French-Ukrainian Workshop — IJCLab, Orsay, France

October 19-23, 2020

Measuring the electromagnetic moments of Λ_c.

Performance assessment of layouts in IR3 and IR8 of the LHC

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contributed by:

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Outline

Introduction

- Electromagnetic moments of baryons
- Spin precession in a bent crystal

Optimal crystal orientation for EDM measurement [1,2]

- Spin precession in a bent crystal
- Initial polarisation of baryons [1,2]
- quantitive analysis

MDM of Σ+ (experiment E761, Fermilab 1990) [3]

- Mirroring the setup
- Cancelation of apparatus biases

Performance assessment of layouts in IR3 and IR8 [4,5,1]

- Double crystal layouts at LHC [4,5]
- Precision of measurement [1]
- Possible improvements [1,4]

[1] A.S. Fomin et al. Eur. Phys. J. C (2020) 80:358

[2] A.S. Fomin, JHEP 08 (2017) 120

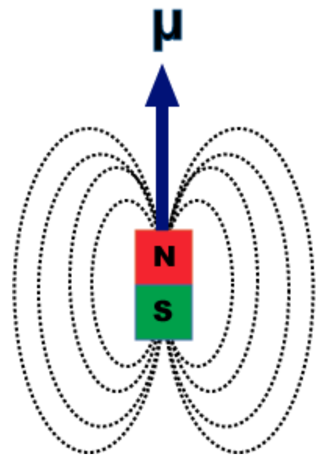
[3] D. Chen, PhD thesis, SUNY, Albany, 1992.

[4] D. Mirarchi et al. Eur. Phys. J. C 80 (2020) 10, 929

[5] CERN Yellow Reports: Monographs, 4/2020

Electromagnetic moments of baryons

Magnetic Dipole Moment:



$$\vec{\mu} = \frac{g}{2}\frac{e}{m}\vec{S}, \quad \vec{S} = \frac{\hbar}{2}\vec{\sigma}$$

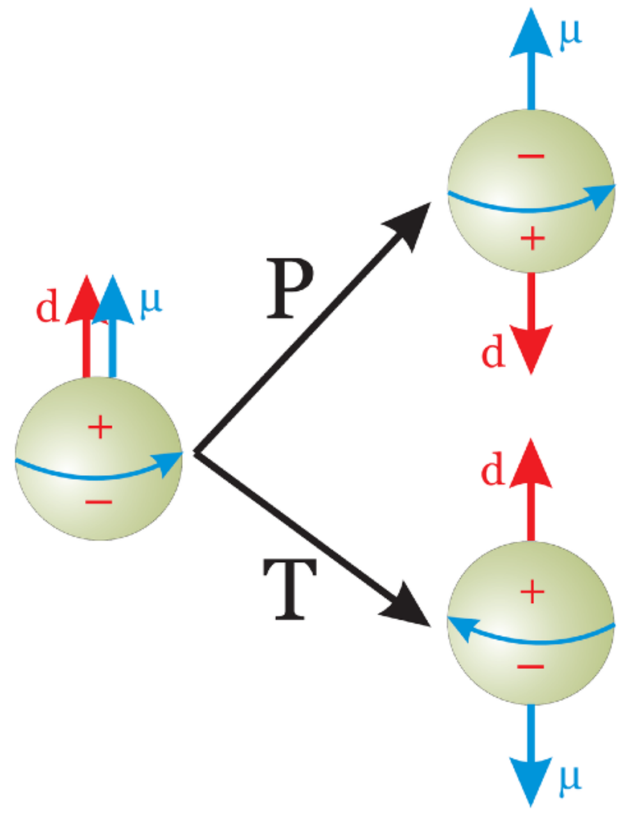
$|g| = 2$ → a point-like Dirac particle

$|g| \approx 2$ → a radiative corrections

$|g| \neq 2$ → a composite structure or NP

Particle	cτ	*g*-factor	Comments	
p	∞	+ 5.585 694 702 (17)	exp.	
n	~∞	– 3.826 085 45 (90)	exp.	
Σ^+	2.4 cm	+ 6.233 (25)	exp.	world-average value
		+ 6.1 $(12)_{stat}$ $(10)_{syst}$	exp.	using Bent Crystals (at Fermilab 1990)
Λ_c^+	60 μm	+ 1.90 (15)	theor.	assuming $g_c \approx 2$
		not measured	exp.	Feasibility studies at LHC

Electric Dipole Moment:



$$\vec{\delta} = \frac{f}{2}\frac{e}{m}\vec{S}, \quad \vec{S} = \frac{\hbar}{2}\vec{\sigma}$$

A nonzero value is forbidden by both:

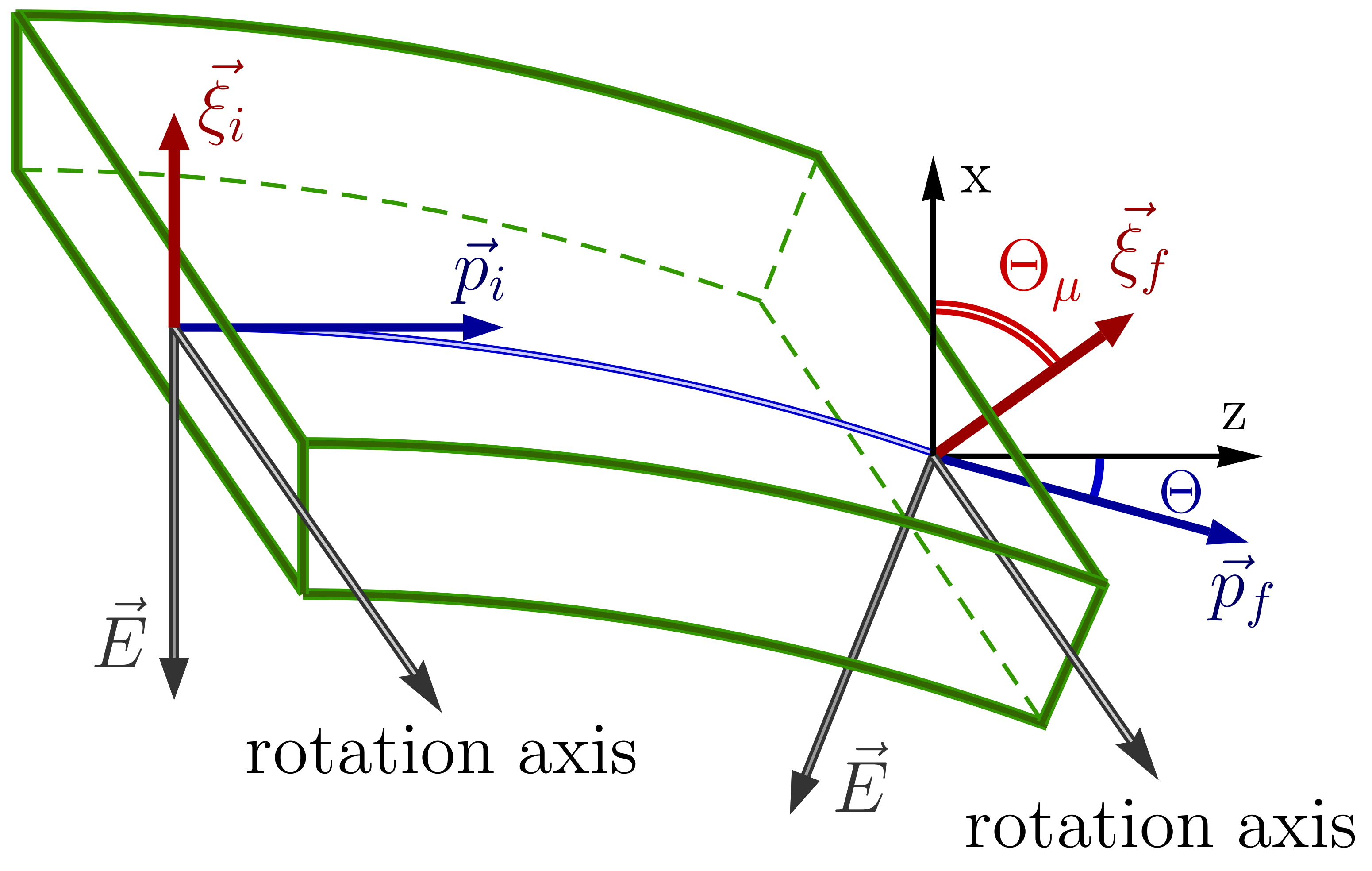
T invariance and P invariance.

Particle	$\lvert\delta\rvert$, *e* cm 10^{-25}
p	< 2.1
n	< 0.18
Σ^+	not measured
Λ_c^+	not measured

Spin precession in a bent crystal

V.G. Baryshevsky, Sov. Tech. Phys. Lett. 5 (1979) 73.

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



$$\Theta_\mu \equiv \angle(\xi_i \xi_f) = (1+\gamma a)\,\Theta \qquad a = \frac{g-2}{2}, \qquad \Theta = \frac{L}{R}$$

$\gamma,\ g,\ a$ – Lorentz factor, g-factor, anomalous MDM of Λ_c

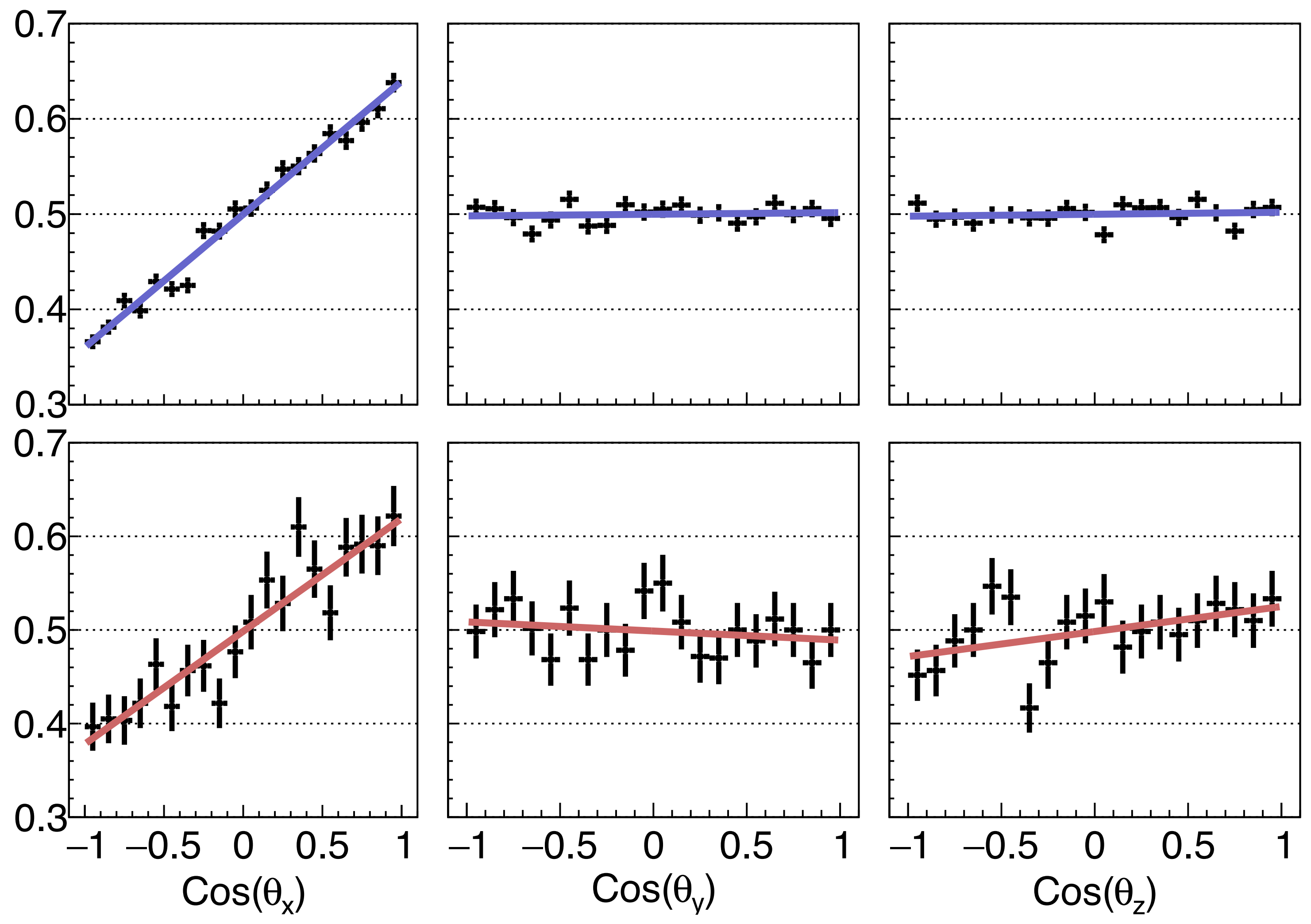
$\Theta,\ L,\ R$ – deflecting angle, length, curvature radius of the crystal

Initial Polarisation:

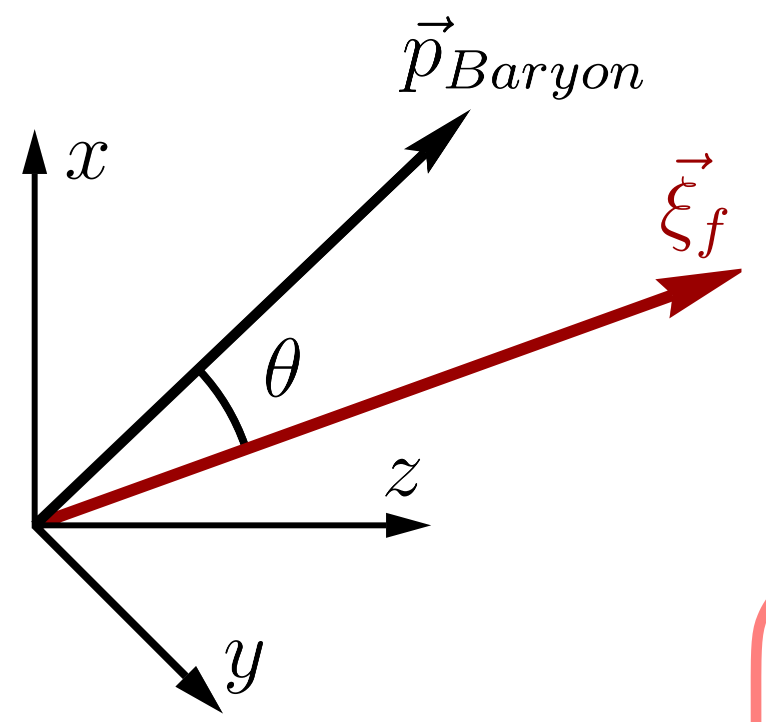
$$\vec{\xi}_i = \xi(\ 1\ ,\ 0\ ,\ 0\ )$$

Final polarisation

$$\vec{\xi}_f = \xi(\cos\Theta_\mu,\ 0\ ,\ \sin\Theta_\mu)$$



$\Lambda_c^+ \to Meson + Baryon$



$$\frac{dN}{d\cos\theta_z} = \frac{1}{2}\left(1 + \alpha\,\xi_{fz}\cos\theta_z\right)$$

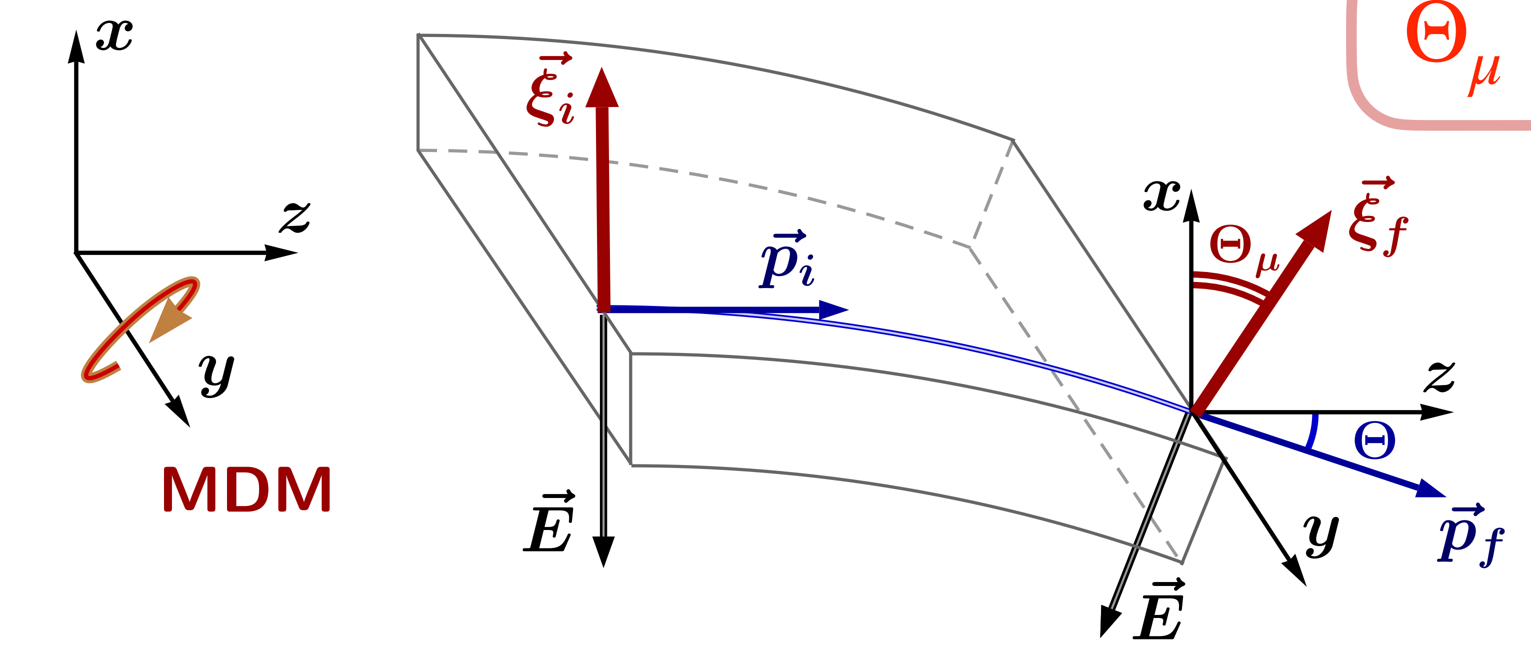
$$b \equiv \alpha\,\xi\,\Theta_\mu \qquad \Delta b = \sqrt{\frac{3}{N}}$$

$$\Delta g = \frac{2}{\alpha\,\langle\xi\,\gamma\rangle\,\Theta}\sqrt{\frac{3}{N}}$$

Optimal crystal orientation for MDM and EDM measurements

V.G. Baryshevsky,
Sov. Tech. Phys. Lett. 5 (1979) 73.

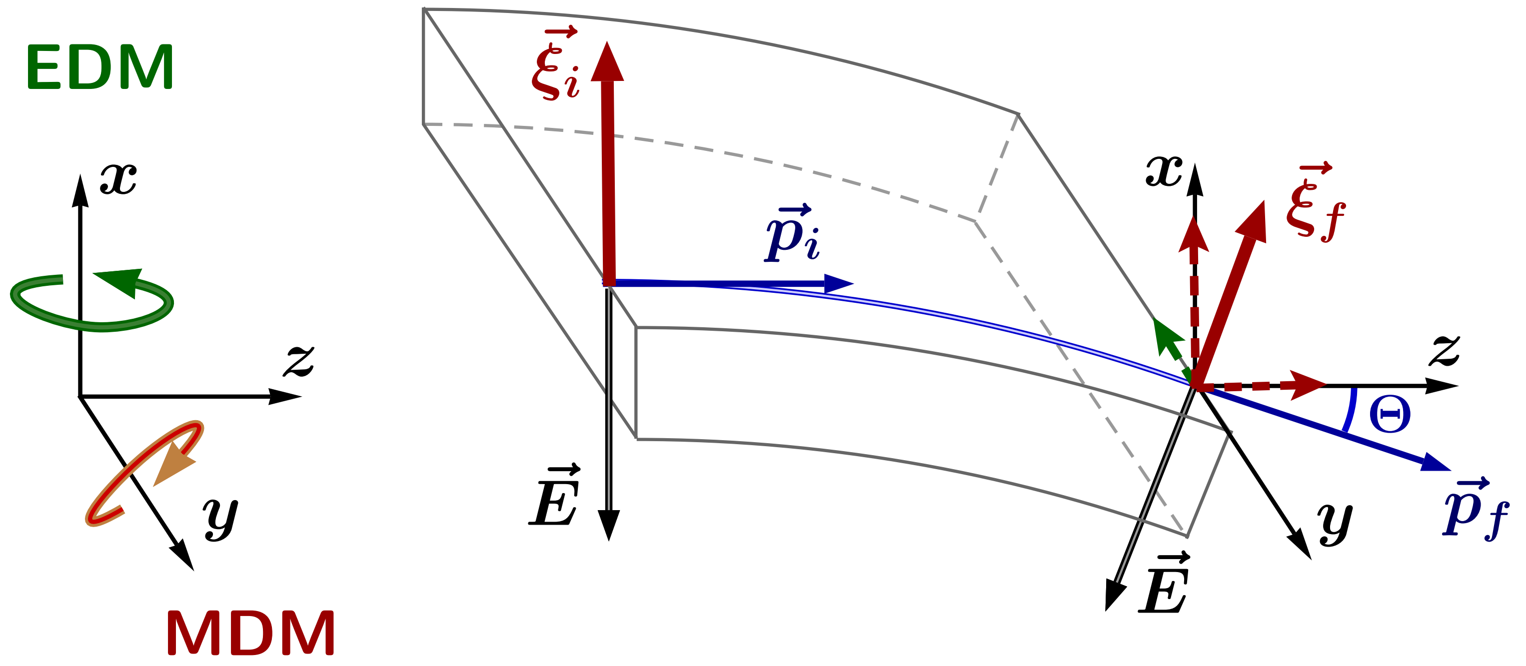
V.L. Lyuboshits,
Sov. J. Nucl. Phys. 31 (1980) 509
[inSPIRE].



$$\Theta_\mu \equiv \angle(\xi_i \xi_f) = (1+\gamma a)\,\Theta$$

$$\Delta g = \frac{2}{\alpha \langle \xi_x \gamma \rangle \Theta}\sqrt{\frac{3}{N}}$$

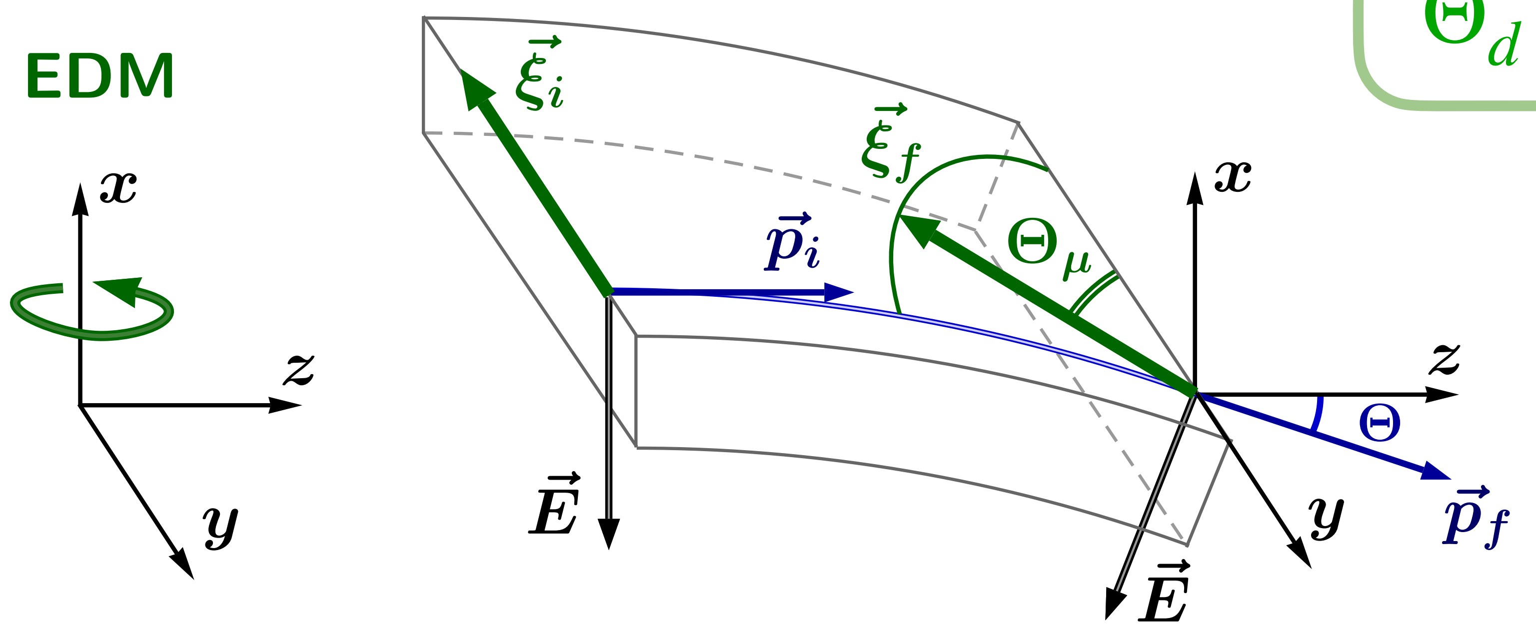
F. J. Botella et al.,
EPJ C77 (2017) 181 [inSPIRE]



$$\frac{\Delta f}{\Delta g} = \frac{2\gamma a}{\Theta\,(1+\gamma a)^2}$$

V.G. Baryshevsky,
EPJ C79 (2019) 350 [inSPIRE]

A.S. Fomin et al.,
EPJ C80 (2020) 358 [inSPIRE]



$$\Theta_d \equiv \angle(\xi_i \xi_f) = (1+\gamma f)\,\Theta$$

$$\Delta f = \frac{2}{\alpha \langle \xi_y \gamma \rangle \Theta}\sqrt{\frac{3}{N}}$$

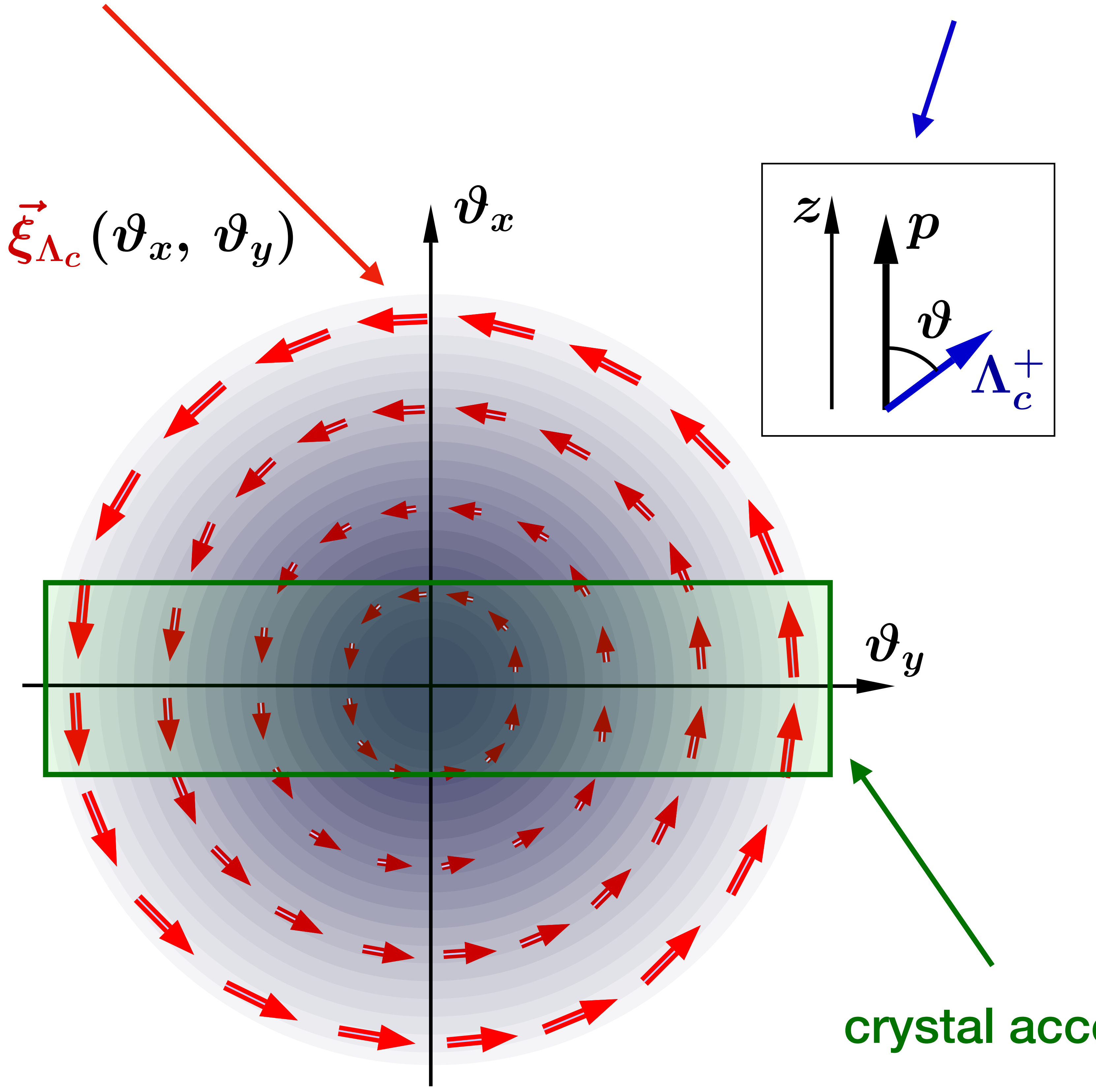
Optimal crystal orientation for EDM measurement: initial polarisation.

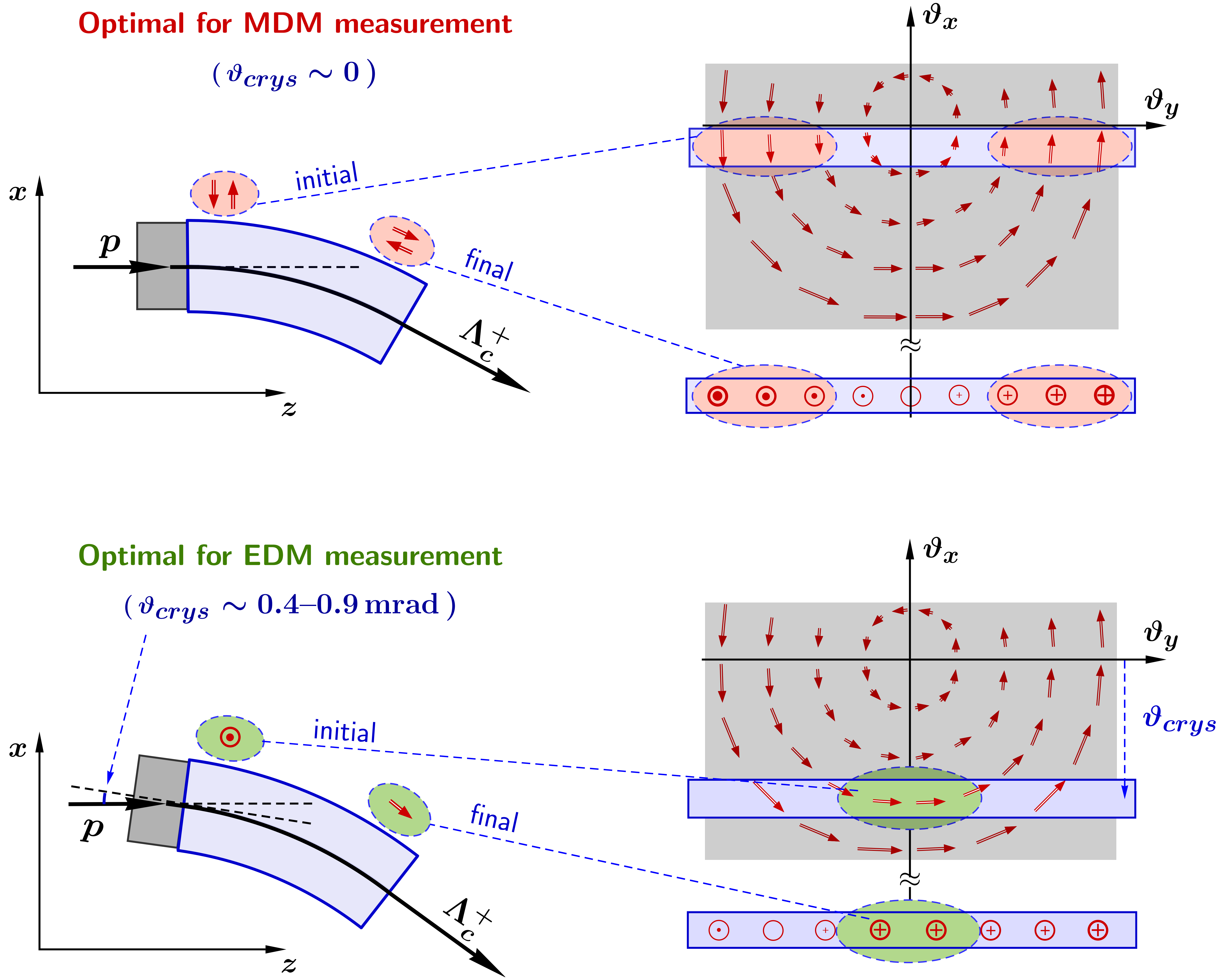
A. Fomin et al. Eur. Phys. J. C (2020) 80:358 [1909.04654]

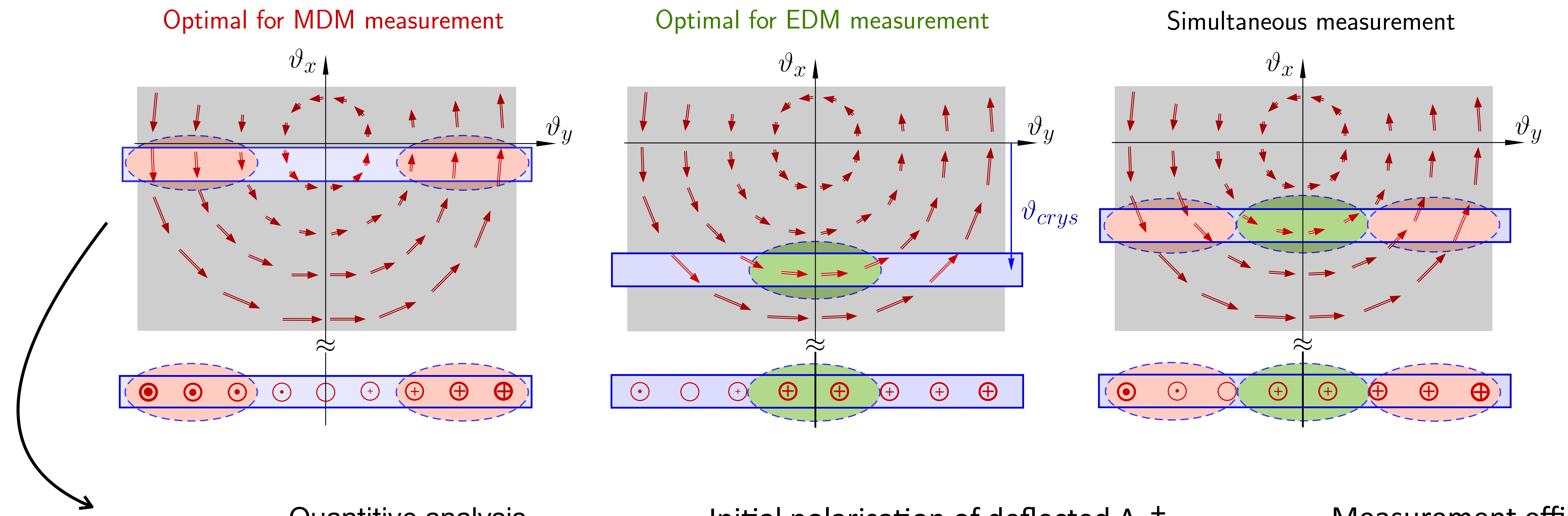
Production of Λ_c^+ in a fixed target $p + p \to \Lambda_c^+ + X$

Due to the space-inversion symmetry of the strong interaction

Λ_c^+ polarisation is perpendicular to the reaction plane

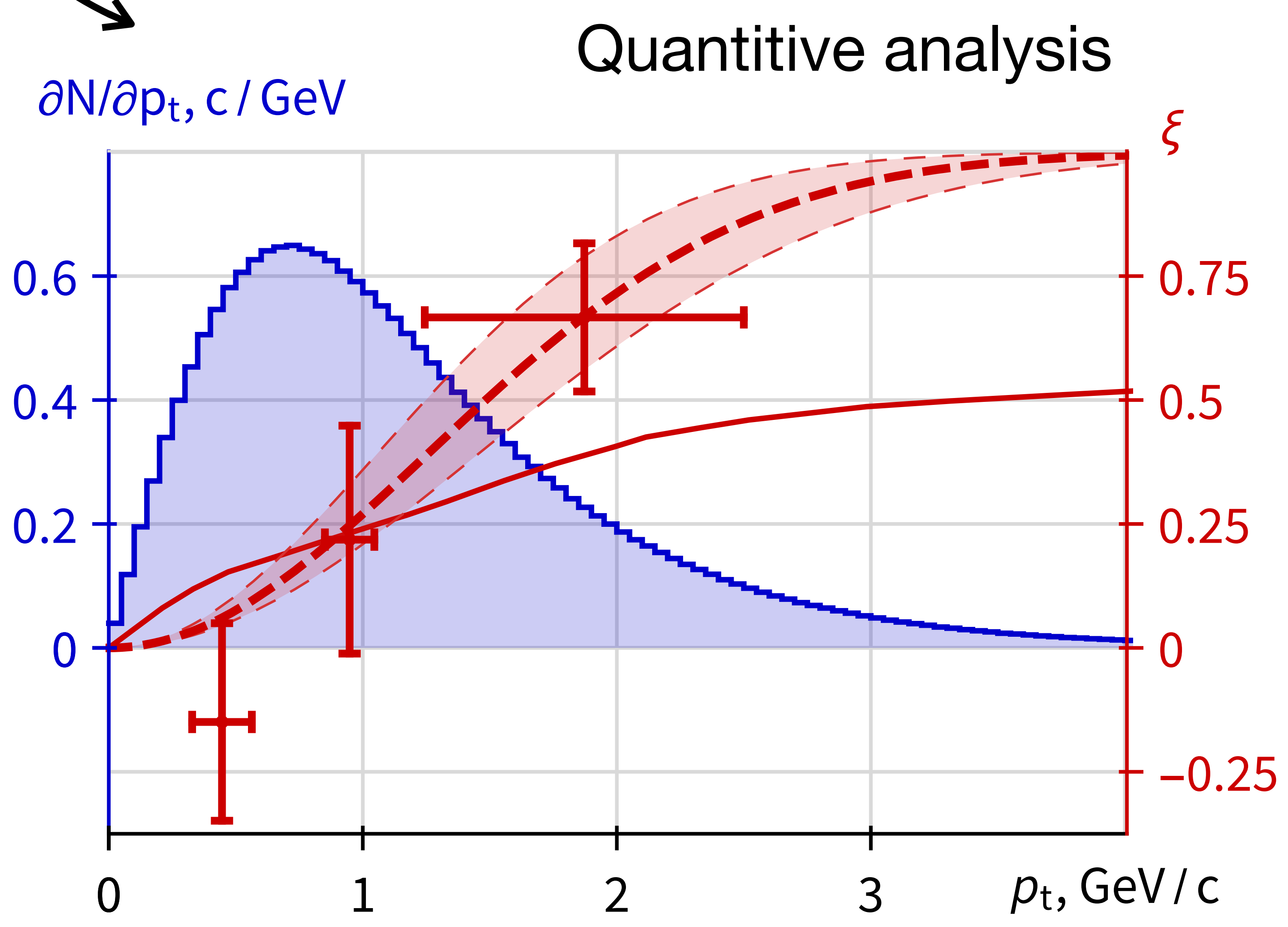


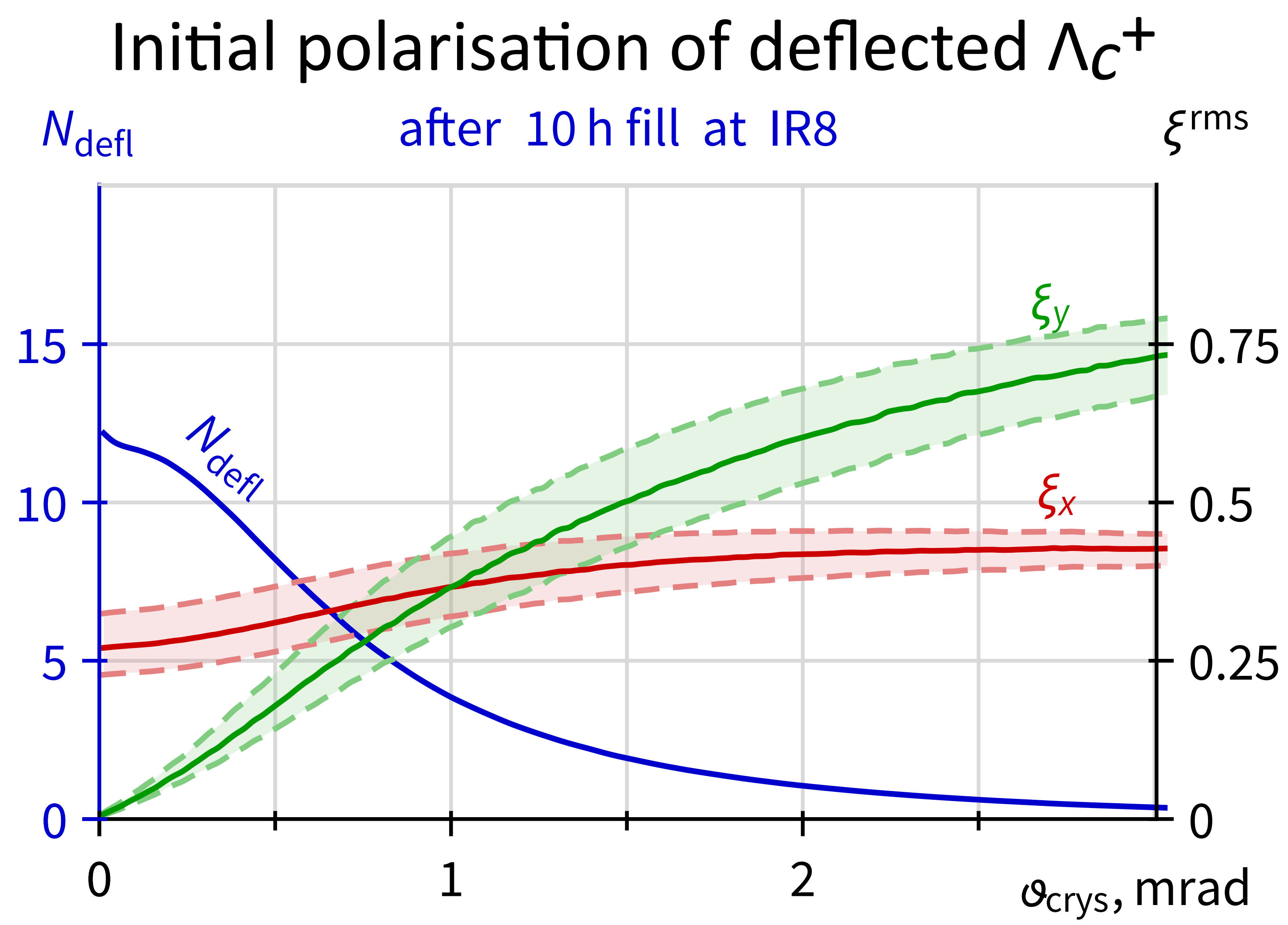


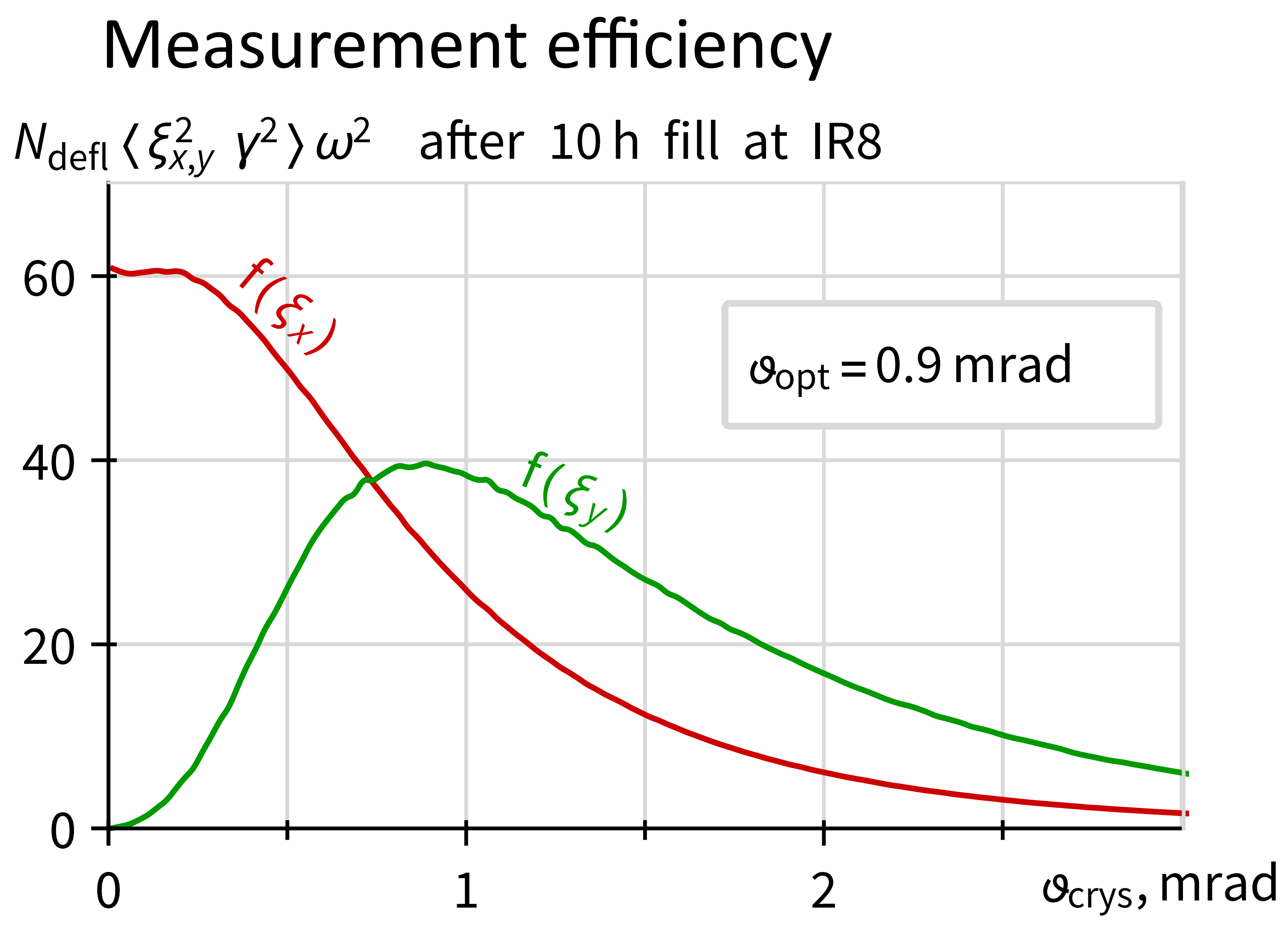


$$\Delta g = \frac{2}{\alpha \langle \xi_x \gamma \rangle \Theta} \sqrt{\frac{3}{N}}$$

$$\Delta f = \frac{2}{\alpha \langle \xi_y \gamma \rangle \Theta} \sqrt{\frac{3}{N}}$$







D. Chen, The Measurement of the Magnetic Moment of Σ+ Using Channeling in Bent Crystals, PhD thesis, SUNY, Albany, 1992.

The main purpose of the experiment was to measure the branching ratio and asymmetry parameter of the Σ^+ radiative decay

A new technique for measuring the magnetic moment of short-lived positively charged particles using channeling in bent crystals was tested.

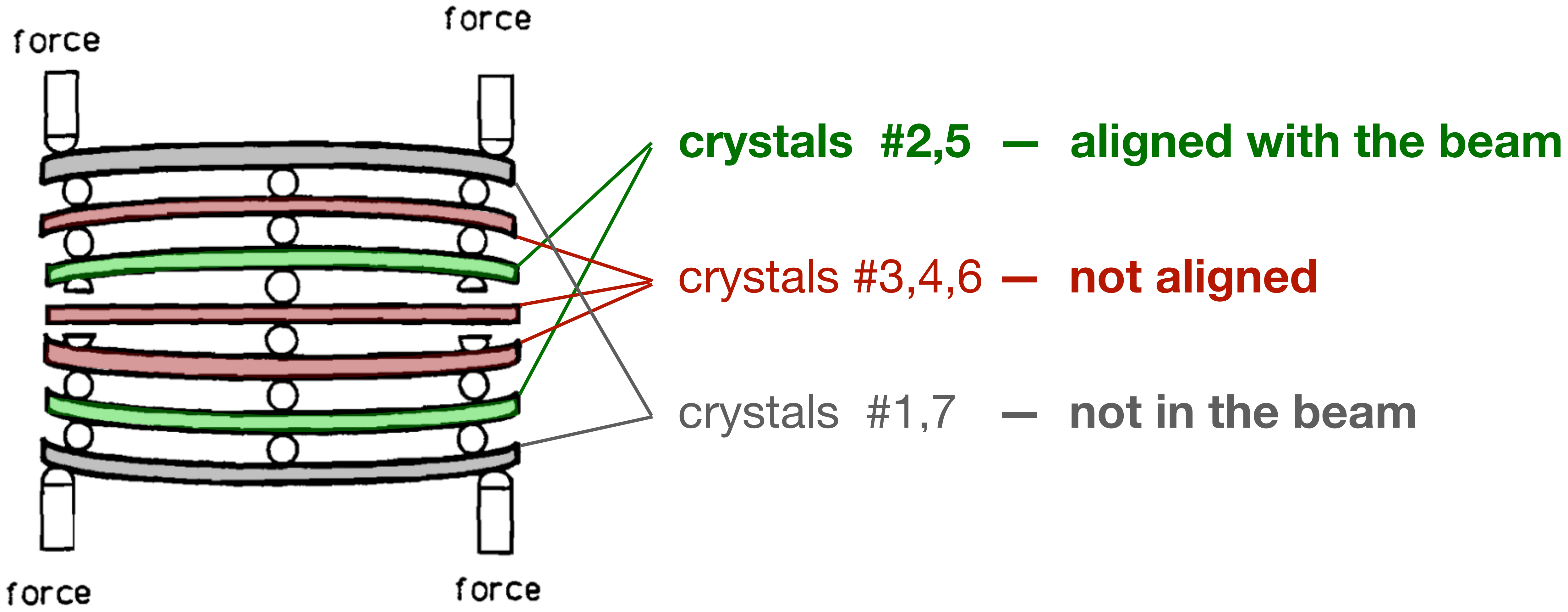
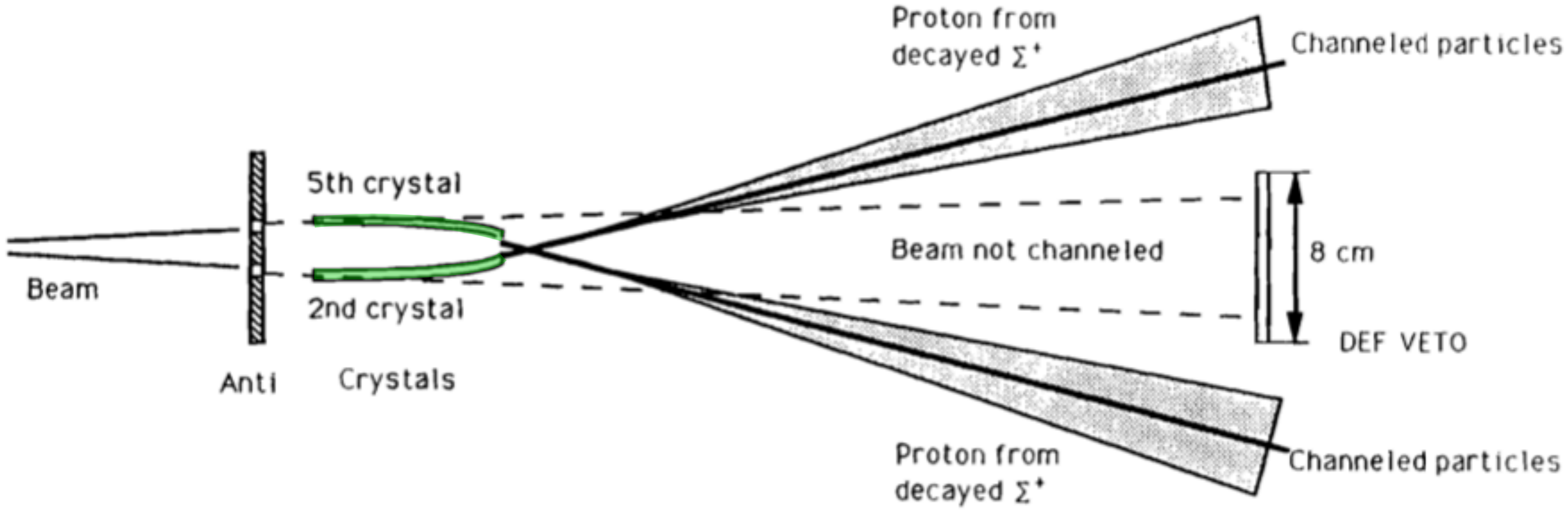
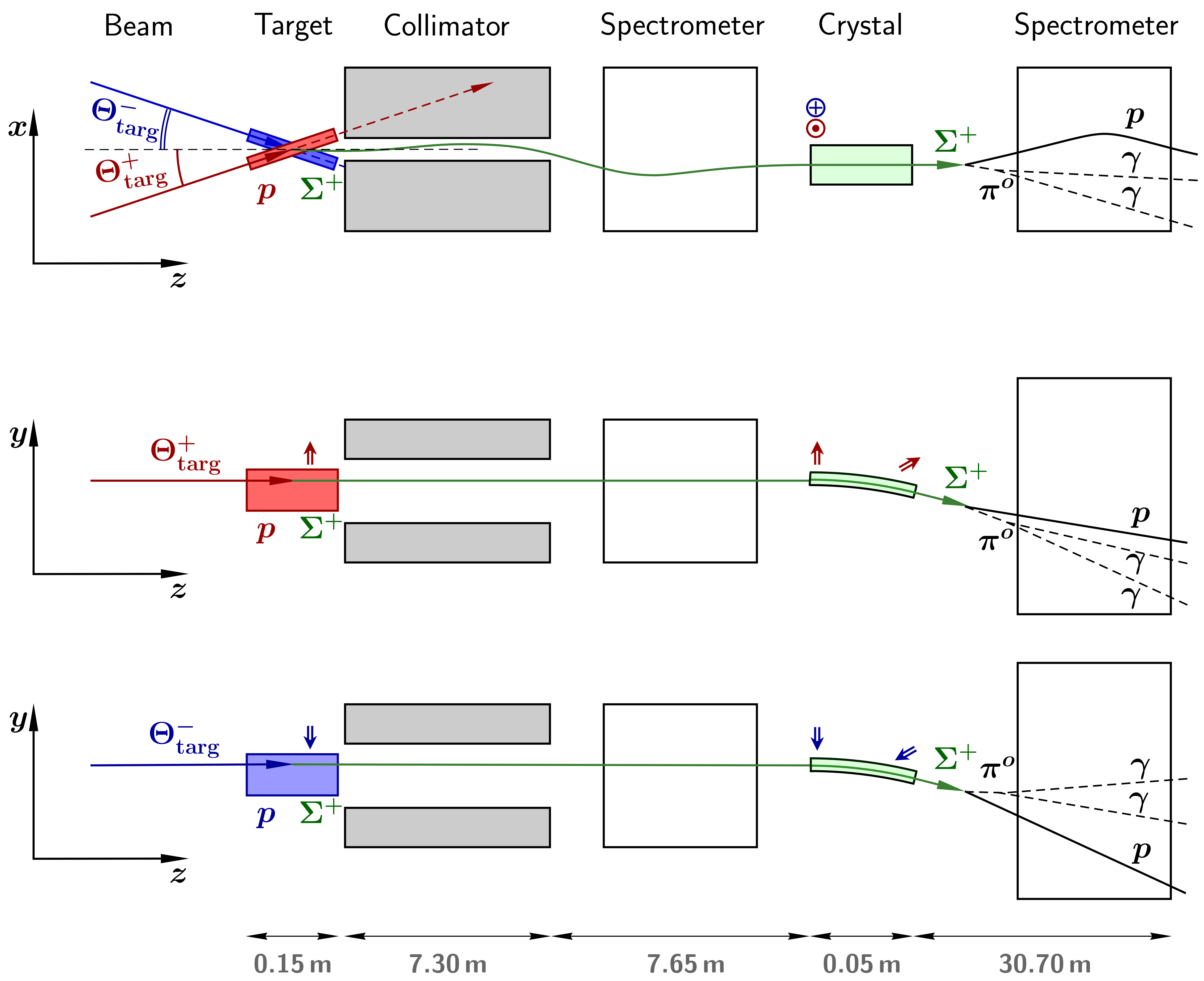


Figure 4.6: Crystal bending device

After some initial testing, we found that only the **five** center **crystals**, from #2 to #6, were inside the Σ^+ beam phase space in they direction.

Then, during the run, we were only able to align **two** of the five **crystals**, **#2 and #5** with the beam.

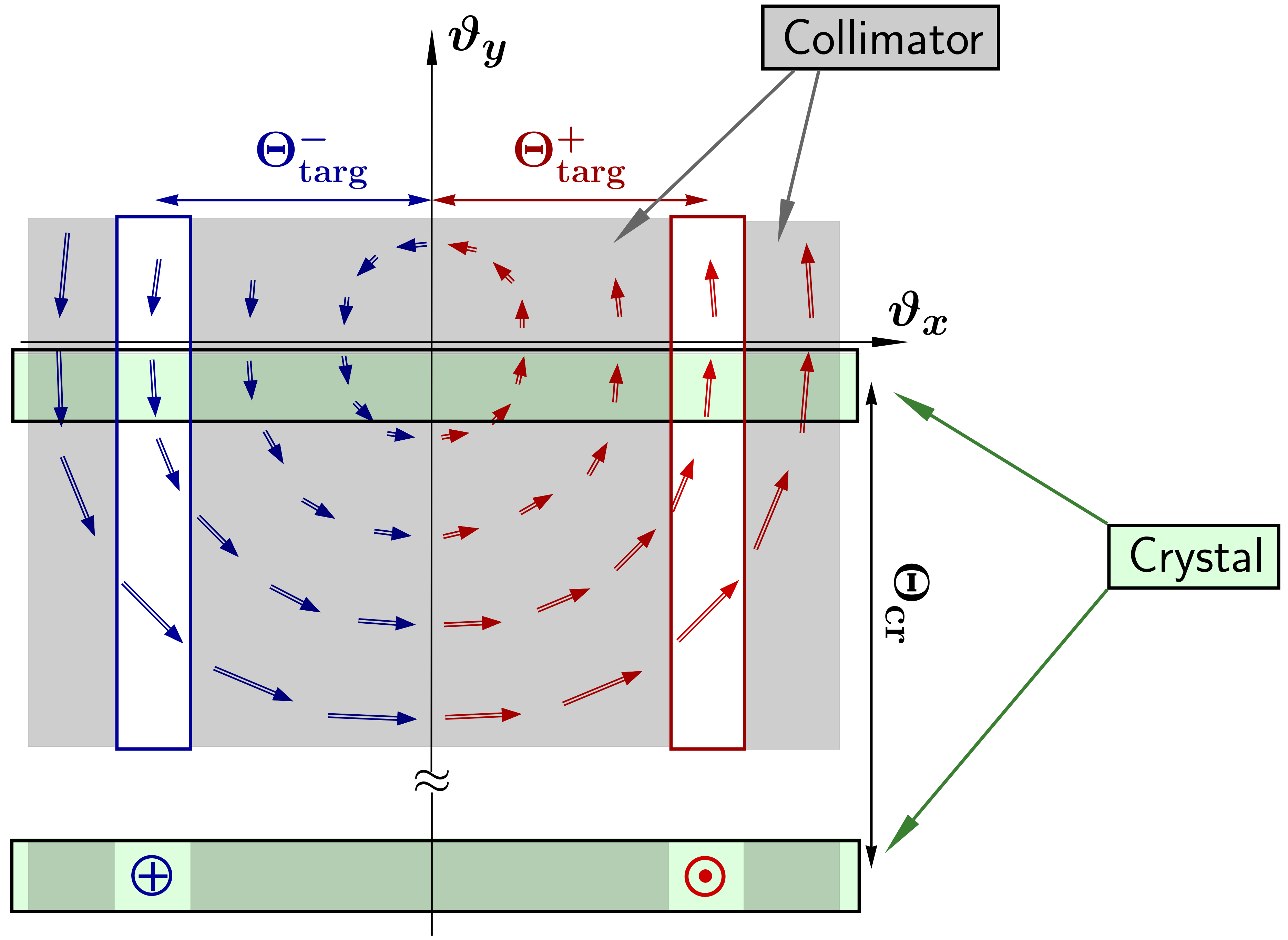




Cancelation of apparatus biases: $\frac{N_j^+ - N_j^-}{N_j^+ + N_j^-} = \alpha\, \xi_j^+ \cos\vartheta_j$

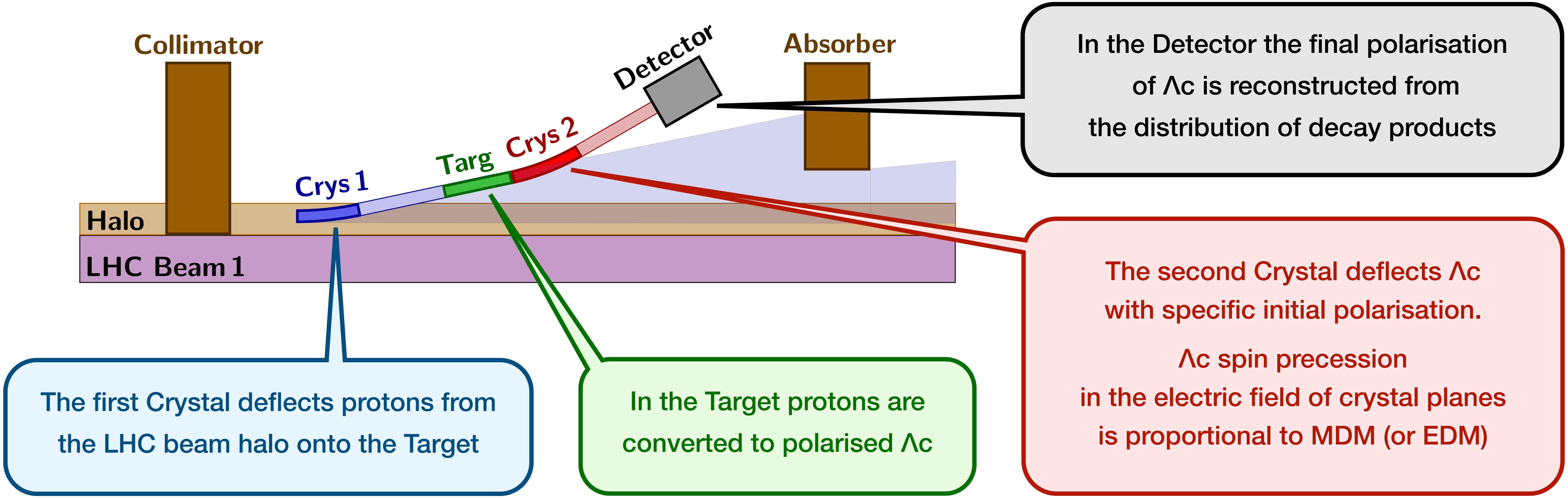
$$N_j^+ \equiv \frac{dN_j^+}{N_{0j}^+\, d\cos\vartheta_j} = \frac{A j(\vartheta_j, \dots)}{2} \left(1 - \alpha\, \xi_j^+ \cos\vartheta_j\right)$$

more details: D. Chen, PhD thesis, SUNY, Albany, 1992.



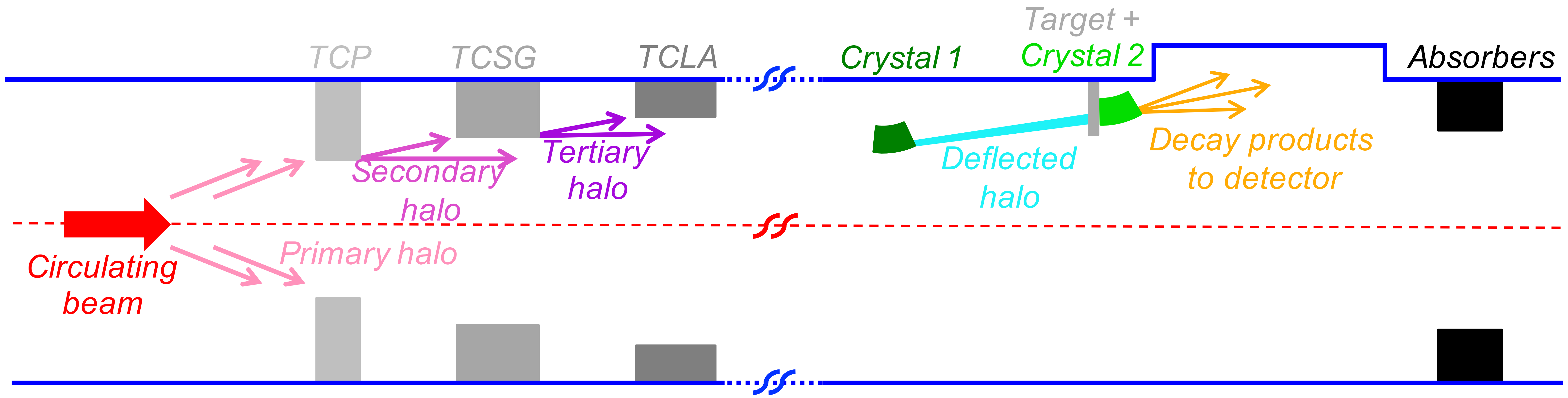
MDM and EDM of charmed baryons: Fixed target at the LHC

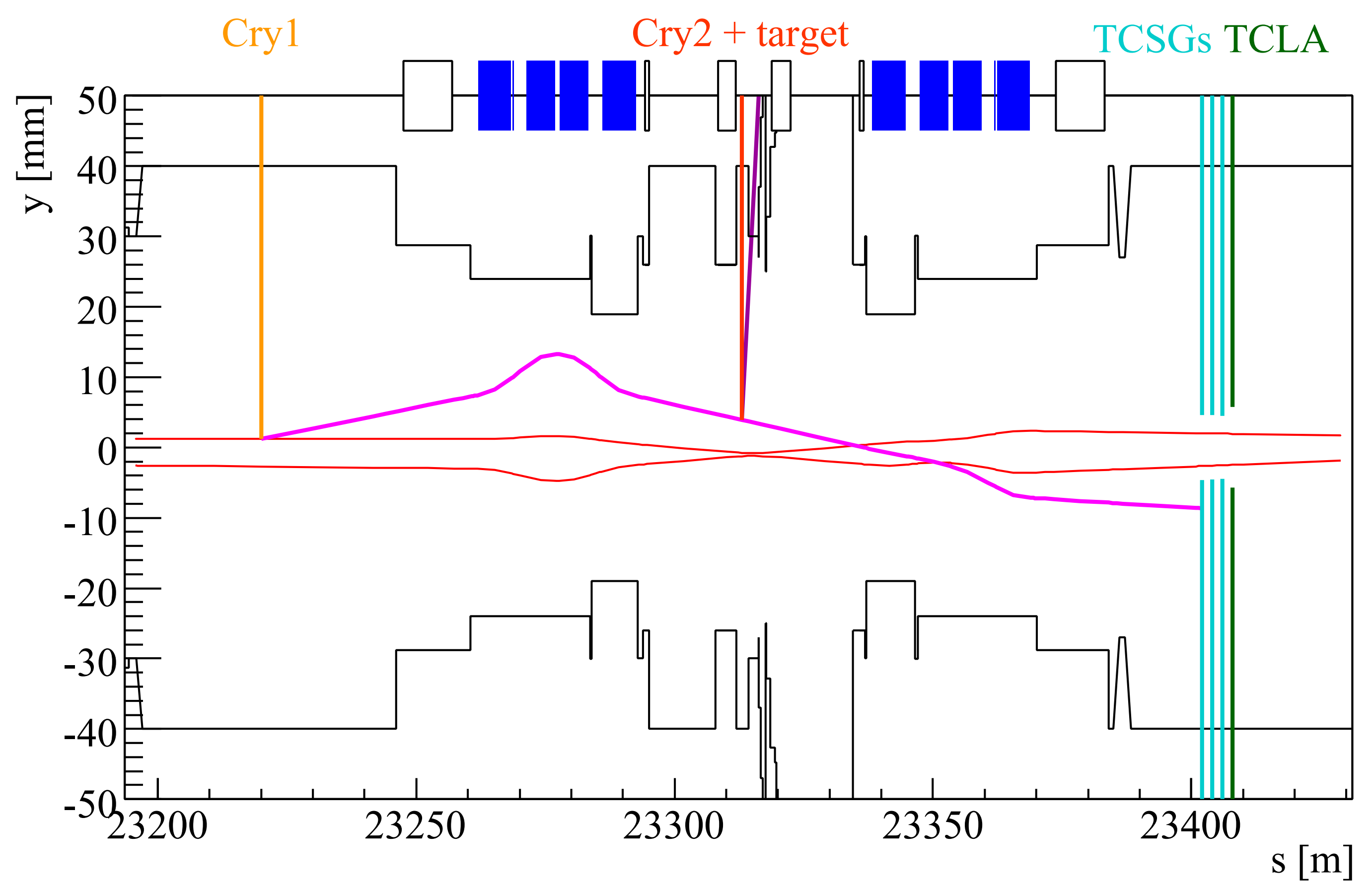
- L. Burmistrov et al., CERN-SPSC-2016-030, CERN, Geneva Switzerland, **June 2016** [SPSC-EOI-012].
- A. Stocchi, W. Scandale, talks at Physics Beyond Collider Workshop, CERN, Geneva Switzerland, **6–7 September 2016**.

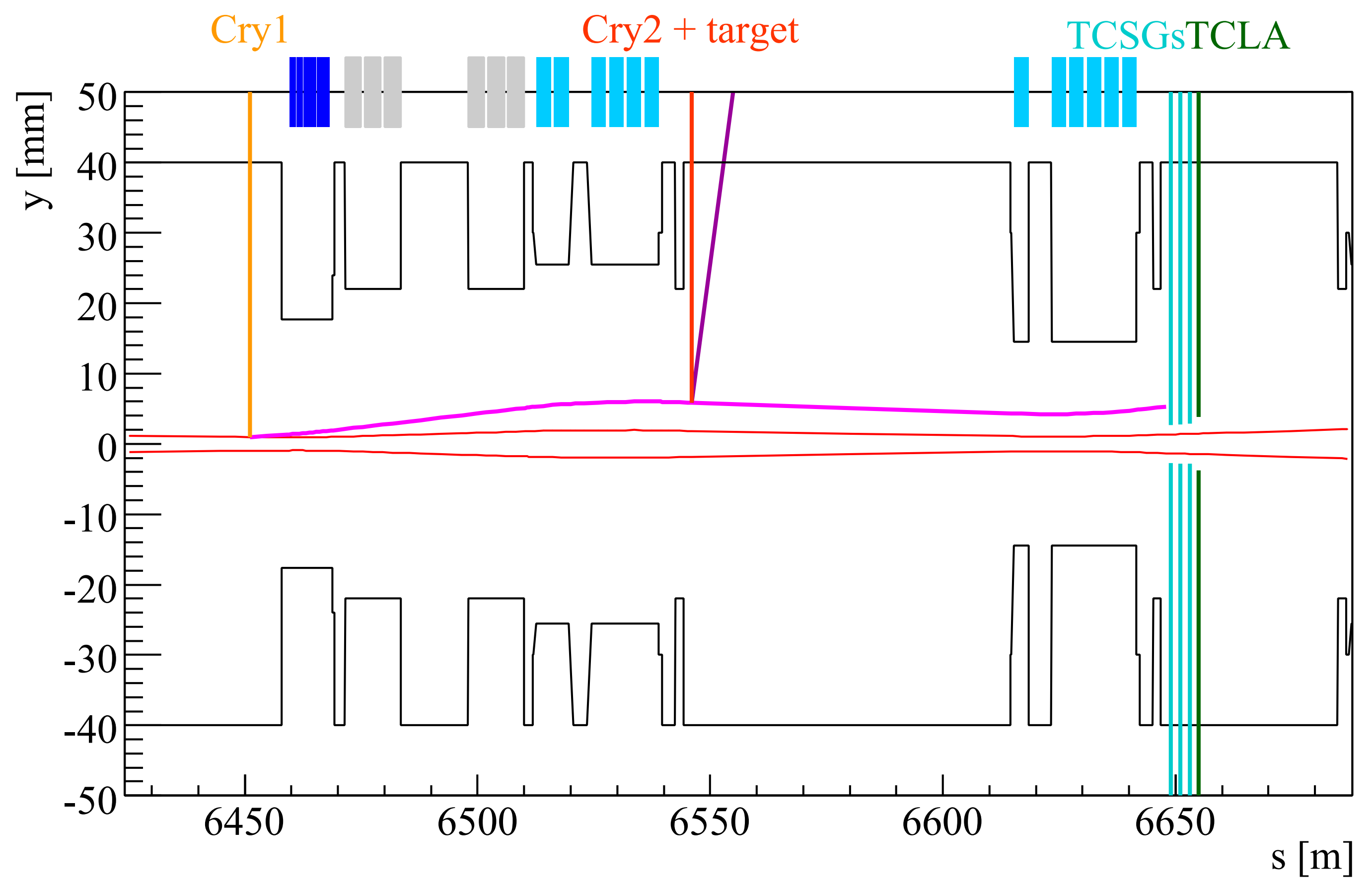


Introduction: double crystal layouts at LHC

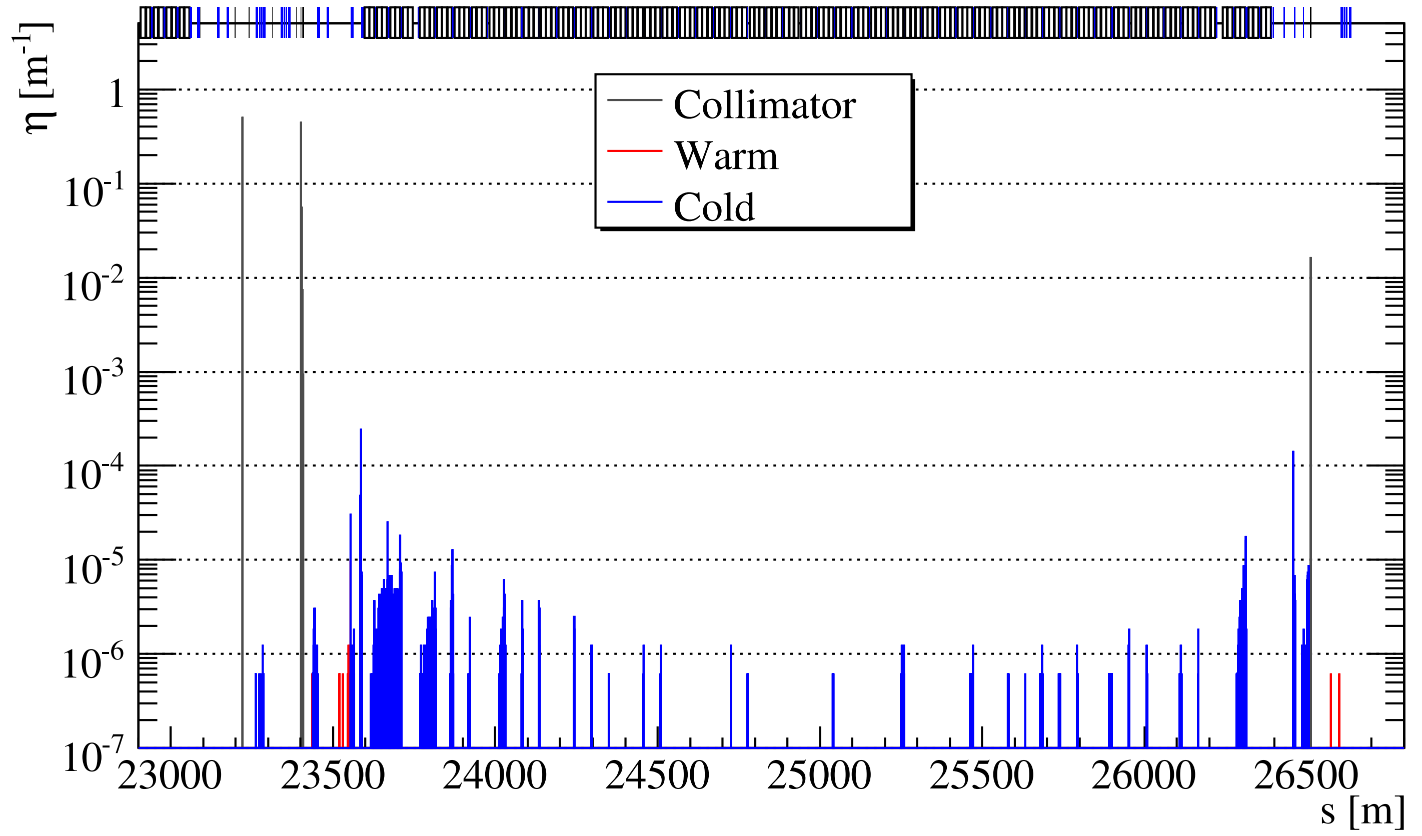
D. Mirarchi et al. Eur. Phys. J. C 80 (2020) 10, 929







- impact on the machine
- optimisation of Crystal 1 and Absorbers positions
- running experiment in a parasitic mode
- layout in front of LHCb (IR8) 4.3×10^{10} POT/fill
- alternative layout at IR3 3.0×10^{10} POT/fill
- restriction on Crystal 2 bending radius



Performance assessment of layouts in IR3 and IR8: precision of measurement

A. Fomin et al. Eur. Phys. J. C (2020) 80:358 [1909.04654]

Layout		IR3	LHCb
Target	proton rate, 10^{10} per 10h fill	3*	4.3*
	length, mm	5	5
Crystal	length, mm	70*	75**
	bending radius, m	14*	5.4**
	deflection angle, mrad	**5**	**14**
Λ_c^+	Average Lorentz factor	**1140**	**600**
	Weighted average polarisation	0.22(5)	0.26(5)
	deflected per 10h fill	**180**	**12**
	relative precision of MDM	**1**	**2.7**
	relative data taking time	**1**	**7.5**

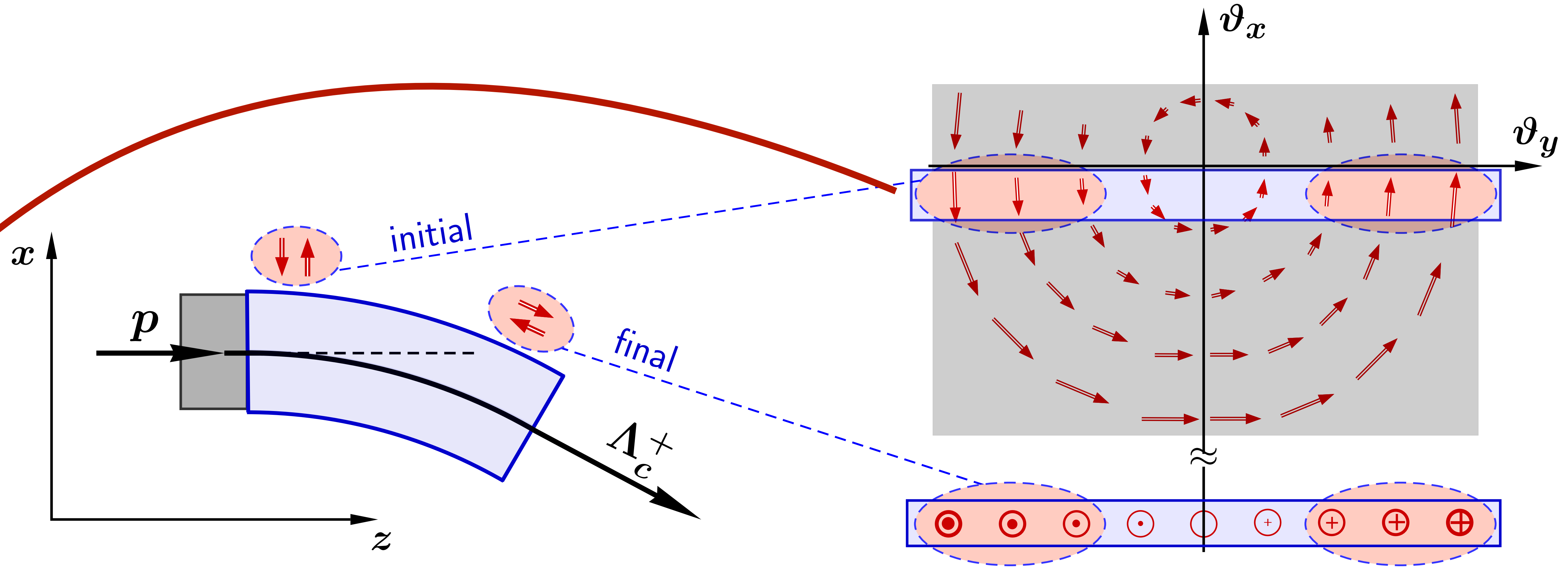
* D. Mirarchi et al. Eur. Phys. J. C 80 (2020) 10, 929

** E. Bagli et al., EPJ C77 (2017) no.12, 828

$$\Delta g = \frac{2}{\alpha \langle \xi_x \gamma \rangle \Theta} \sqrt{\frac{3}{N}}$$

Thorough evaluation of initial polarisation of channeled Λ_c^+

- Spectra-angular distribution of Λ_c^+ (Pythia 8.243)
- Channeling probability as a function of Λ_c^+ energy, bending radius and length of the crystal
- Initial polarisation of Λ_c^+ as a function of transverse momentum



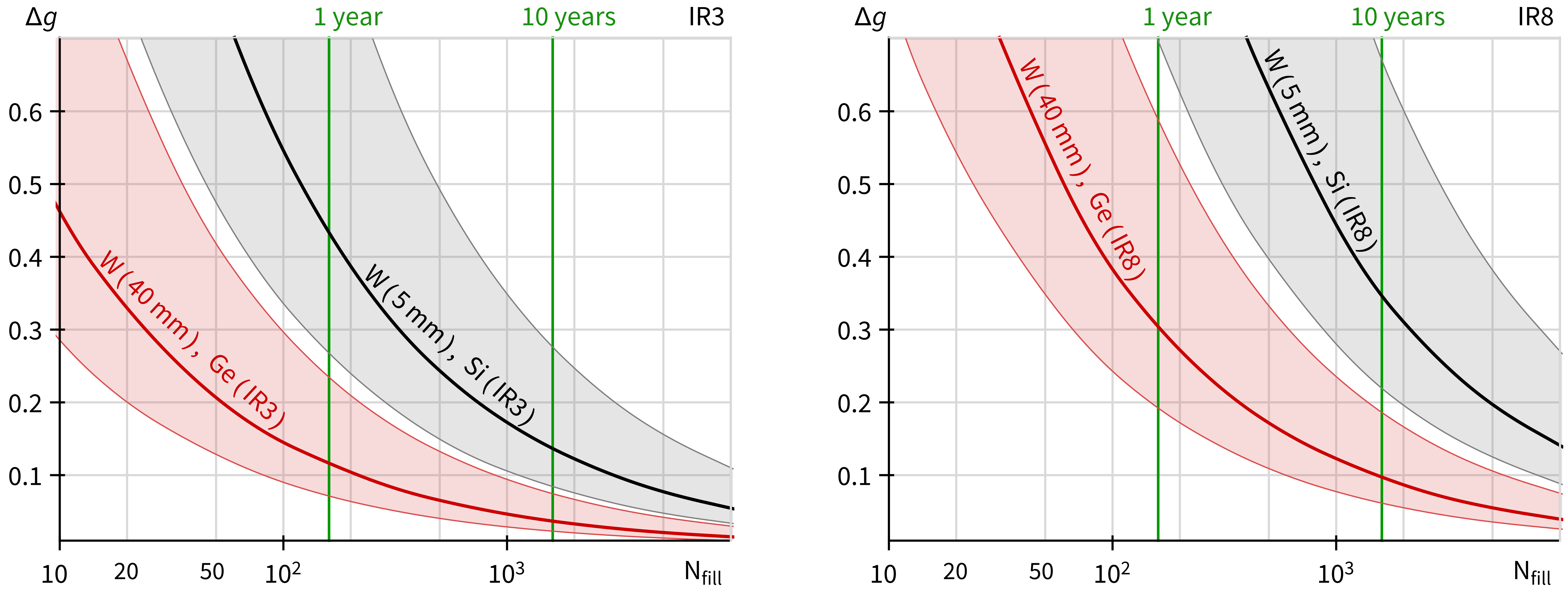
The error of g-factor Δg is calculated considering:

- Detector at IR3 would have the same resolution as LHCb for higher energies, and angular acceptance ≥ 5 mrad
- Systematical error from poor knowledge of α and ξ

Performance assessment of layouts in IR3 and IR8: possible improvements

A. Fomin et al. EPJ C80 (2020) 358

- Thicker target 5 mm → 40 mm: ionisation energy losses and multiple scattering can be neglected, showers production - to be checked
- Proton rate, 3–4.3×10^{10} per 10h fill
  D. Mirarchi et al. EPJ C80 (2020) 10, 929



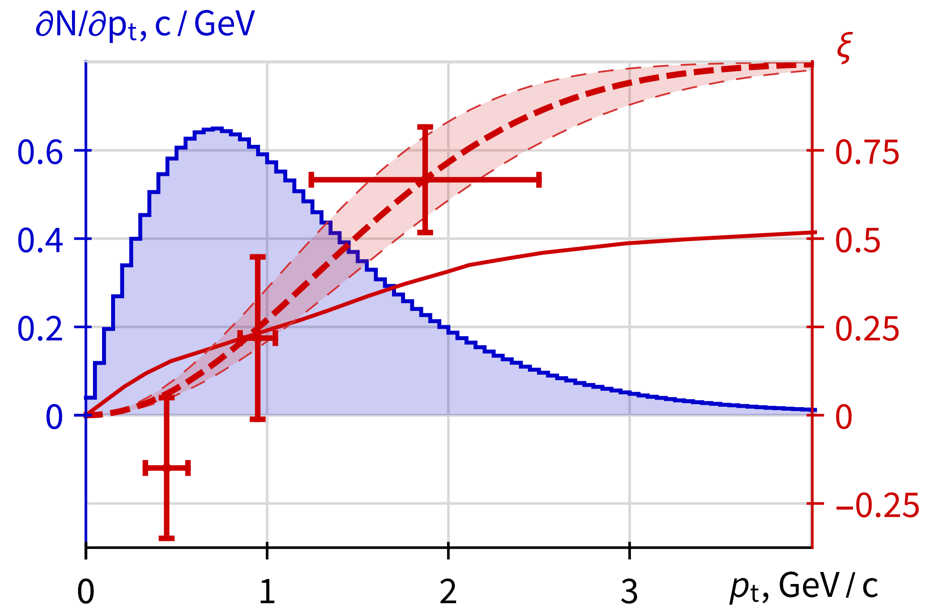
Possible improvements:

	1 → 2	**t1/t2**
Target	5 mm → 40 mm	**6**
Crystal	silicon → germanium	**2.4**
Detector	LHCb (IR8) → dedicated at IR3	**7.5**
Beam exitation	currently under studies	**…**

- **10 year** at **LHCb**, ~7×10^{13} POT, **5mm**, **Si** → Δg ~ **0.35**
- **1 year** at **IR3**, ~0.5×10^{13} POT, **40mm, Ge** → Δg ~ **0.12**
- big uncertainty (×10) due to α parameter

Conclusions

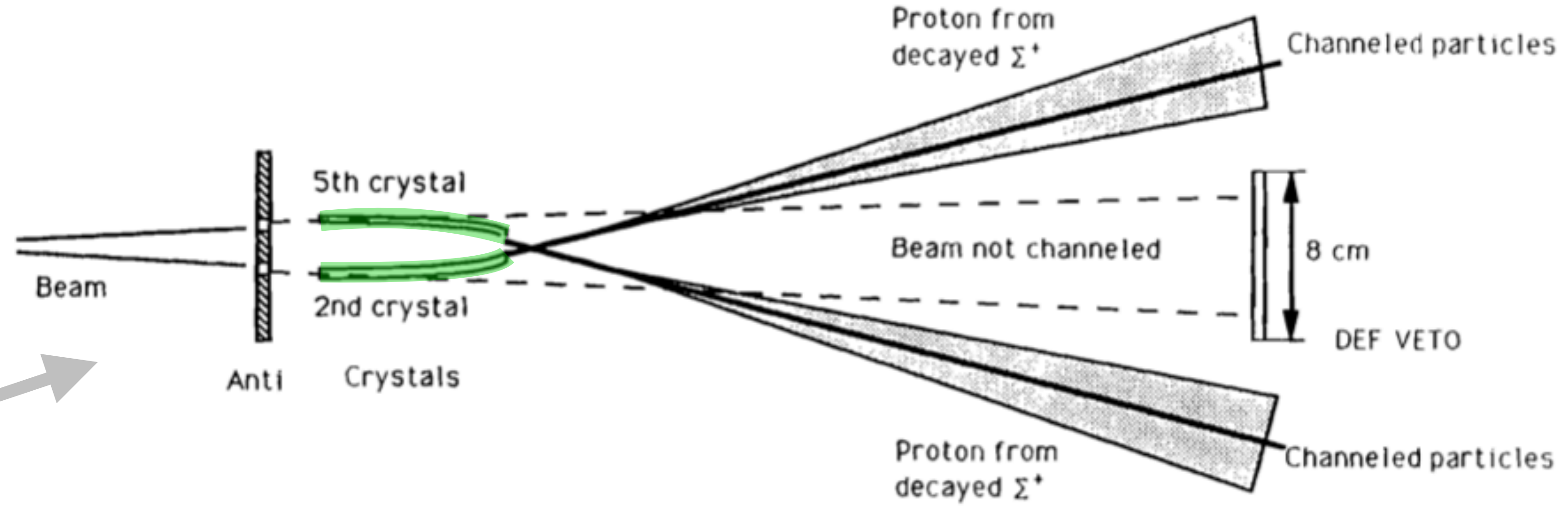
Initial polarisation in double crystal setup



- new corrected value of initial polarisation of channeled Λ_c^+ : 0.22(5) and 0.26(5) for IR3 and LHCb

Performance assessment of layouts in IR3 and IR8

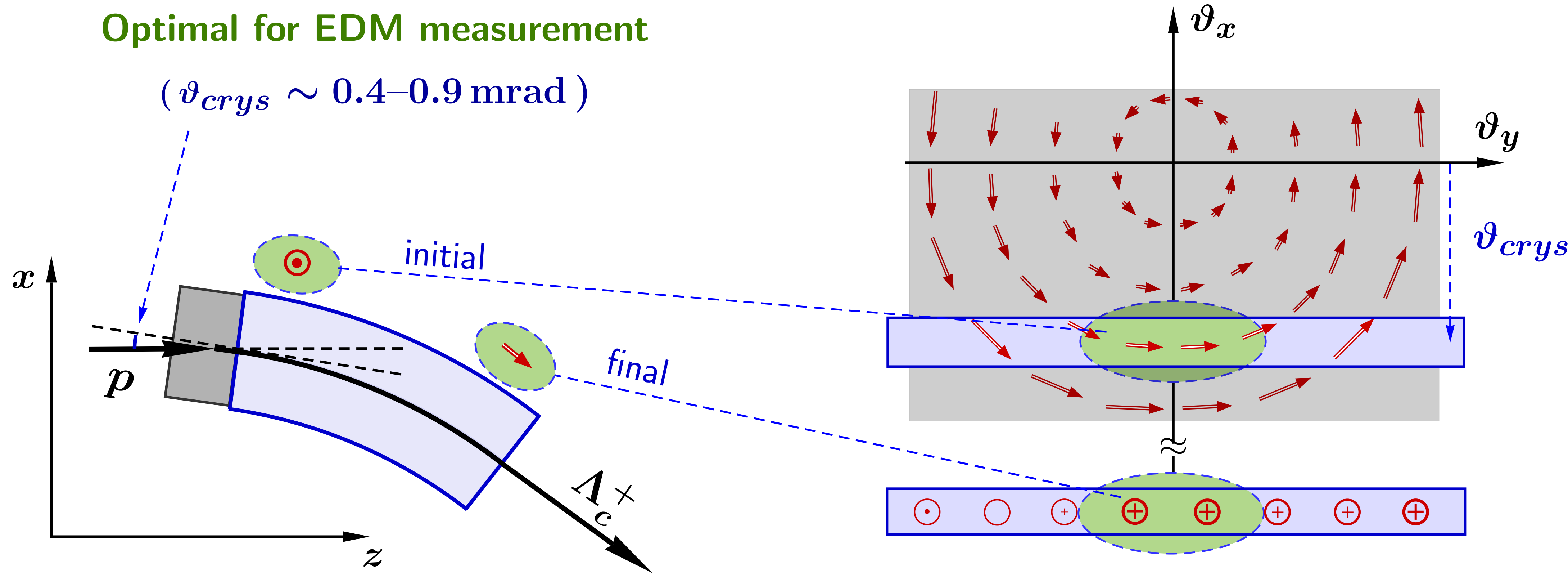
- dg=0.35 (LHCb) and dg=0.14 (IR3) after 10 years
- 5 mm → 40 mm ~ **6** time reduction
- silicon → germanium ~ **2.4** time reduction
- LHCb (IR8) → dedicated at IR3 ~ **7.5** time reduction



MDM of Σ+ (experiment E761, Fermilab 1990)

- Mirroring the setup — doubling the statistics

Optimal crystal orientation for EDM measurement



- slight tilt around bending axis ~ 0.9 mrad (for LHCb)
- data taking time reduced by ~170
- 10 years at IR8, 40mm, Ge, Δd ~ 2.6 10^{-16} e cm

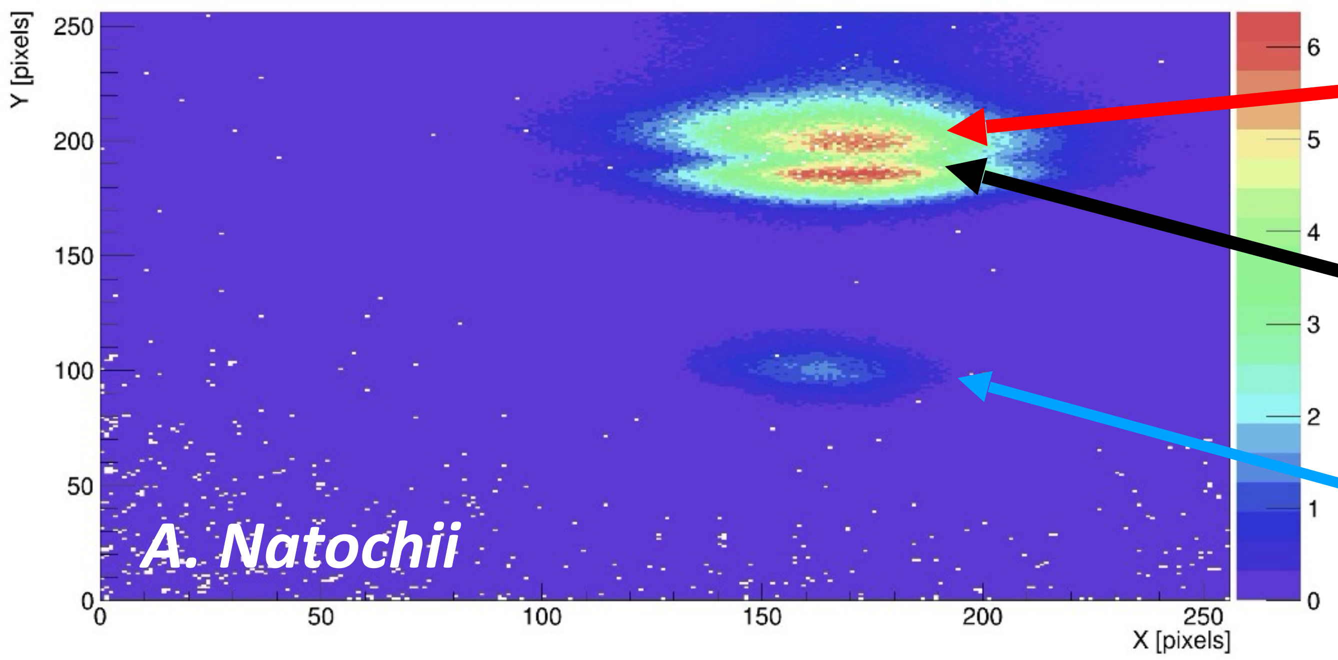
Outlook

Polarisation of Λc (from SMOG data)

- initial polarisation as a function of transverse momentum
- reconstruction of final polarisation

Crystals in circulating machines

- channelling of secondary halo in the LHC
- double channelling scheme proved at SPS (2018)



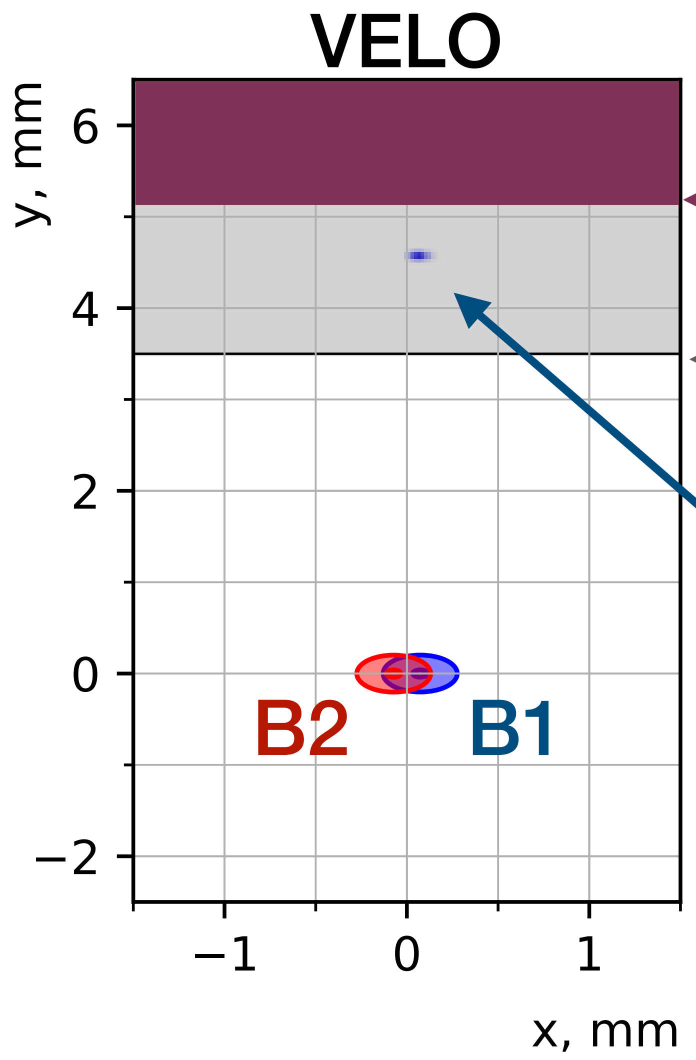
Deflected halo by Crystal 1

Crystal 2 shadow

Second channelling by Crystal 2

Long crystal channeling efficiency

- UA9 at H8 180GeV
- SELDOM at H8 180GeV   Si(111), 8cm, 5m; Ge(110) 5.5cm, 3.7m
- simulations vs experiment
- extrapolation to TeV energies



the first pixel

inner foil radius

Channeled halo

Considerations for the layouts in LHC

- Mirroring the setup — doubling the statistics
- Channeled halo and new VELO aperture
- Dynamic changes during levelling at IR8
- Increasing the statistics of the LHC fixed-target experiments through bunch excitation

thank you

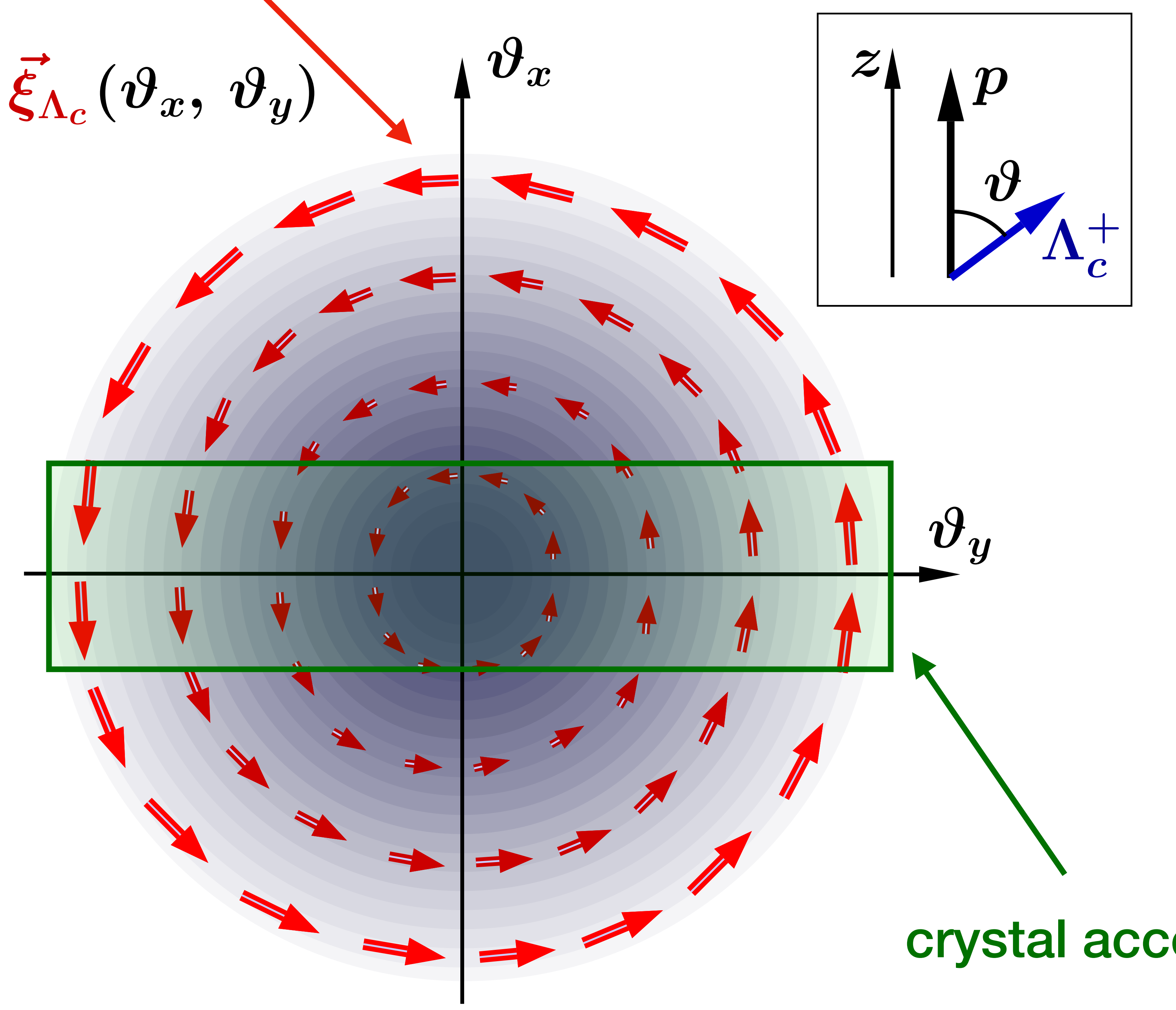
BackUp

A. Fomin et al. Eur. Phys. J. C (2020) 80:358 [1909.04654]

Production of Λ_c^+ in a fixed target $p + p \to \Lambda_c^+ + X$

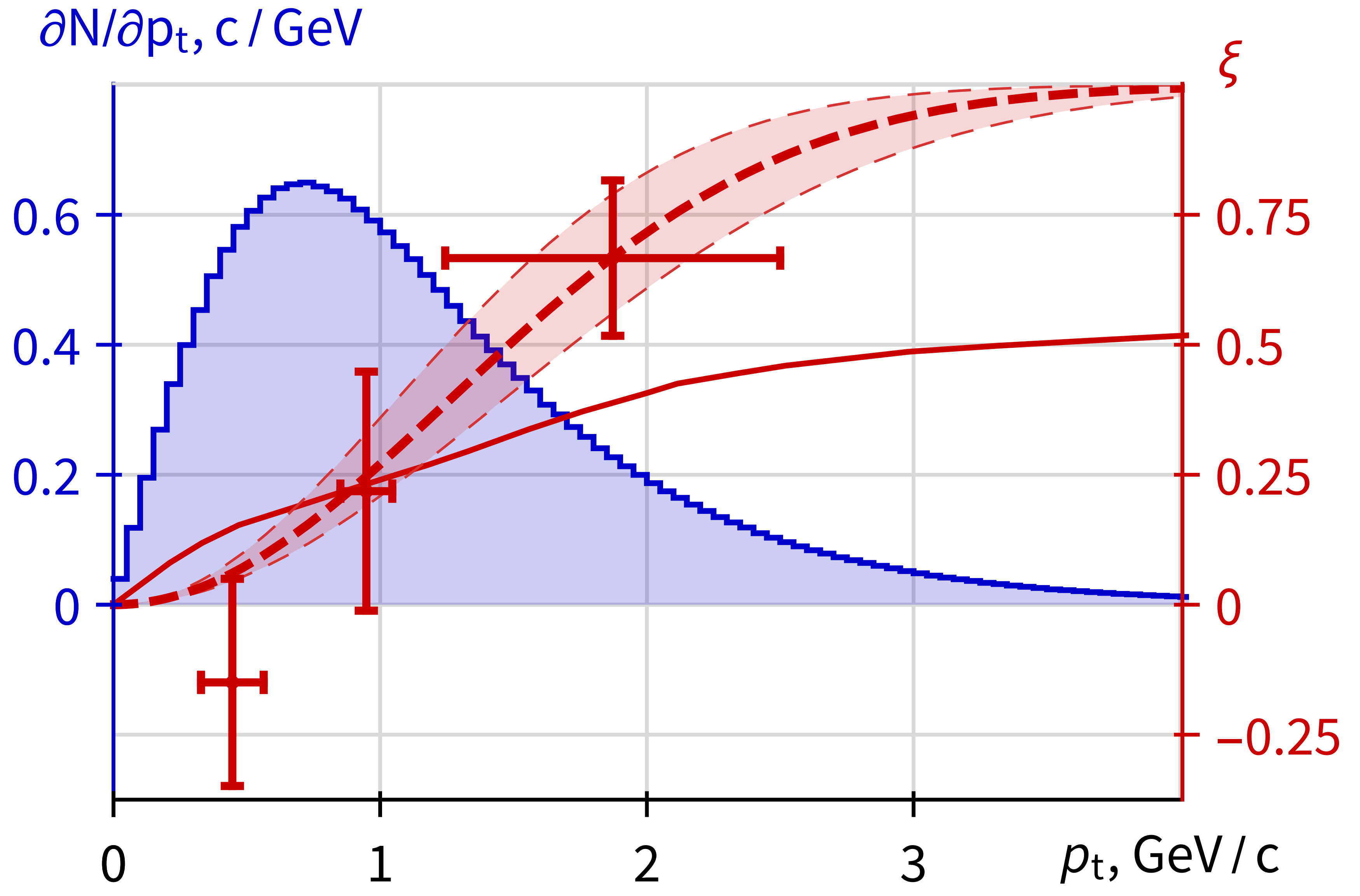
Due to the space-inversion symmetry of the strong interaction

Λ_c^+ polarisation is perpendicular to the reaction plane



Distribution of Λ_c^+ over transverse momentum (Pythia 8.243)

Initial polarisation as a function of transverse momentum



Extrapolated from experimental data $|\xi| = 1 - e^{-\frac{p_t^2}{2\langle p_t^2 \rangle}}$

E791 collaboration, Phys. Lett. B 471 (2000) [inSPIRE]

G.R. Goldstein, hep-ph/0001187 (2000) [inSPIRE]

D. Chen, The Measurement of the Magnetic Moment of Σ+ Using Channeling in Bent Crystals, PhD thesis, SUNY, Albany, 1992.

crystal #5

crystal #2

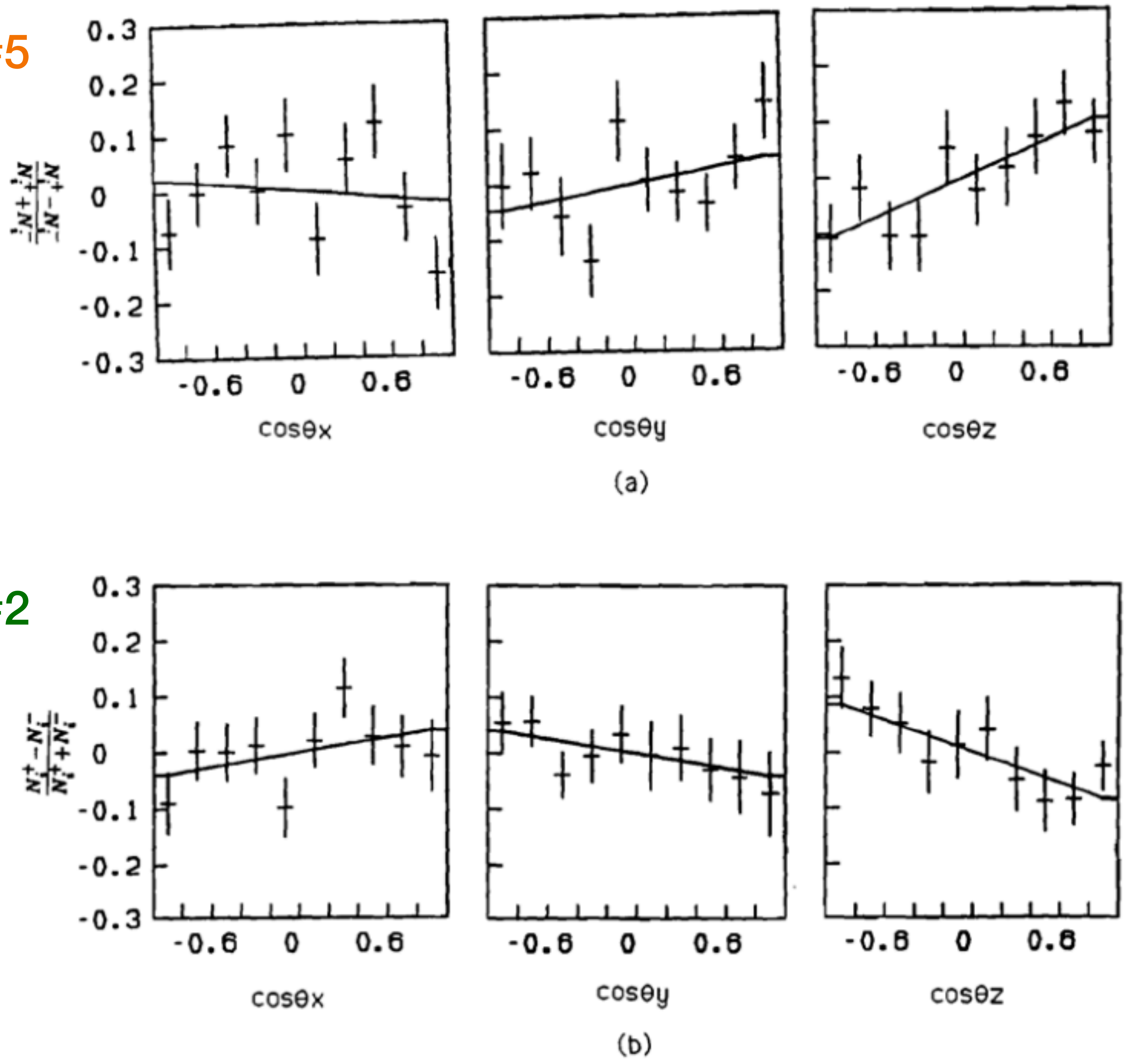


Figure 8.5: The $\frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$ distribution of the events in the signal area for (a) the 5th crystal and (b) the 2nd crystal.

Separate analyses have been done for crystal #5 and #2

We used a bias cancelling technique to cancel the A_i. The distribution of the data with a positive targeting angle, i.e. with the polarization $\mathbf{P}^+$, can be written as

$$\frac{dN_i^+}{N_{0i}^+ dcos\theta_i} = \frac{1}{2}A_i(1 + \alpha \mathbf{P}_i^+ \cos\theta_i). \quad (8.3)$$

And the equation for negative targeting angle, i.e. with the polarization $\mathbf{P}^-$, is

$$\frac{dN_i^-}{N_{0i}^- dcos\theta_i} = \frac{1}{2}A_i(1 + \alpha \mathbf{P}_i^- \cos\theta_i). \quad (8.4)$$

Assuming the same amplitude for the positive and the negative targeting angle, $\mathbf{P}_i^+ = -\mathbf{P}_i^-$, we can rewrite equation (8.4) as

$$\frac{dN_i^-}{N_{0i}^- dcos\theta_i} = \frac{1}{2}A_i(1 - \alpha \mathbf{P}_i^+ \cos\theta_i). \quad (8.5)$$

If we redefine $N_i^+ = \frac{dN_i^+}{N_{0i}^+ dcos\theta_i}$ and $N_i^- = \frac{dN_i^-}{N_{0i}^- dcos\theta_i}$ and assume that A_i is the same for both targeting angles, from equation (8.3) and equation (8.5), we can derive

$$\frac{N_i^+ - N_i^-}{N_i^+ + N_i^-} = \alpha \mathbf{P}_i^+ \cos\theta_i. \quad (8.6)$$

From the plot of $\frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$ versus $\cos\theta_i$, we obtained the $\alpha \mathbf{P}_i^+$ from the slope of the distribution.

	$\mu_{\Sigma+}$ (μ_N) with channeling cut	$\mu_{\Sigma+}$ (μ_N) no channeling cut
5th crystal	2.15 ± 0.61	2.32 ± 0.58
2nd crystal	2.74 ± 0.71	2.62 ± 0.73
Average	2.40 ± 0.46	2.44 ± 0.46
PGD	2.42 ± 0.05	

Table 8.4: Results of the $\mu_{\Sigma+}$ measurement with statistical error only.

Systematical error of g-factor from poor knowledge of α and ξ

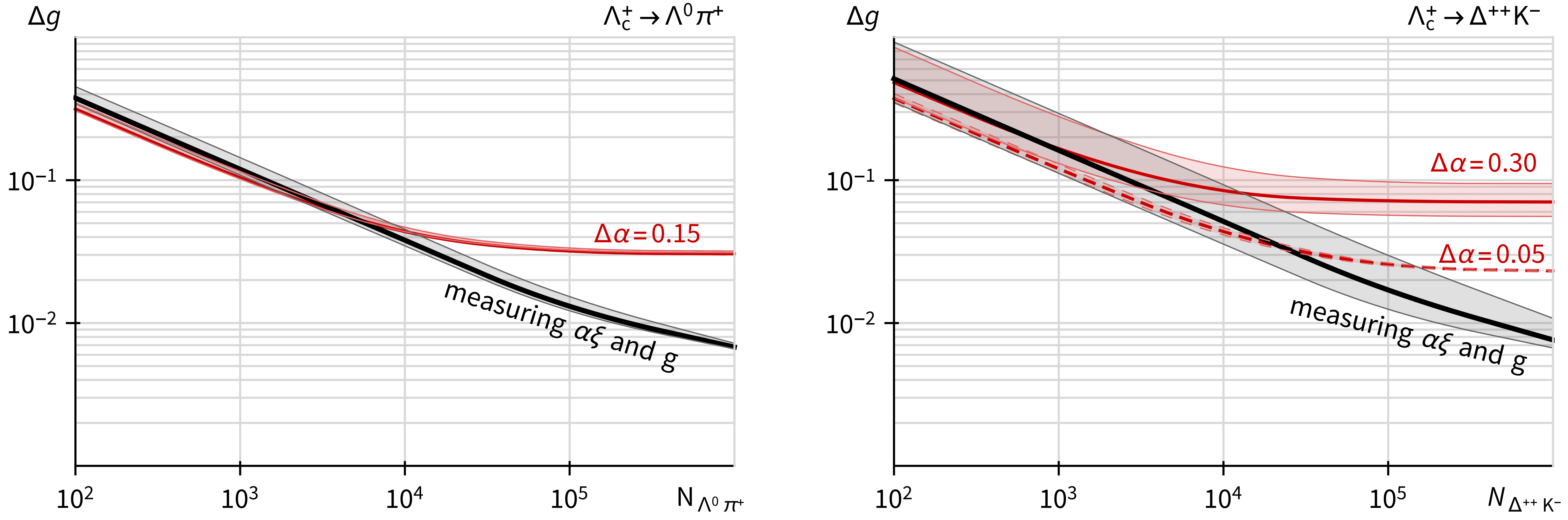
A. Fomin et al. Eur. Phys. J. C (2020) 80:358

1) use pre-measured values of $\alpha\cdot\xi$ factor

2) measure $\alpha\cdot\xi$ and g-factor simultaneously

$$\frac{dN}{d\cos\theta_z} = \frac{1}{2}\left(1 + \alpha\,\xi_z\,\cos\Theta_\mu\,\cos\theta_z\right)$$

$$\frac{dN}{d\cos\theta_x} = \frac{1}{2}\left(1 + \alpha\,\xi_x\,\sin\Theta_\mu\,\cos\theta_x\right)$$



Decay channel	Branching ratio, %	Weak decay parameter α	Detector efficiency		Wieght $(\Delta g/\Delta gj)^2$
			IR3	IR8*	
$\Lambda_c^+ \rightarrow p\,K^*(892)$	1.96(27)	0.66(28)	0.2	0.2	~ **0.60**
$\Lambda_c^+ \rightarrow \Delta^{++}(1232)\,K^-$	1.08(25)	−0.67(**30**)	0.2	0.2	~ **0.35**
$\Lambda_c^+ \rightarrow \Lambda(p\pi^-)\,\pi^+$	0.83(5)	0.91(**15**)	0.02	0.004	0.01–0.05
$\Lambda_c^+ \rightarrow \Lambda(1520)\,\pi^+$	2.20(5)	−0.11(60)	0.2	0.2	0.02

* E. Bagli et al., EPJ C77 (2017) no.12, 828

Performance assessment of layouts in IR3 and IR8: possible improvements

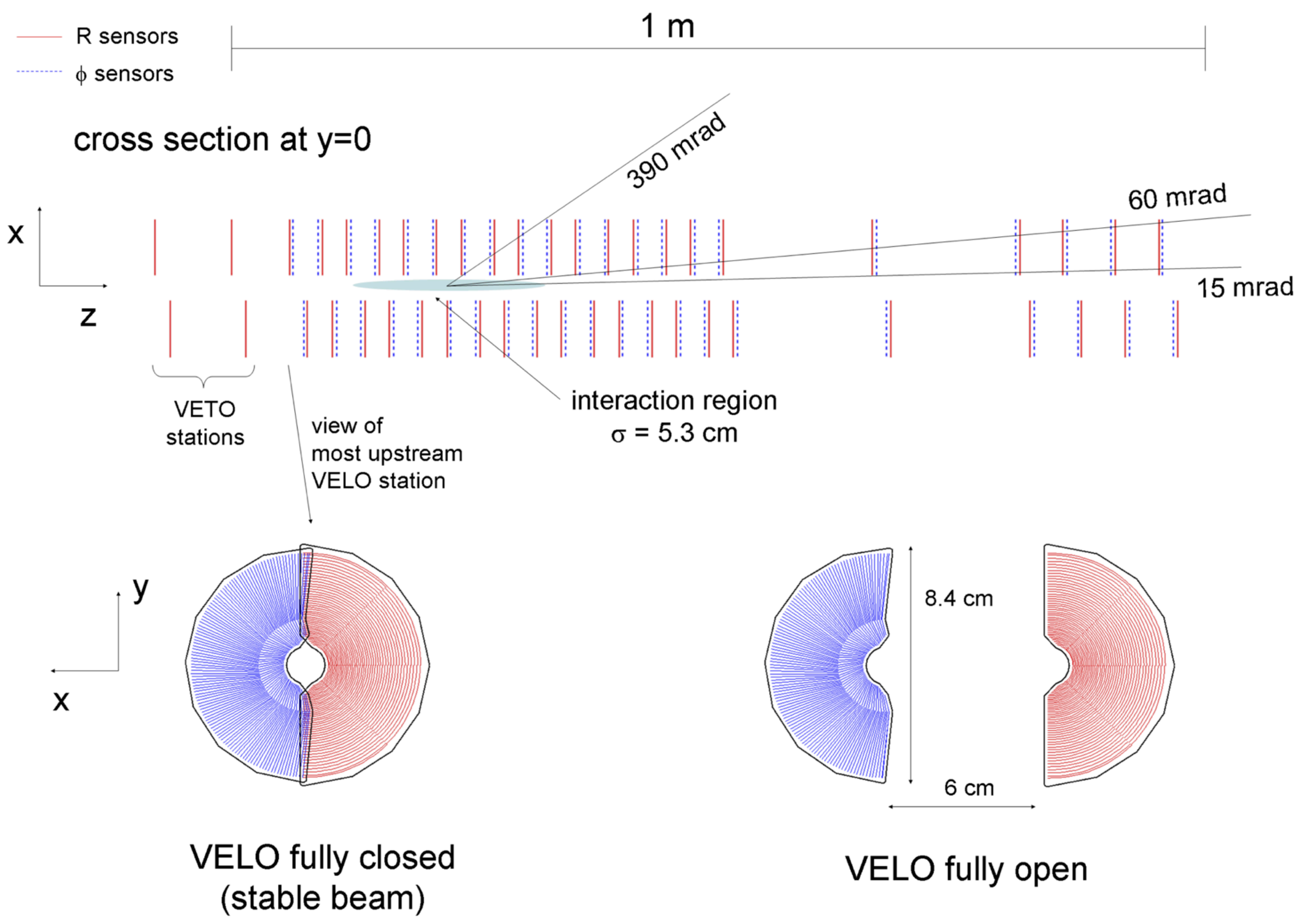
A. Fomin et al. EPJ C80 (2020) 358

			Central values of absolute statistical error of g-factor		Data taking time	
Configuration			Δg after		Time (years) to reach	
Target length	Crystal	Place	1 year	10 years	$\Delta g = 0.1$	$\Delta g = 0.04$
5 mm	Silicon	IR8	1.10	0.35	123	–
		IR3	0.43	0.14	19	120
40 mm	Silicon	IR8	0.49	0.16	25	160
		IR3	0.17	0.06	3	19
40 mm	Germanium	IR8	0.31	0.10	10	62
		IR3	0.12	0.04	1.5	8.5

Channeled halo
and
new VELO aperture

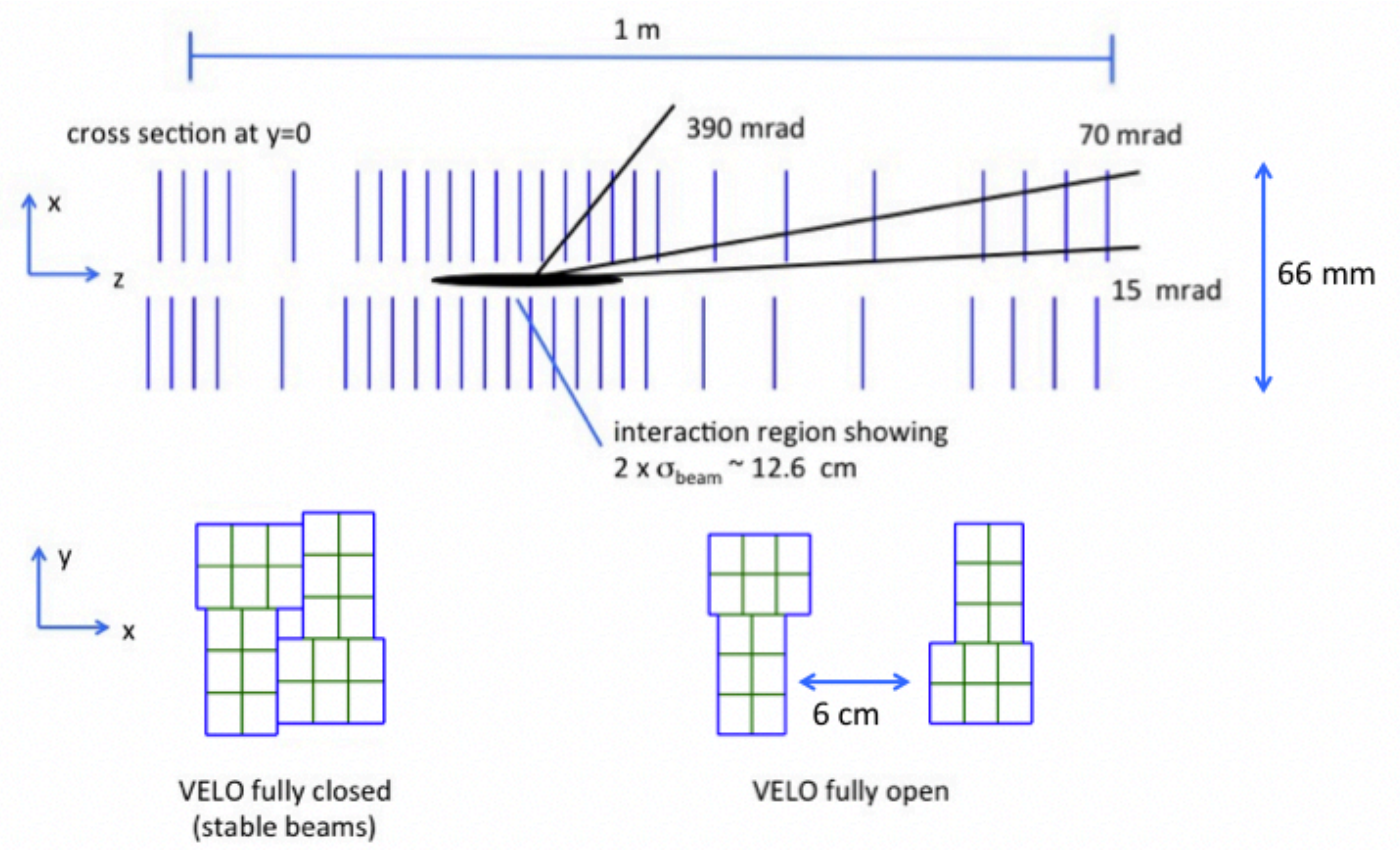
Upgraded VELO aperture: ~5 mm → 3.5 mm

LHCb collaboration, A. A. Alves Jr. *et al.*, *The LHCb detector at the LHC*, JINST **3** (2008) S08005.



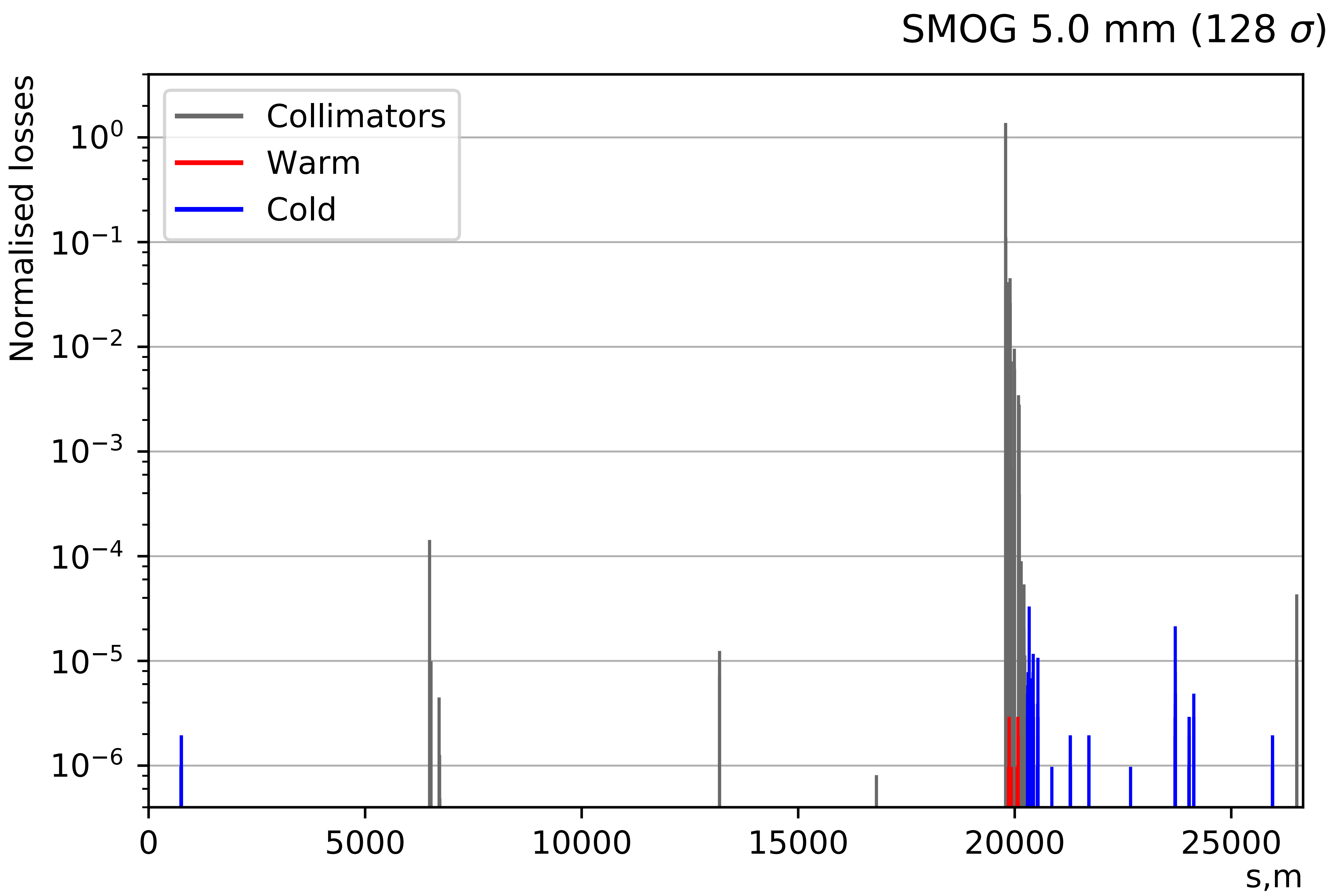
- the old VELO foil inner radius ranges between 4.9 and 5.6 mm, as determined from particle interaction tomography

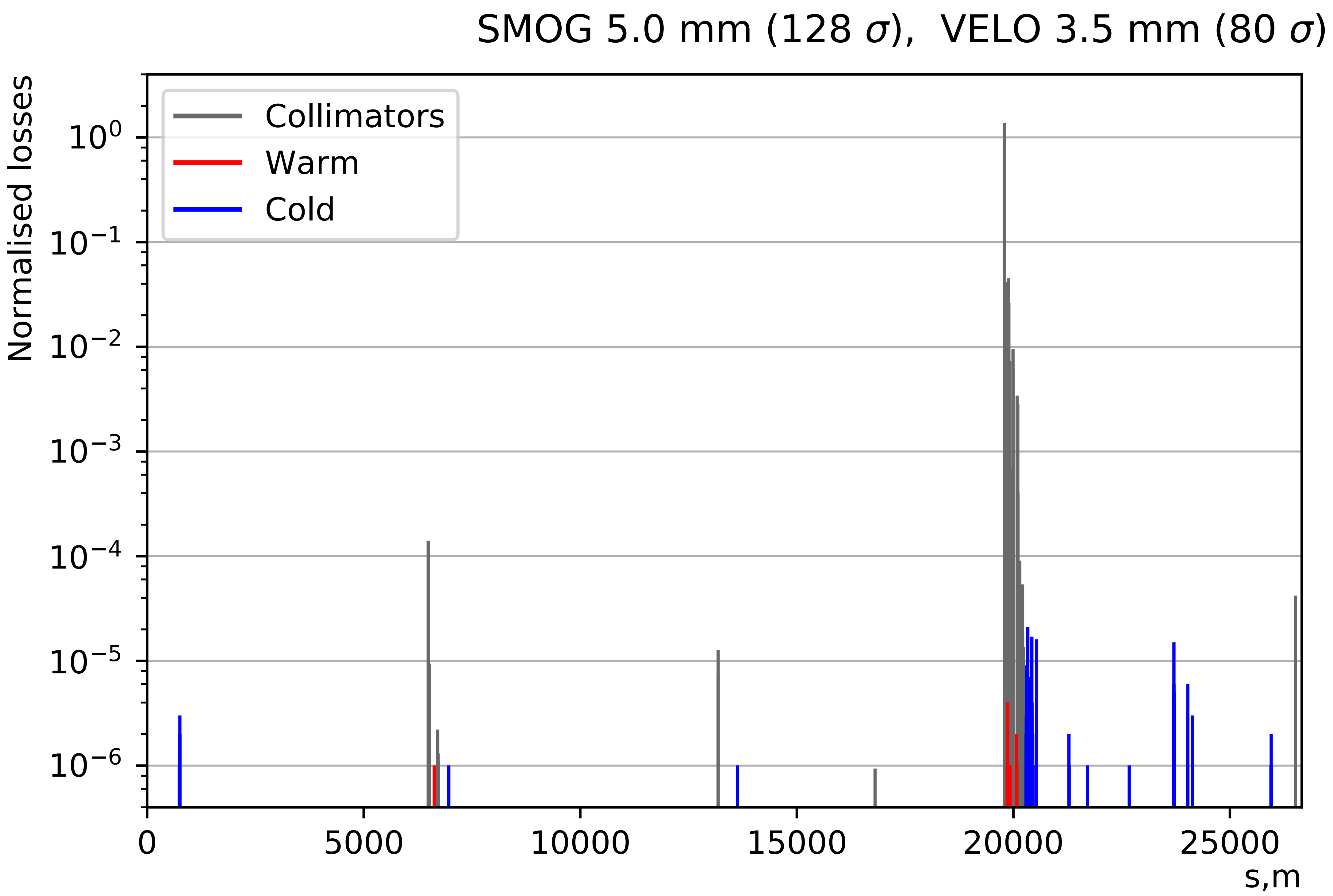
CERN/LHCC 2013-021, LHCb TDR 13, November 29 2013



- an inner foil radius of 3.5 mm was proposed and agreed upon
- a closest distance of approach to the LHC beams of just 5.1 mm for the first sensitive pixel

Upgraded VELO aperture: Loss maps (no crystal)

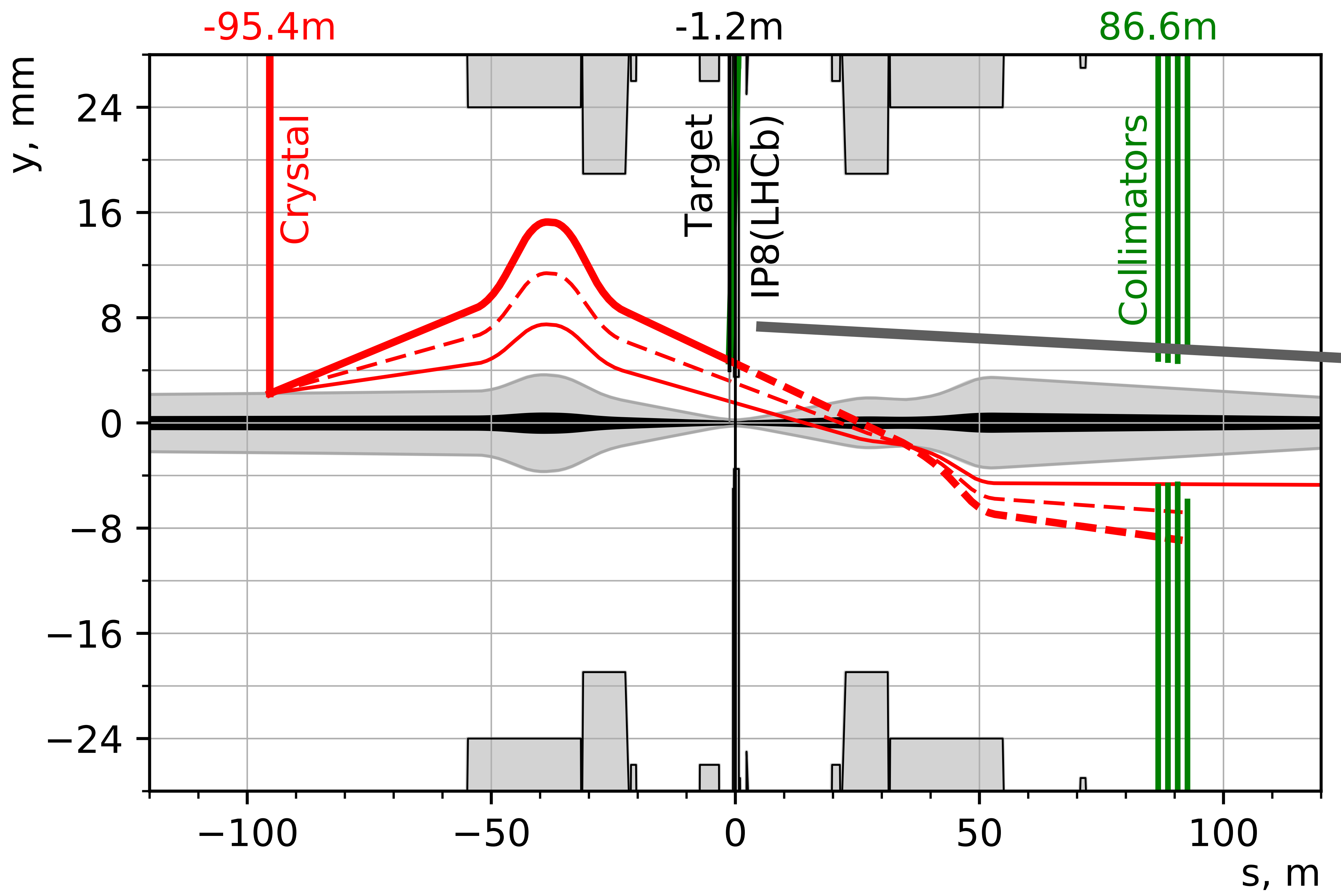


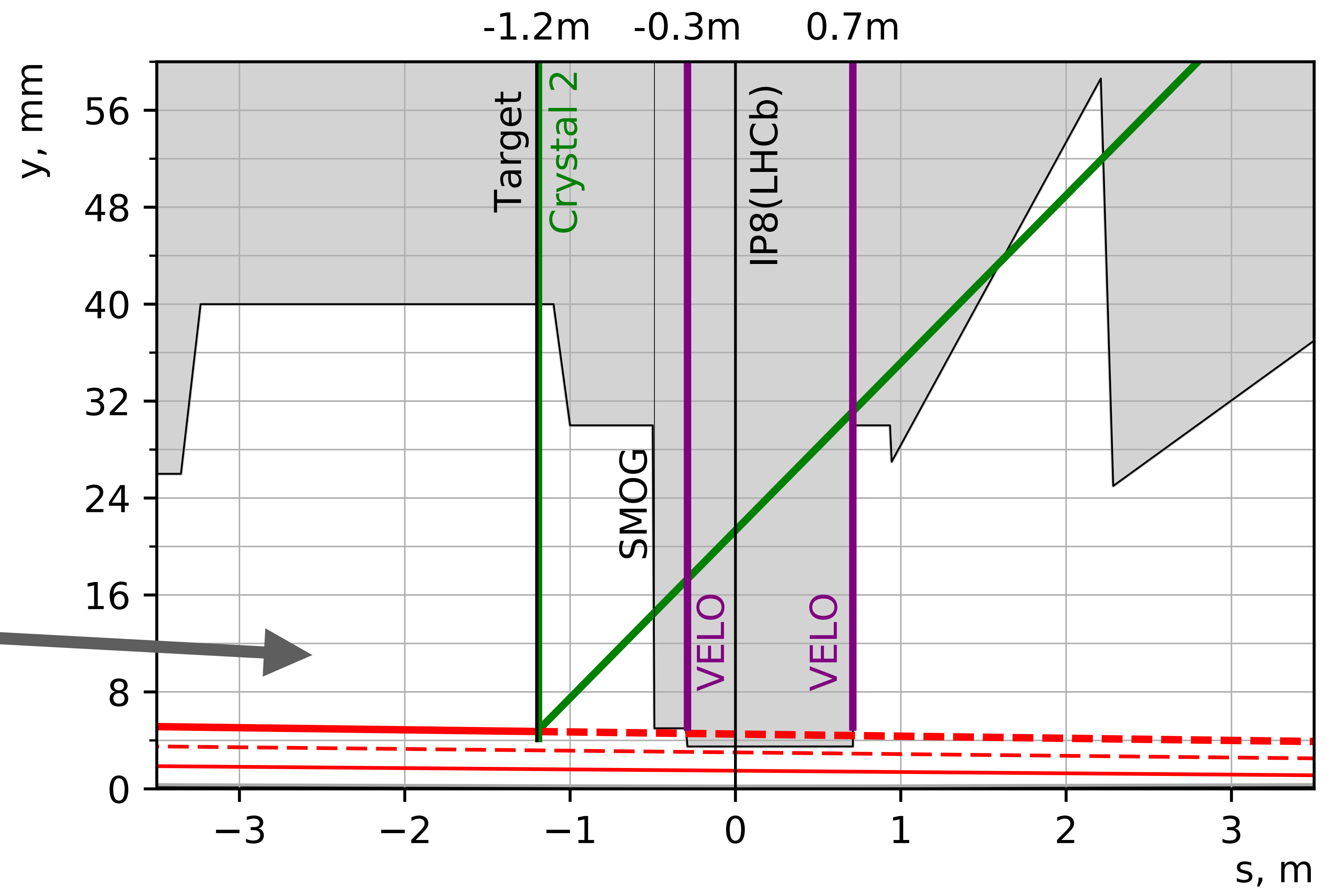


- SixTrack simulation with a new VELO aperture: 3.5 mm (80 σ, emit = 3.5 μm)
- No additional losses during the normal operation
- For a double crystal setup the additional check is needed

- Optics of 2018 machine configuration at “End of Squeeze”

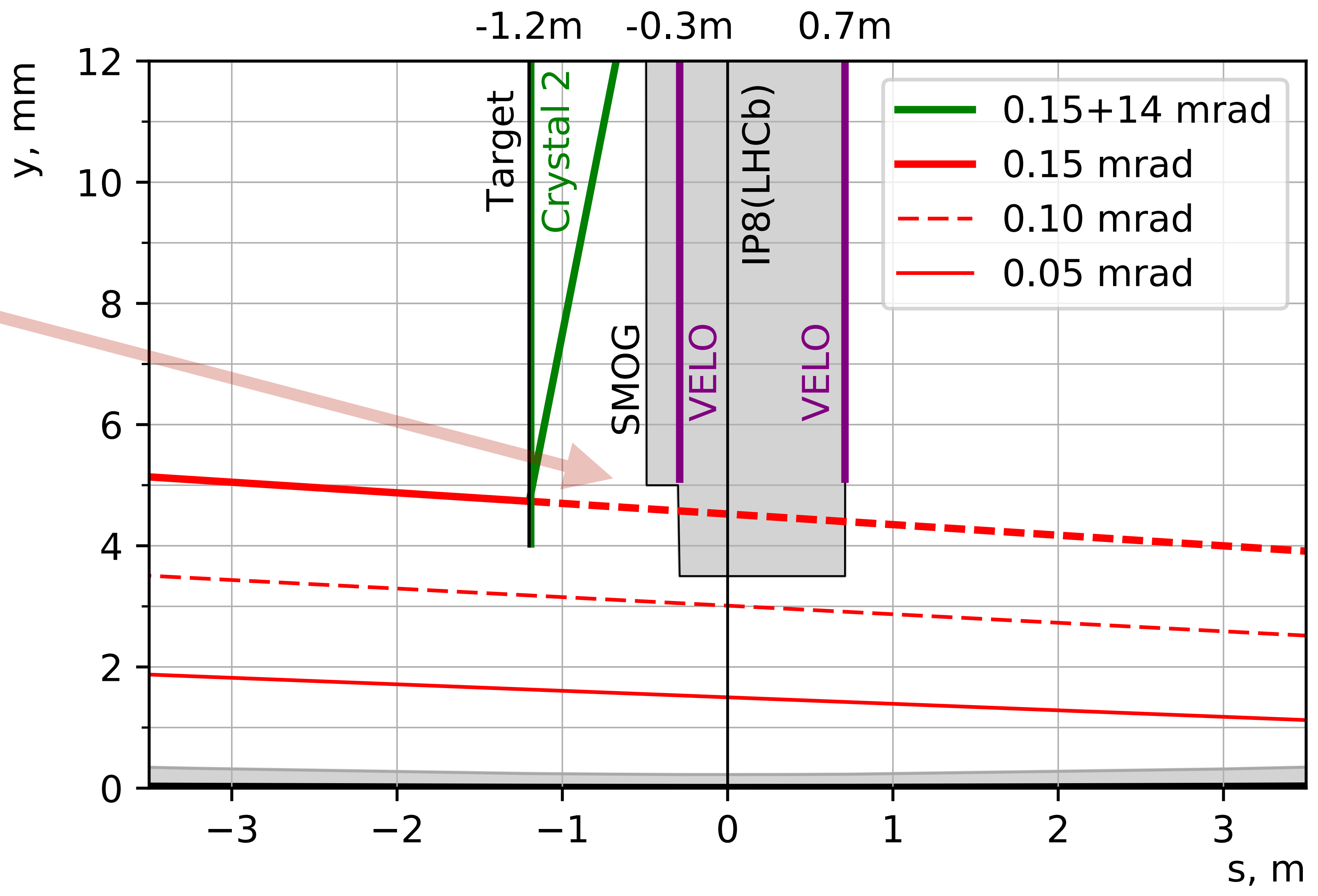
Double crystal layout considered in [D. Mirarchi et al., (2019), 1906.08551]





Problem:

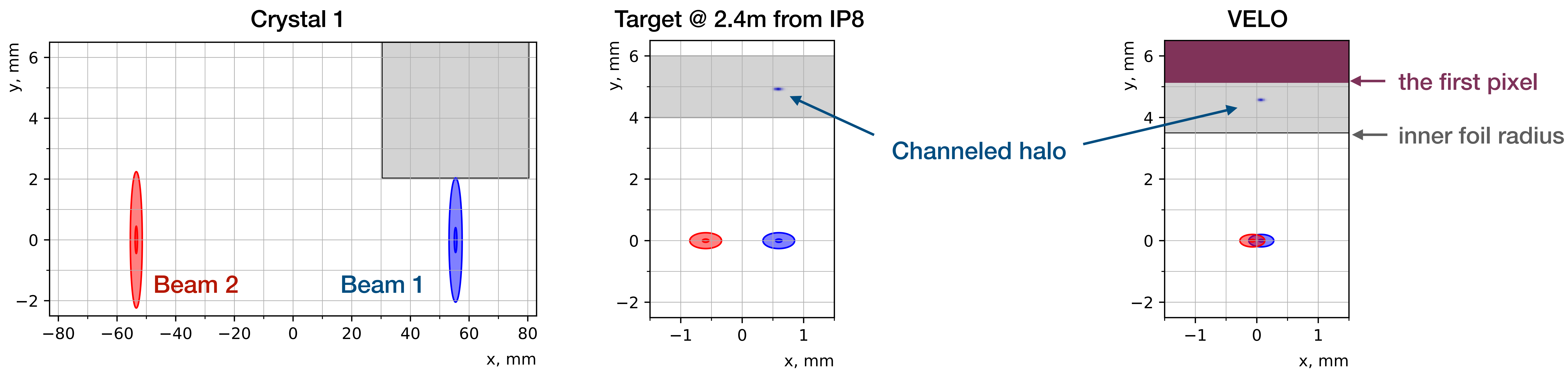
In present layout, the deflected by Crystal 1 halo hits the upgraded VELO detector



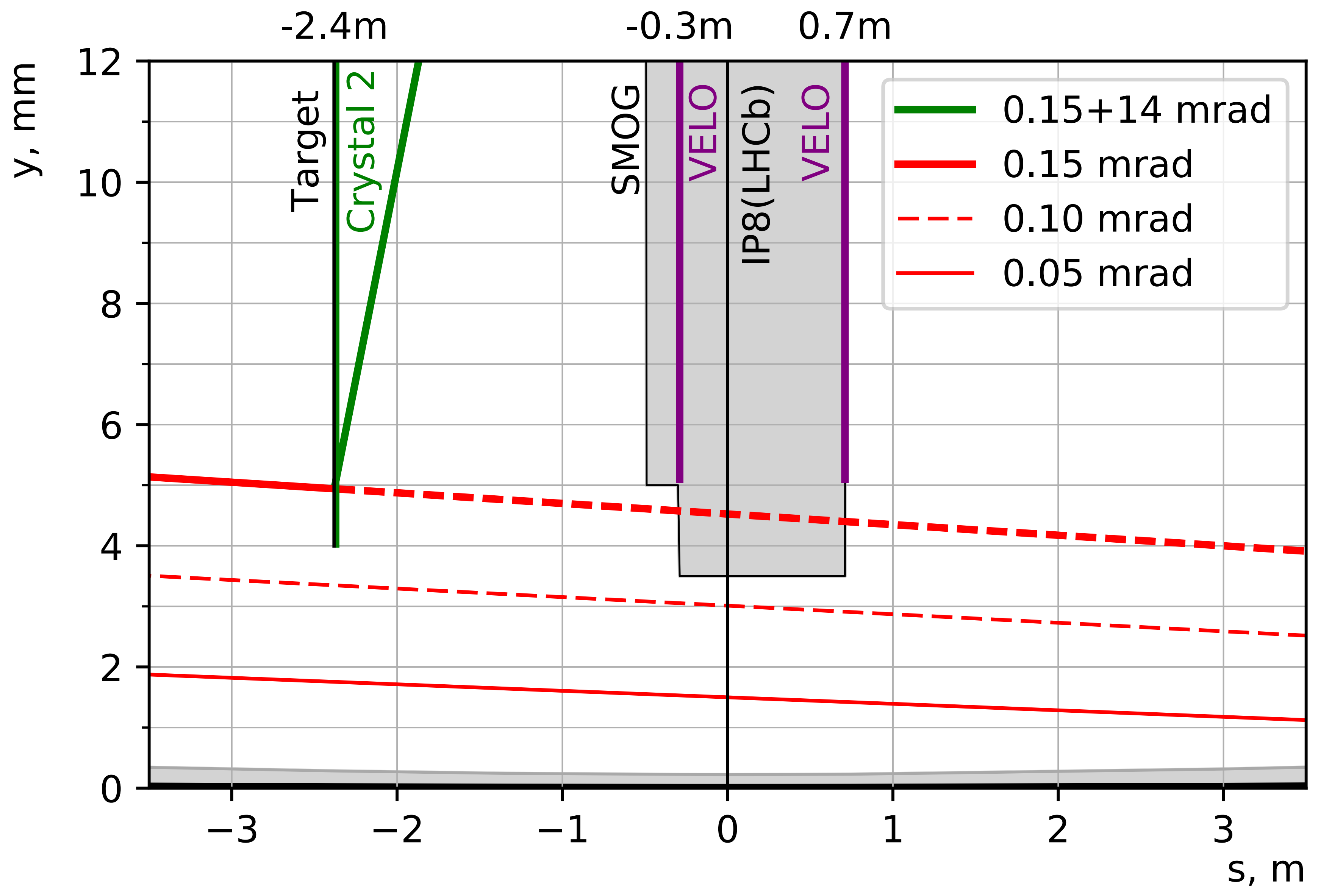
TO BE CHECKED:

Can the deflected beam cause a problem to the VELO ?

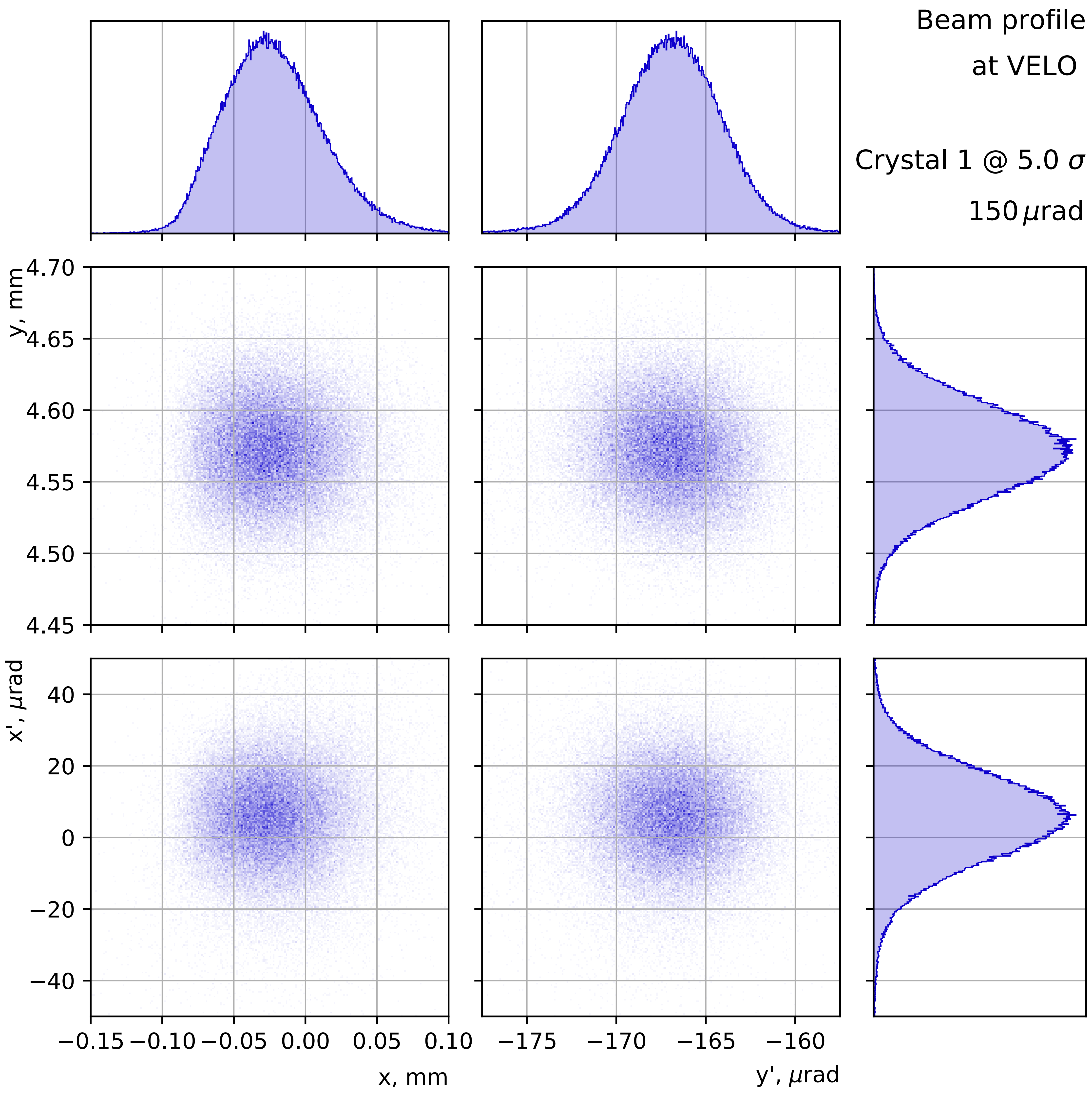
Channeled halo and new VELO aperture: profiles and positions of the beams



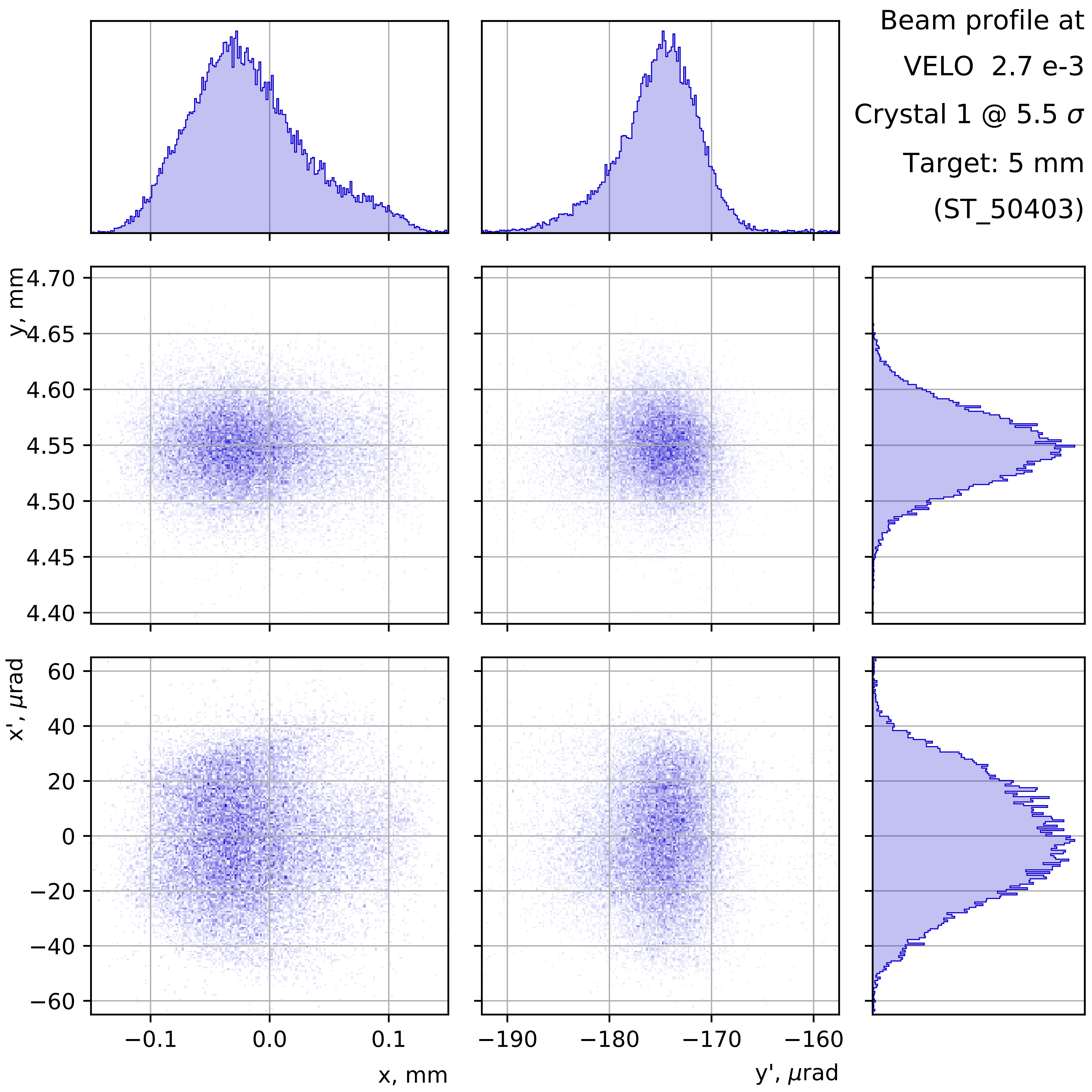
- Optics of 2018 machine configuration at “Stable Beam” used for all simulations
- Evaluation to be performed also with RunIII configurations when frozen
- Space is tight and conflicts between the two beams have to be studied for a final design of the crystal support/holder
- Potential problem: the channeled halo hits the aperture of new VELO (~1 mm inside VELO from inner foil, 0.5 mm from the first pixel)



Max. flux of protons hitting VELO: ~10^8 p/s (~10^{11} p/s for 10s)



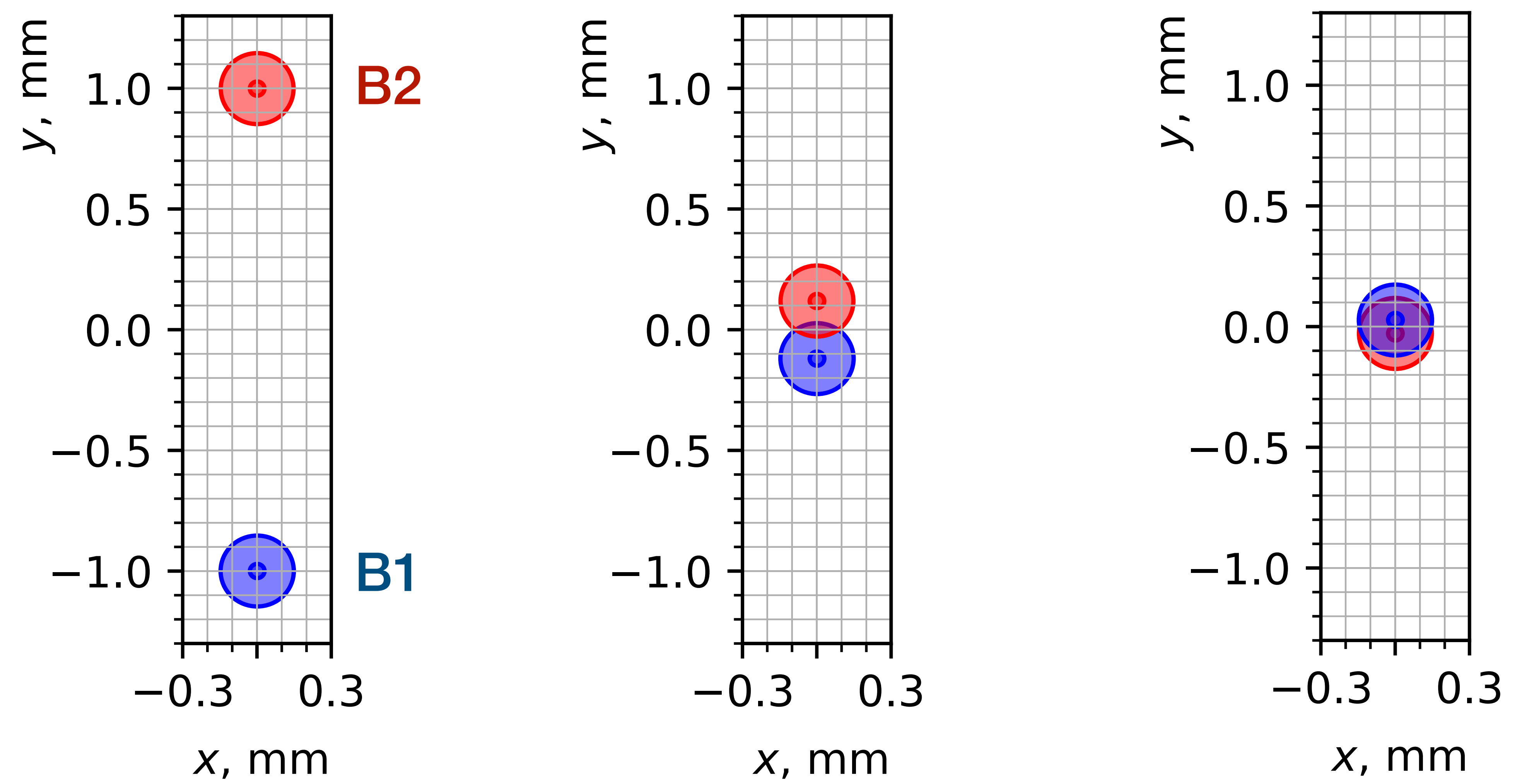
Max. flux of protons hitting VELO: ~1.5x10^6 p/s (~1.5x10^9 p/s for 10s)



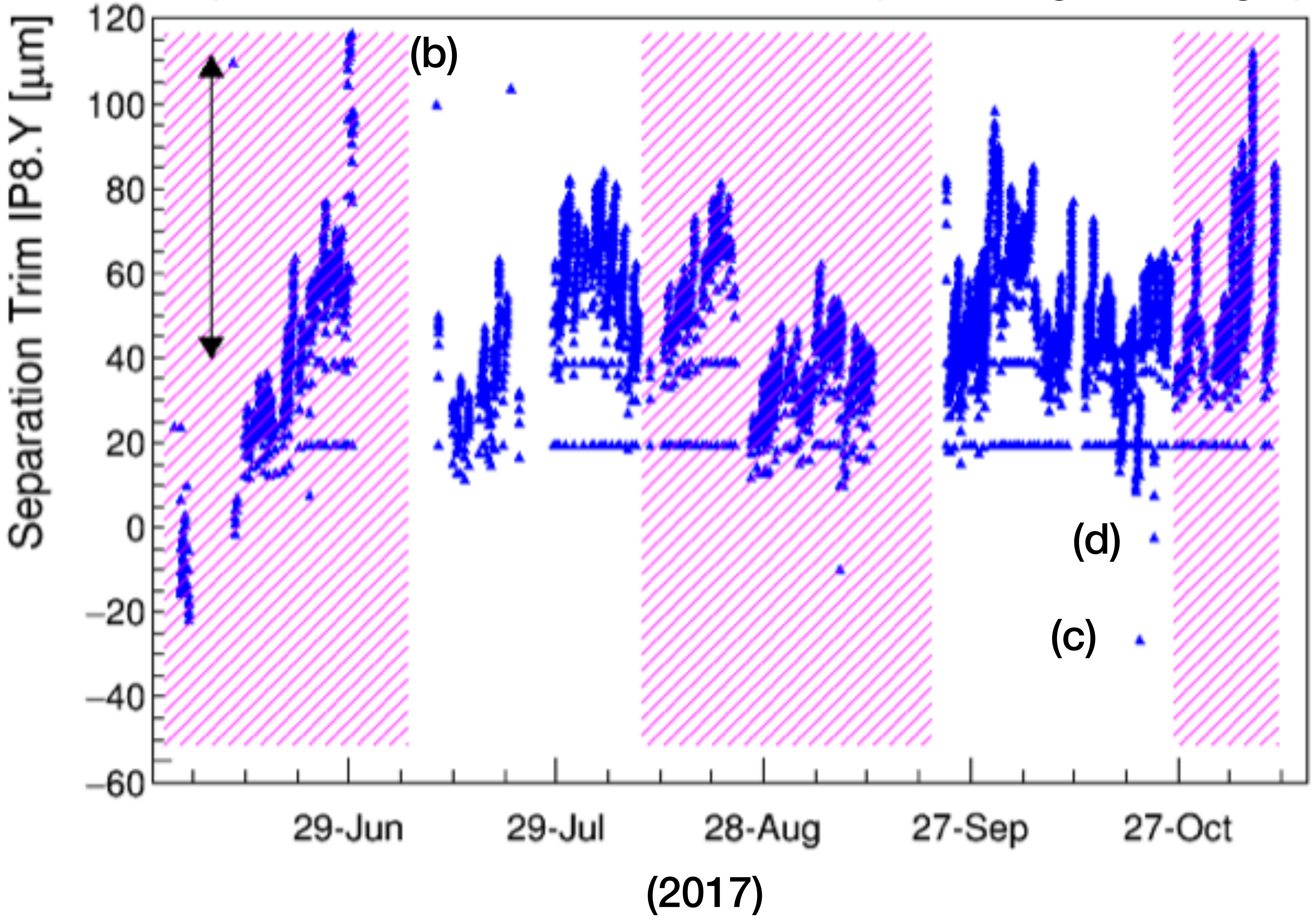
Dynamic changes during levelling

Dynamic changes during levelling

at IP8: a) End of Squeeze 1mm b) Max separation, 60μm c) Min separation, -13μm



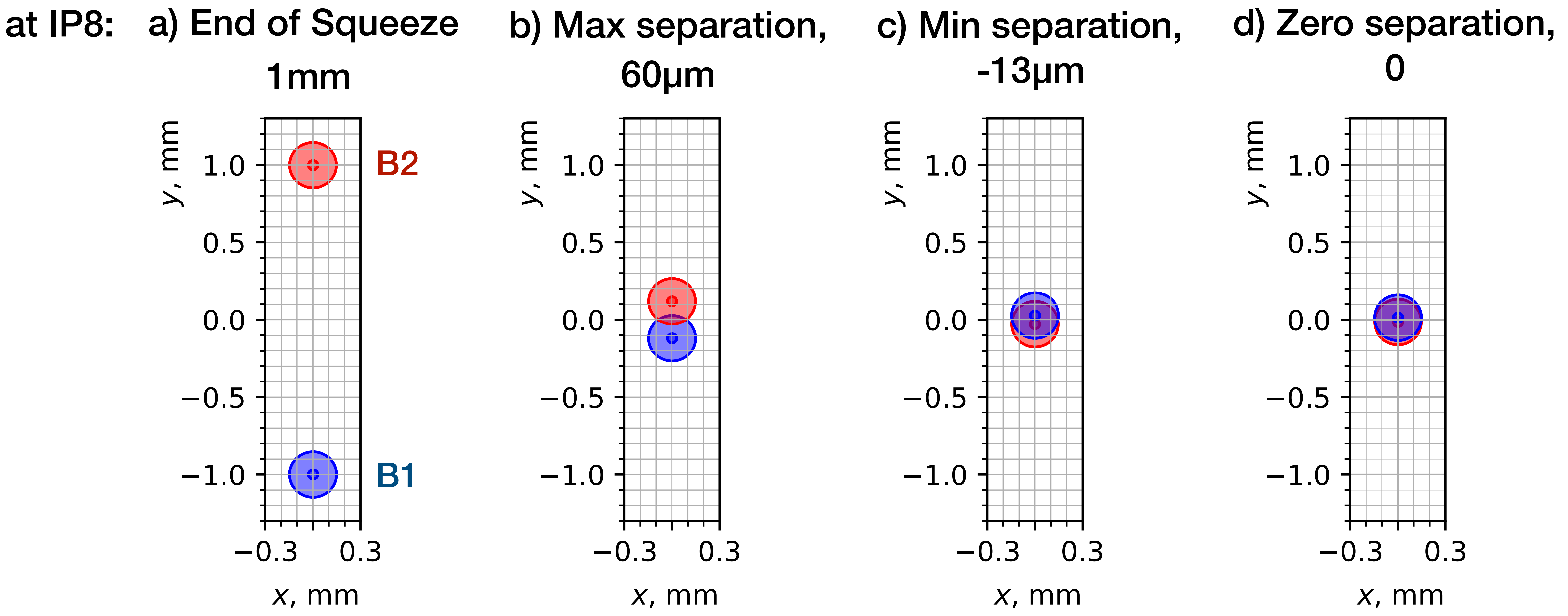
Sep = B1_trim — B2_trim (from Jorg Wenninger)

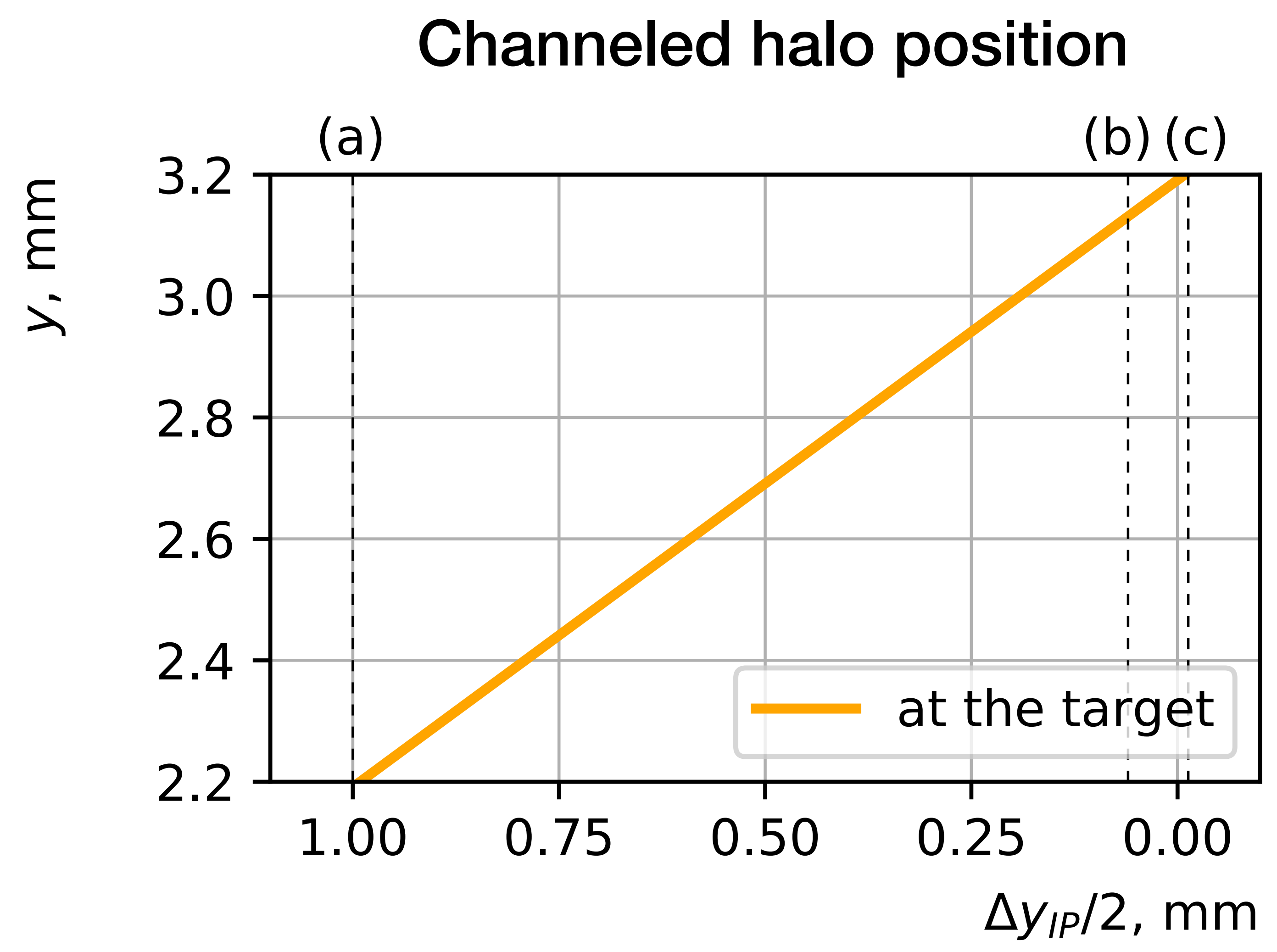


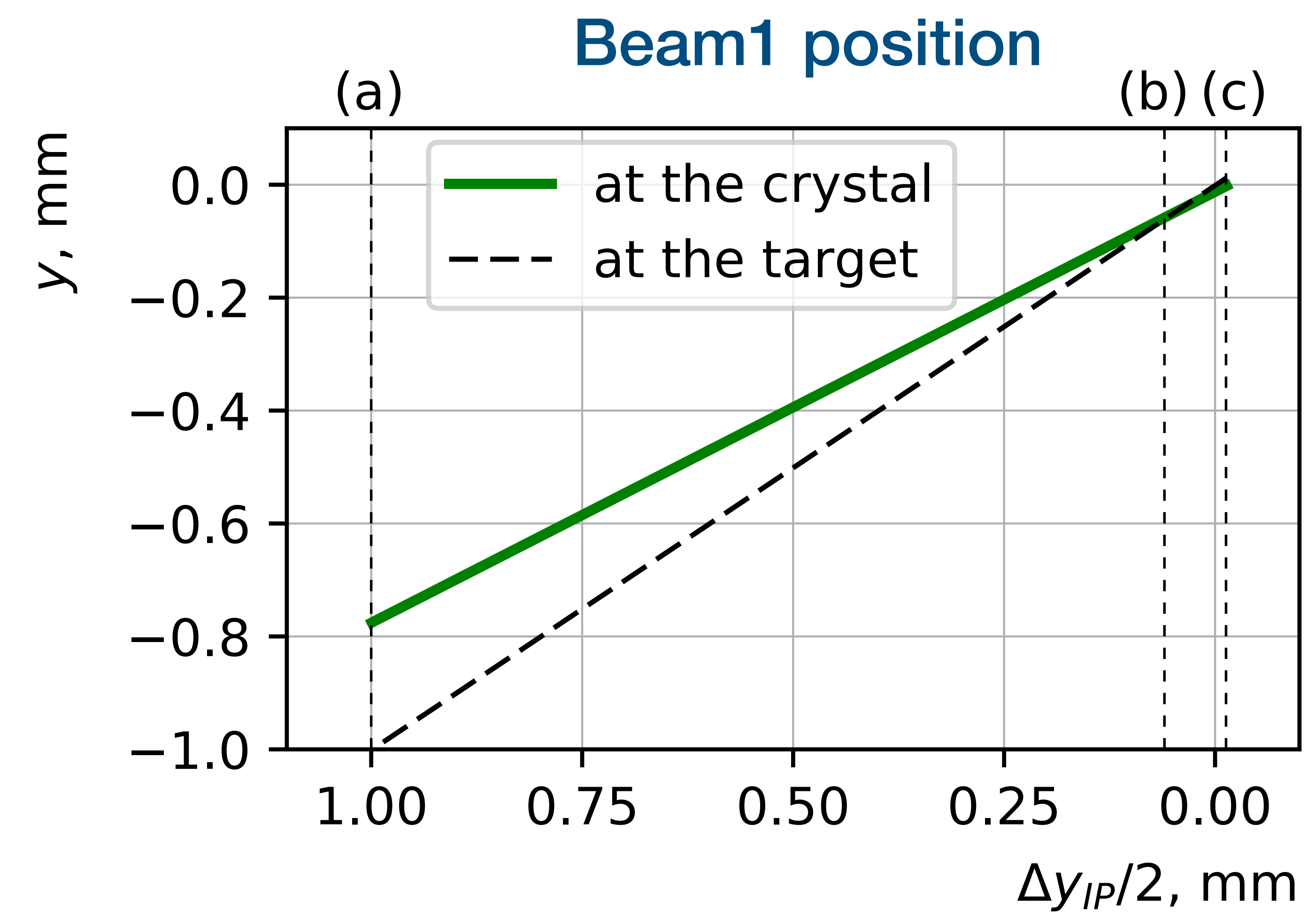
Beam separation, Δy_{IP} at the IP8		
	mm	σ (0.03 mm)
a) End of Squeeze	1.00	34
b) Max separation	0.06	2
d) Zero separation	0.0	0
displacement during levelling	0.06	2

- Optics of 2018 machine configuration at “Stable Beam”

Dynamic changes during levelling: beam and channeled halo displacements







Beam separation, Δy_{IP}			Beam 1 position, y			Deflected beam, y	
at the IP8			at the Crystal 1		at the Target		
	mm	σ (0.03 mm)	mm	σ (0.3 mm)	*mm*	mm	σ (0.04 mm)
a) End of Squeeze	1.00	34	-0.78	-2.62	*-1.00*	2.20	58
b) Max separation	0.06	2	-0.05	-0.16	*-0.06*	3.12	83
d) Zero separation	0.0	0	0.00	-0.01	*0*	3.20	85
displacement during levelling	**0.06**	**2**	**0.05**	**0.15**		**0.08**	**2**

- Optics of 2018 machine configuration at “Stable Beam”

Dynamic changes during levelling: Possible changes in the optics for Run III

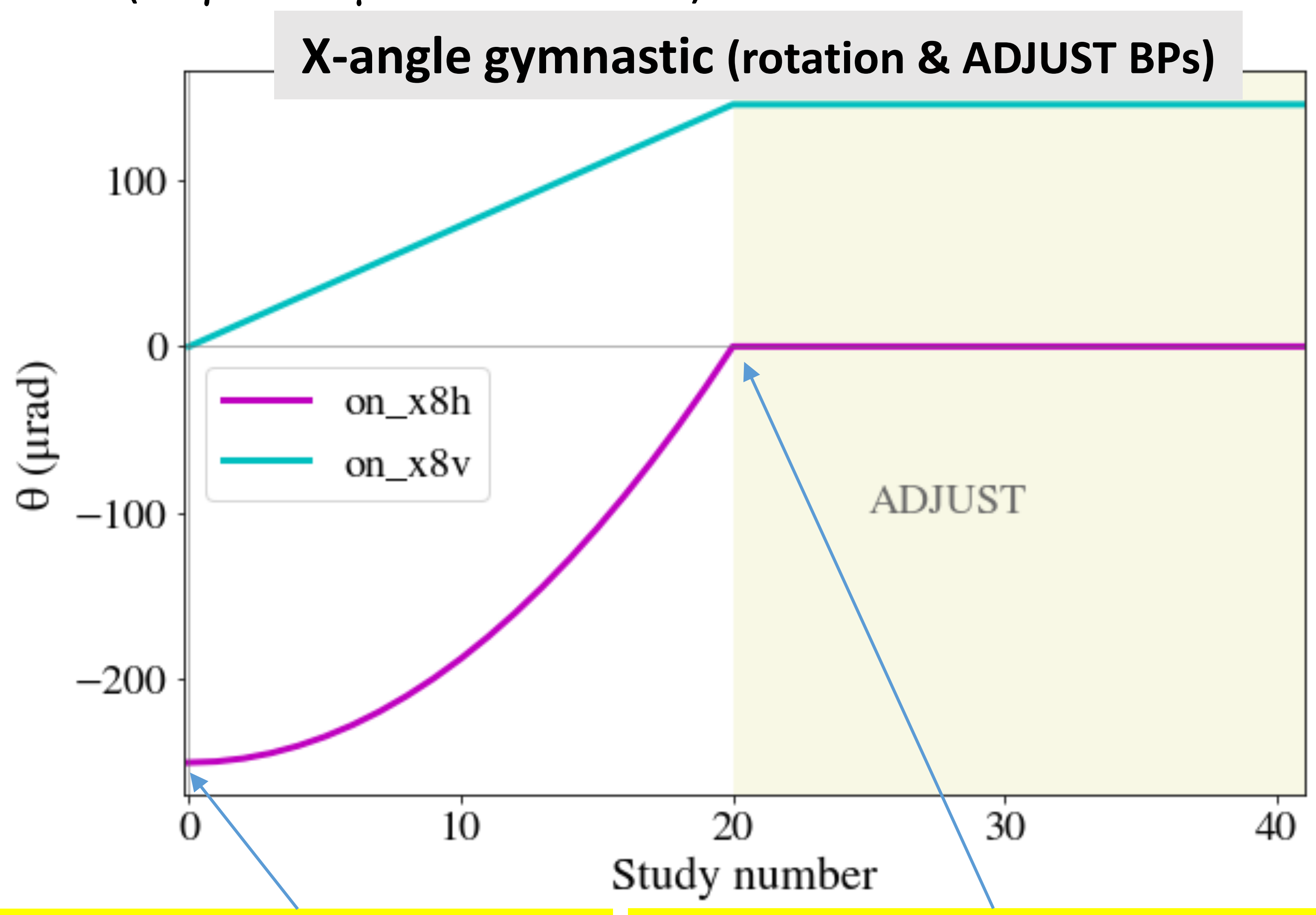
from presentation by S. Fartoukh at Special LHC Run 3 meeting

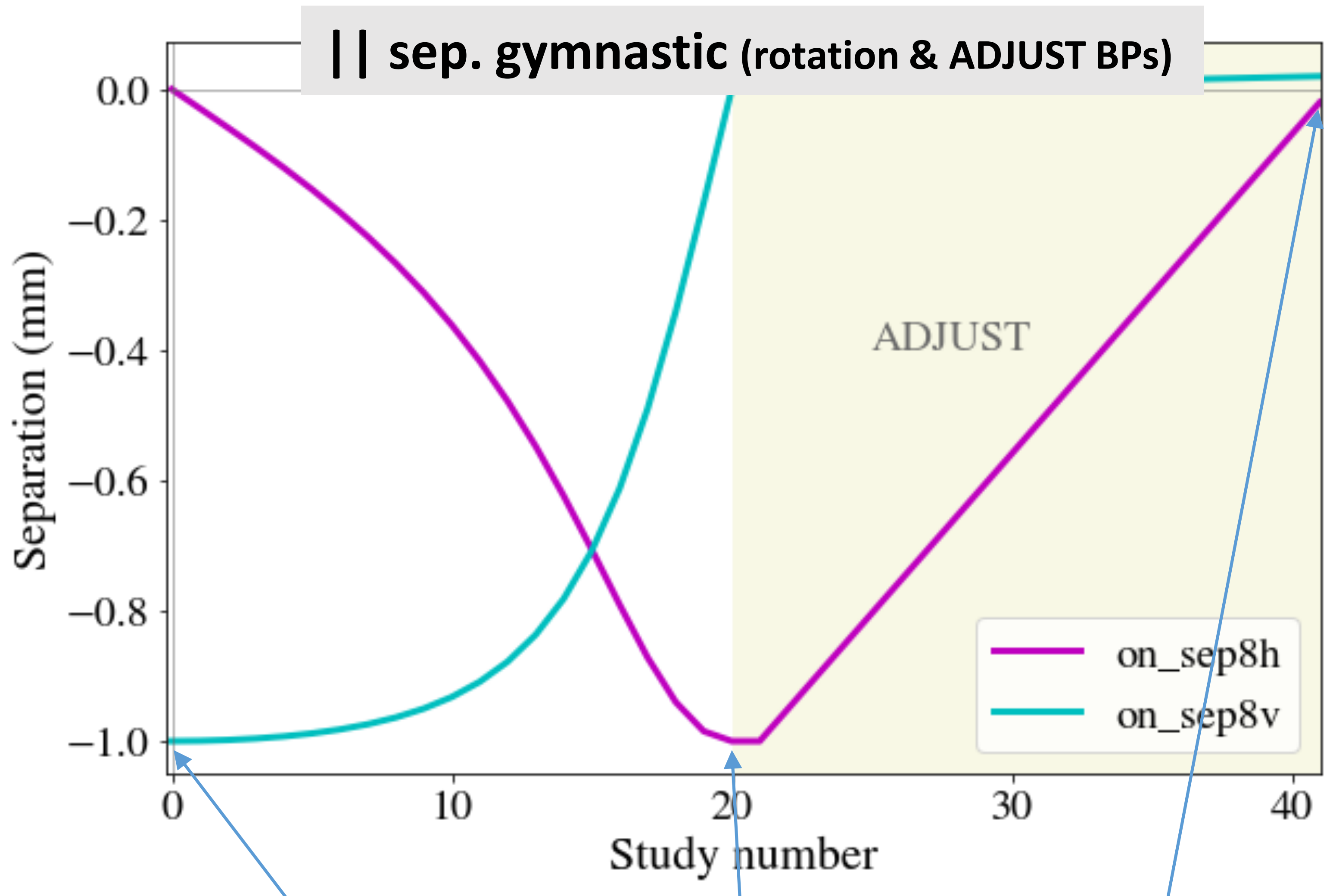
LHCb rotation

- Redundant request from LHCb (since 2012) to establish similar physics conditions regardless of the spectrometer polarity

→ **External V crossing**, i.e. collision at ~45° and ~135° depending on the spectro polarity for an external vertical X-angle of 135 μrad @ 7 TeV (145 μrad @ 7 TeV). An external V crossing also maximize the luminous region in collision

- Injection with a V crossing is NOT possible unless ramping the spectrometer
- Making the rotation during the ramp could be possible (towards flat top), but after gaining some experience
- An **"universal" rotation BP seems to exist, warranting a minimum bb sep of 13 σ at the worst BBLR during the rotation** (at γε=2.5 μrad and 7 TeV) → minimize re-validation steps after each polarity





EoR @ β^*=1.5 m at IP8 (with ΔQ=0.03) α_H= - 250 μrad & α_v =0

End of rotation α_H= 0 μrad & α_v =135 μrad (145 μrad @ 6.5 TeV)

EoR x^*= 0 & y^*=-1 mm

End of rotation x^*= -1 mm & y^* = 0 mm

End of adjust x^*= +/- y^* ~ 0 mm

...cial LHC Run 3 meeting

- Optics for Run III are in preparation. If the LHCb request is maintained, offset will need to be studied.