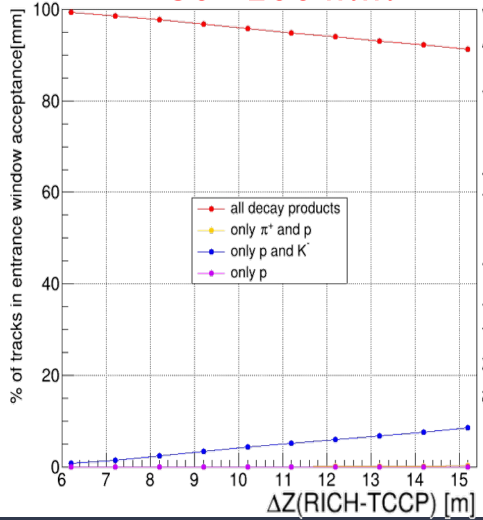
- high acceptance for Λ_c^+ daughters & optimize the size of entrance window
- reduce photon losses due to the bottom surface of the vessel

Distribution of tracks from $\Lambda_c^+ \rightarrow pK^-\pi^+$ at the RICH entrance for $\Delta z = 6.2\ m$

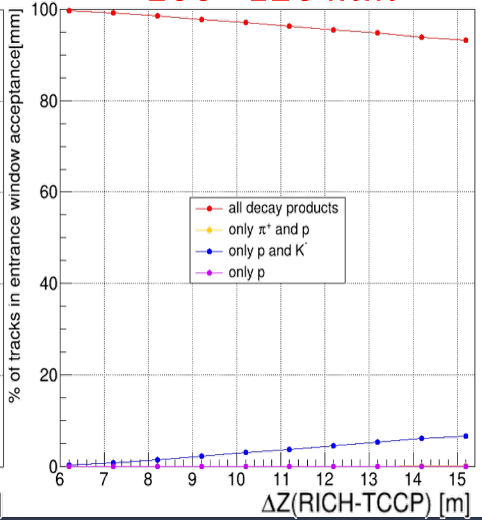


Track acceptance for different entrance window sizes as a function of Δz

$80 \times 100\ mm^2$



$100 \times 120\ mm^2$



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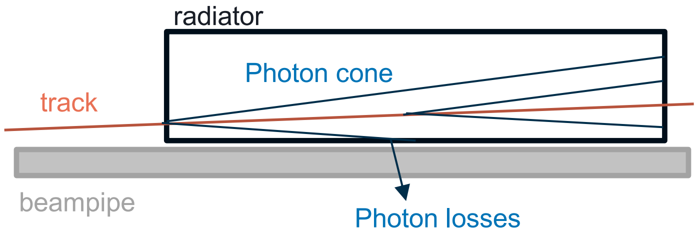
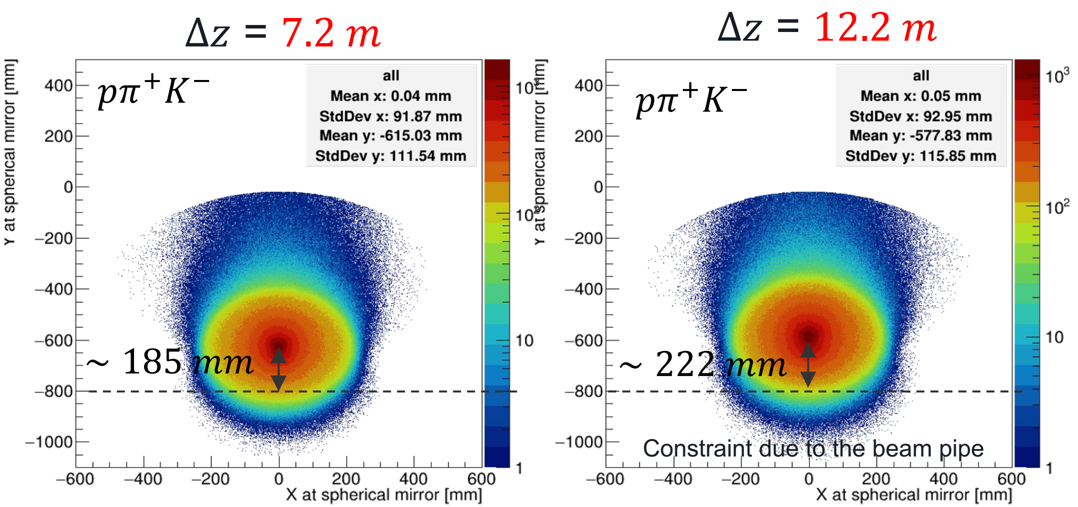


Photons impinge on the mirror with a maximum radius of $R_{max} \sim 220\ mm$

➔ To reduce losses, the RICH detector needs to be placed at least ~12m from TCCP

Photon distribution at the mirror



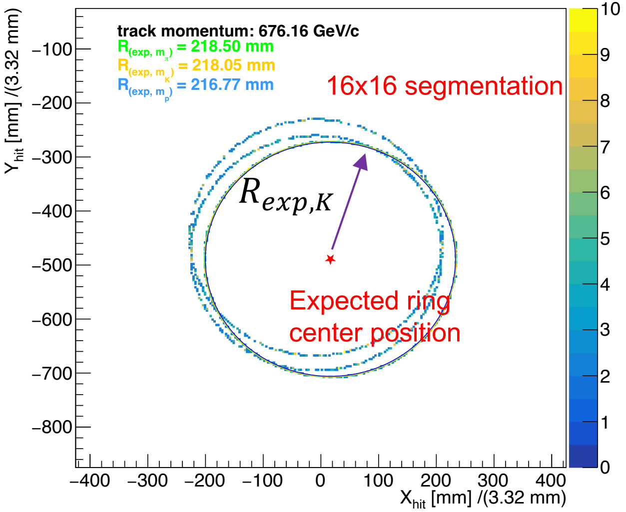
p/K/π separation and pixel granularity

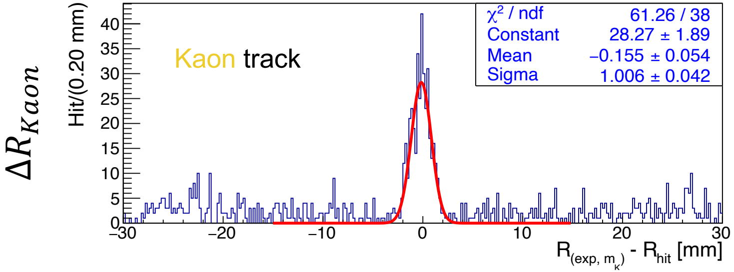
p/K/π separation needs to be evaluated as a function of the pixel size

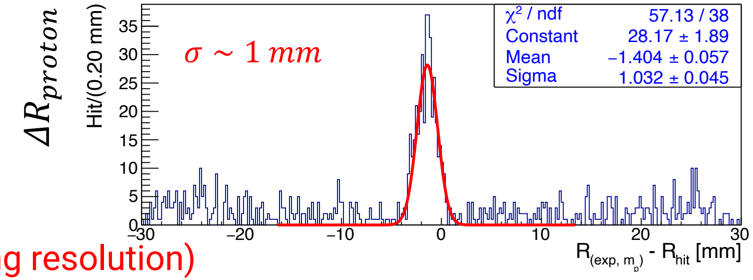
- Two possile solutions with MCPs/SiPM: 16×16 channels (~ 3 mm pitch); 32×32 channels (~ 2 mm pitch)

For each track, we compute:

- Expected ring center position and ring radius, $R_{exp,m}$, under the 3 mass hypotheses: $m_p(blue), m_K(orange), m_\pi\ (green)$







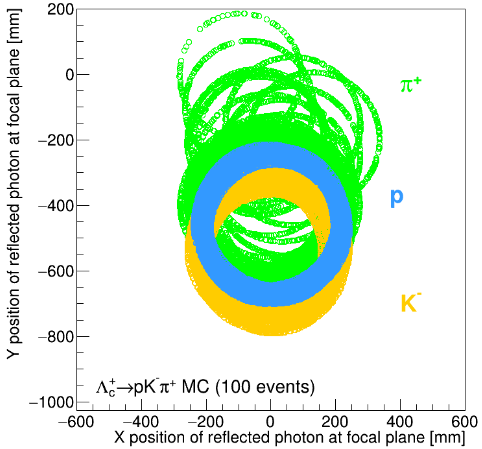
Separation between tracks if $\Delta R_{mK} - \Delta R_{mp} > \sigma$ (ring resolution)

➔ Segmentation of 16x16 is already at the limit to distinguish between p-π tracks in the ideal scenario

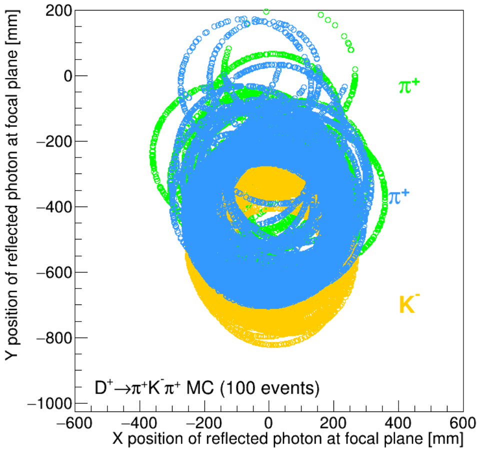
Signal separation from D^+/D_s background

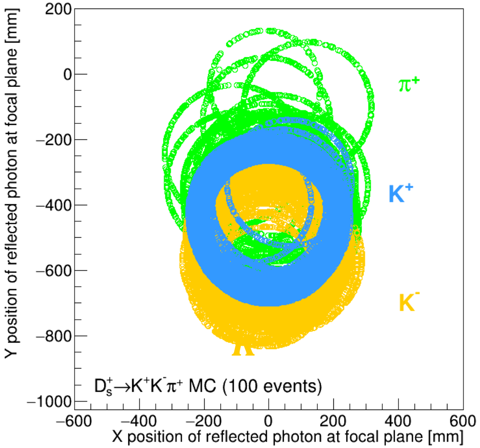
One of the background sources is from decays of channeled D^+, D_s charmed hadrons

Focal plane illumination plots for signal and background decays in single reflection 20 m vessel



signal





background

➔ To identify signal events wrt backgrounds: good separation between p of signal decay and π^+/K^+ of background decays

NEXT: The π^+/p and K^+/p separation needs to be evaluated as a function of the **pixel size**

R&D of photodetectors: SiPM vs MCP

Photosensor option: SiPM

R&D from Genoa group

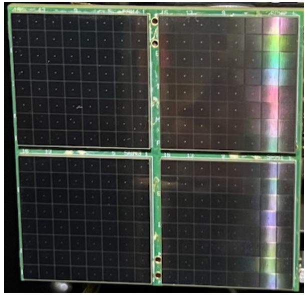
SiPM/MCCP: high detection efficiency and fine granularity.
It might need active cooling to control dark count rates

Prototype module is designed to house SiPM/MPPCs, featuring **integrated active cooling:**

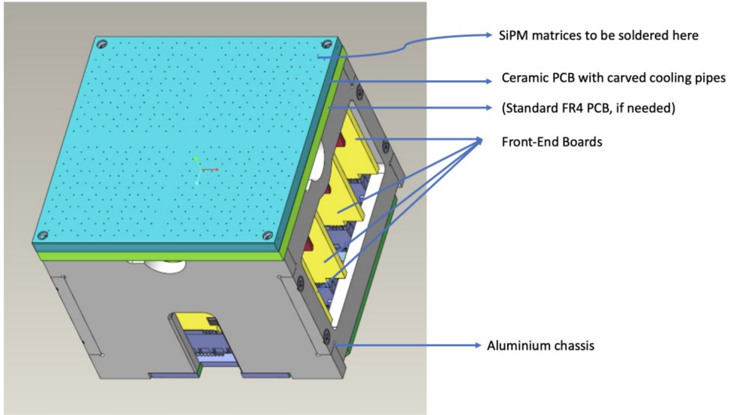
In collaboration with LHCb/RICH and within the DRD4-WP3 and WP4

- Built on the **Elementary Cell (EC) layout** [1] which currently houses MaPMTs for the *LHCb/RICH Upgrade I*
- Integrated active cooling using **Ceramic PCB** with fluid coolant circulation; to cool down a small region as low as −60 ℃/−80 ℃ (see R. Cardinale's talk)
- **Readout** by ALCOR v2.1 chip

BaseBoard:
SiPM/MPPC matrixes,
8 x 8 pixel array of 3 mm
(Hamamatsu
S13361-3050NE-08)



EC with Ceramic PCB



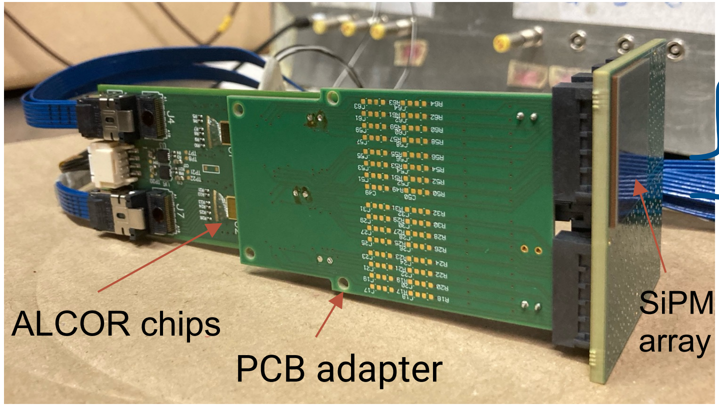
[1] https://arxiv.org/pdf/2305.10515

Setup with ALCOR chip

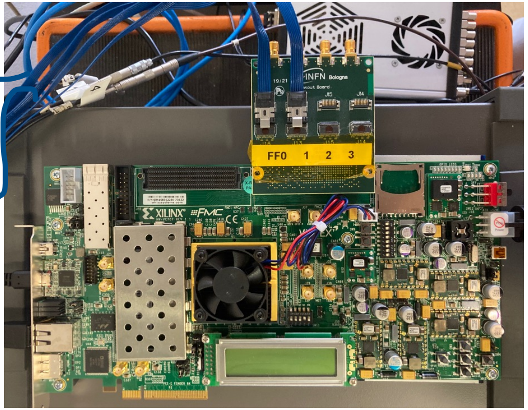
New front-end setup assembled in Genoa in collaboration with INFN-TO and INFN-BO under the DRD4 collaboration

- FE electronics: ALCOR FE-DUAL + ALCOR v2.1 (32 channels) (INFN Torino)
- PCB adapter to integrate the EC with ALCOR v2 & SiPM array (Genova)
- DAQ/configuration: via IPbus ETH interface with Xilinx VC707 and FMC-Firefly link to ALCOR (Bologna)

New module with ALCOR v2.1

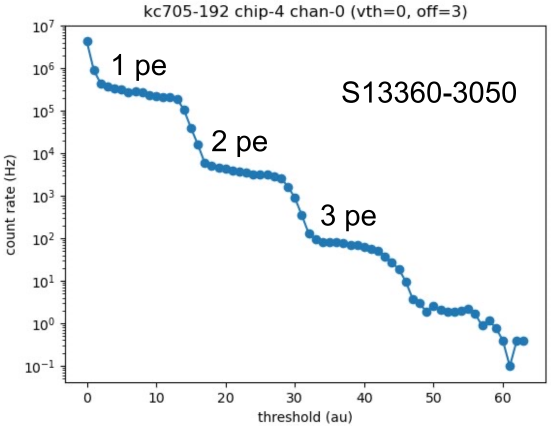


Readout board



Xilinx VC707 & FMC-FireFly

Threshold scan



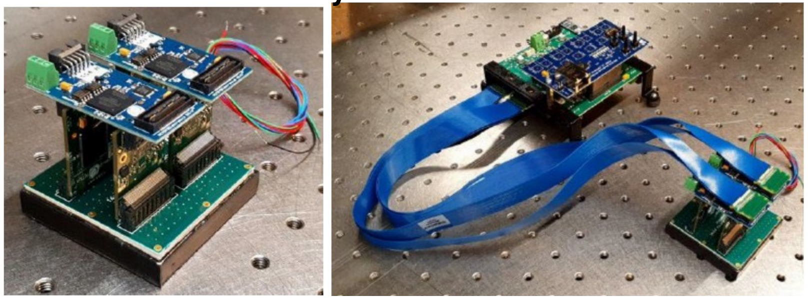
Photosensor option: MCP-PMT

R&D from Florence group

Microchannel Plate PMTs (MCP-PMTs) is another possible solution thanks to high granularity, good detection and no need for cooling.
→ **Photek MCP-PMT (MAPMT253)**, 53x53 mm2 large, with 32x32 pixels (pixel size: 1.6x1.6 mm)

- Start to evaluate crosstalk and performance of the Photek MCP-PMT with 16x16 pixels
- PETsysElectronics system, based on 4 PCBs with a TOFPET2 ASIC with 64 channels to perform lab tests
- Check if SiPM readout used in Genoa is suitable for MCP-PMT

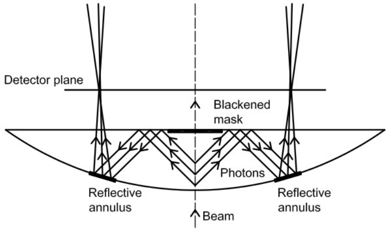
PETsysElectronics

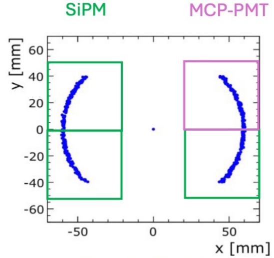


Goal of 2026:

- A test beam is foreseen to test the two photo-sensor technologies in *June 26* at SPS
- The choice of the optimal photodetector sensor and readout electronics will be made upon the test beam results

Test beam: use of a solid lens as radiator
[DOI:10.48550/arXiv.1610.10006]





Expected ring shape

Conclusions & outlook

Design and performance of a RICH detector for the ALADDIN experiment are presented:

- Geometrical layout is studied with OpticaEM simulation
- Preliminary results of full simulations for realistic detector condition and pattern recognition

Geometry: 20 m – Ne

- Best solution is to use a long radiator with a single reflection
- Ne: to increase photon yield as used in other experiments such as NA62

⟹ Final choice will be made based on the results of the discrimination between signal and background tracks obtained with the pattern recognition algorithm

Photodetectors

- Two photodetector choices are under investigation: SiPM/MCP-PMT

⟹ Decision is expected after test beam of June 26

TDR is in preparation and will be submitted end of '25

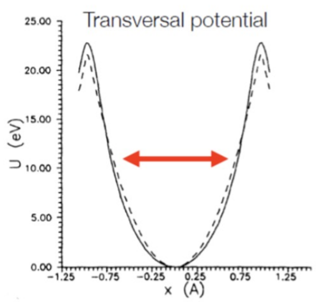
Thanks for the attention!

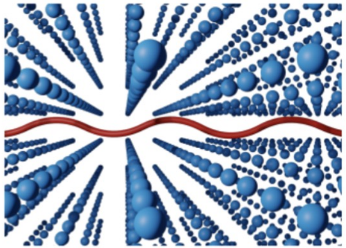
Backup slides

Channeling in bent crystals

For positive charged particles, bent crystals can be used to

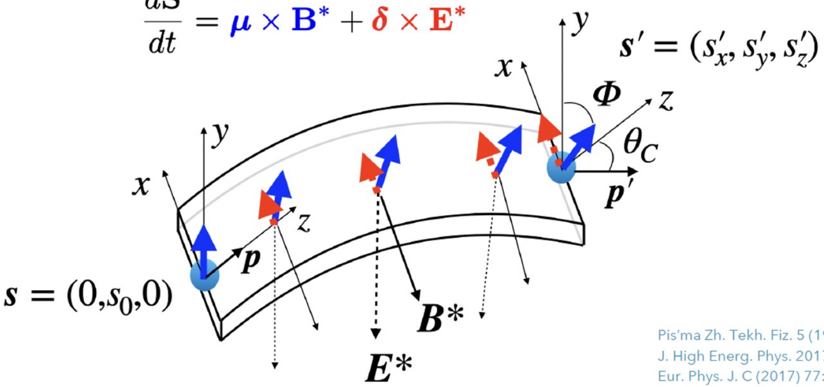
Steer particles at a given angle





Induce **spin precession** in short distance

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

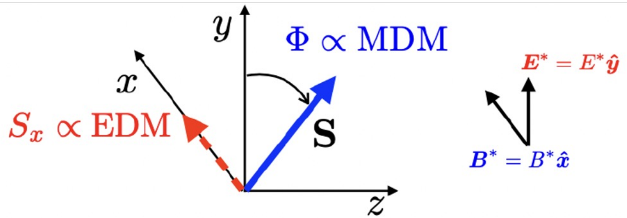


Pis'ma Zh. Tekh. Fiz. 5 (1979) 182
J. High Energ. Phys. 2017 (2017) 120
Eur. Phys. J. C (2017) 77:181
Eur. Phys. J. C (2017) 77:828

In bent crystal we obtain:

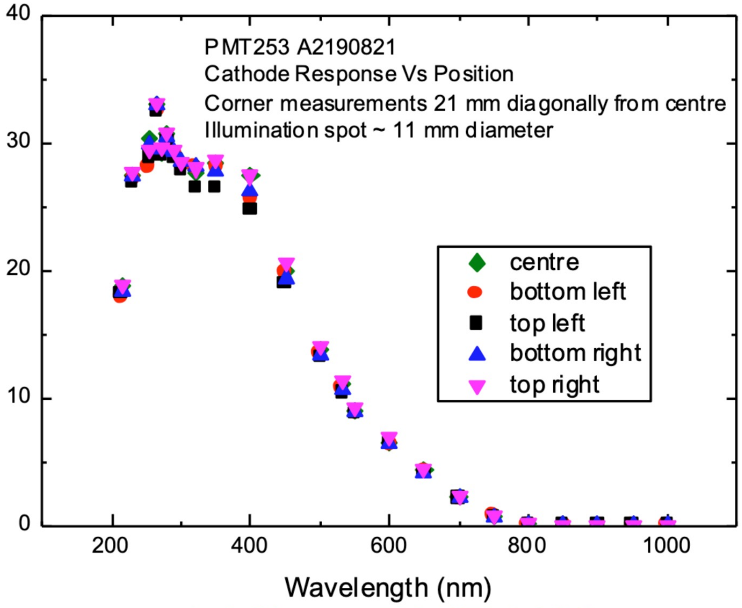
- Electric field: E ~1 GeV/cm
- Effective magnetic field: B ~500 T

$$\Phi \approx \frac{g-2}{2}\gamma\theta_c \qquad s'_x \approx s_0 \frac{d}{g-2}$$



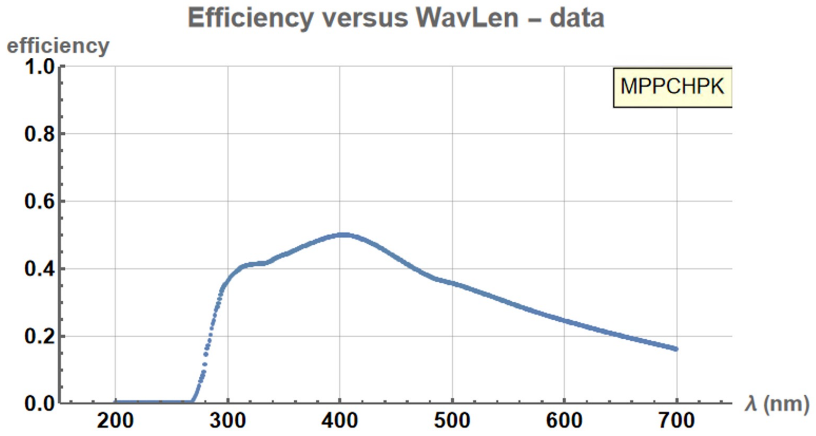
QE/PDE of photosensors

QE of MCP-PMT



J. Milnes, FAST 2023

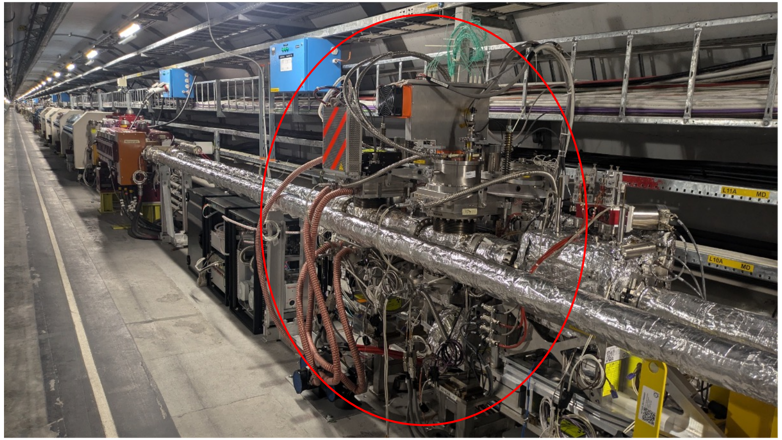
PDE for MCCP Hamamatsu

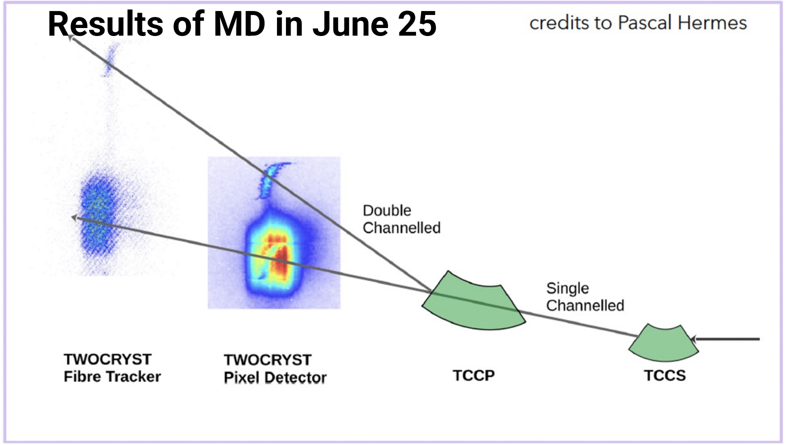


Proof-of-principle test: TWOCRYST

Proof of principle **TWOCRYST** approved by the LMC committee and installed in March 2025:

- Demonstration of feasibility and measurement of double channeling at TeV energy





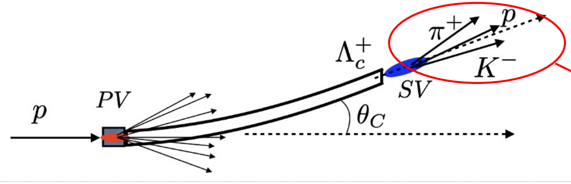
Snapshot of double-channelling signals as seen from both detectors

- **Roman Pots**: allow tracker detectors to be placed in a secondary vacuum within beam pipe

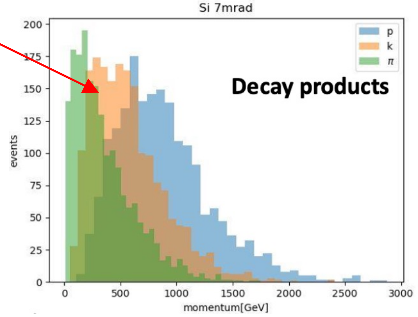
Λ_c^+ signal and identification

Charm baryons are produced

- with very high momentum O(1 TeV)
- in forward direction at 7 mrad and very collimated (<3mrad)



Momentum of Λ_c^+ products



- Spectrometer composed of 4 stations of pixel trackers (VeloPix) is used to reconstruct particle momentum:
  p resolution ~ 2% at 1 TeV

- RICH detector is essential to distinguish signal from **background** decays (channeled $D^+ \rightarrow K\pi\pi, D_s \rightarrow KK\pi$)

PID based on momentum (highest momentum = p) gives a signal efficiency of 60% with poor background rejection (~80%)

→ with RICH we can achieve a signal efficiency of 90% vs bkg rejection 95%