Direct measurement of electromagnetic dipole moments of charm baryons at LHC (part of the PBC-FT WG at CERN)

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Fixed Target Experiments at LHC - Strong 2020

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UNIVERSITÀ DEGLI STUDI DI MILANO
SELDOM
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SELDOM webpage

Outline

- Introduction and physics motivations
- Experimental method to measure dipole moments for charm baryons
- R&D and preparatory studies

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- **Introduction and physics motivations**
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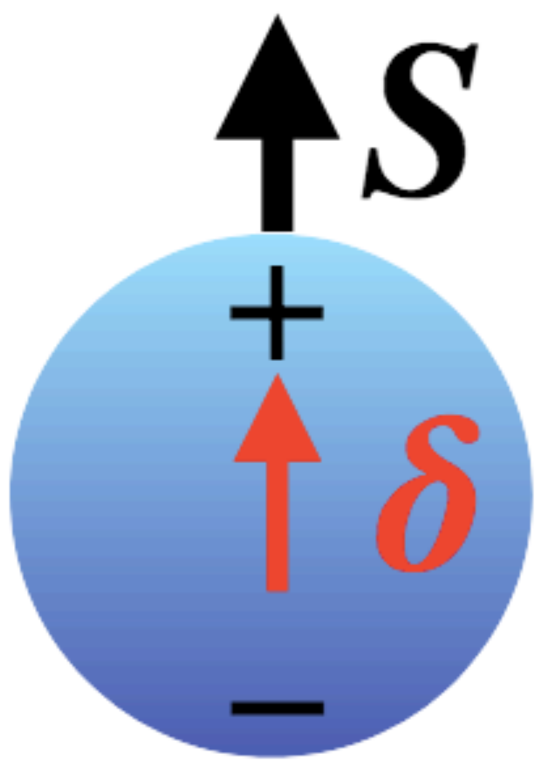
Electromagnetic dipole moments

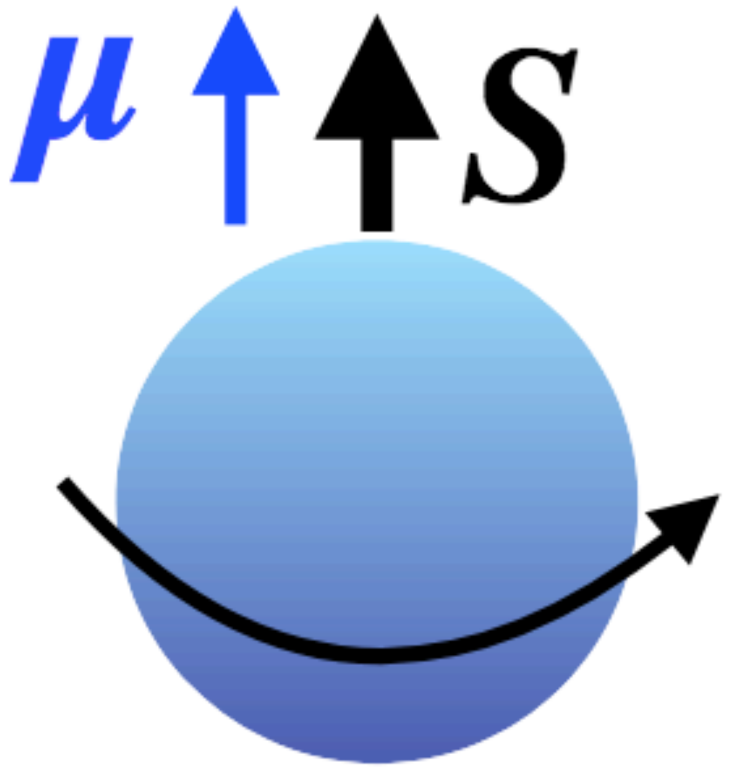
δ = electric dipole moment (EDM)

μ = magnetic dipole moment (MDM)

- Quantum system:

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





- Hamiltonian:

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

Time reversal (T), parity (P): $\xrightarrow{\text{T}} +\boldsymbol{\delta} \cdot \boldsymbol{E} - \boldsymbol{\mu} \cdot \boldsymbol{B}$

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

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

Physics motivation for EDM measurements

- CP violation (CPV) is a necessary condition for baryogenesis:

New CPV sources are expected to exists

EDM: a probe for CPV beyond the SM

$$\mathscr{L}_{CPV} = \mathscr{L}_{CKM} + \mathscr{L}_{\bar{\theta}} + \mathscr{L}_{BSM}$$

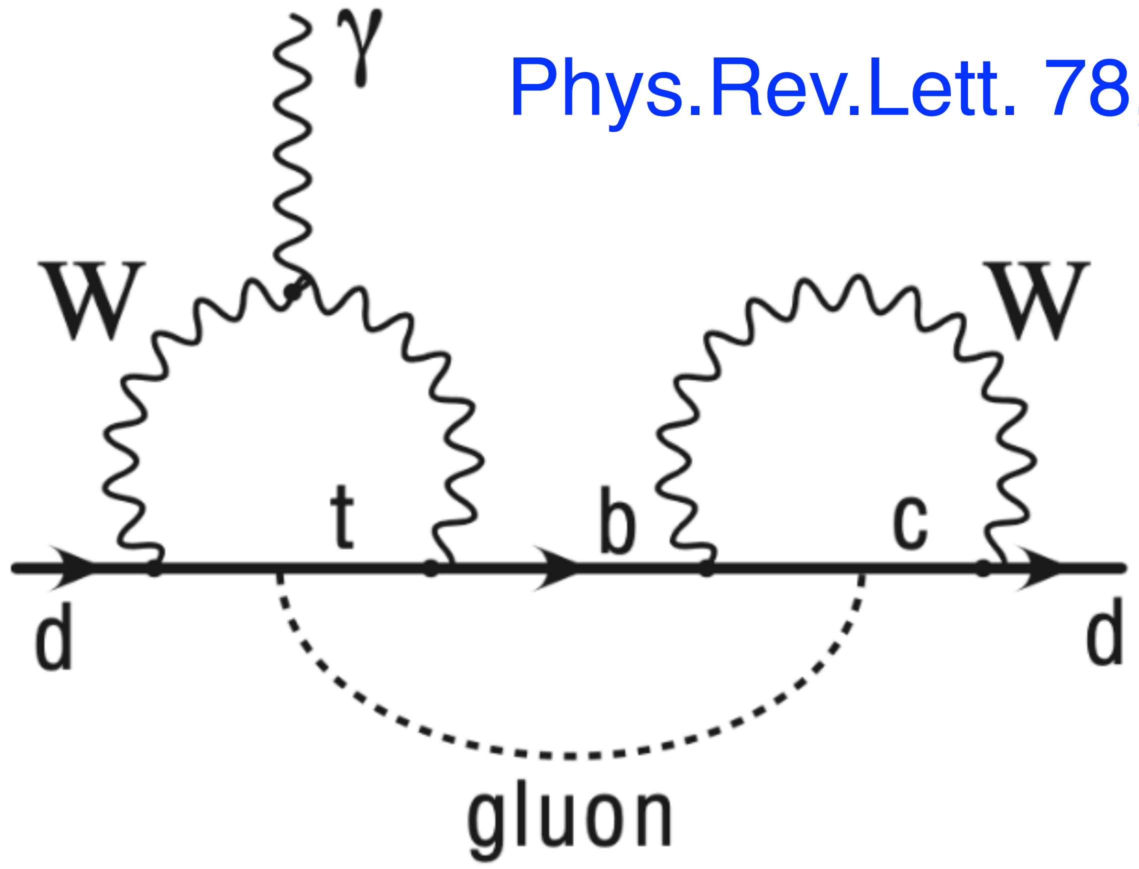
- CPV in weak interactions via CKM mechanism in the SM is too small
- $\bar{\theta}$-QCD for possible CPV in strong interactions allowed in the SM. Stringent experimental limit from neutron EDM:

$$\delta_n \approx (10^{-16}\, e\,\text{cm})\bar{\theta} < 1.8 \times 10^{-26}\, e\,\text{cm} \implies \bar{\theta} \lesssim 10^{-10}$$

Example of SM CKM contribution

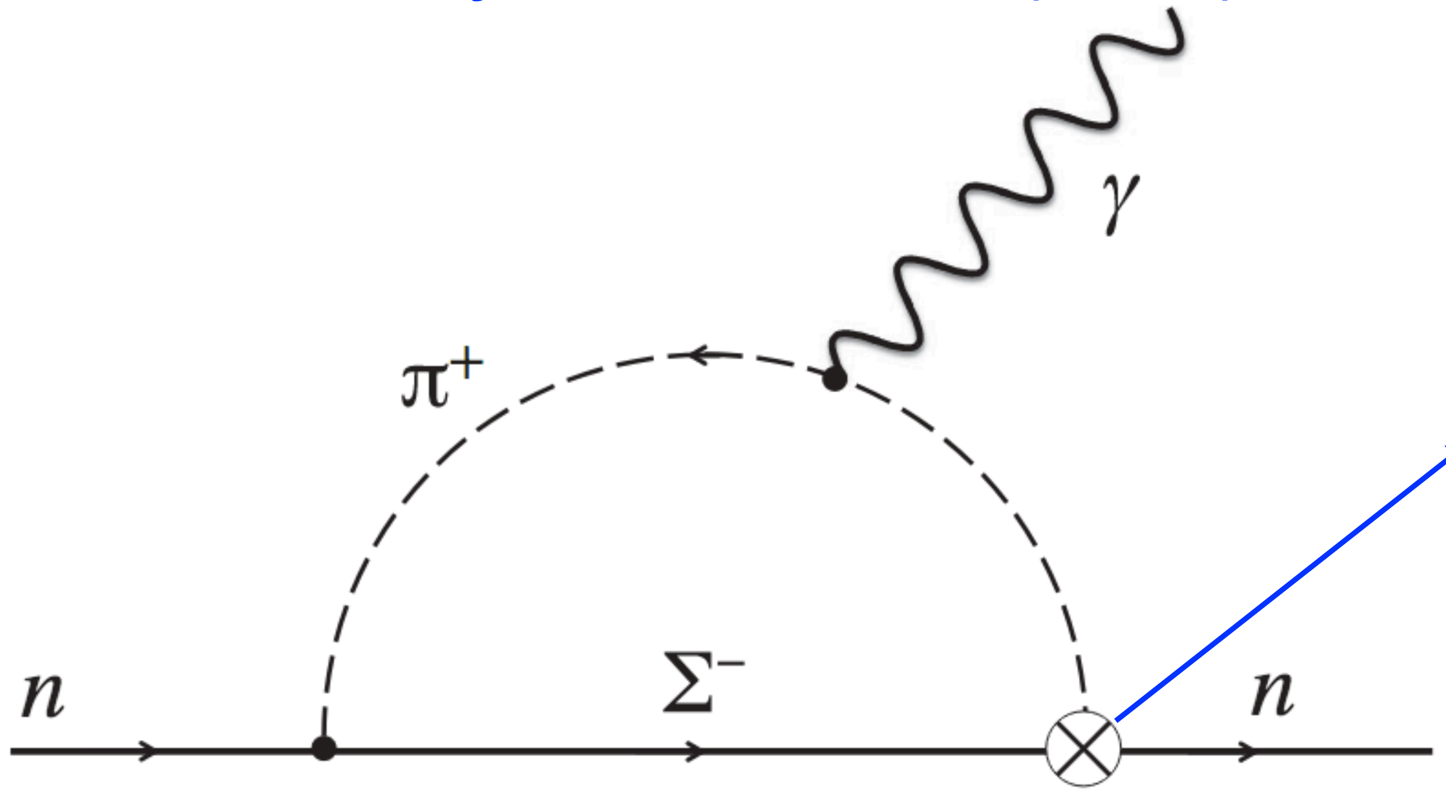
$$\delta_d \propto Im\left(V_{tb}V^*_{td}V_{cd}V^*_{cb}\right) m_d m_c^2 \alpha_S G_F^2 \approx 10^{-34}\, e\,\text{cm}$$

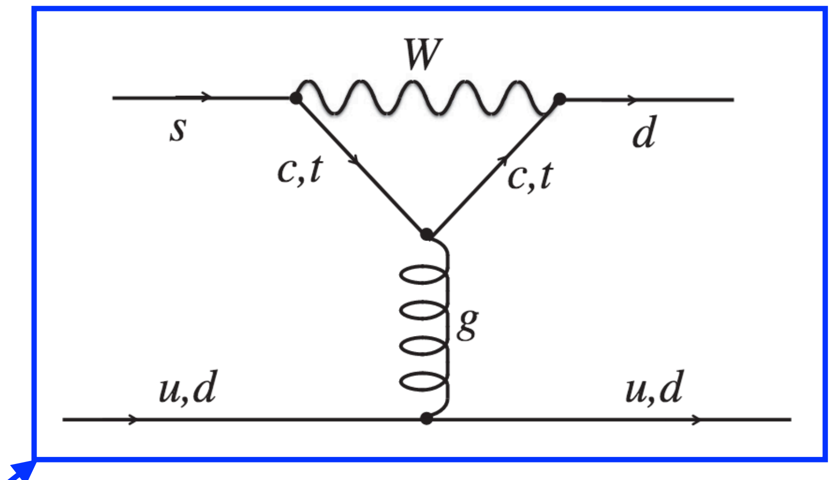
Phys.Rev.Lett. 78, 4339 (1997)



“Long distance” contribution

Rev.Mod.Phys. 91, 015001 (2019)





EDM: a probe for CPV beyond the SM

$$\mathscr{L}_{CPV} = \mathscr{L}_{CKM} + \mathscr{L}_{\bar{\theta}} + \mathscr{L}_{BSM}$$

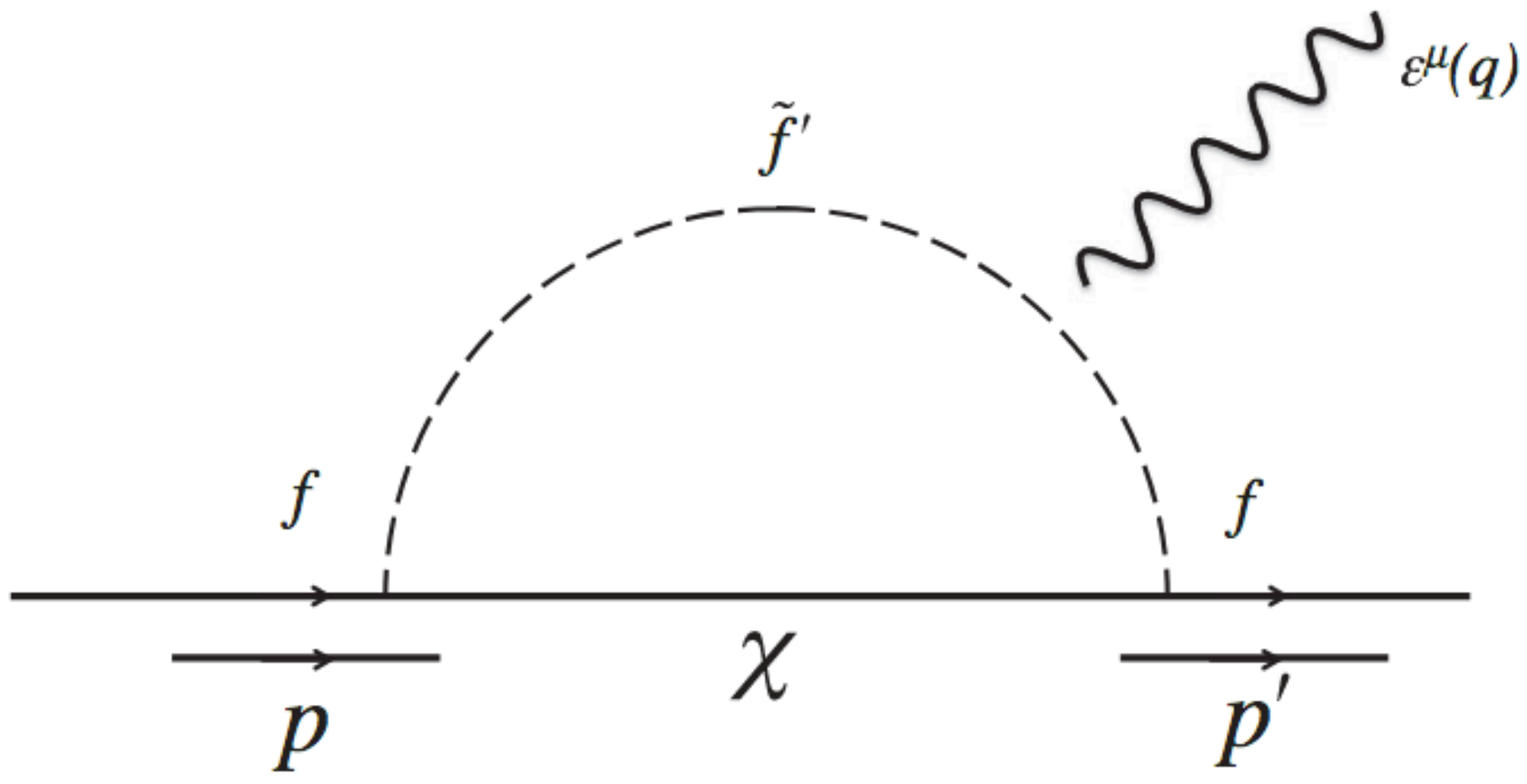
- BSM: potential large contributions by new physics scale Λ_{NP} and CP violation phase ϕ_{CPV}

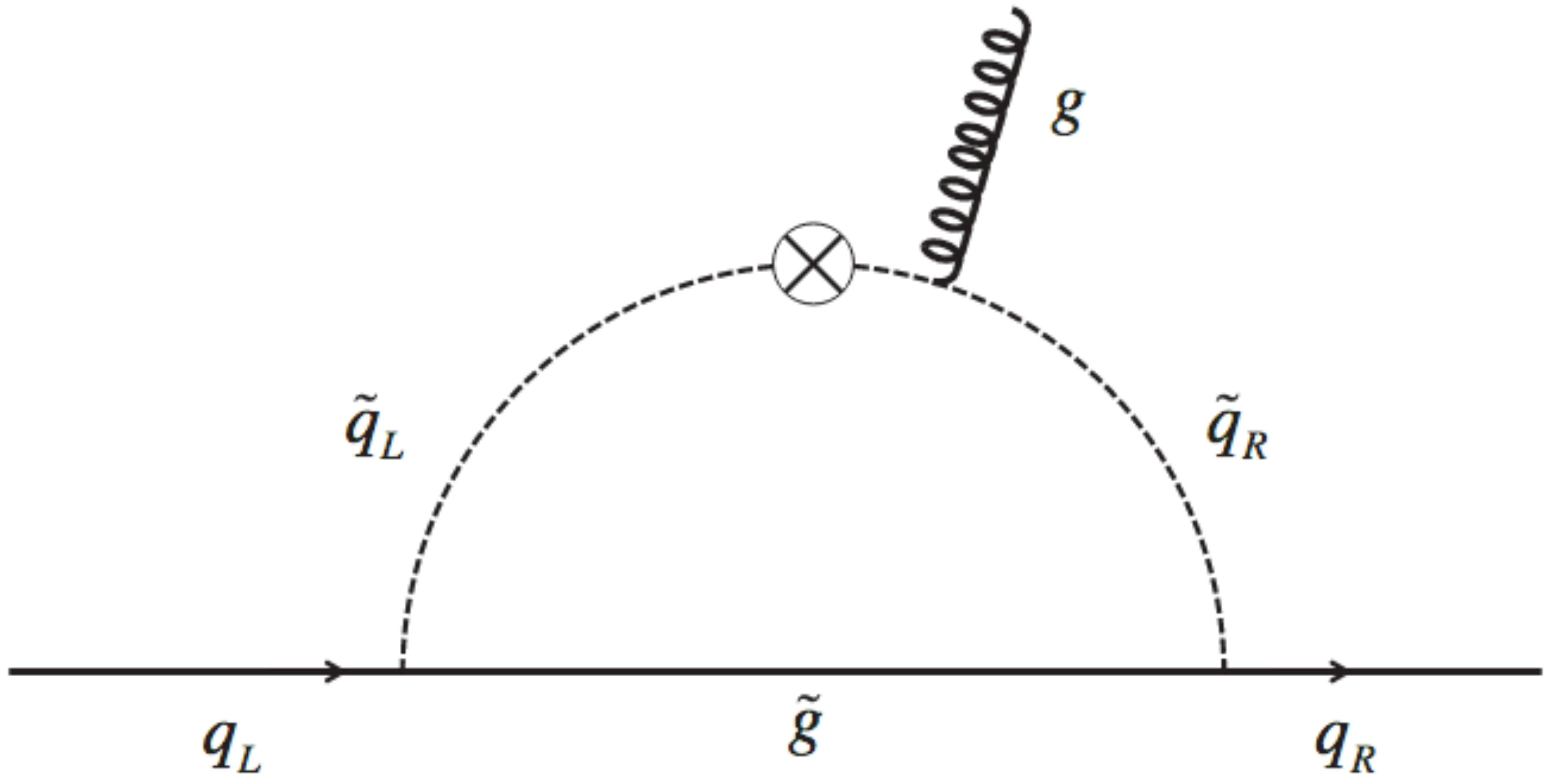
$$\delta_{BSM} \approx (10^{-16}\, e\, \text{cm}) \left(\frac{246\,\text{GeV}}{\Lambda_{NP}} \right)^2 \sin \phi_{CPV} y_f F$$

y_f Yukawa coupling
F accounts for dynamics

- Example of BSM contributions

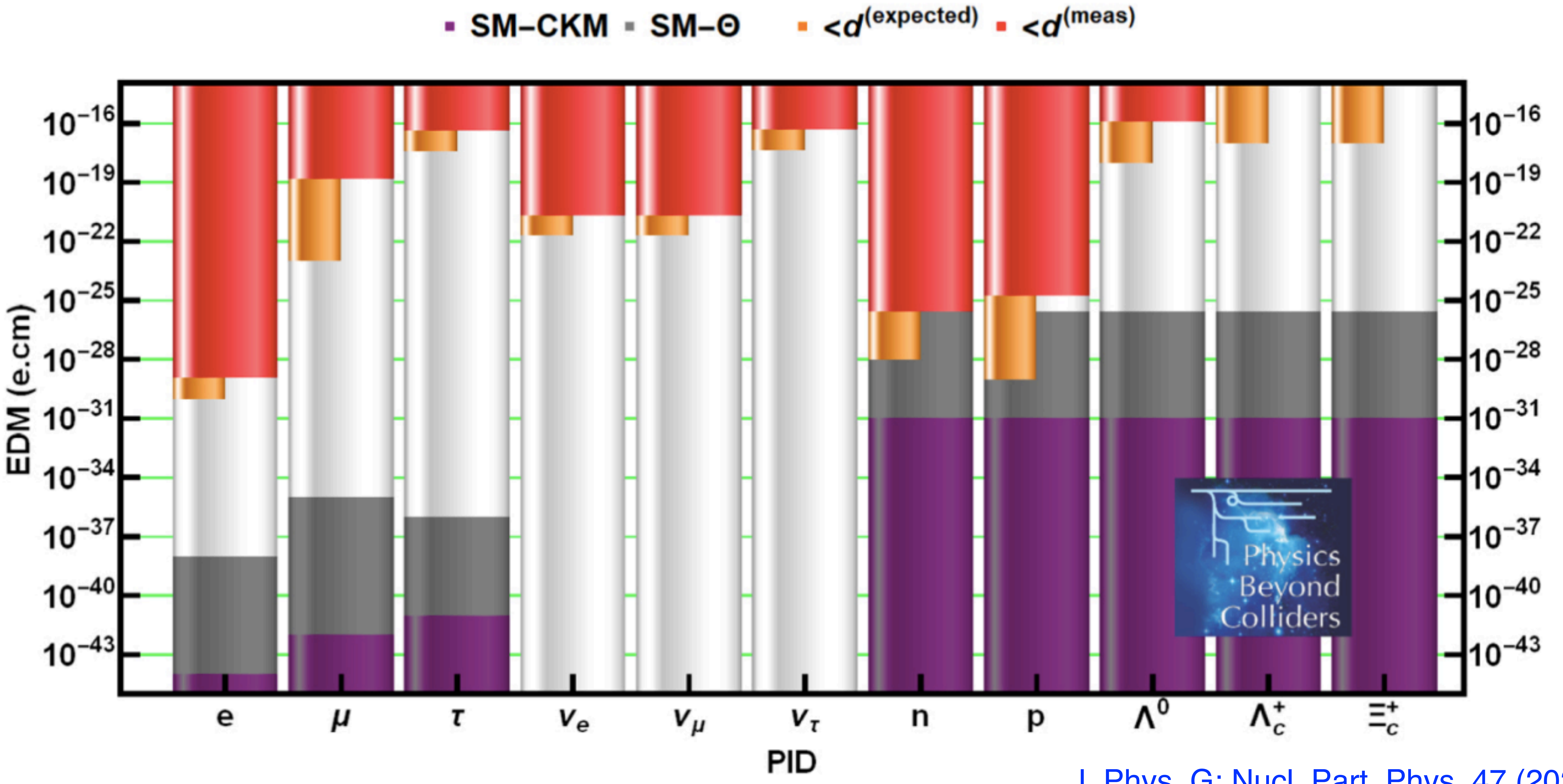
Rev.Mod.Phys. 91, 015001 (2019)





Status of EDM measurements

- Measure many systems to disentangle the underlying source of CPV



J. Phys. G: Nucl. Part. Phys. 47 (2020) 010501

Physics motivation for MDM measurements

- No direct measurements for charm baryons
- Further information on baryon substructure

$$\mu_{\Lambda_c^+} = g_{\Lambda_c^+} \frac{e\hbar}{2m_{\Lambda_c^+}} \text{ with } g_{\Lambda_c^+} \neq 2 \text{ (not point-like fermion)}$$

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

MDM theoretical predictions

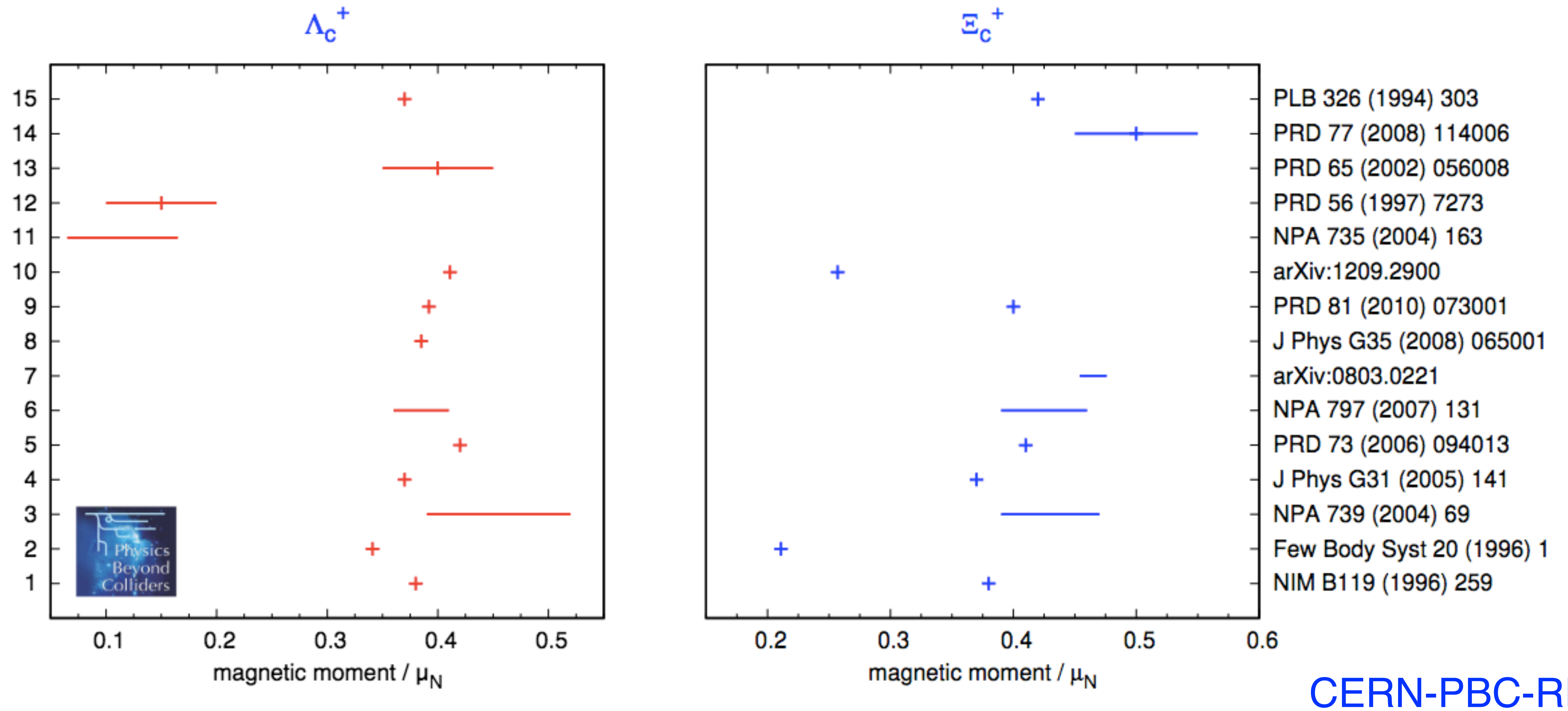
- In the quark model

$$\Lambda_c^+ = [ud]c \qquad \Xi_c^+ = [us]c$$
$$\mu_{\Lambda_c^+} = \mu_c \qquad \mu_{\Xi_c^+} = \mu_c$$

$$\mu_{\Lambda_c^+} = (0.48 \pm 0.03)\mu_N$$

EPJC 80, 358 (2020)

- Beyond the quark model: heavy quark effective theories



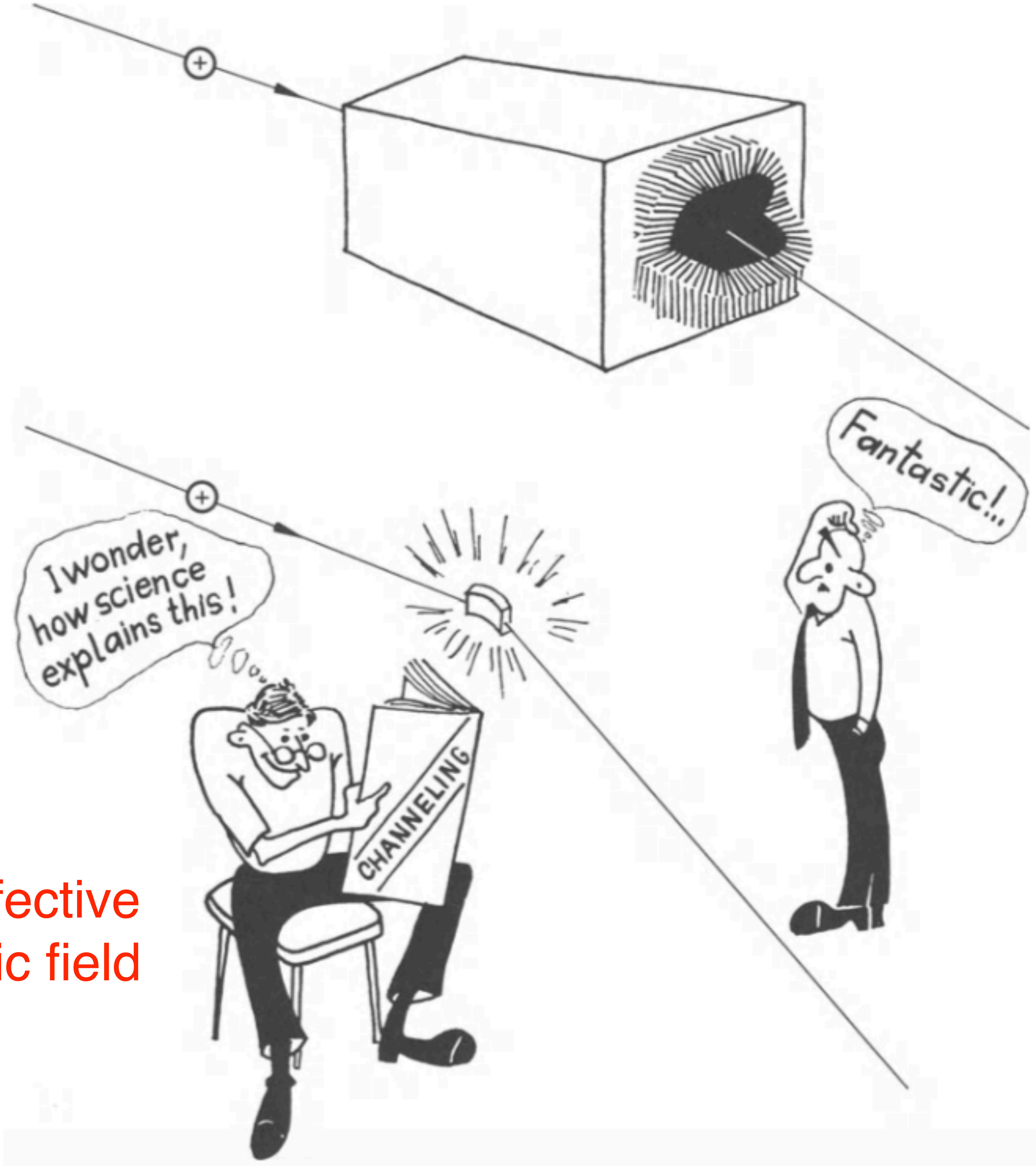
CERN-PBC-REPORT-2018-008

Outline

- Introduction and physics motivations
- **Experimental method to measure dipole moments for charm baryons**
- R&D and preparatory studies

Many contributions from CERN, ICJLab, Milano, UCAS, Valencia groups:
V. G. Baryshevsky, Phys.Lett.B 757 (2016) 426
L. Burmistrov et al, CERN-SPSC-2016-030, SPSC-EOI-012 (2016)
F. J. Botella et al., Eur.Phys.J.C 77 (2017) 181
A. S. Fomin et al., JHEP 1708 (2017) 120
E. Bagli et al., Eur.Phys.J.C 77 (2017) 828
A. S. Fomin et al., Eur.Phys.J.C 80(2020) 358
S. Aiola et al., Phys.Rev.D 103 (2021) 072003

Channeling in bent crystals

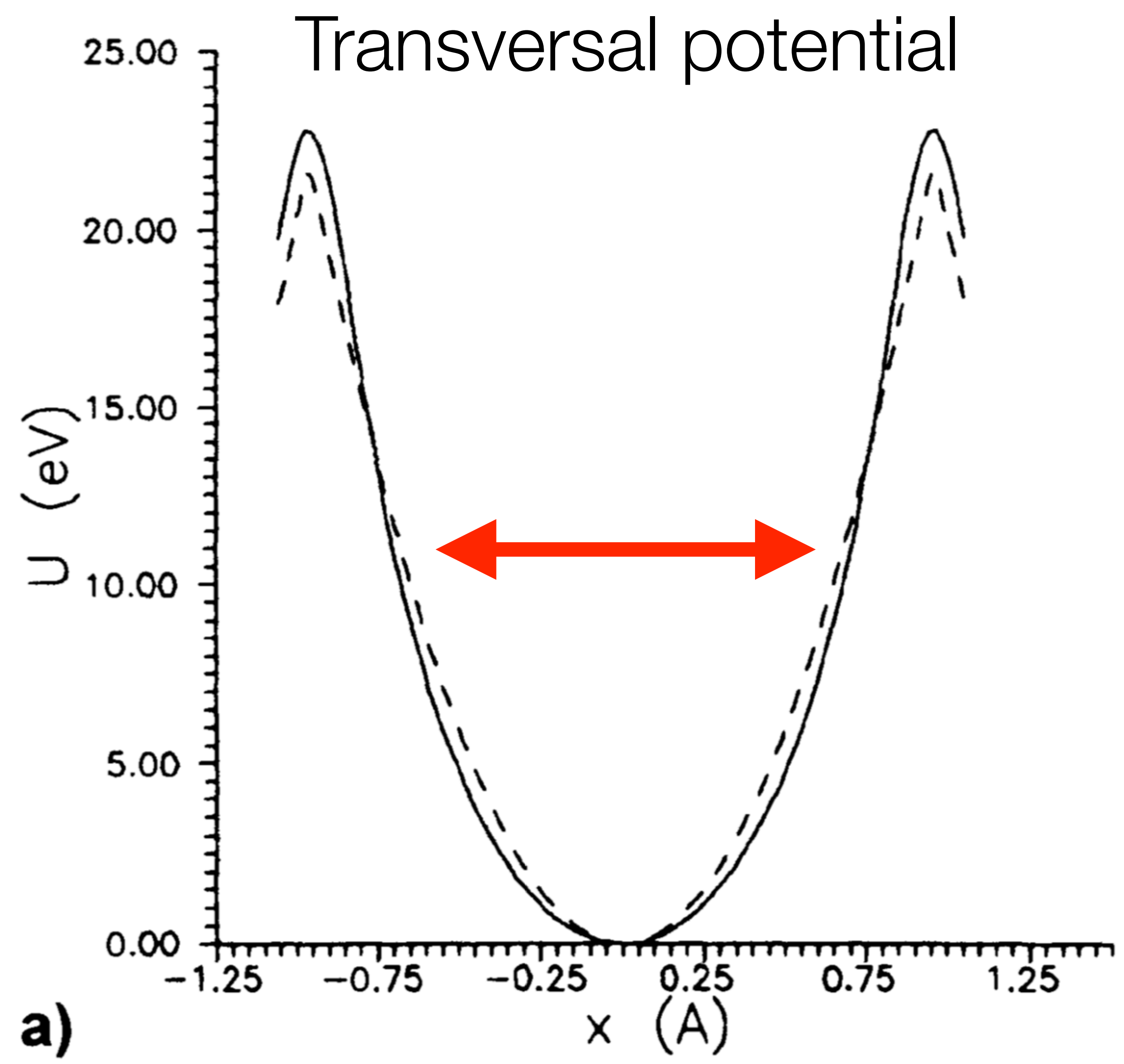


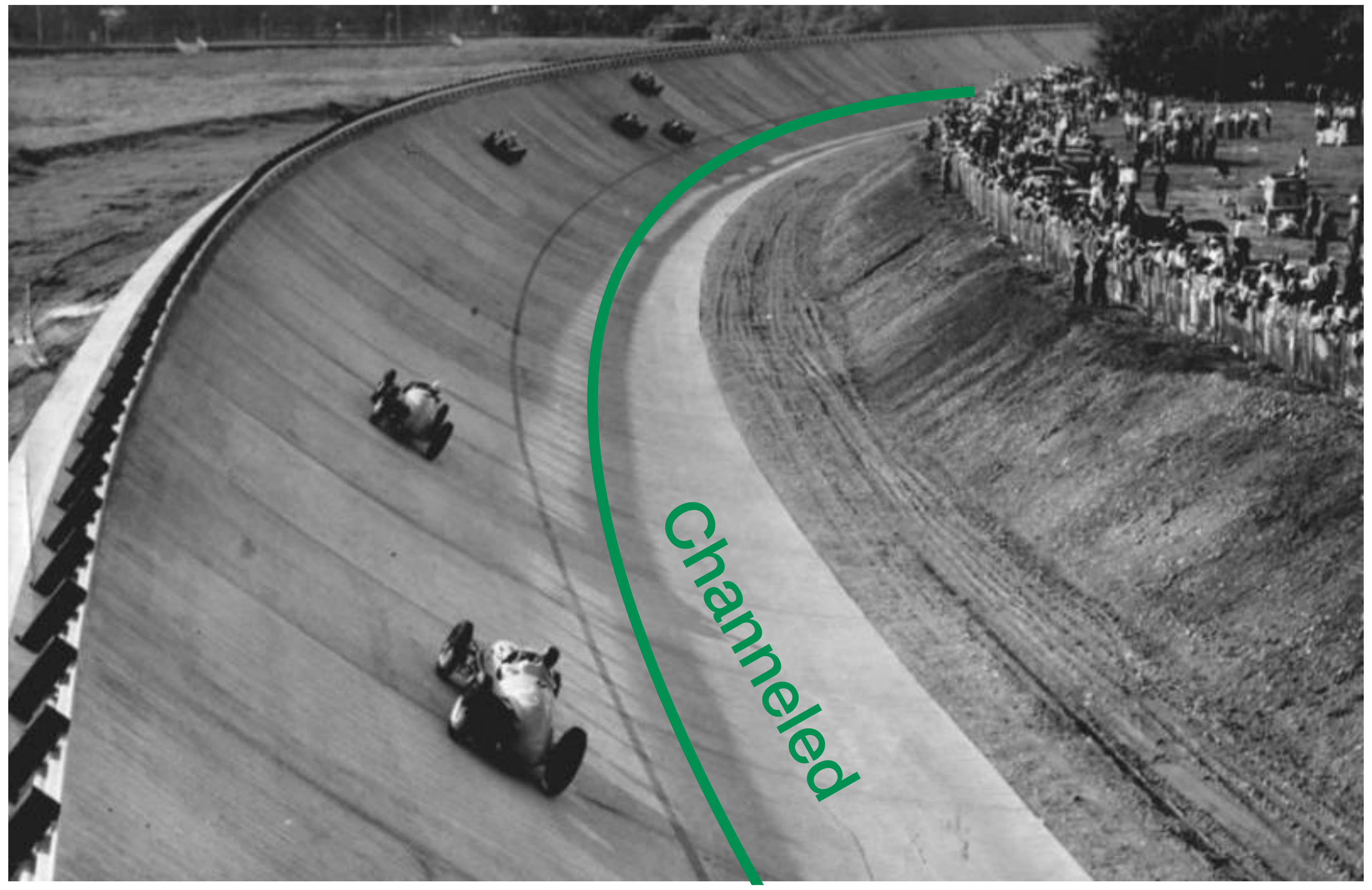
x500 effective magnetic field

Biryukov, Chesnokov, Kotov, "Crystal channeling and its applications at high-energy accelerators" (Springer)

Channeling in bent crystals

- Potential well between crystal planes $E \approx 1\ \mathrm{GeV/cm}$
- 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, very high effective magnetic field $B \approx 500\ \mathrm{T}$
  - **Induce spin precession**





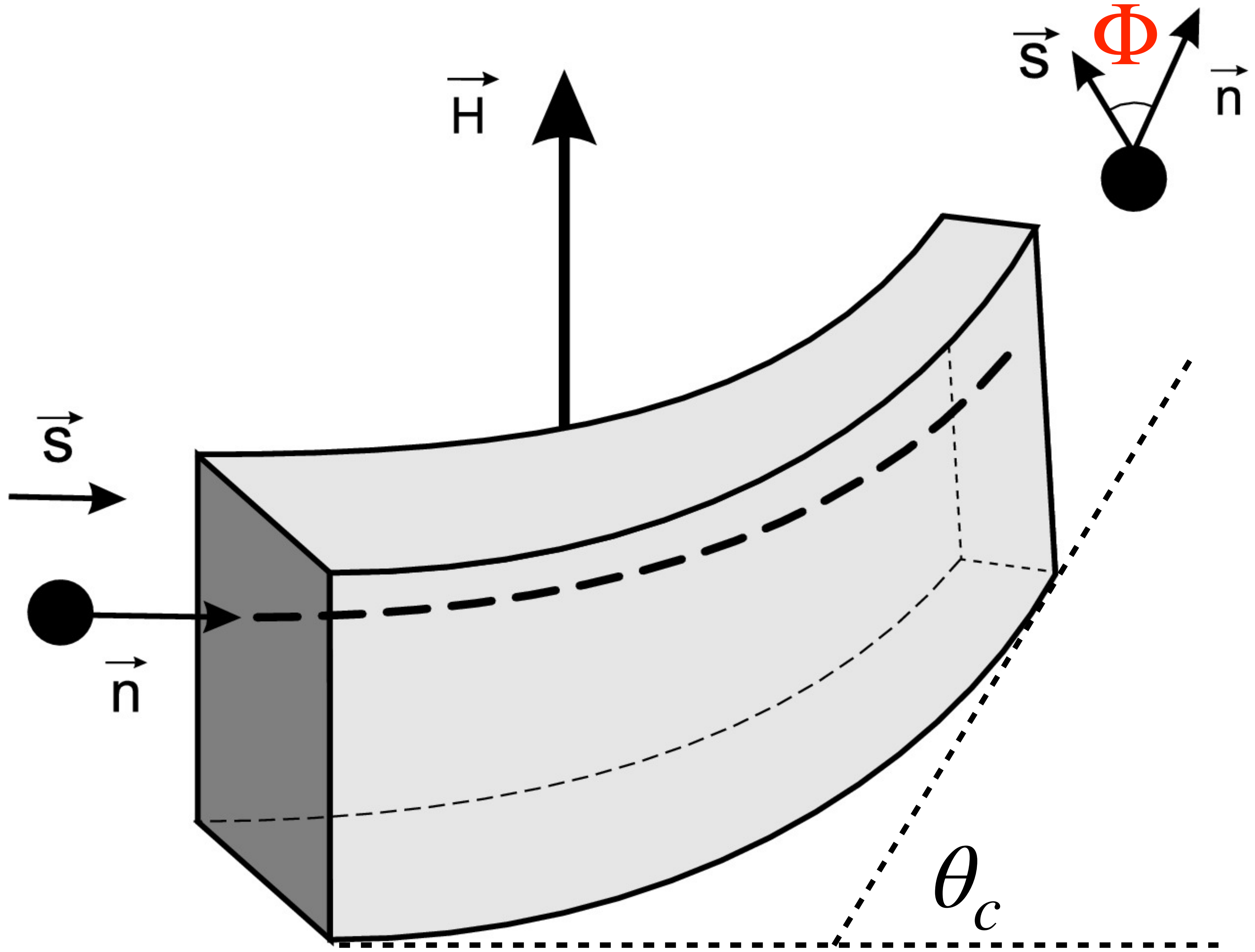
Spin precession in bent crystals

- Firstly predicted by Baryshevsky (1979)

  V.G. Baryshevsky, Pis'ma Zh. Tekh. Fiz. 5 (1979) 182

- Determine particle gyromagnetic factor from TBMT equation

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



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

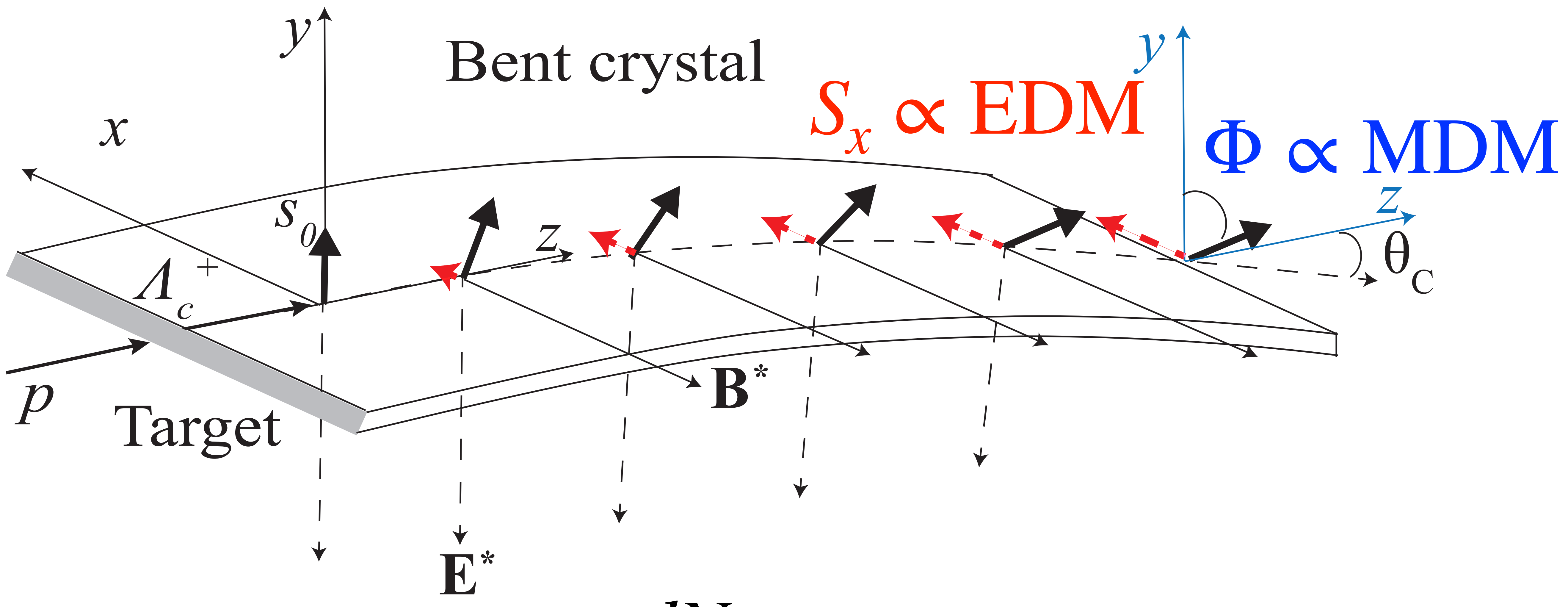
Φ = spin rotation angle
θ_C = crystal bending angle
g = gyromagnetic factor
γ = Lorentz boost

- Experimental proof by E761 Fermilab experiment with Σ^+ hyperon   Phys. Rev. Lett. 69 (1992) 3286

Λ_c^+, Ξ_c^+ spin precession in bent crystals at LHC

- Spin precession angle $\Phi = \frac{g-2}{2}\gamma\theta_c$ measurable for baryons with large $\gamma \approx 500$ and crystals with bending angle $\theta_c \approx 15\,\mathrm{mrad}$

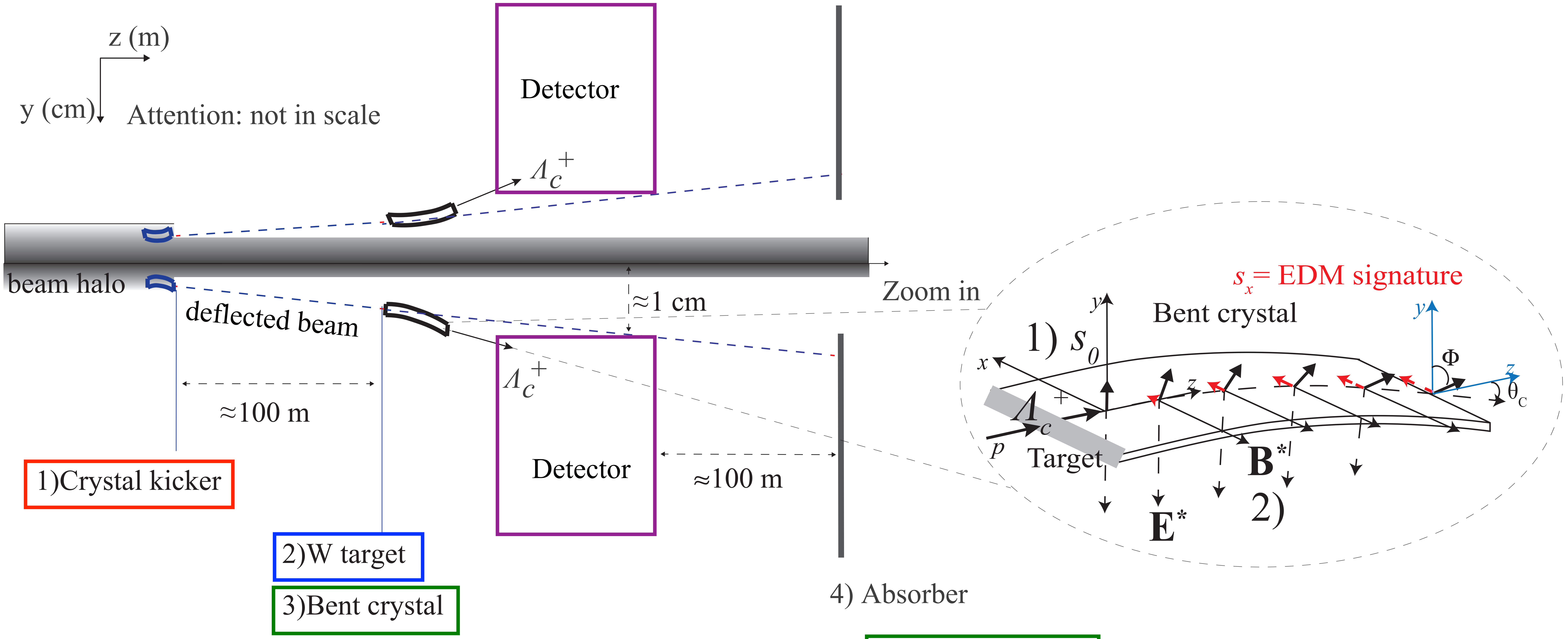
$$\frac{d\vec{S}}{d\tau} = \vec{\mu} \times \vec{B}^* + \vec{\delta} \times \vec{E}^*$$



- Sensitivity to MDM and EDM via spin-polarisation analyser $\frac{dN}{d\Omega} \propto 1 + \alpha \vec{s}' \times \hat{k}$
- MDM and EDM precession in the limit $\gamma \gg 1,\ d \ll g-2$ EPJC 77 (2017), 181

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

Proposed fixed target experiment at LHC



p extraction

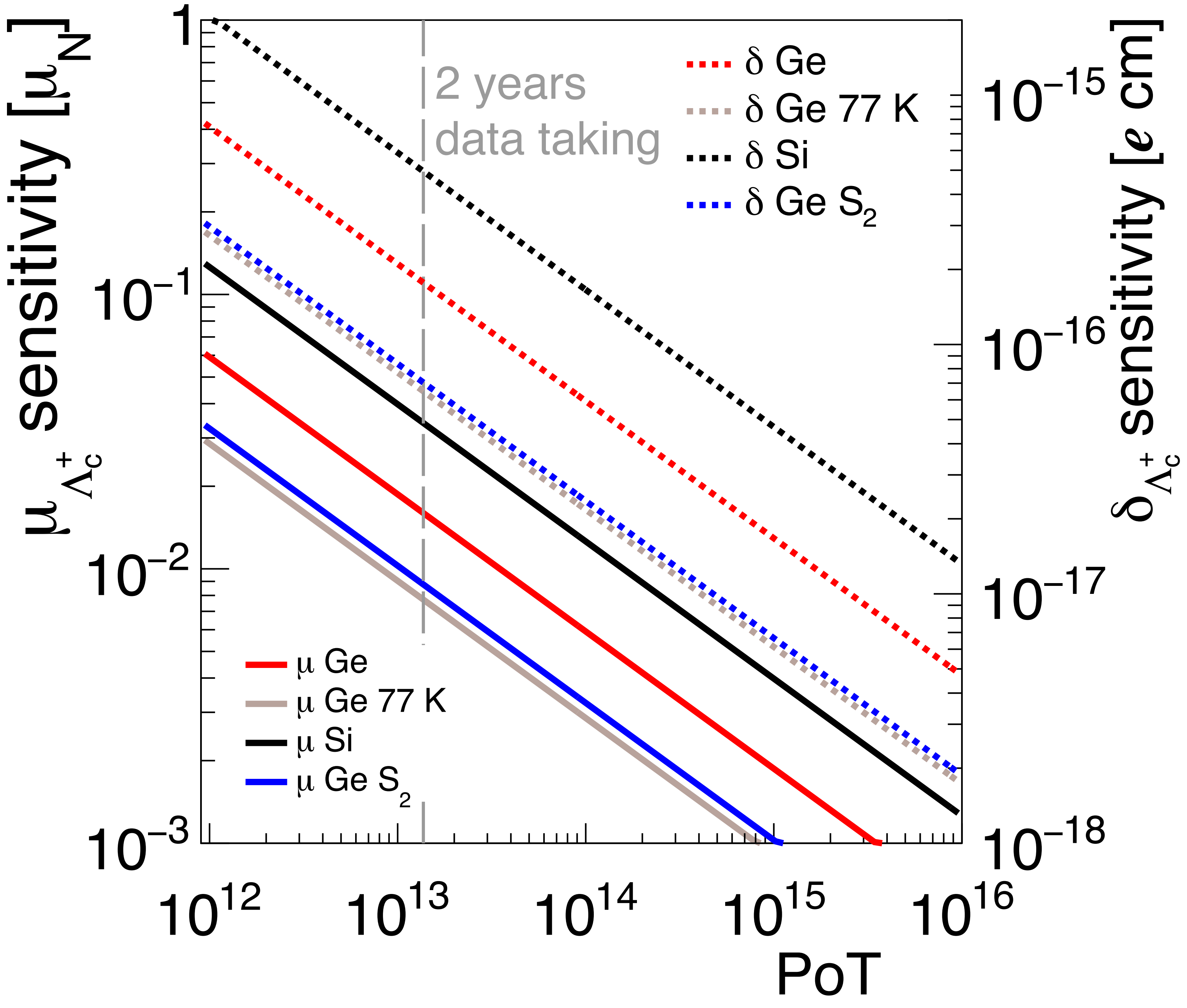
Heavy baryon polarised production

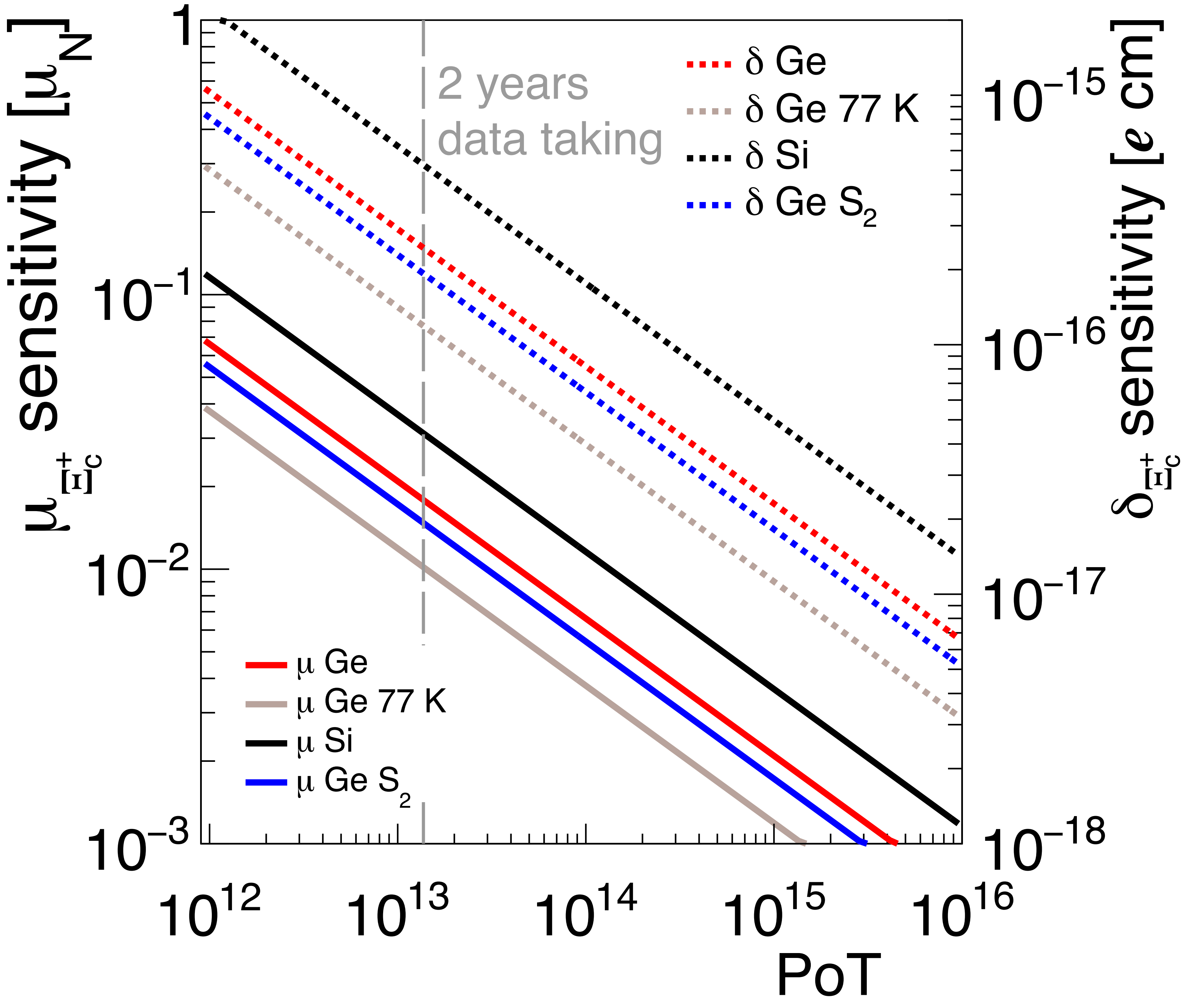
Channeling
Spin precession

Event reconstruction

Sensitivity to MDM and EDM measurements

- S1 configuration: LHCb detector, Ge (Si) crystal length 10cm, bending 16 mrad
- S2 configuration: dedicated experiment, Ge crystal length 7 cm, bending 7 mrad





PoT = protons on target
W target 2cm thick

- Measurements are statistically dominated

PRD 103, 072003 (2021)

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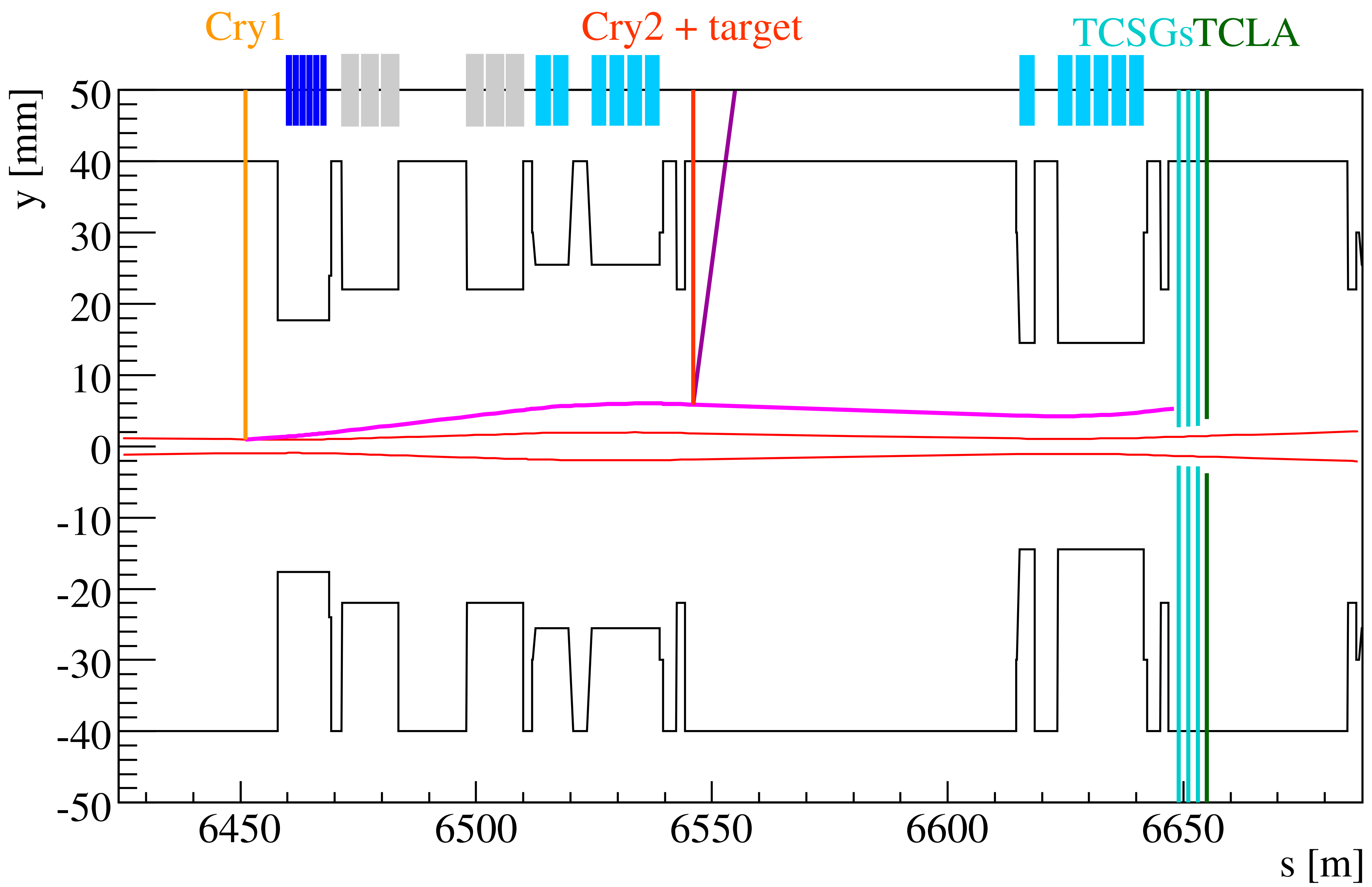
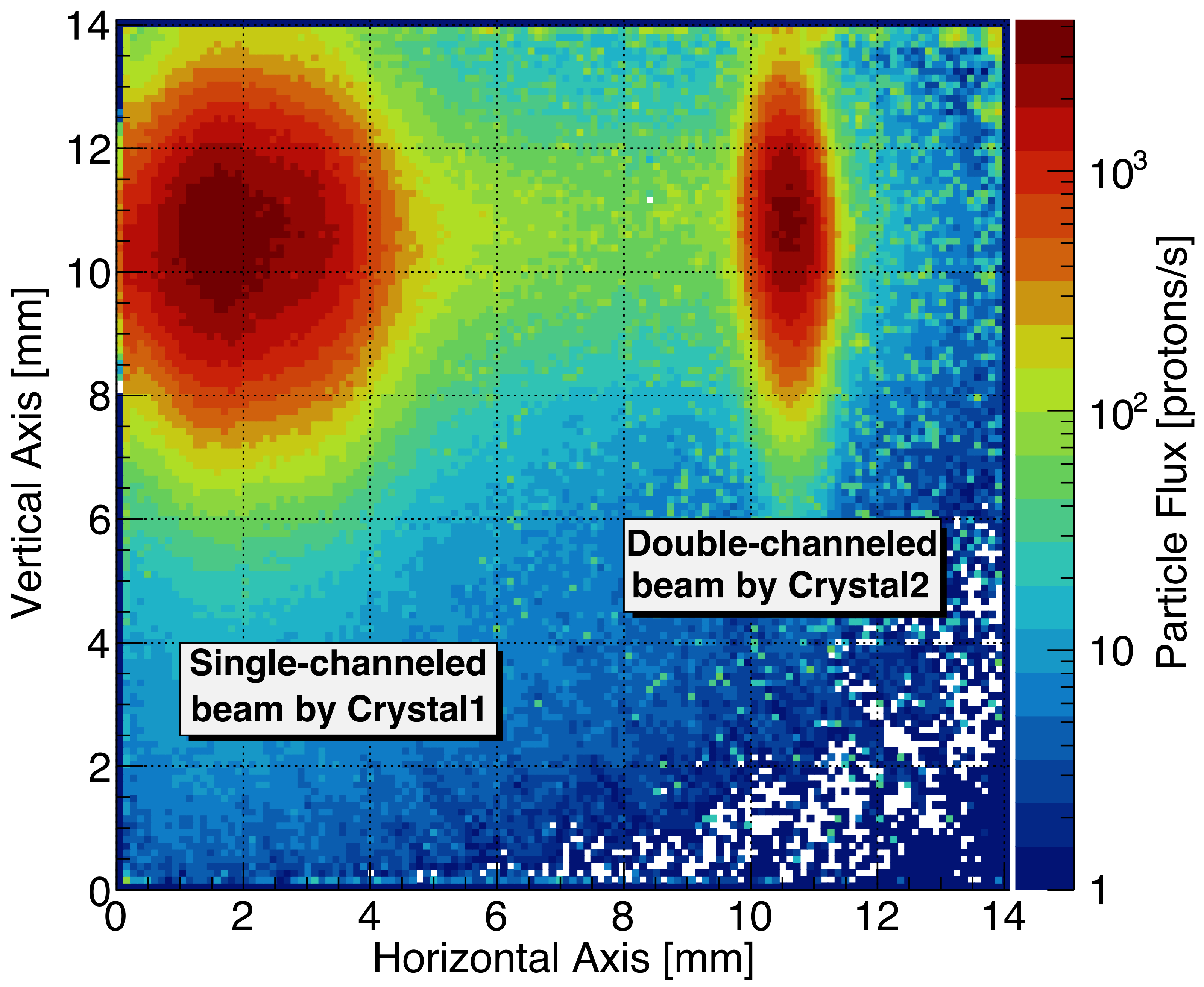
LHC (SPS) machine studies

- Channeling of 6.5 TeV at LHC already demonstrated by UA9 Phys. Lett. B, 758 (2016) 129
- Viable layout: $10^{6(7)}$ p/s on target close to LHCb (IR3)
- Double crystal layout successfully tested at SPS. Test in LHC possibly during Run3



EPJC 80 (2020) 10, 929

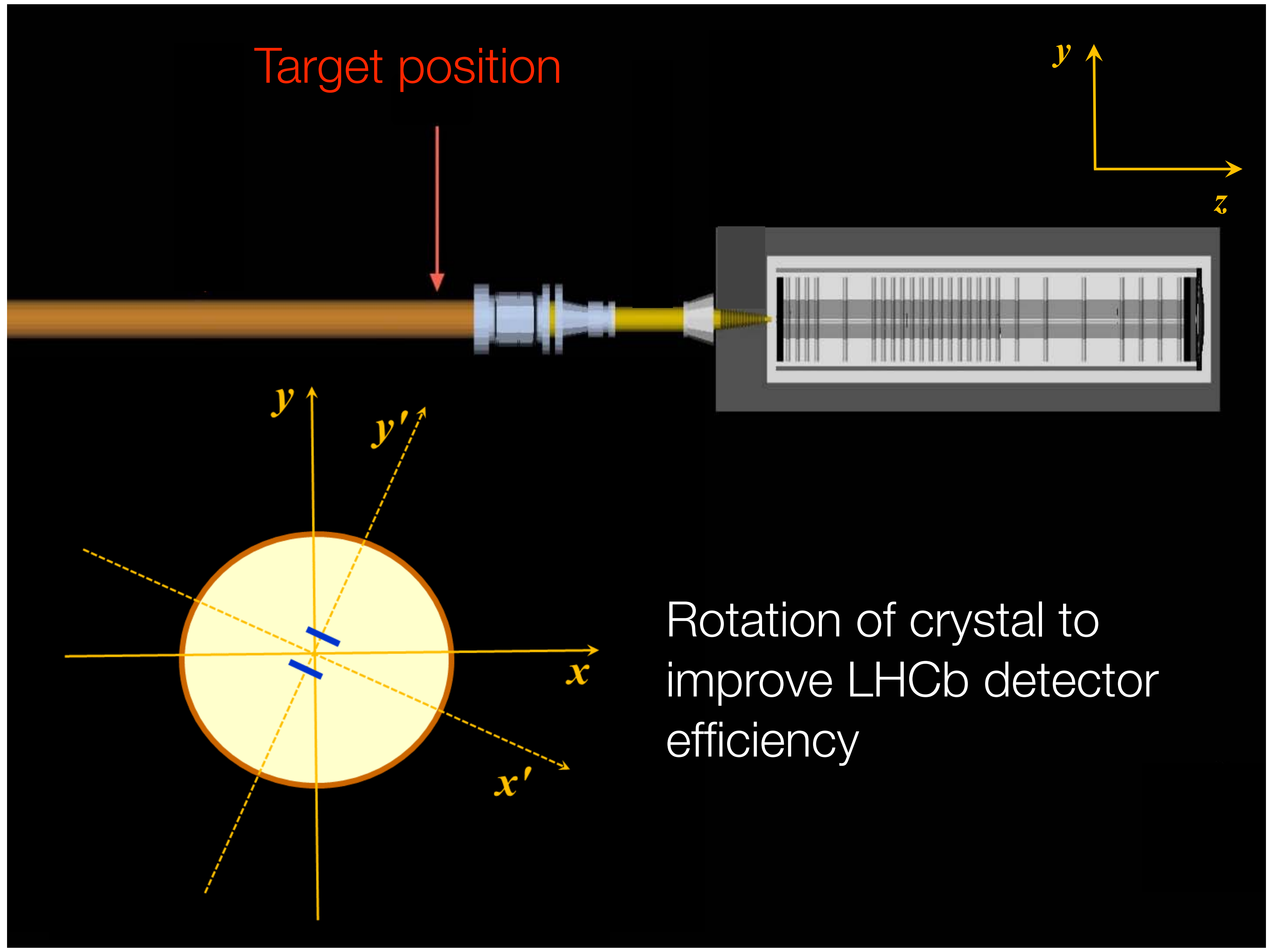


J. NIMA, 1015 (2021) 165747

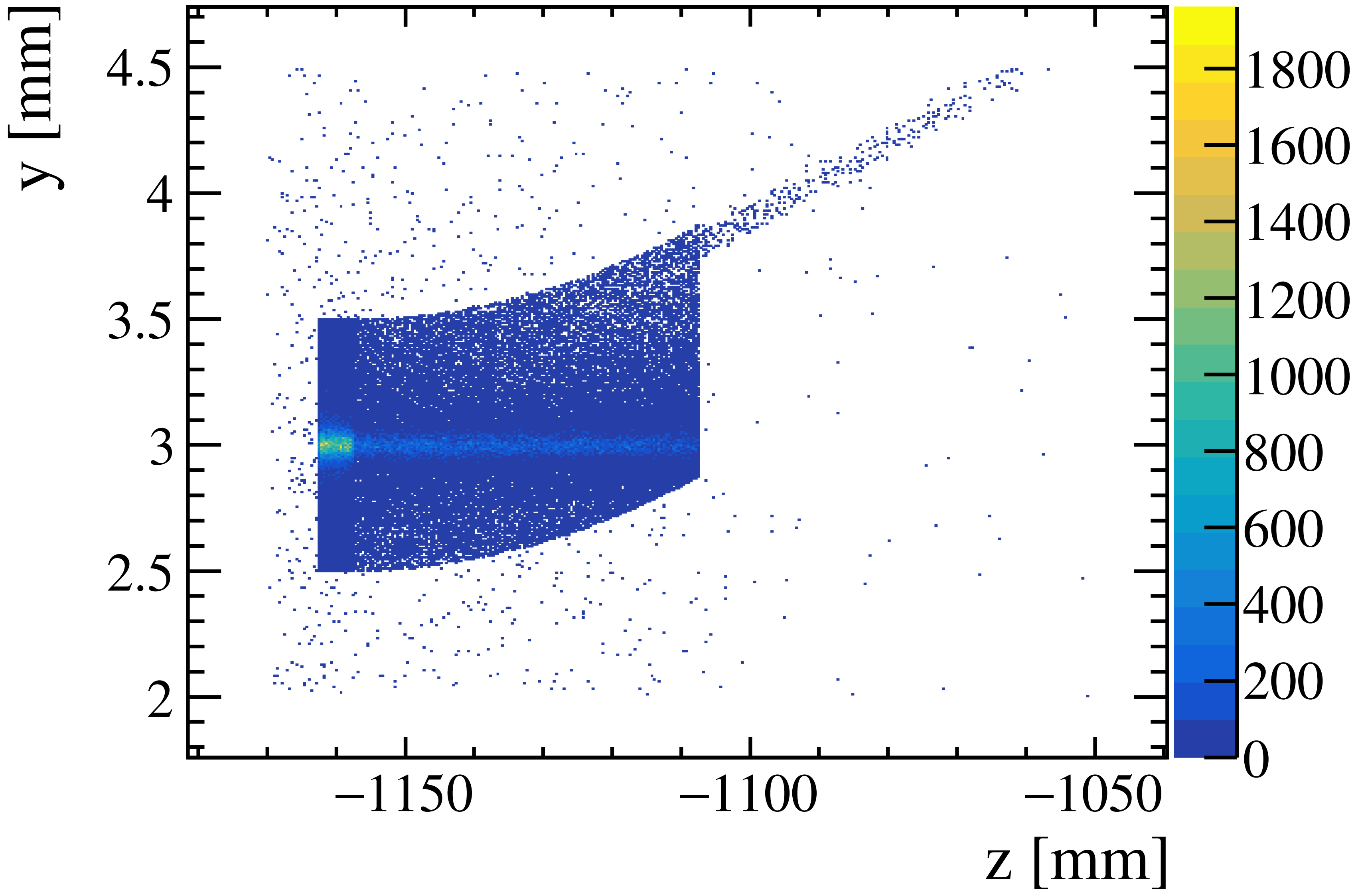
Simulation studies in LHCb

LHCb-INT-2017-011

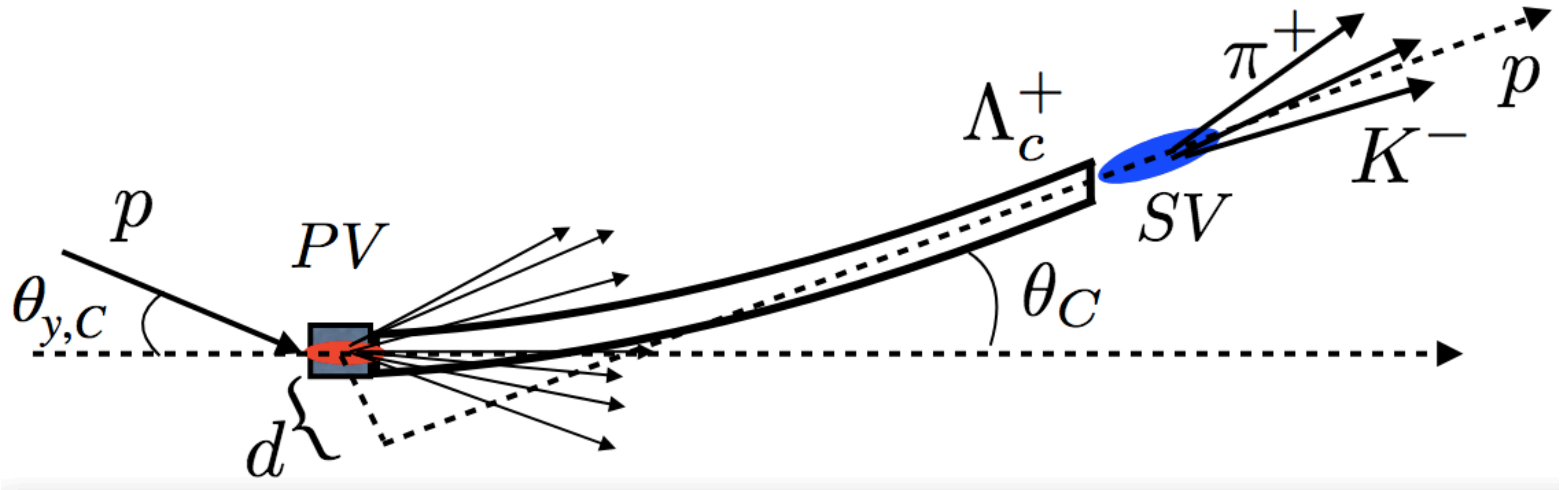
Andrea Merli PhD thesis CERN-THESIS-2019-108



- Good performance (signal and bkg) with LHCb detector. Full simulation of fixed-target setup: W target 0.5-2.0 cm and bent crystal
- $\nu_{target} < 0.01$ with 10^6 p/s on target, negligible impact on the detector occupancies
- About 10^{-4} Λ_c^+ are channeled and have high momentum $\geq$1 TeV

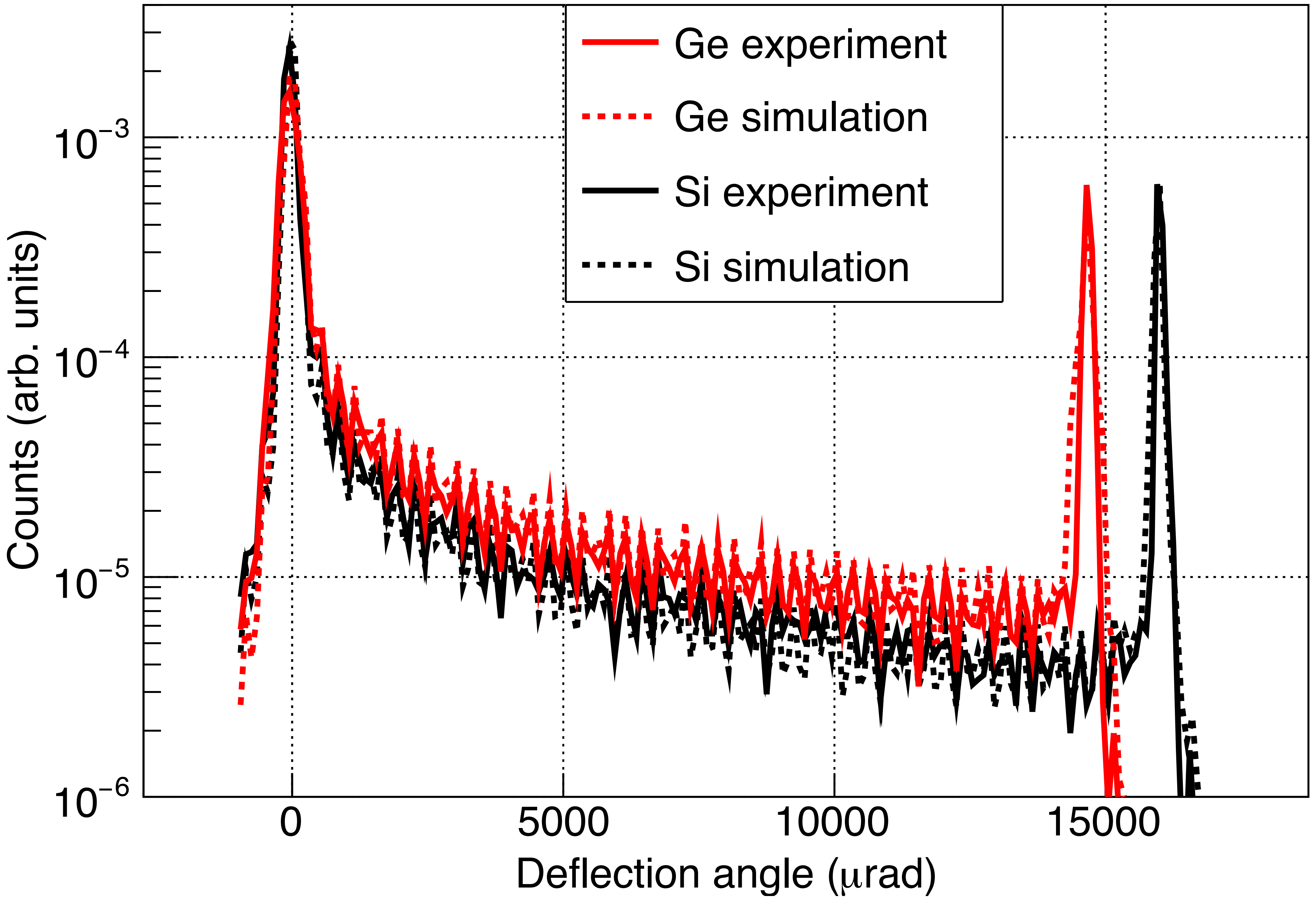


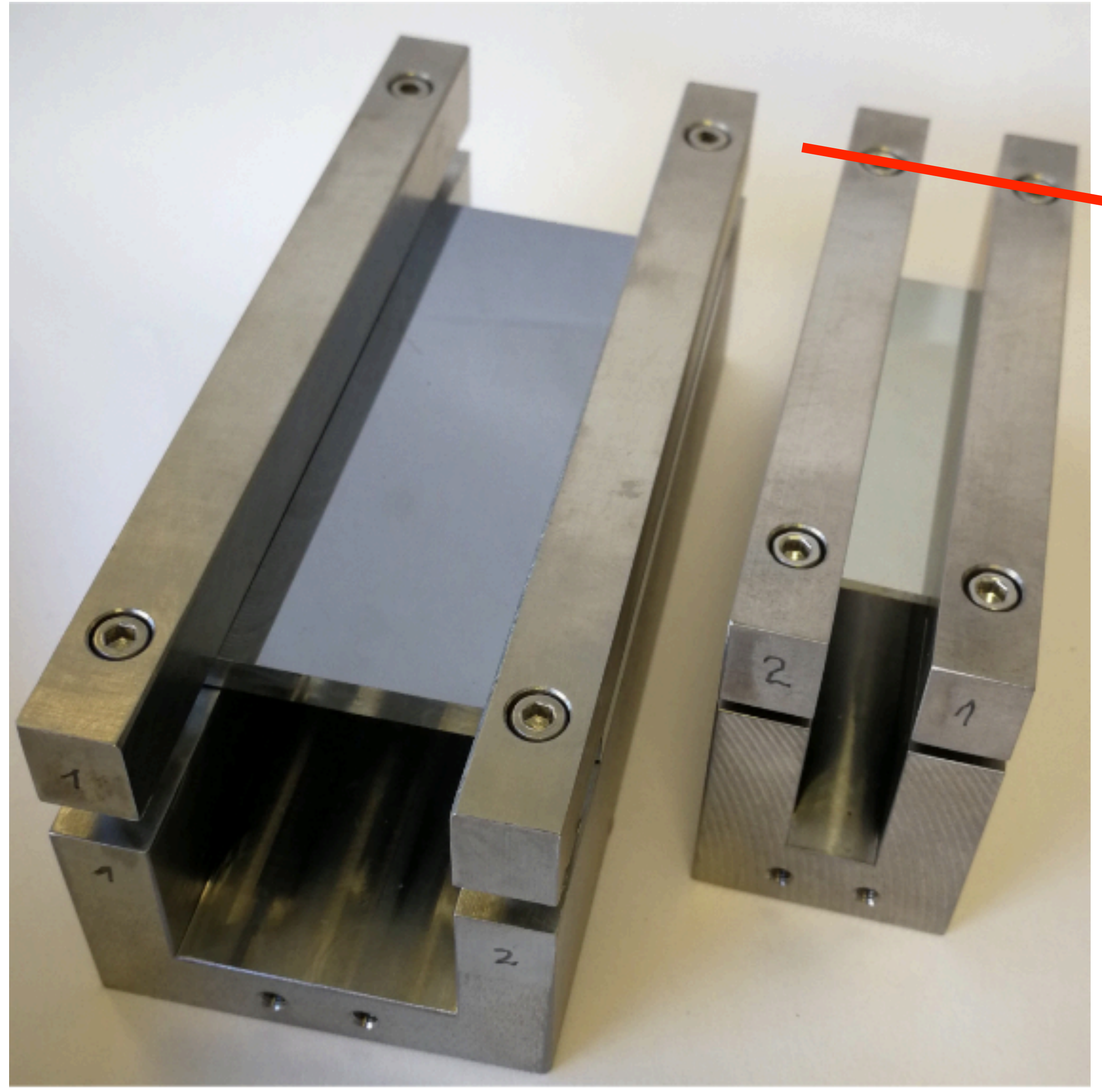
- Good resolution on production and decay vertex (7-8mm), θ_c angle (25 μrad), m(pKπ) (20 MeV)

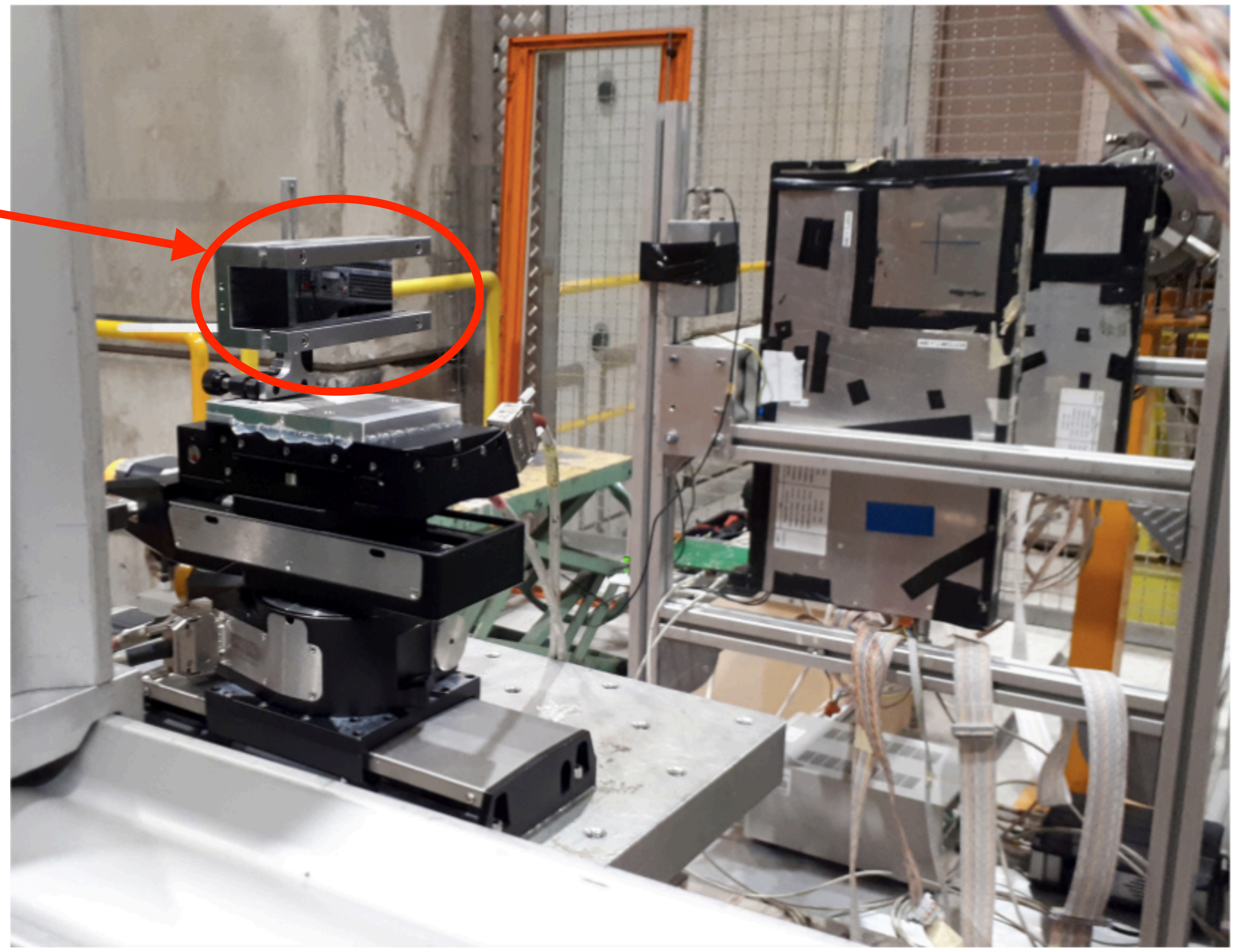


Long bent crystal prototypes

- **Si crystal**: 8 cm long, bent @ 16.0 mrad
- **Ge crystal**: 5 cm long, bent @ 14.5 mrad



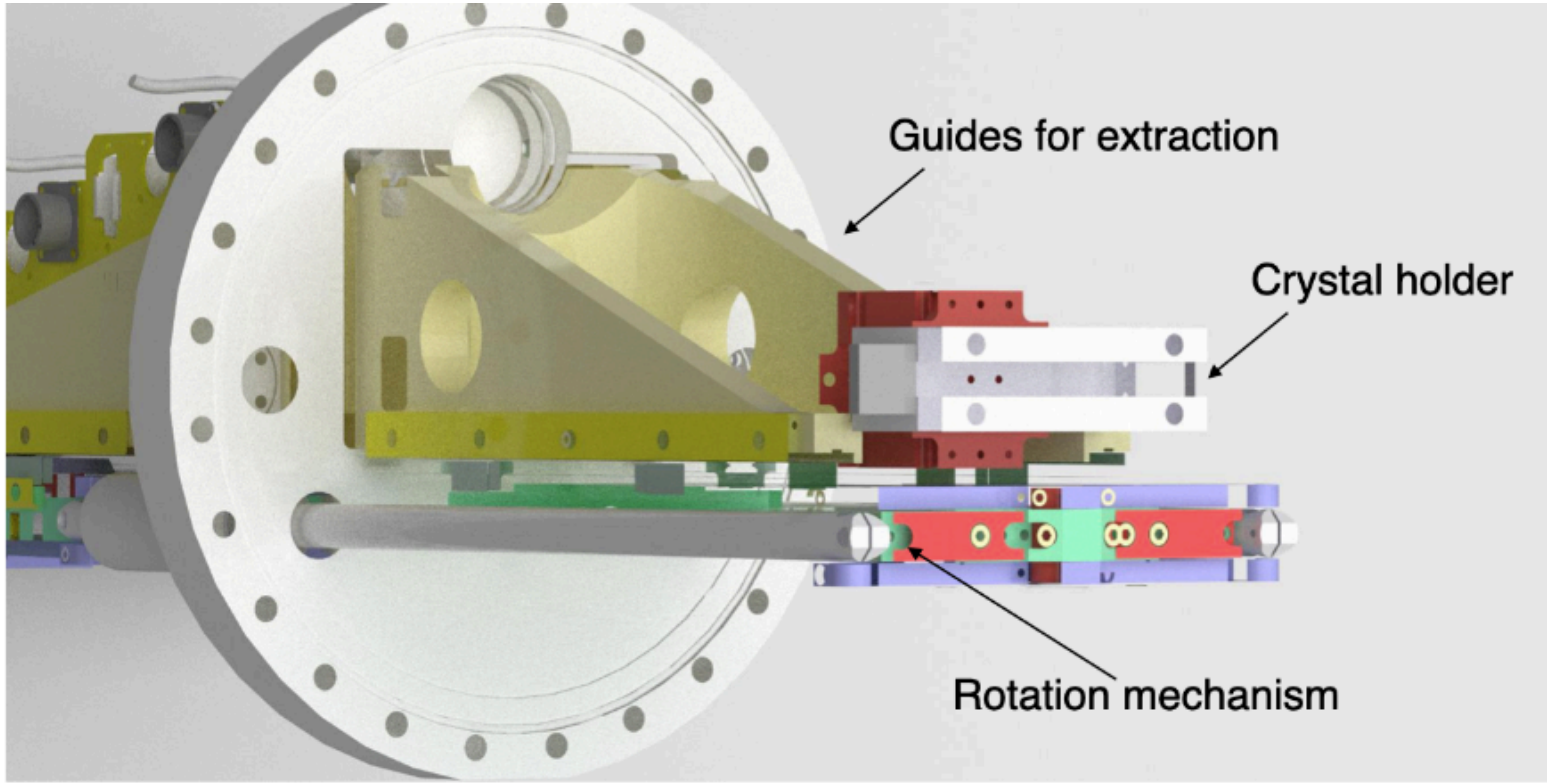




- Si and Ge long bent crystals developed at INFN-Ferrara and tested on beam
- Channeling efficiency >10% for 180 GeV/c pions tested on beam

Fixed target setup

- Goniometer for target+crystal positioned in the region upstream of the LHCb detector or in IR3
- Goniometer internal structure: compatible with operations in ultra-high vacuum
- Accuracy on position ~20 μm, rotation angle ~20 μrad

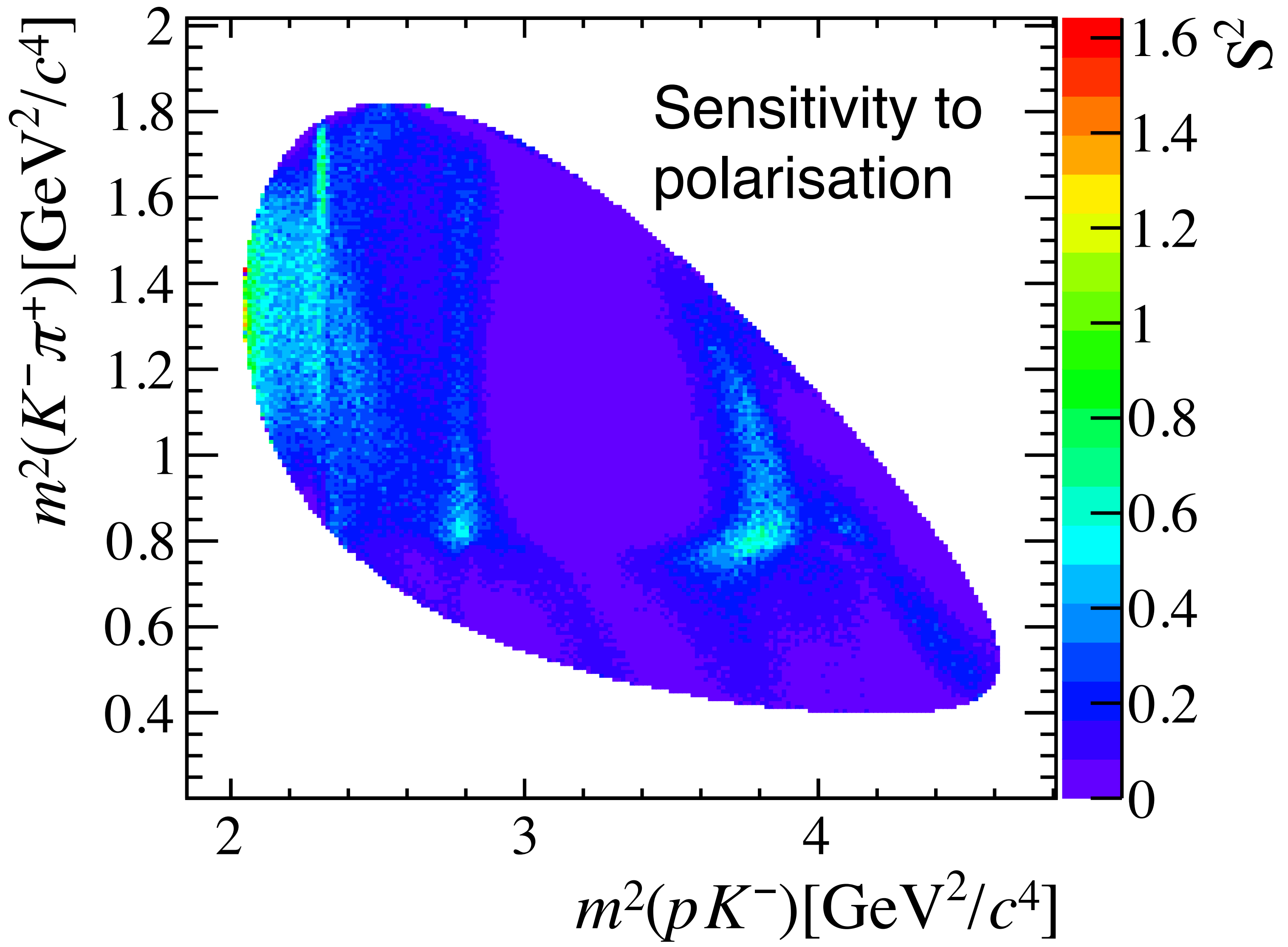


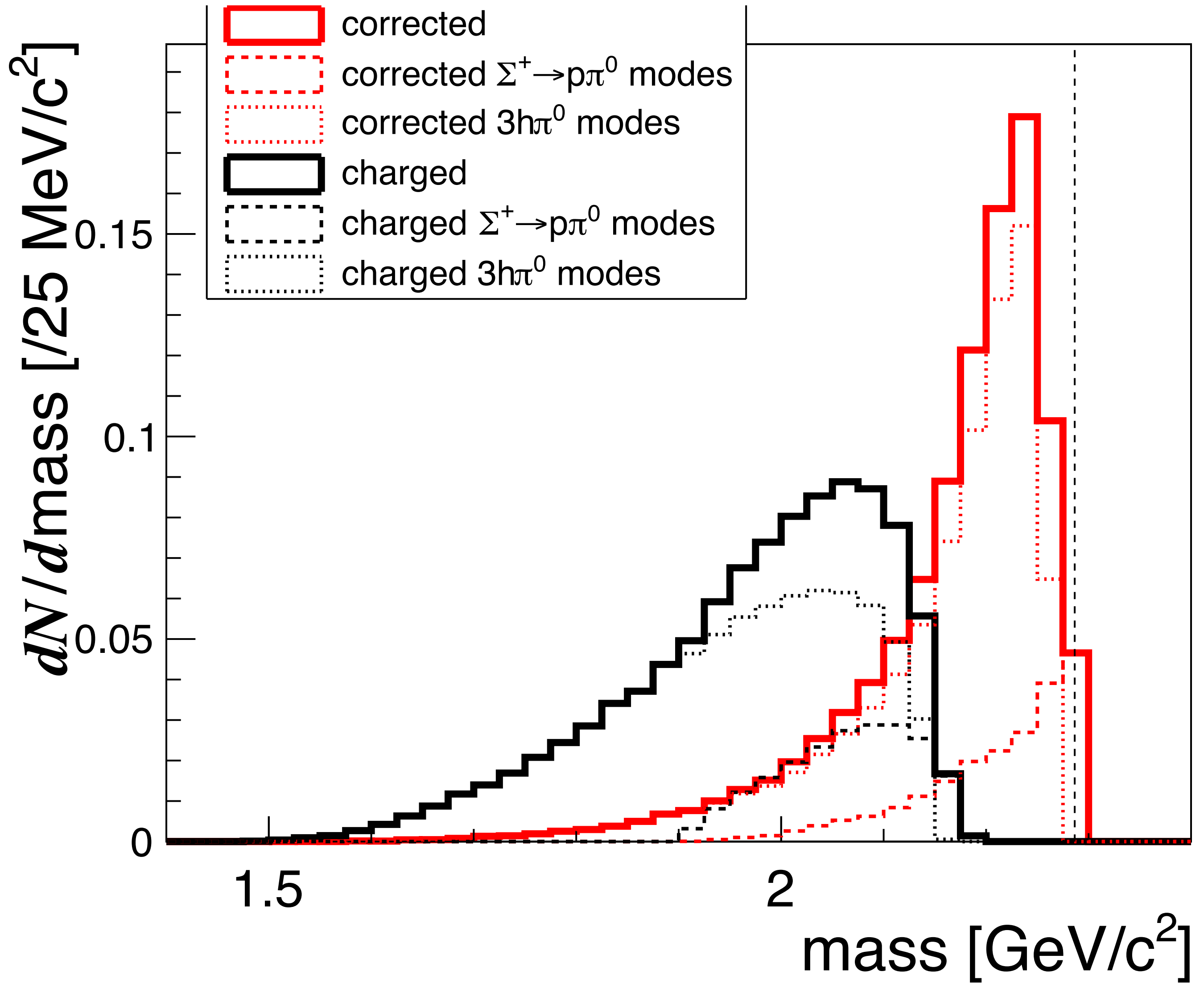
Use copious Λ_c^+, Ξ_c^+ multibody decays

- Use 3 body decays to increase the signal yield
- Extract maximum information on polarisation via full amplitude analysis of the 3-body decays AHEP (2020) 7463073
- Use corrected mass for decays with missing π^0

PRD 103, 072003 (2021)

Λ_c^+ final state	$\mathcal{B}$ (%)	ϵ_{3trk}	$\mathcal{B}_{eff}$ (%)
$pK^-\pi^+$	6.28 ± 0.32	0.99	6.25
$\Sigma^+\pi^-\pi^+$	4.50 ± 0.25	0.54	2.43
$\Sigma^-\pi^+\pi^+$	1.87 ± 0.18	0.71	1.33
$p\pi^-\pi^+$	0.461 ± 0.028	1.00	0.46
$\Xi^-K^+\pi^+$	0.62 ± 0.06	0.73	0.45
$\Sigma^+K^-K^+$	0.35 ± 0.04	0.51	0.18
pK^-K^+	0.106 ± 0.006	0.98	0.11
$\Sigma^+\pi^-K^+$	0.21 ± 0.06	0.54	0.11
$pK^-\pi^+\pi^0$	4.46 ± 0.30	0.99	4.43
$\Sigma^+\pi^-\pi^+\pi^0$	3.20	0.54	1.72
$\Sigma^-\pi^+\pi^+\pi^0$	2.1 ± 0.4	0.71	1.49
$\Sigma^+[p\pi^0]\pi^-\pi^+$	2.32	0.46	1.06
$\Sigma^+[p\pi^0]K^-K^+$	0.18	0.46	0.08
$\Sigma^+[p\pi^0]\pi^-K^+$	0.11	0.46	0.05
All	...	...	20.2

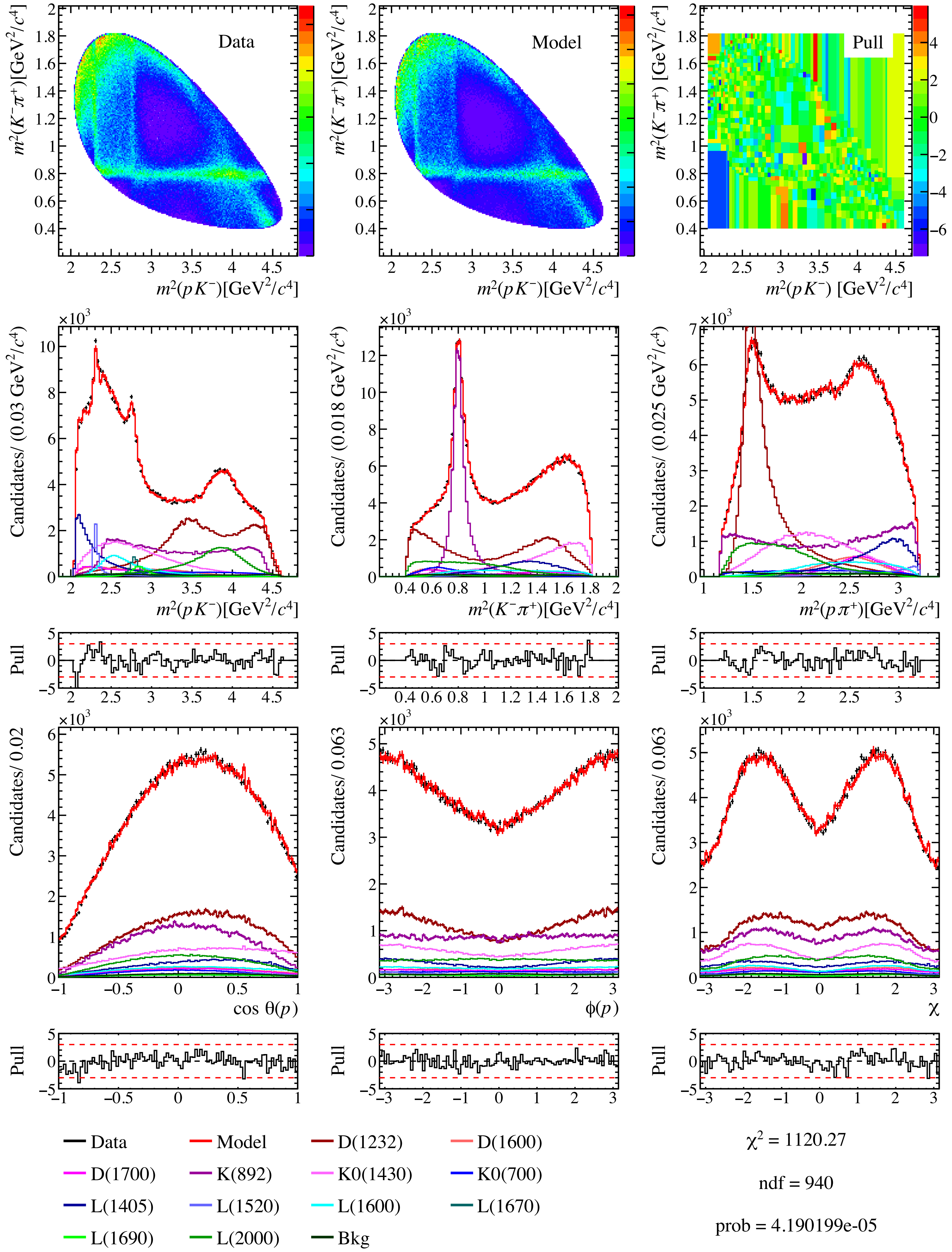




$\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis

LHCb-PAPER-2022-002

- Measurement of polarisation and amplitude model with LHCb Run 2 data (with semileptonic and prompt selections)
- Issue found and addressed in spin matching among different decay chains AHEP (2020) 6674595
- $\Xi_c^+ \to pK^-\pi^+$ amplitude analysis and polarisation measurement are ongoing

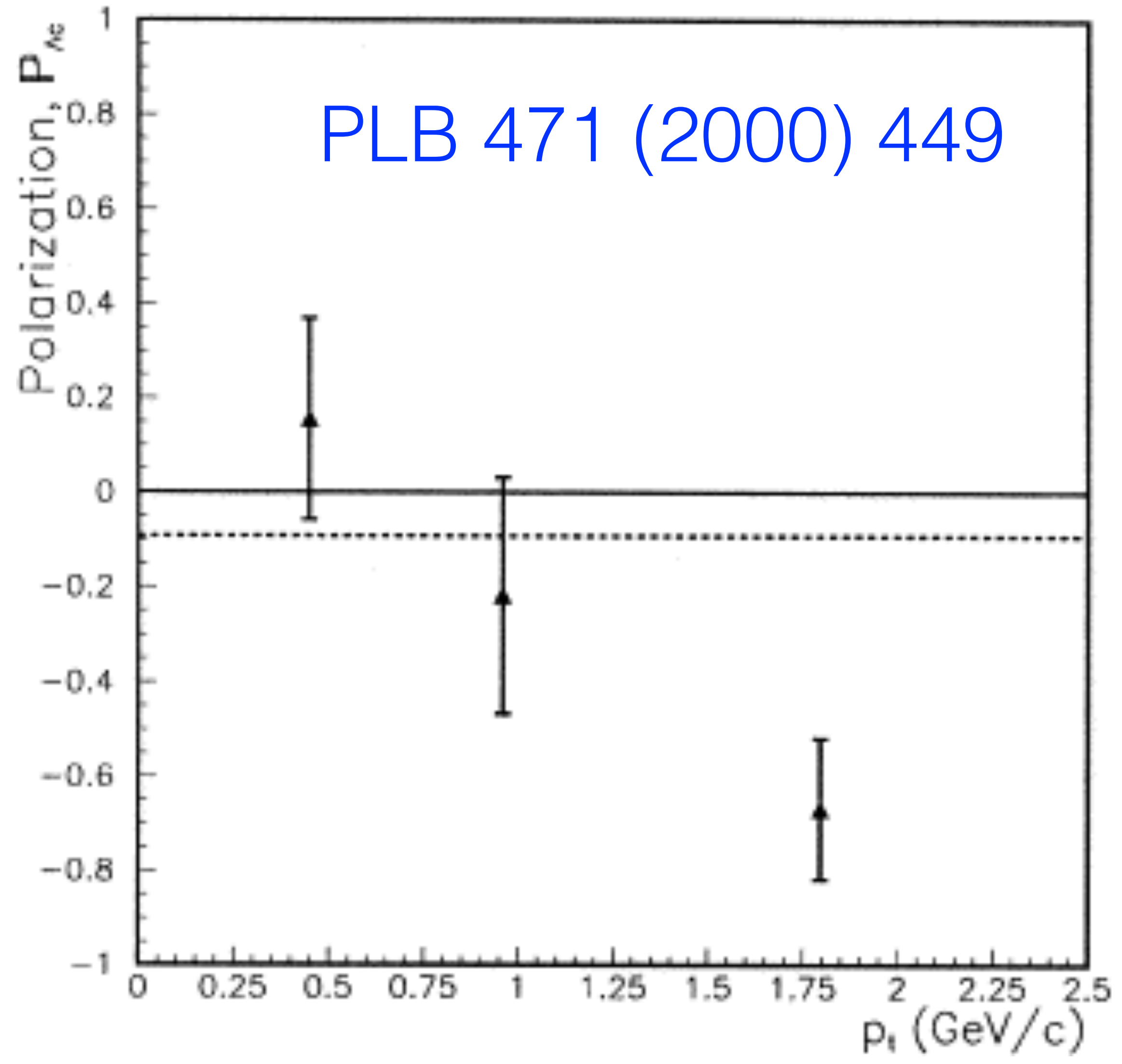


Λ_c^+ polarization in fixed target collisions

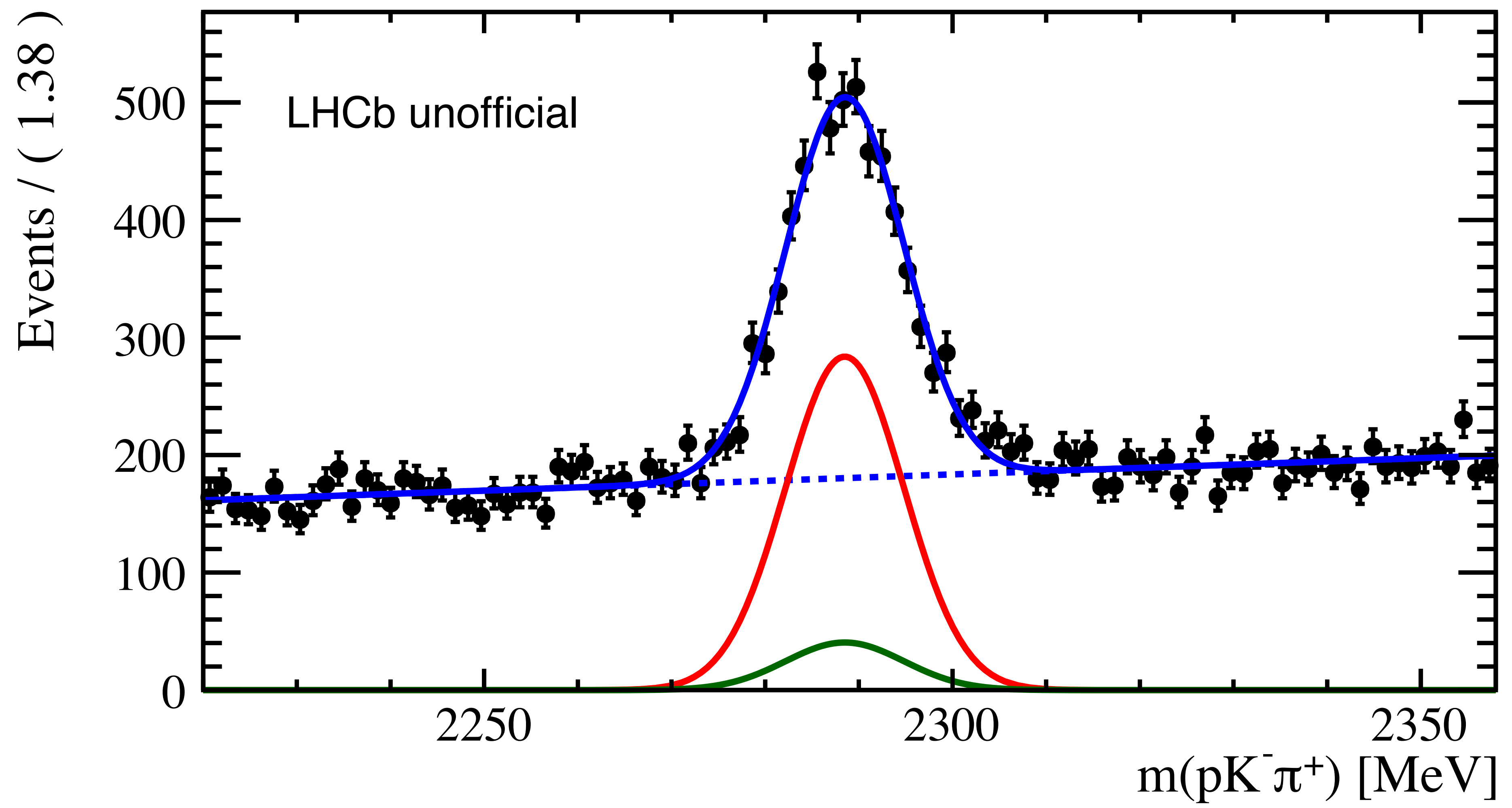
- Production cross section and polarisation are crucial inputs to sensitivities for magnetic and electric dipole moment measurements proposal with bent crystals
- Λ_c^+ polarisation poorly known in fixed target production
  - Polarisation mechanism in fixed target production not clear for baryons

EPJC 6 (1999) 265

- Measured from Dalitz fit to $\Lambda_c^+ \to pK^-\pi^+$ decays produced in 500 GeV beam $\pi^- - N$ interactions at $\sqrt{s} = 30.6$ GeV by the E791 experiment at Fermilab
  - ≈ 1000 signal events with a tentative amplitude model

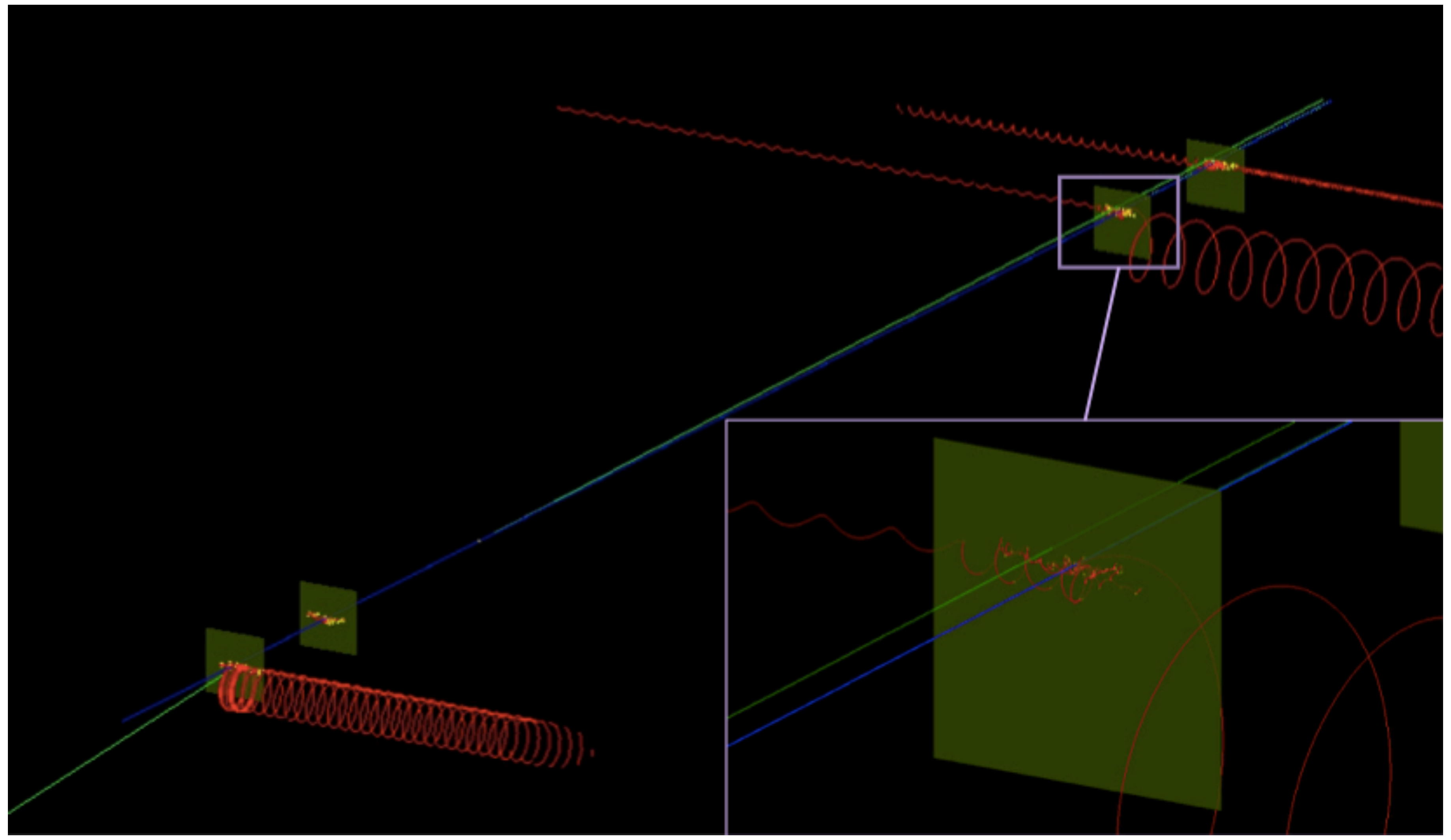


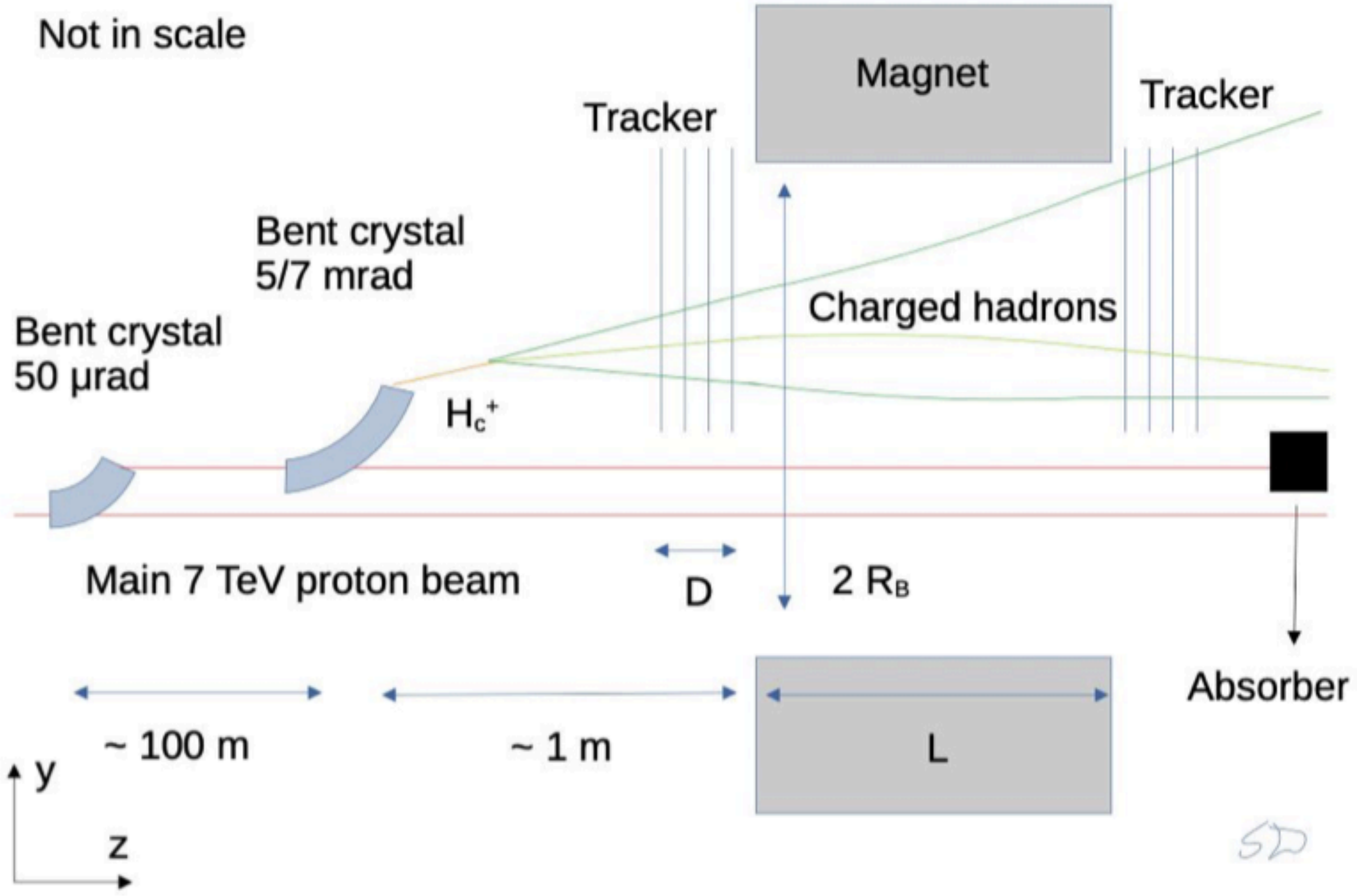
- **Λ_c^+ polarisation and cross-section** in SMOG **p-Ne collisions** $\sqrt{s_{NN}} = 68.6\,\mathrm{GeV}$ at LHCb in progress
  - Signal $pNe \to \Lambda_c^+(\to pK^-\pi^+)X, \sqrt{s_{NN}} \approx 68\,\mathrm{GeV}$: ≈ 3250 events
  - Peaking bkg $pp \to \Lambda_c^+(\to pK^-\pi^+)X, \sqrt{s} = 5\,\mathrm{TeV}$: ≈ 460 events
- Expected sensitivity $\approx 5\,\%$ on the polarisation

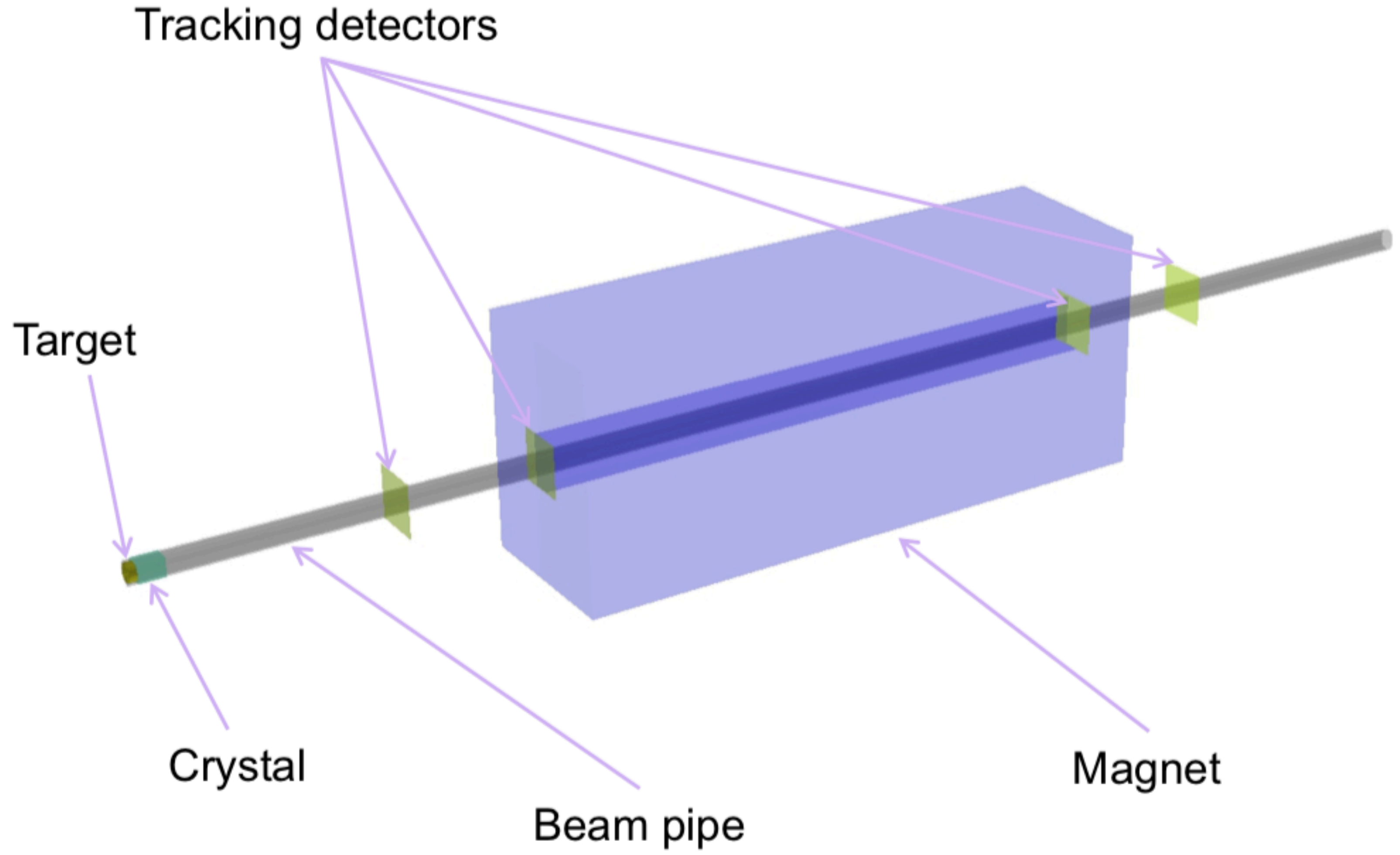


Test in LHC at IR3

- A proof-of-principle test at the insertion region 3 (IR3) is considered with LHC machine people
- Channeled Λ_c^+ in bent crystal are very focused in few cm²
- Preliminary simulations: with 8 pixel sensors + existing 1.9 Tm dipole magnet in IR3 can build a spectrometer
- Ongoing activity to prepare the hardware for the test during Run3







Conclusions

- Measurements of MDM/EDM of particles are sensitive to physics within and beyond the SM
- Measurements of MDM/EDM of short-lived charm particles are foreseen at LHCb or in a dedicated experiment in IR3
- First measurements are possible in 2 year data taking:
  - require a fixed-target setup to be installed
- Milestones achieved: feasibility detector studies, long bent crystal prototypes, preparatory studies in LHCb, machine layout, physics program extended
- Machine test in LHC, possibly during Run3
- Fruitful discussions ongoing, planned workshop in Gargnano del Garda 26-28th September 2022
- Join! (agenda will be published soon here)