Progress towards the charm baryon dipole moments with bent crystals

F. Martínez Vidal

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Outline

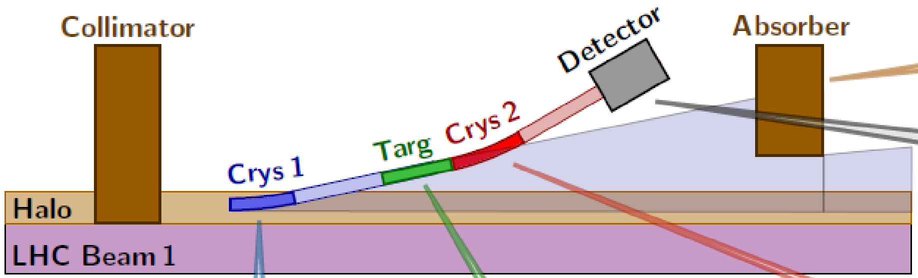
Machine aspects at M. Ferro-Luzzi's talk on Wednesday

- Introduction
- Polariser and target
- LHCb detector studies
- Charm baryon yields
- Long bent crystal prototypes and R&D
- Goniometer
- Performance at optimal crystal parameters
- Outlook

Introduction

Machine aspects at M. Ferro-Luzzi's talk on Wednesday

D. Mirarchi et al, EPJC **80** (2020) 929



Beam halo particles that do not interact with the Target+Crys2 assembly are intercepted by 4 double-sided LHC-type collimators

Spin analyser

In the Detector the final polarisation of Λc is reconstructed from the distribution of decay products

The first Crystal deflects protons from the LHC beam halo onto the Target

Spin movement

Source of polarised charm baryons

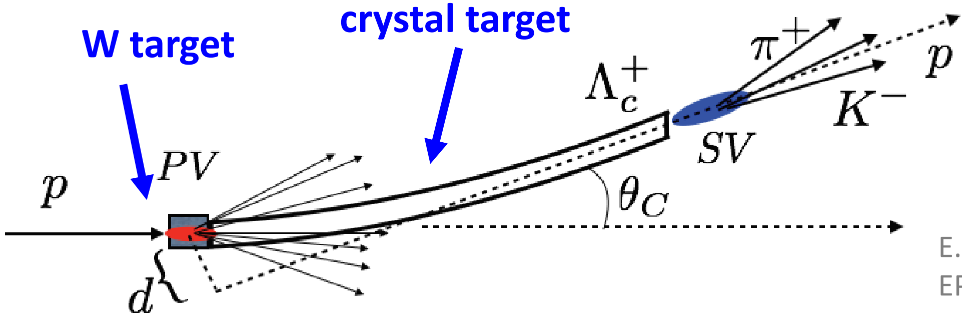
In the Target protons are converted to polarised Λc

The second Crystal deflects Λc with specific initial polarisation.

Λc spin precession in the electric field of crystal planes is proportional to MDM (or EDM)

Si or Ge bent crystal target

W target



Two scenarios:

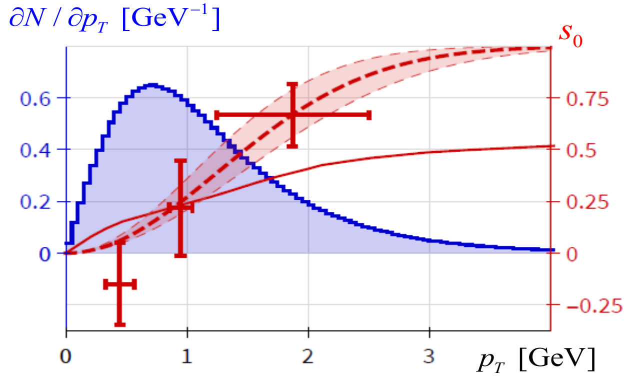
- **IR8 (LHCb), ≈16 mrad bending angle**
- **IR3 (dedicated exp.), 5-7 mrad**

E. Bagli et al, EPJC *77* (2017) 828

Polariser

A. Fomin et al, EPJC **80** (2020) 358

- Parity-conserving production, polarization transverse to the p-Λ_c^+ production plane
- Unknown for p-N at $\sqrt{s} \approx 115$ GeV



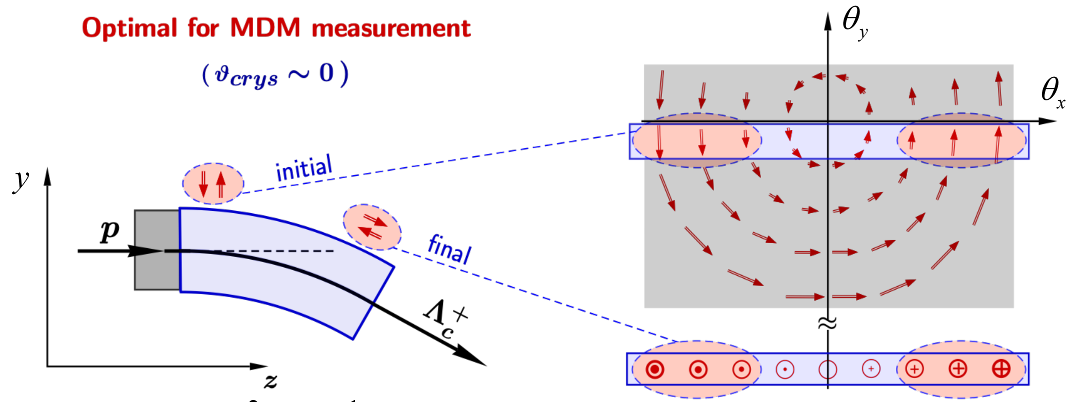
Model from experimental data $s_0(p_T) \approx 0.9\left(1-e^{-0.4 p_T^2}\right)$

E791 data (500 GeV/c π^-) PLB **471** (2000) 449

G.R. Goldstein hep-ph/0001187 (2000)

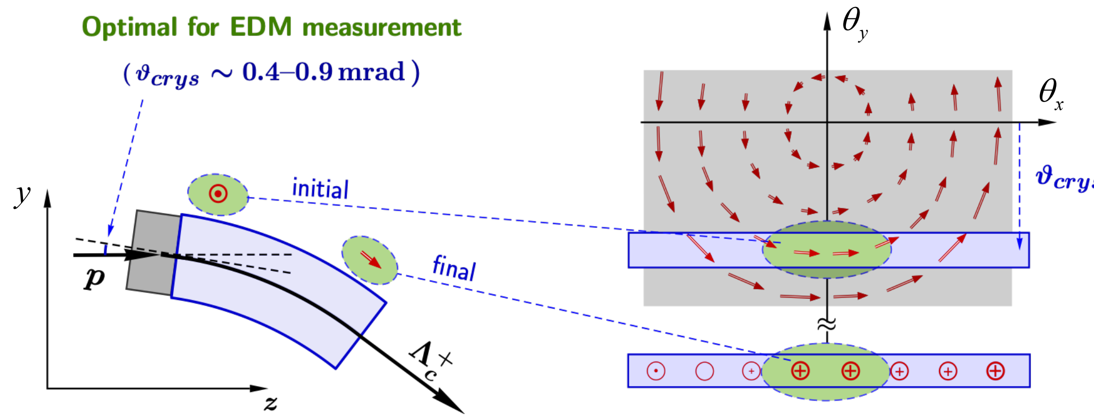
- Large room to measure and improve with SMOG(2) data (in progress)

- Induced initial polarization along the crystal x and y axes



$$\sigma_g \approx \frac{2}{S\langle s_{0y}\rangle\langle\gamma\rangle\theta_C}\frac{1}{\sqrt{N}}$$

S: event information (analyser sensitivity)



$$\sigma_d \approx \frac{g-2}{S}\frac{1}{\sqrt{\langle s_{0y}\rangle^2\eta^2+2\langle s_{0x}\rangle^2\eta}}\frac{1}{\sqrt{N}}$$

$$\eta = 1-\cos\langle\Phi\rangle$$

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

$$\mathbf{s}_0 = (s_{0x}, s_{0y}, s_{0z}) \approx \frac{s_0(p_T)}{p_T}(-p\sin\vartheta_{crys}, p_{xL}, 0)$$

S. Aiola et al, arXiv:2010.11902, accepted by PRD

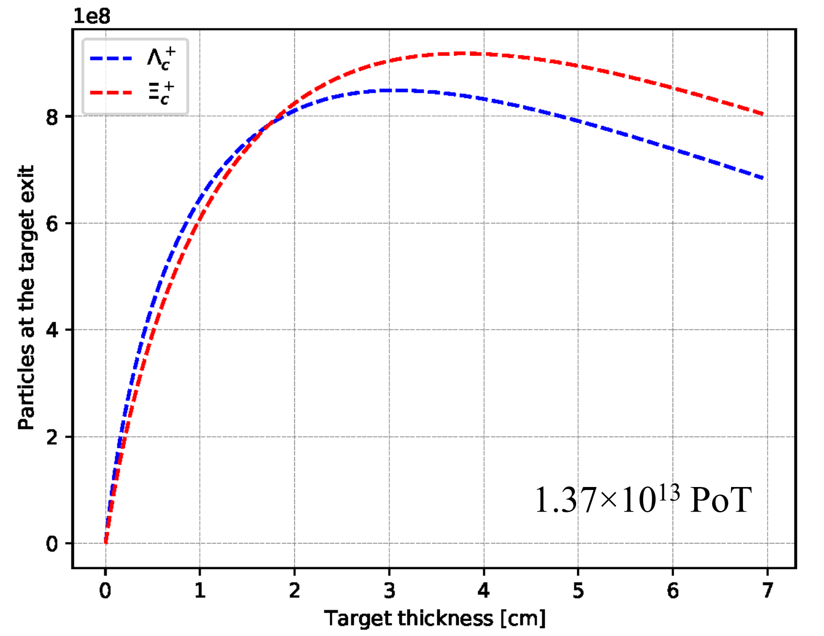
Target

S. Aiola et al, arXiv:2010.11902

- Tungsten, paired to the bent crystal
- Rate of produced baryons at target exit saturates with thickness $T \approx 3$ cm

✓ Accounts for baryon decay and absorption (inelastic interactions) within the target

✓ Absorption reduces ≈20% at $T \approx 2$ cm



@115 GeV

$\lambda_W \approx 8.87$ cm — Nuclear interaction length in W (includes nuclear matter effects, Glauber model)

$\lambda_W^{(\Lambda_c^+)} \approx \lambda_W$ — Λ_c^+ interaction length in W, regulates target absorption

$\lambda_{W,\Lambda_c^+} \approx 81.35$ m — Mean free path for Λ_c^+ production

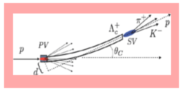
- $T \approx 2$ cm for detector operation & safety reduces DM sensitivities <20% with respect maximal value at $T \approx 4$ cm

LHCb detector studies

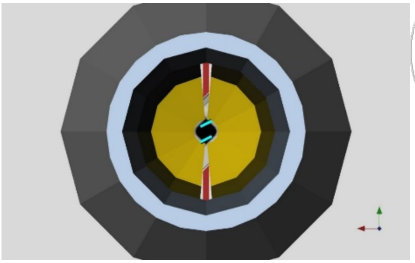
- Single-arm forward spectrometer, optimized for b- and c-hadron physics.
- The only LHC experiment fully instrumented at large η (2<η<5).

FT setup
$z \approx$ -1.2 m

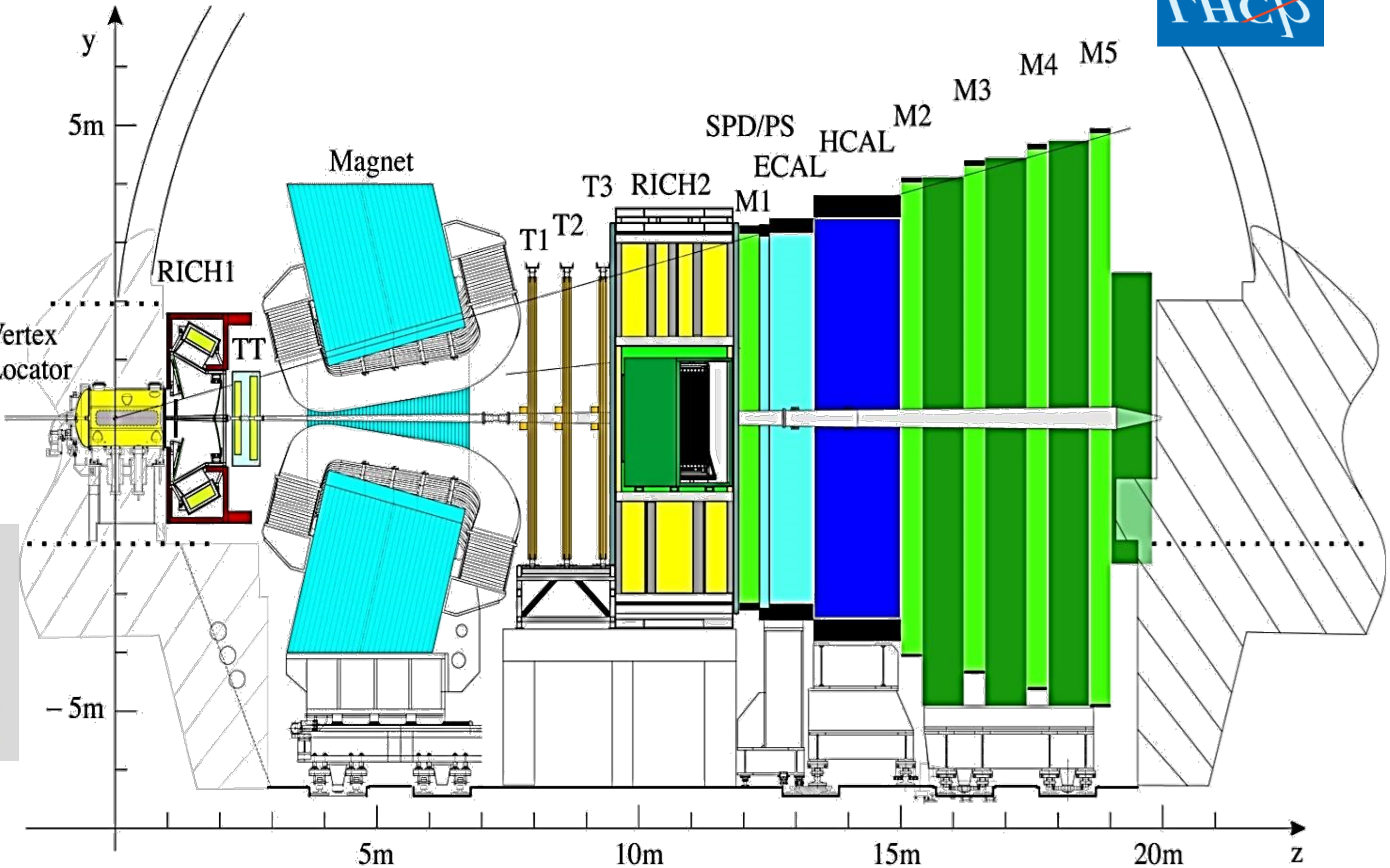
≈16 mrad
≈10 cm



Not to scale



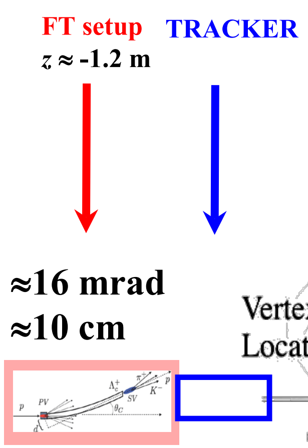
Downstream view of the up- and down-bent crystals
(≈9° rotation)



- Previous studies have shown compatibility with the FT setup (including new valve)

LHCb detector studies

- Further feasibility studies and potential benefit of a dedicated tracker between the target+crystal and VELO



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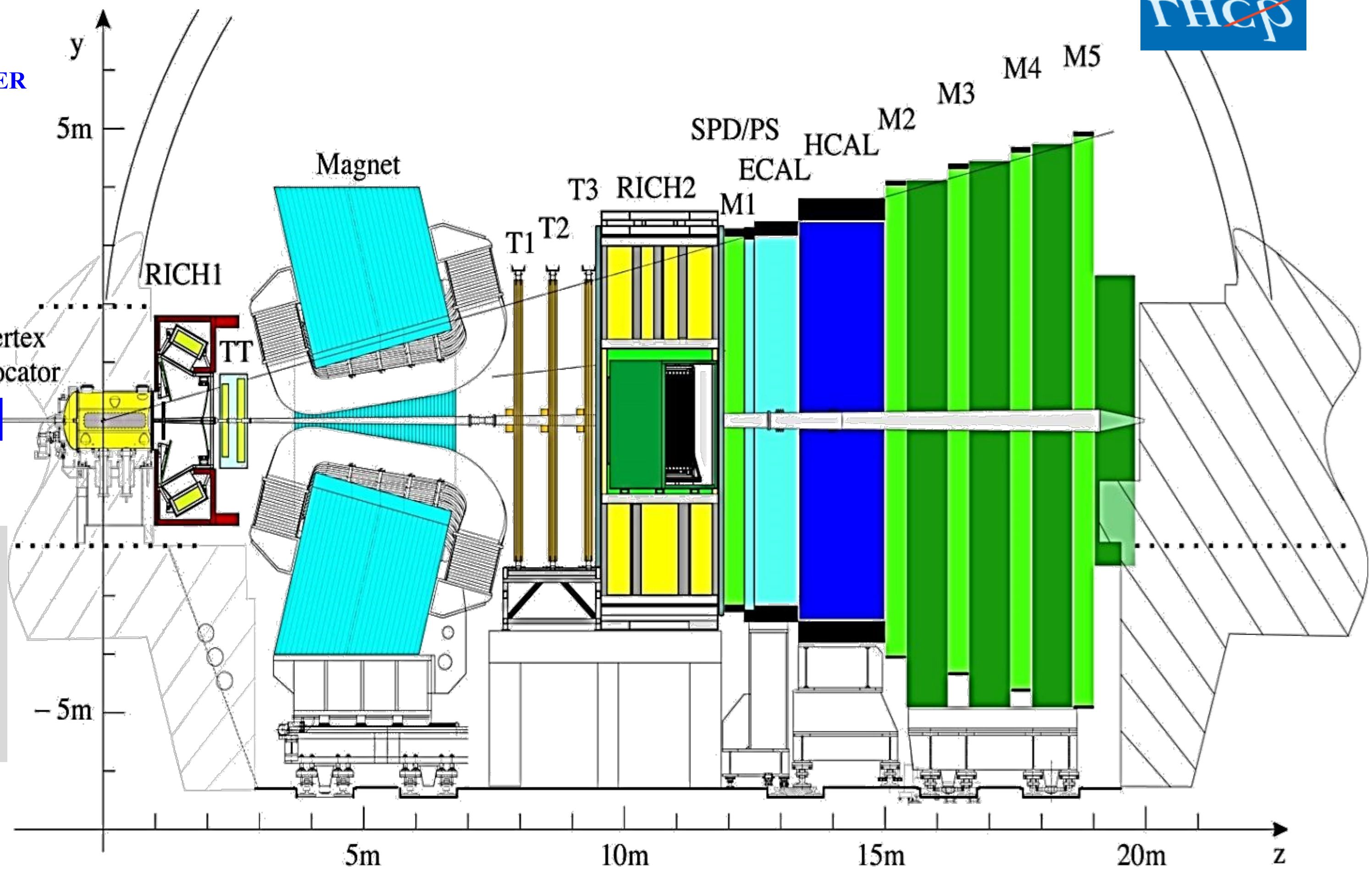
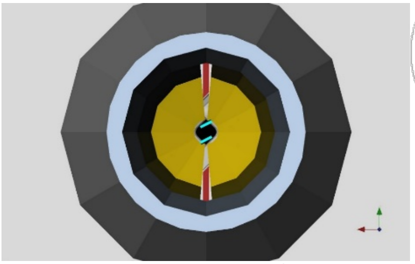


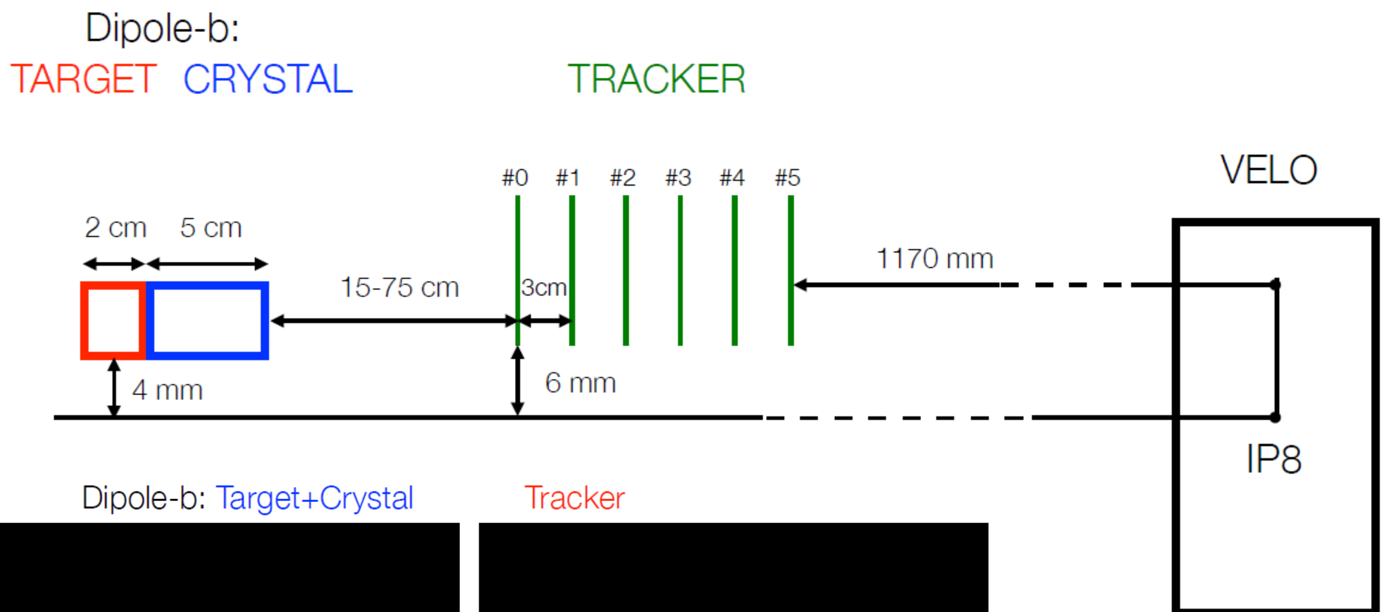


Downstream view of the up- and down-bent crystals (≈9° rotation)

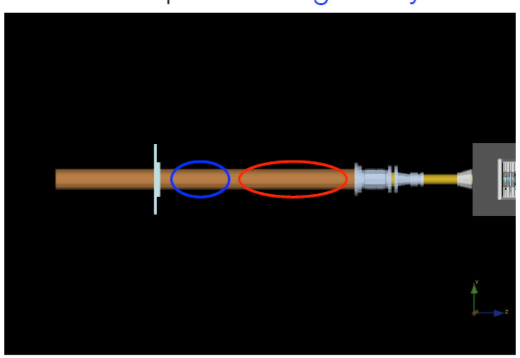
Implemented geometry

A. Merli at 20th PBC FT meeting, 20th November, 2020
https://indico.cern.ch/event/975835/

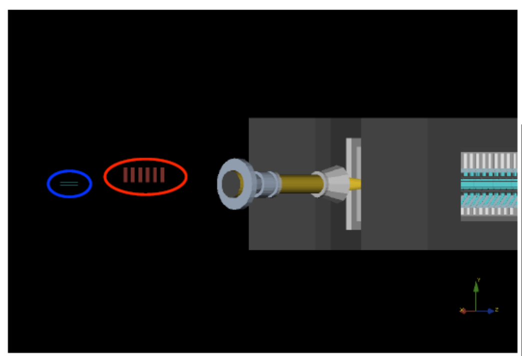
- Simulated tracker chip is VeloPix (LHCb upgrade, state-of-the art pixels)
- Studied different positions of the target, with a crystal-tracker sensor distance ranging from 15 cm to 75 cm, and bending angles between 15 and 5 mrad, for 1-2 TeV Λ_c^+

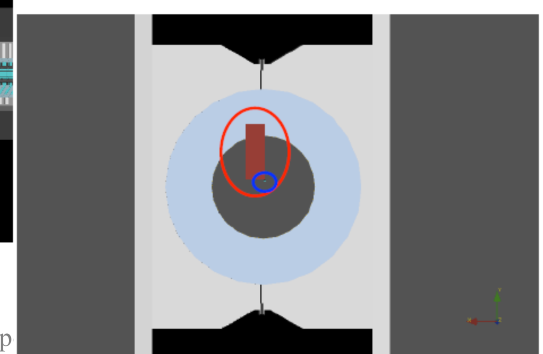


Dipole-b: Target+Crystal



Tracker





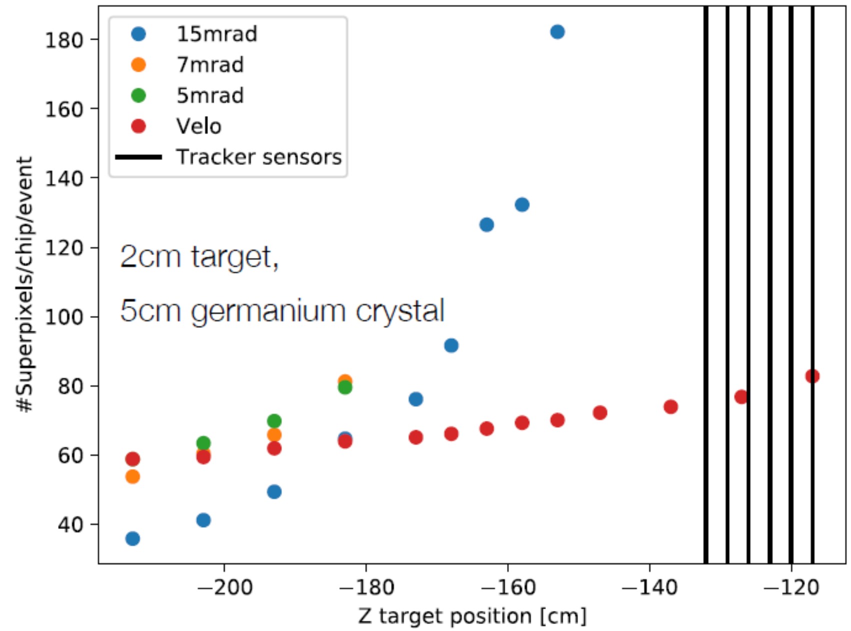
Implemented geometry: main results

- Possible (challenging) readout of FT ("busy", high occupancy) events, as they occur at low rate (≈1% @ 10^6 p/s with respect to colliding pp events)

- Increase of output & ghost track rates, and decrease of efficiencies with
  - ✓ lowering of crystal bending angle
  - ✓ reduction of target-tracker distance

- ≈40% degradation of *z* vertex resolution by lowering angle, and improvement in *xy* (geometrical)

VeloPix #superpixels (4x2 pixels)/chip/event
Max. #superpixels/chip/event in pp collisions <15



VeloPix ASICs (LHCb upgrade)

- VELO is positioned at ≈optimal distance from the target, ≈90 cm

⇒ Very difficult to improve LHCb detector performance

⇒ Applies also for a dedicated experiment at IR3

Charm baryon yields

S. Aiola et al, arXiv:2010.11902

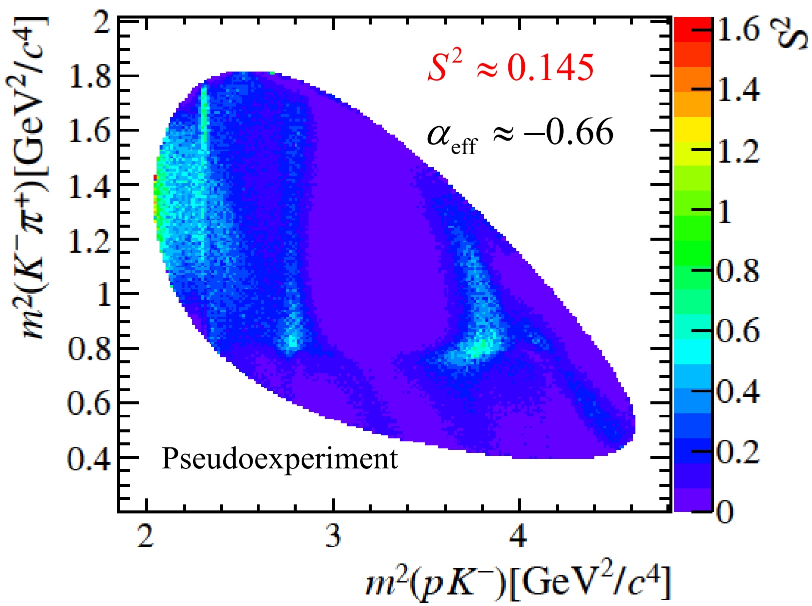
- Preliminary full amplitude analysis of $\Lambda_c^+ \to pK^-\pi^+$ (BF≈6%) provides ≈ the same analyser sensitivity S as benchmark $\Delta^{++}K^-$ (≈1%) ⇒ ≈ factor 6 more events

$$\sigma_{pol} \approx \frac{1}{S\sqrt{N}} \qquad S = \frac{\alpha_{eff}}{\sqrt{3}}$$

→ Effective (phase-space averaged) parity-violating Λ_c^+ decay parameter

E791, PLB **471** (2000) 449

D. Marangotto PhD Thesis, https://cds.cern.ch/record/2713231



- ≈ factor 3 from additional modes containing:
  - ✓ Long-lived hyperons $\Sigma^\pm$, Ξ^-, most of which can be reconstructed as usual tracks
  - ✓ A missing neutral pion (unreconstructed)

- Ξ_c^+ baryon with similar yields to Λ_c^+:
  - ✓ Lower production rate (≈70%), smaller BF
  - ✓ But lifetime twice larger

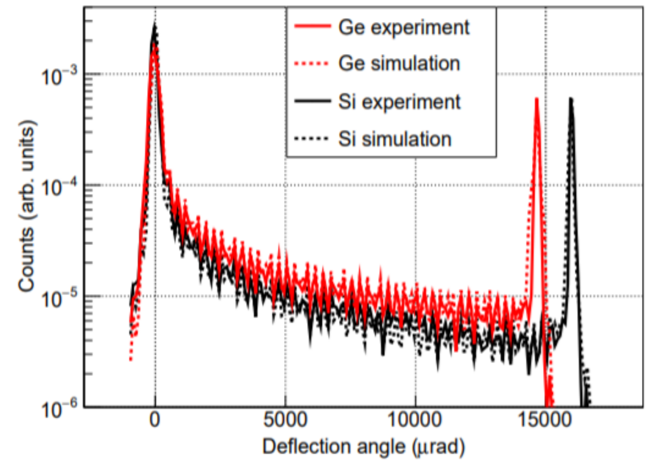
Long bent crystal prototypes

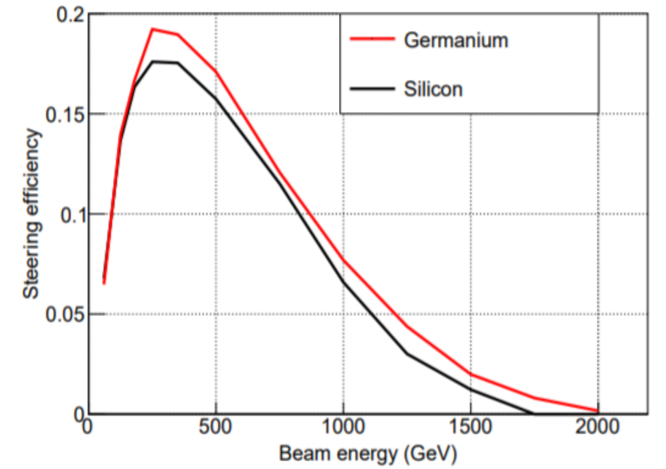
- Si and Ge long bent crystals were produced and tested on SPS beam (H8, Oct'18) to characterize steering efficiency and precise bending angle
- At 180 GeV ≈10% channeling efficiency

	Silicon	Germanium
Crystal length (mm)	80	55
Crystal thickness (mm)	5	1
Channeling plane	(111)	(110)
Bending angle (mrad)		
Particle beam	15.988±0.005	14.670±0.002
X-ray	16.1±0.8	14.5±0.8
Channeling efficiency (experimental, %)*	8.9±0.5	10.8±0.5
Channeling efficiency (simulation, %)*	9.9±0.5	12.3±0.5

*efficiency for particles reaching the crystal at a nominal angle of ± 30 μrad, including beam divergence and tracker resolution, with CRYSTALRAD simulation.

Some discrepancy among groups with details of the performance estimation.



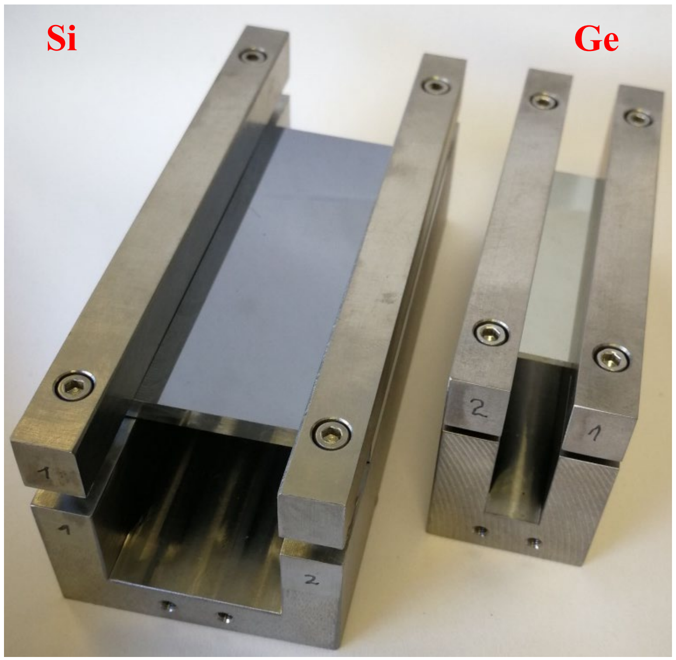


S. Aiola et al, arXiv:2010.11902

R&D on crystals

- First prototypes are based on a mechanical bender

- A second generation based on bonding of a crystal on a prefigured substrate with a cylindrical surface of radius 5 m is under development



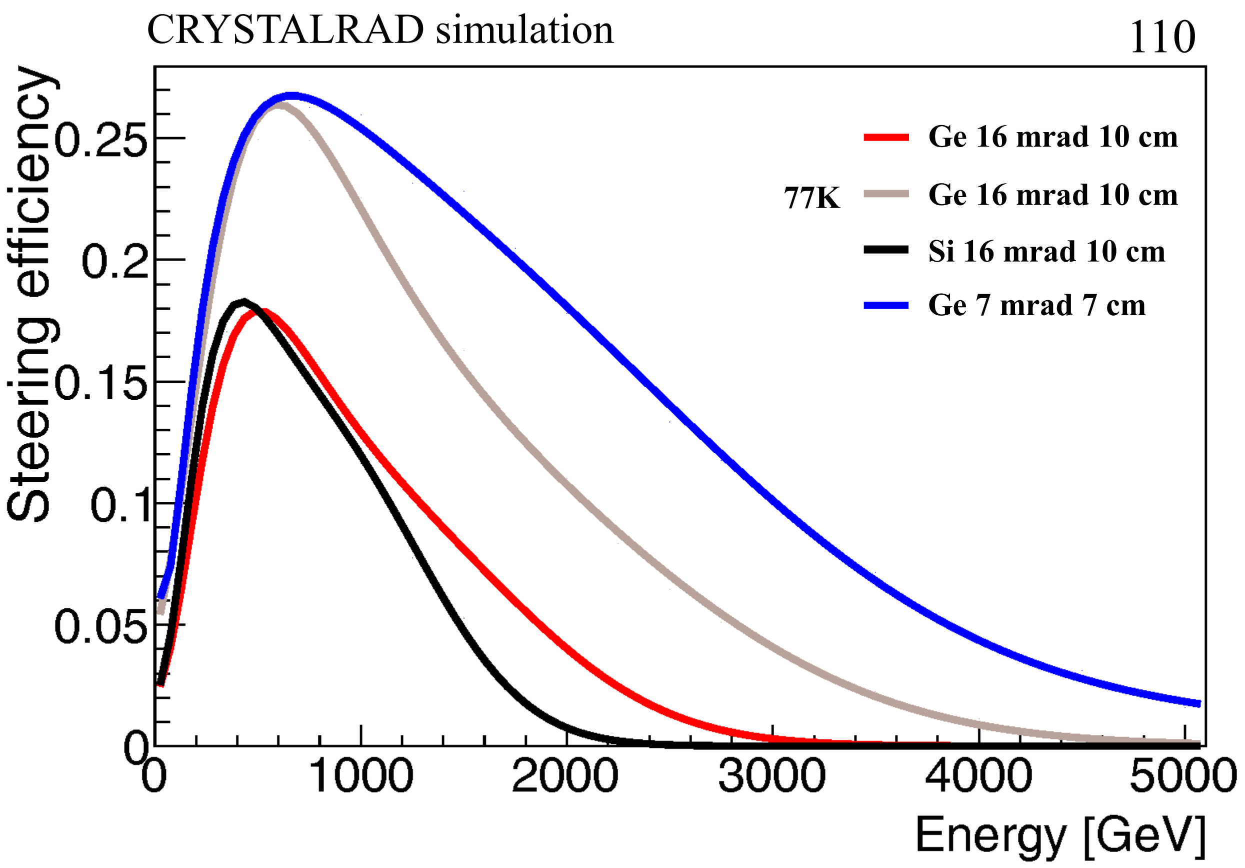
1 mm (≈20 × σ_x, σ_y beam) thick bent **Si** crystal

Prefigured substrate (glass)

- Manufacturing of a crystal compatible with cryo-cooling (~77K) and other requirements also under investigation

Steering efficiency

- Channeling efficiency for stable particles impinging with angle uniformly distributed within ± the acceptance (Lindhard) angle

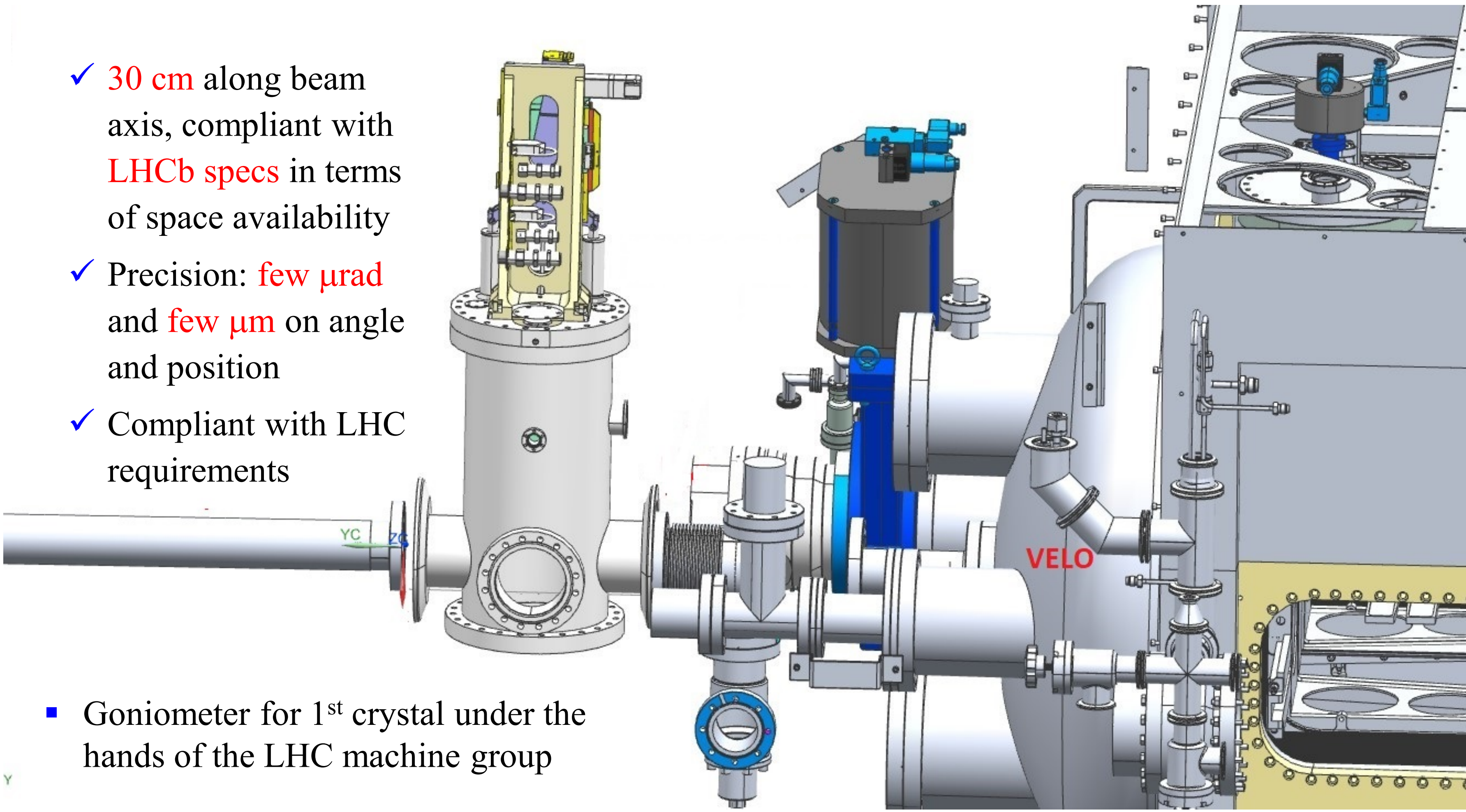


Similar curves for other configurations

✓ Germanium @77K promising in terms of overall efficiency (acceptance+steering) at higher momentum, and sensitivity

Goniometer

- Working with CINEL company on a goniometer design developed at CERN
- Preliminary compact new design to house the long bent crystal and holder:



✓ 30 cm along beam axis, compliant with LHCb specs in terms of space availability

✓ Precision: few μrad and few μm on angle and position

✓ Compliant with LHC requirements

- Goniometer for 1st crystal under the hands of the LHC machine group

Performance at optimal crystal parameters

- Comparison of key parameters to assess performance for different crystal configurations

PRELIMINARY

		Si				Ge		Ge @ 77K	
Crystal	Deflection angle, mrad	14	16	7	5	16	7	16	7
	Length, mm	75	100	70	70	100	70	100	70
Λ_c^+	Average boost factor	610 459	720 539	960 685	1150 815	960 666	1190 821	1060 794	1270 900
	Average polarization	0.26 0.23	0.25 0.23	0.24 0.21	0.23 0.21	0.24 0.21	0.23 0.20	0.24 0.21	0.23 0.20
	Deflected per 10^{10} PoT	7 3	5 1.6	70 24	160 39	28 4.5	220 43	64 12.4	370 75
	Relative MDM precision (analytical estimates)	1.13 0.94	1 1	0.49 0.50	0.39 0.48	0.35 0.52	0.23 0.32	0.21 0.27	0.17 0.23

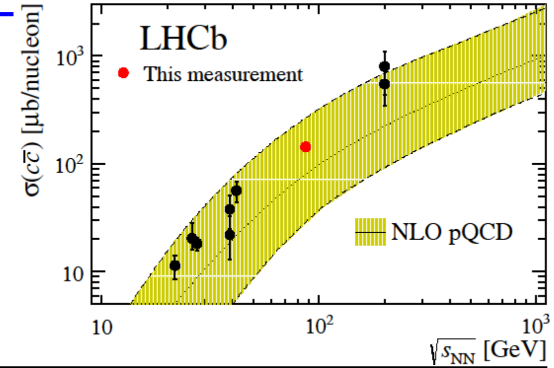
A. Fomin et al, EPJC **80** (2020) 358

S. Aiola et al, arXiv:2010.11902

- Large gain in deflected Λ_c^+ yields and boost from Si → Ge → Ge @ 77K
- Gain in sensitivity at 7 mrad (IR3) wrt 16 mrad (LHCb) with Ge/Ge@77K and same PoT ≈ factor 1.5/1.2
- Differences in yields up to ≈ factor 4 (6) for Si (Ge), and momentum ≈30-40% ⇒ discrepancy in absolute sensitivities

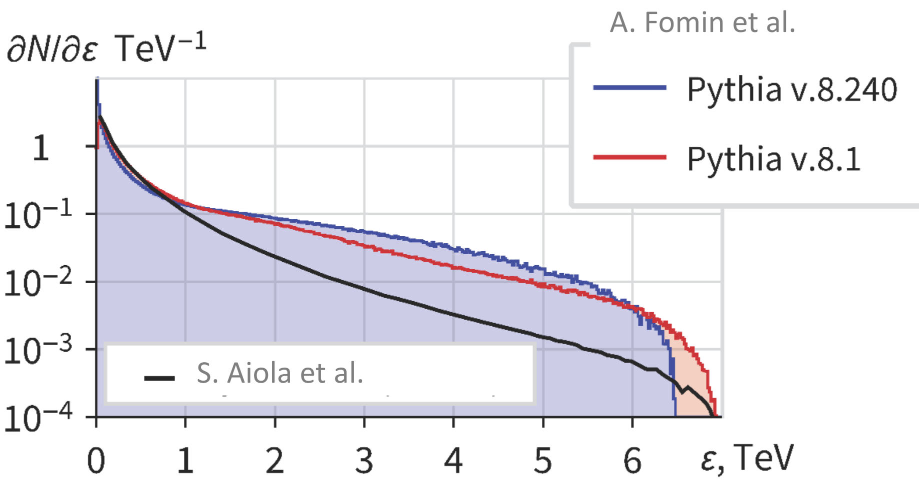
pp cross-section

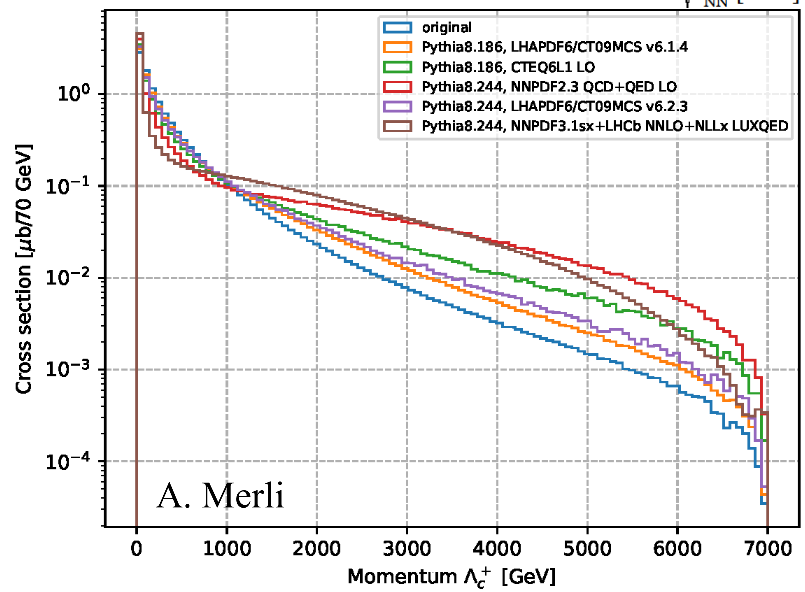
PRL **122** (2019) 132002



- pp → Λ_c^+ cross-section @ 115 GeV from LHCb p-Ne (SMOG) data @ 86.6 GeV (scaled linearly): 10.6 μb
- Λ_c^+ differential cross-section from Pythia

PRELIMINARY





✓ Large differences in hard part of the spectrum, explains previous discrepancies

✓ Large uncertainties of PDFs at very small-x, LO vs NLO vs NNL approximations, besides production (matrix elements) and fragmentation

✓ Ongoing discussion with theorists

⇒ unique experimental setup for studies of charm production in the very forward region

Outlook

- Progress during last year in the different aspects of the proposal (target, 2nd crystal, goniometer, detector, analysis)

  And machine, see M. Ferro-Luzzi's talk

- With ≈1.37×10^{13} PoT (≈2 years @ 10^{6} p/s) can perform unique measurements:
  - ✓ Λ_c^+ and Ξ_c^+ dipole moments
  - ✓ D^+, D_s^+, Λ_c^+, Ξ_c^+ production and differential cross-sections in the very forward region
  - ✓ Charm baryon polarization

- This program looks feasible from the point of view of detector performance and machine layout at LHCb during Run 3, and would be coherent/complementary with SMOG2
  - ✓ Outstanding issue of absorbers downstream LHCb

- These results and experience could set the basis for a dedicated experiment at LHC with higher PoT (~ factor 100)
  - ✓ Form an international collaboration
  - ✓ *O*(10Meuro) to construct a new detector with cutting edge technology pixel tracker, PID system, dipole magnet (~4 Tm), calorimeter, etc.
  - ✓ More ambitious physics program, including charm, beauty and τ MDM/EDMs

A. Fomin et al, JHEP **03** (2019) 156
J. Fu et al, PRL **123** (2019) 011801

Backup

Average event information S

- For a multibody decay (like $\Lambda_c^+ \to pK^-\pi^+$), the helicity formalism shows that the decay rate can be written generally as

$$\Gamma(\xi \mid s) = f(\xi) + s g(\xi)$$

s polarization along a given axis

f, g functions of the phase-space variables ξ (5)

- The average event information gives the sensitivity to the polarization measurement s_0 along the given axis:

PLB **306** (1993) 411

$$S^2 = \int \frac{g^2(\xi)}{f(\xi) + s_0 g(\xi)} d\xi \qquad \sigma_{s_0} = \frac{1}{S\sqrt{N}}$$

- For the case of a (quasi)two-body decay with completely known kinematics, $S^2 = \alpha^2_{eff}/3$, where α_{eff} is the effective parity-violating asymmetry parameter
- For $\Lambda_c^+ \to \Delta^{++}K^-$, used so far to asses sensitivities,

$$\alpha_{eff} = -0.67 \pm 0.30 \Rightarrow S^2 \approx 0.15 \text{ (with large uncertainty)}$$

Many more Λ_c^+ & Ξ_c^+ decay modes

S. Aiola et al, arXiv:2010.11902

- Many additional decay modes if we consider final states containing:
  - ✓ Long-lived hyperons, i.e. $\Sigma^\pm$, Ξ^-, most of which can be reconstructed as usual tracks given the large boost (requires ≈9.4 m track length)
  - ✓ A neutral pion

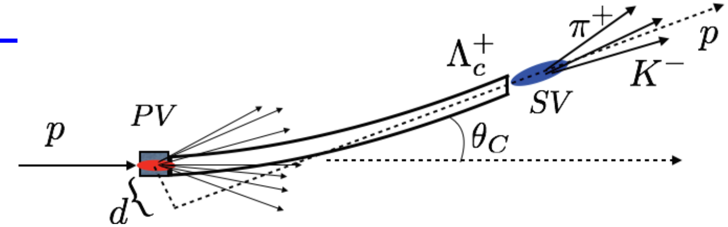
Λ_c^+ final state	$\mathcal{B}$ (%)	ϵ_{3trk}	$\mathcal{B}_{eff}$ (%)
$pK^-\pi^+$	6.28 ± 0.32	0.99	6.24
$\Sigma^+\pi^-\pi^+$	4.50 ± 0.25	0.51	2.28
$\Sigma^-\pi^+\pi^+$	1.87 ± 0.18	0.68	1.28
$p\pi^-\pi^+$	0.461 ± 0.028	1.00	0.46
$\Xi^-K^+\pi^+$	0.62 ± 0.06	0.70	0.44
$\Sigma^+K^-K^+$	0.35 ± 0.04	0.49	0.17
pK^-K^+	0.106 ± 0.006	0.99	0.11
$\Sigma^+\pi^-K^+$	0.21 ± 0.06	0.48	0.10
$pK^-\pi^+\pi^0$	4.46 ± 0.30	0.99	4.43
$\Sigma^+\pi^-\pi^+\pi^0$	3.20	0.50	1.60
$\Sigma^-\pi^+\pi^+\pi^0$	2.1 ± 0.4	0.61	1.45
$\Sigma^+[p\pi^0]\pi^-\pi^+$	2.32	0.50	1.15
$\Sigma^+[p\pi^0]K^-K^+$	0.18	0.53	0.09
$\Sigma^+[p\pi^0]\pi^-K^+$	0.11	0.46	0.05
All	-	-	19.85

Ξ_c^+ final state	$\mathcal{RB}$	$\mathcal{B}$ (%)	ϵ_{3trk}	$\mathcal{B}_{eff}$ (%)
$\Xi^-\pi^+\pi^+$	1	2.86 ± 1.27	0.60	1.71
$\Sigma^+K^-\pi^+$	0.94 ± 0.10	-	0.38	1.02
$\Sigma^+\pi^-\pi^+$	0.48 ± 0.20	-	0.39	0.54
$pK^-\pi^+$	0.21 ± 0.04	-	0.99	0.60
$\Sigma^-\pi^+\pi^+$	0.18 ± 0.09	-	0.58	0.30
$\Sigma^+K^-K^+$	0.15 ± 0.06	-	0.37	0.16
$\Omega^-K^+\pi^+$	0.07 ± 0.04	-	0.37	0.08
$\Sigma^+[p\pi^0]K^-\pi^+$	0.48	-	0.62	0.86
$\Sigma^+[p\pi^0]\pi^-\pi^+$	0.25	-	0.61	0.44
$\Sigma^+[p\pi^0]K^-K^+$	0.08	-	0.63	0.14
All	-	-	-	5.83

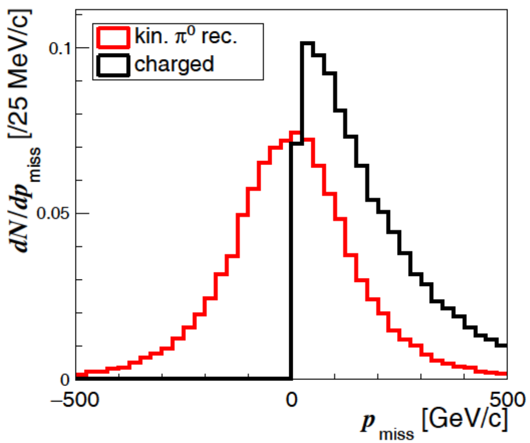
- ➢ Additional ×3 increase of statistics wrt to $\Lambda_c^+ \to pK^-\pi^+$

- ➢ Lower production rate wrt Λ_c^+, ≈70%
- ➢ Smaller effective branching fraction
- ➢ Lifetime twice larger
- ➢ Similar rates wrt Λ_c^+

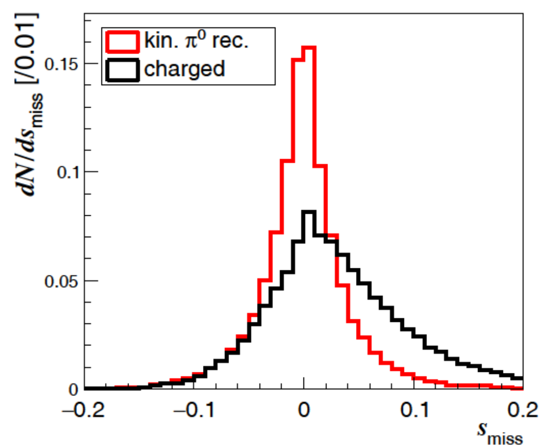
Modes with a π^0



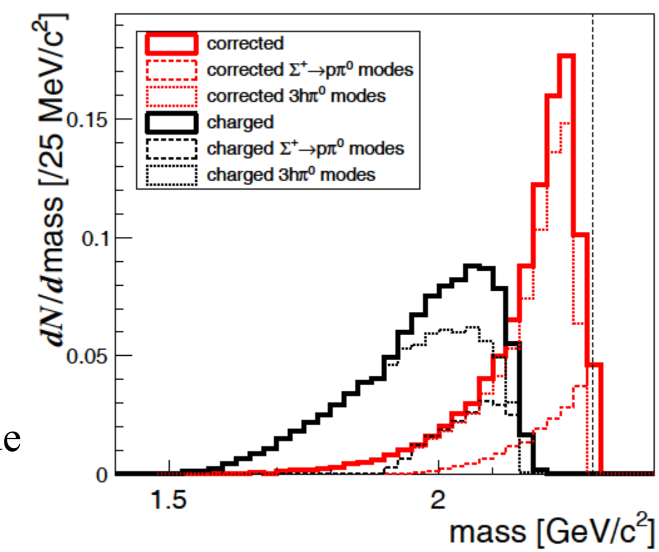
- Decay modes with a π^0 can be partially reco'd using only charged tracks, as the Λ_c^+ momentum can be determined up to a two-fold ambiguity using charged track momentum and Λ_c^+ flight direction



Missing momentum (difference to true momentum)



Missing polarization magnitude



Can use standard corrected mass to characterize the candidates

S. Aiola et al, arXiv:2010.11902

Crystals R&D: cryo-compatible crystals

INFN-Ferrara

- Channeling experiments with cryo-cooled crystal (100 K) were performed at CERN 36 years ago

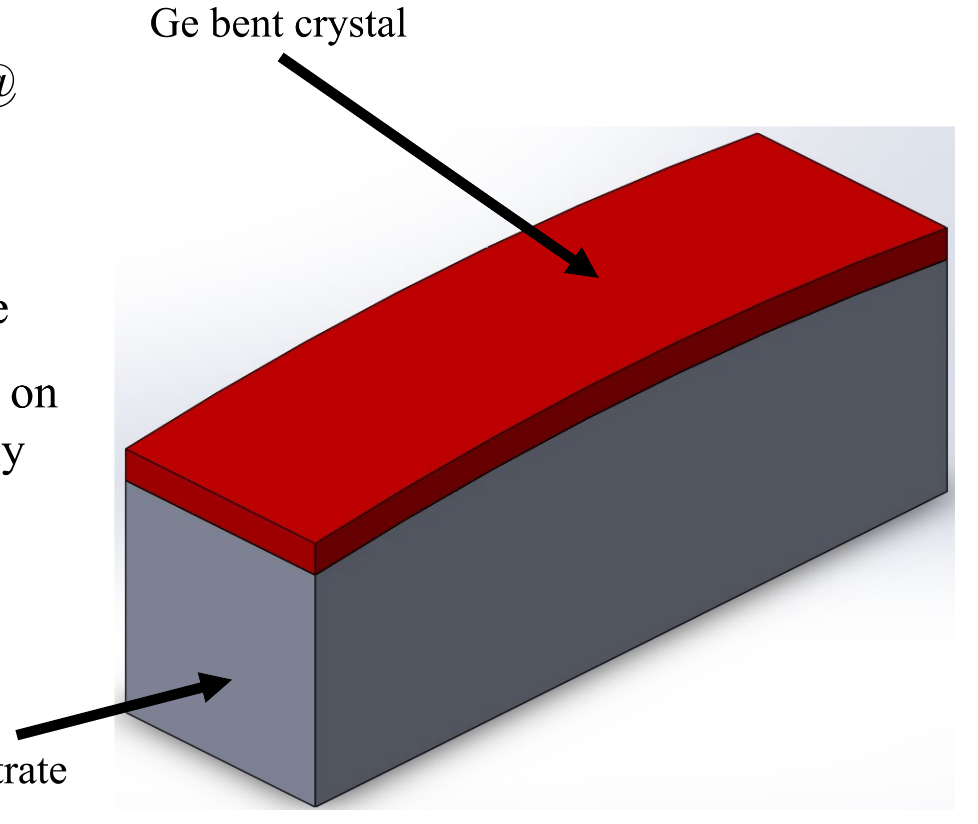
  A. Belkacem at al, PL B**177** (1986) 211

- Particle steering through a cryo-cooled crystal already accomplished (128 K) @ Fermilab more than 30 years ago

  Forster at al, NP B**318** (1989) 301

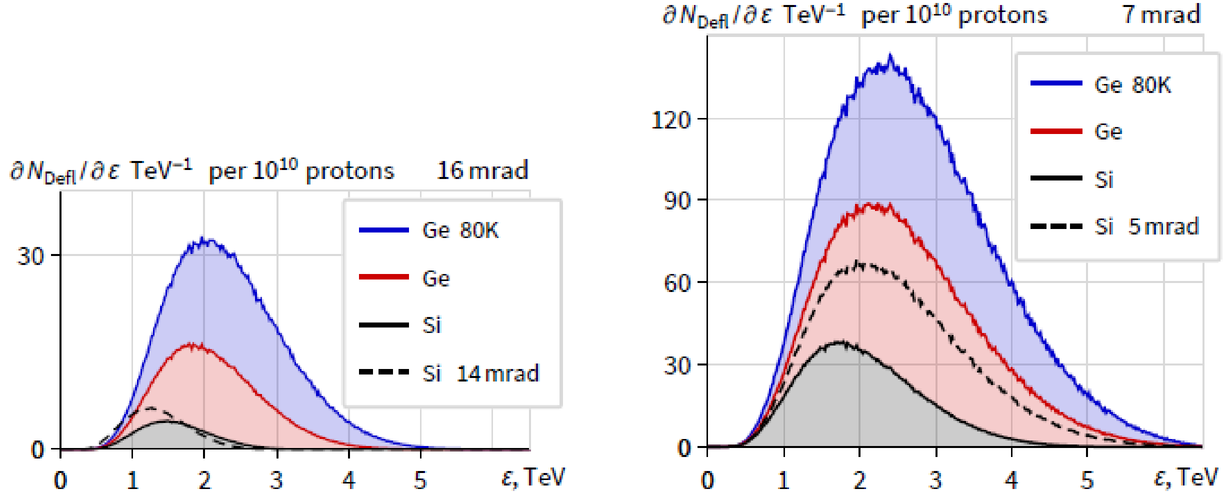
- Cry-cooling is not simple but is feasible
- Cryo-cooling of bent crystals (mounted on high resolution goniometers) is routinely performed at worldwide synctrotrons
- Manufacturing of a crystal compatible with cooling and other requirements is under investigation

To avoid thermal stress the plan is to bond a Ge crystal to a prefigured substrate of the same thermal expansion coefficient as the crystal

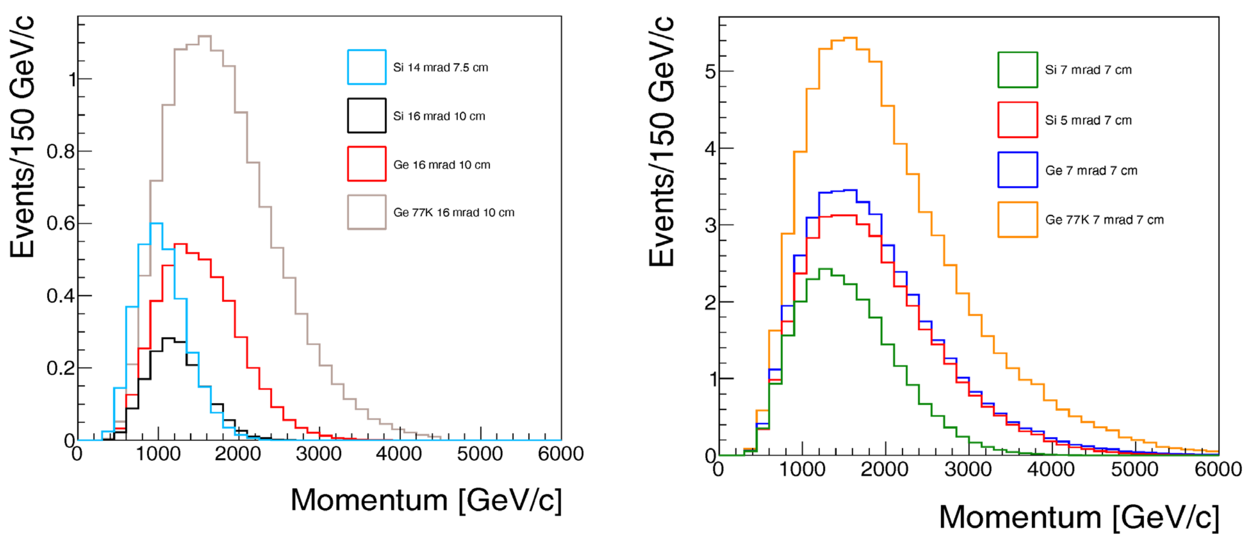


Performance at optimal crystal parameters

- Spectra of channeled Λ_c^+ ($\times 10^{10}$ PoT)



A. Fomin et al, EPJC **80** (2020) 358



S. Aiola et al, arXiv:2010.11902