Search for new physics via baryon EDM at LHC with bent crystals

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INFN Istituto Nazionale di Fisica Nucleare

SELDOM

erc European Research Council Established by the European Commission

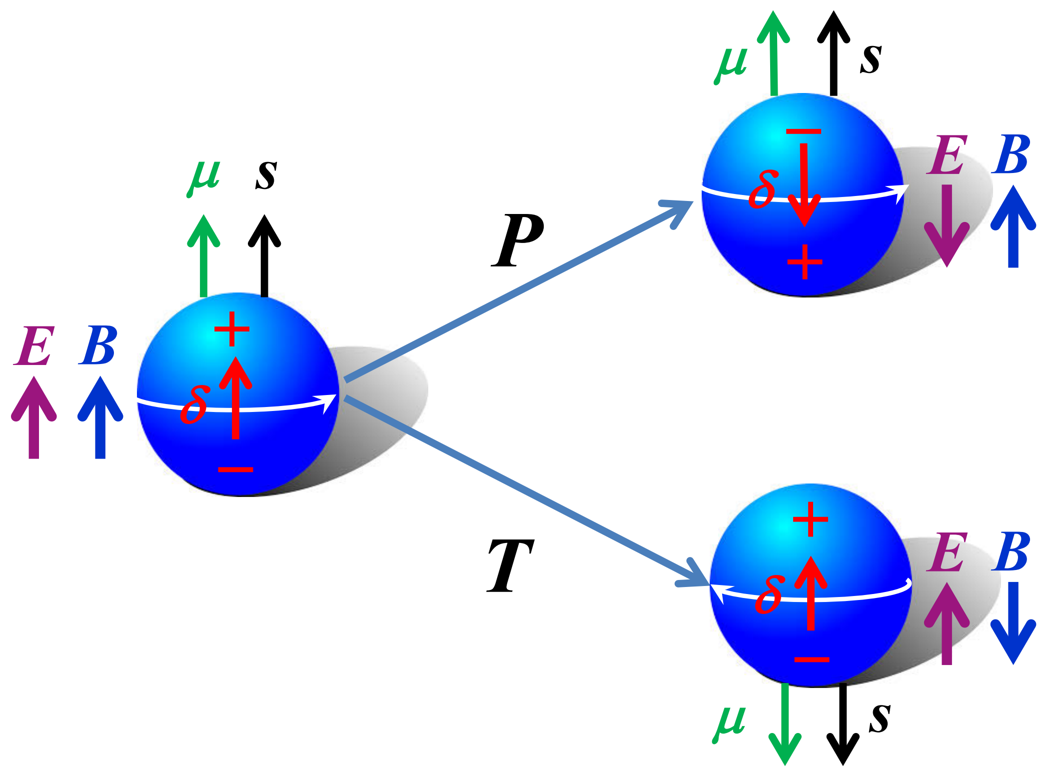
LHCb

Electromagnetic dipole moments

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

- Classic systems

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



- 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

Physics motivation for EDM

- CP violation (CPV) is a necessary condition for baryogenesis:
  - CPV in weak interactions via CKM mechanism in the SM is too small to explain the absence of antimatter in the Universe
  - CPV in strong interactions allowed in the SM. Stringent experimental limit from neutron EDM

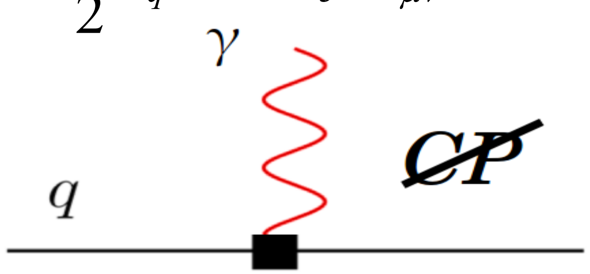
New CPV sources are expected to exists

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:

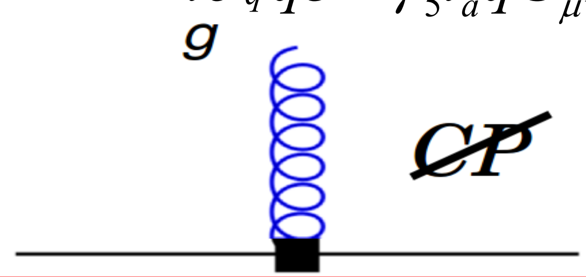
qEDM

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



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

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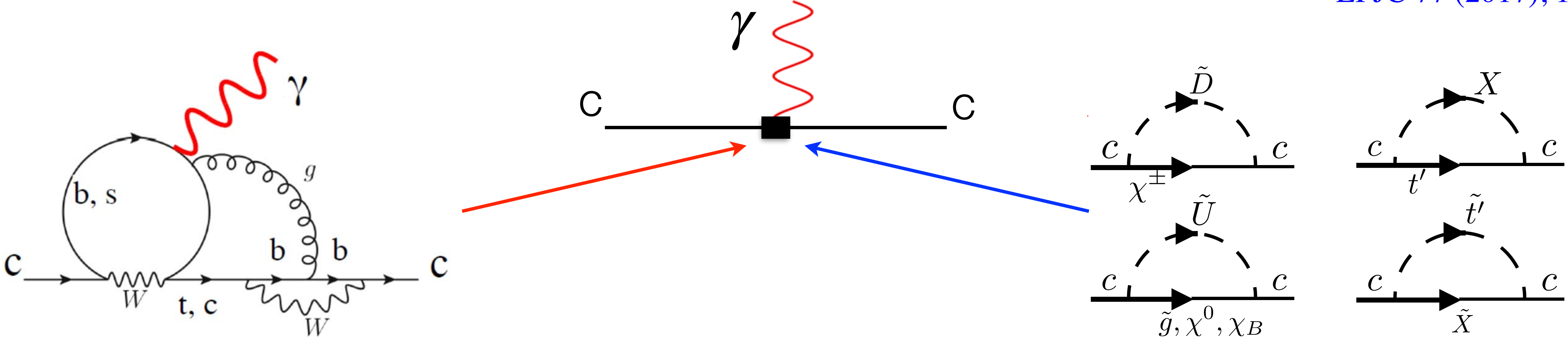


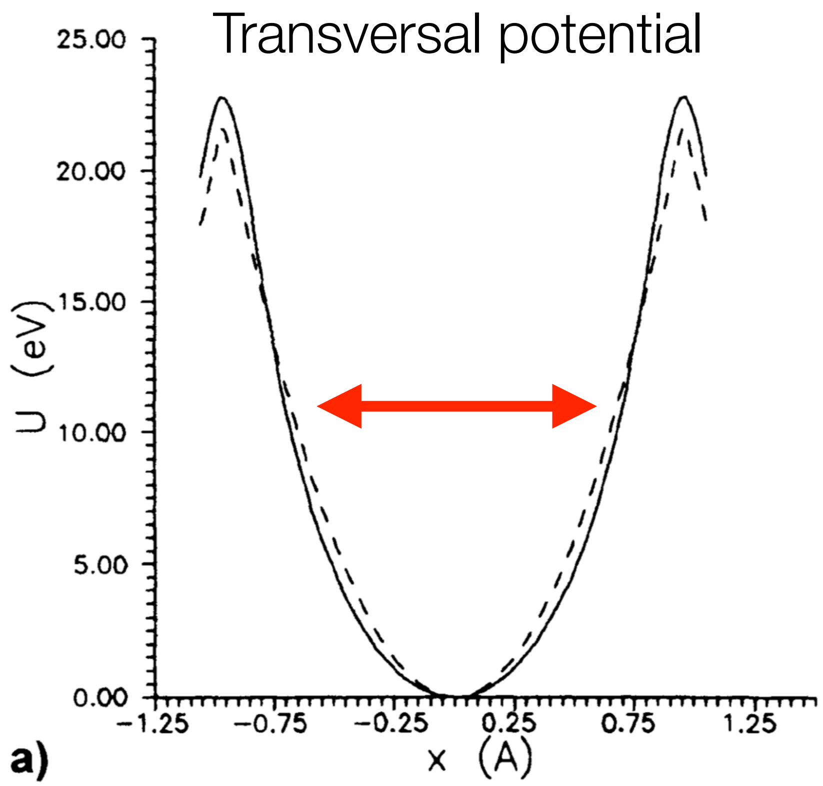
EDM observation = clear sign of **new physics**

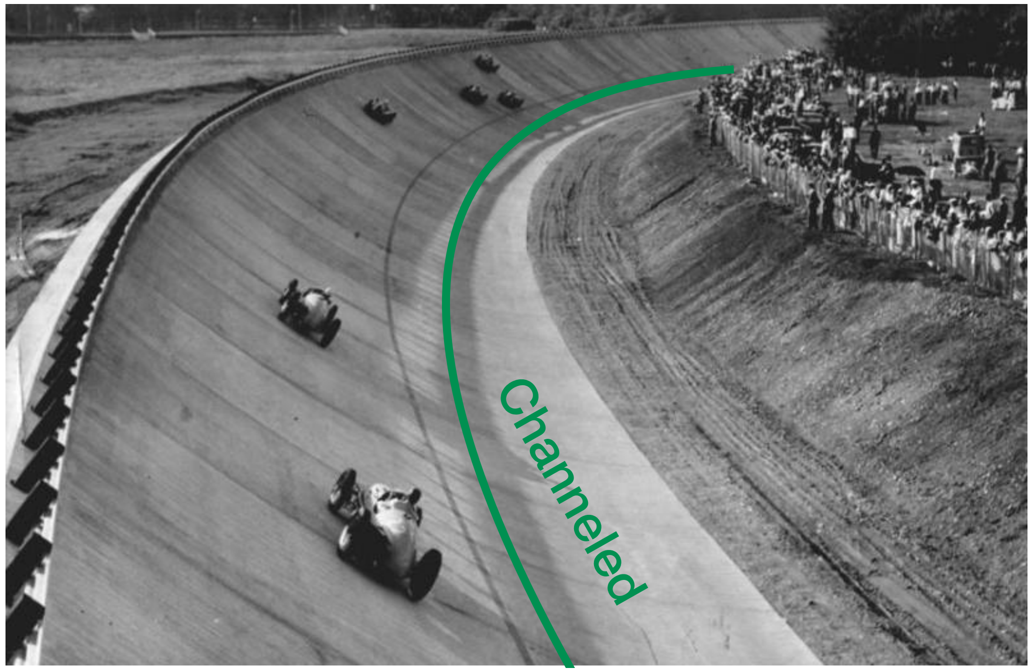
Physics motivation for MDM

- Experimental anchor points for tests of low-energy QCD models, related to non-perturbative QCD dynamics
- Test of quark substructure
- Measurement of MDM of particles and antiparticles would allow a test of CPT symmetry

Channeling in bent crystals

- Potential well between crystal planes
- Incident positive charged particle can be trapped if parallel to crystal plane (within few μrad)
- Well understood phenomenon (Lindhard 1965)
- Effect of the bent crystals:
  - Steer high energy particle beams
  - Induce spin precession





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~ $4\text{-}5 \cdot 10^2$

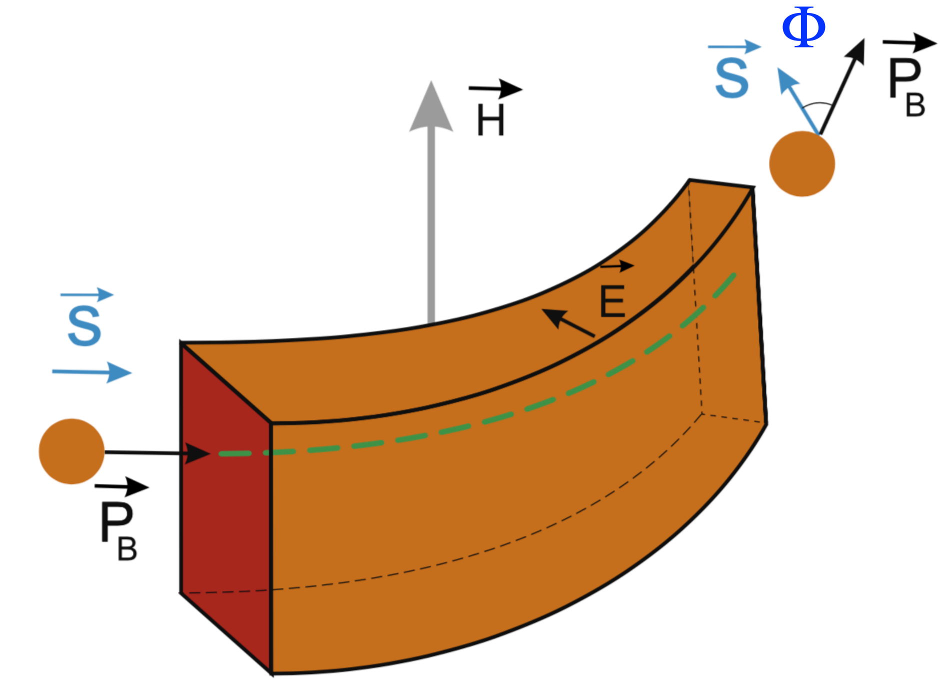


Fig. 1. Spin rotation in a bent crystal.

- Before decay the baryons experience a huge electric field in the crystal
- MDM and EDM precession in the limit $\gamma \gg 1,\, d \ll g-2$
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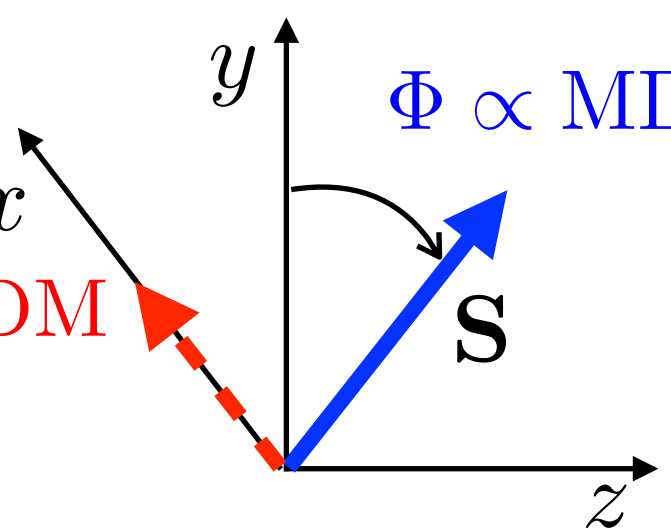
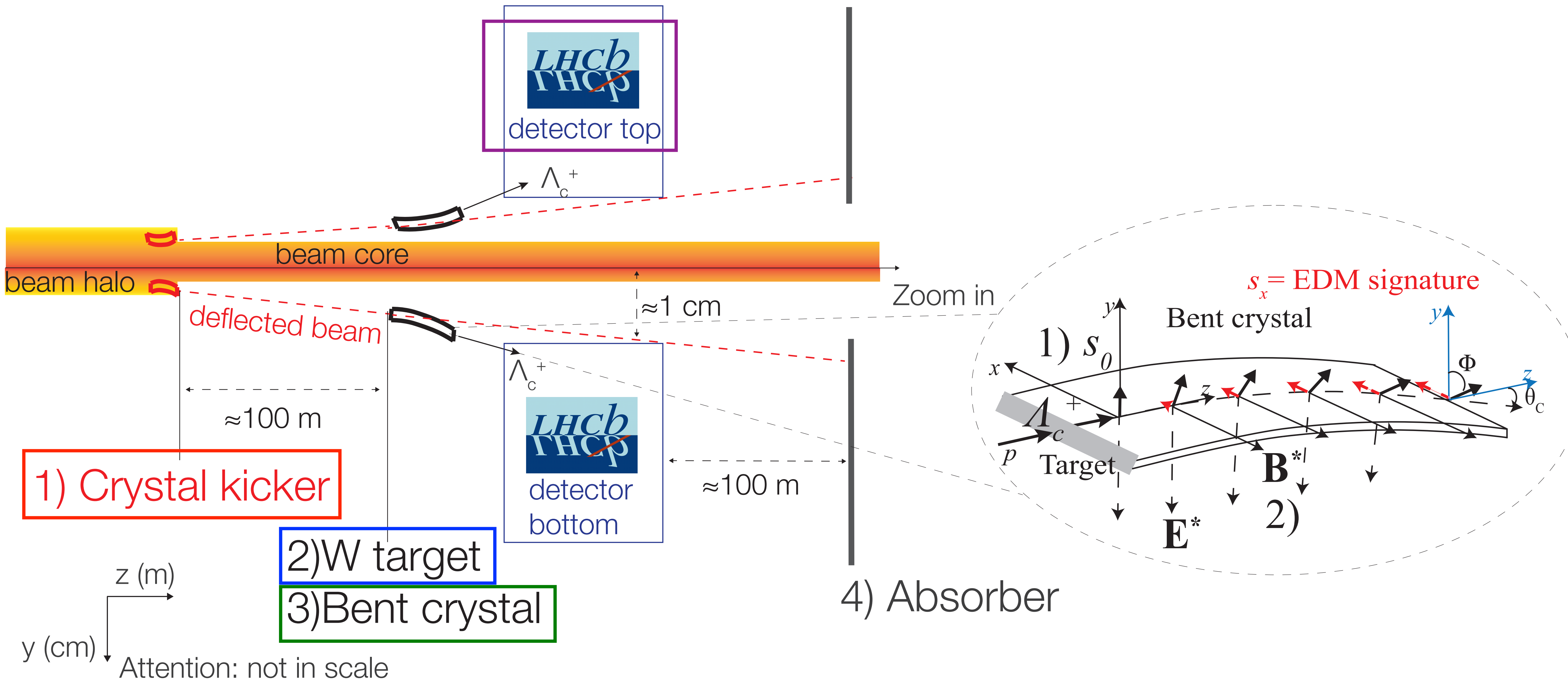
$$S_x = S_0 \frac{d}{g-2}(\cos\Phi - 1)$$



Experimental proposal



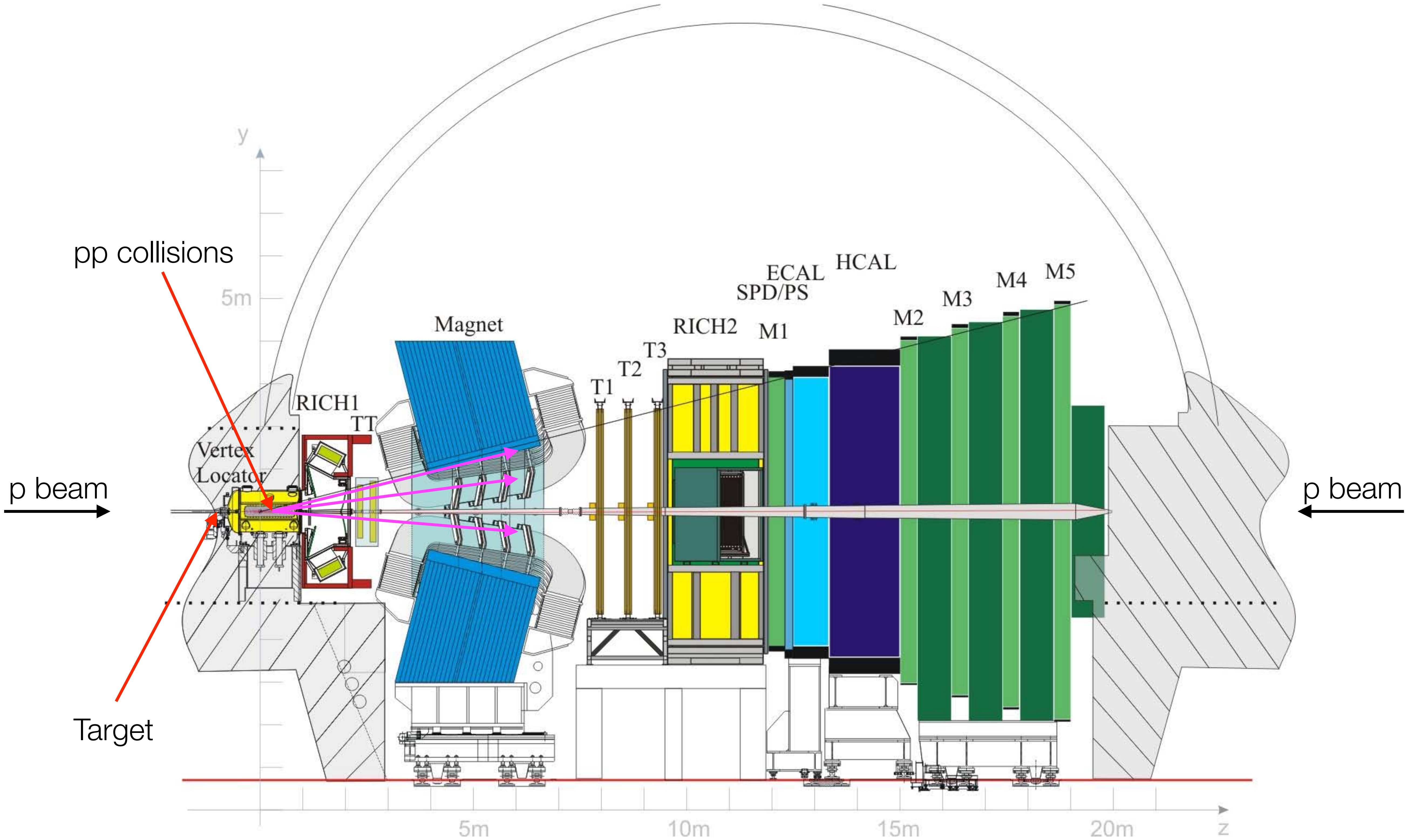
p extraction

Heavy baryon polarised production

Channeling
Spin precession

Event reconstruction

LHCb detector

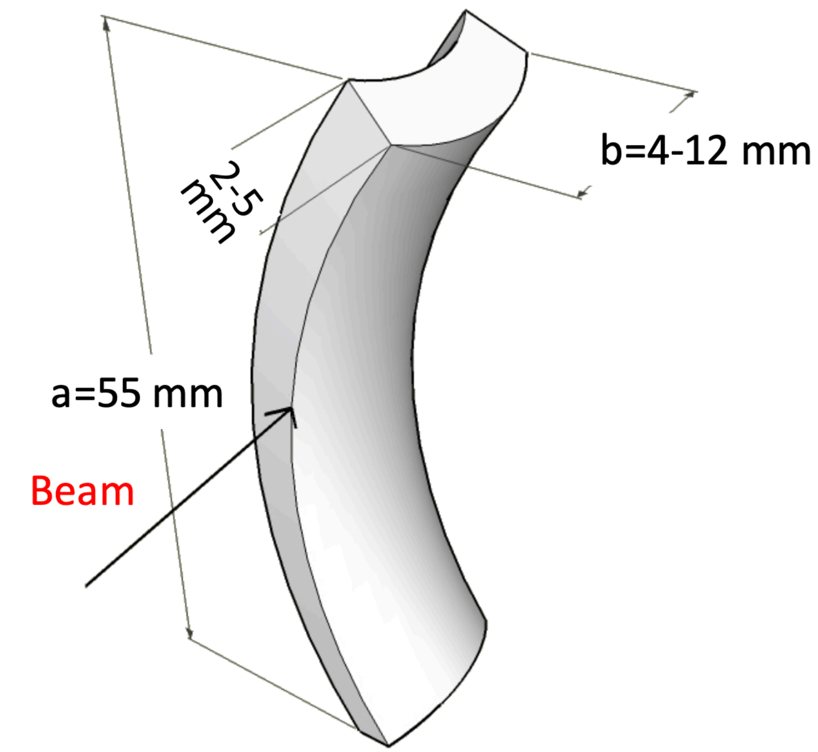


Bent crystal manufacturing techniques

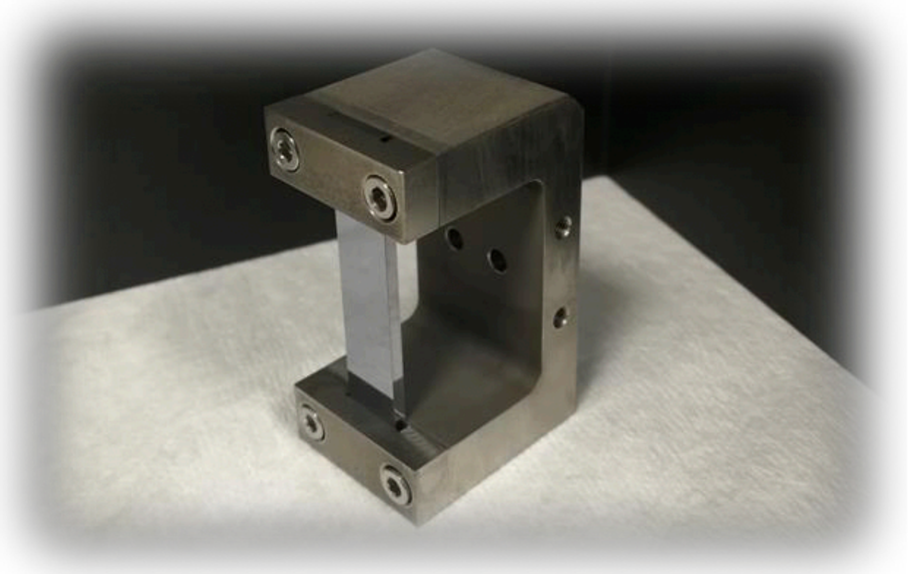
- Bending angle of a few mead (3-4 mrad) for 8 cm long Silicon crystal obtained through "anticlastic deformation", but scheme not exploitable for larger bending angles

- Bending angles of 15 mrad requires innovative bending schemes

- R&D at INFN for both Silicon and Germanium long crystals: achieved large bending angles (16 mrad)



Crystal for extraction
12 mm, 300 μrad

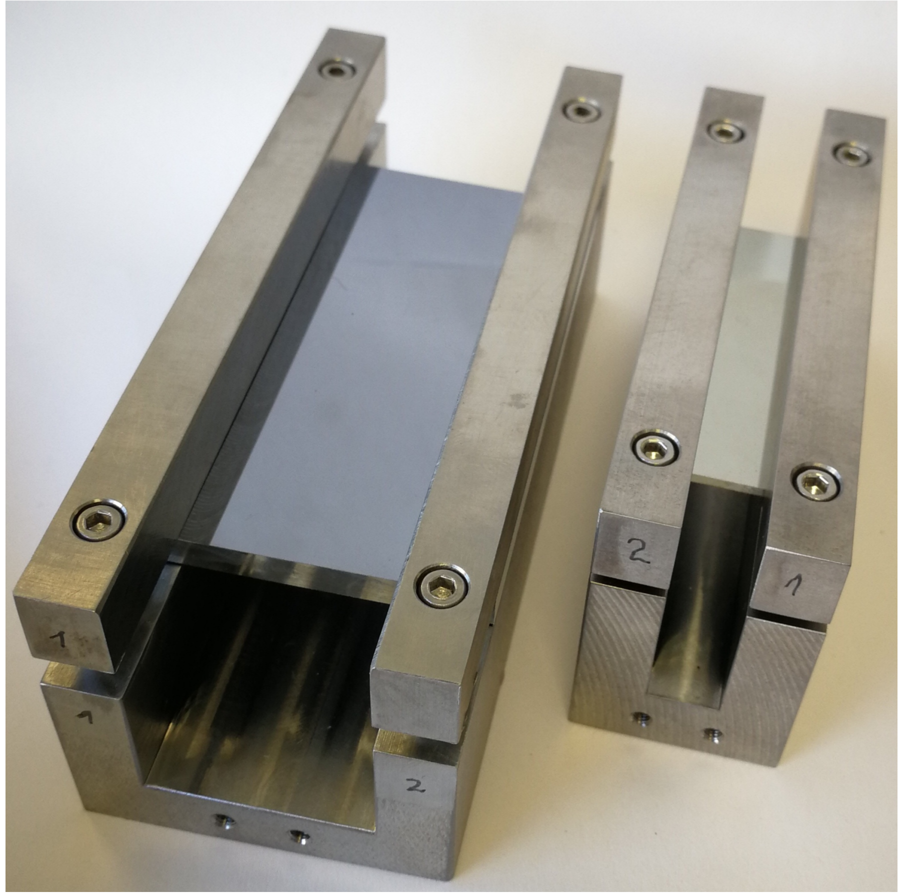


Long bent crystal prototypes

Crystal material	Si, Ge
Length along the beam	7-8 cm for Si 5-6 cm for Ge
Crystal height	2-5 mm
Weight	to be determined
Channeling axis	<111>, <110>, <100>
Miscut for planar	To be determined
Torsion	<10 urad/mm
Bending angle	16-17 mrad
Dislocation density	<1 /cm^2
Holder material	Titanium grade 5, steel 316 LN, other?

Si: 8.0 cm, 16.0 mrad, 5mm (height)

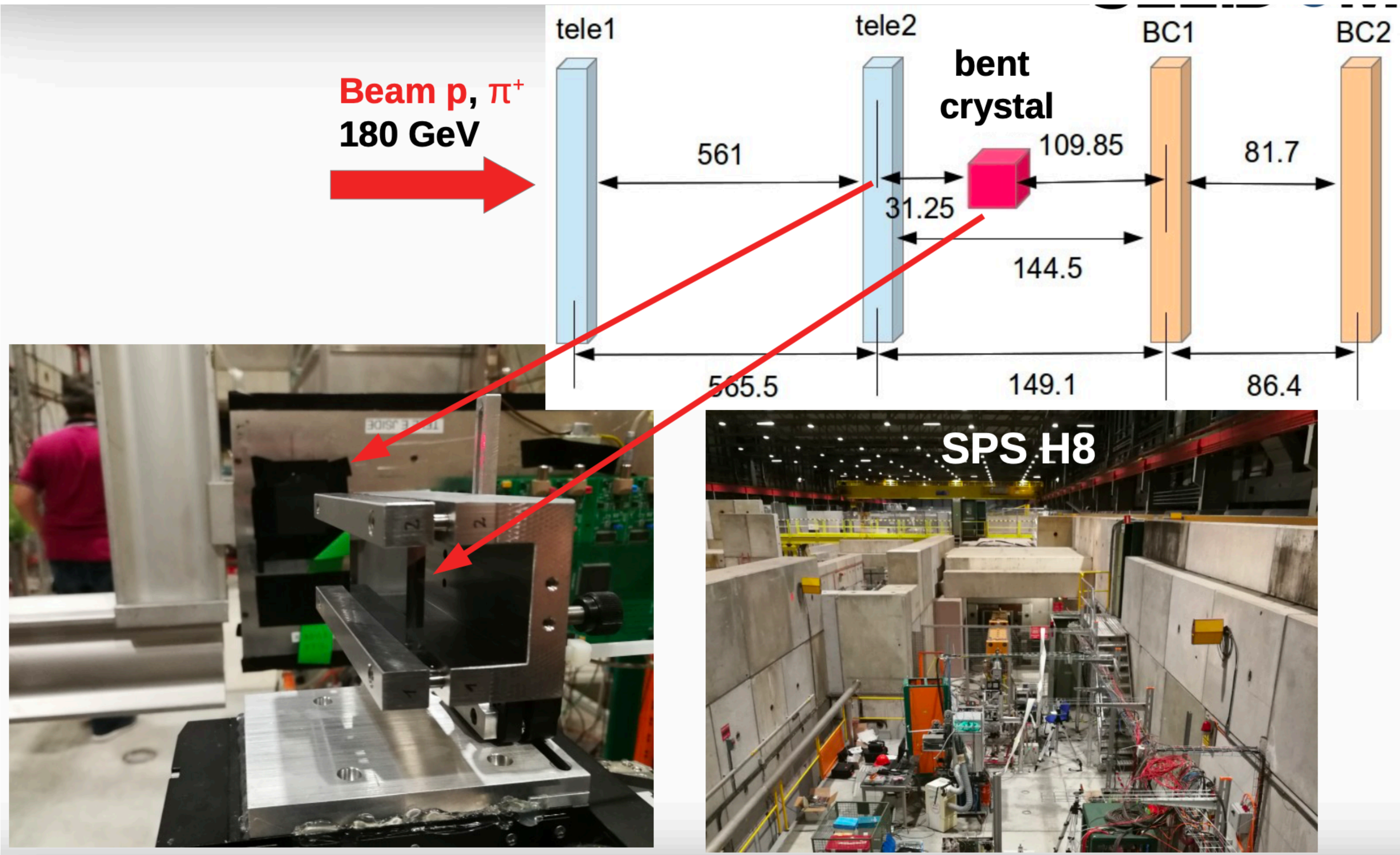
Ge: 5.5 cm, 14.7 mrad, 5mm (height)



Courtesy of A. Mazzolari

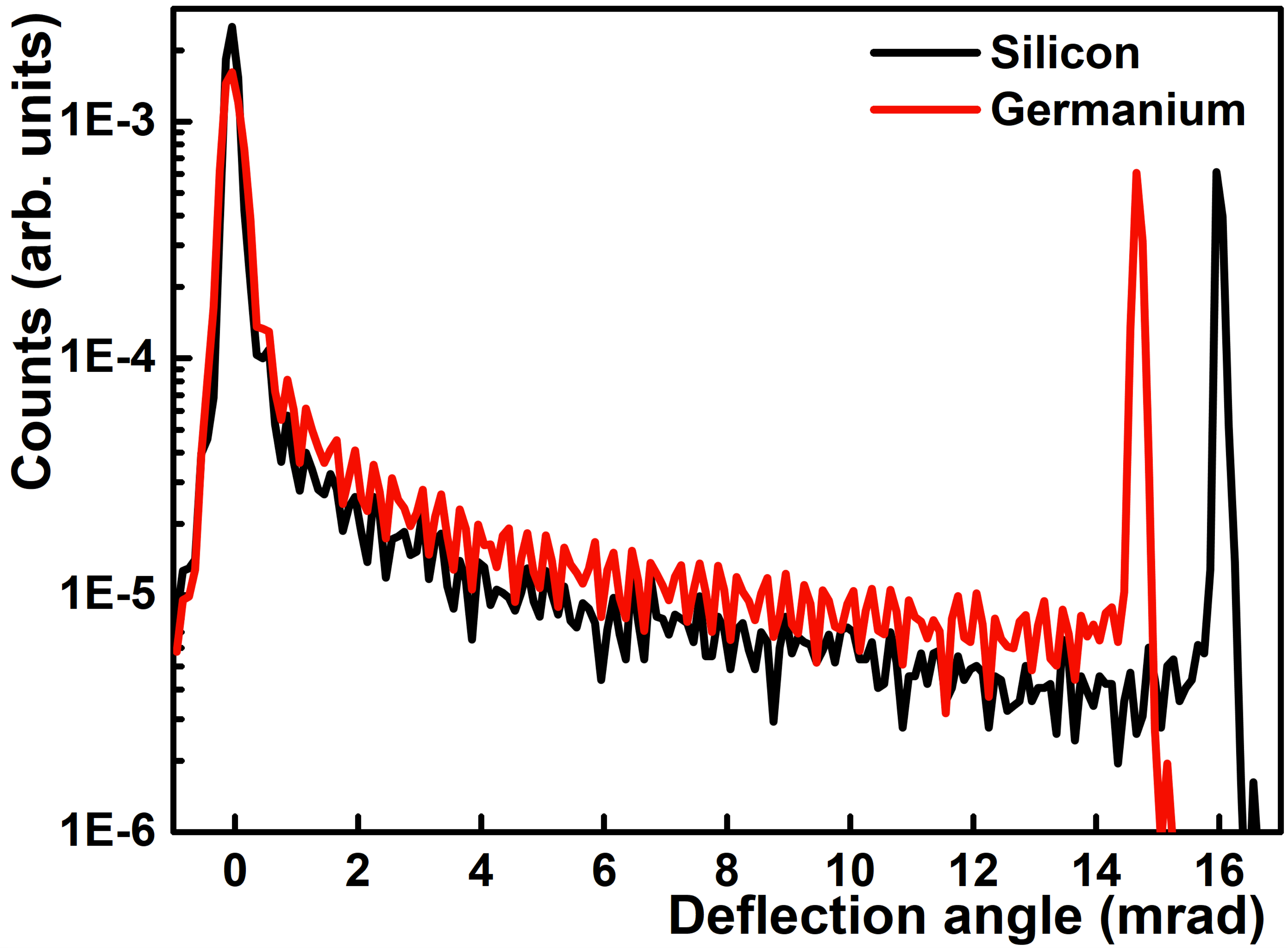
- **Silicon** and **germanium** long bent crystal prototypes

Testbeam at CERN

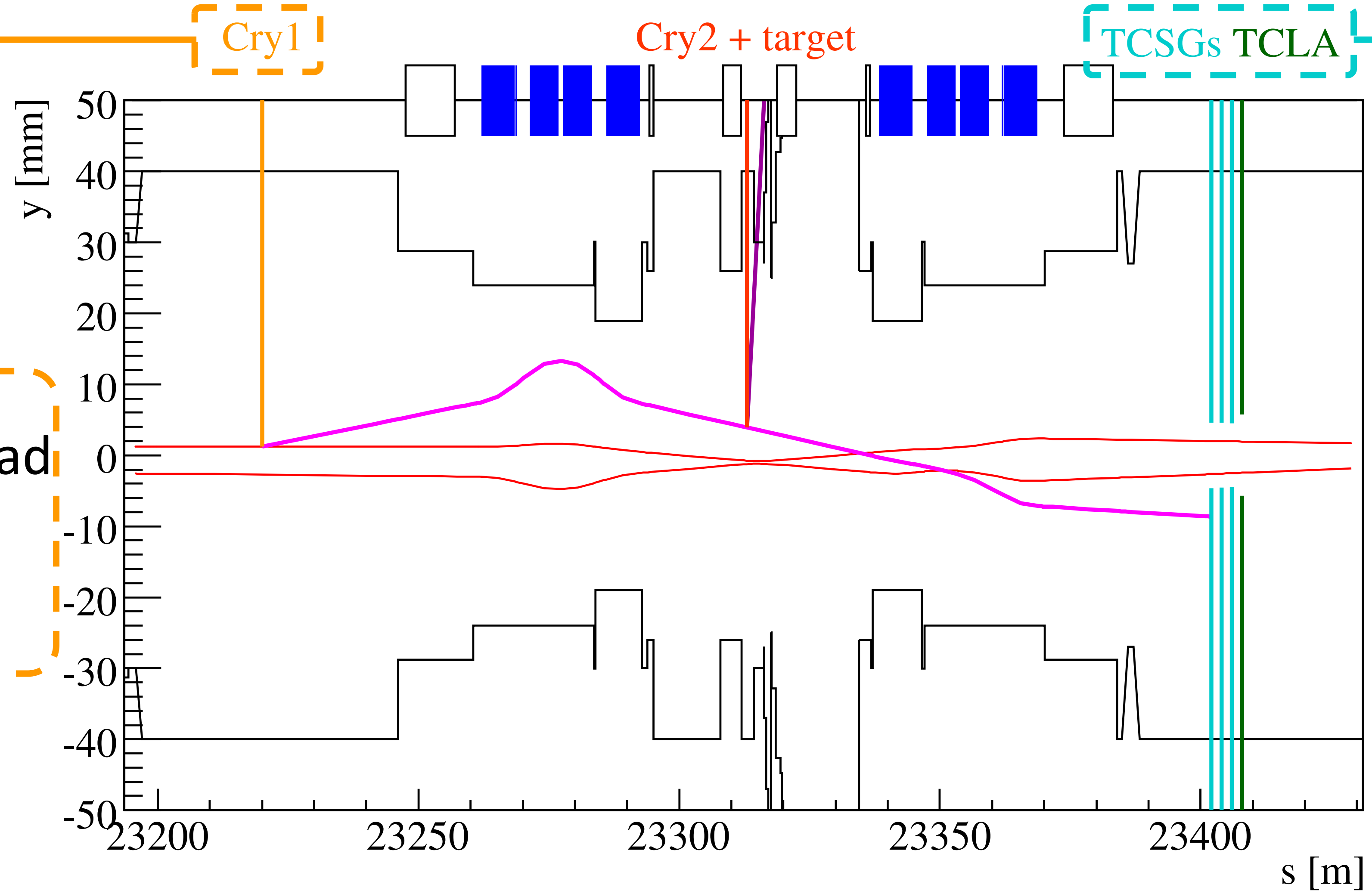


Deflection angle distribution

- Channeling clearly observed for both silicon and germanium crystals



Machine simulations



Cry1

Bending = 150μrad

Length = 1.2cm

R = 80 m

4 LHC-type collimators

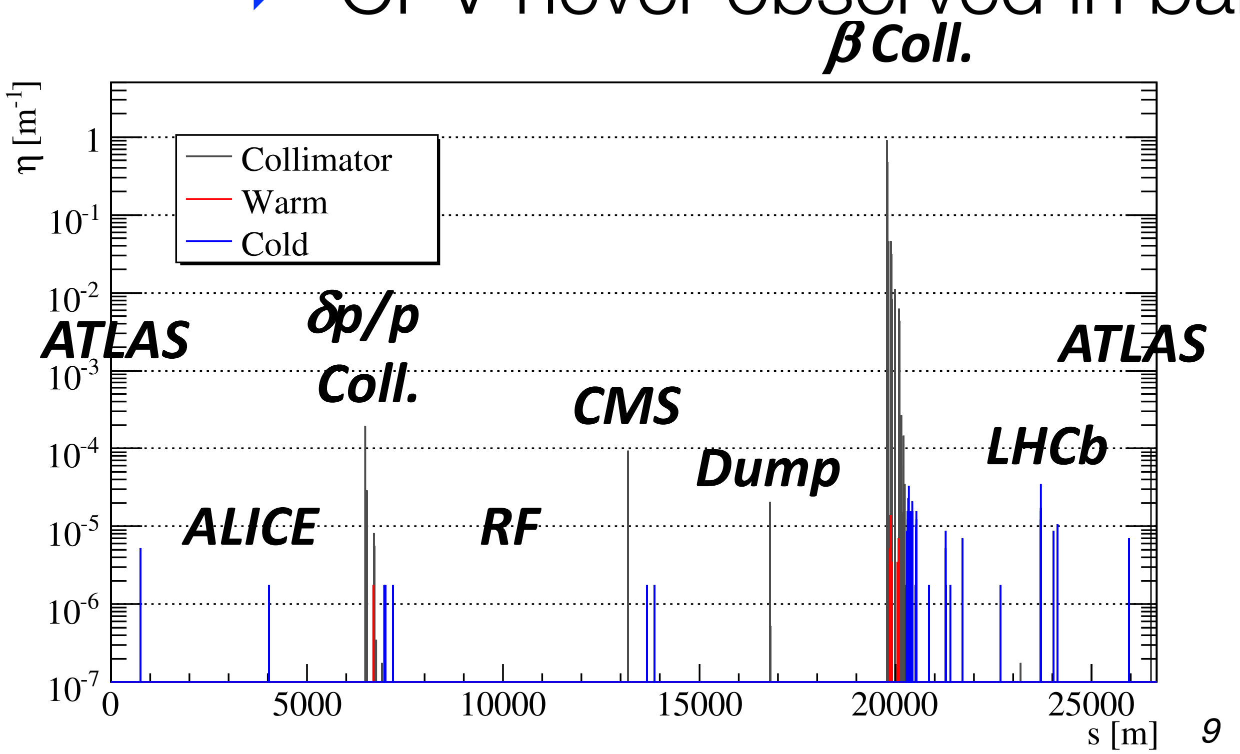
Initial “performance oriented” setup

Angular cut ~60 μrad

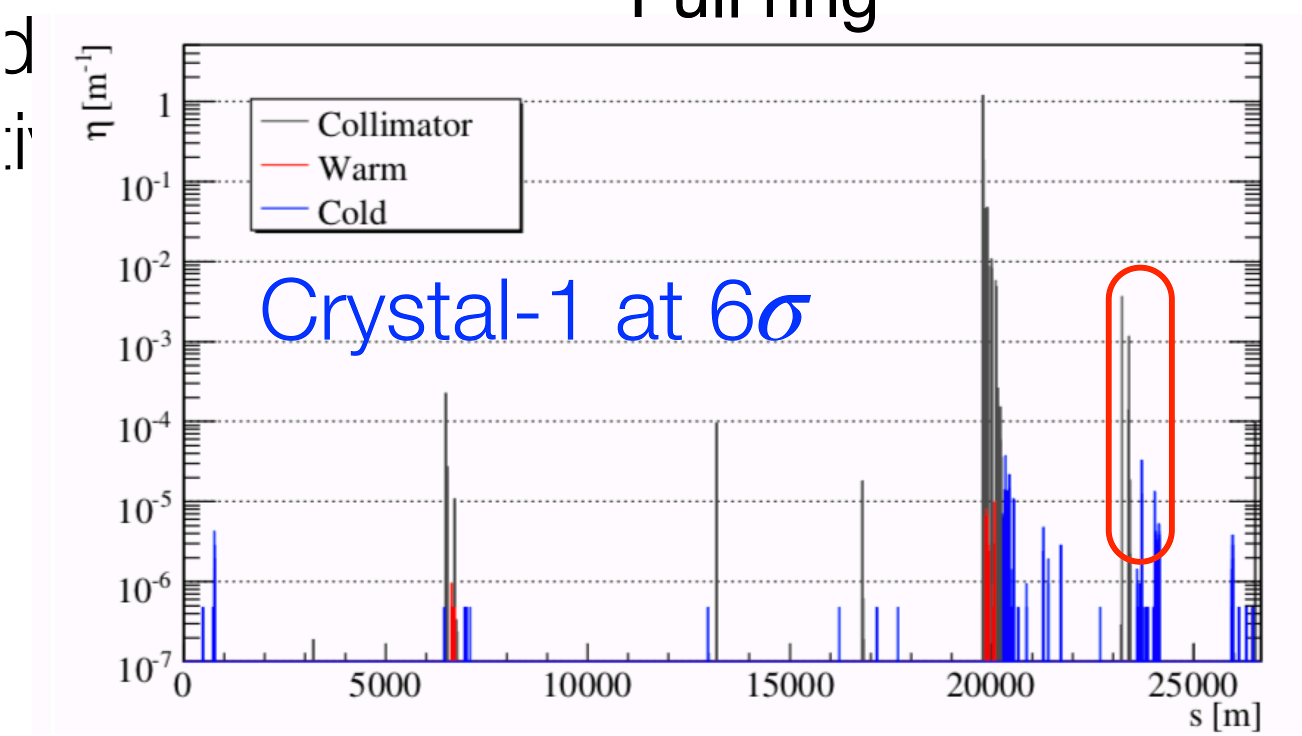
- All new devices in the vertical plane. 5mm long target of W
- Bending angle Cry2=14mrad, length=7cm

Machine simulations

- New collimators downstream of IR8 are quite effective in reducing losses
- Losses checked also for the scenario where crystal lost the angle alignment
  - CPV never observed in bar

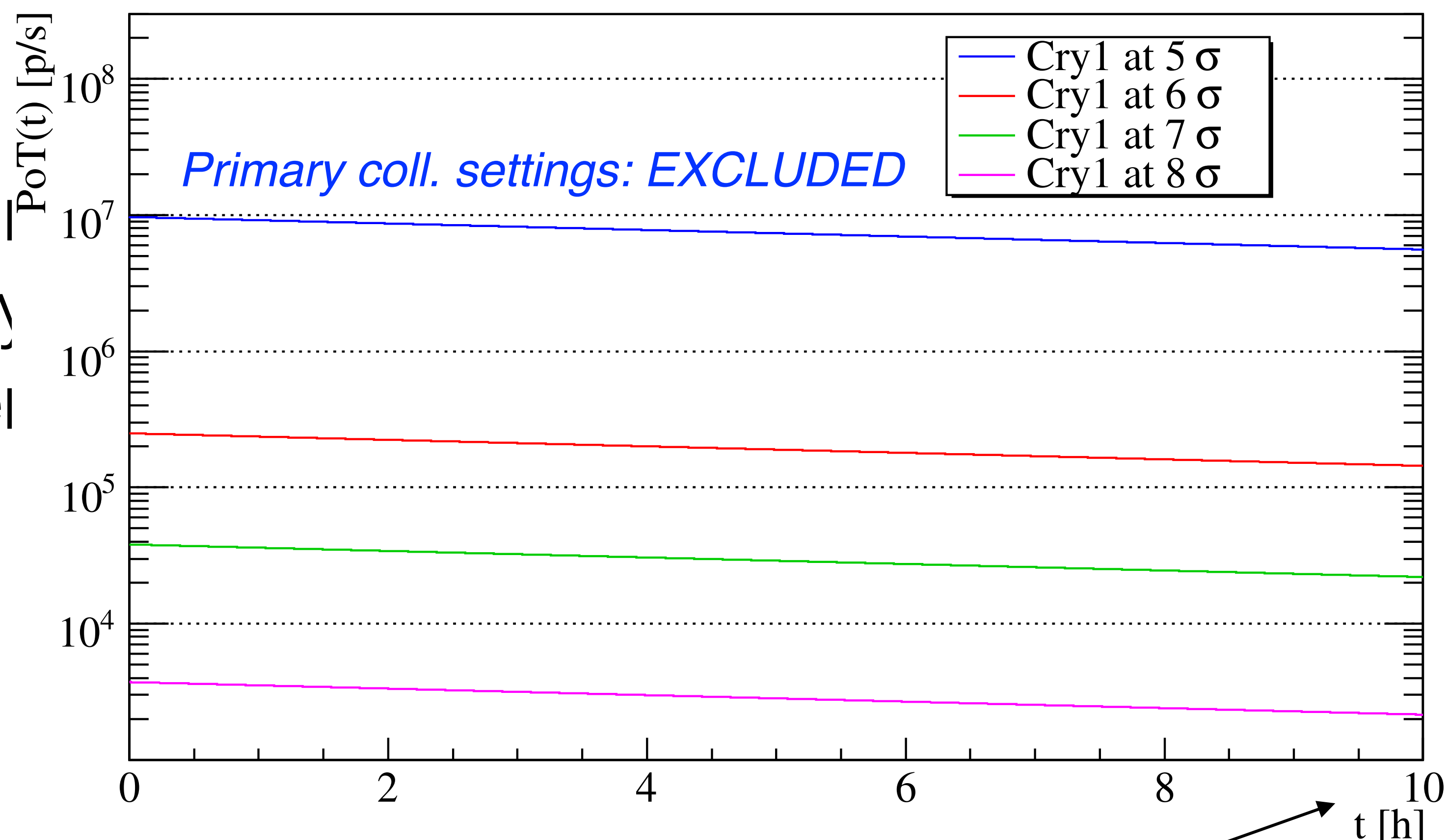


Full ring



Protons on Target

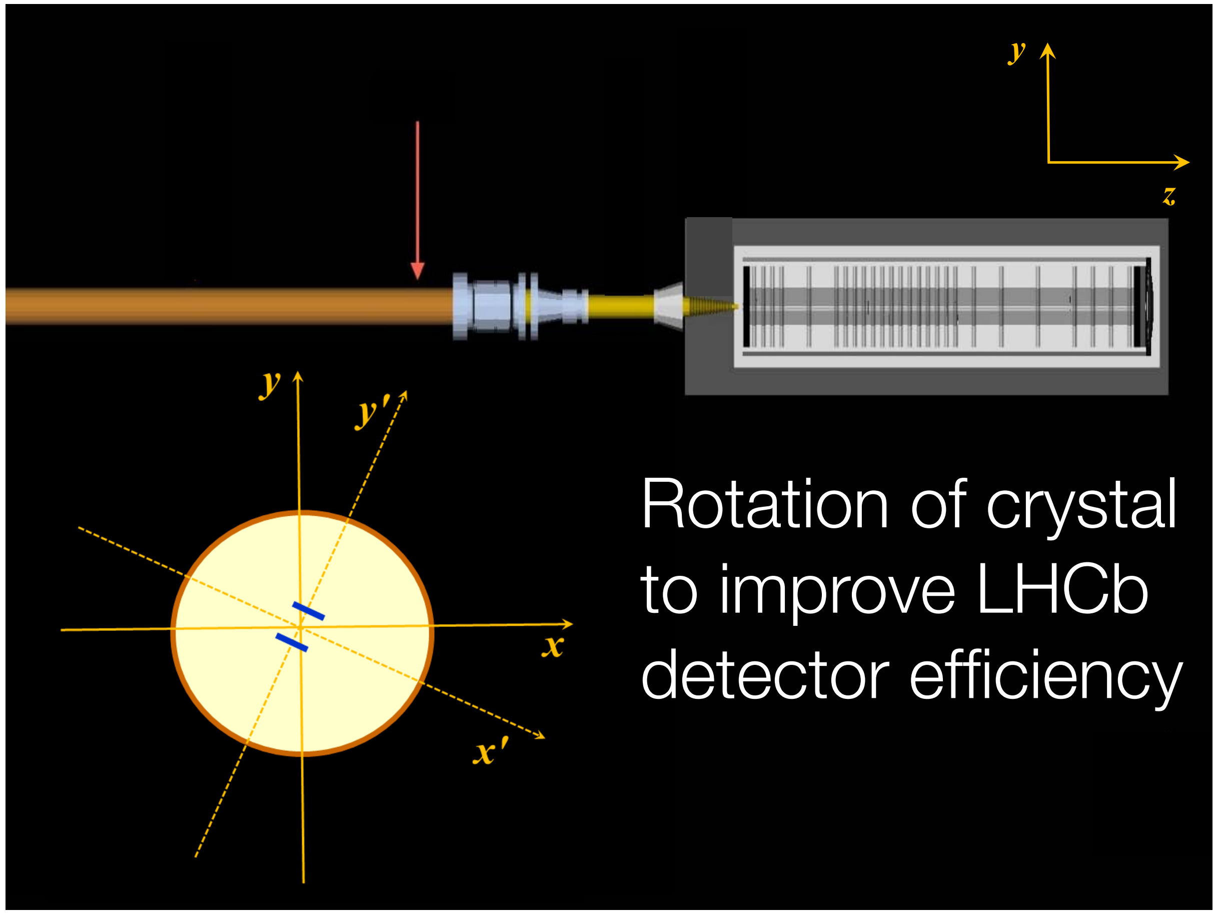
- Typical 10^6 p/s is feasible, possibility to reach 10^7 p/s
- 5σ line assumes 250 bunches, whereas the other cases are computed for the full machine ~ 2500 bunches
- CPV i[...]body decay[...]ring patter[...]hases

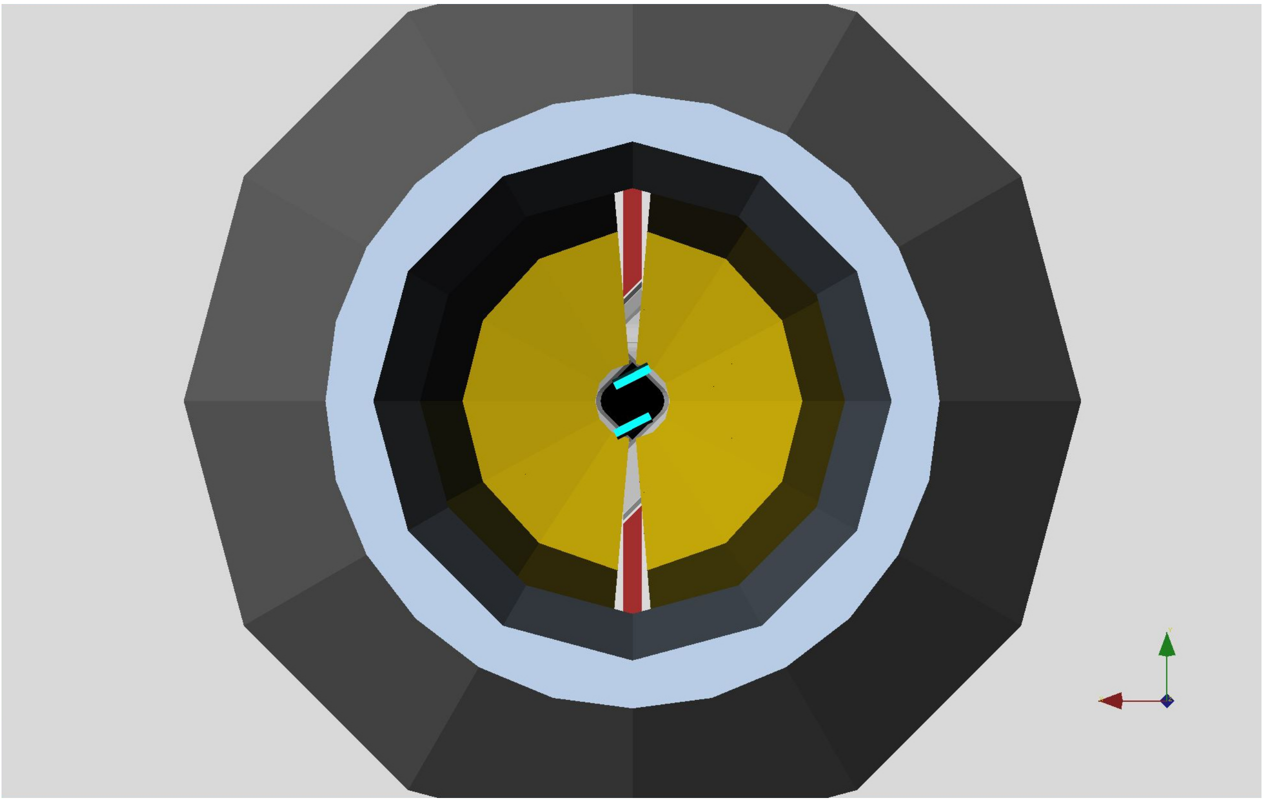


Time during stable beam, assuming typical losses.

Simulation studies

- Tungsten (W) 5mm fixed target + bent crystal positioned at 116cm before the interaction point

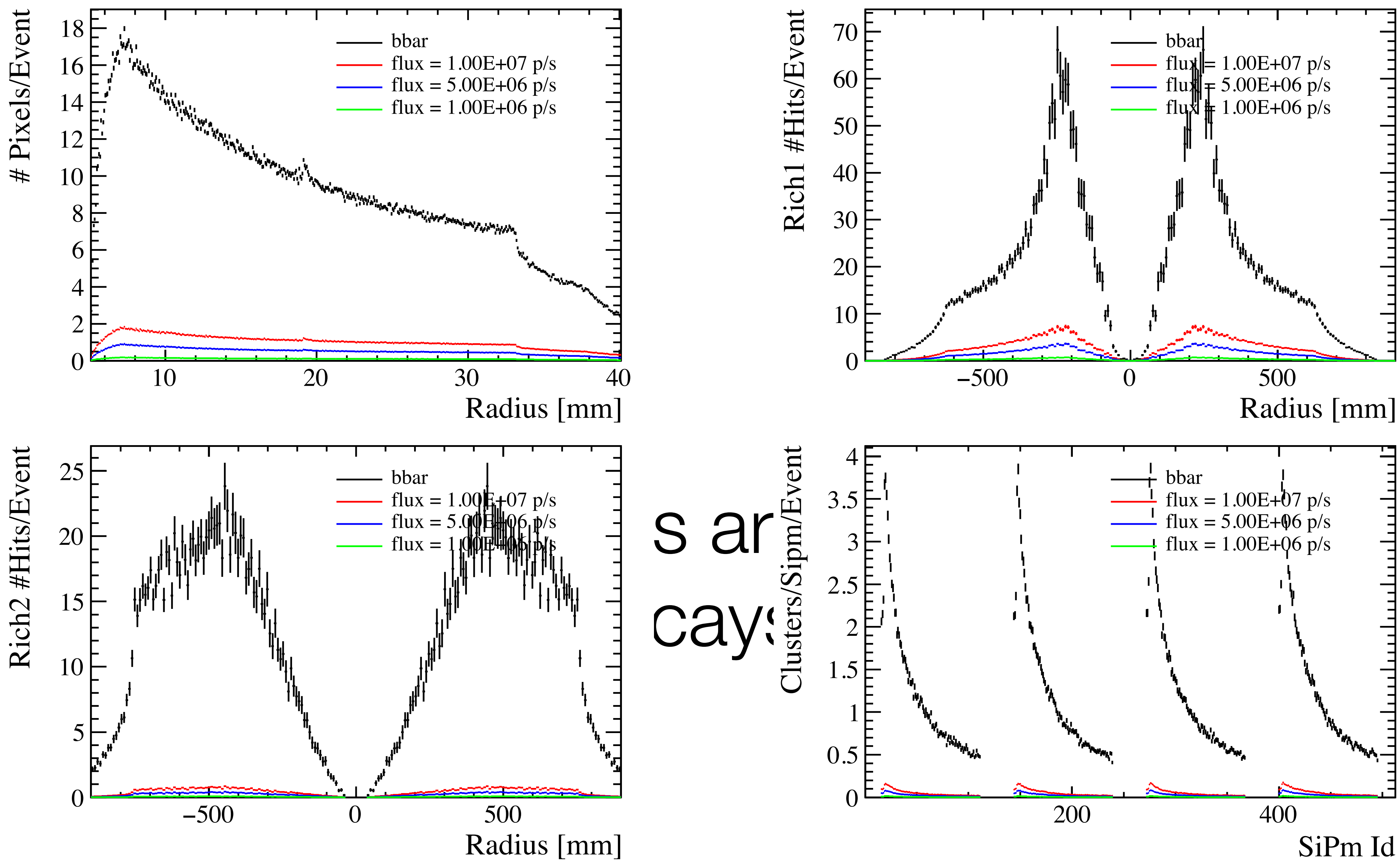




- Use EPOS for fixed target minimum bias events, PYTHIA for baryons produced in pW hard collisions
- Signal reconstruction and background rejection studied using LHCb full simulation

Detector occupancy

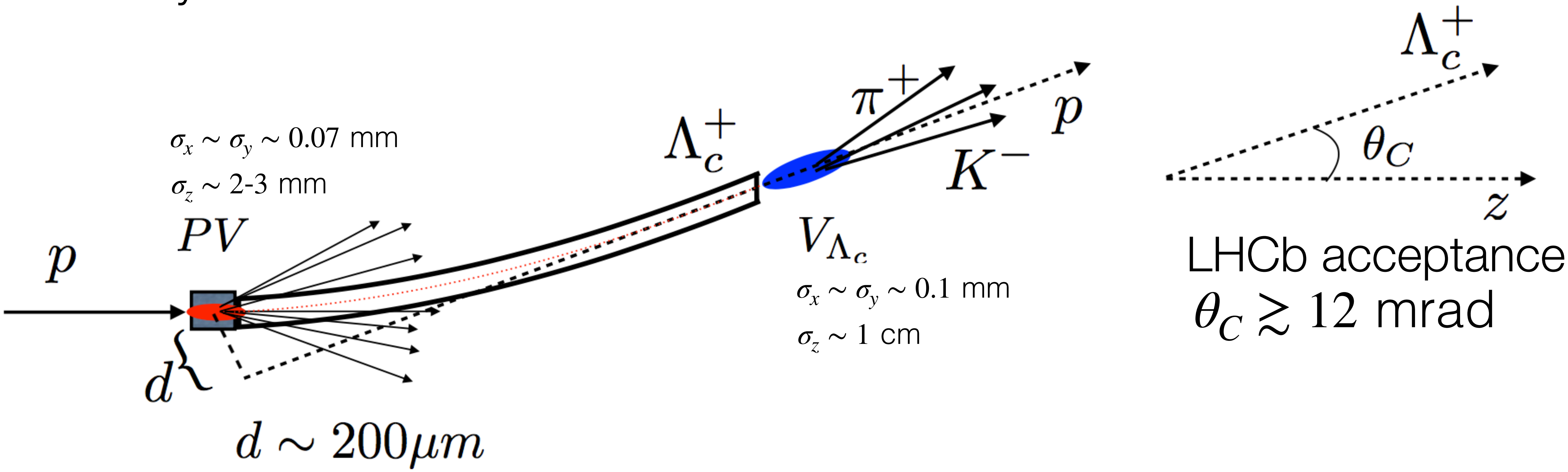
- W target size (10,2,10) mm



- Occupancies for **fixed-target events** under control wrt generic **bb events** (ν=7.6)

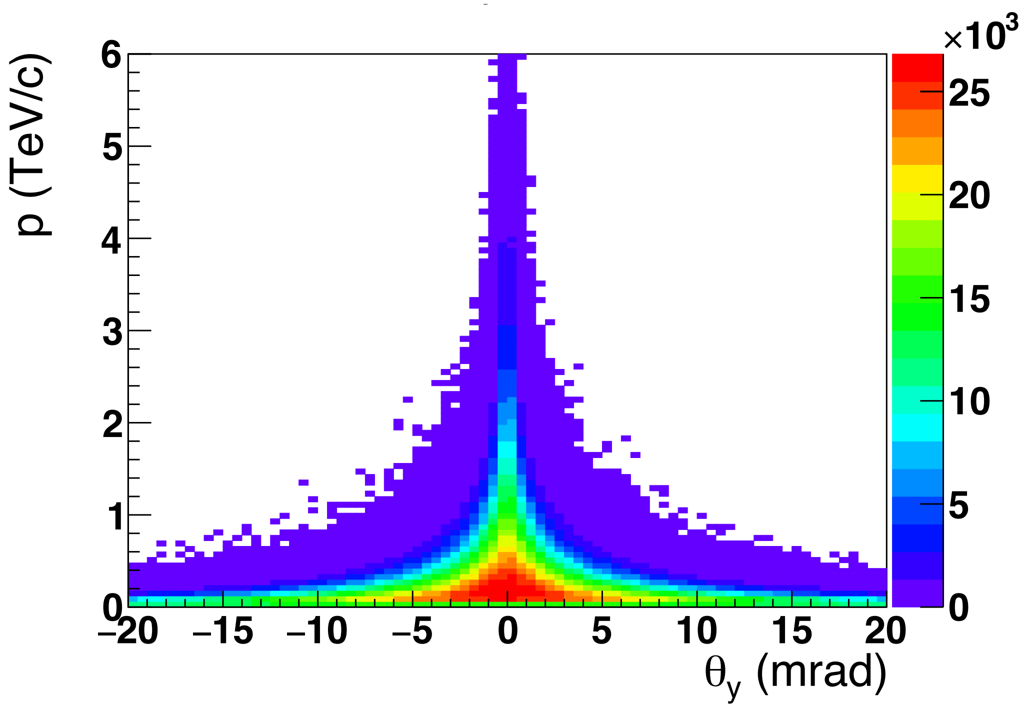
Identification of signal events

- About 10^-4 Λ_c^+ produced in the target are channeled in the bent crystal



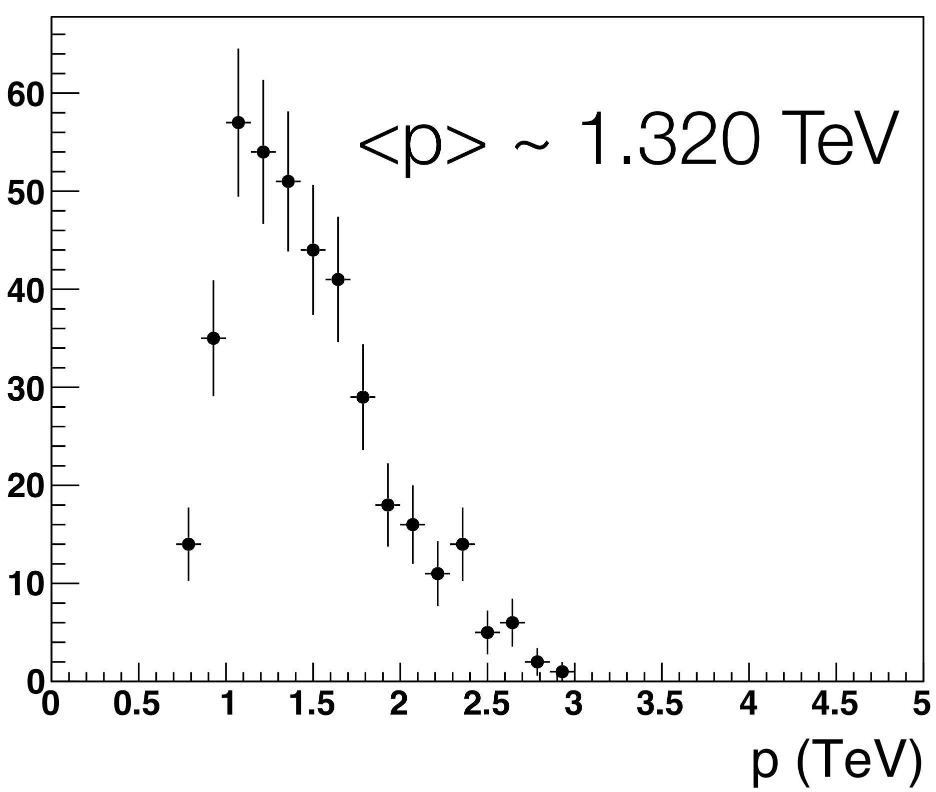
- Use PV to identify Λ_c^+ produced in W target, and Λ_c^+ vertex helps to identify decays outside of the crystal (max spin precession)
- Λ_c^+ angle determined by crystal bending angle, e.g. θ_C=15mrad
- Channeled baryons have high momentum $\gtrsim$ 1 TeV/c

Λ_c^+ momentum distribution

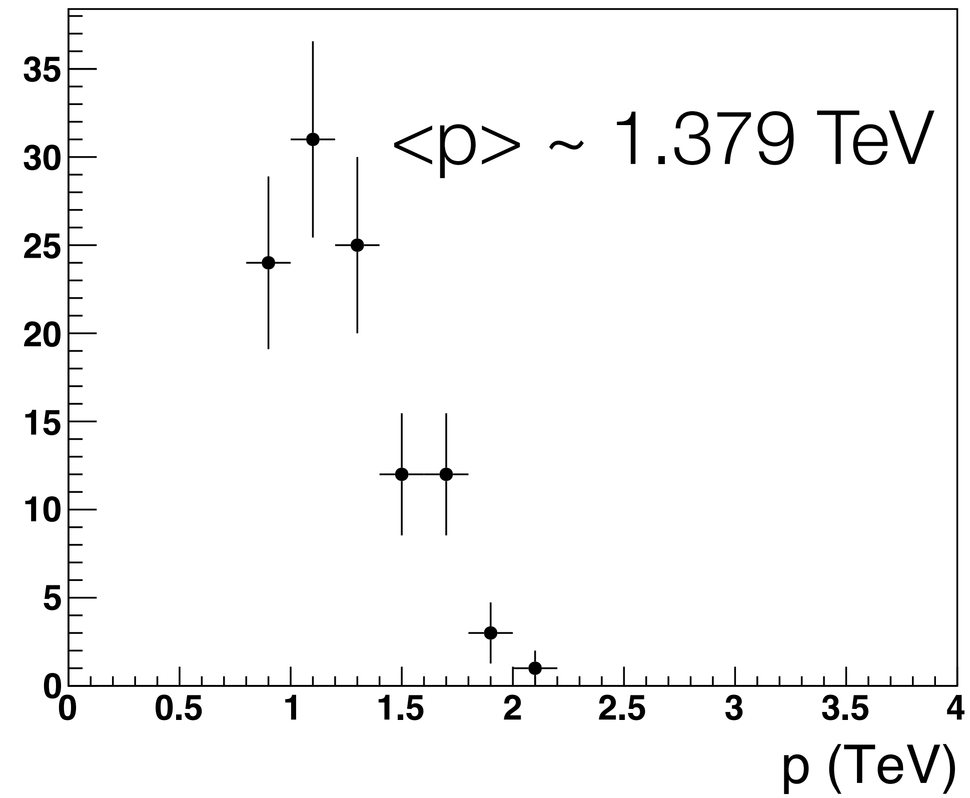


- At production (top)
- After channeling and p>800 GeV/c

Si, L~7cm, θC~14mrad



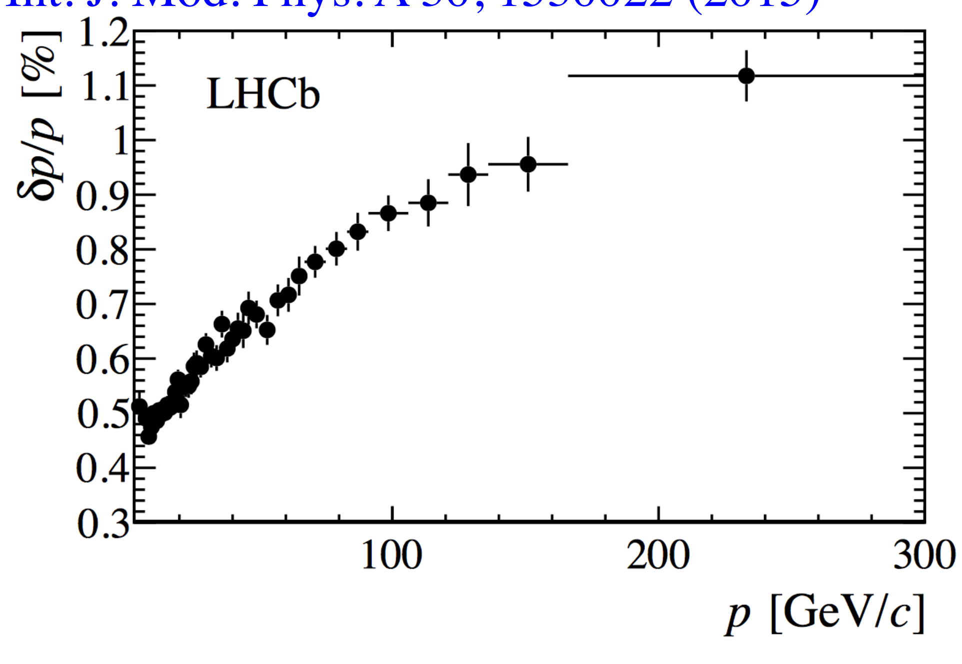
Ge, L~5cm, θC~15mrad

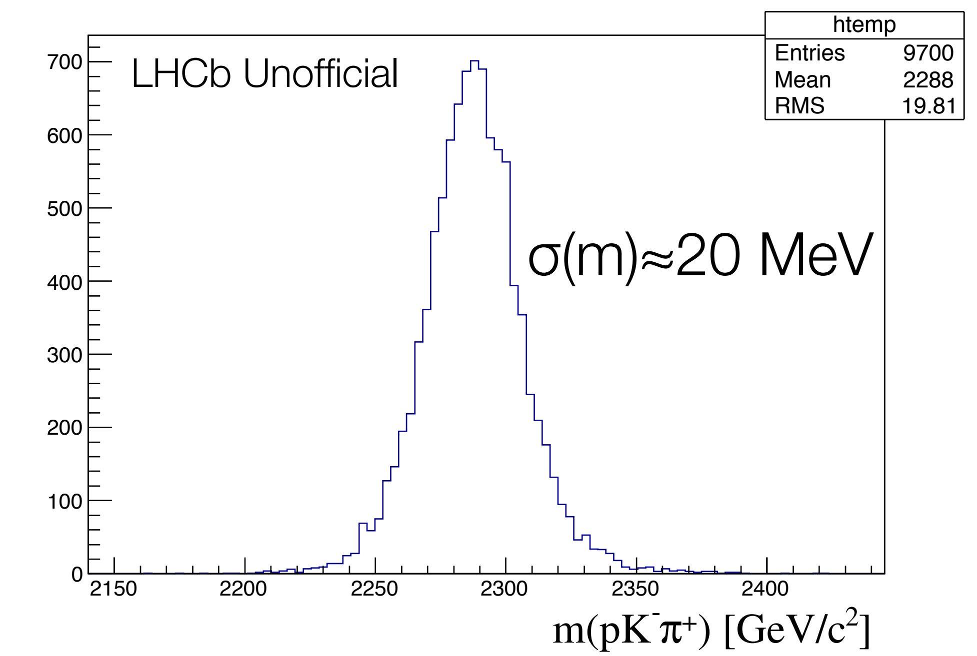


Reconstruction of signal events

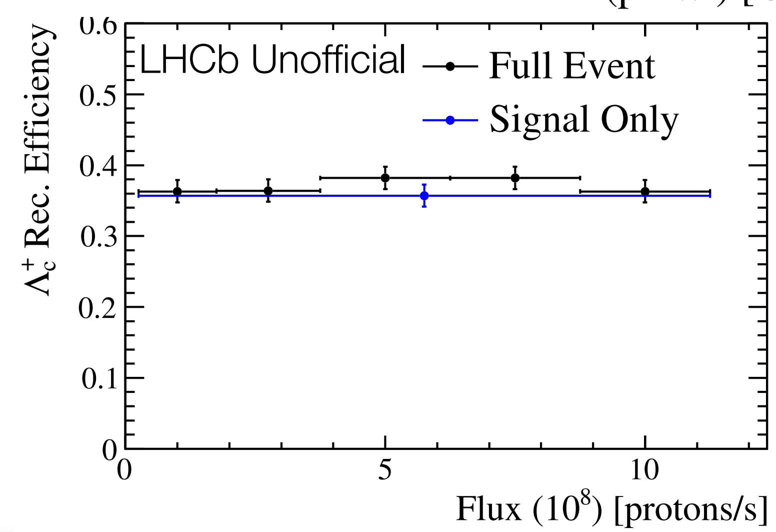
- LHCb Upgrade performs well in reconstructing these events
- $\Lambda_c^+ \to pK^-\pi^+$ daughter particles (p>300 GeV) have reduced momentum resolution >1%
- Invariant mass resolution 20 MeV is good enough for signal reconstruction and background rejection

Int. J. Mod. Phys. A 30, 1530022 (2015)



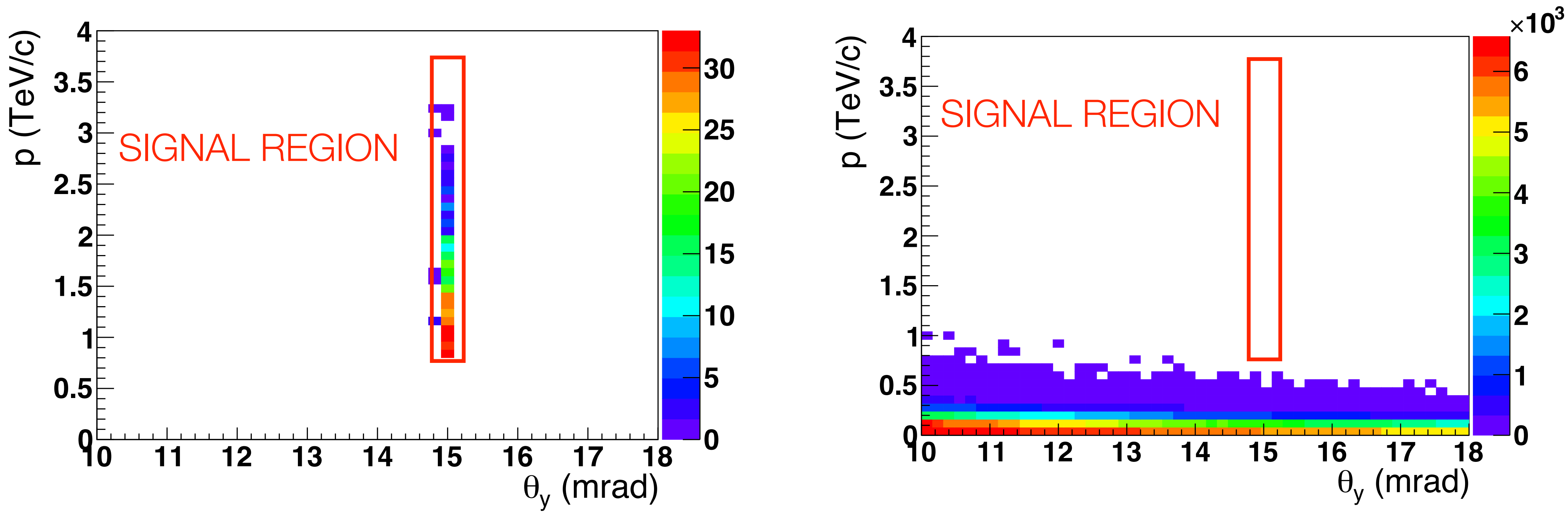


- Reconstruction independent on the proton flux



Background rejection

- Rejection of unchanneled Λ_c^+ produced in W target



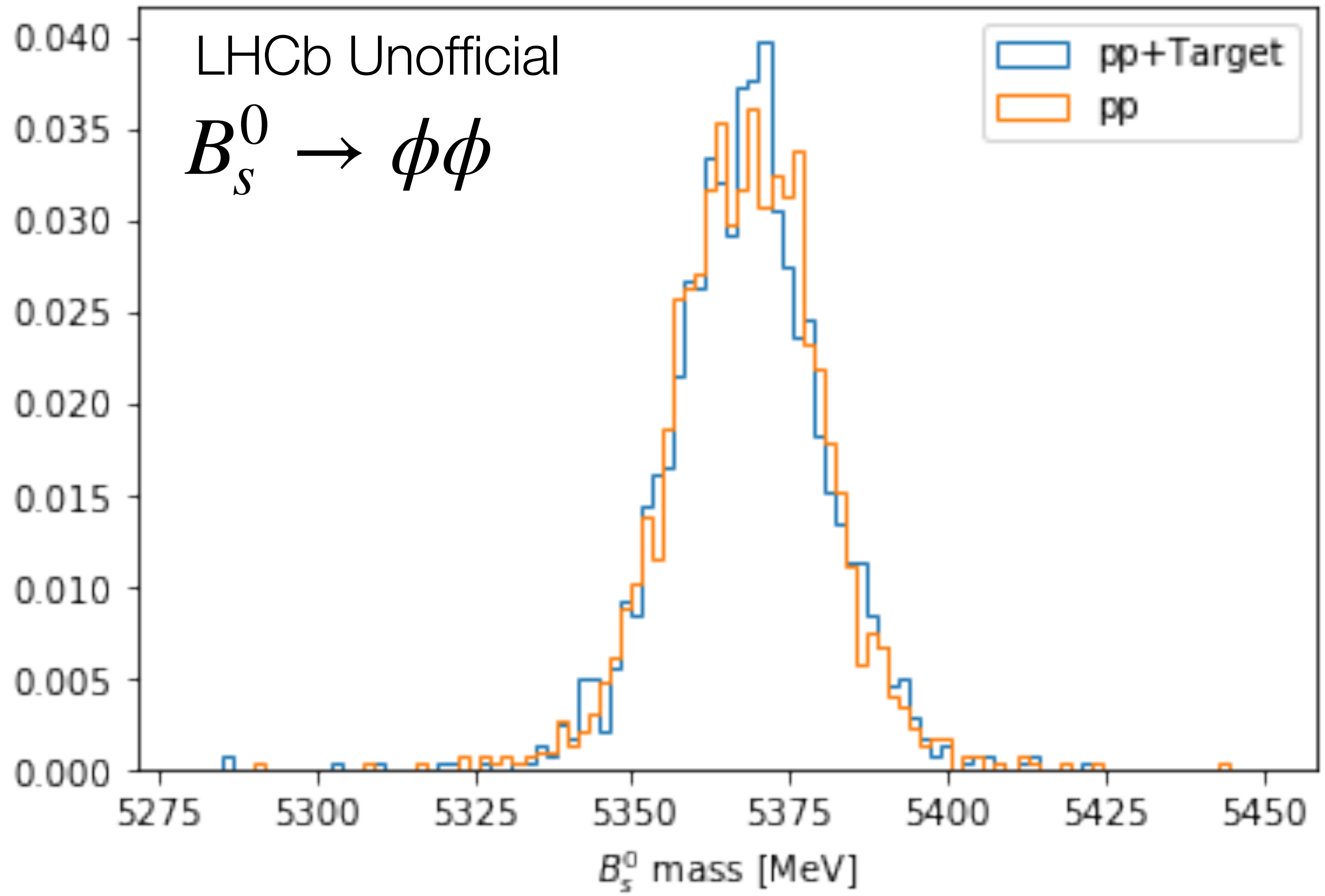
Channeled particles

Unchanneled particles

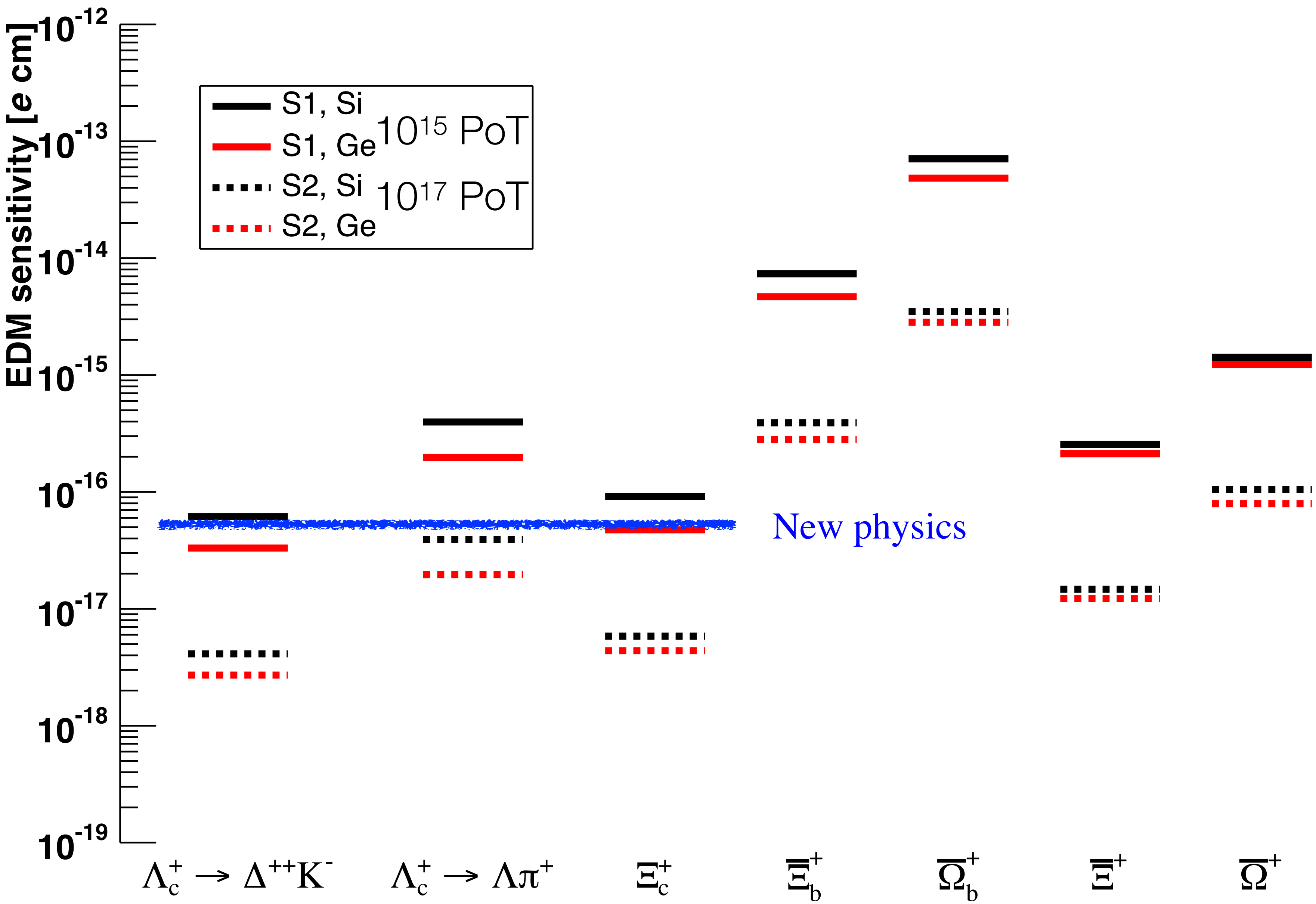
- Background rejection 10^{-7} level and signal efficiency 80%
- High momentum Λ_c^+ most sensitive for EDM measurements

Synergetic run with LHCb

- Synergetic running with LHCb feasible for small flux < 10^7 p/s
- Simulated one PV in the target and ν=7.6 pp collisions
- The presence of the target doesn't impact the reconstruction of pp events



Sensitivity on EDM



PoT: protons on target
W target 5 mm thick

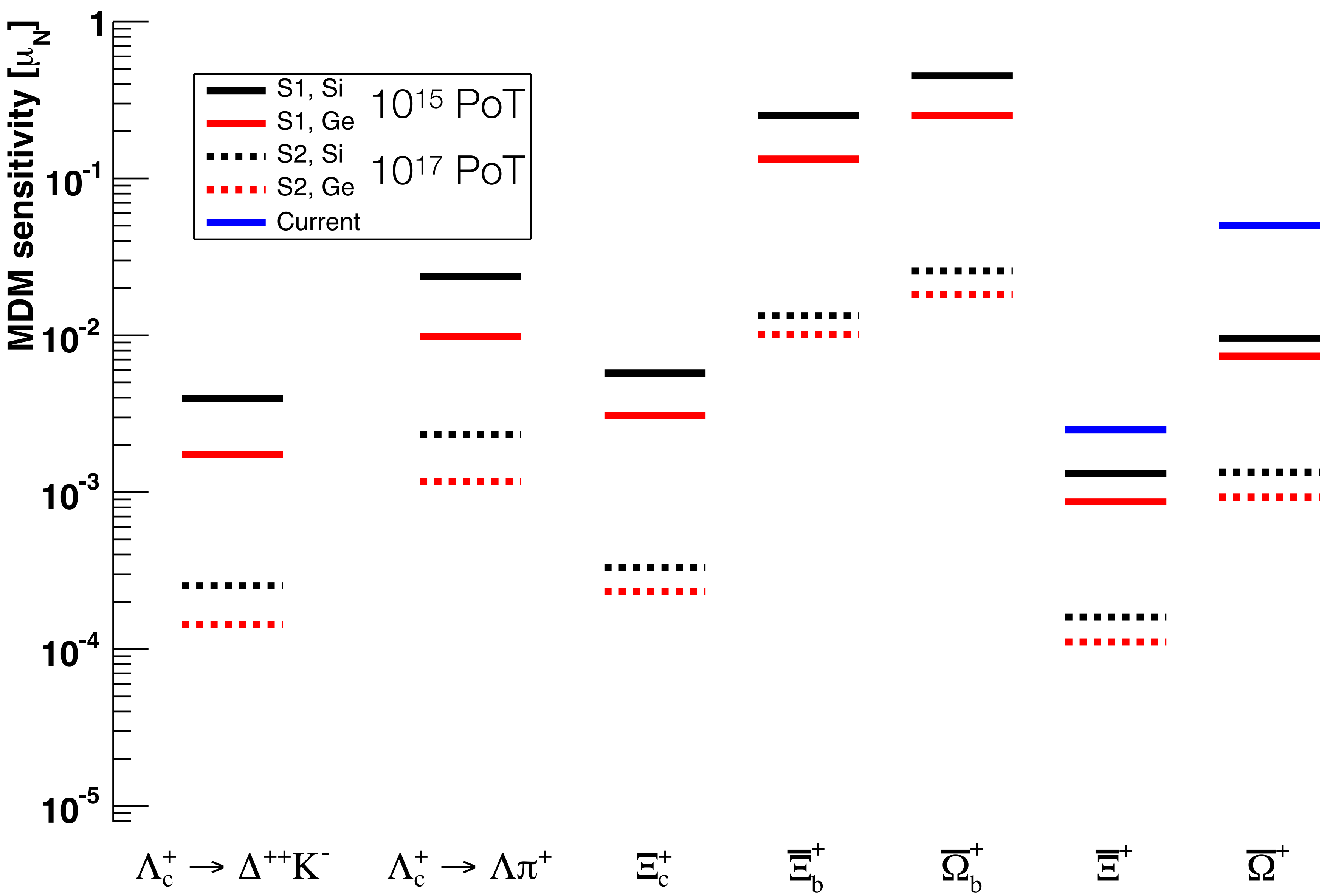
EPJC 77 (2017), 828

S1: configuration at LHCb
S2: dedicated experiment at LHC

Material of the crystal:
→ **Silicon**
→ **Germanium**

- Technique applies to all short-lived positive baryons
- Possibility to test new physics models

Sensitivity on MDM



PoT: protons on target
W target 5 mm thick

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S1: configuration at LHCb
S2: dedicated experiment at LHC

Material of the crystal:
→ **Silicon**
→ **Germanium**

- First MDM measurements

Conclusions

- Experimental proposal for unique baryon EDM/MDM measurements in LHCb was presented
- Those searches will extend the new physics discovery potential of LHC
- Synergetic runs with pp collisions feasible

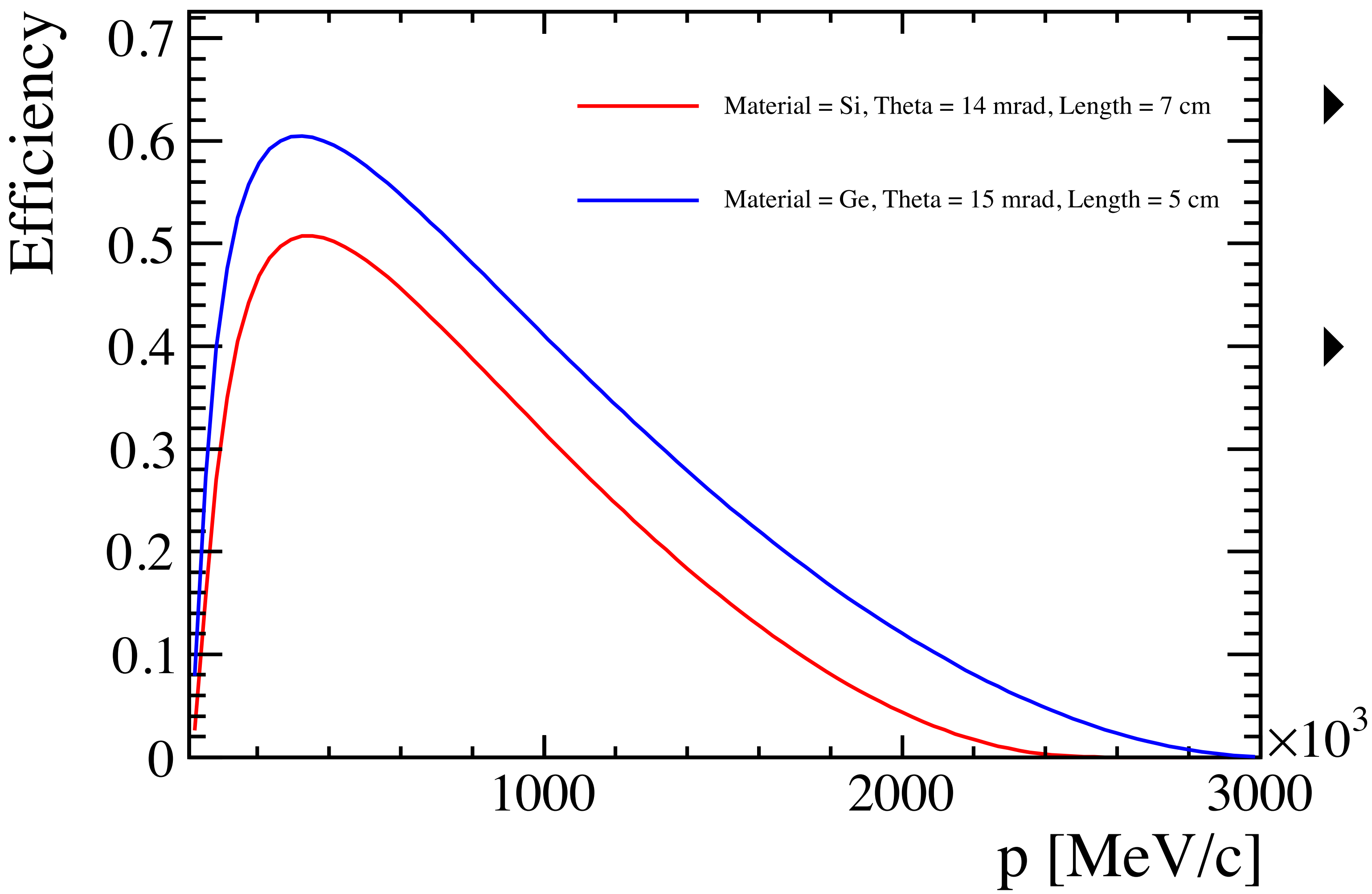
Aknowledgment

- Proponents within LHCb: S. Aiola, J. Fu, L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N. Neri, P. Robbe, J. Ruiz Vidal
- References:

- E. Bagli, L. Bandiera, G. Cavoto, V. Guidi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Mazzolari, A. Merli, N. Neri, J. Ruiz Vidal, *Electromagnetic dipole moments of charged baryons with bent crystals at the LHC*, arXiv: 1708.08483 (2017), Eur. Phys. J. C **77** (2017) 828.
- A.S. Fomin , A.Yu. Korchin, A. Stocchi, O.A. Bezshyyko, L. Burmistrov, S.P. Fomin, I.V. Kirillin, L. Massacrier , A. Natochii, P. Robbe, W. Scandale, N.F. Shul'ga, *Feasibility of measuring the magnetic dipole moments of the charm baryons at the LHC using bent crystals*, JHEP **1708** (2017) 120.
- V. G. Baryshevsky, *On the search for the electric dipole moment of strange and charm baryons at LHC and parity violating (P) and time reversal (T) invariance violating spin rotation and dichroism in crystal,* arXiv:1708.09799 (2017).
- L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N. Neri, P. Robbe, J. Ruiz Vidal, CERN- LHCb-INT-2017-011, *Proposal to search for baryon EDMs with bent crystals at LHCb*.
- F. J. Botella, L. M. Garcia Martin, D. Marangotto, F. Martinez Vidal, A. Merli, N. Neri, A. Oyanguren, J. Ruiz Vidal, *On the search for the electric dipole moment of strange and charm baryons at LHC*, Eur. Phys. J. C **77** (2017) 181.
- V. G. Baryshevsky, *The possibility to measure the magnetic moments of short-lived particles (charm and beauty baryons) at LHC and FCC energies using the phenomenon of spin rotation in crystals*, Phys. Lett. B**757** (2016) 426.
- L. Burmistrov, G. Calderini, Yu Ivanov, L. Massacrier, P. Robbe, W. Scandale, A. Stocchi, *Measurement of short living baryon magnetic moment using bent crystals at SPS and LHC*, CERN-SPSC-2016-030 ; SPSC-EOI-012.

Back-up slides

Channeling efficiency



- Channeling efficiency for Λ_C^+ particles within Lindhard angle
- Total channelling efficiency: Lindhard angle, dechanneling, Λ_C^+ decay flight: $1 \cdot 10^{-5}$ (Si), $4 \cdot 10^{-5}$ (Ge)

$$w(\theta_C, R) = \left(1 - \frac{R_c}{R}\right)^2 \exp\left(-\frac{\theta_C}{\theta_D \frac{R_c}{R}(1 - \frac{R_c}{R})^2}\right)$$

- Parametrisation from Biryukov, Valery M. (et al.), *Crystal Channeling and Its Application at High-Energy Accelerators*, Springer Verlag (1997)

Sensitivity to EDM/MDM

- Studies based on:
  - Λ_c^+ from fixed-target (Pythia + EvtGen)
  - Reconstruction, Decay flight efficiency (LHCb simulation)
  - Channeling efficiency (parametrization)
  - Fit to spin precession (pseudo experiments)

$$N^{\text{reco}}_{\Lambda_c^+} = N_{\Lambda_c^+}\mathcal{B}(\Lambda_c^+ \to f)\varepsilon_{\text{CH}}\varepsilon_{\text{DF}}\varepsilon_{\text{det}}$$

$$\sigma(pp \to \Lambda_c^+ X) \approx 18.2\mu\text{b}$$

$$|S_0| \approx 0.6$$

$$\epsilon_{\text{det}} \approx 20\,\% \qquad \epsilon_{\text{DF}} \approx 10\,\%$$

$$\epsilon_{\text{ch}} \approx 10^{-4}$$

$$\frac{dN}{d\Omega} \propto 1 + \alpha_f\, \boldsymbol{S}\cdot\boldsymbol{p}$$

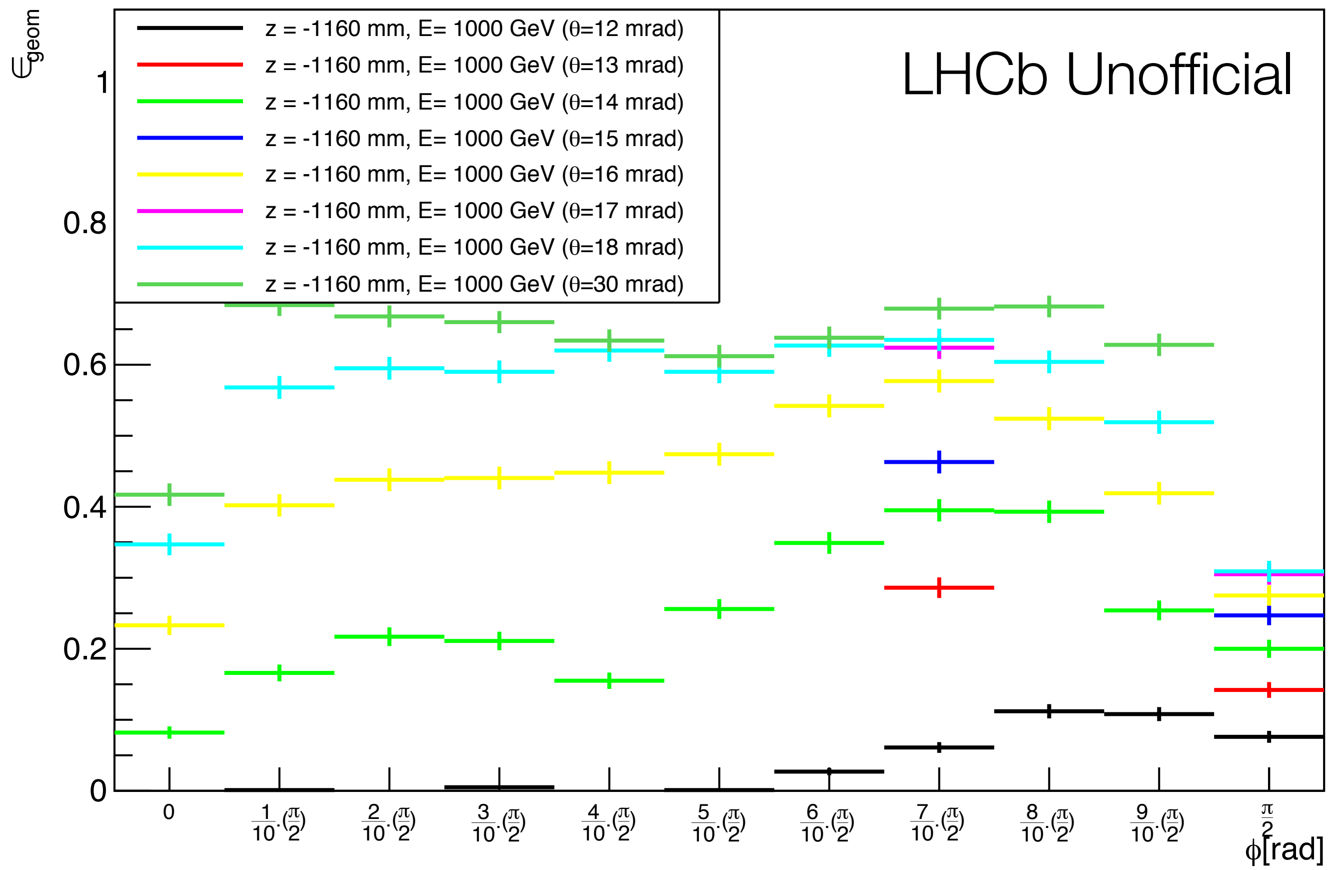
$$\alpha_{\Delta^{++}K^-} \approx -0.67$$

$$\sigma_d \approx \frac{g-2}{\alpha_f s_0 (\cos\Phi - 1)} \frac{1}{\sqrt{N^{\text{reco}}_{\Lambda_c^+}}}$$

$$\sigma_g \approx \frac{2}{\alpha_f s_0 \gamma \theta_C} \frac{1}{\sqrt{N^{\text{reco}}_{\Lambda_c^+}}}$$

LHCb acceptance

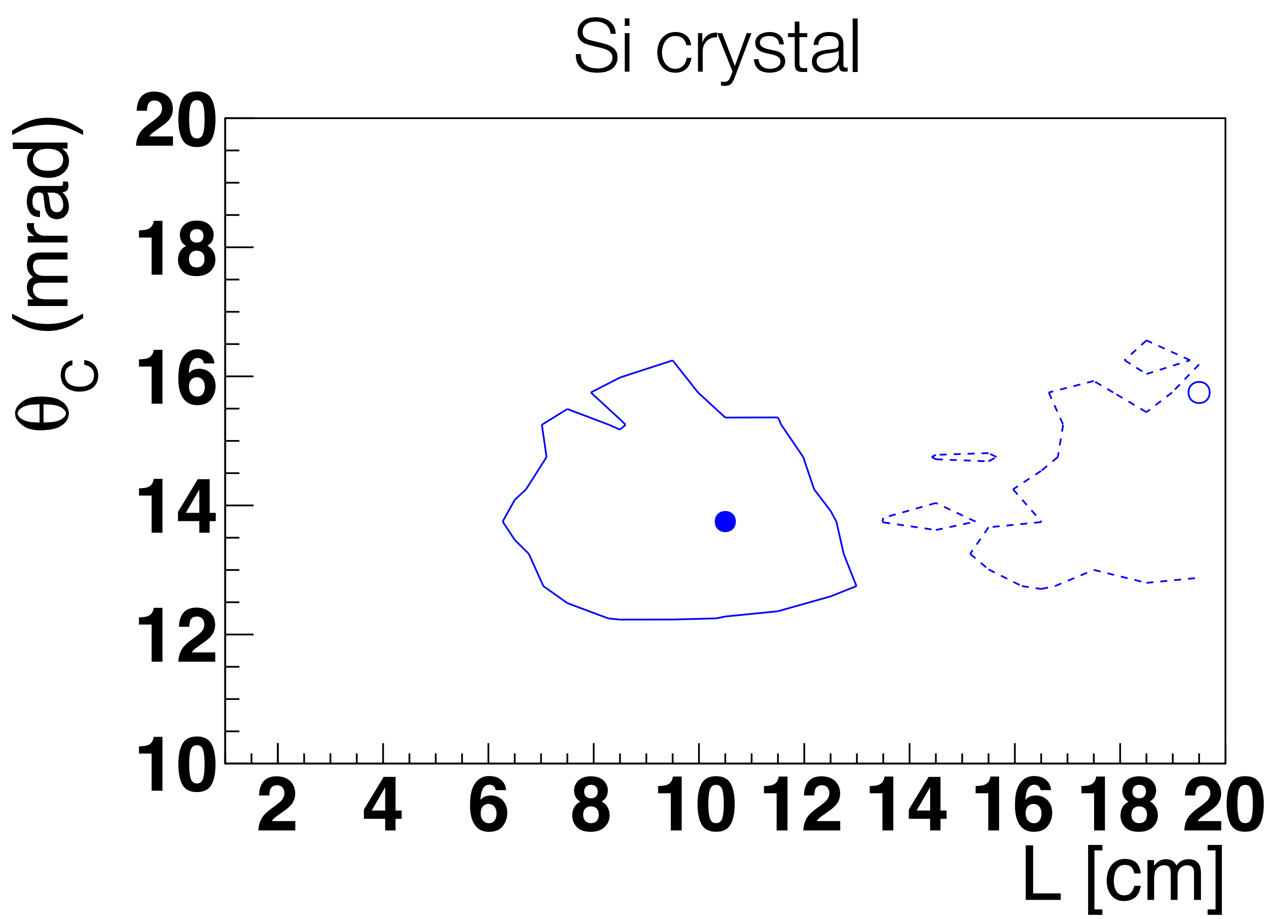
- Channeled particles with crystals with bending angle < 14/15mrad has low reconstruction efficiency

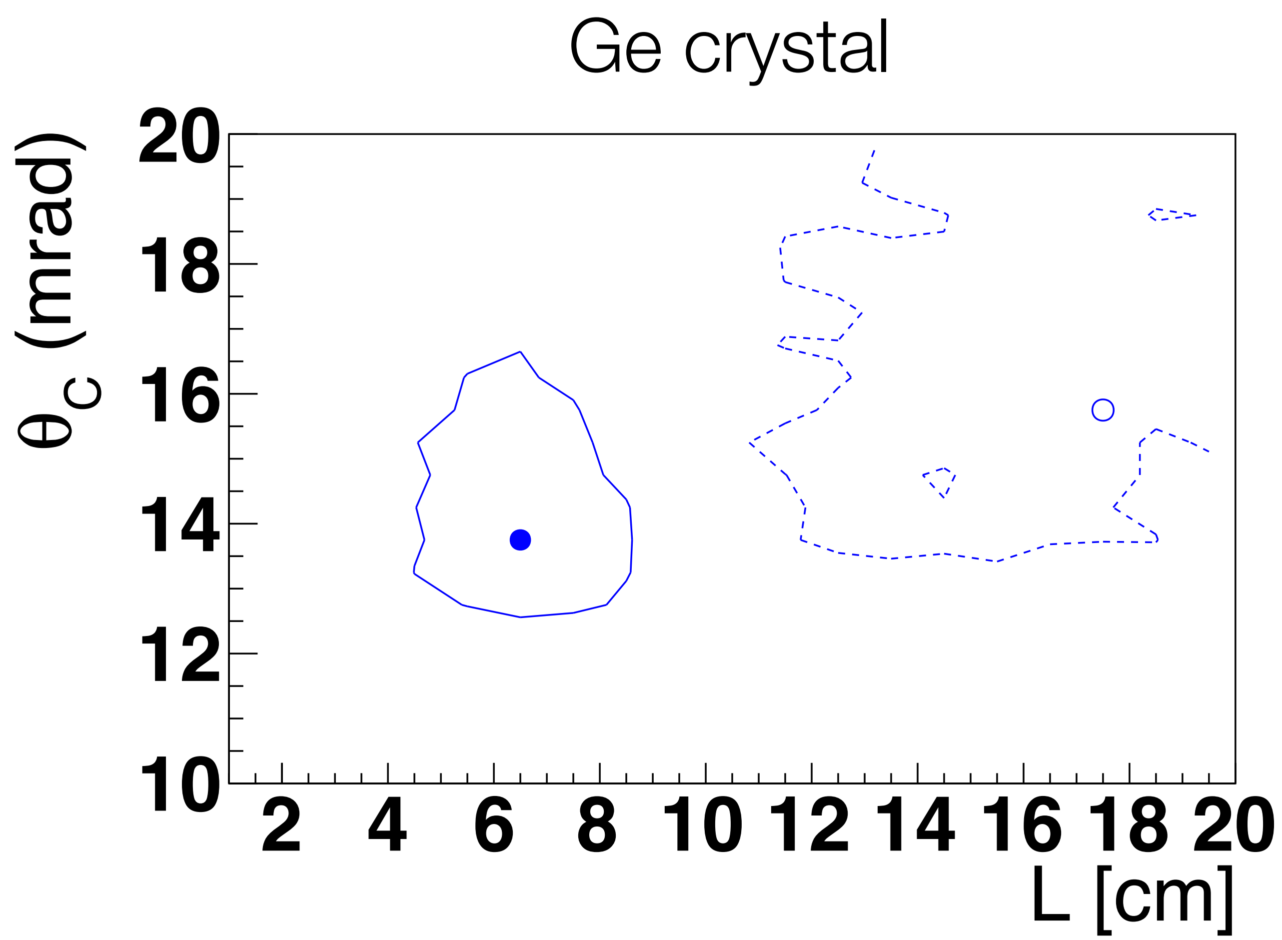


- Dependence of the reconstruction efficiency over azimuthal angle due to the LHCb detector geometry

Crystal optimisation

- Optimised sensitivity to EDM and MDM
- Channeling and reconstruction efficiency included





- Regions of minimal uncertainty of EDM (continuous line) and MDM (dotted line) defined as +20% uncertainty wrt the minimum (point marker)