

Physics opportunities with double crystal fixed-target setup

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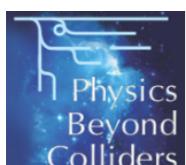
Physics Beyond Collider Annual Workshop
CERN, 7-9 November 2022



[SELDOM webpage](#)
 [@SeldomTeam](#)

Acknowledgements

- ▶ **LHCb** contributors: S. Aiola, S. Barsuk, N. Conti, F. De Benedetti, J. Fu, J. Grabowski, L. Henry, Y. Hou, S. Jaimes, C. Lin, D. Marangotto, F. Martinez Vidal, J. Mazorra, A. Merli, N. Neri, S. Neubert, E. Niel, A. Oyanguren, M. Rebollo, P. Robbe, J. Ruiz Vidal, I. Sanderswood, E. Spadaro Norella, A. Stocchi, G. Tonani, Z. Wang
- ▶ **LHCb FITPAN** review members: T. Eric, M. Ferro-Luzzi, G. Graziani, R. Kurt, R. Lindner, C. Parkes, M. Palutan, G. Passaleva, M. Pepe-Altarelli, V. Vagnoni, G. Wilkinson
- ▶ **Contributions** also from: G. Arduini, E. Bagli, L. Bandiera, O.A. Bezshyyko, L. Burmistrov, G. Cavoto, D. De Salvador, K. Dewhurst, A.S. Fomin, S.P. Fomin, F. Galluccio, M. Garattini, M.A. Giorgi, V. Guidi, P. Hermes, A.Yu. Korchin, E. Kou, I.V. Kirillin, Y. Ivanov, C. Maccani, L. Massacrier, V. Mascagna, A. Mazzolari, H. Miao, D. Mirarchi, S. Montesano, A. Natochii, M. Prest, S. Redaelli, M. Romagnoni, W. Scandale, N.F. Shul'ga, A. Sytov, E. Vallazza, F. Zangari
- ▶ Interesting **discussions/suggestions**: V. Baryshevsky, V. M. Biryukov



UA9 UA9



SELDOM



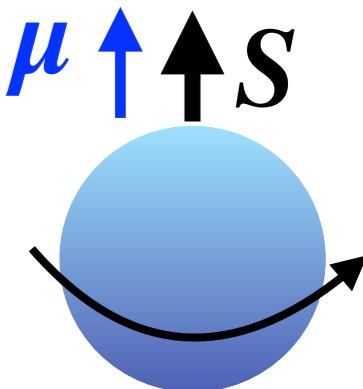
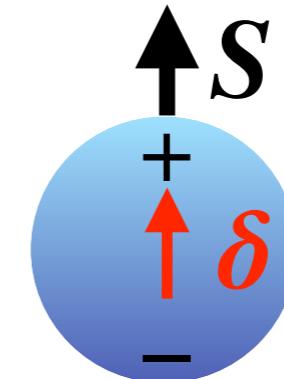
Physics opportunities

- ▶ First direct measurement of **charm** and beauty baryons, and τ lepton (see backup) **dipole moments**

$$\delta = d \frac{q\hbar}{2m} \frac{S}{\hbar}$$

$$\mu = g \frac{q\hbar}{2m} \frac{S}{\hbar}$$

- **MDM**: low energy QCD models for charm and beauty, SM test for τ
- **EDM**: sensitive to new physics



- ▶ **Fixed-target experiment** in the very forward region

- cross-sections and production asymmetries
- polarisation measurements
- small-x physics

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

MDM theoretical predictions

In the quark model

$$\Lambda_c^+ = [ud]c$$

$$\mu_{\Lambda_c^+} = \mu_c$$

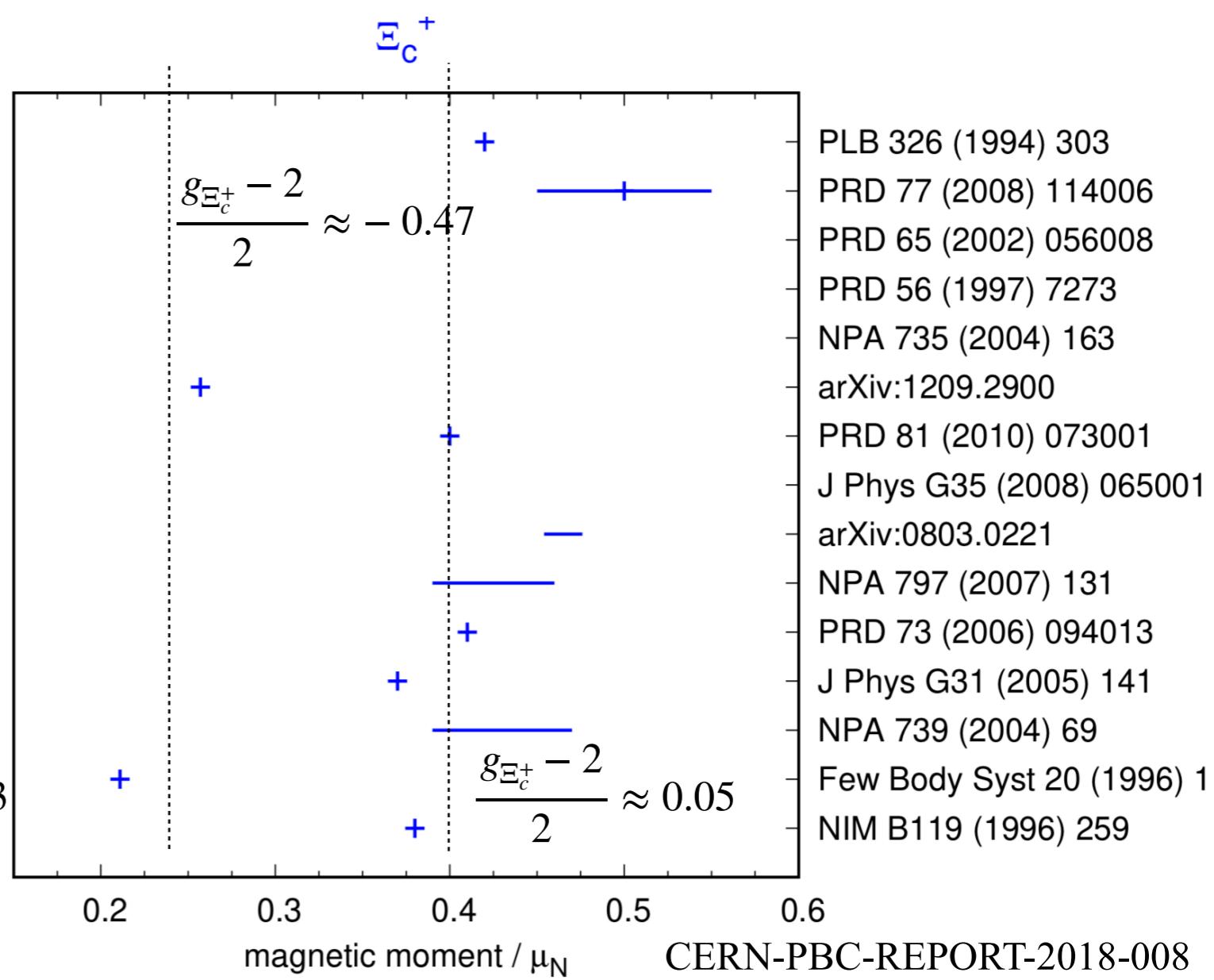
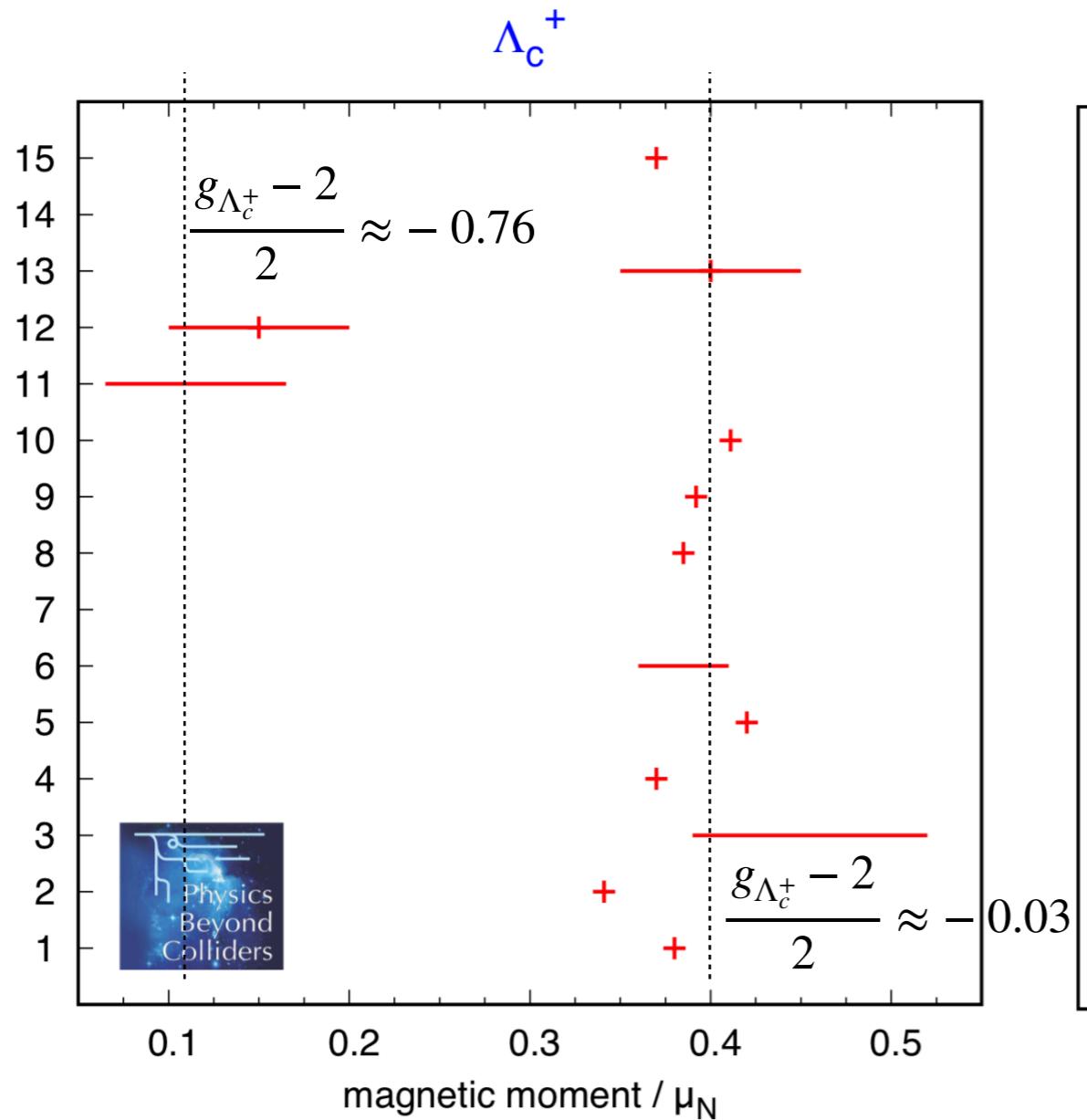
$$\Xi_c^+ = [us]c$$

$$\mu_{\Xi_c^+} = \mu_c$$

EPJC 80 (2020) 358

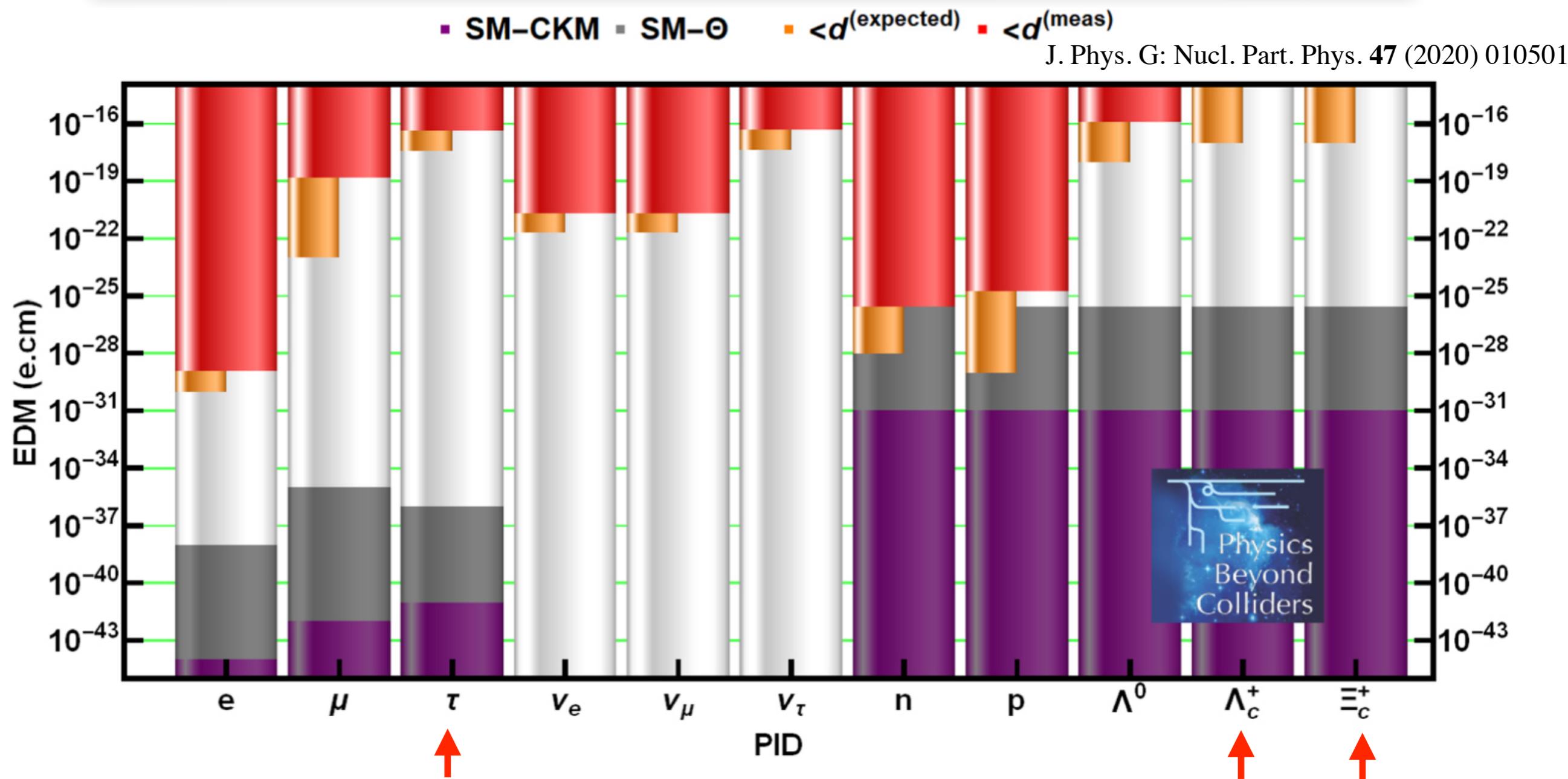
$$\mu_c = (0.48 \pm 0.03)\mu_N$$

Beyond the quark model: e.g. heavy quark effective theories



CERN-PBC-REPORT-2018-008

Status of EDM measurements



Indirect limit: **charm** baryon $\approx 3.4 \times 10^{-16} \text{ e cm}$ (F. Sala 2014),

$1.5 \times 10^{-21} \text{ e cm}$ (H. Gisbert, J. Ruiz Vidal 2020)

τ lepton $\approx 4.5 \times 10^{-17} \text{ e cm}$ (K. Inami et al. 2003)

Kinematic region complementary to LHCb SMOG

From F. Martinez-Vidal at PBC-QCD [link](#)

Kinematic variable	> 15 mrad (~SMOG2)	Ge 293K 16 mrad 10 cm
Momentum (GeV)	< 500	>800
Transverse momentum	> 0.5	< 1
Pseudorapidity*	-4 to 0, central & backward	1 to 3.5, very forward
Momentum transfer Q	20 to 115	≈ 4
Bjorken-x	Down to $\approx 10^{-3.5}$	Down to $\approx 10^{-3}$
Feyman-x	Large negative	Large positive

- ▶ Double crystal fixed-target setup gives access to **zero angle production** of positive charged particles (e.g charm baryons and mesons)

Proposed experimental method for charm baryons at LHC: Λ_c^+ , Ξ_c^+

$\tau \approx 10^{-13}$ s

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

CERN-PBC-REPORT-2019-001
D. Mirarchi et al., EPJC 80 (2020) 929

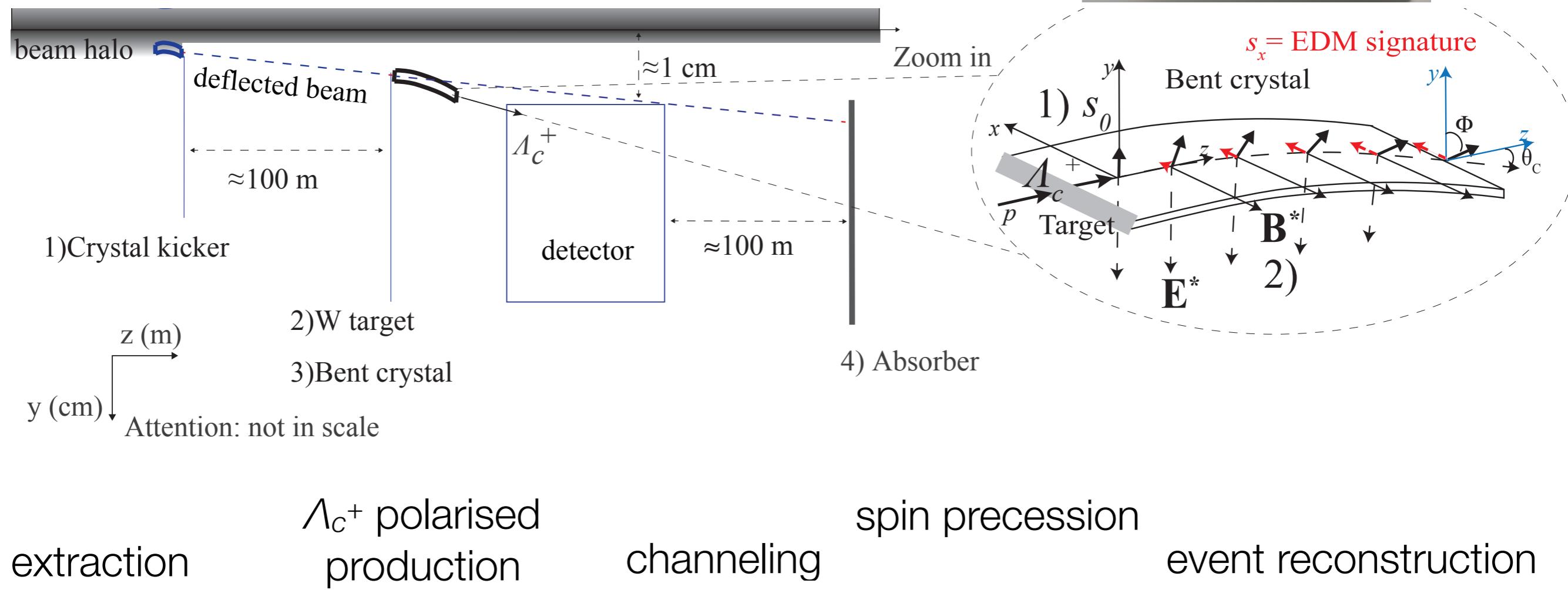
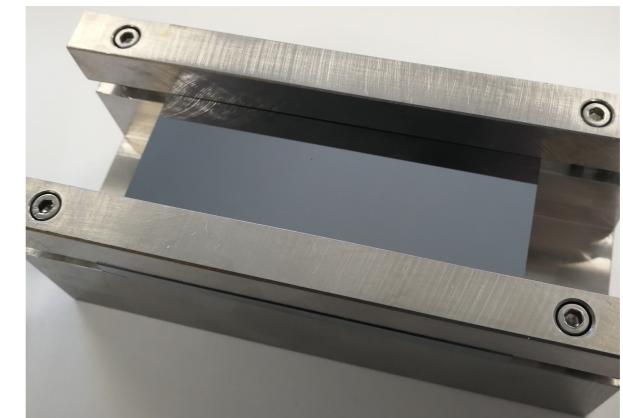
Double crystal fixed-target setup

CERN-PBC-REPORT-2019-001

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

See P. Hermes talk

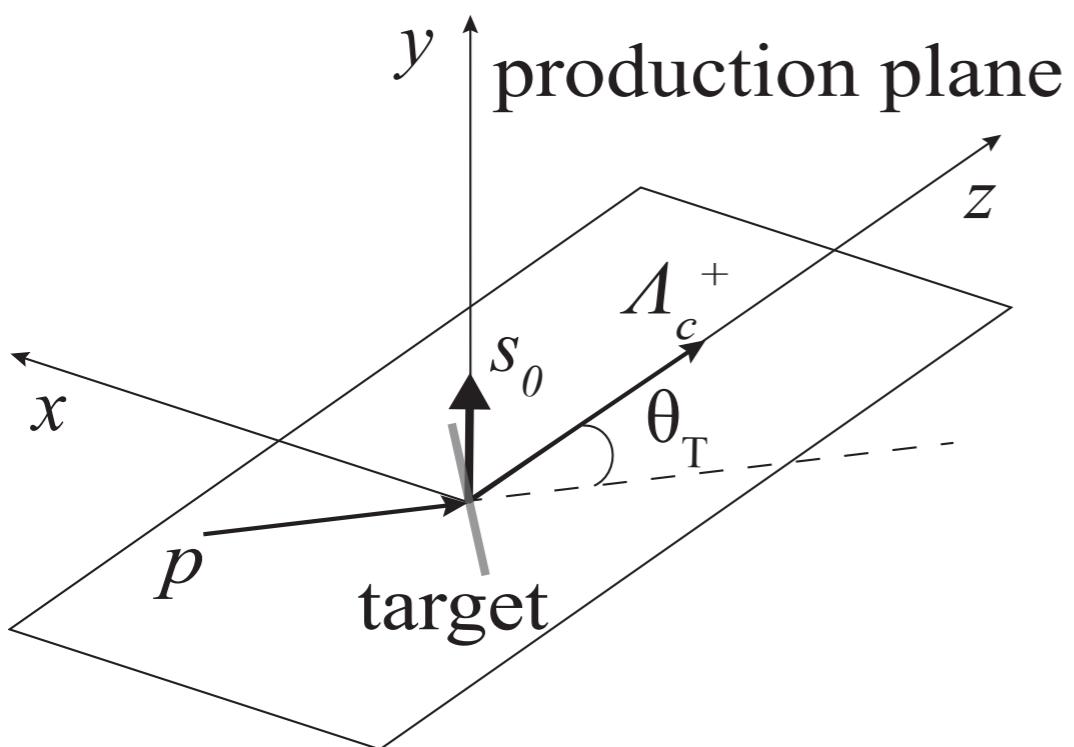
- ▶ **EDM/MDM** from spin precession of channeled baryons in **bent crystals**



Λ_c^+ polarisation

Polarisation perpendicular to production plane due to parity conservation in strong production

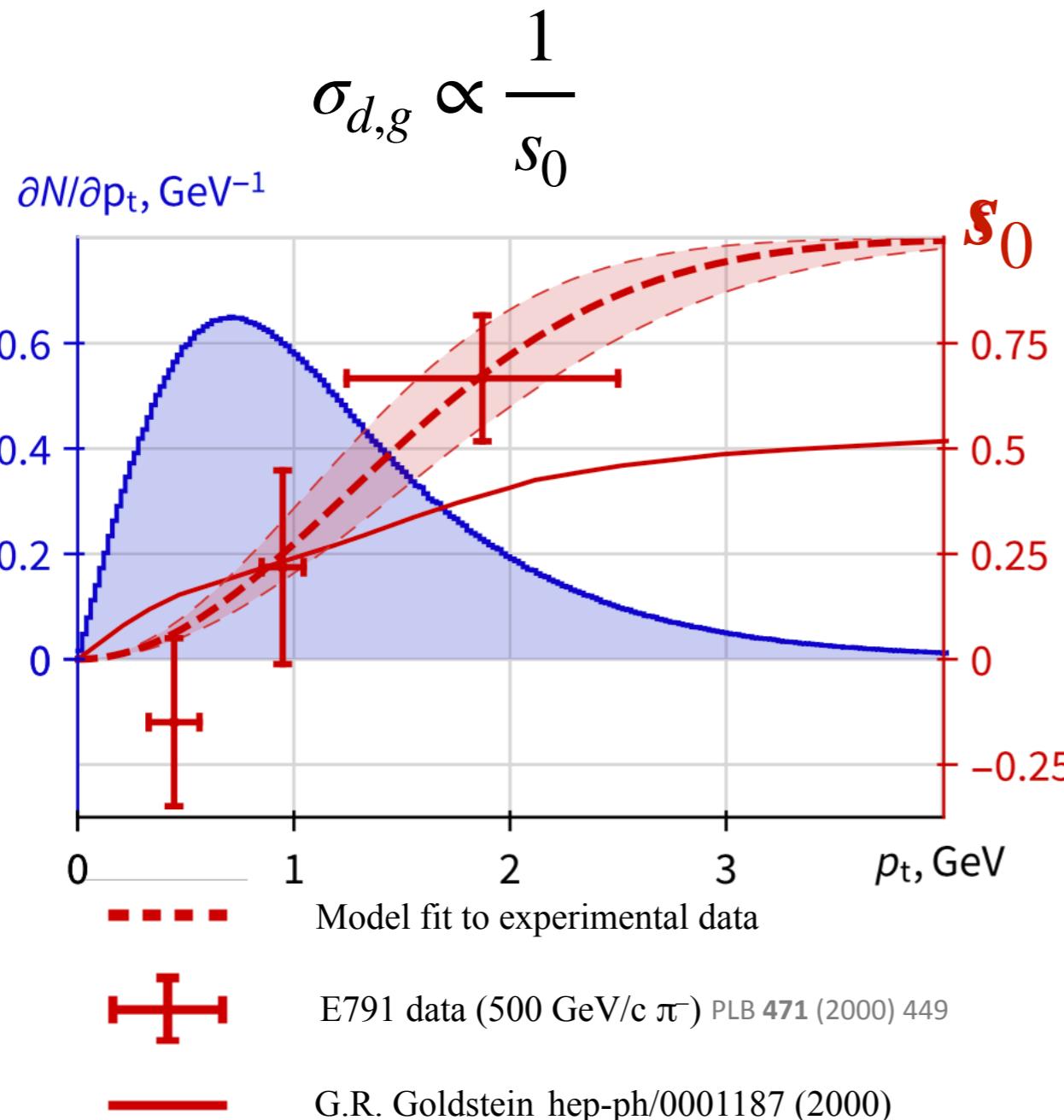
$$\sigma_{d,g} \propto \frac{1}{s_0}$$



Λ_c^+ polarisation

Eur. Phys. J. C (2020) 80:358

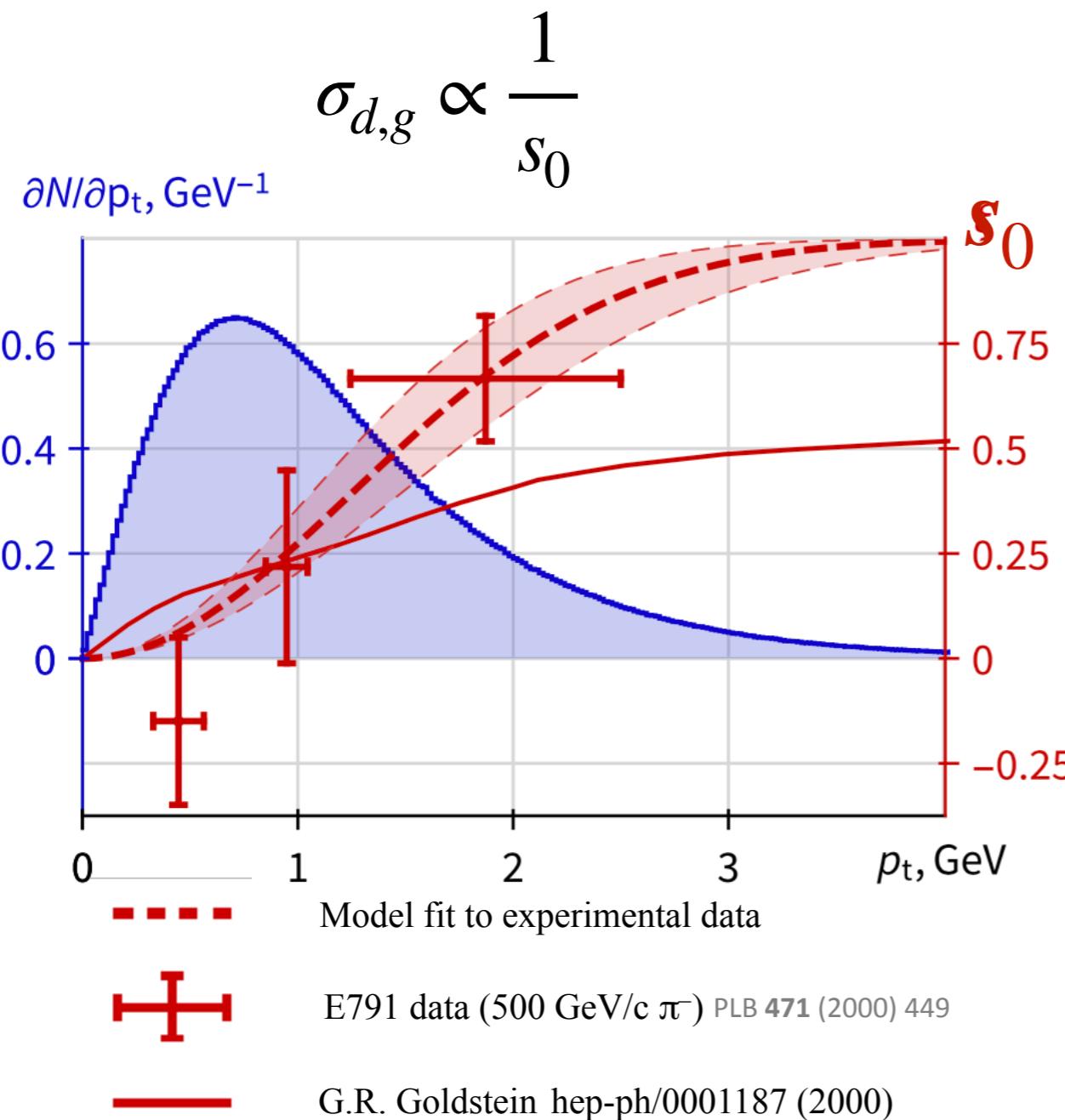
Polarisation perpendicular to production plane due to parity conservation in strong production



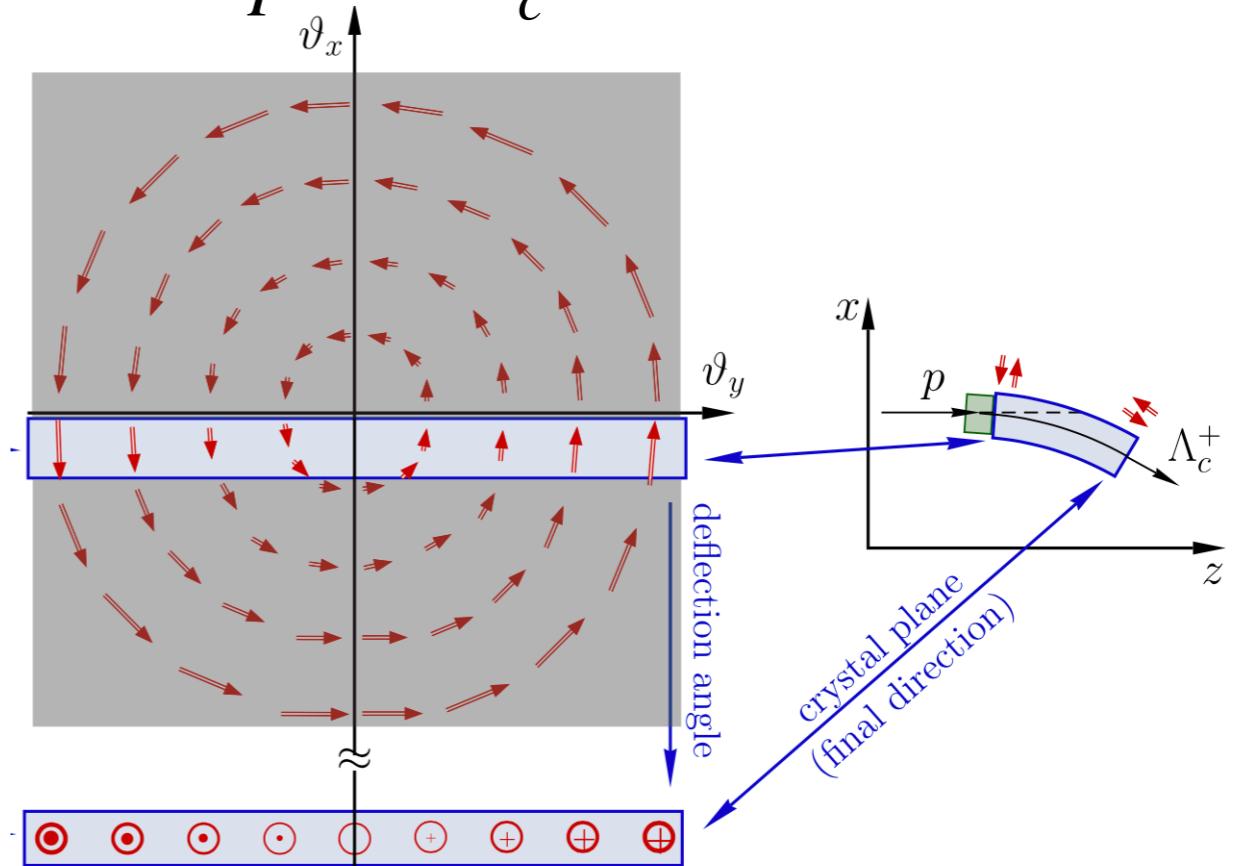
Λ_c^+ polarisation

Eur. Phys. J. C (2020) 80:358

Polarisation perpendicular to production plane due to parity conservation in strong production



Polarisation in crystal frame vs angle between p and Λ_c^+ directions



Polarisation in crystal frame vs angle between p and crystal axis

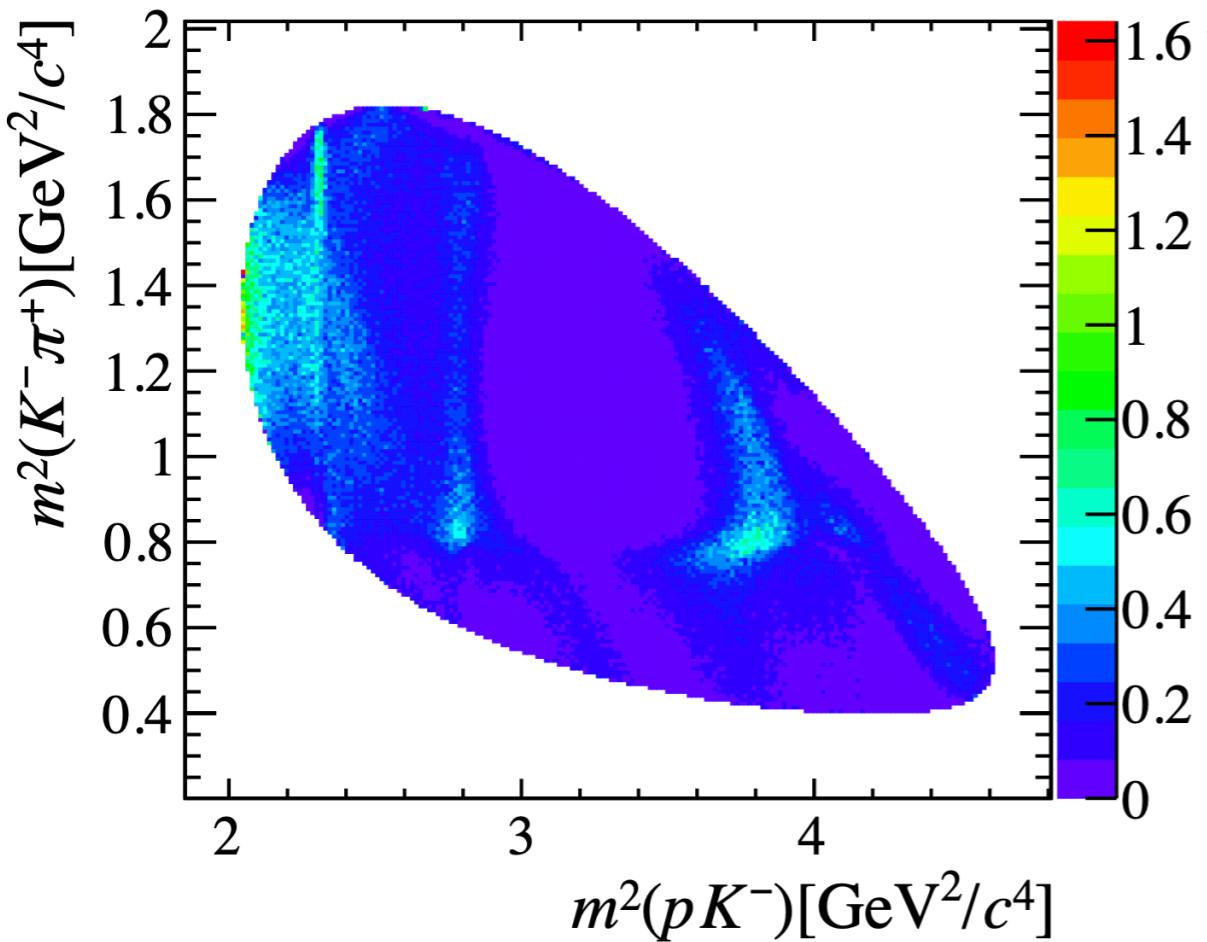
$$s_0 = (s_{0x}, s_{0y}, s_{0z}) \approx \frac{s_0(p_T)}{p_T} (-p \sin \theta_{\text{crys}}, p_{xL}, 0)$$

PRD 103, 072003 (2021)

Polarisation via full amplitude analysis

- ▶ High statistics LHCb pp data sample to study Λ_c^+, Ξ_c^+ decays
- ▶ Extract maximum information via full amplitude analysis of the 3-body decays D. Marangotto, AHEP (2020) 7463073

PRD 103, 072003 (2021)



Decay distribution

$$W(\xi | s) = f(\xi) + sg(\xi)$$

ξ = phase space variable
 s =spin polarisation

Sensitivity: average event information

$$S^2 = \int \frac{g^2(\xi)}{f(\xi) + s_0 g(\xi)} d\xi \approx 0.145$$

$$\sqrt{3}S = 0.662 \pm 0.005 \pm 0.010 \pm 0.007$$

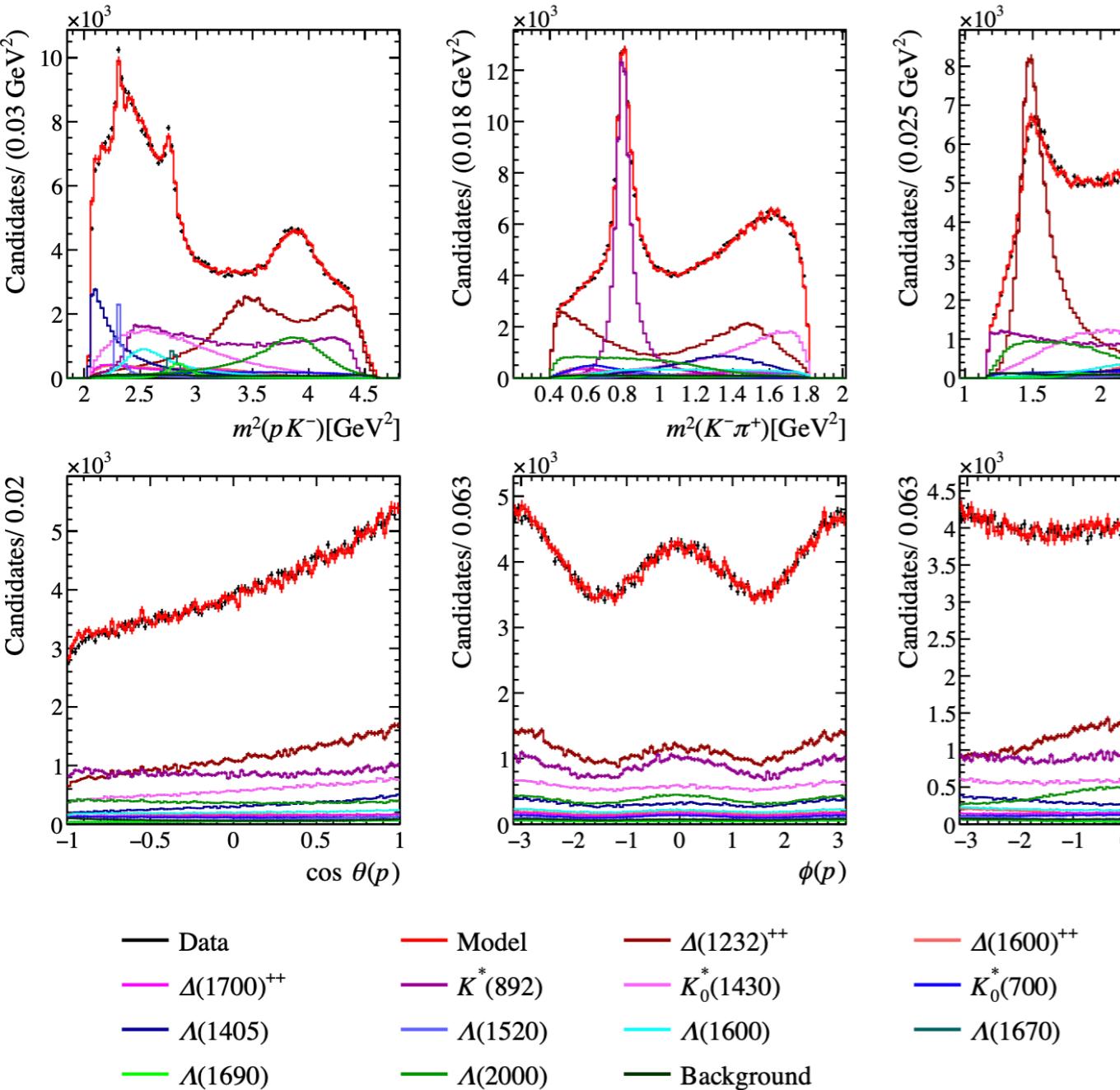
details in LHCb-PAPER-2022-002

arXiv: [2208.03262](https://arxiv.org/abs/2208.03262) (accepted by PRD)

$\Lambda_c^+ \rightarrow p K^- \pi^+$ amplitude analysis

Λ_c^+ selected from $X_b \rightarrow \Lambda_c^+ \mu^- X$ decays

400k signal yield, 98% purity



LHCb-PAPER-2022-002
arXiv: [2208.03262](https://arxiv.org/abs/2208.03262) (accepted by PRD)

Amplitude model

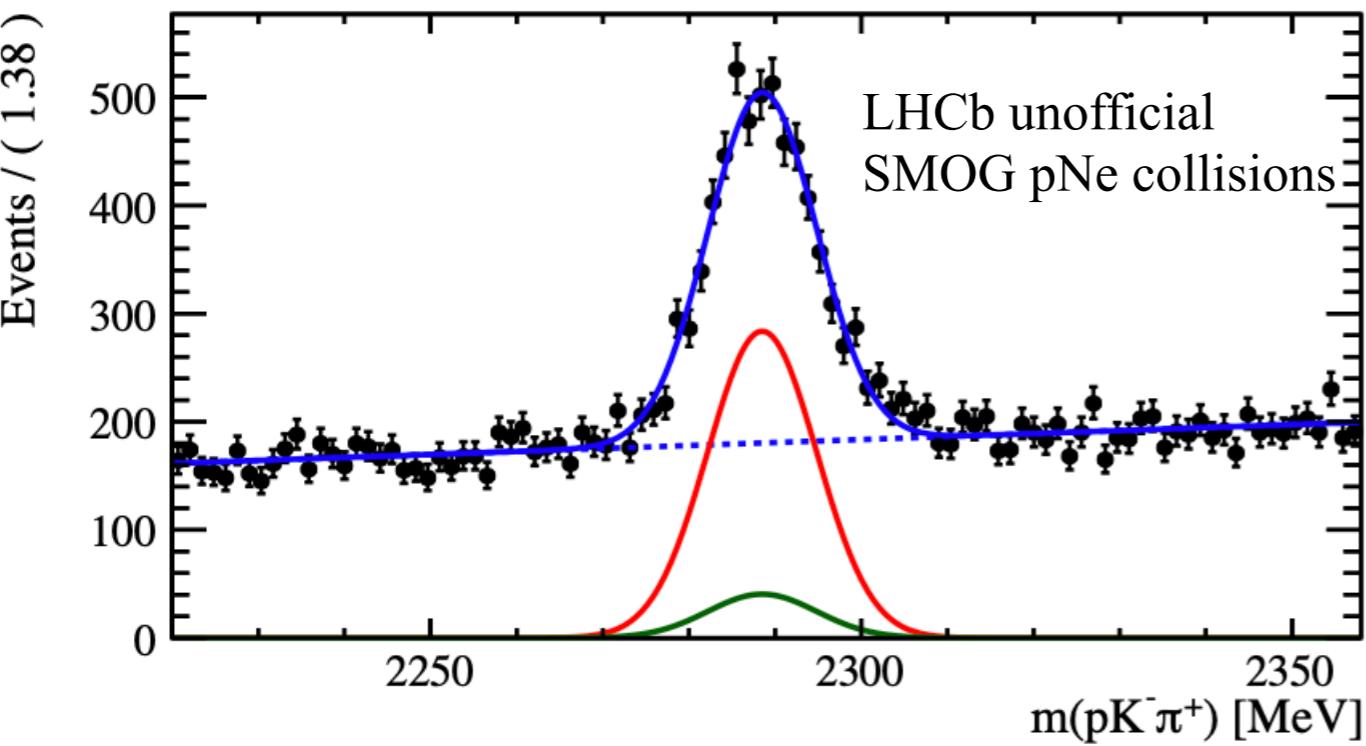
Resonance	J^P	Mass (MeV)	Width (MeV)	Fit Fraction (%)
$\Lambda(1405)$	$1/2^-$	1405.1	50.5	7.7
$\Lambda(1520)$	$3/2^-$	1515 – 1523	10 – 20	1.86
$\Lambda(1600)$	$1/2^+$	1630	250	5.2
$\Lambda(1670)$	$1/2^-$	1670	30	1.18
$\Lambda(1690)$	$3/2^-$	1690	70	1.19
$\Lambda(2000)$	$1/2^-$	1900 – 2100	20 – 400	9.58
$\Delta(1232)^{++}$	$3/2^+$	1232	117	28.60
$\Delta(1600)^{++}$	$3/2^+$	1640	300	4.5
$\Delta(1700)^{++}$	$3/2^-$	1690	380	3.90
$K_0^*(700)$	0^+	824	478	3.02
$K^*(892)$	1^-	895.5	47.3	22.14
$K_0^*(1430)$	0^+	1375	190	14.7

Polarisation measurement

Component	Value (%)
P_x (lab)	$60.32 \pm 0.68 \pm 0.98 \pm 0.21$
P_y (lab)	$-0.41 \pm 0.61 \pm 0.16 \pm 0.07$
P_z (lab)	$-24.7 \pm 0.6 \pm 0.3 \pm 1.1$
P_x (\tilde{B})	$21.65 \pm 0.68 \pm 0.36 \pm 0.15$
P_y (\tilde{B})	$1.08 \pm 0.61 \pm 0.09 \pm 0.08$
P_z (\tilde{B})	$-66.5 \pm 0.6 \pm 1.1 \pm 0.1$

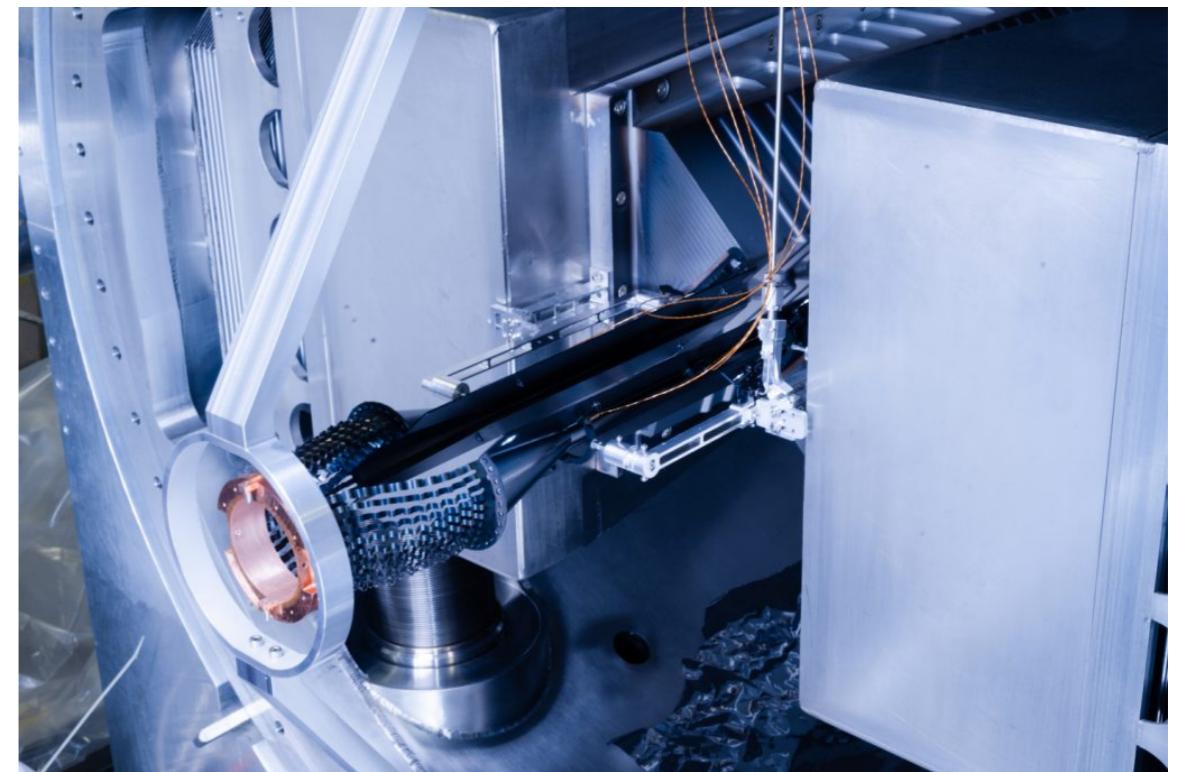
Λ_c^+ polarisation using SMOG data

- ▶ Λ_c^+ polarisation and cross-section in SMOG p-Ne collisions
 $\sqrt{s}=68.6$ GeV at LHCb in progress (signal yield ≈ 2500)
- ▶ Expected precision on polarisation 5%

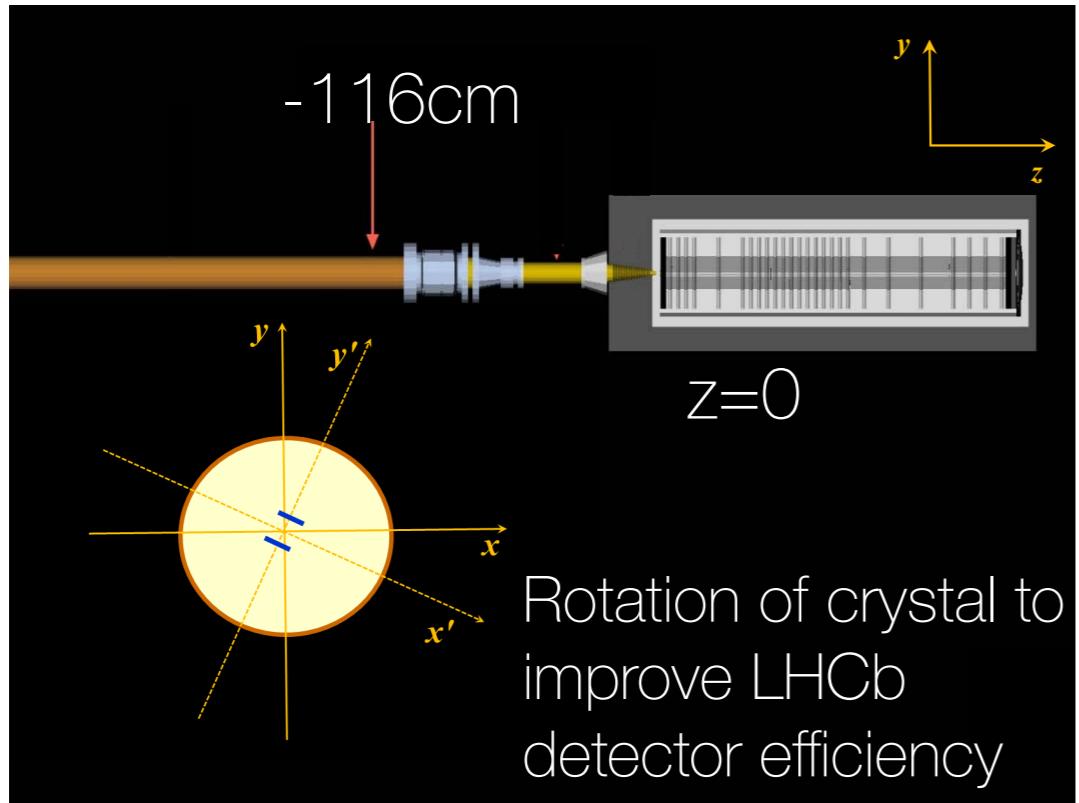


In Run3 SMOG2 system with gas density increased of 2 orders of magnitude → higher yields

See *L.L. Pappalardo talk*



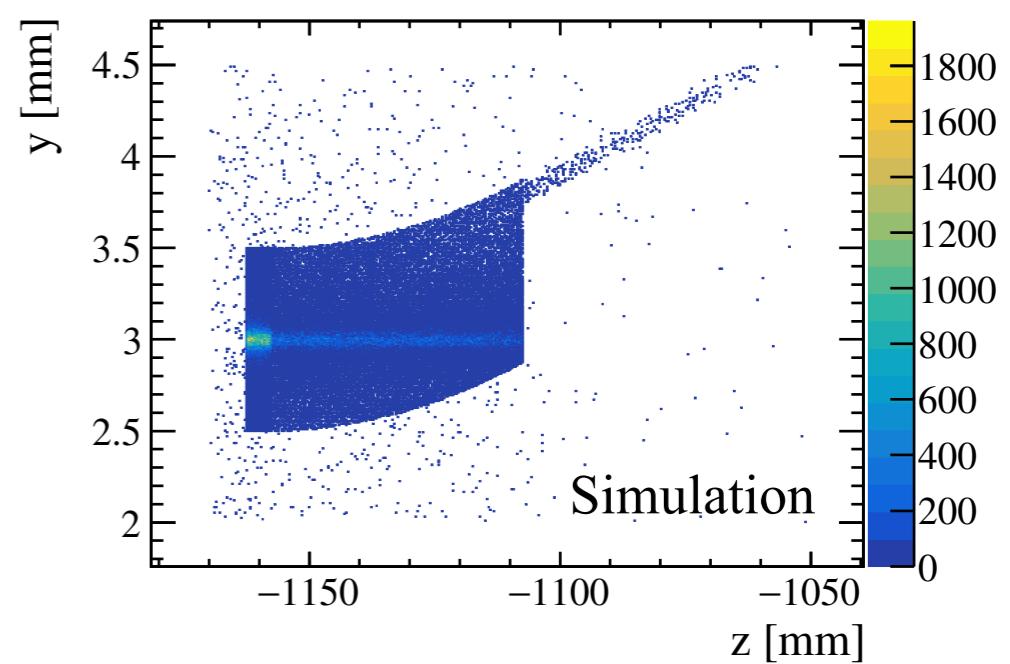
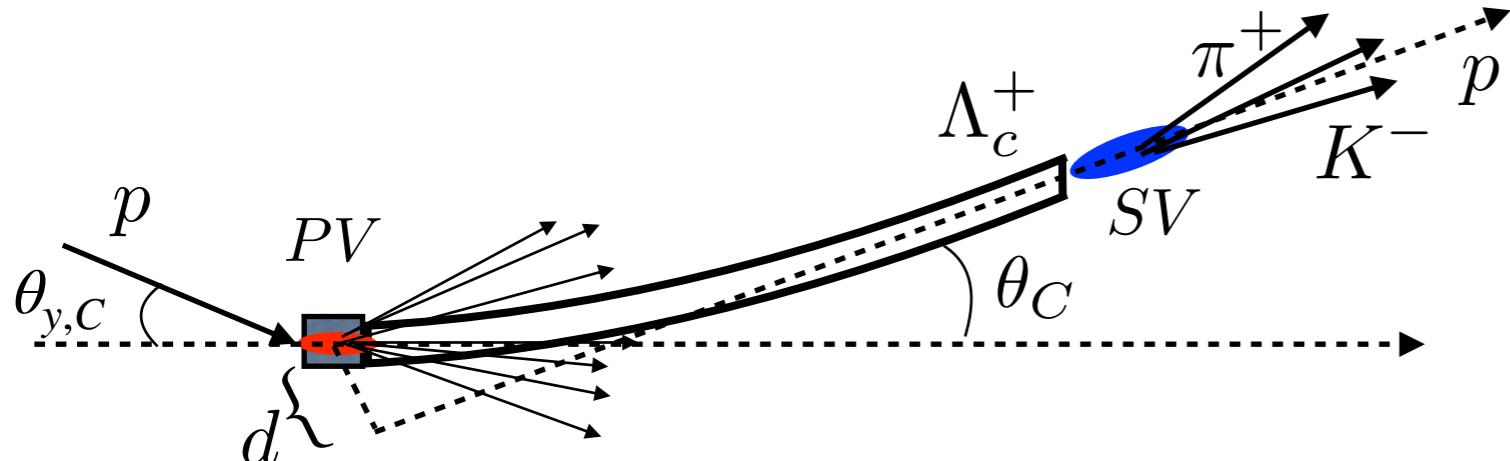
Simulation studies in LHCb



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

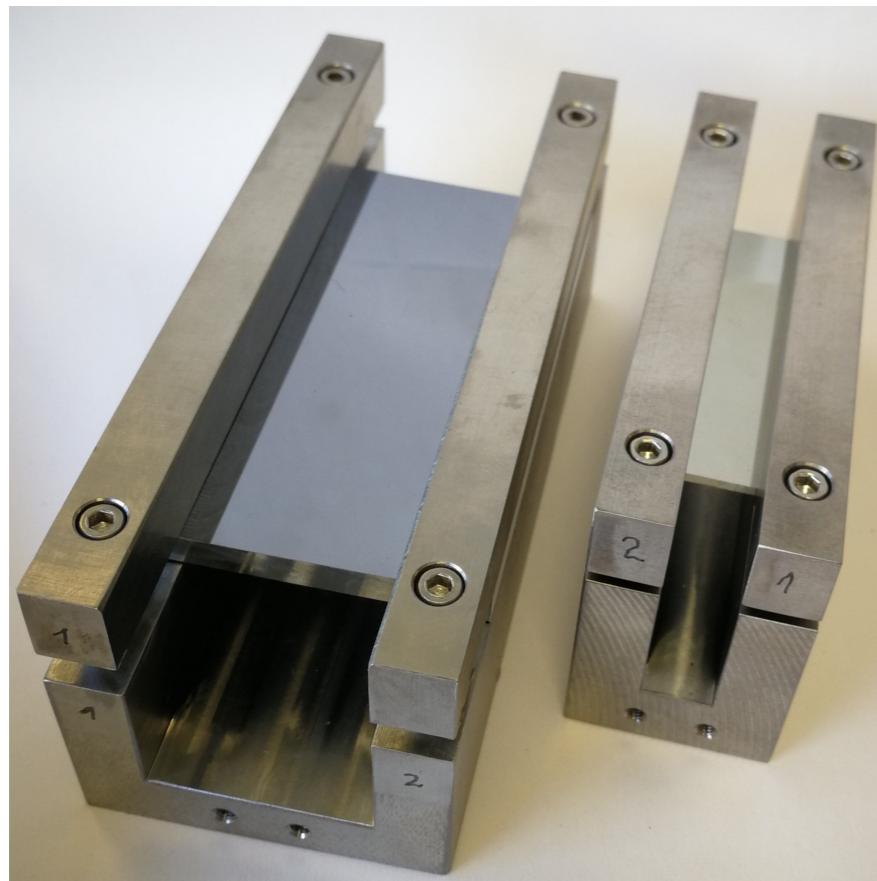
Andrea Merli PhD thesis CERN-THESIS-2019-108

Good res. on production and decay vertex
(7-8mm), θ_C angle ($25\mu\text{rad}$), $m(pK\pi)$ (20 MeV)



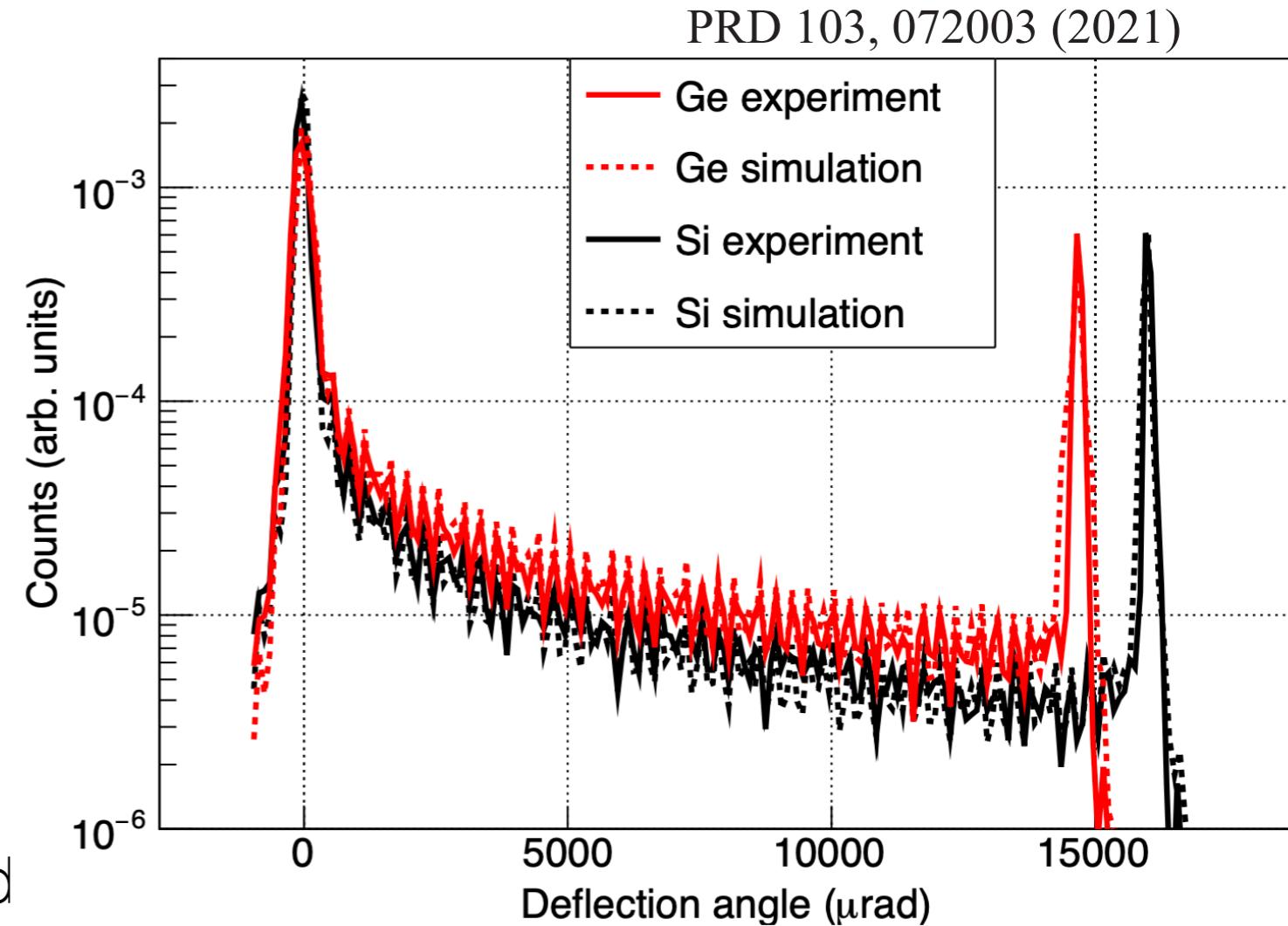
Long bent crystal prototypes

INFN Ferrara



Si: 8 cm long, bent @16.0 mrad

Ge: 5 cm long, bent @14.5 mrad



- Channeling efficiency 10% for 180 GeV/c pions at CERN SPS
- Specifications for bent crystals test in LHC were recently approved (EDMS 2742008)

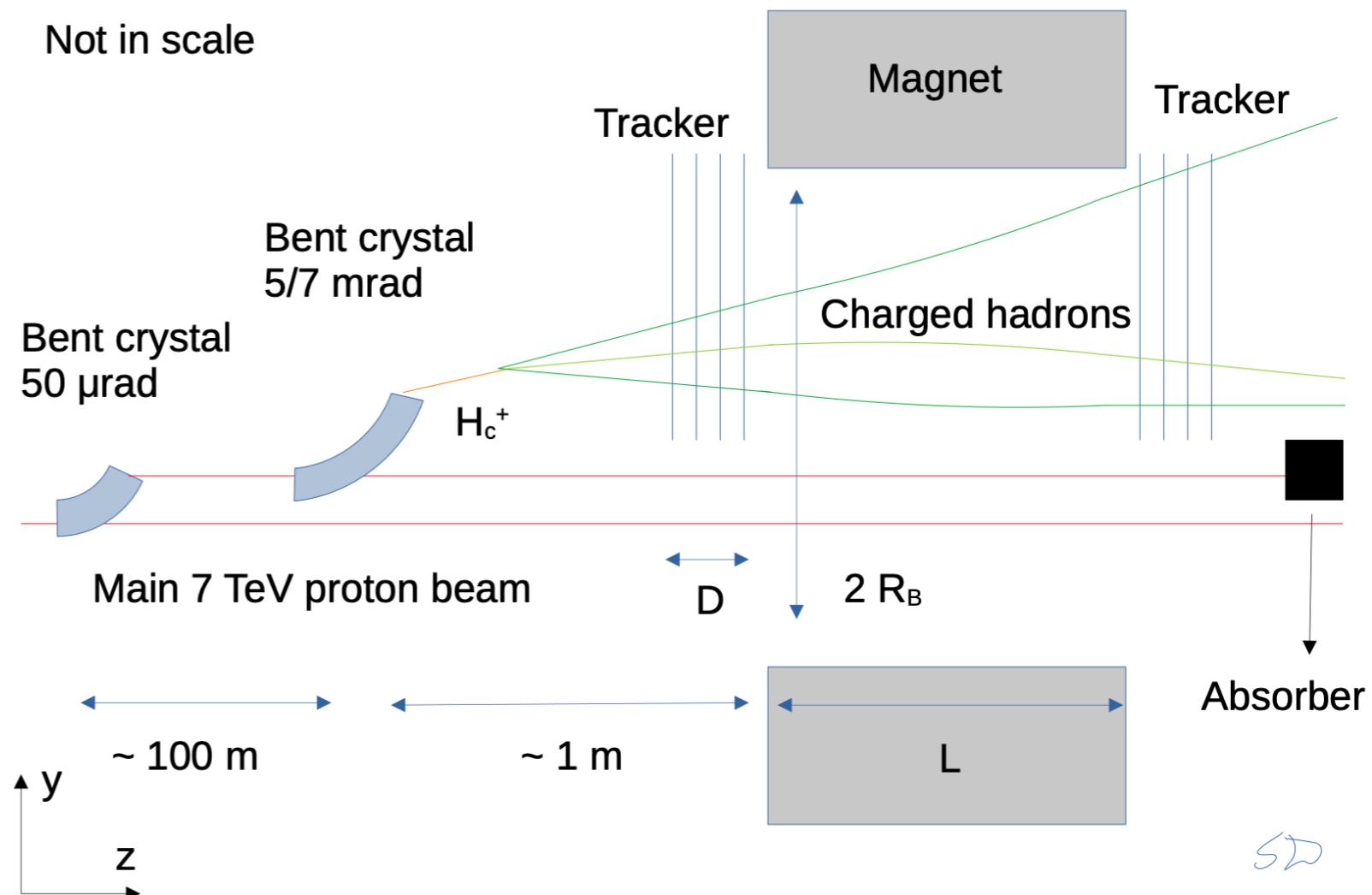
See P. Hermes talk

Test in LHC at IR3

See P. Hermes talk

- ▶ A **proof-of-principle** test at the insertion region 3 (IR3) is considered with LHC machine people

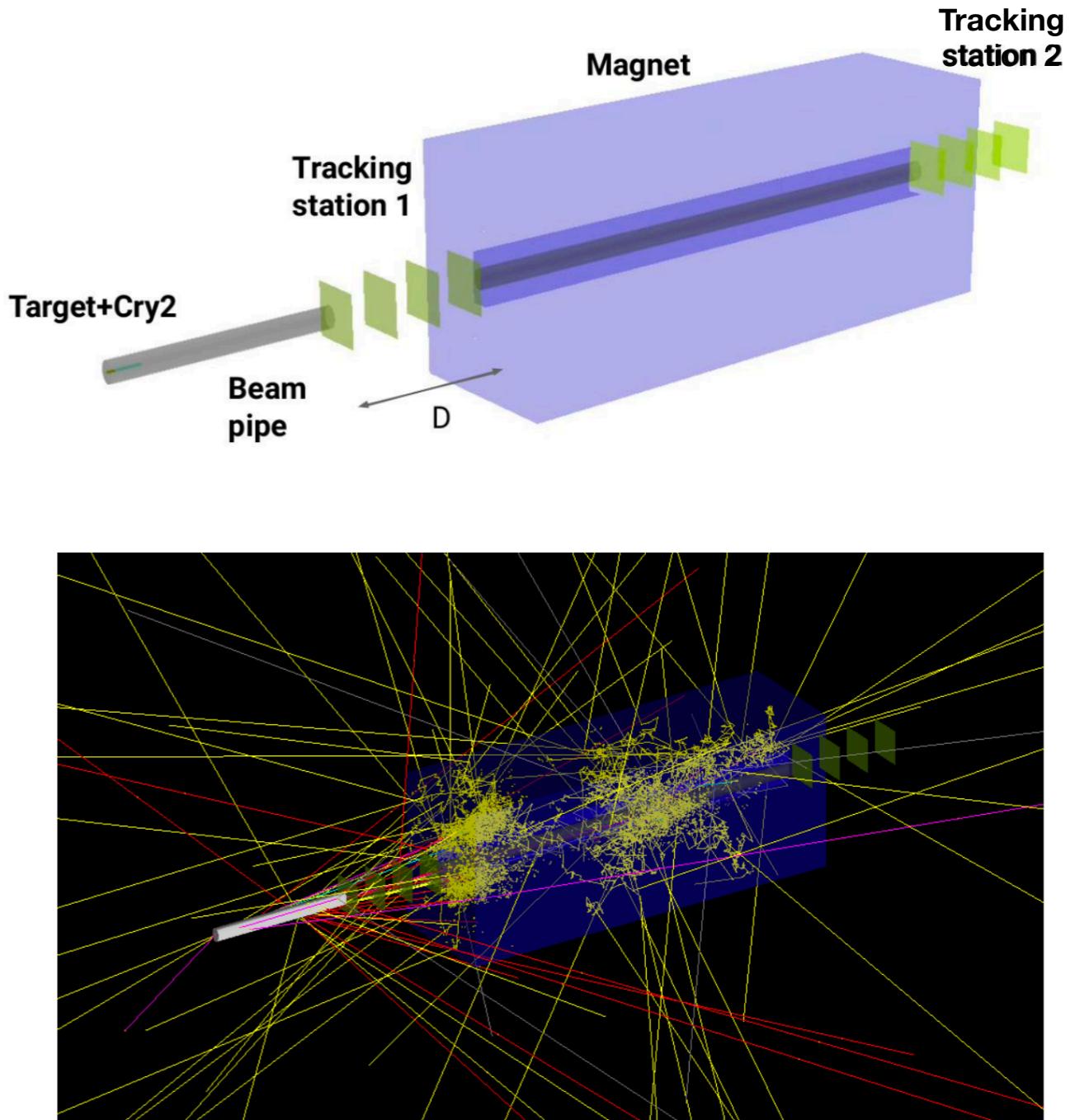
- ▶ Main goals of the test
 - test machine and operational aspects
 - measure channeling efficiency at TeV energies
 - study detector performance and background level



Simulation framework for IR3

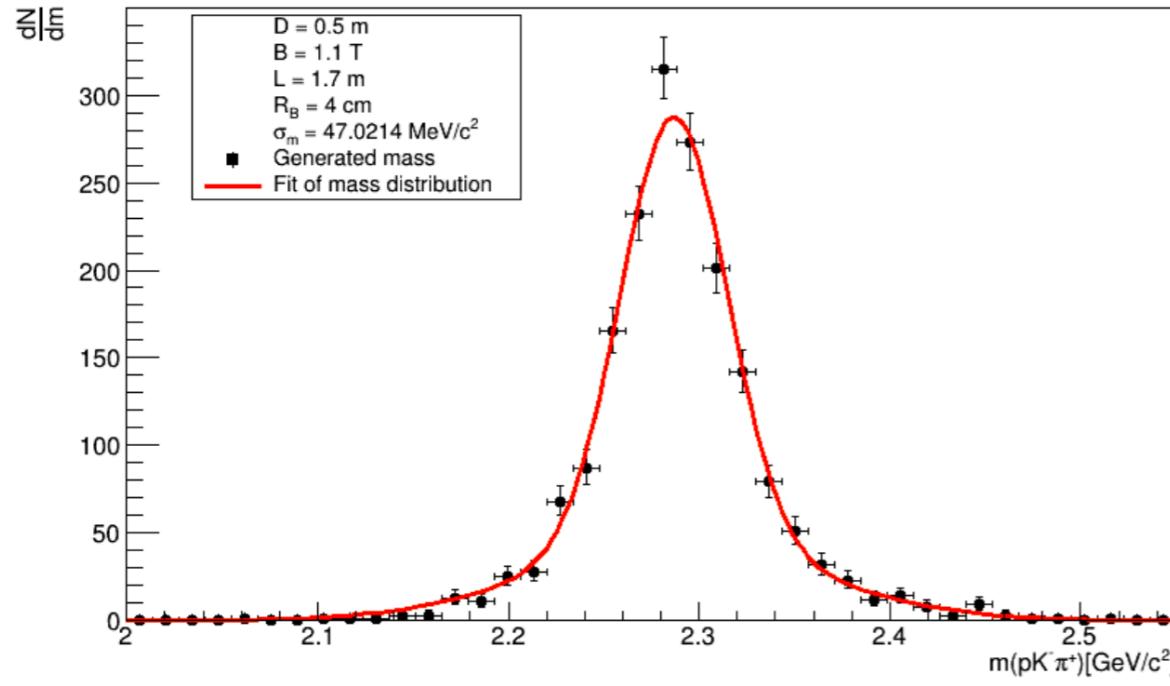
Simulation framework for the test at IR3 and experiment following the PoP

- ▶ Geometry based on DD4Hep
- ▶ Generators: Phythia/Angantyr, particle gun, general particle source
- ▶ Visualisation: geoDisplay
- ▶ Event model: DDG4
- ▶ Channeling: Geant4
- ▶ Tracking: GenFit

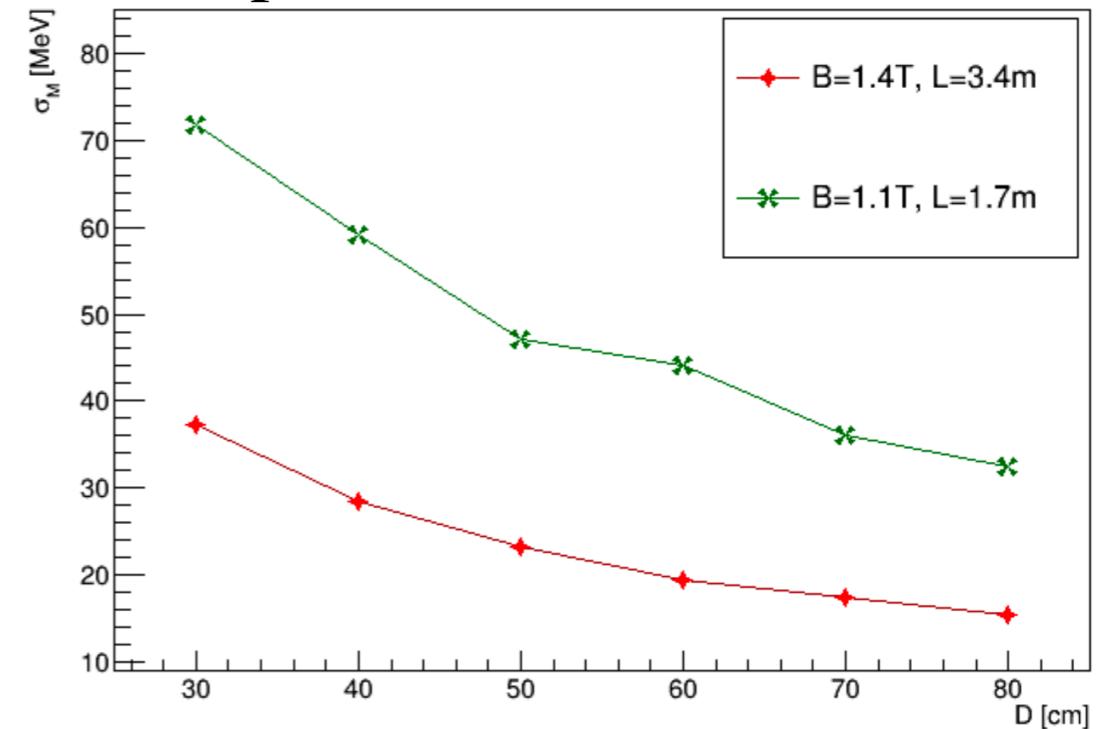


Simulation studies for IR3

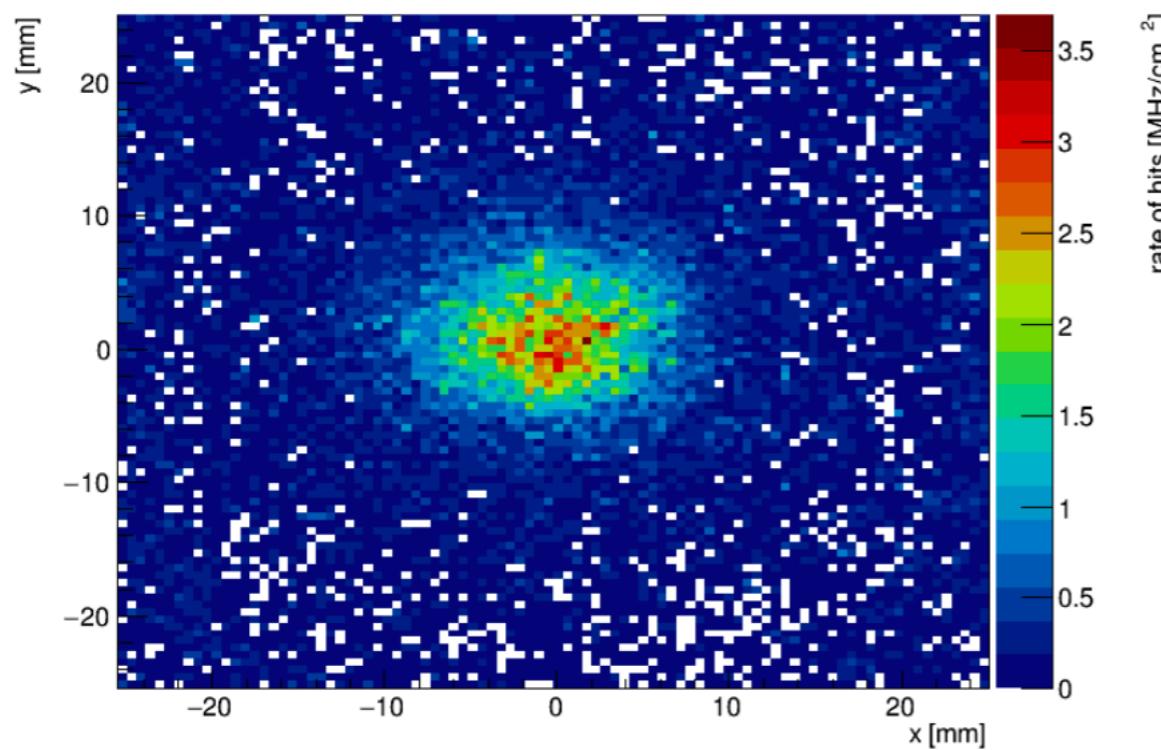
$m(pK^-\pi^+)$ distribution



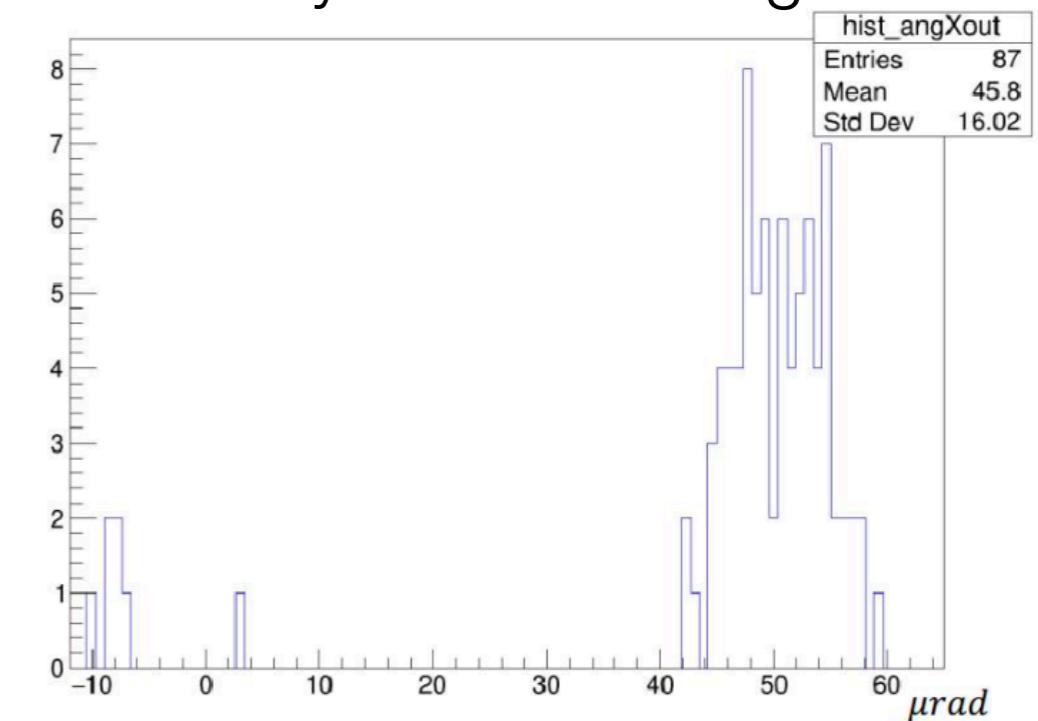
$m(pK^-\pi^+)$ vs spectrometer



pixel hit rate MHz/cm^2

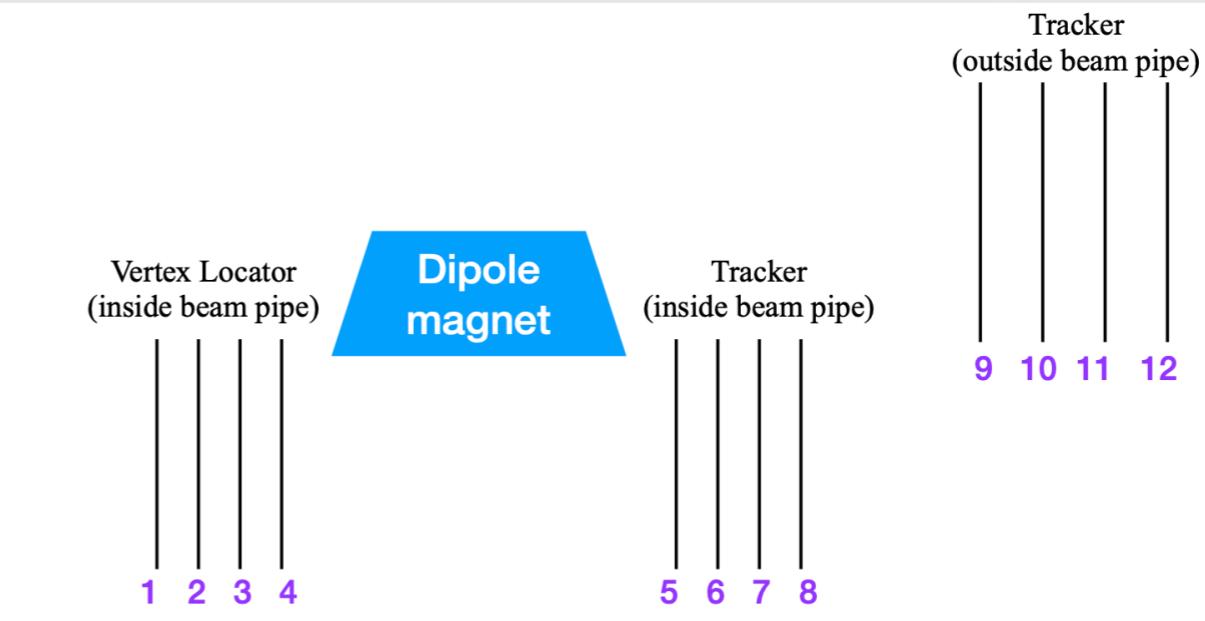


crystal channeling



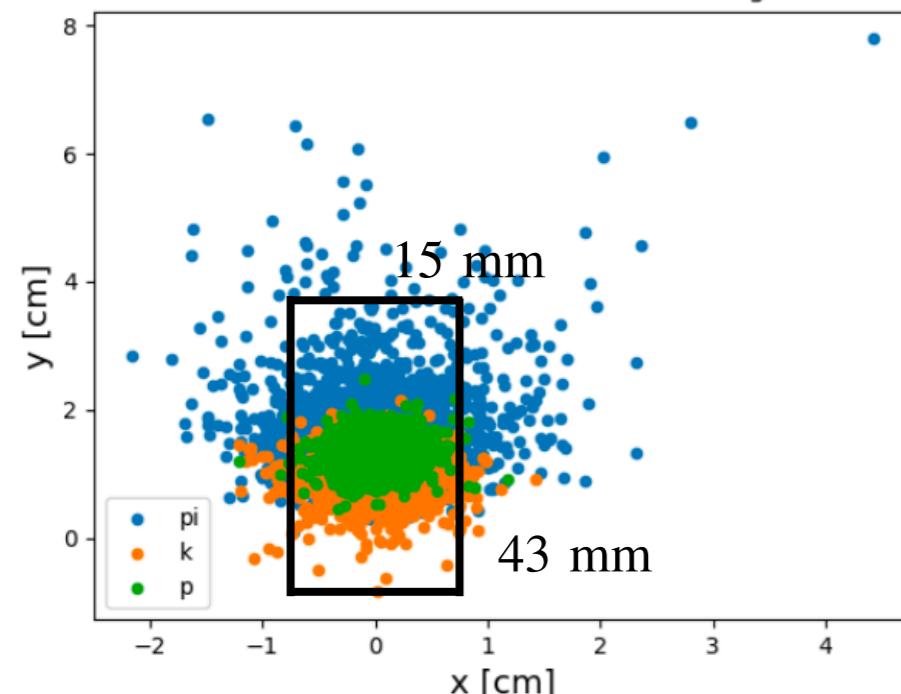
Spectrometer for a dedicated experiment at IR3

- ▶ Channeled Λ_c^+ in bent crystal are very focused in few cm²
- ▶ Preliminary simulations: with 8 **VELO tiles** + existing 1.9Tm dipole magnet in situ can build a spectrometer



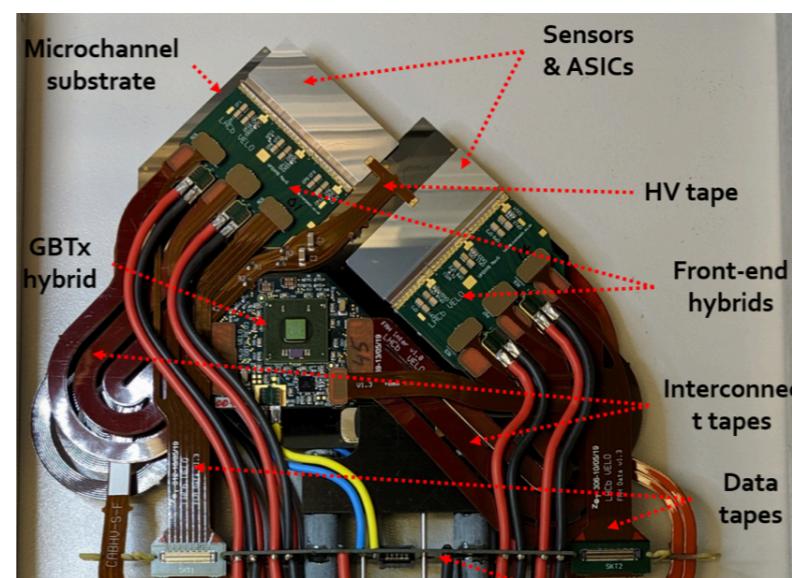
Hit distribution for $\Lambda_c^+ \rightarrow pK^-\pi^+$
Area \approx few cm². rate \approx 100 MHz/cm²

Last tracker station at z=0.4 m from magnet

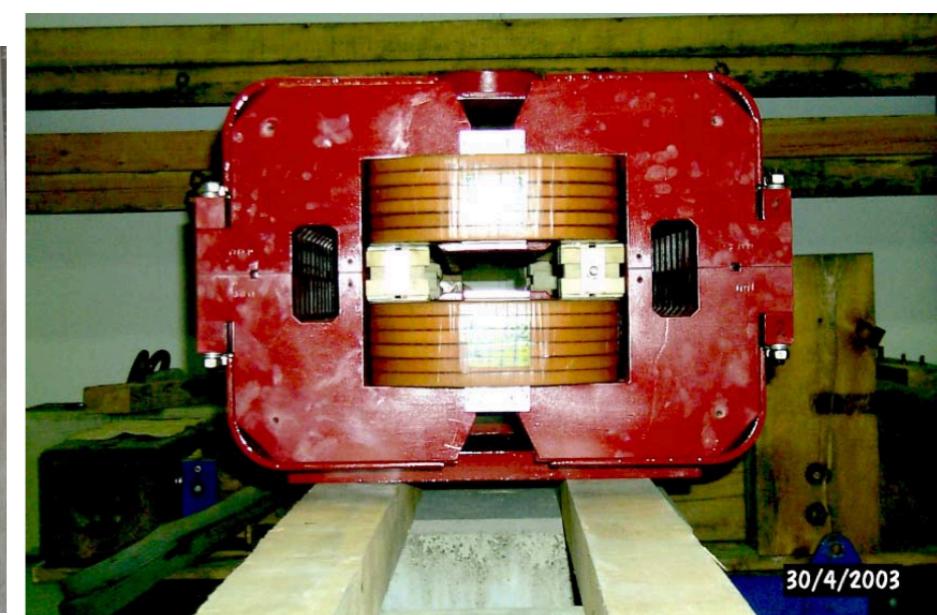


VeloPix modules in Roman Pots

for Vertex and Tracker stations
1 cm from the beam
55x55 μm^2 pixel,
pixel hit rate 600 MHz/cm²,
12 μm hit resolution



LHC orbit correction dipole MCBW (1.7 m, 1.1 T) is considered for the spectrometer
(Credits: Pascal Hermes, CERN)

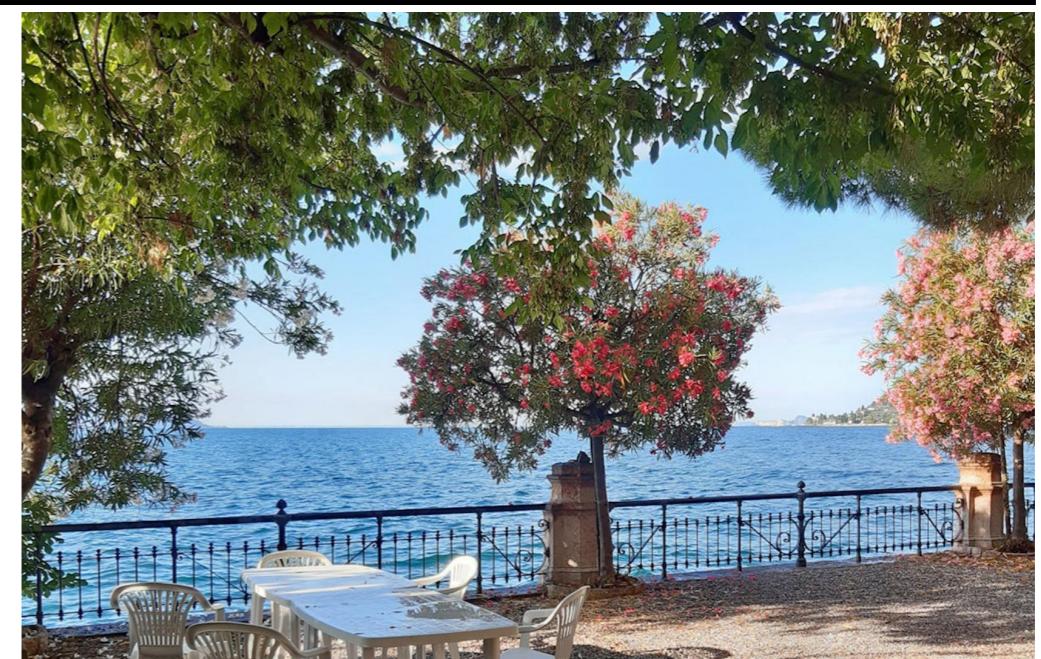
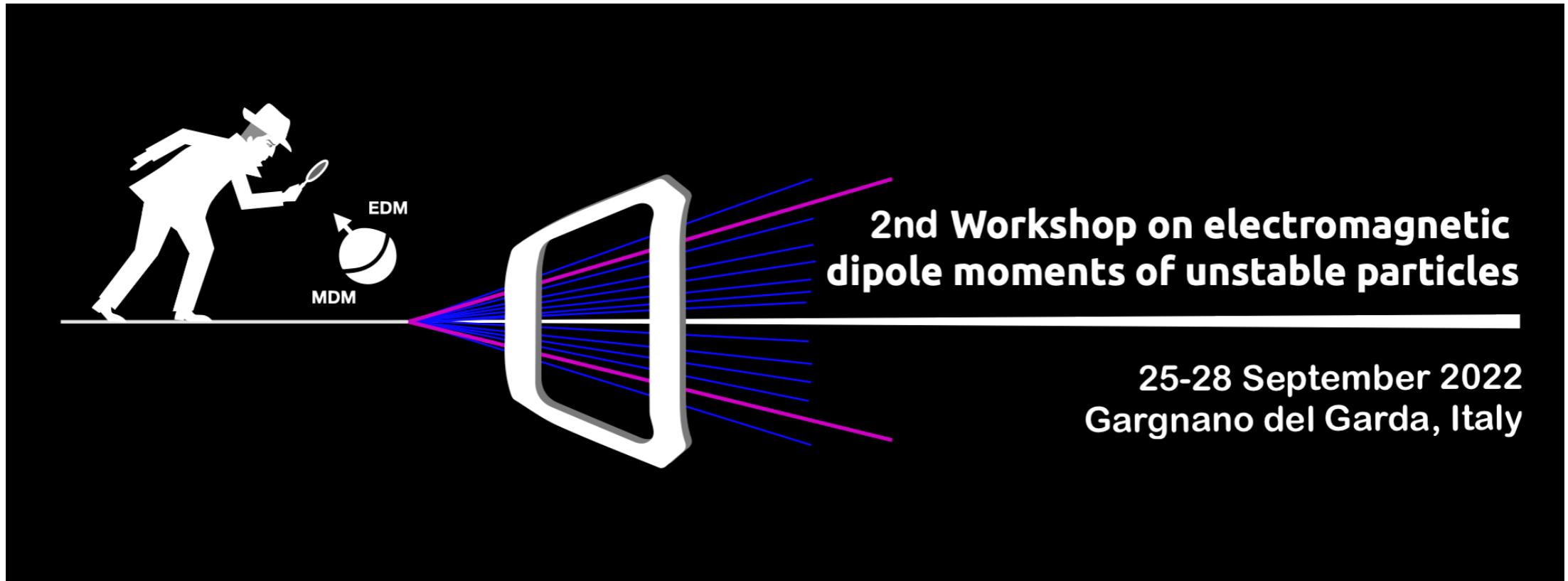


Summary

- ▶ **First measurements** of **charm baryons** are possible in 2 year data taking using the LHCb detector
- ▶ **Milestones** achieved: feasibility detector studies, long bent crystal prototypes, preparatory studies in LHCb, machine layout, physics program extended
- ▶ Machine **test in LHC** during Run3. MoU for contributions is ready for signatures
- ▶ Possibility to design a **dedicated fixed-target** experiment at LHC at high statistics for a more **ambitious physics program**, possibly including the τ lepton
- ▶ Interested community is preparing a Letter of Intent for the LHCC

Recent topical workshop

- ▶ Agenda of the workshop at this [link](#)



Recent topical workshop

- ▶ Agenda of the workshop at this [link](#)



Thanks for your attention!

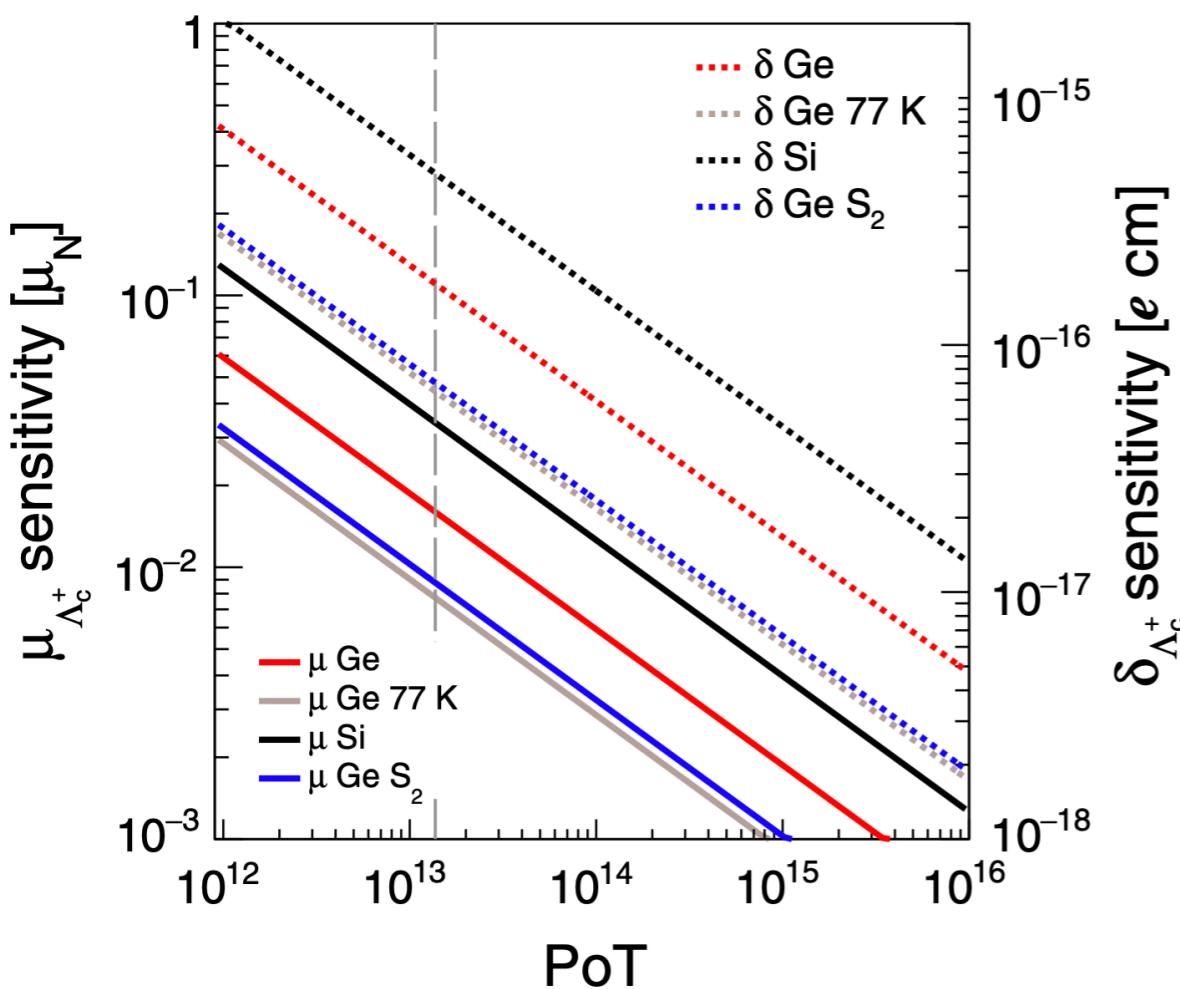
Backup slides

Sensitivity on MDM/EDM

- ▶ S1 configuration: **LHCb detector, Ge (Si) 16 mrad, 10 cm**
- ▶ S2 configuration: **dedicated experiment, Ge 7 mrad, 7 cm**

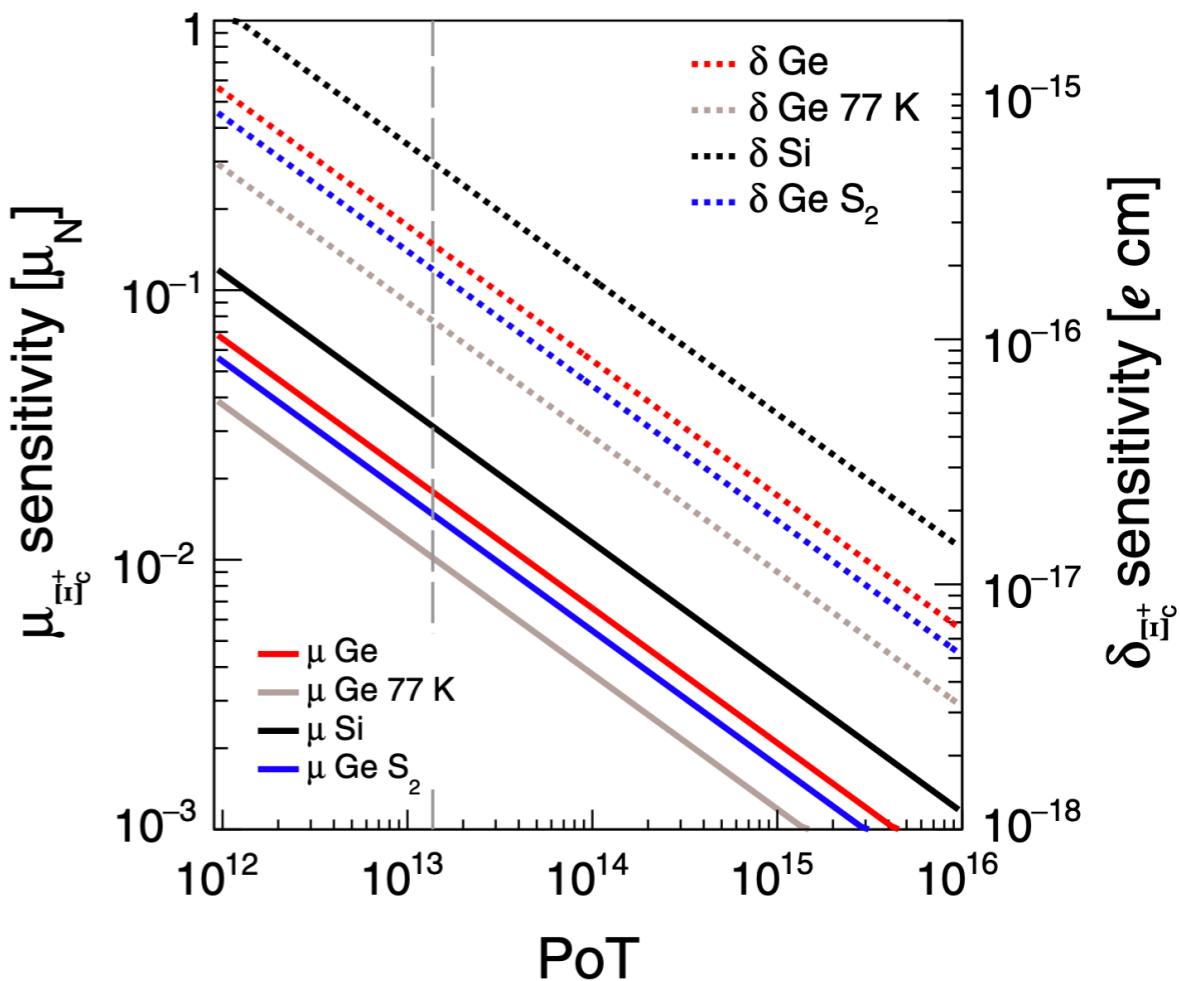
PoT = proton on target
W target 2 cm thick

Λ_c^+ baryon



PRD 103, 072003 (2021)

Ξ_c^+ baryon



- ▶ Measurements are **statistically limited**

References for baryons

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- A. S. Fomin, S. Barsuk, A. Yu. Korchin, V.A. Kovalchuk, E. Kou, A. Natochii, E. Niel, P. Robbe, A. Stocchi, *The prospects of charm quark magnetic moment determination*, arXiv:1909.04654 (2020), Eur. Phys. J. C **80**, 358(2020).
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- 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.
- 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.

References for τ lepton

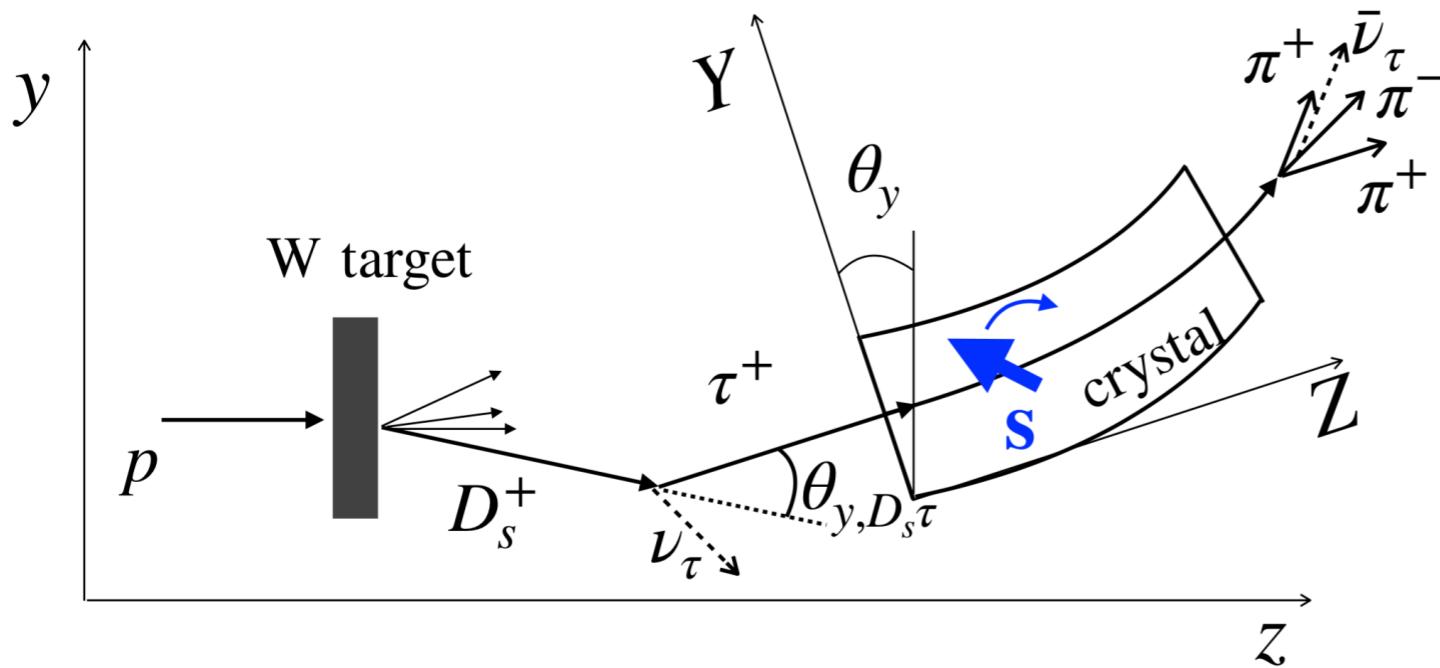
- J. Fu, M. A. Giorgi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N. Neri, J. Ruiz Vidal, *Novel method for the direct measurement of the τ lepton dipole moments*, Phys. Rev. Lett. 123, 011801 (2019)
- A.S. Fomin , A. Korchin, A. Stocchi, S. Barsuk, P. Robbe, *Feasibility of τ lepton electromagnetic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

Proposals for τ lepton

- 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. 03 (2019) 156 (see backup slides)
- J. Fu, M. A. Giorgi, L. Henry, D. Marangotto, F. Martinez Vidal, A. Merli, N. N., J. Ruiz Vidal, *Novel method for the direct measurement of the τ lepton dipole moments*, Phys. Rev. Lett. 123, 011801 (2019)

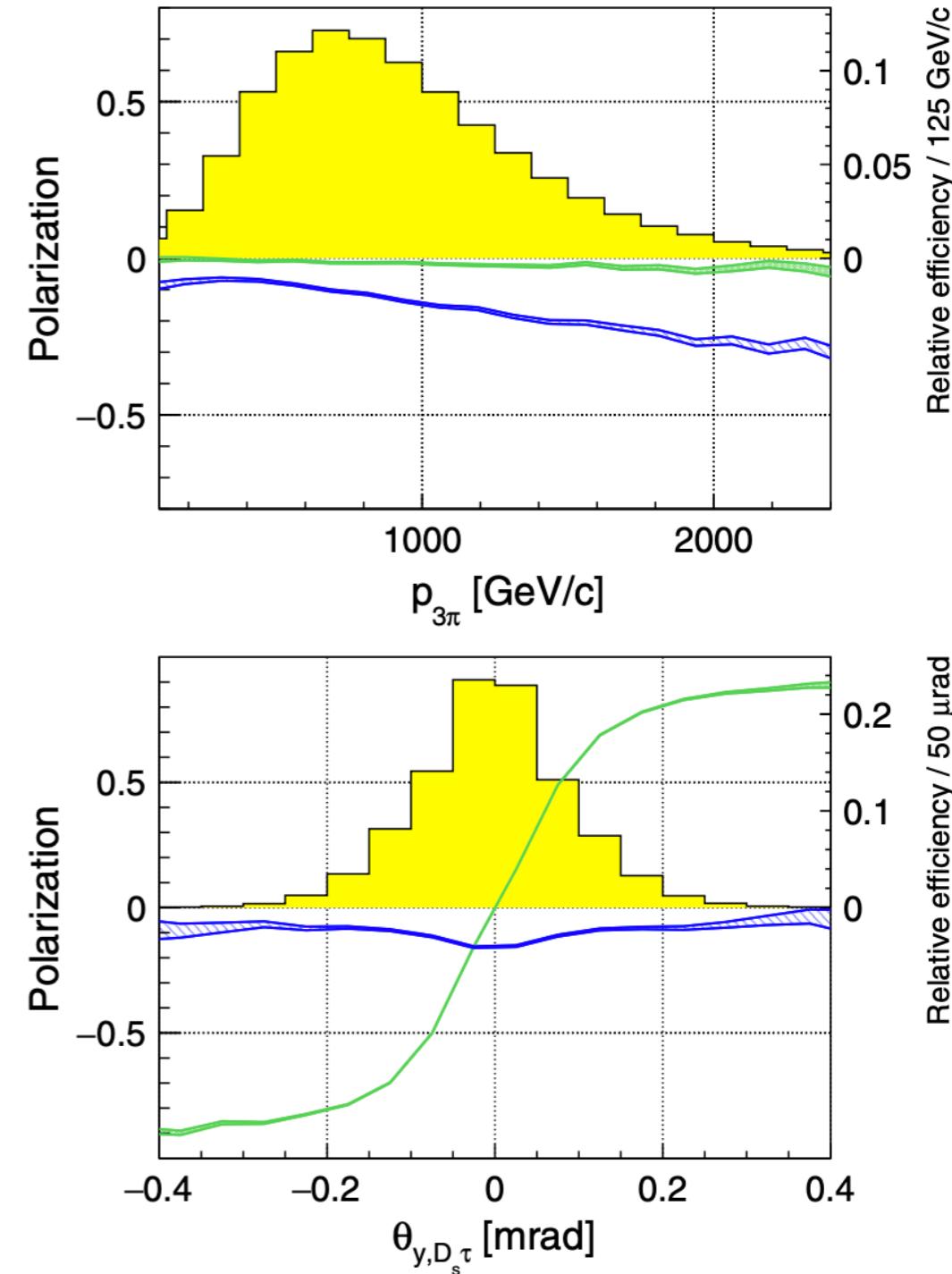
Direct measurement of τ lepton dipole moments

- ▶ **Fixed-target** production: $D_s^+ \rightarrow \tau^+ \nu_\tau$ with $\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}_\tau$
- ▶ **Bent crystal** for spin precession



Spin polarisation

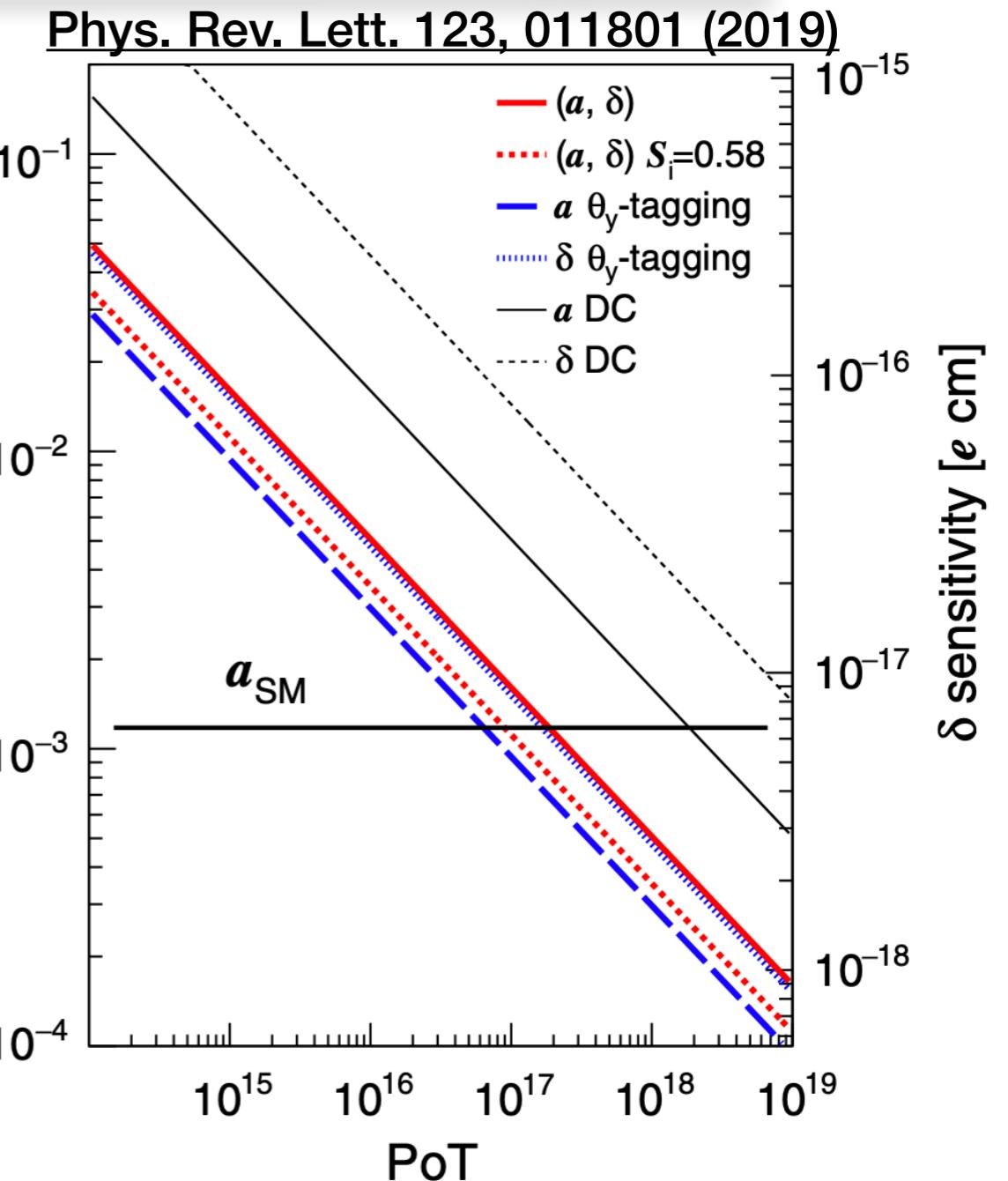
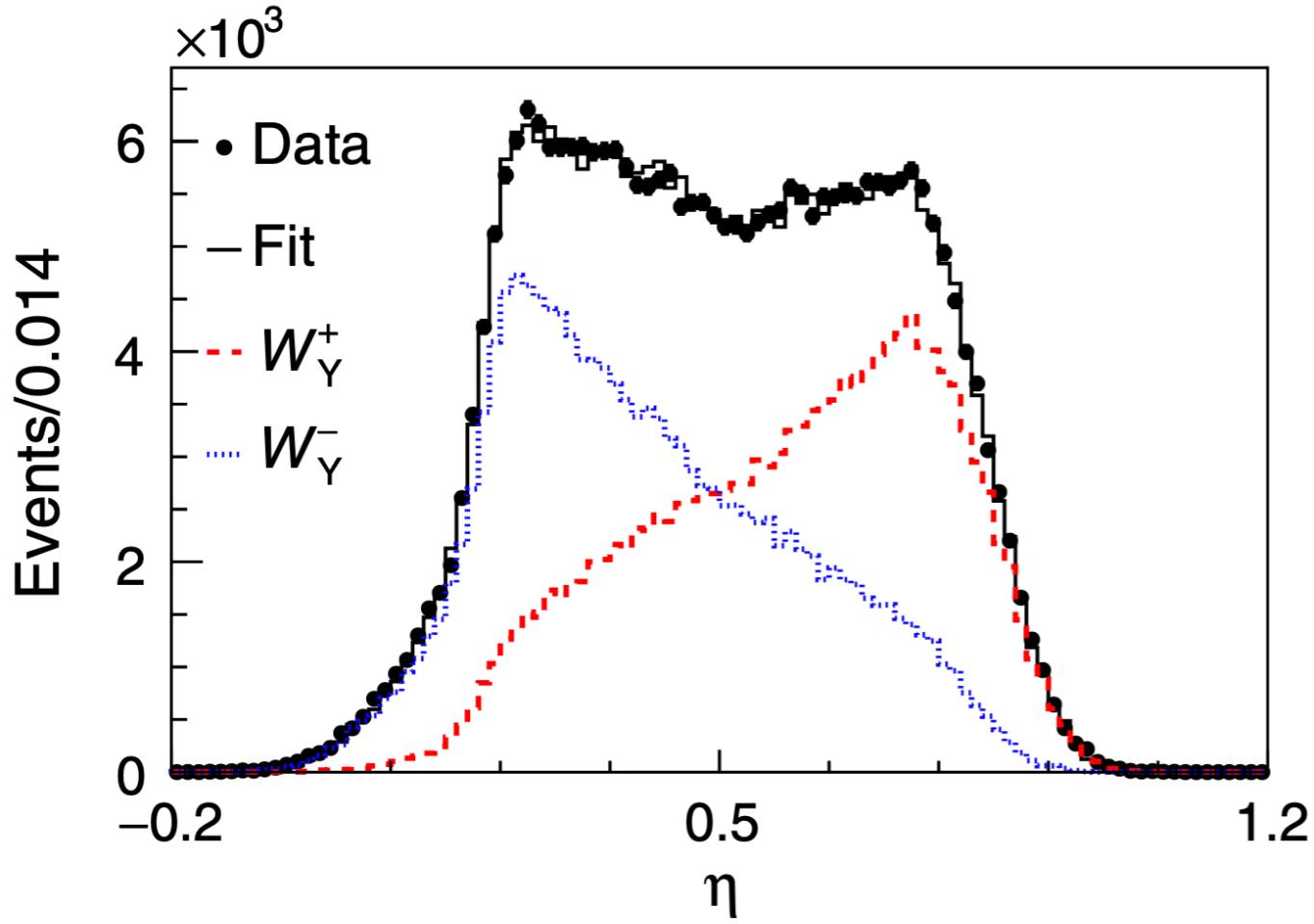
- kinematic selection on $p_{3\pi} > 0.8$ TeV, **longitudinal (z) polarisation** for MDM and enhanced EDM sensitivity
- Tagging $\theta(D_s, \tau) \leq 0$ (e.g. 2 crystals, other) **transverse (y) polarisation** for enhanced MDM sensitivity



Sensitivity to dipole moments for τ lepton

Multivariate classifier based on reconstructed τ variables to determine the polarization and average event information $S=0.42$

$$S_i^2 = \frac{1}{N_{\tau^+}^{\text{rec}} \sigma_i^2} = \left\langle \left(\frac{\mathcal{W}_i^+(\eta) - \mathcal{W}_i^-(\eta)}{\mathcal{W}_i^+(\eta) + \mathcal{W}_i^-(\eta)} \right)^2 \right\rangle$$



Test g-2 SM prediction with $\sim 10^{17}$ PoT

EDM sensitivity $\sim 10^{-17} e \text{ cm}$

Challenging: dedicated experiment needed

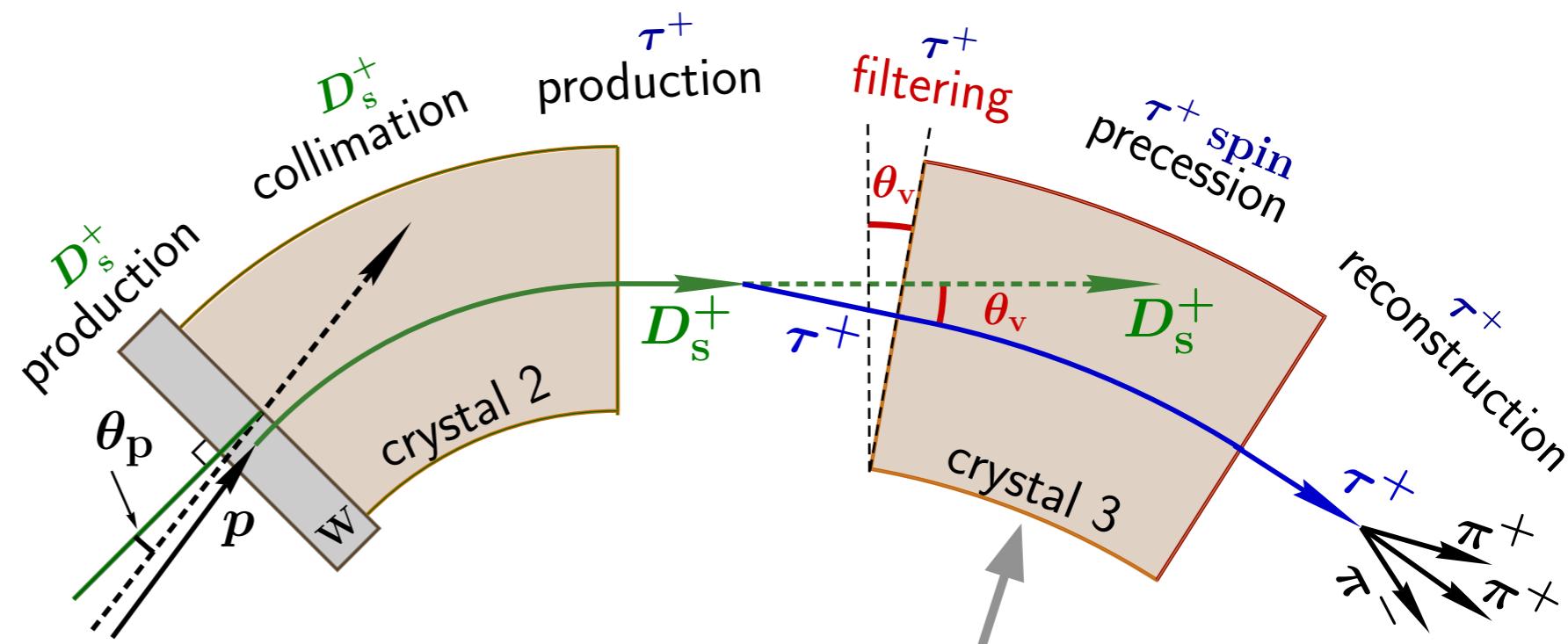
Future plans

- ▶ New proposals for τ lepton MDM/EDM direct determination using bent crystals
 - A.S. Fomin , A. Korchin, A. Stocchi, S. Barsuk, P. Robbe, *Feasibility of τ lepton electromagnetic dipole moments measurements using bent crystals at LHC*, arXiv:1810.06699
 - 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*, arXiv:1901.04003
-
- ▶ Large statistics needed for interesting measurements, i.e. PoT $\gtrsim 10^{17}$ [2.5 cm W target]
 - ▶ Many challenges: dedicated experiment needed
 - ▶ Preparatory studies in LHCb

Feasibility of τ lepton electromagnetic dipole moments measurement using bent crystal at the LHC

Crystal 1:

- directing a part of LHC primary halo on Target



Target:

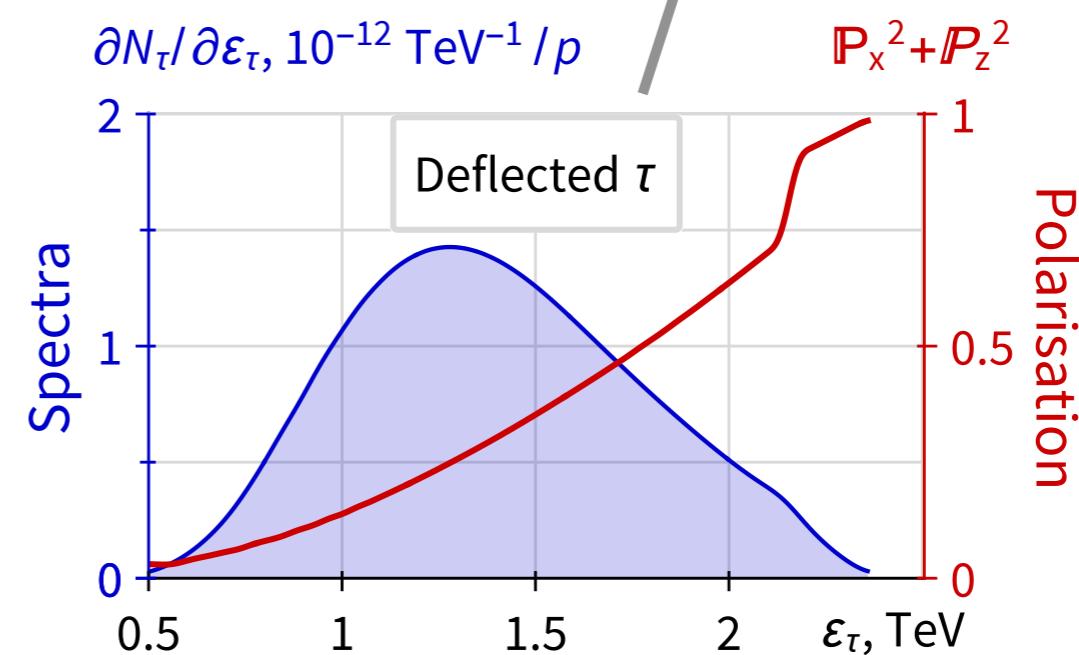
- production of $D_s^+ (\rightarrow \tau^+ \bar{\nu}_\tau)$
- $\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}_\tau$

Crystal 2:

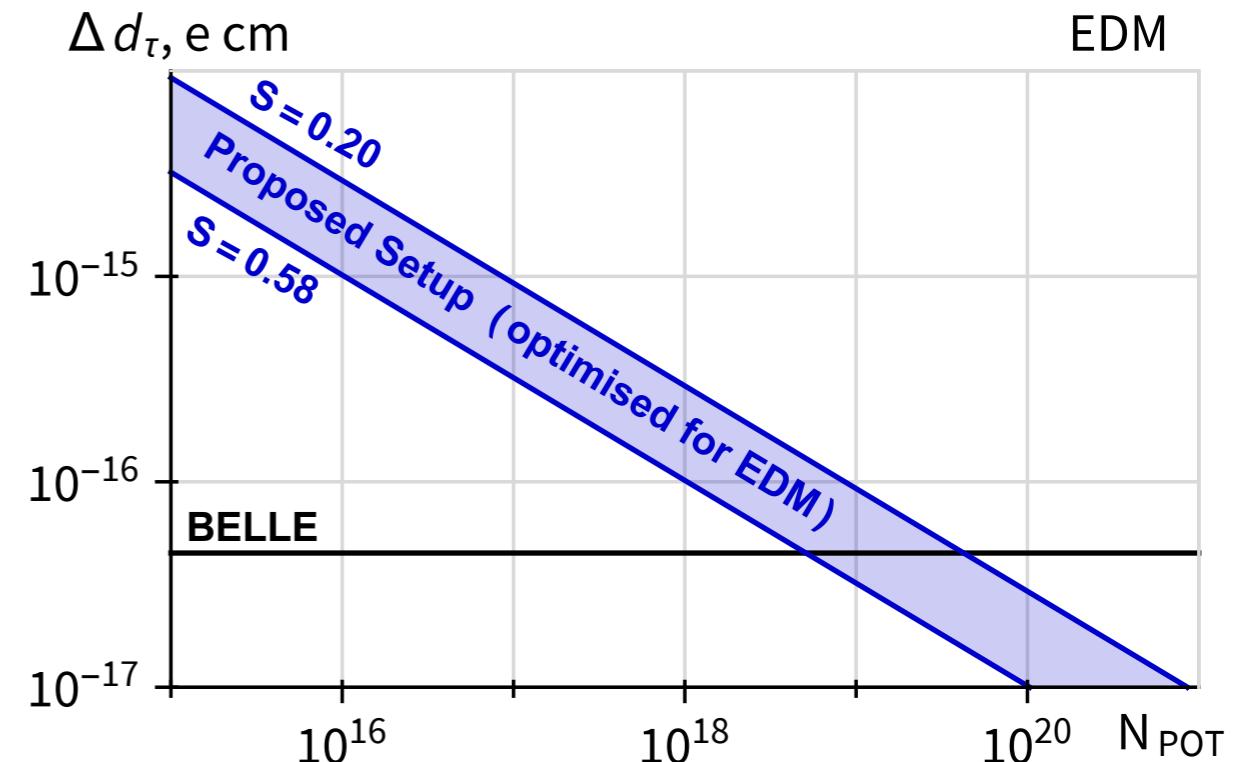
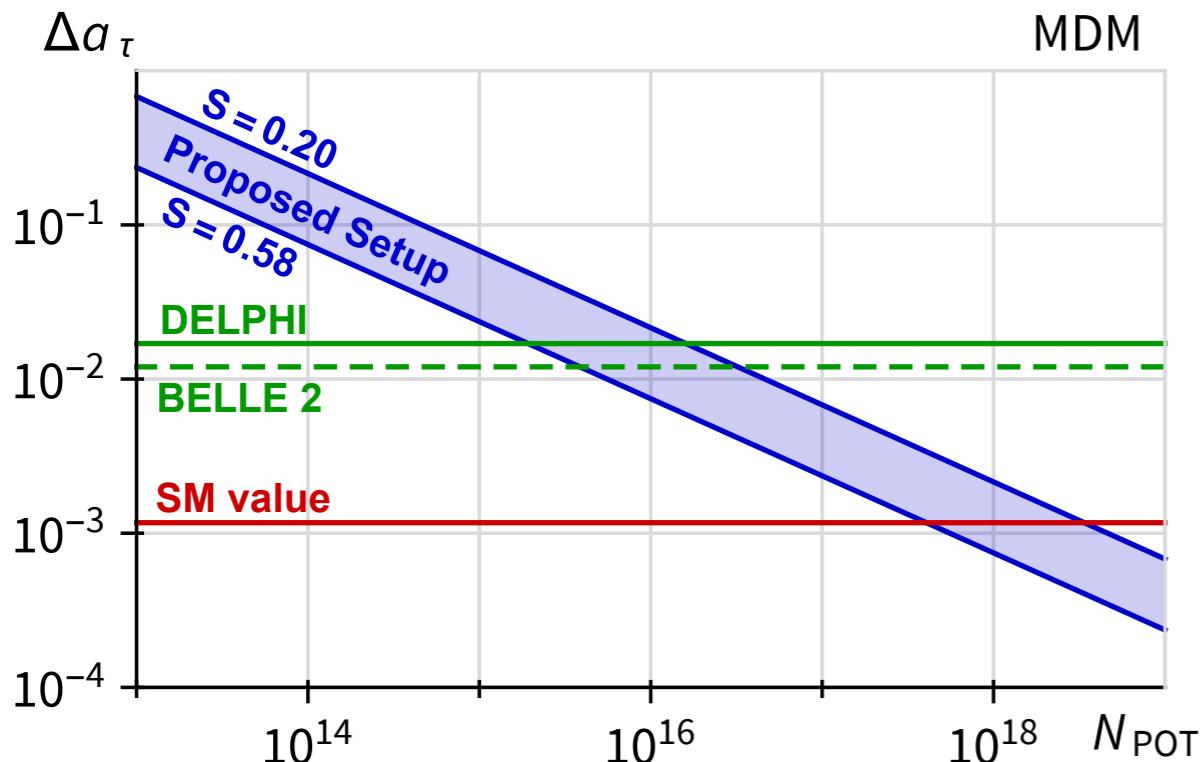
- deflection and “collimation” of D_s^+

Crystal 3:

- selecting τ produced by D_s^+
- filtering τ initial polarisation
- τ spin precession



Feasibility of τ lepton electromagnetic dipole moments measurement using bent crystal at the LHC



MDM: 10^{16} PoT — to reach the present accuracy [DELPHI: J. Abdallah et al. EPJC 35:159–170, 2004]

10^{18} PoT — to reach an accuracy equivalent to the Standard Model value

EDM: 10^{19} PoT — to reach the present accuracy [BELLE: K. Inami et al. PLB 551:16–26, 2003]

Channeling in bent crystals



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

Spin precession in bent crystals

- ▶ Firstly predicted by **Baryshevsky** (1979)
- ▶ Determine particle gyromagnetic factor from BMT equation

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

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

D. Chen et al., Phys. Rev. Lett. 69 (1992) 3286

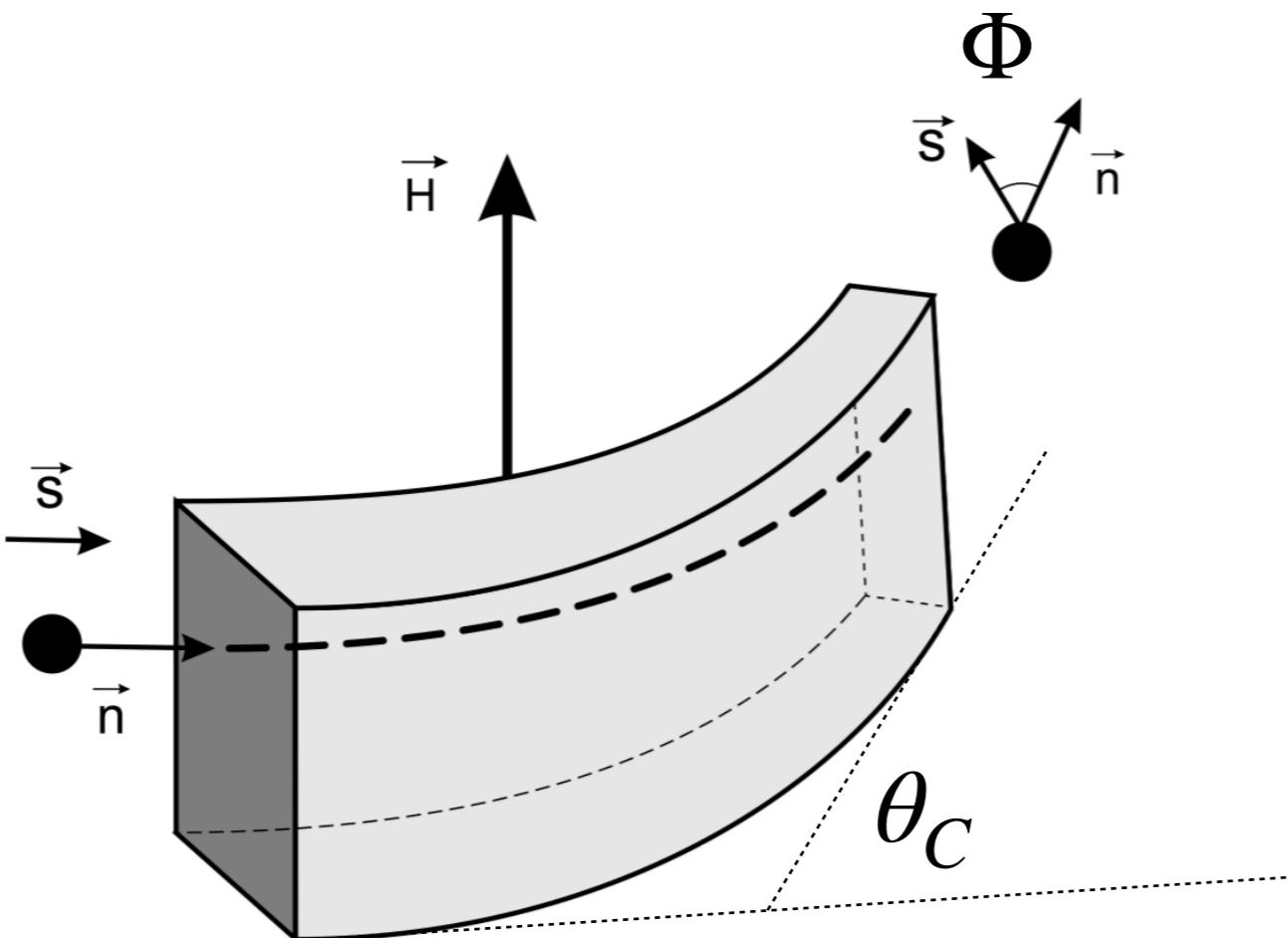


Fig. 1. Spin rotation in a bent crystal.

Proof of principle at Fermilab

- ▶ E761 Fermilab experiment firstly observed **spin precession** in bent crystals and measured MDM of Σ^+
- ▶ **350 GeV/c Σ^+** produced from interaction of 800 GeV/c proton beam on Cu target
- ▶ Used **upbent** and **downbent** silicon **crystals** $L=4.5\text{cm}$, $\theta_C=1.6\text{ mrad}$ for opposite spin precession, reduced systematics

D. Chen et al., Phys. Rev. Lett. 69 (1992) 3286

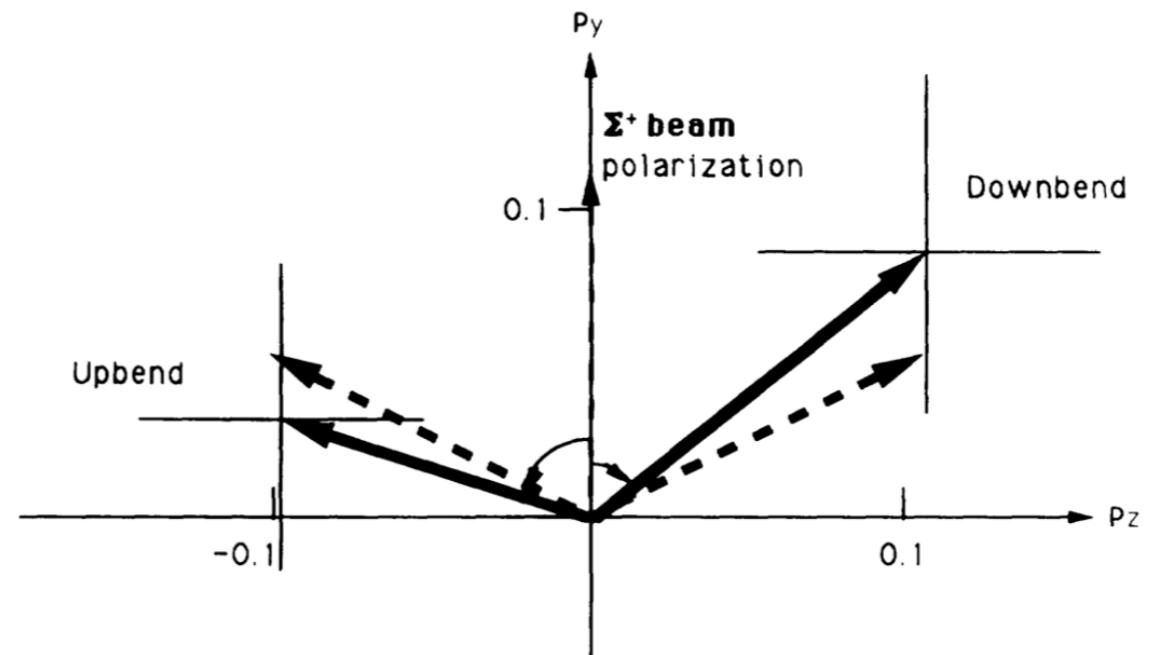
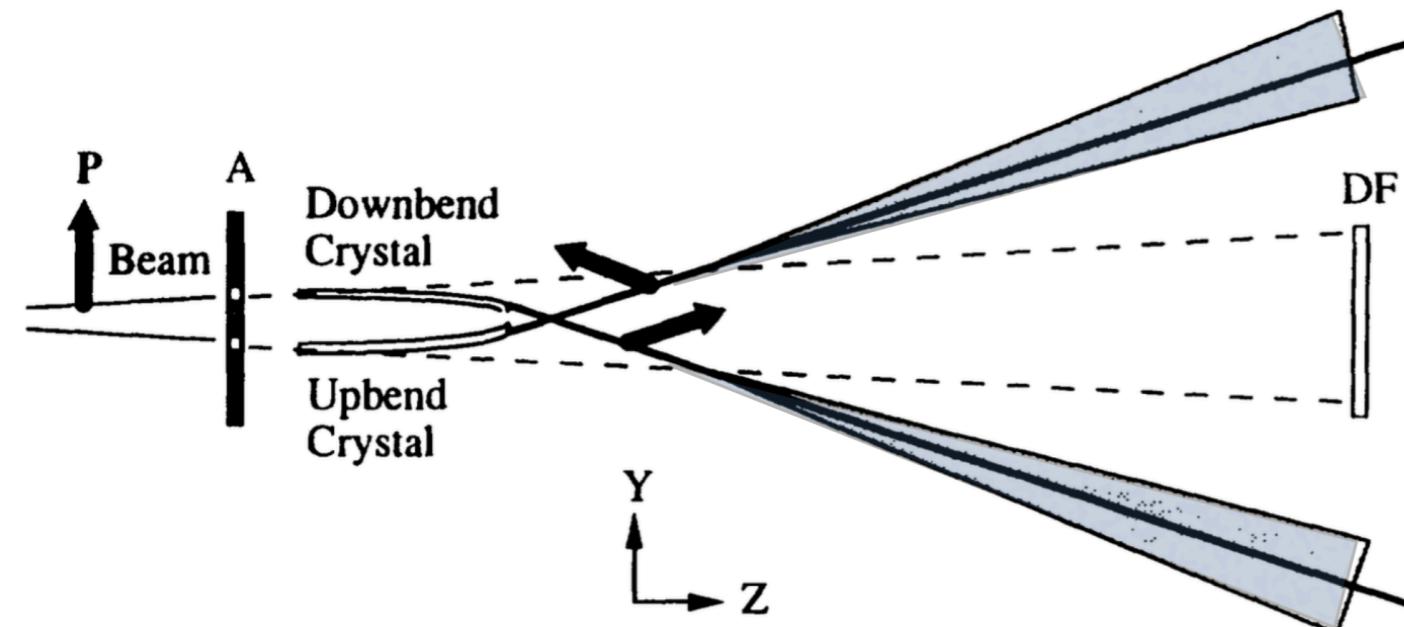
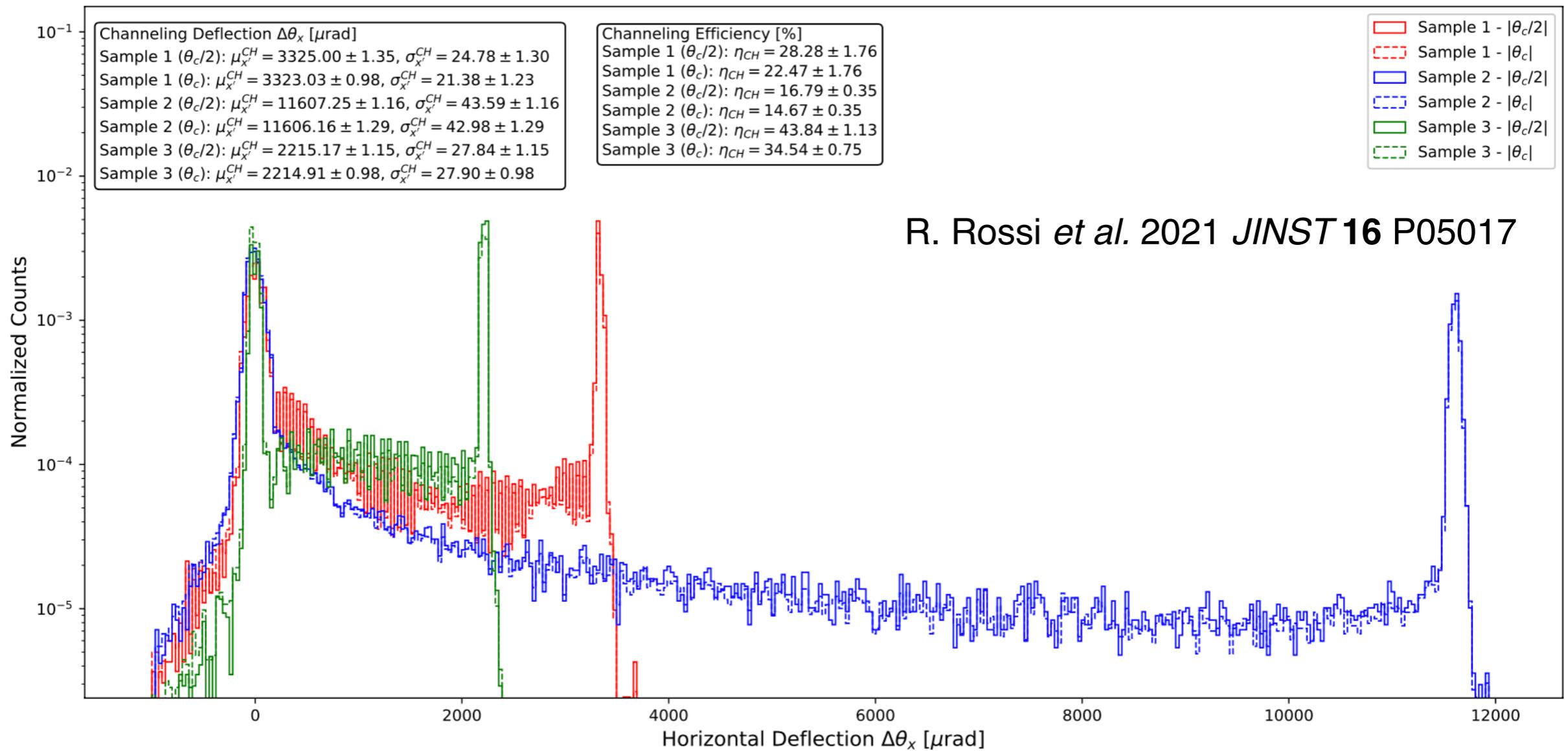


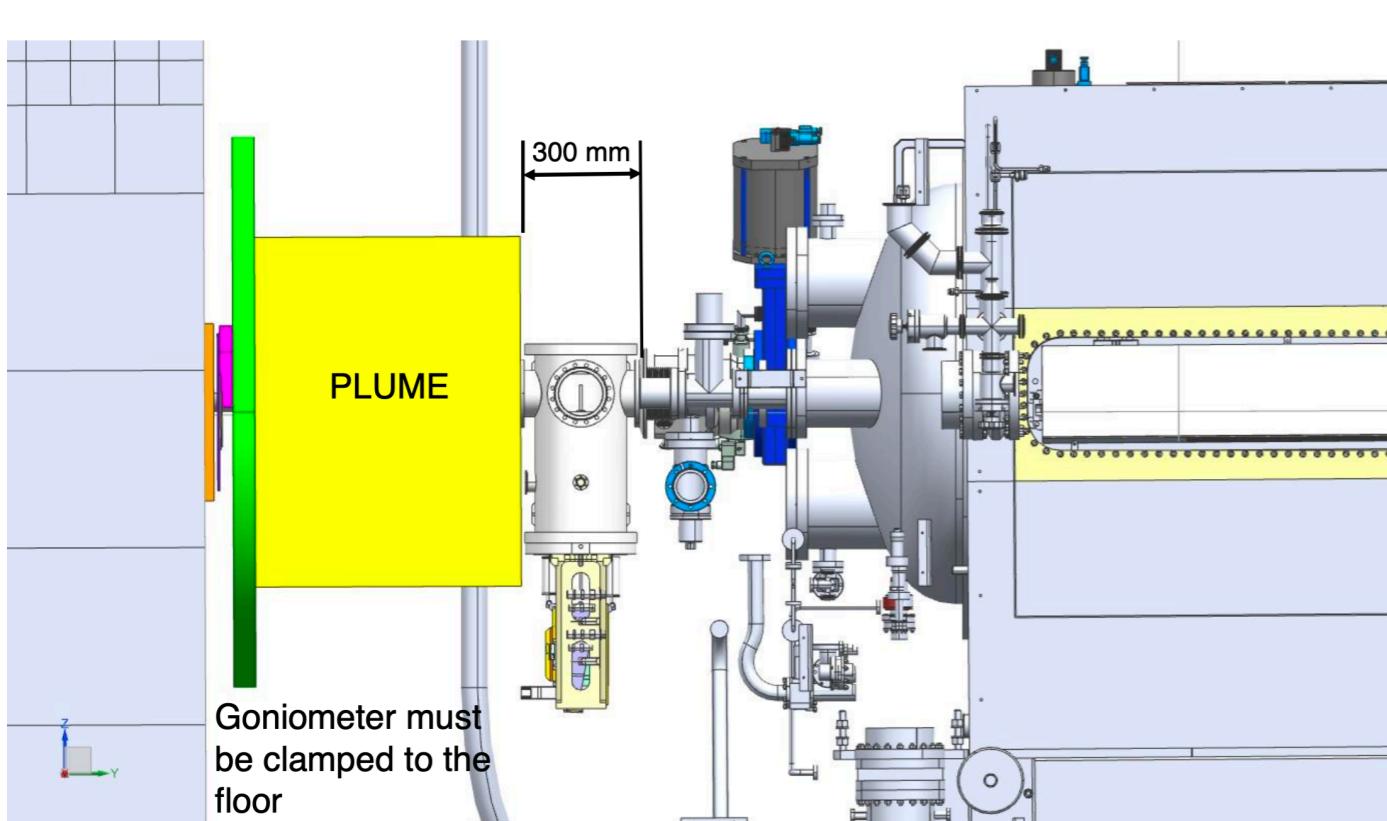
FIG. 3. Measured polarizations and uncertainties (1σ statistical errors) after spins have been precessed by the two crystals. The dashed arrows show the expected precessions.

Long bent crystal prototypes



- Si crystals produced at INFN-Ferrara	length (cm)	bending (mrad)	ch. eff. (%)
	8.0	11.6	14.7
	8.0	3.3	22.5
	2.5	2.2	34.5

Fixed-target setup upstream of LHCb



- ▶ Goniometer for target+crystal positioned in the region upstream of the LHCb detector

- ▶ Goniometer internal structure: compatible with operations in ultra-high vacuum
- ▶ Accuracy on position $\sim 20 \mu\text{m}$, rotation angle $\sim 20 \mu\text{rad}$

