Proof-of-principle test for a charm baryon dipole moment experiment at the LHC

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UNIVERSITY OF MILAN AND INFN

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Acknowledgments

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- Interesting **discussions/suggestions**: V. Baryshevsky, V. M. Biryukov

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

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

$$\downarrow \text{T,P}$$

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

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 baryons)

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

Phys. Lett. B291 (1992) 293

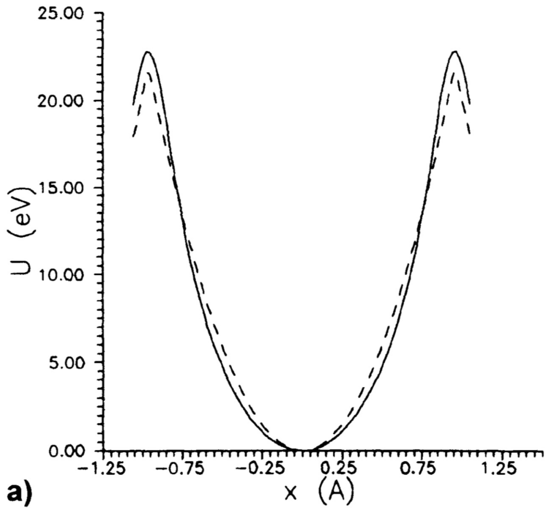
Channeling in bent crystals

To measure EDM and MDM of short-lifetime particles (~5cm) strong EM field are needed.

In bent crystal we obtain:

- Electric field E ≈ 1 GV/m

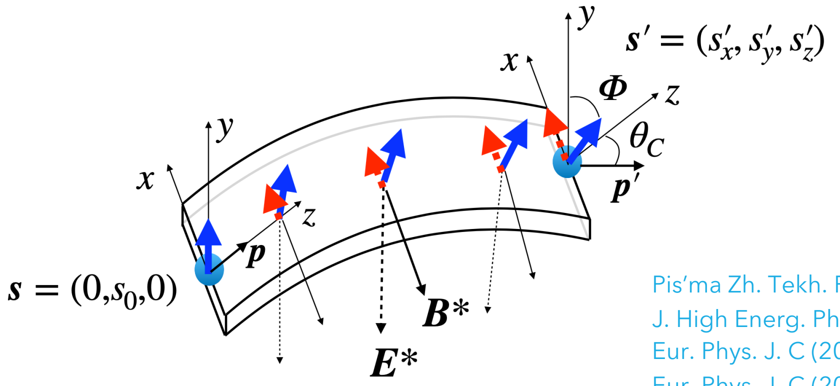
- Effective magnetic field B ≈ 500 T



Positively charged particles are **channeled** between the atomic planes if their impact angle is small enough.

- Steer the particle trajectories of a given angle.
- Induce a **spin precession** of the particles in a short distance

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



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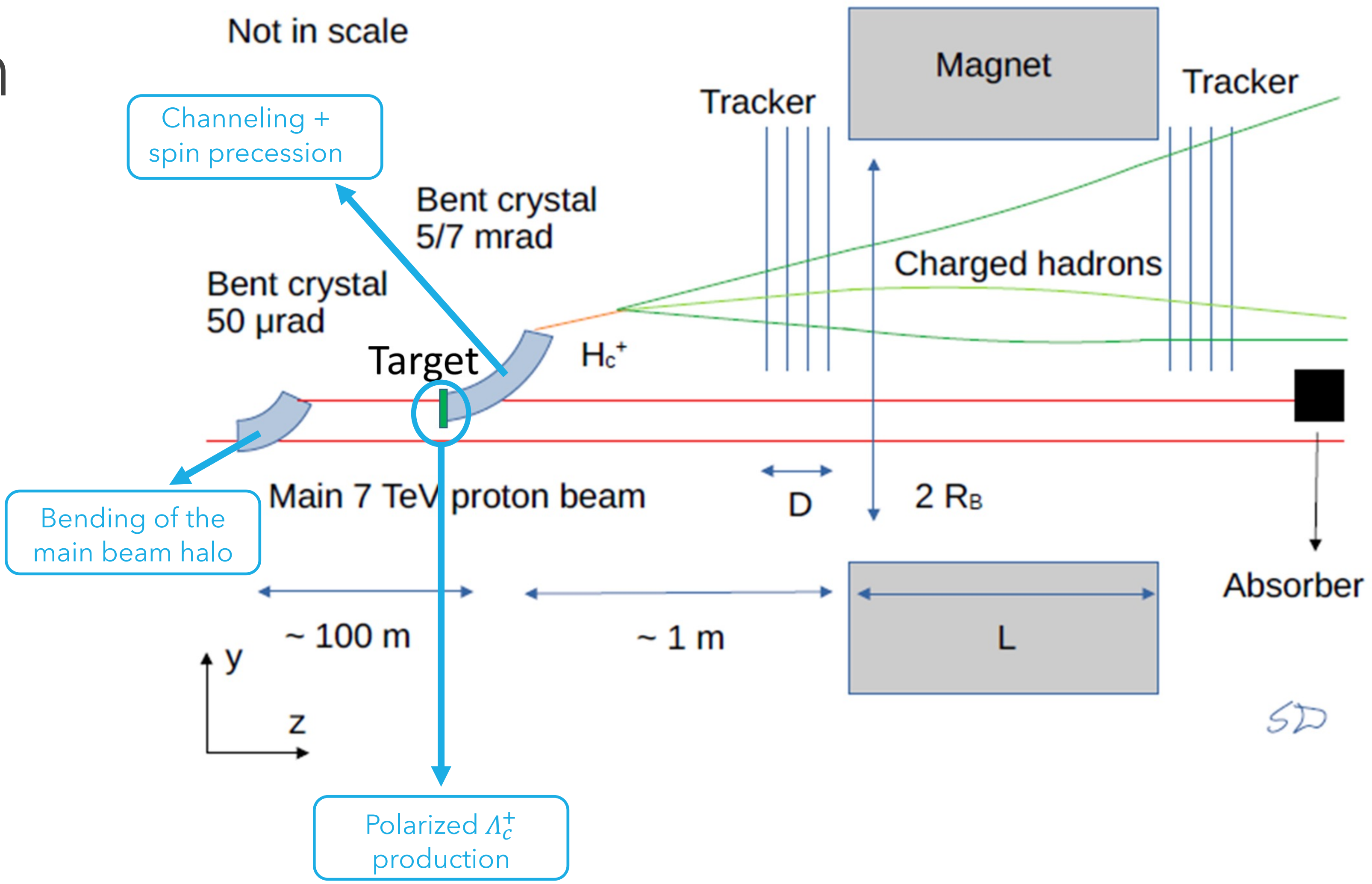
Fixed target experiment with bent crystals

Two different scenarios:

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

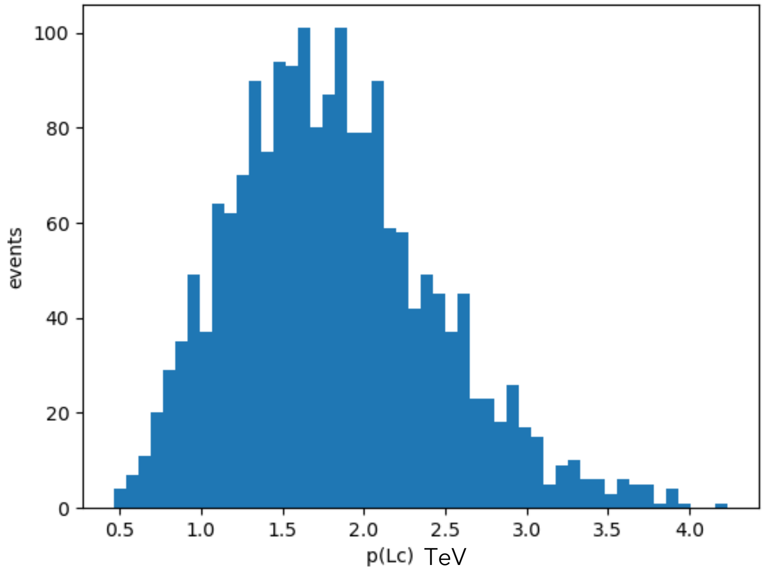


Λ_c^+ production and kinematic

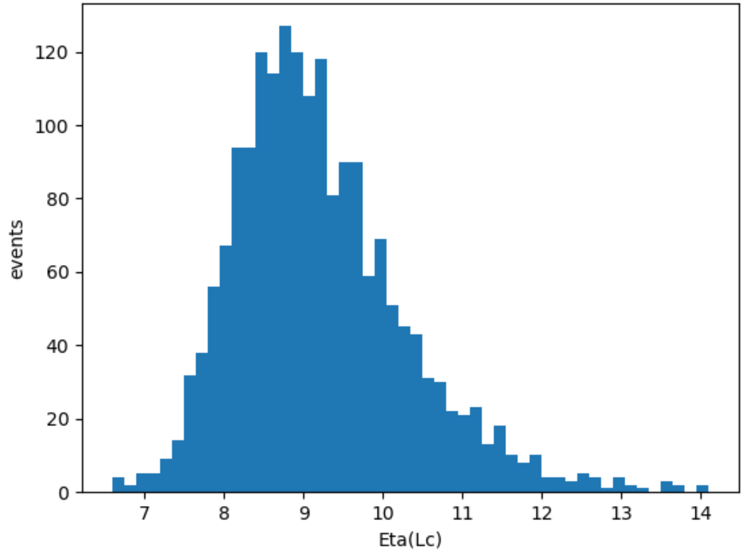
Λ_c^+ **production spectra** from Pythia after channeling through 7cm length, 7mrad bent Si crystal.

Starting from the 7 TeV protons of LHC, the charm baryons are produced in a **very forward** direction and with very high momentum, higher than **1 TeV.**

Momentum



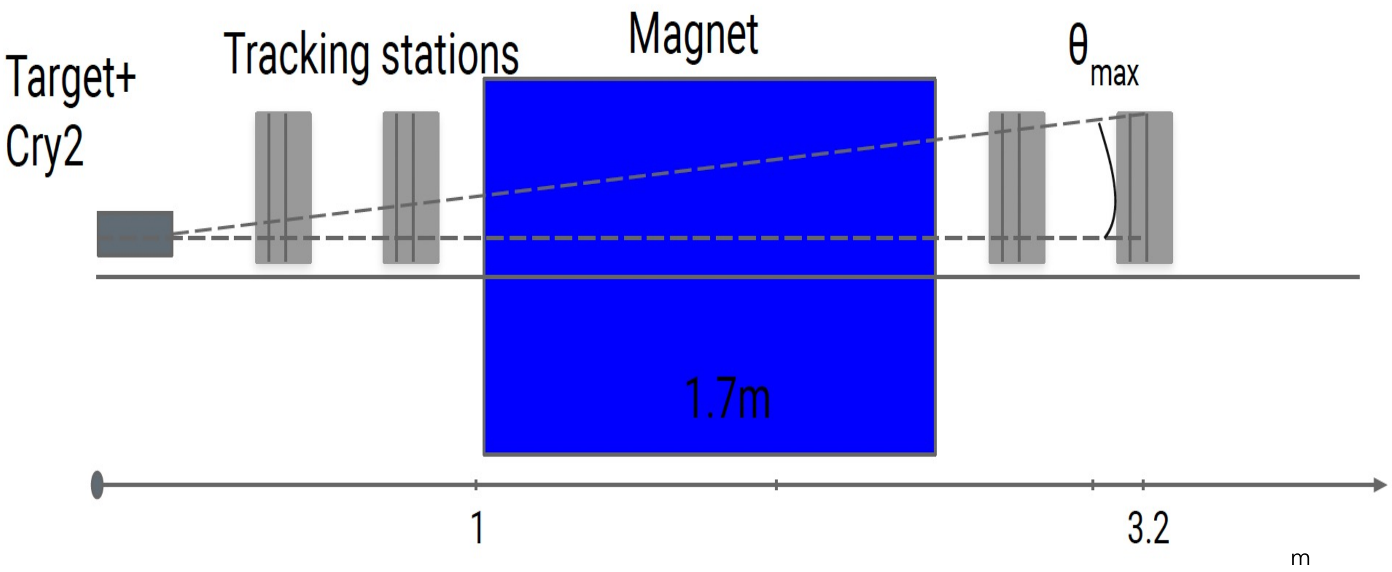
Pseudorapidity



Geometrical Acceptance at IR3

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

The bent crystals allow to extract the main beam halo and place the tracking layers in front of the target.



Pseudorapidity $5 < \eta < 10$

The upper limit is given by the granularity of the traking sensors.

Very forward region!
Complementary to LHCb

$2 < \eta < 5$

Expected luminosity

The first bent crystal is aligned to the **secondary halo** of the main proton beam of LHC at 7 TeV.

The halo extraction allows to have a flux of proton on the 2 cm W target of 10^6 p/s.

Fixed target experiment

$$\mathcal{L} = \phi_{projectile} \times \theta_{Nucleon}$$

$$\theta_{Nucleon} = \frac{N_A \rho l A}{M}$$

$$\rho = 19.3\ g/cm^3$$

$$N_A = 6.02 \cdot 10^{23}$$

$$l = 2\ cm$$

$$M = 184 g\ /mol$$

$\theta_{\text{Nucleon}} = 0.9 \times 10^{25}\ \text{cm}^{-2}$

Flux: 10^6 p/s

2 years of data taking

Time(s)/year: 0.69×10^6

Istantaneous Luminosity $\mathcal{L} = 0.9 \times 10^{31}\ \text{cm}^{-2}\text{s}^{-1}$

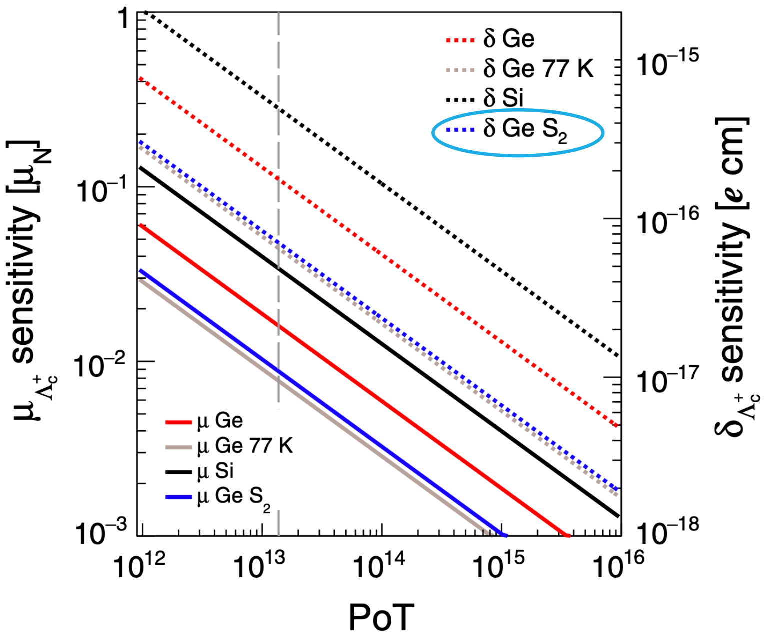
Integrated Luminosity $\int \mathcal{L} = 12\ \text{pb}^{-1}$

Sensitivity on EDM/MDM

- 2 cm W target
- Flux of 10^6 p/sec
- 2 years of data taking → total of 1.37×10^{13} PoT

LHCb
EDM precision = 2×10^{-16} e cm
MDM precision = 4%

Λ_c^+



At IR3
EDM precision = 7×10^{-17} e cm
MDM precision = 2%

The experiment at IR3 gains a factor 2 in precision and has a higher flux

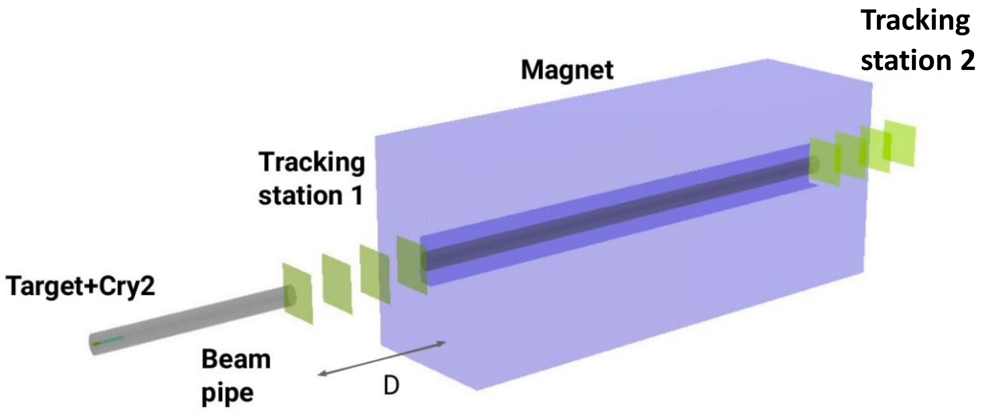
↓

higher PoT &/or reduced data taking time

PRD 103, 072003 (2021)

Simulation studies with DD4hep

- 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



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

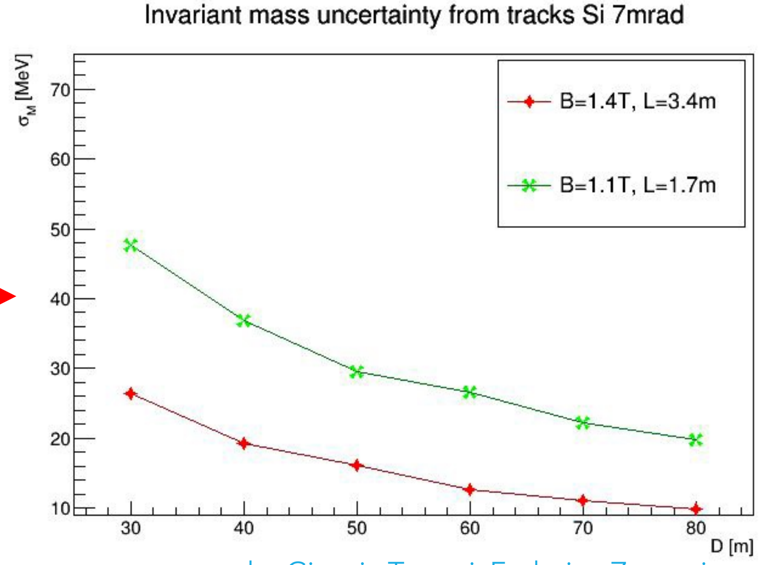
Simulation framework:

- 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

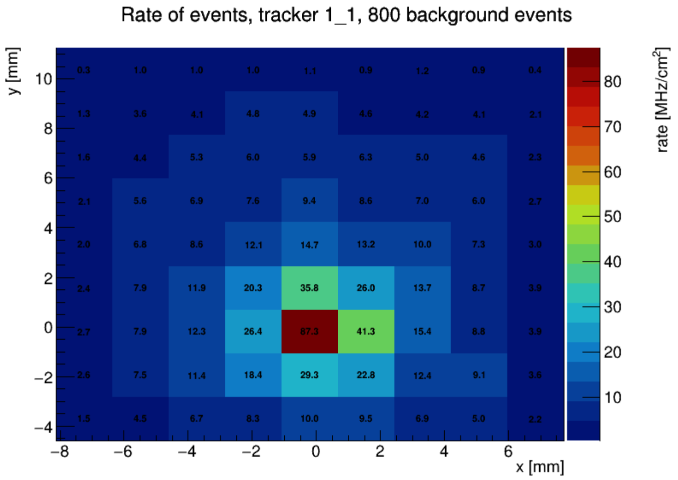
$\sigma_M < 50$ MeV for tracker lenght D > 40 cm

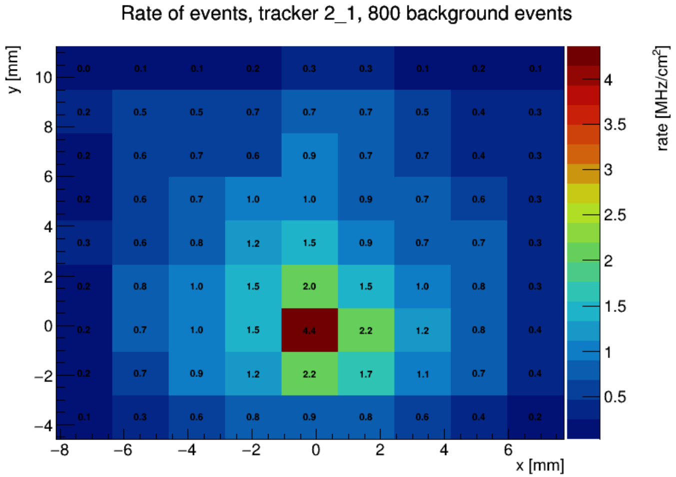


by Giorgia Tonani, Federico Zangari

Occupancy and acceptance of the detector

Simulation for 10^6 p/s on 2.0 cm of W target

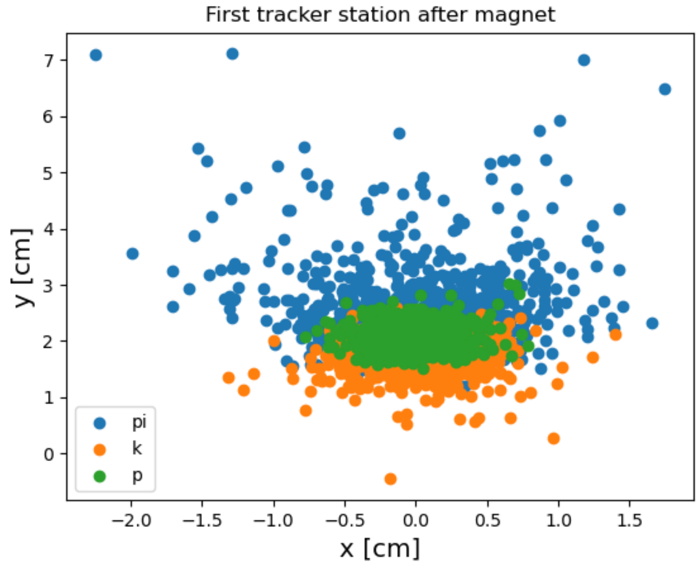




Rate/area in pixel sensors :

Before magnet $<100\ \mathrm{MHz/cm^2}$ (left plot)

After magnet $<10\ \mathrm{MHz/cm^2}$ (right plot)



Hit distribution for channeled $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays

Acceptance with 1 tile ~90%

Other physics opportunities

Unique forward acceptance $\mathbf{5 < \eta < 10}$

↓

Worth to enlarge the physics case!

1. Cross section measurements for D mesons production

RESULTS:

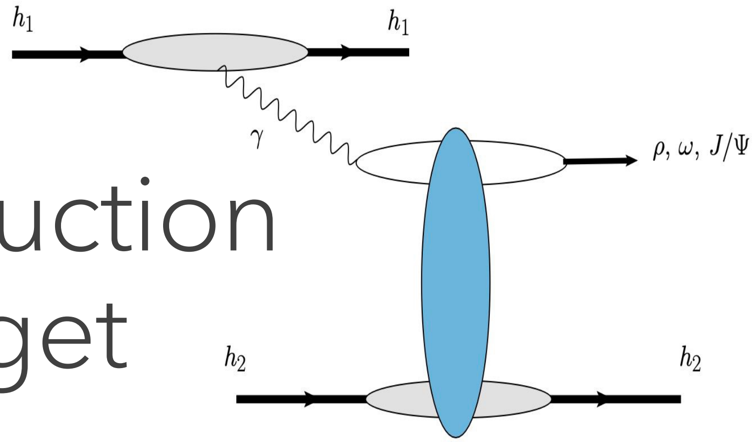
- $D^+ \to K^- \pi^+ \pi^+$, most abundant decay:
  ⇒ **O(1000)** of events in **few days**
- D_s^+ and Λ_c^+:
  resolvable with reso < 50 MeV
  ⇒ **O(1000)** of events in **~2 months**

Unique opportunity to study not only Λ_c^+ forward production but also D mesons and to measure their cross sections.

PRD, 103, 072003

by Daniele Marangotto

Photoproduction in fixed-target



Photoproduction of pentaquark states at the LHC. Gonçalves, V.P., Jaime, M.M. PhysicsLettersB805(2020)135447

Exclusive vector meson photoproduction in fixed-target collisions at the LHC. Gonçalves, V.P., Jaime, M.M. *Eur. Phys. J. C* 78, 693 (2018).

S. R. Klein, J. Nystrand, et al, STARlight: A Monte Carlo simulation program for ultra-peripheral collisions of relativistic ions, Comput.Phys.Commun. 212 (2017) 258-268,

2. Meson photoproduction:

J/ψ photoproduction in ultraperipherical collisions pW at $\sqrt{s} = 115$ GeV

- Estimated Yield: 26000 in two years of datataking

3. Pentaquarks photoproduction:

- Estimated Cross section: σPc = 0.5 nb /√5 = 0.2 nb
- Estimated Yield: 400 in two years of datataking

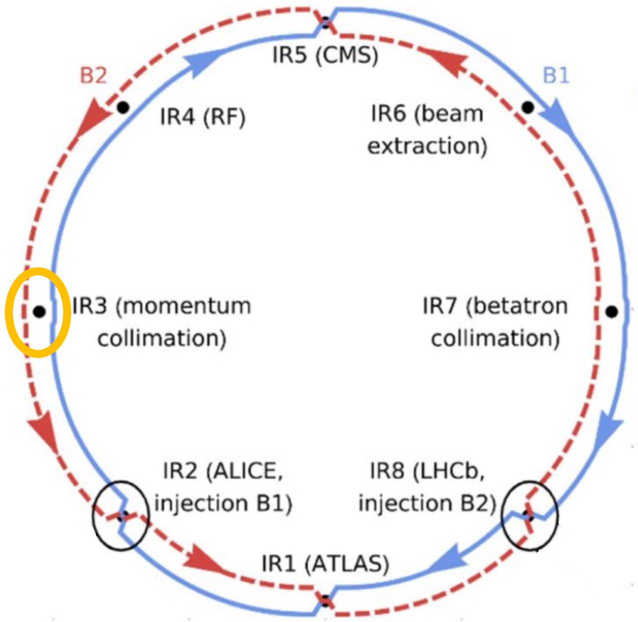
The cross section has been estimated starting from upper limit of GlueX in 2019 and scaled to their new statistic.

These are preliminary estimates → More detailed studies are needed and will be done using the MC STARLight package

Need for the addition of Muon chambers and PID detector

Proof-of-Principle test

Phase 0 - PoP at IR3



A first proof-of-principle test is scheduled before the end of 2025 at IR3 of of the two collimation region of LHC.

Goals of the test:

1. Control channeling of secondary halo
2. Measure channeling efficiency of long crystals at TeV energies
3. Test PoT rate capability and identify challenges

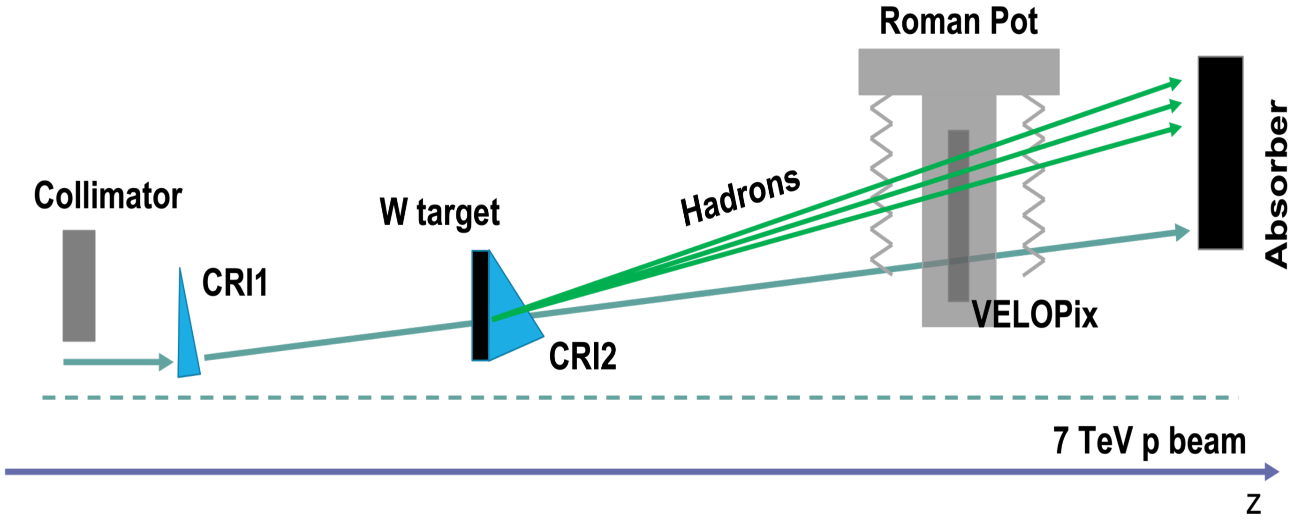
Advantages with respect to IR8 (LHCb):

- Single-beam vacuum pipe
- Collimation region with no nearby cold magnets
- Lower bending angle ➜ higher channeling efficiency
- No interference from other upstream devices of LHCb

EPJC 80, 929 (2020)

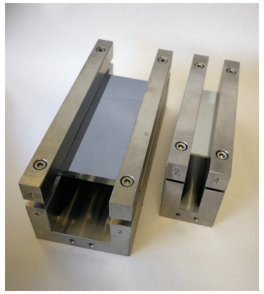
Experimental set-up

- Short crystal for beam-halo deflection
- W target
- Long crystal for Λ_c^+ channeling
- One tracking station in a Roman Pot (phase 0)
- Absorber



S. Redaelli

Ongoing R&D: Crystals



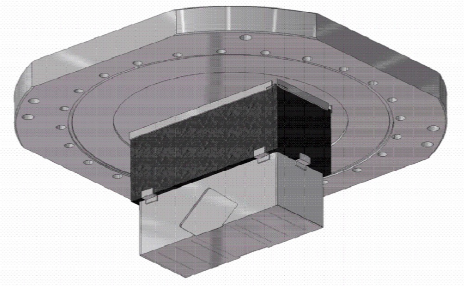
INFN Ferrara

Goniometer with accuracy on position ~20 μm and rotation angle ~20 μrad

Short crystal: length 4 mm, bending angle 55 μrad.

Long crystal:length 70 mm, bending angle 7 mrad.

Roman Pots



The pots are cylindrical vessels, which are **separated from the machine vacuum** and equipped with bellows that allow the pots to approach the beam.

Detectors are placed inside the pot and the primary vacuum is preserved.

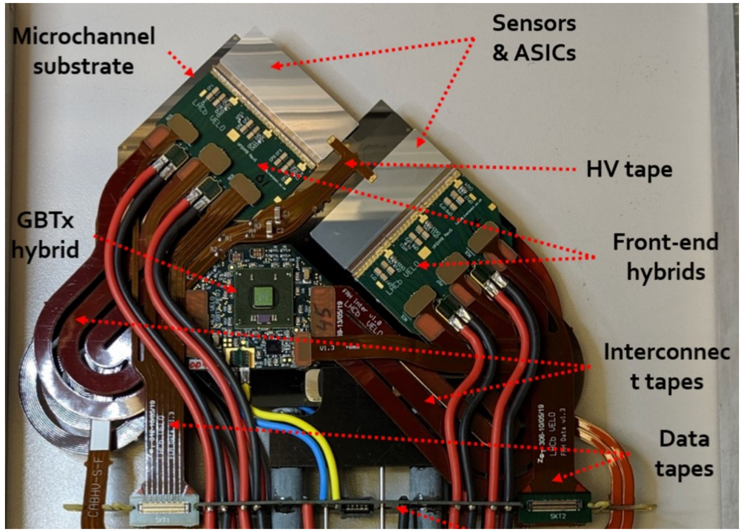
Pixel sensors for tracking

PCIe40 VeloPix readout board
FPGA Intel Arria 10
24 optical links
max throughput 100 Gbit/s

VELO sensors for Tracker stations
housed inside Roman Pots

- 55x55 μm2 pixel
- pixel hit rate **600 MHz/cm2**
- 12 μm hit resolution
- Tile : silicon sensors bump-bonded to 3 ASICs (1.4x4.2 cm2)

Full spectrometer - 8 layers of single VELO tiles.



Summary

- Opportunity for unique physics case at LHC with a fixed-target experiment in the very forward region: **MDM/EDM of charm baryons**, study of **charm hadron production**, study of **Pentaquark** ($P_c -> J/\psi\ p$) in photoproduction

- Two possible scenarios for the final experiment: LHCb vs IR3
- First Proof of Principle in 2025 at LHC IR3
- R&D in advanced status to start soon the construction of the IR3 setup

Thank you for the attention!

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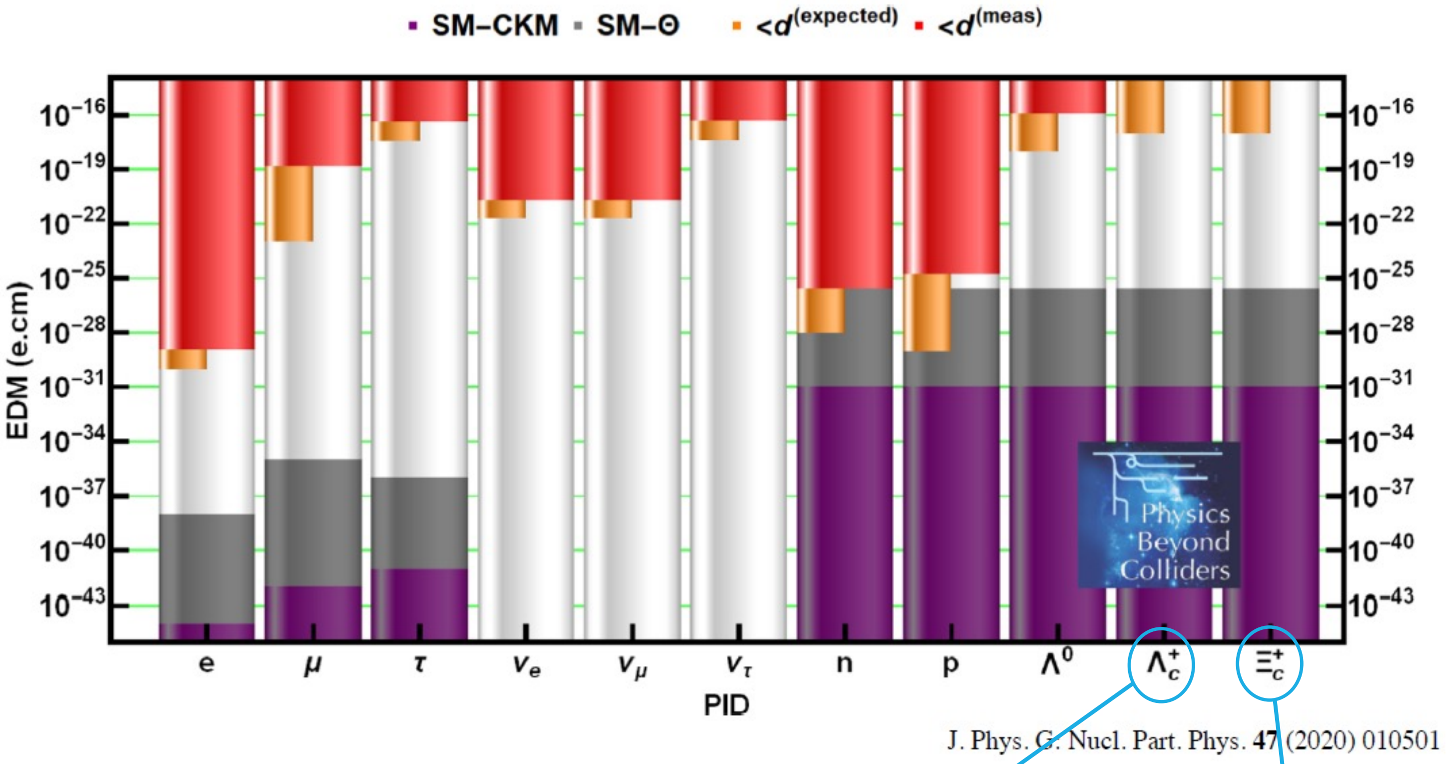
Backup slides

Status of EDM measurements

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

For the charm quark (chromo-) EDM only indirect limits exist based on the experimental bounds on the neutron EDM.

(EDM $\Lambda < 10^{-26}$e cm)



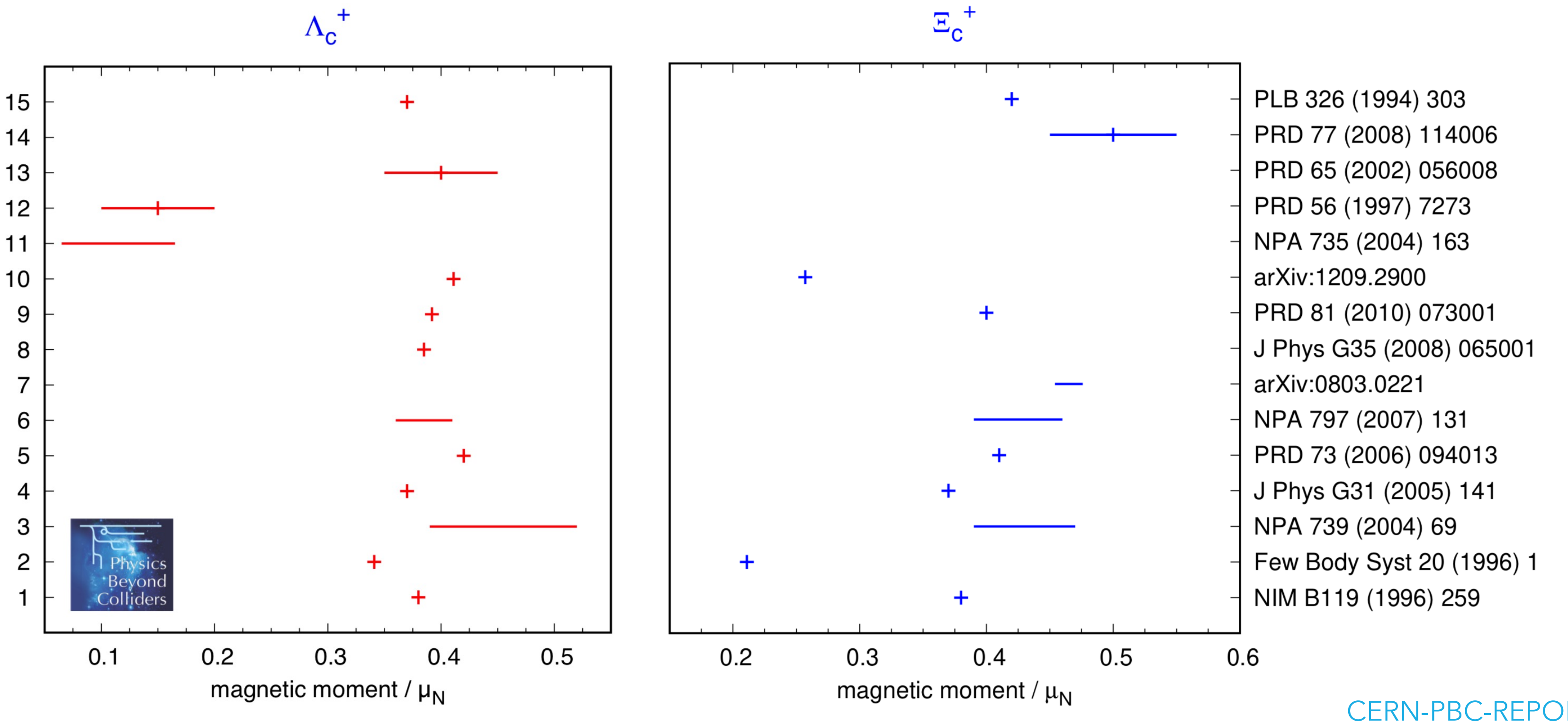
$\tau \sim 10^{-13}$ s

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

J. Phys. G: Nucl. Part. Phys. 47 (2020) 010501
CERN-PBC-REPORT-2018-008

MDM theoretical predictions

MDM measurements would provide important anchor points for QCD calculations, helping to discriminate between **different models** and would improve the current understanding of the **internal structure of hadrons**.



CERN-PBC-REPORT-2018-008

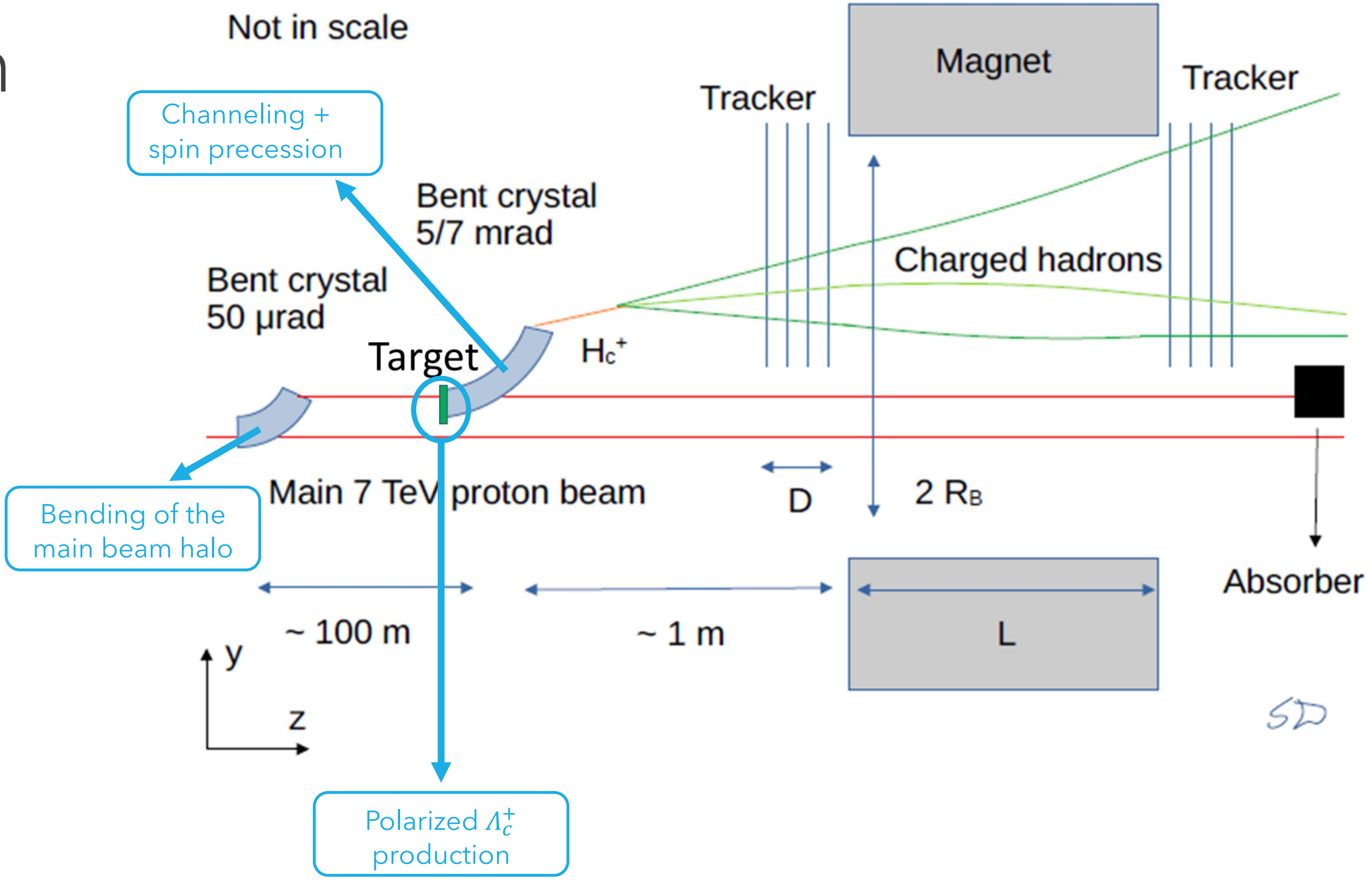
Fixed target experiment with bent crystals

Phase 0: PoP at IR3 (RUN 3)

Phase I: set-up to perform first physics measurements (RUN 4)

Phase II: set-up to perform ultimate precision physics measurements (RUN 5)

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



Lhcb

- Excellent spectrometer, just required to install target + bent crystal in front

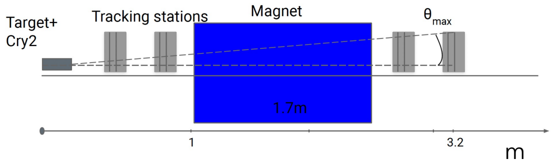
- High bending of Cry1 and angular cuts of absorbers at IR8 [1]
- High bending of Cry2 (14 mrad) for LHCb acceptance, less efficient crystal
- Limited proton flux 10^6 p/s
- EMDM program must live together with main LHCb physics program

New experiment

- Low bending of Cry1 and collimators already in place at IR3 [1]
- Forward acceptance, less bending crystal (5/7 mrad) with higher efficiency
- Possibility of higher flux 10^6 p/s → higher Λ_c yield

- New spectrometer, high investment and long time needed

Geometrical acceptance



Pseudorapidity y [5:10]

Very forward region!
Complementary to LHCb

Luminosity at IR3

Flux: 10^6 p/s

$\mathcal{L} = 1.26 \times 10^{-9}\ \mathrm{cm^{-2}s^{-1}}$

Time(s)/year: 0.69×10^6

2 years

↓

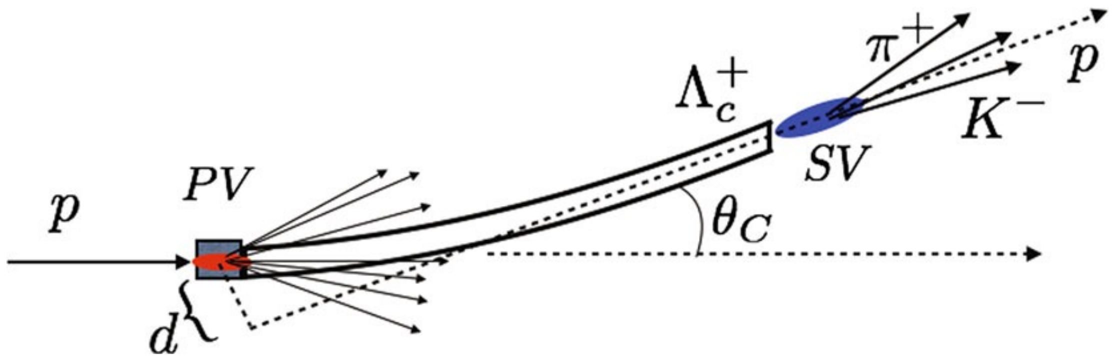
$\int \mathcal{L} = 1.78\ \mathrm{pb^{-1}}$

From F. Martinez-Vidal at PBC-QCD link

Charm production

Double crystal fixed-target setup gives access to **zero angle production** of positive charged particles (e.g charm baryons and mesons)

Kinematic variable	> 15 mrad (~SMOG2)	Ge 293K 16 mrad 10 cm
Momentum (GeV)	< 500	>800
Transverse momentum	> 0.5	< 1
Pseudorapidity*	-4 to 0, central & backward	1 to 3.5, very forward
Momentum transfer Q	20 to 115	≈ 4
Bjorken-x	Down to ≈ $10^{-3.5}$	Down to ≈ 10^{-3}
Feyman-x	Large negative	Large positive



Charm production

	Λ_c^+ baryon			
σ (μb/nucleon)	10.6			
$a = (g-2)/2$	≈ -0.03 [-0.76]			
d	0			
$\mathcal{B}_{\text{eff}}$ (%)	20.2	19.5	20.6	20.6
ϵ_{CH} ($\times 10^{-4}$)	4.5	2.7	8.7	11.1
ϵ_{DF} ($\times 10^{-2}$)	3.3	1.7	4.9	13.1
N_{rec}	586	181	1748	5879
$\langle\gamma\rangle$	709	573	834	855
$\langle p_{\text{T}}\rangle$ (GeV/c^2)	0.79	0.71	0.86	0.87
s_x (%)	11.8	8.6	14.1	15.6
s_y (%)	-15.3	-14.2	-16.1	-16.1
$\sigma_{\boldsymbol{\mu}}$ ($\times 10^{-2}$ $\boldsymbol{\mu}_{\text{N}}$)	1.6	3.4	0.8	0.9
$\sigma_{\boldsymbol{\delta}}$ ($\times 10^{-16}$ e cm)	2.2 [9.8]	5.6 [17.1]	0.9 [5.7]	1.0 [2.9]

Other physics opportunities

Cross section measurements for D mesons production

Flux of 10^6 p/s and Ge crystal as demonstrated in [1], 5 mrad bending

Decays of D^+, D_s^+ and Λ_c^+ to three final state particles

RESULTS:

- $D^+ \to K^- \pi^+\pi^+$, most abundant decay:
  $\Rightarrow$ **O(1000)** of events in **few days**
- D_s^+ and Λ_c^+:
  resolvable with reso < 50 MeV
  $\Rightarrow$ **O(1000)** of events in **~2 months**

$\Rightarrow$

Enough statistics for IR3 test

Preliminary results demonstrate that we can make it!

BUT we need full simulation to study detector response

[1] PRD, 103, 072003

by Daniele Marangotto

D mesons yields

Yields for positive charm hadrons decaying to three charged tracks

- $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to K^+K^-\pi^+$, $\Lambda_c^+ \to pK^-\pi^+$

Starting from PRD 103, 072003 (2021)

- Dedicated fixed-target experiment scenario with 7 TeV proton beam, intensity $10^6 p/s$
- Λ_c^+ production spectrum from Pythia after channeling through 7cm length, 7mrad bent Ge crystal

Rescaled to D^+, D_s^+ meson case

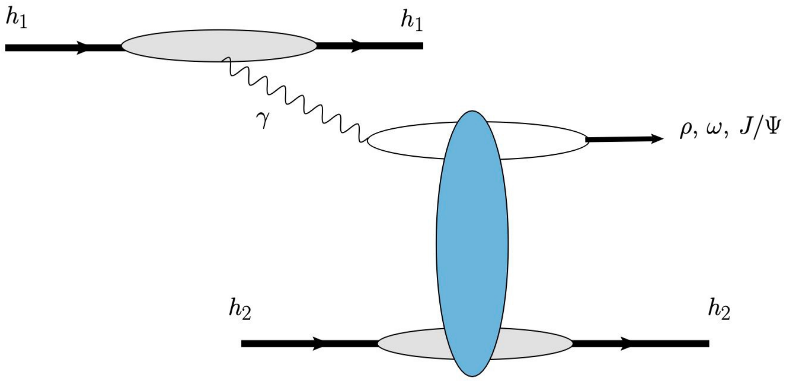
- Longer meson lifetime (τ_{D^+}= 1 ps,$\tau_{D_s^+}$= 0.5 ps, $\tau_{\Lambda_c^+}$= 0.2 ps), assuming same energy spectrum
- Different branching ratios and c-quark fragmentation fractions

Rescaled for different crystal material and bending using simulation described earlier (Slide 5)

Considered acceptance for MCBW magnet with $R_B = 2.5$ cm

by Daniele Marangotto

Photoproduction in fixed-target

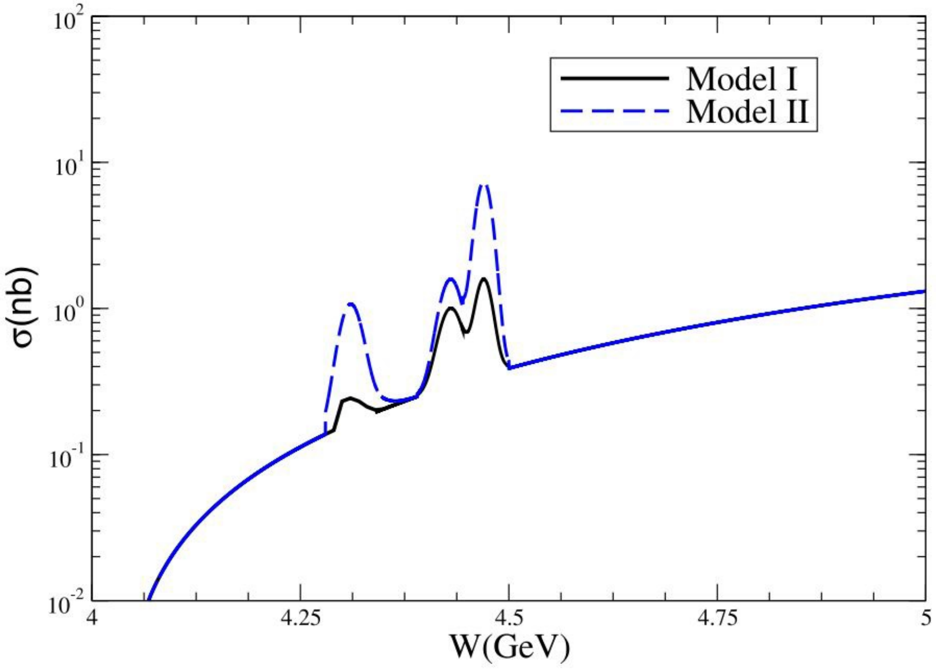


3. Pentaquarks photoproduction:

- Estimated Cross section: σPc = 0.5 nb /√5 = 0.2 nb
- Estimated Yield: 400 in two years of datataking

We expect an enhancement in the pseudorapidity range

$$5 < \eta < 8$$



History of the proposal

Developed in the framework of the CERN Physics Beyond Collider WG by groups with complementary expertise: LHCb, LHC collimation, UA9

2016

MDM proposal: using bent crystals at SPS and LHC, *by Stocchi et al*
CERN-SPSC-2016-030

Initial EDM proposal: Measurement of charm baryon EDMMs from spin precession in bent crystal **using LHCb detector**
Eur. Phys. J. C 77, 181 (2017)

2017

Charm baryon MDM with bent crystals at LHCb *by Fomin etal*
JHEP**1708**(2017)120

Dec 2017

Update: Proposal for 2 experimental scenarios: **LHCb vs dedicated experiment**
Eur. Phys. J. C 77, 828 (2017)

Test of bent crystal prototypes at SPS H8

2018

2019

Feasibility studies of fixed-target layouts at different LHC points *by Mirarchi et al*
EPJC 80, 929 (2020)

Double bent crystal setup proof-of-principle at CERN SPS *by Scandale et al.*
Nucl. Instrum. Meth. A 1015 165747 (2021)

2020

2021

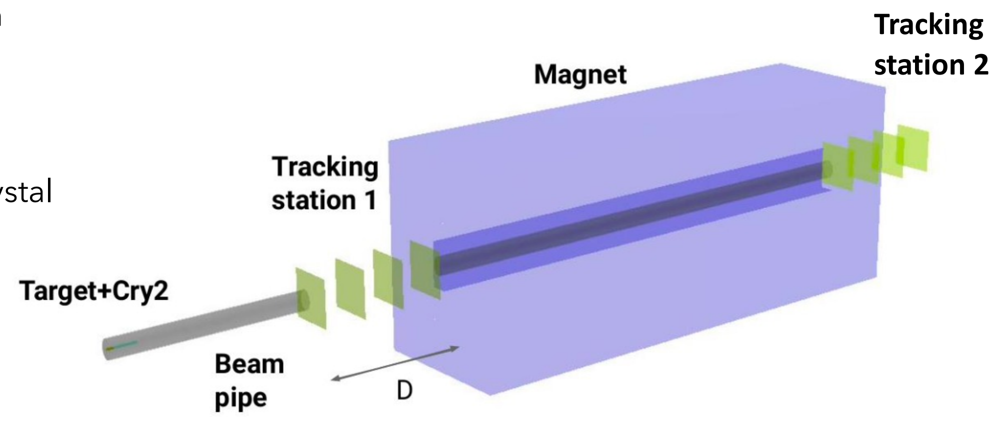
Progress towards the first measurement of charm baryon dipole moments *by Aiola et al*
Phys. Rev. D 103, 072003 (2021)

Simulation studies with DD4hep

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



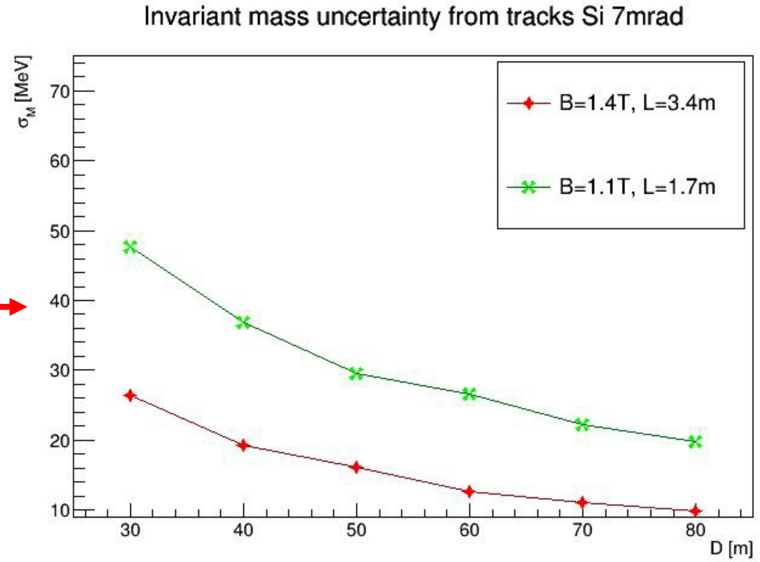
Simulation framework:

- 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

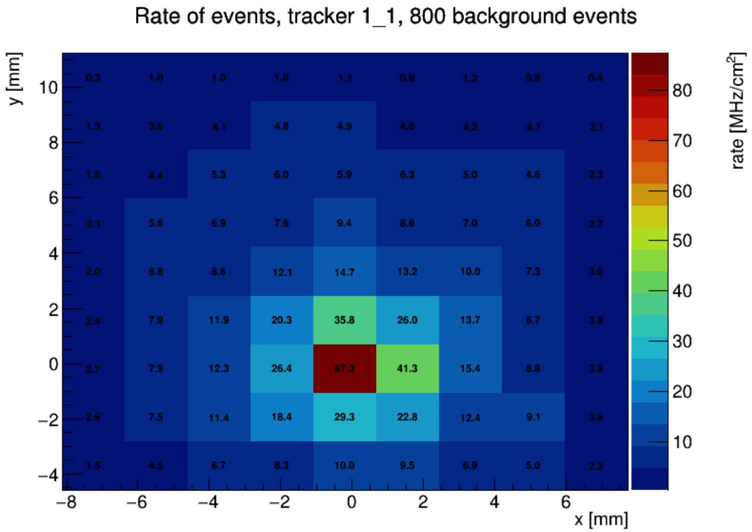
$\sigma_M < 50$ MeV for tracker lenght D > 40 cm

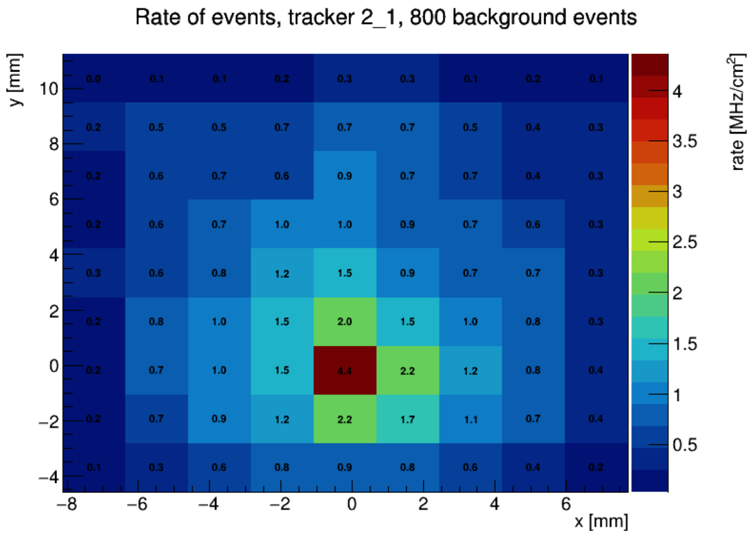


by Giorgia Tonani, Federico Zangari

Occupancy and Acceptance studies

Simulation for 10^6 p/s on 2.0 cm of W target

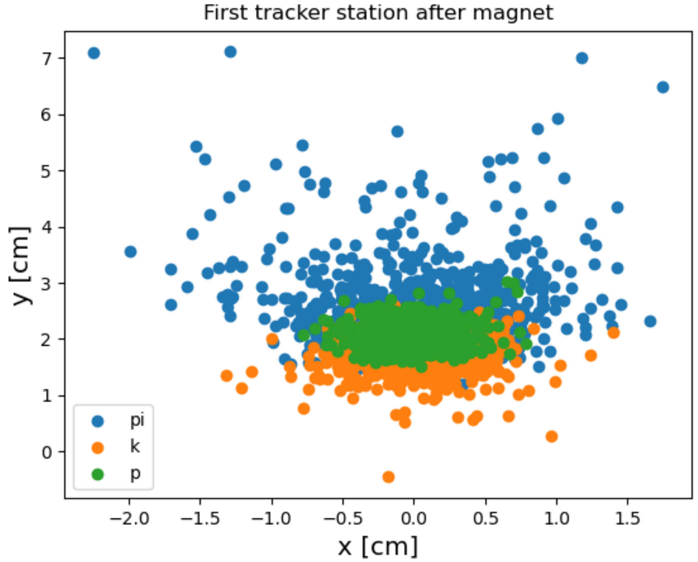




Rate/area in pixel sensors :

Before magnet $<100\ \mathrm{MHz/cm^2}$ (left plot)

After magnet $<10\ \mathrm{MHz/cm^2}$ (right plot)



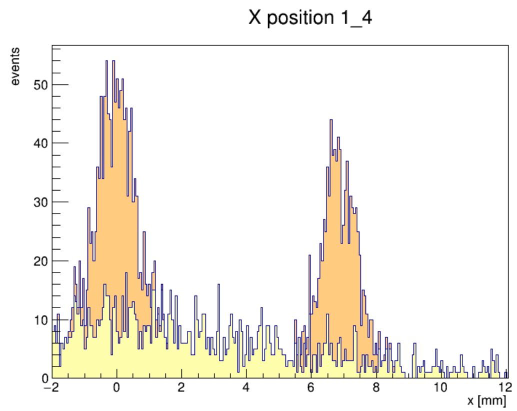
Hit distribution for channeled $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays

Acceptance with 1 tile ~90%

Channeling efficiency

The channeling efficiency was previously measured with an hadron beam of 180 GeV at SPS.

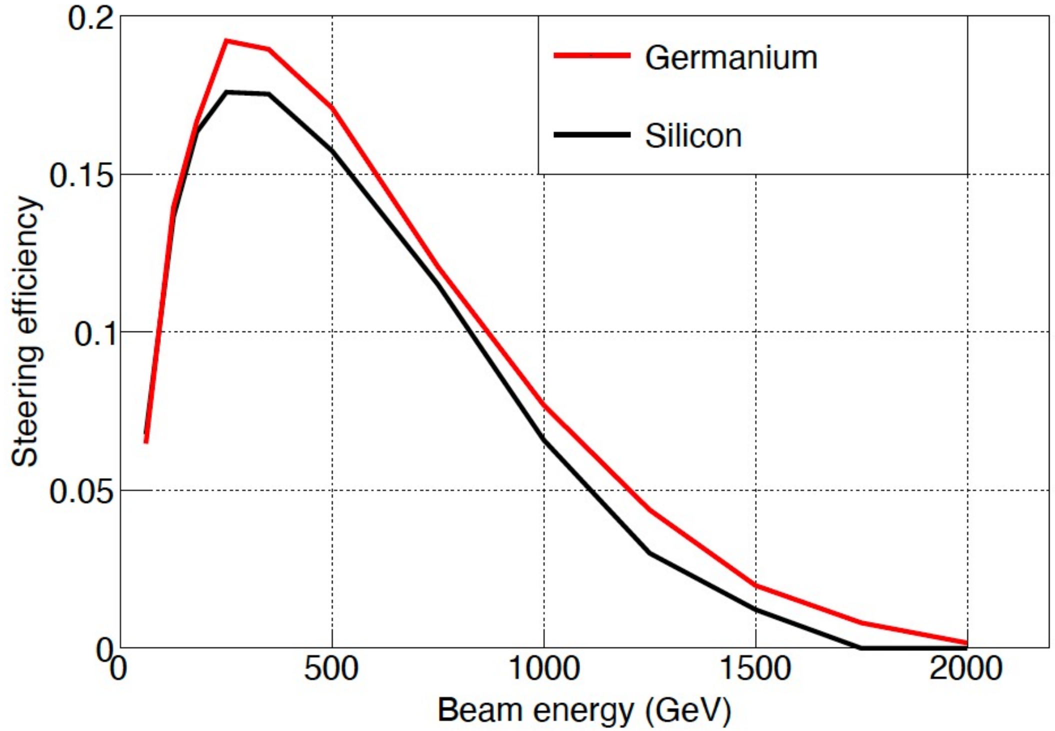
S. Aiola et al., Phys. Rev. **D** 103 (2021) 072003



The first goal of the PoP is the measurement of the channeling efficiency.

Simulations of the channeling efficiency are performed using Geant4.

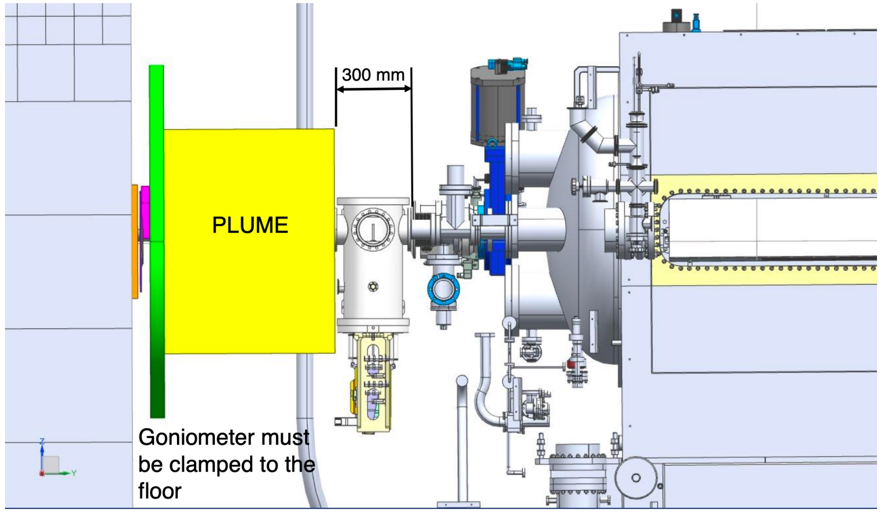
Needs to be validated on data:
At IR3 possibility of dedicated runs at different energies > 450 GeV



Fixed target experiment at LHCb

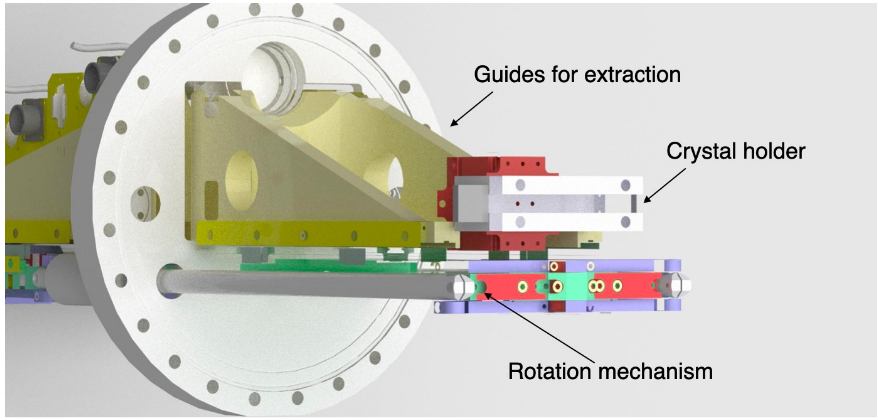
Goniometer for target+crystal positioned in the region upstream of the LHCb detector.

Compatible with ultra-high vacuum operations.



Full simulation of fixed-target setup: W target + crystal

- Good performance for signal and background
- The crystal should be rotated to improve the efficiency
- $\nu_{target} \lesssim 0.01$ with 10^6 p/s on target
- About 10^{-4} Λ_c^+ are channelled and have high momentum p $\gtrsim$1 TeV
- Good resolution on production and decay vertex



CERN-THESIS-2019-108