Progress towards the charm baryon dipole moments with bent crystals

Andrea Merli, Università degli Studi di Milano & INFN Milano

Join Workshop GDR-QCD/QCD@short distances and STRONG 2020/PARTONS/FTE@LHC/NLOAccess

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G. Arduini[2], L. Bandiera[3], S. Bursuk[4], O.A. Bezshyyko[5], L. Burmistrov[4], G. Calderini[6], G. Cavoto[7], F. De Benedetti[1], S.P. Fomin[8,9], A.S. Fomin[2], J. Fu[1,10], M.A. Giorgi[11], V. Guidi[3,12], L. Henry[1,13], Yu. Ivanov[14], I.V. Kirillin[8,9], A. Yu. Korchin[8,9], V.A. Kovalchuk[8,9], E. Kou[4], M. Liul[4,9], D. Marangotto[1,10], F. Martinez Vidal[13], V. Mascagna[15,16], L. Massacrier[17], J. Mazorra de Cos[13], A. Mazzolari[3], A. Merli[1,10], D. Mirarchi[2], A. Natochii[4,5], N. Neri[1,10], E. Niel[4], M. Prest[15,16], S. Radaelli[2], P. Robbe[4], M. Romagnoni[3,12], L. Rossi[2,10], J. Ruiz Vidal[13], W. Scandale[2,4,7], N.F. Shul'ga[8,9], M. Soldani[15,16], A. Sytov[3], V. Tikhomirov[18], E. Vallazza[15]

[1]INFN Milano, [2]CERN, [3]INFN Ferrara, [4]LAL, [5]KNU, [6]LPNHE, [7]INFN Roma & U. La Sapienza, [8]KIPT, [9]KhNU, [10]U. Milano, [11]INFN Pisa & U. Pisa, [12]U. Ferrara, [13]IFIC-Valencia, [14]PNPI, [15]INFN Bicocca, [16]U. Insubria, [17]IPN, [18]INP & U. Belarusian State

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Electromagnetic dipole moments

δ = electric dipole moment (EDM) μ = magnetic dipole moment (MDM)

- Classic systems

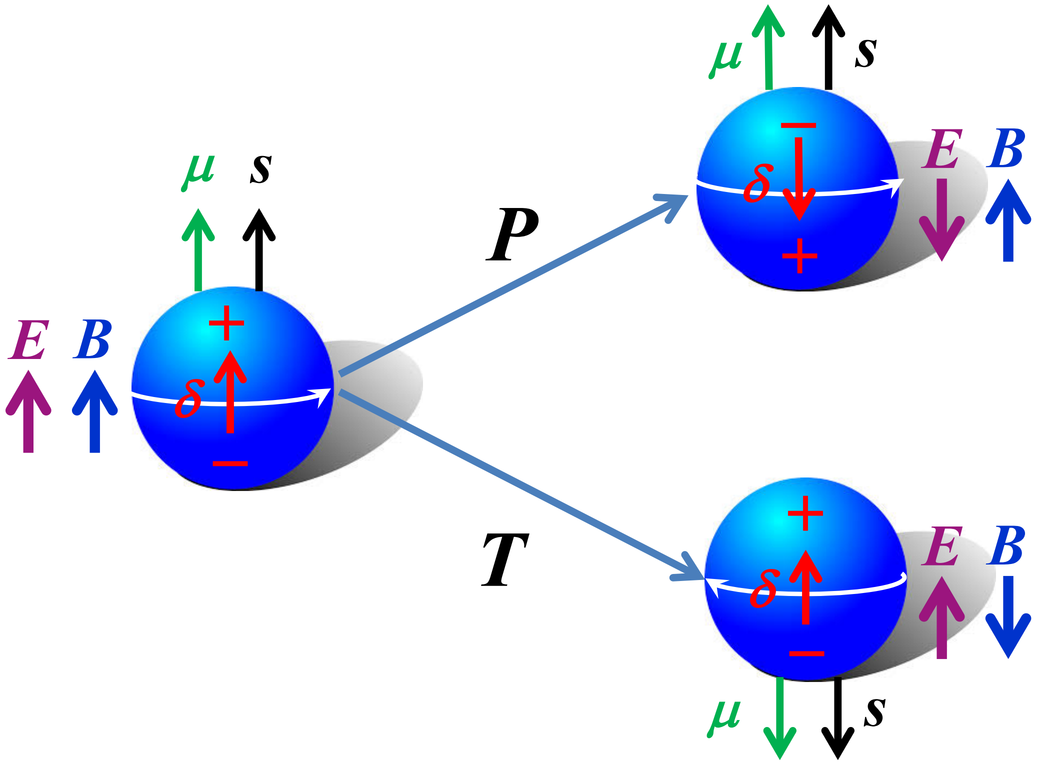
$$\boldsymbol{\delta} = \int \boldsymbol{r}\rho(\boldsymbol{r})d^3r \qquad \boldsymbol{\mu} = \int \boldsymbol{r}\times\boldsymbol{j}(\boldsymbol{r})d^3r$$

- Quantum systems

$$\boldsymbol{\delta} = d\mu_N\frac{\boldsymbol{S}}{2} \qquad \boldsymbol{\mu} = g\mu_N\frac{\boldsymbol{S}}{2}$$

- Hamiltonian

$$H = -\boldsymbol{\delta}\cdot\boldsymbol{E} - \boldsymbol{\mu}\cdot\boldsymbol{B}$$



Time reversal, Parity:

$$\xrightarrow{\text{T}} \; +\boldsymbol{\delta}\cdot\boldsymbol{E} - \boldsymbol{\mu}\cdot\boldsymbol{B}$$

$$\xrightarrow{\text{P}} \; +\boldsymbol{\delta}\cdot\boldsymbol{E} - \boldsymbol{\mu}\cdot\boldsymbol{B}$$

The EDM violates T and P and via CPT theorem, violates CP

EDM as a possible solution for baryogenesis

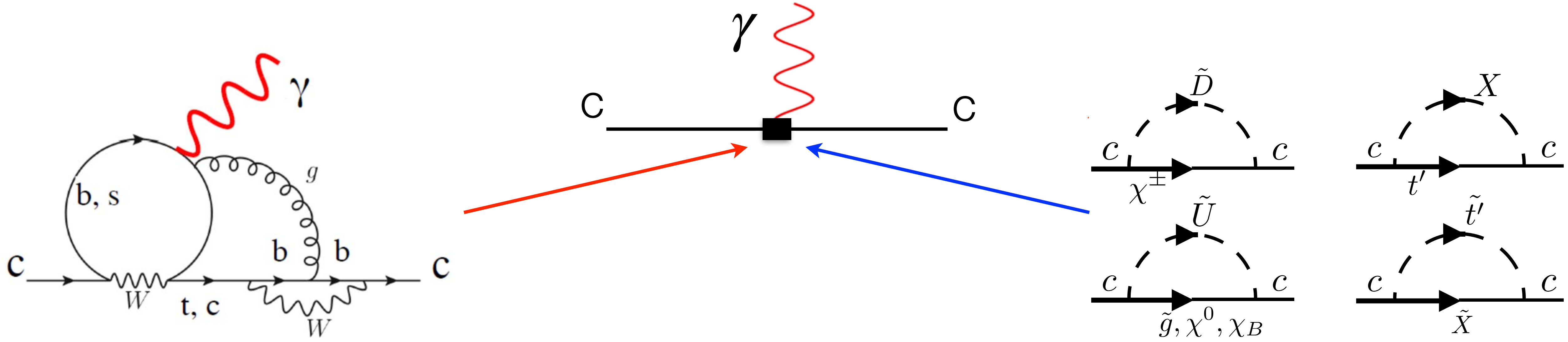
- EDM of fundamental particles from the structure of quarks and gluons, and processes with photon and flavour-diagonal coupling
- A measurement of a heavy baryon EDM is directly sensitive to:

qEDM

$$-\frac{i}{2}\delta_q\bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu}$$

qCEDM

$$i\tilde{\delta}_q\bar{q}\sigma^{\mu\nu}\gamma_5 t_a q G^a_{\mu\nu}$$



Charm EDM in Standard Model ~10^{-32} ecm

Charm EDM in new physics ~10^{-17} ecm

EPJC 77 (2017), 102

EDM observation = clear sign of **new physics**

Physics motivation for MDM

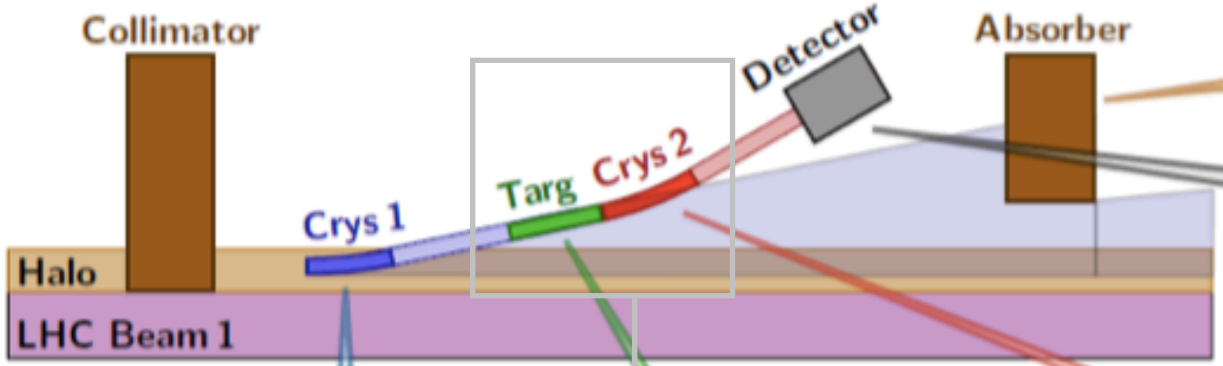
- Experimental anchor points for tests of low-energy QCD models, related to non-perturbative QCD dynamics

- Test of baryon substructure

- Measurement of MDM of particles and antiparticles would allow a test of CPT symmetry

Experiment layout

Machine aspects covered in EPJC 80 (2020) 929
See Alex Fomin's presentation



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

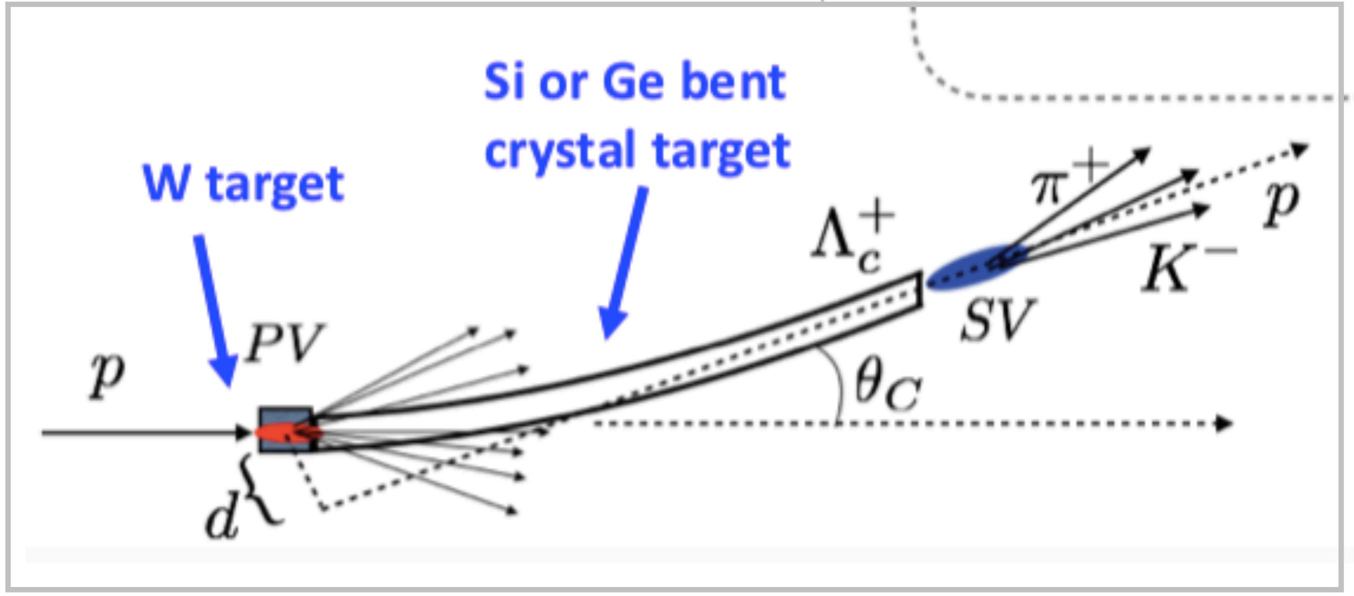
Spin movement

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)



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

EPJC 77 (2017) 181
JHEP 08 (2017) 120
EPJC 77 (2017) 828
PRD 103 (2021) 072003

Spin precession in bent crystals

- Firstly predicted by **Baryshevky (1979)**
- Determine particle gyromagnetic factor from TBMT equation

V.L. Lyuboshits, Sov. J. Nucl. Phys. 31 (1980) 509

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

Φ = spin rotation angle

θ_C = crystal bending angle~10^{-2} rad

g = gyromagnetic factor

γ = Lorentz boost~ $4\text{-}5 \cdot 10^2$

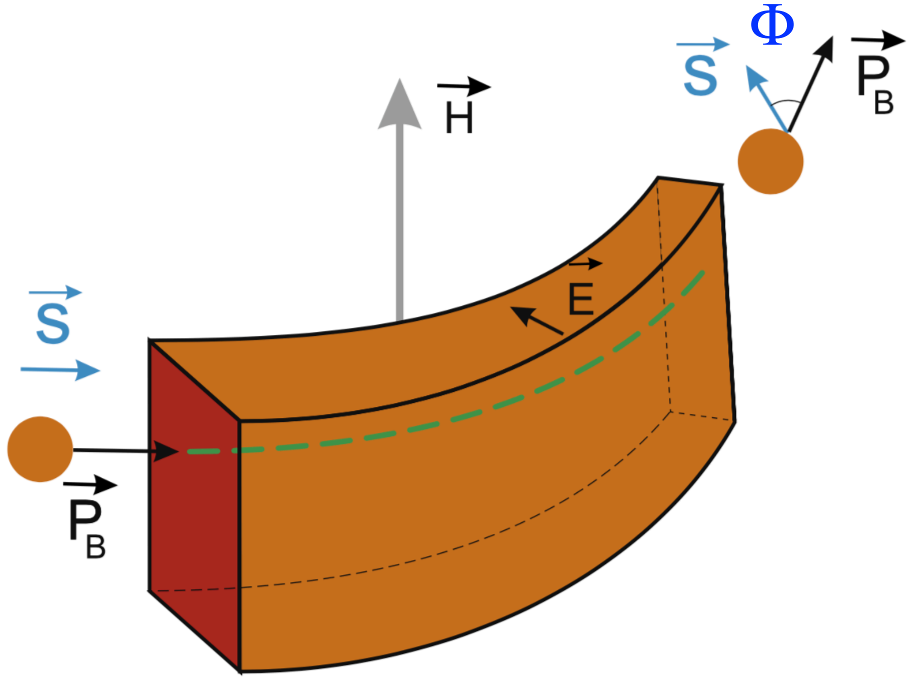
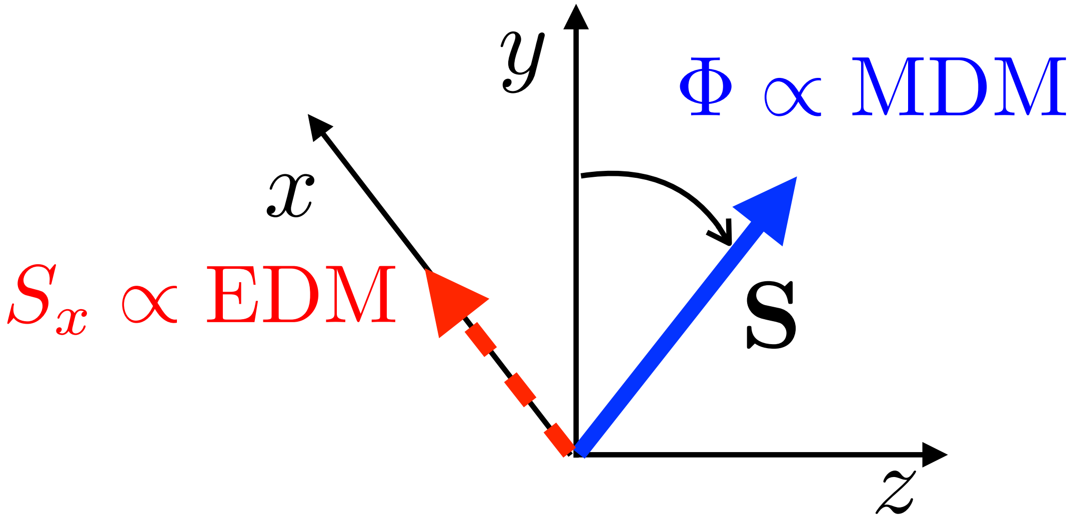


Fig. 1. Spin rotation in a bent crystal.

- Before decay the baryons experience a huge electric field in the crystal
- MDM and EDM precession in the limit $\gamma \gg 1,\, d \ll g-2$

EPJC 77 (2017), 181

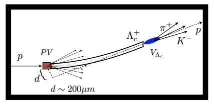
$$S_x = S_0 \frac{d}{g-2}(\cos\Phi - 1)$$



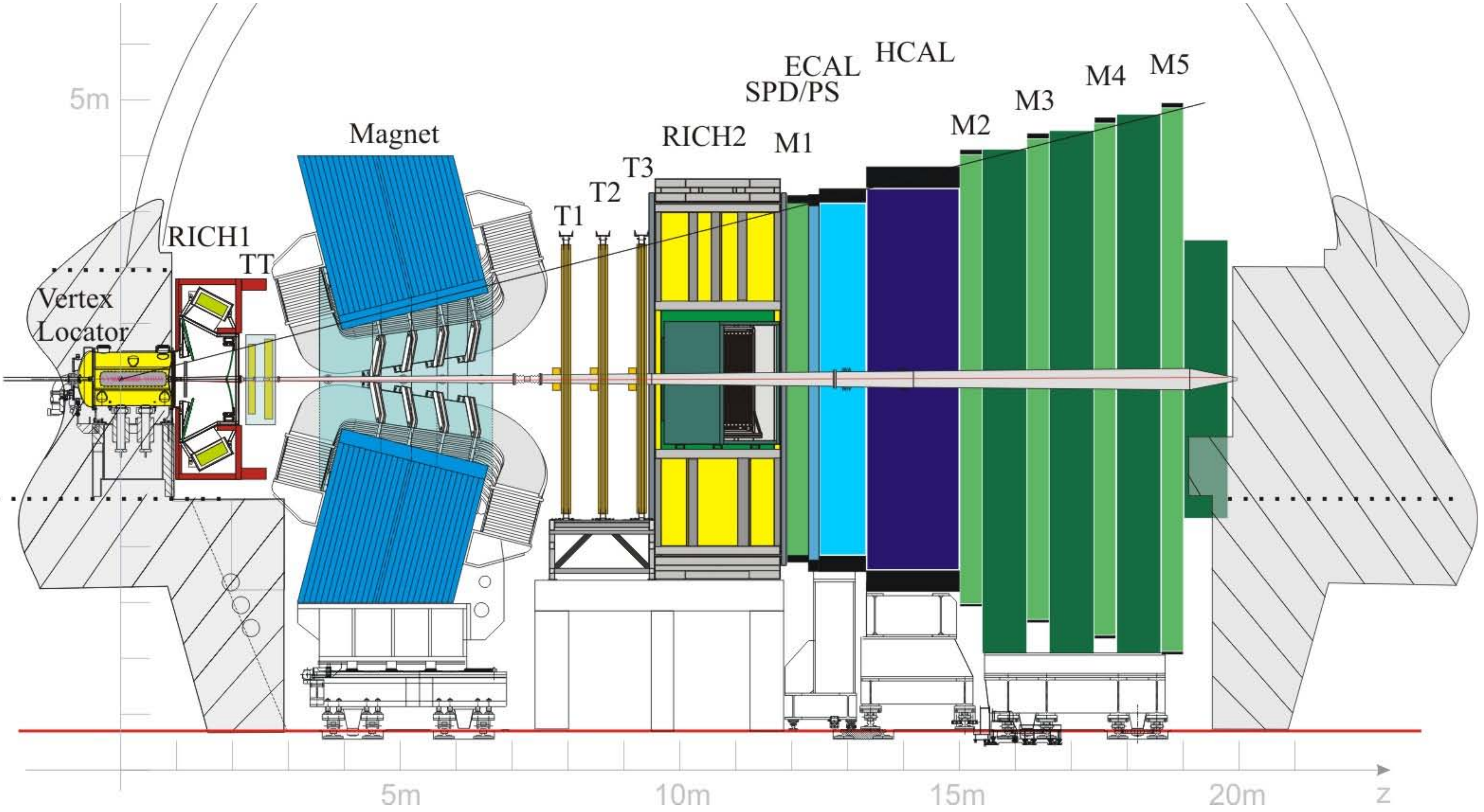
LHCb detector studies

- Experiment to be installed at z~-1.2m, ~90cm upstream the first VELO station
- The only experiment at LHC instrumented at large η, $(2 < \eta < 5)$

FT+bent crystal setup



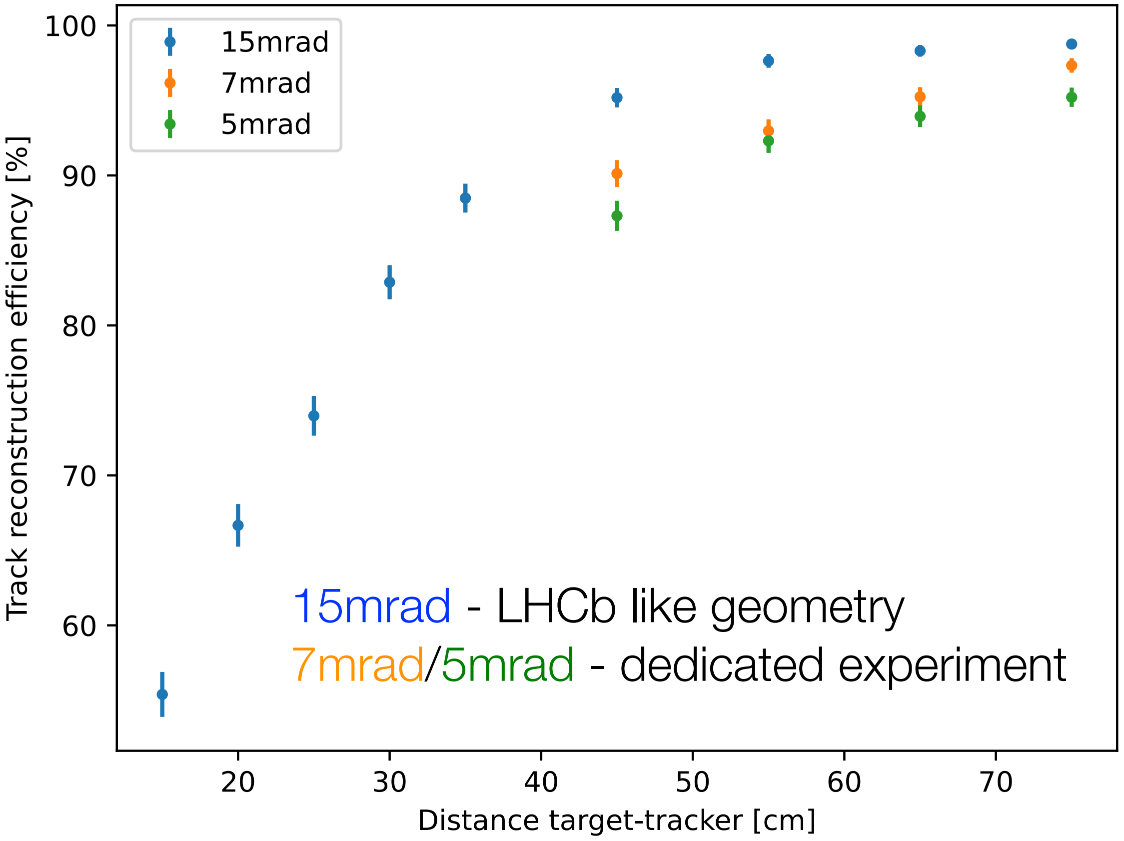
See Federico’s presentation about the integration

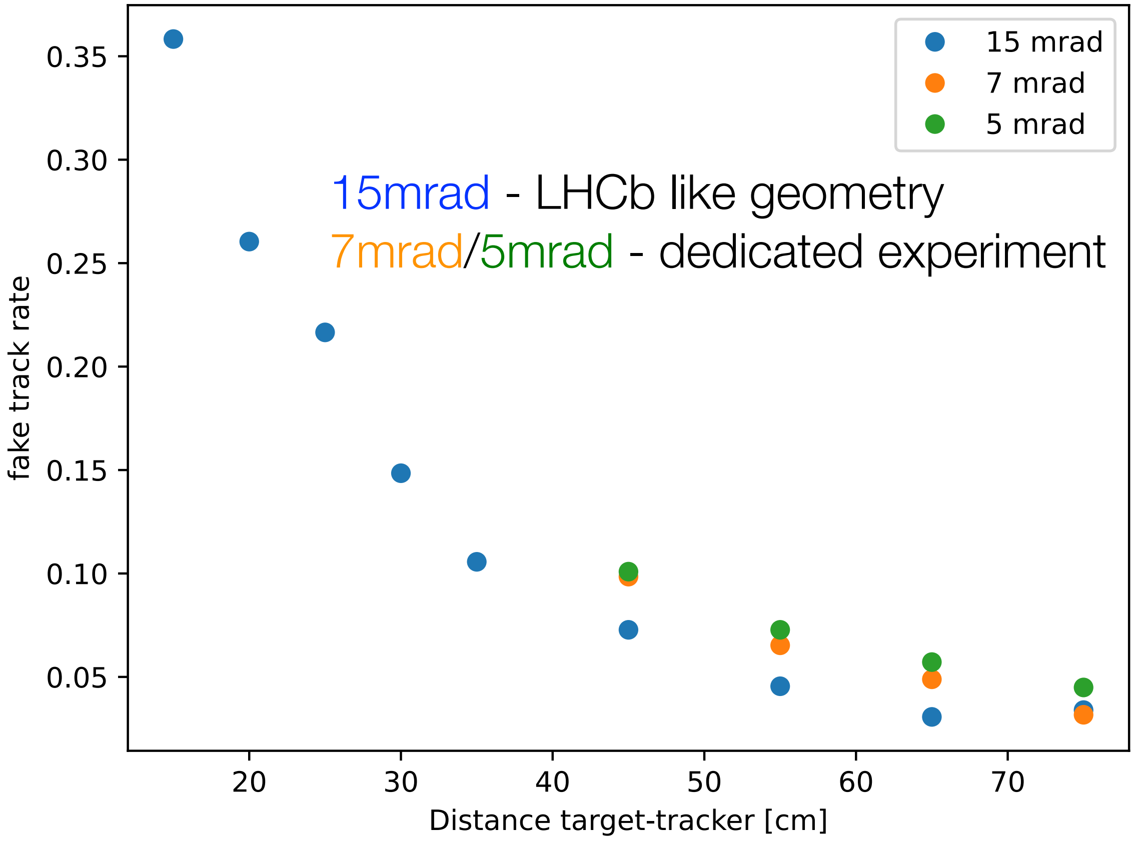


- Detailed simulations demonstrated the feasibility of this proposal:
  - Occupancy under control (busy events wrt pp collisions, but low rate ~1% @ 10^6 p/s)
  - The detector can reconstruct tracks with ~TeV energy, originated ~1/2m upstream the luminous region

Studies for a dedicated detector

- The acceptance of LHCb is limited to $\eta < 5$ ($\theta > 13\,\mathrm{mrad}$)
- Aim of a dedicated detector is a further forward acceptance, with a smaller distance target-tracker
- Simulated tracker chip is VeloPix (LHCb upgrade, state-of-the-art pixel asic), with an area of 55x55 μm^2

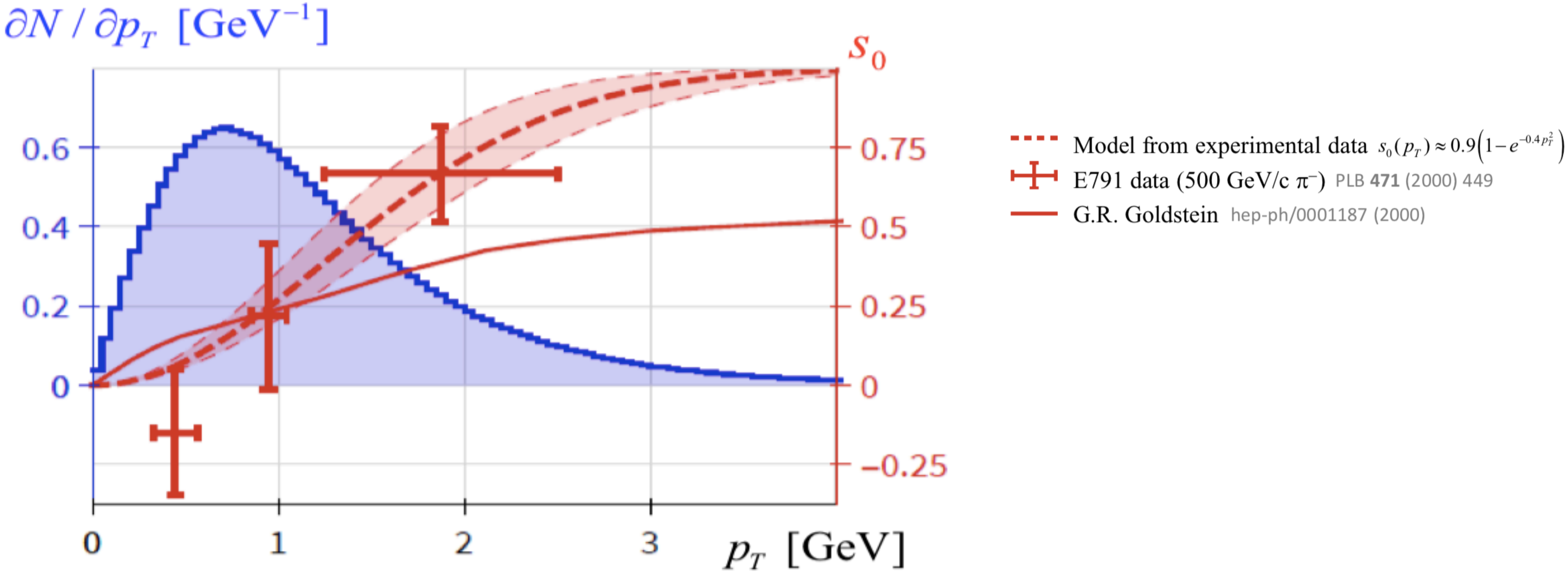




- Small distances -> fake track rate explode, reconstruction efficiency drop
- With the current technology available today, VELO (LHCb) is already at the optimal detector, placed at the optimal position (70-90 cm)
- A new dedicated detector will have to face new challenges (R&D required)

Initial heavy baryon polarisation

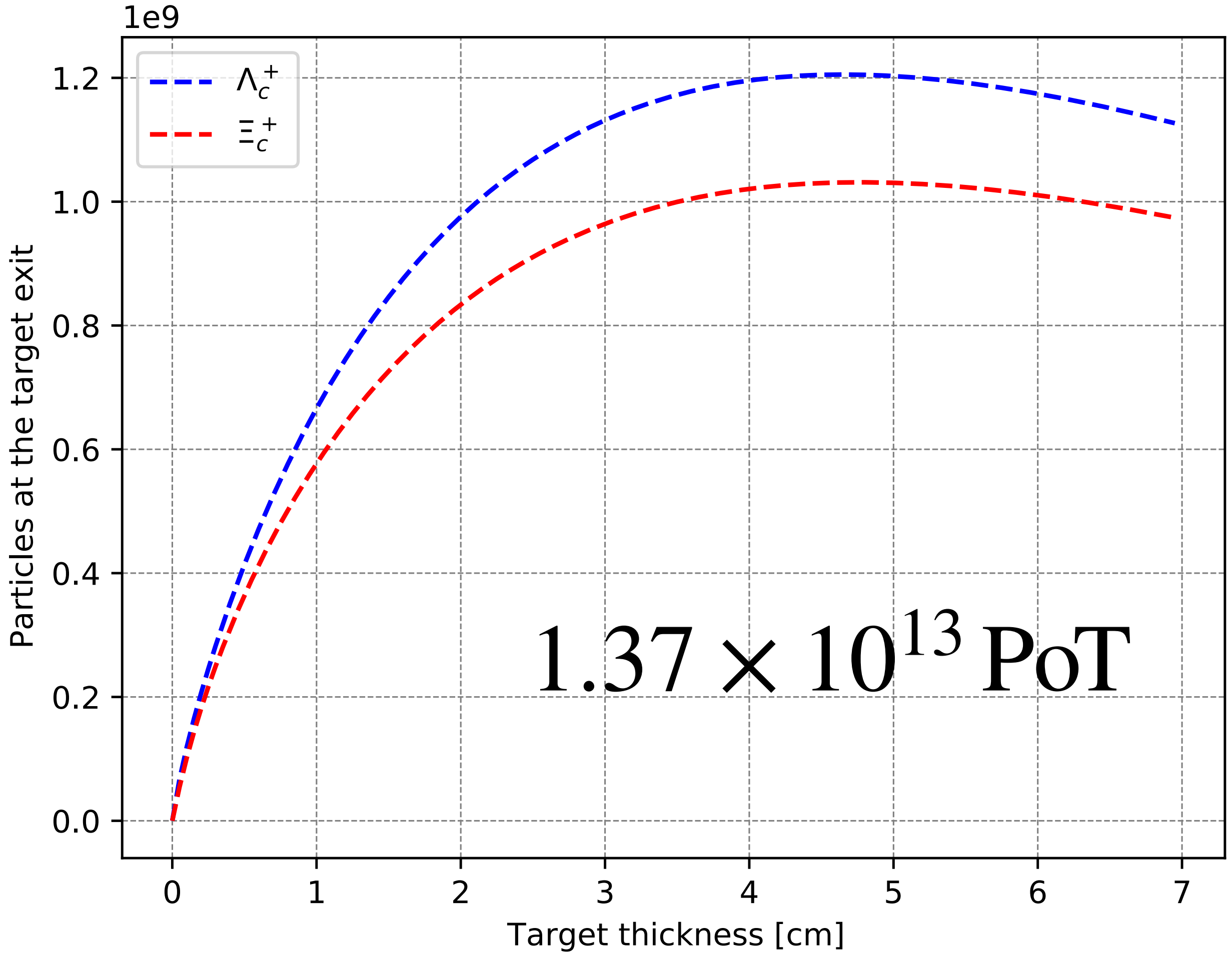
- Strong production of baryons: parity is conserved
    - Polarisation transverse to the p-baryon production plane
- Unknown for p-N at $\sqrt{s} \approx 115\,\mathrm{GeV}$



- Only one polarisation measurement in fixed target exists
- A deeper understanding on how the polarisation arises is still lacking
- In LHCb we have the opportunity to measure the polarisation in SMOG data, where gas is injected in the beam pipe (see Elisabeth's talk)

Target

- Tungsten, paired to the bent crystal



- Rate of produced baryons at the target exit saturates with thickness $T \approx 4\,\mathrm{cm}$
  - Account for baryon decay and absorption (inelastic interactions) within the target
- $T \approx 2\,\mathrm{cm}$ is a good compromise in terms of yields and detector operation & safety

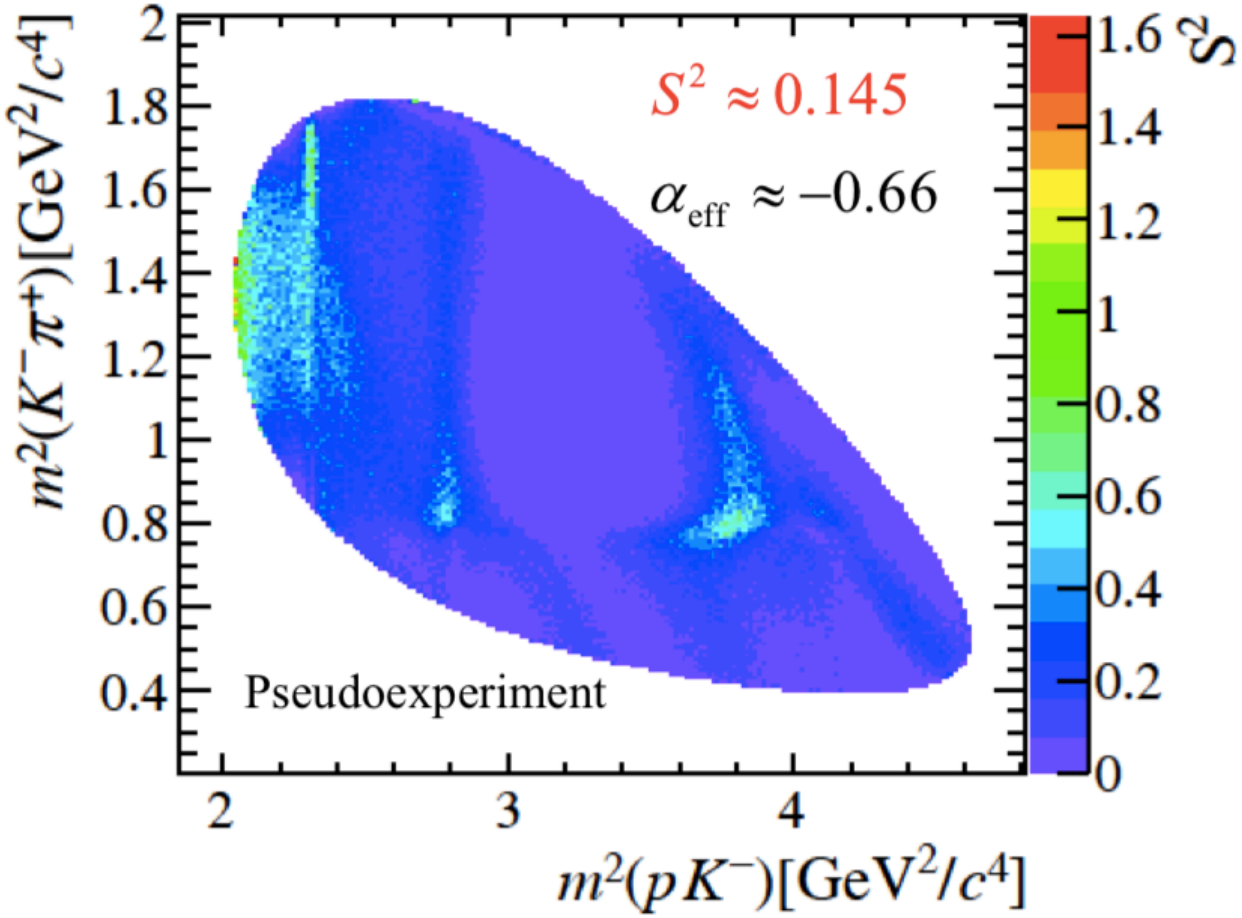
Charm baryon yields

- Polarisation measured with a full amplitude analysis
- Full amplitude analysis of $\Lambda_c^+ \to pK^-\pi^+$ (BF $\approx 6\,\%$) provides the same analyser sensitivity S as benchmark $\Lambda_c^+ \to \Delta^{++}K^-$ (BF $\approx 1\,\%$) –> x6 improvement in statistics

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

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

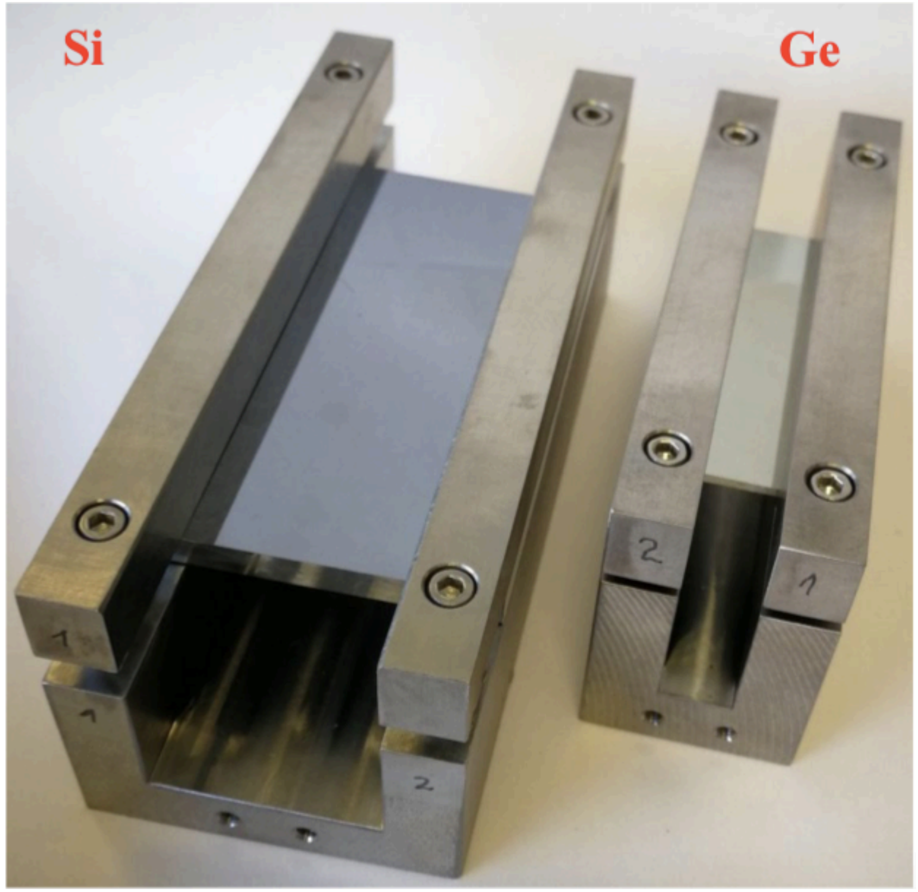
D.Marangotto PhD thesis

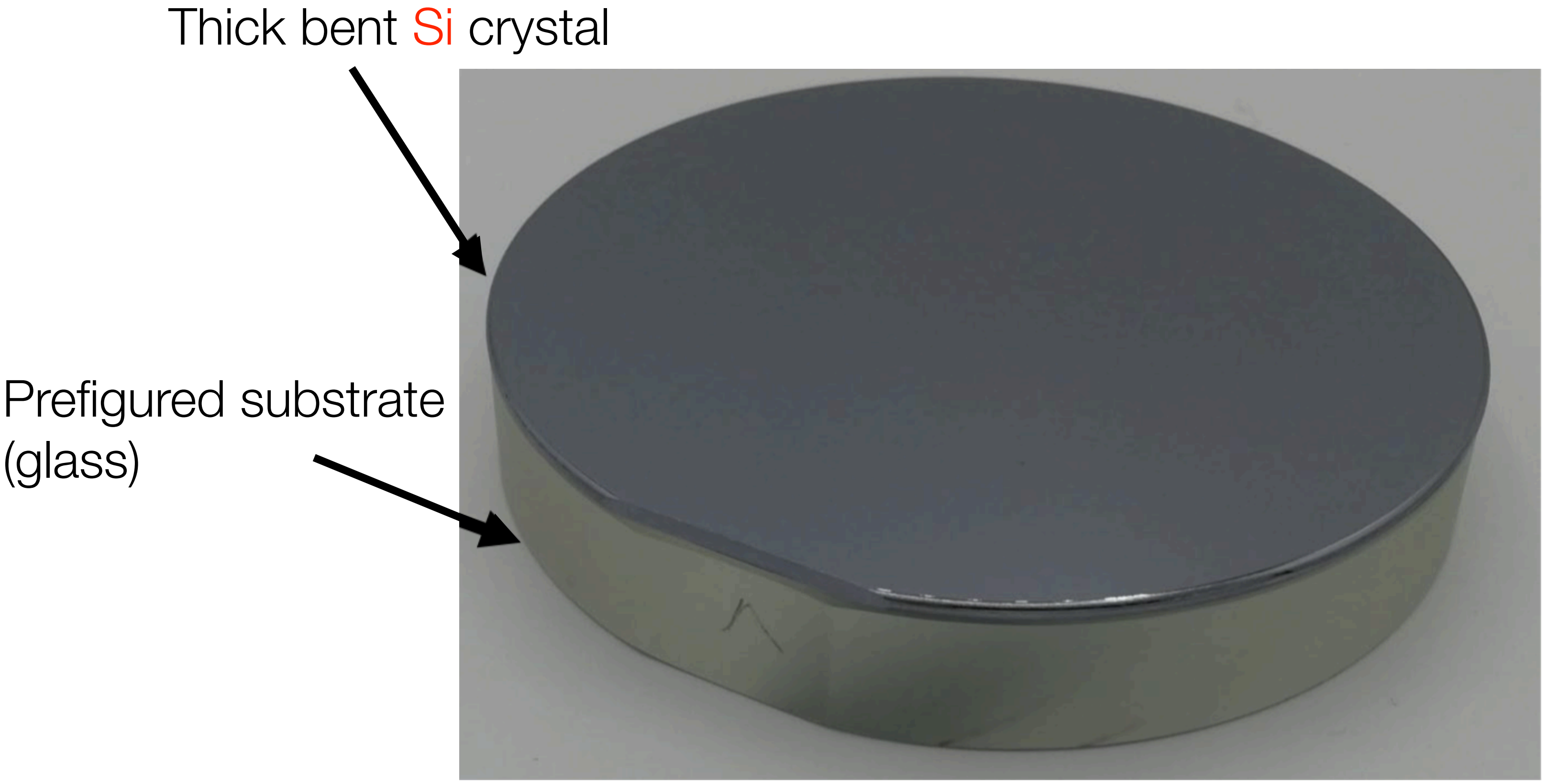


- x3 from additional modes containing:
  - Long-lived hyperons, most of which can be reconstructed as usual tracks
  - A missing neutral pion (unreconstructed)
- Ξ_c^+ baryon with similar yields to Λ_c^+:
  - Lower production rate (70%), smaller BF
  - Lifetime twice larger

R&D on crystals

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



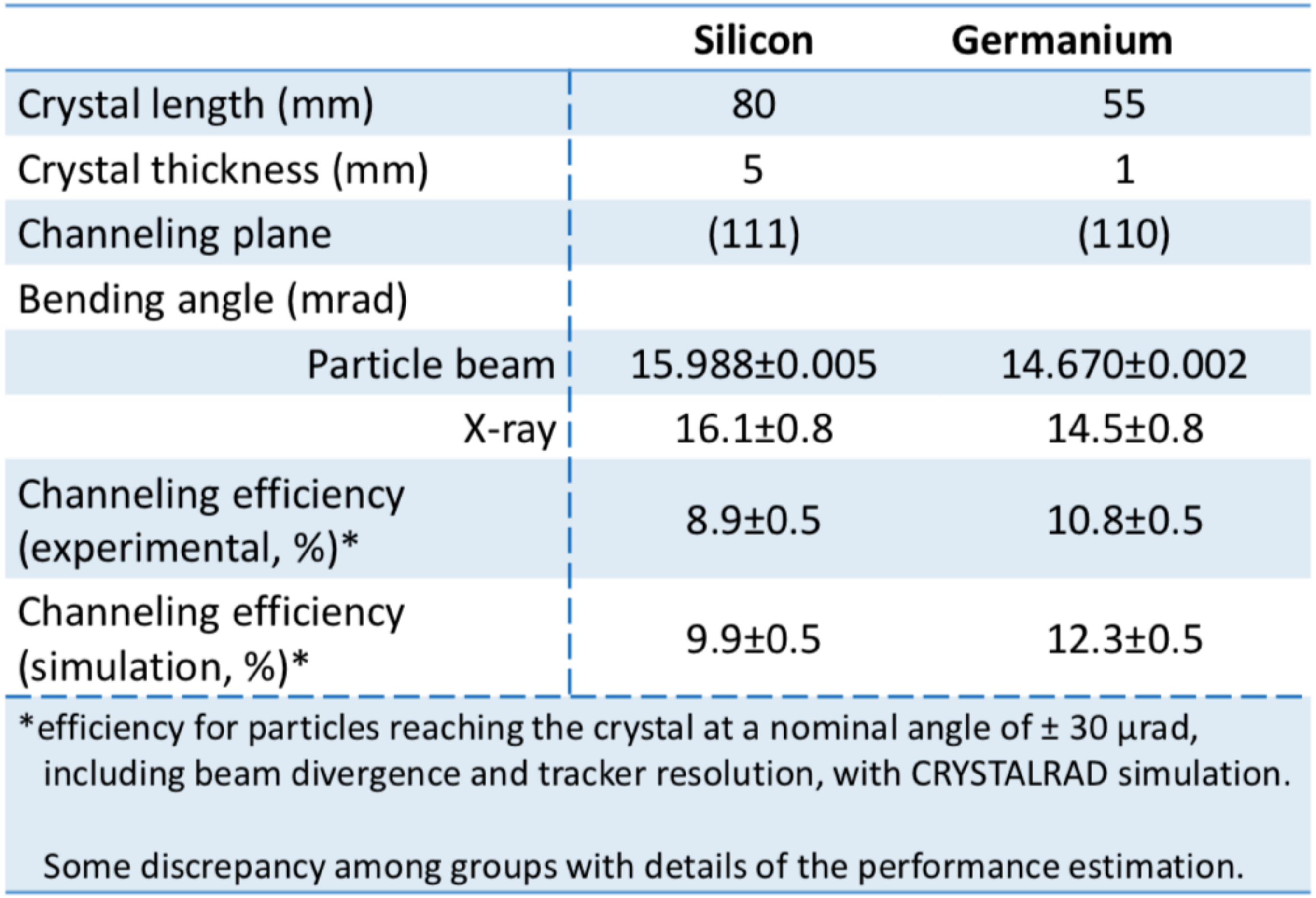


- Manufacturing of a crystal compatible with cryo-cooling (~77K) and other requirements also under investigation

See Federico's presentation

Testbeam of long bent crystal prototypes

- Si and Ge long bent crystal were tested on SPS beam (Oct'18) to characterise steering efficiency and precise bending angle
- At 180 GeV $\approx 10\,\%$ channeling efficiency

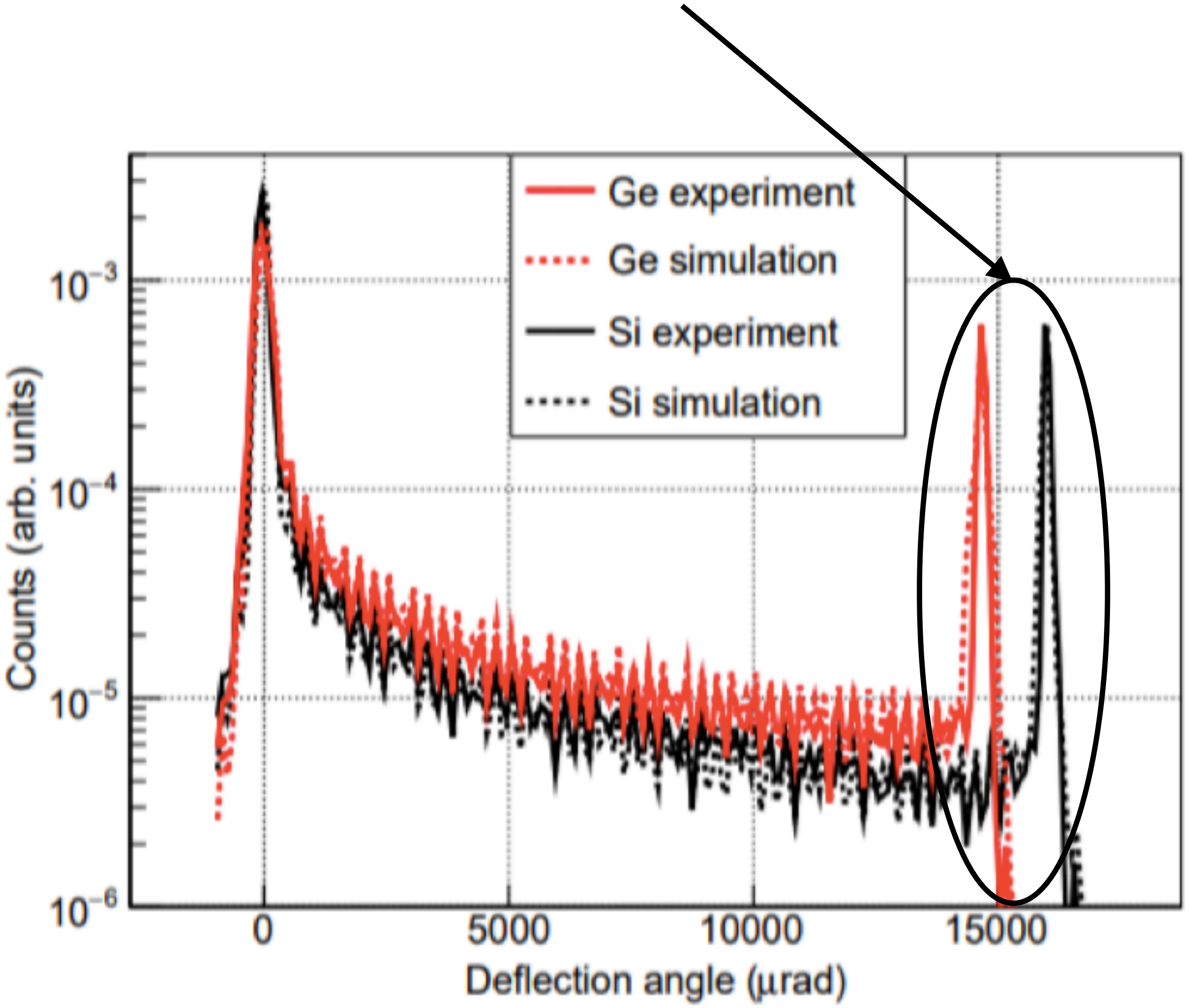


	Silicon	Germanium
Crystal length (mm)	80	55
Crystal thickness (mm)	5	1
Channeling plane	(111)	(110)
Bending angle (mrad)		
Particle beam	15.988±0.005	14.670±0.002
X-ray	16.1±0.8	14.5±0.8
Channeling efficiency (experimental, %)*	8.9±0.5	10.8±0.5
Channeling efficiency (simulation, %)*	9.9±0.5	12.3±0.5

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

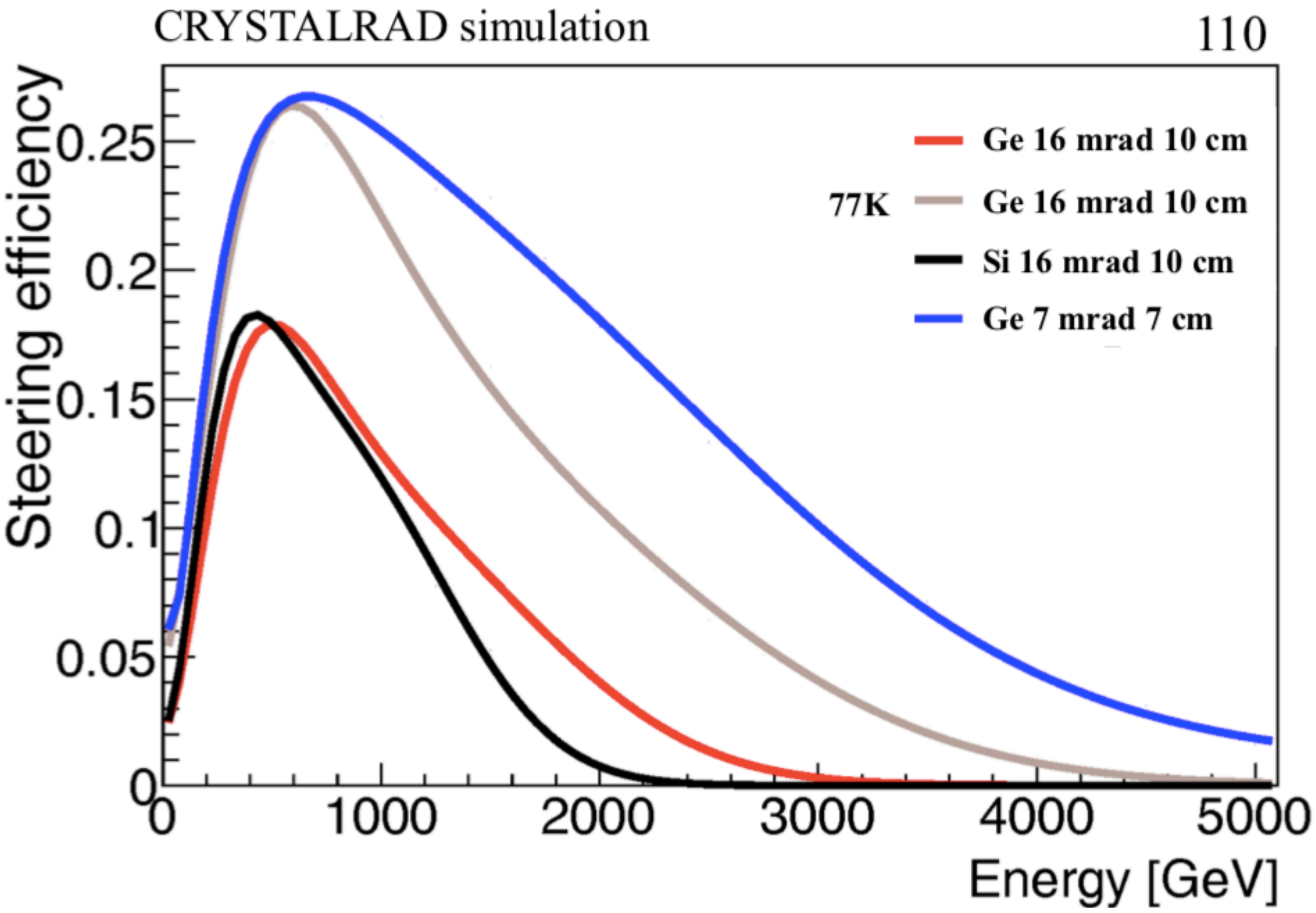
Some discrepancy among groups with details of the performance estimation.

Channeled and bent particles



Steering efficiency

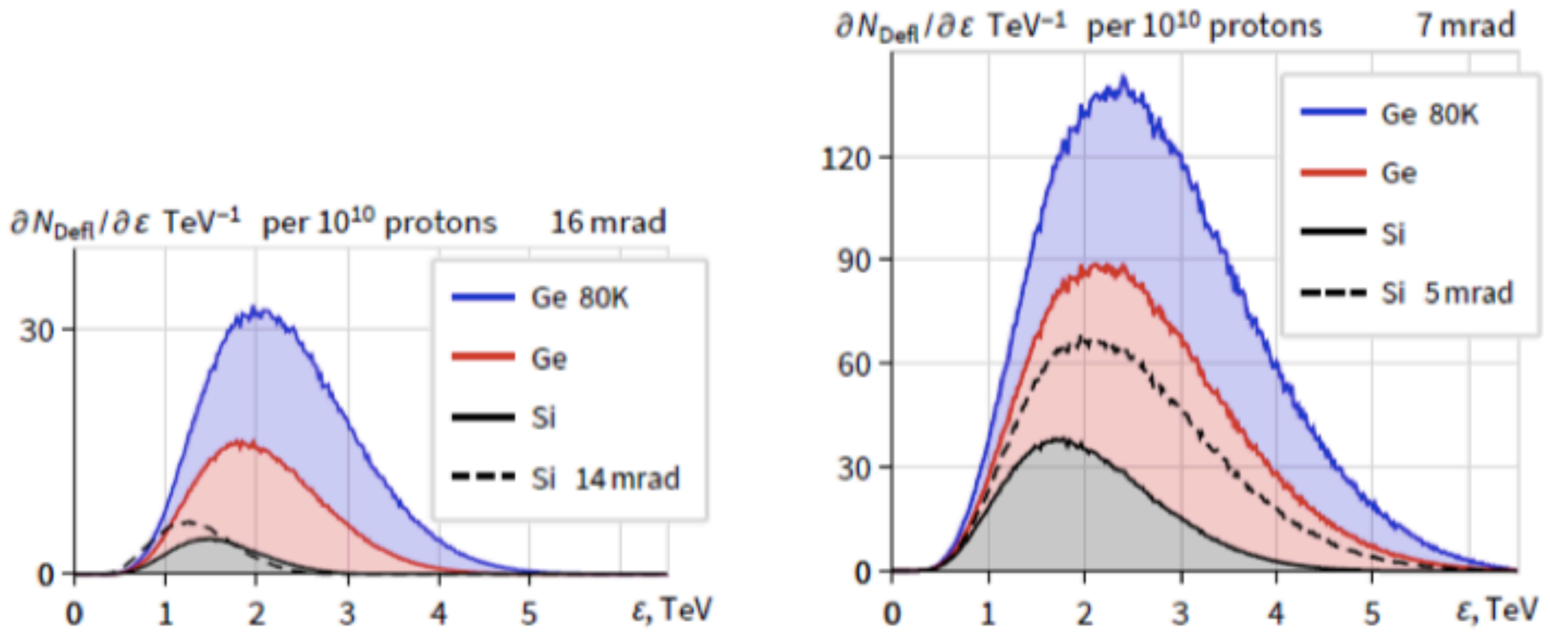
- Channeling efficiency for stable particles impinging with angle uniformly distributed within ± the acceptance (Lindard) angle



- Germanium @77K promising in terms of overall efficiency at higher momentum

Spectra of channeled particles

- The crystal takes the very forward produced particles (the most energetic) and bent them towards the detector
- Multi-TeV energy spectra for channeled particles



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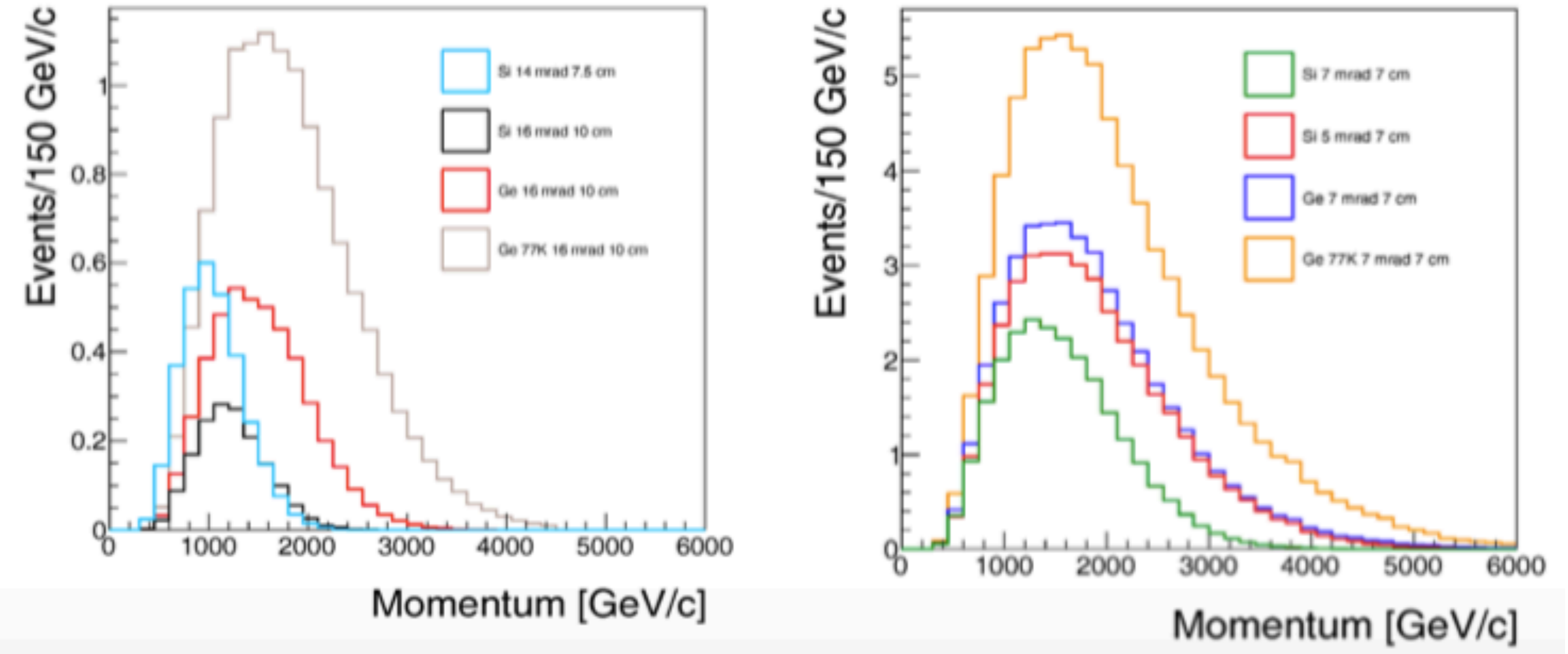

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Performances at optimal crystal parameters

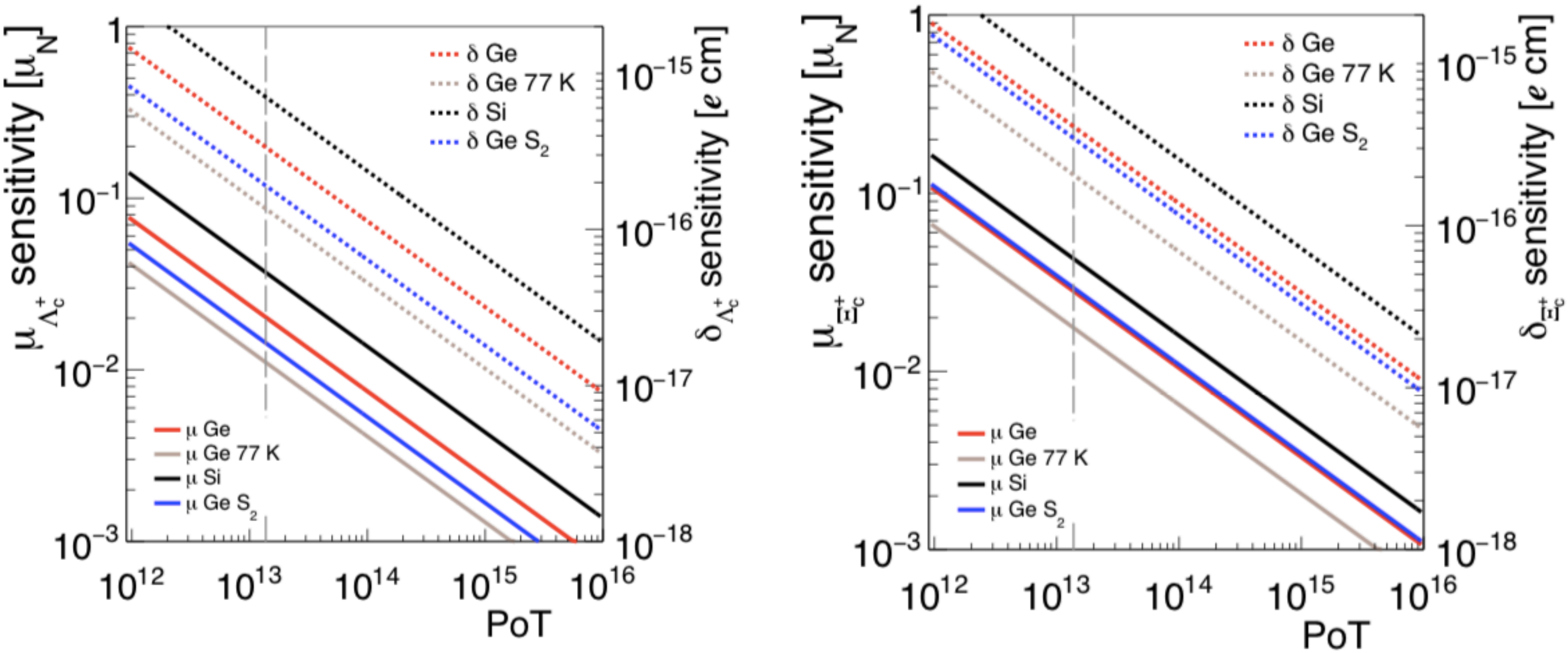
- Comparison of key parameters to assess performance for different crystal configurations
- Estimates valid for 1.37x10^{13} PoT, corresponding to 2 years of data taking

		Si	**Ge**	**Ge@77K**	**Ge S_2 (larger acceptance)**
Crystal	**Deflection length [mrad]**	16	16	16	7
	Length [cm]	10	10	10	7
Λ_c^+	**Average boost factor**	573	709	834	855
	Deflected per 1.37x10^{13} PoT	181	586	1784	5879
	Sensitivity MDM (x10^{-2} μ_N)	3.4	1.6	0.8	0.9
	Sensitivity EDM (x10^{-16} ecm)	5.6	2.2	0.9	1.0

- Large gain in deflected Λ_c^+ yields from Si->Ge->Ge@77K

Expected sensitivities

- Ge@77K could already do better than implanting a detector with a larger acceptance (Ge S_2)



- A dedicated experiment could be designed to have may different improvements:
  - Ge@77K
  - Detector with larger acceptance (i.e. lower bending angle for the crystal)
  - Higher fluxes, i.e. higher number of PoT (10^{15})

—> Improvement in the sensitivity by more than one order of magnitude

- An R&D is required, along with a new installation and instrumentation at IR3

Complementary with SMOG2

- The same system could be used as a fixed target setup
- Tiny crystal acceptance for channeling (~$10^{-3}/10^{-4}$)
  - Most of the particle are not channeled and could be reconstructed with the downstream detector (LHCb)
- Accumulated statistics (tungsten target with thickness 2cm):

$$\int \mathcal{L}_{pN} = A \int \mathcal{L} = N_{PoT} \frac{\rho N_A}{A[g/mol]} A\lambda \left(1 - e^{-T/\lambda}\right) \approx 285\,\mathrm{pb}^{-1} \qquad \int \mathcal{L} \approx 1.5\,\mathrm{pb}^{-1}$$

$N_{PoT} = 1.37 \times 10^{13}$

$\rho = 19.3\,\mathrm{g/cm^3}$

$N_A = 6.022 \times 10^{23}\,\mathrm{mol^{-1}}$

$\lambda = 8.87\,\mathrm{cm}$

$T = 2.0\,\mathrm{cm}$

- SMOG2 integrated luminosity (from technical proposal):
  - pAr run (18h): ~ 2 nb^{-1}
  - pNe run (84h): 7.6 nb^{-1}
- Complementary with SMOG2:
  - higher statistics
  - different target (solid vs gas)
  - Technically more difficult to change the target material as done with SMOG2

Conclusions

- Progress during last year in the different aspects of the proposal (target, 2nd crystal, detector, analysis and on machine aspects

- With $\approx 1.37 \times 10^{13}$ PoT ($\approx$ 2 years @10^6 p/s) can perform unique measurements:
  - Dipole moments
  - Production and differential cross-sections in the very forward region
  - Charm baryon polarisation

- This program looks feasible from the point of view of detector performance and machine layout at LHCb during Run3, and would be coherent/complementary with SMOG2

- These results and experience could set the basis for a dedicated experiment at LHC with higher PoT (x100)
  - Form an international collaboration
  - O(10Meuro) to contract 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

JHEP 03 (2019) 156
PRL 123 (2019) 011801