Overview of the IR3 proof-of-principle test and beyond

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Outline

- Proposal of fixed-target experiment and IR3 test:
    - LHCb vs IR3
- Main goals of IR3 test
- IR3 detector layout
- Simulations of IR3 test:
    - parametric simulation
    - initial results of full simulation

A bit of history

See also talk by
Joan Ruiz

2016

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

2017

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

2018

Test of bent crystal prototypes at SPS H8

2019

Feasibility studies of fixed-target layouts at different LHC points *by Mirarchi et al*

EPJC 80, 929 (2020)

2020

Double bent crystal setup proof-of-principle at CERN SPS *by Scandale et al.*

Nucl. Instrum. Meth. A 1015 165747 (2021)

2021

Progress towards the first measurement of charm baryon dipole moments *by Aiola et al*

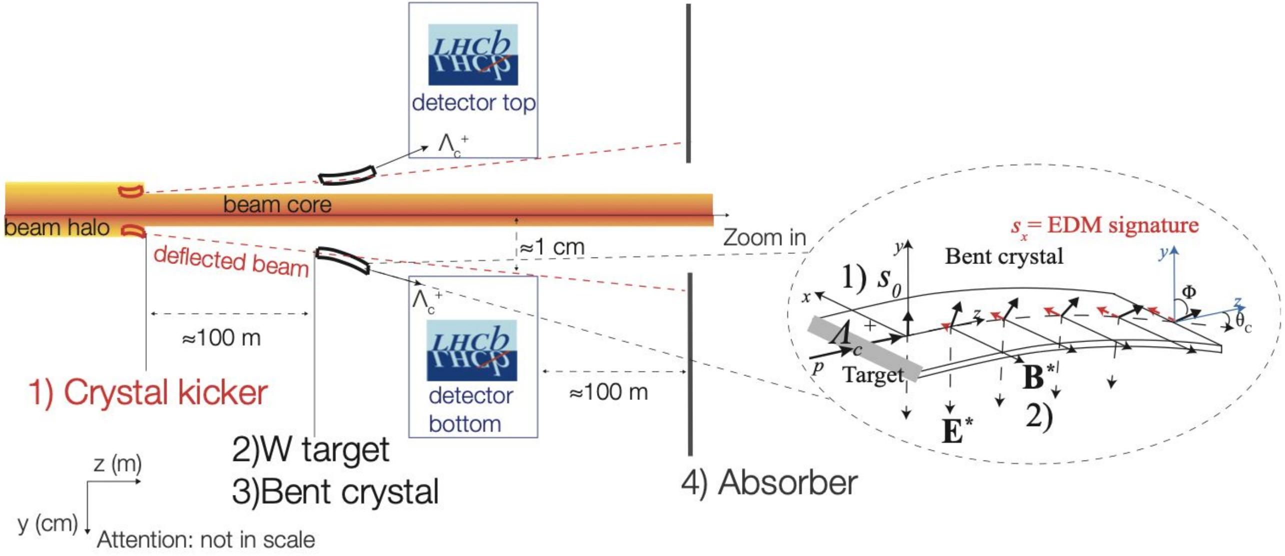
Phys. Rev. D 103, 072003 (2021)

Fixed-target layout at LHCb

In 2017, SELDOM team proposed LHCb detector as spectrometer Eur. Phys. J. C 77, 181 (2017)

- other proposal for MDM measurement at LHCb JHEP **1708** (2017) 120

1) First bent crystal (Cry1) to extract protons from LHC
2) W Target
3) Second bent crystal (Cry2) for spin precession
4) Absorbers to stop deflected protons and background, downstream to LHCb



LHCb review

LHCb declared its interest in the experiment

- under evaluation among fixed-target experiments at LHCb (FITPAN)
- installation of the target-crystal setup discussed in internal note (LHCb-INT-2017-011)

BUT requires a **proof-of-principle demonstration** in a different LHC point
to mitigate risks and demonstrate:

1) Feasibility of double bent crystal setup
2) Good channelling efficiency at TeV energies
3) Safety for detector operations
4) Good background suppression

Outcome

- Fixed-target in LHCb
- New experiment @ IR3

LHCb

- ➕ Excellent spectrometer, just required to install target + bent crystal in front
- ➖ High bending of Cry1 and angular cuts of absorbers @ 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

Dedicated experiment

- ➖ New spectrometer, high investment and long time needed
- ➕ Low bending of Cry1 and collimators already in place @IR3 [1]
- ➕ Forward acceptance, less bending crystal (5/7 mrad) with higher efficiency
- ➕ Possibility of higher flux 10^7 p/s → higher Λ_c yield
- ➕ Possibility of synergetic runs with LHC

[1] EPJC 80, 929 (2020)

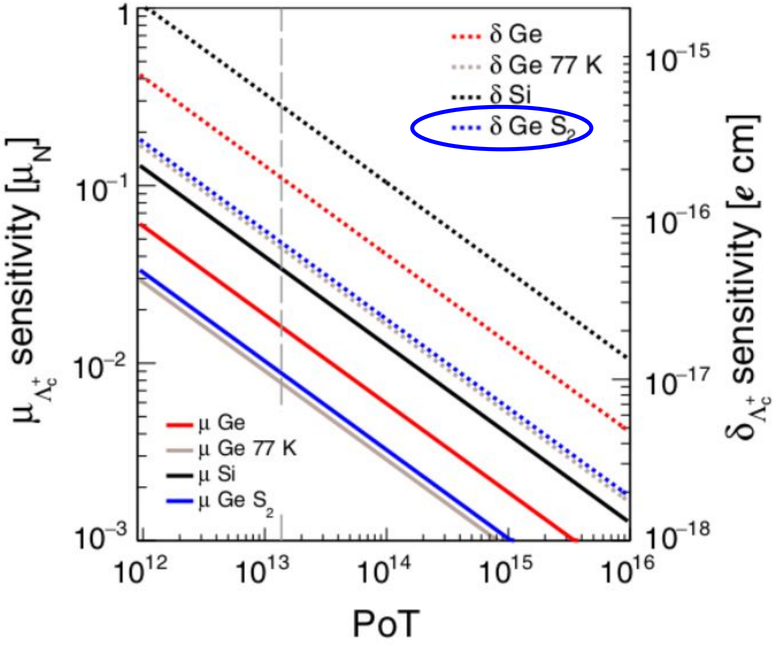
Sensitivity studies

2cm W target,
2 years, $F=10^6$ p/s
→ 1.37×10^{13} PoT

LHCb

EDM precision
= 2×10^{-16} e cm

MDM precision
= 4%



@IR3

EDM precision
= 7×10^{-17} e cm

MDM precision
= 2%

Dedicated experiment better than LHCb scenario by factor 2

+ higher flux ⇒ higher PoT &/or reduced data-taking time

Test of bent crystals at SPS

Channelling efficiency measured at GeV energy scale:

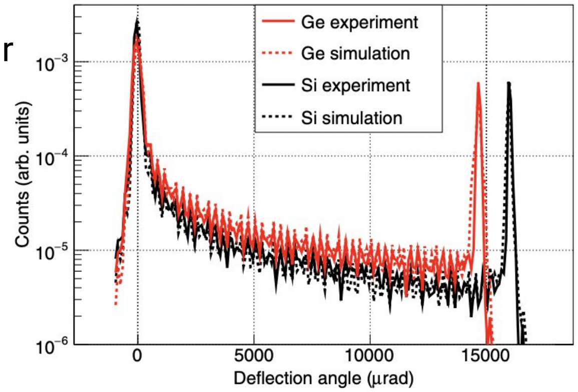
→ **test at CERN SPS** (H8) in *Oct 18*, with 180 GeV particles

Two bent crystal prototypes to comply with LHCb acceptance

- Silicon: 80 mm length, 16 mrad bending
- Germanium: 55 mm length, 15 mrad bending

Channeling observed near bending angle (right)

Channeling efficiency:
8.9 ± 0.5% (Si)
10.8 ± 0.5% (Ge)

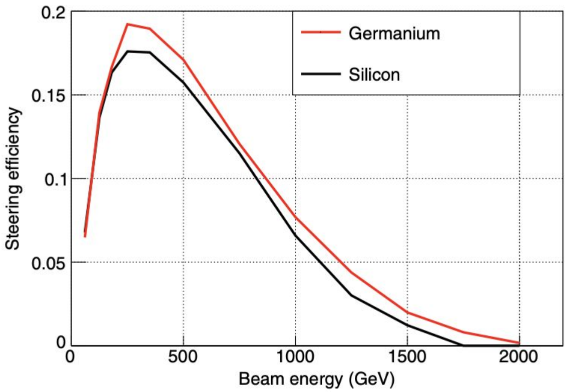


Energy dependence:

Extrapolation to TeV energy scale with MC simulation

⇒ Need to be validated on data:

- **Possibility of dedicated runs at LHC** at different energies > 450 GeV



IR3 test

Main goals

Demonstrate feasibility of a dedicated experiment @IR3 for EDM of charmed baryons

- **Double-channeling layout in LHC** demonstrated at SPS [1] but not yet at LHC
- **Channelling efficiency** of Cry2 with high yield and efficiency at TeV energy

} Minimal setup of
Double bent crystal
+Target
+1 tracking station

- **Background level** and invariant mass resolution measurement

⇒ Reconstruction with **spectrometer** composed of magnet+tracking stations

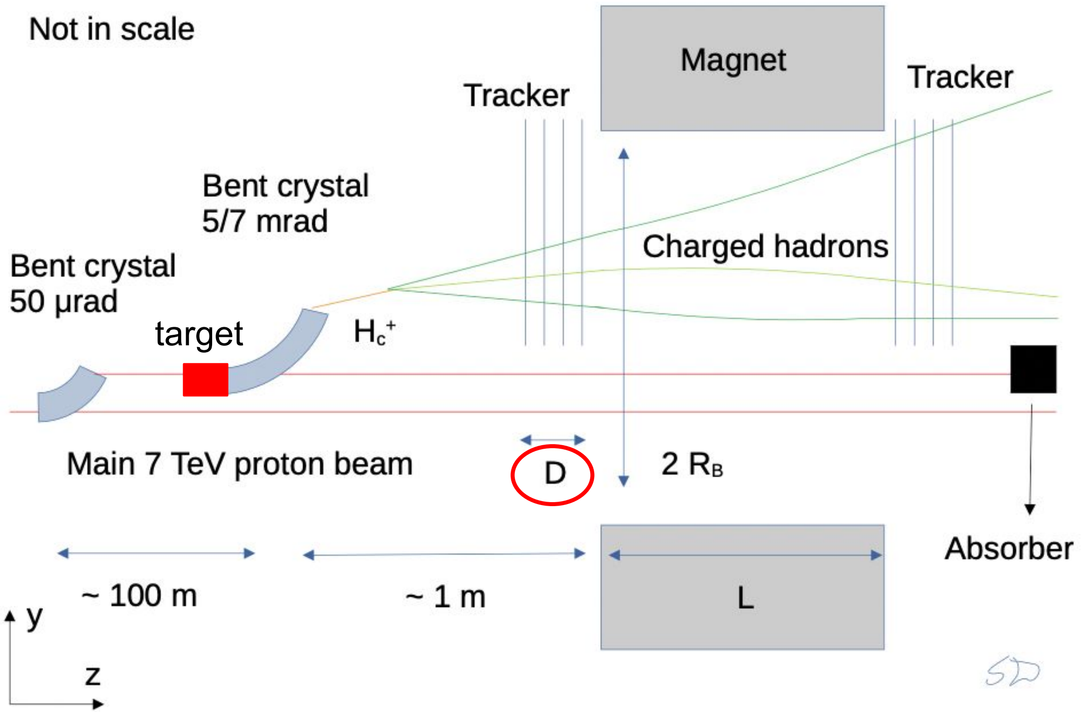
[1] *Nucl.Instrum.Meth.A* 1015 (2021) 165747

IR3 detector layout

First bent crystal for secondary beam

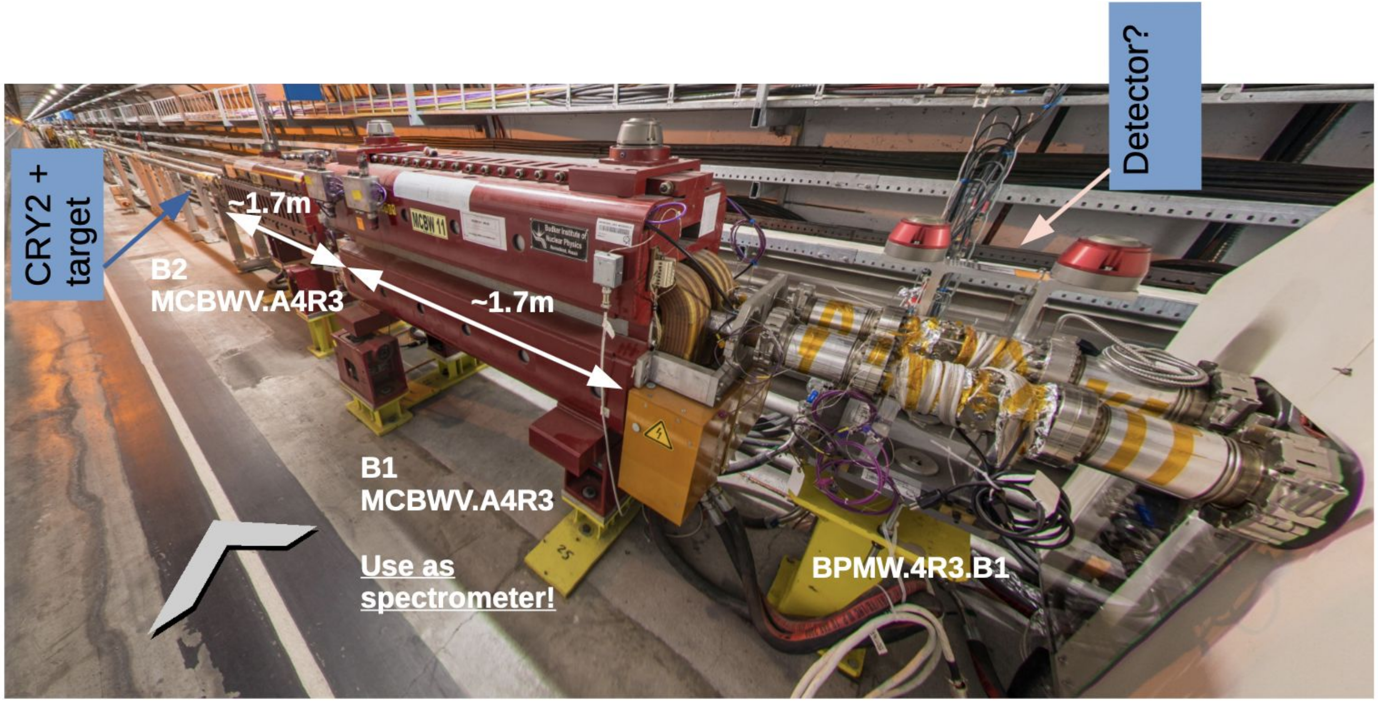
Second bent crystal channeling charm hadrons (5/7 mrad of bending)

Spectrometer composed by warm/permanent magnet + tracking stations



Picture of IR3

by Pascal Hermes



https://edms.cern.ch/panoramas/viewer?fov=90.00&id=36409858&lat=-27.06&lon=241.01

Spectrometer for IR3

Magnets

- Existing dipole magnets at IR3

Magnet	L [m]	B [T]
MBW	3.4	1.4
MCBW	1.7	1.1

⇒ Talk by Hermes

- Dedicated high-intense-field magnet (4 Tm) for better invariant mass resolution

⇒ Talk by Sorbi

Tracking stations

Si pixel detectors due to high particle rate

The best detector in terms of performances is **VELOPixel** (TDR):
⇒ possibility of using tiles with pixels, 55x55 μm^2

⇒ Talk by Coco

Preliminary IR3 simulations

talk by Giorgia at 29th PBC working group meeting

Parametrization of acceptance and invariant mass resolutions; detector response not simulated

Simulation of $\Lambda_c^+ \to pK^-\pi^+$ decays:

Pythia 8.244, (NNPDF3.1sx+LHCb_NNLO+NLLxLUXQED)

Λ_c^+ production in 7 TeV proton on fixed-target collisions, phsp decay

Study of:

- Spectrometer acceptance
    - for 5 and 7 mrad bent crystals
- Invariant mass resolution:
    - in order to distinguish between Λ_c^+ and D_s^+
    - as a function of tracker length *D*
- Charm hadron yield estimate
    - for D^+, D_s^+ and Λ_c^+ decays to three final state particles

Acceptance and invariant-mass resolution

by Giorgia Tonani, Federico Zangari

Spectrometer acceptance

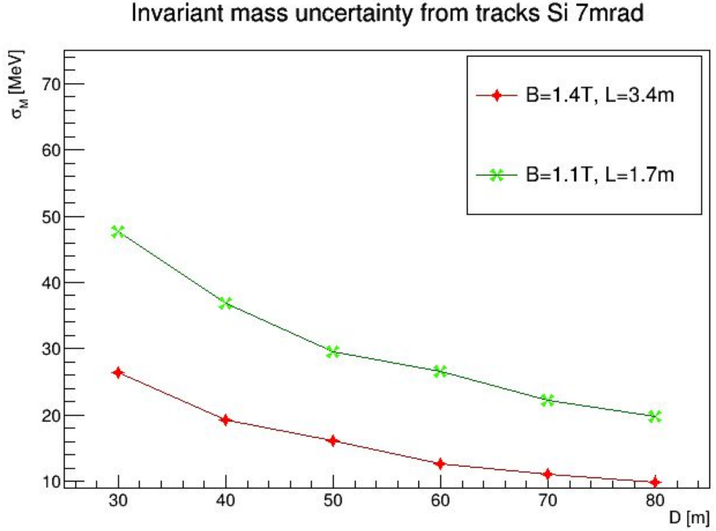
B_x field, for different magnet aperture, bending angle and Si/Ge

	Si 7 mrad	$R_B = 2\,\mathrm{cm}$	$R_B = 2.5\,\mathrm{cm}$	$R_B = 3\,\mathrm{cm}$	$R_B = 4\,\mathrm{cm}$
MBW	$B = 1.4\,\mathrm{T}$, $L = 3.4\,\mathrm{m}$	0%	0%	0%	14%
MBCW	$B = 1.1\,\mathrm{T}$, $L = 1.7\,\mathrm{m}$	0%	18%	81%	97%

Ge 5 mrad	$R_B = 2\,\mathrm{cm}$	$R_B = 2.5\,\mathrm{cm}$	$R_B = 3\,\mathrm{cm}$	$R_B = 4\,\mathrm{cm}$
$B = 1.4\,\mathrm{T}$, $L = 3.4\,\mathrm{m}$	0%	0%	16%	74%
$B = 1.1\,\mathrm{T}$, $L = 1.7\,\mathrm{m}$	38%	89%	96%	99%

MBCW with good acceptance for $R_{B,x}$ > 3 cm

Invariant mass resolution vs tracker length



σ_M< 50 MeV for tracker length D > 40 cm

- MCBW magnet can be considered as a valuable solution
- Si 7mrad, best Cry2 configuration for invariant mass resolution

Charm hadron yield

by Daniele Marangotto

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:

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

⇒

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

Full simulation of IR3 detector

Simulation of	Softwares & tools
Detector geometry	DD4hep: in `xml` format ⇒ talk by Han Miao
Particle generation (p+target interactions)	Pythia, Angantyr model for heavy-ion collisions
Particle simulation:	DD4hep/DDG4: based on Geant4
propagation, interaction with matter and decay	
channelling effects	
Track reconstruction and digitalization	ACTS/GENFIT ⇒ talk by Jascha Grabowsky

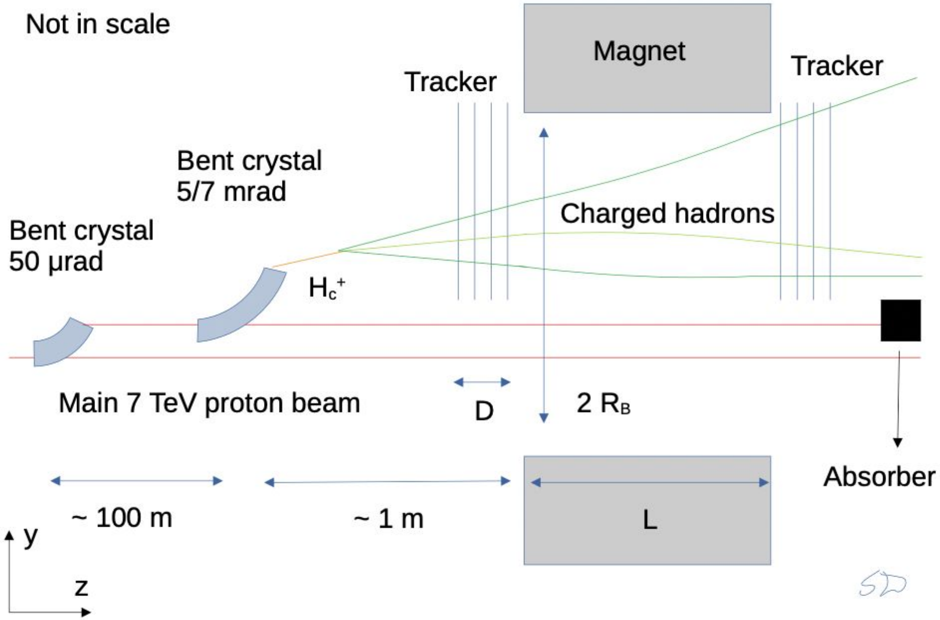
Goals of full simulation

1) **Channeling efficiency** study using GEANT4

2) **Background studies**
   - Occupancy of tracking stations
   - Secondary particles interaction with magnet and after magnet

3) **Invariant mass resolutions** of charmed hadrons

⇒ Optimization of **tracking system layout**
position of trackers and usage of VeloPix



IR3 detector geometry

Target: W, 2 cm long

Cry2: Si, 7 cm long, 7 mrad

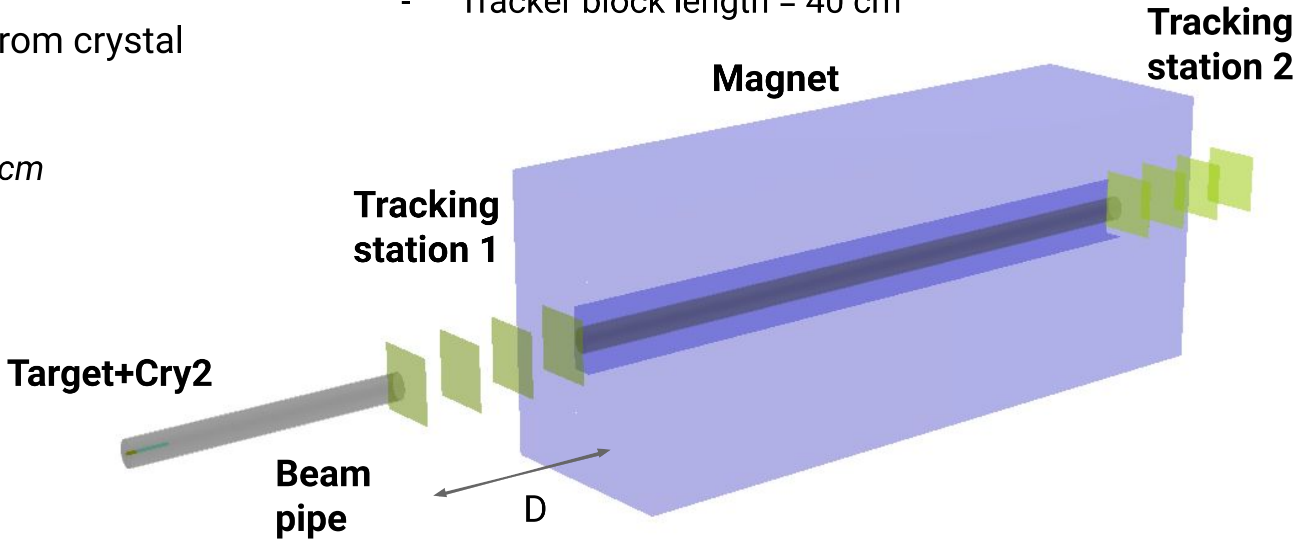
Beam pipe: Cu OFE, elliptical form

MCBW Magnet: Fe, at 1m from crystal

- B=1.1 T, L =1.7 m
- Bore: $R_B(x,y)=(2.6, 7.2)$ *cm*

Tracking stations: 2 blocks of 4 trackers before/after magnet

- Si, 300 μm thick, 15x15 cm^2
- Tracker block length = 40 cm



Preliminary occupancy studies

by Federico Zangari

Background events: Minimum bias (p+W interaction, Pythia 8.3 Angantyr)

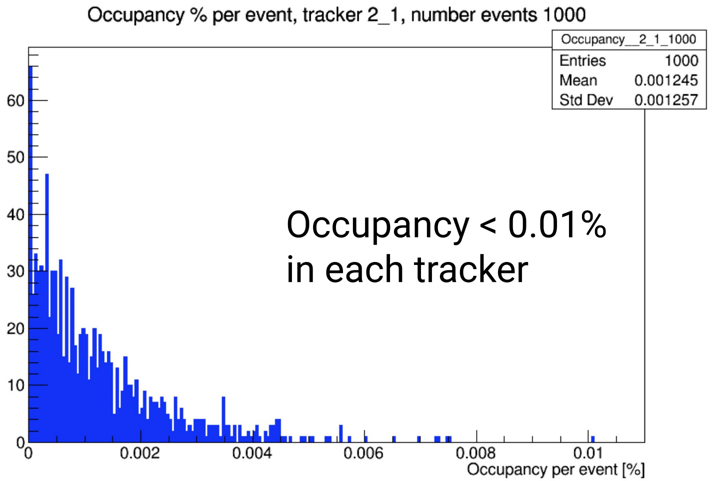
Simulation of full detector, no crystal channelling

$$\text{Occupancy} = \frac{N_{pixel}(E_{deposit} > E_{th})}{N_{pixel}}$$

VeloPixel specifications: TDR

- Pixel size = 55x55 μm^2
  Tracker stations of 15x15 cm^2
  ⇒ 2727 × 2727 pixels grid

- Minimum energy deposit: E_{th}=1.8 keV
  - E = 3.6 eV to create e^--h
  - Threshold of 500 e^-



Occupancy < 0.01%
in each tracker

Rate of Background events

by Federico Zangari

$$\text{Rate} = N_{\text{hits}}/cm^2/s$$

Scaled by the fraction of interacting protons:

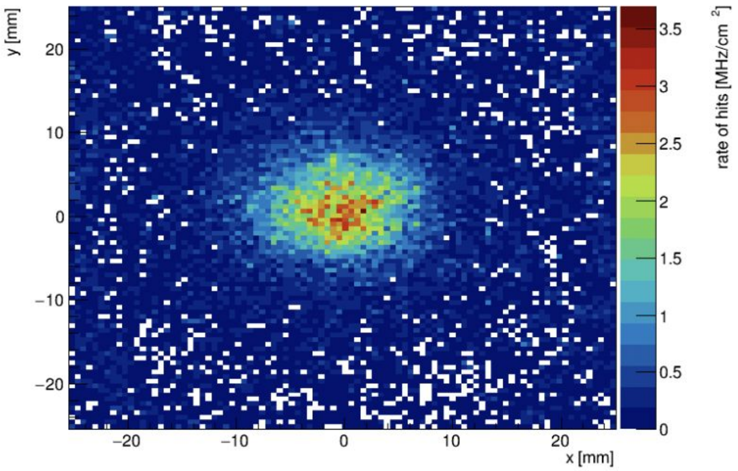
Proton flux

Probability of interaction pW

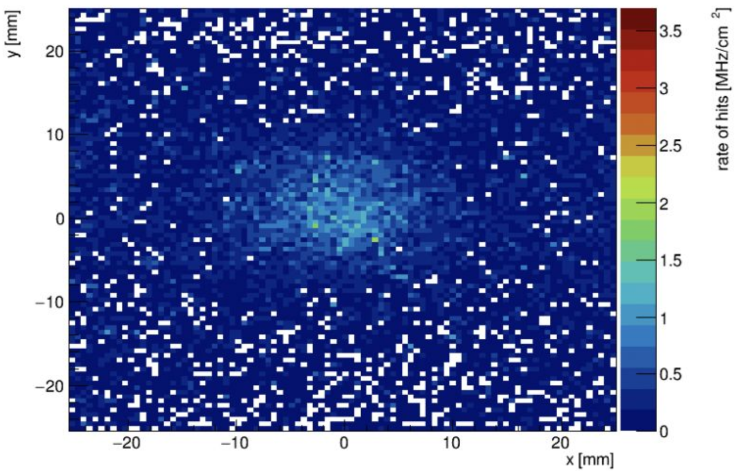
$$\Phi = 10^6 \mathbf{p/s} \left(1 - e^{-\frac{x_W}{\lambda_{I,W}}}\right)$$

x_W = target length, $\lambda_{I,W}$ = nuclear interaction length

Tracker **before** magnet



Tracker **after** magnet



Rate of Background events

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Proton flux — Probability of interaction pW

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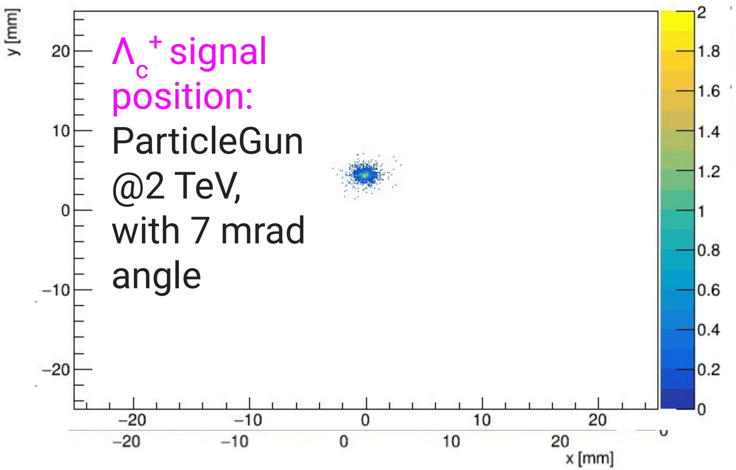
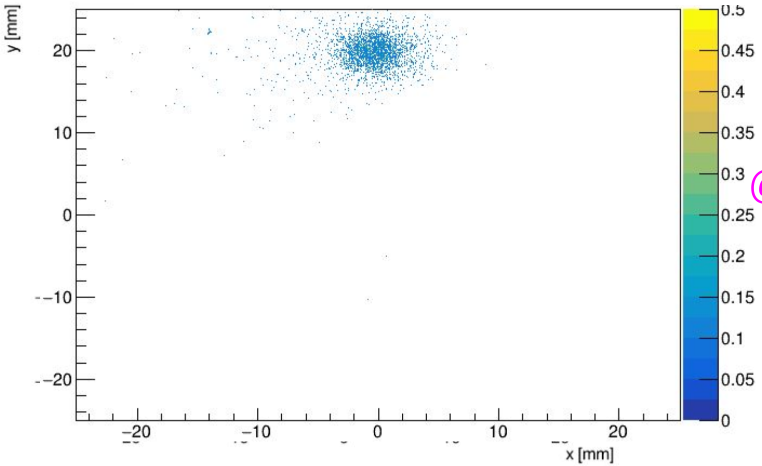


Tracker **after** magnet



@y~20 mm

Conclusions

IR3 proof-of-principle test requested by LHCb to demonstrate low risks of fixed-target experiment

- Double-channeling at IR3
- Channeling efficiency at TeV scale
- Background level and detector performances

Simulations of IR3 setup already in place

- simple geometry layout implemented
  ⇒ preliminary **occupancy studies** show good performances

Next steps

- Channelling is being included in DD4hep
  ⇒ estimate channelling efficiency
- Track reconstruction and digitalization ⇒ see talk by **Jascha Grabowsky**
  ⇒ measure acceptance, background level & invariant mass resolutions

Thank you for the attention!

References

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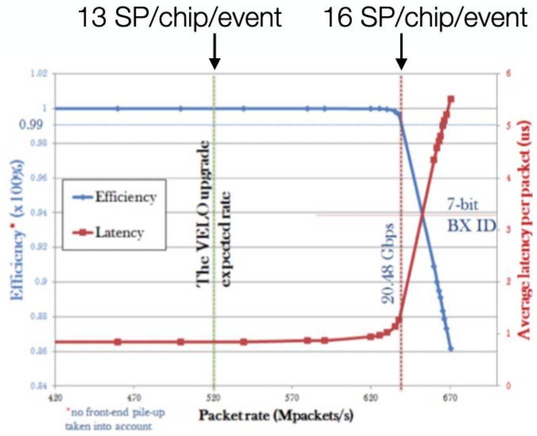
For Leptons:

- J. Fu, M. A. Giorgi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N. Neri, J. Ruiz Vidal, *Novel method for the direct measurement of the τ lepton dipole moments,* Phys. Rev. Lett. 123, 011801 (2019)
- A.S. Fomin , A. Korchin, A. Stocchi, S. Barsuk, P. Robbe, *Feasibility of τ lepton electromagnetic dipole moments measurements using bent crystals at LHC*, J. High Energ. Phys. (2019) 2019: 156.

Backup slides

Simulation with VeloPix @LHCb



Full simulation with target+Cry1 in front of LHCb

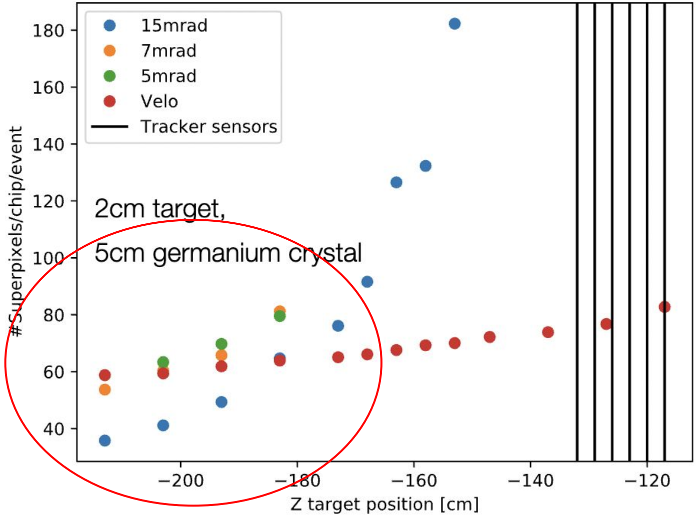
VeloPix: readout organized in superpixels = 4x2 pixels

- Maximum of 640M super pixels/chip/second output rate

Challenging rate for VeloPix:

- ~70 superpixel/chip/s
- higher output rate for 5 mrad than 15 mrad

More superpixels/chip/event are allowed for low collision rate



A bit of history

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- Measurement of charm baryon EDMMs from spin precession in bent crystal **using LHCb detector** as spectrometer

Update in Eur. Phys. J. C 77, 828 (2017)

- Proposal for 2 experimental scenarios: **LHCb vs dedicated experiment**

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