French-Ukrainian Workshop — IJCLab, Orsay, France

October 27-29, 2021

Feasibility of measuring the electromagnetic moments of Λc at the LHC

Alex Fomin

NSC Kharkiv Institute of Physics and Technology (KIPT), Kharkiv, Ukraine

CERN, Geneva, Switzerland

contributed by:

S. Barsuk (IJCLab), O.A. Bezshyyko (KNU), L. Burmistrov (IJCLab), G. Calderini (LPNHE), S.P. Fomin (KIPT, KhNU), Yu. Ivanov (PNPI), I.V. Kirillin (KIPT, KhNU), A.Yu. Korchin (KIPT, KhNU), V.A. Kovalchuk (KIPT, KhNU), E. Kou (IJCLab), M. Liul (LAL, KhNU), L. Massacrier (IPN), D.Mirarchi (CERN), A. Natochii (LAL, KNU), E. Niel (IJCLab), S. Redaelli (CERN), P. Robbe (IJCLab), W. Scandale (CERN), N.F. Shul'ga (KIPT, KhNU), A. Stocchi (IJCLab)

Outline

Introduction

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

Optimal crystal orientation for EDM measurement

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

Performance assessment of layouts in IR3 and IR8 of LHC

- Double crystal layouts at LHC [3,4]
- Precision of measurement [1]
- Possible improvements [1,3]

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

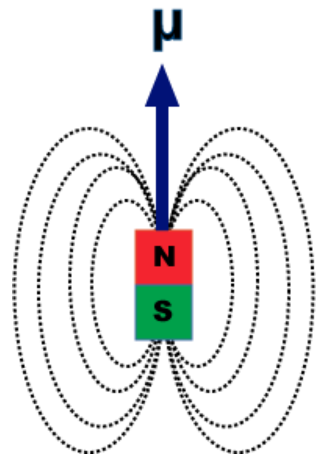
[2] A.S. Fomin, JHEP 08 (2017) 120

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

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

Electromagnetic moments of baryons

Magnetic Dipole Moment:



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

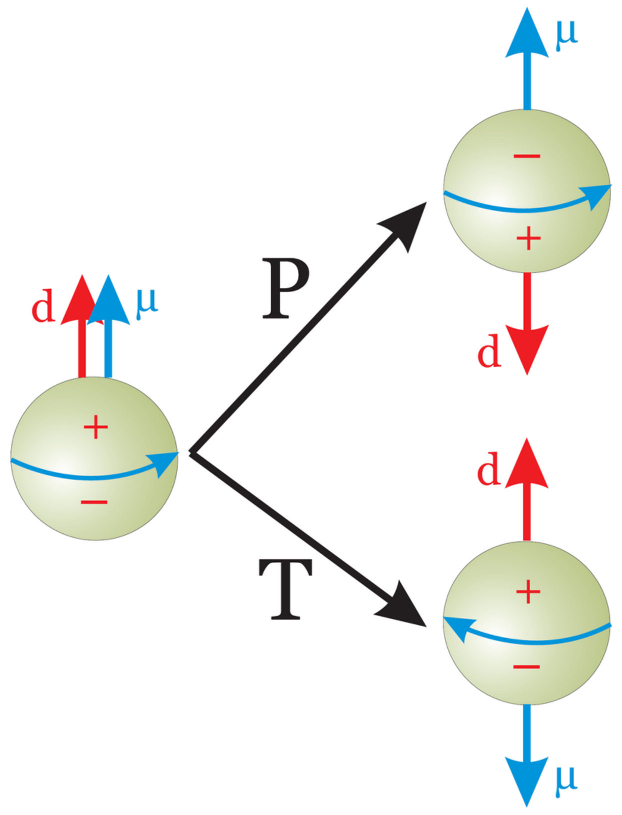
$|g| = 2$ → a point-like Dirac particle

$|g| \approx 2$ → 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 $(1.2)_{stat}$ $(1.0)_{syst}$	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:



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

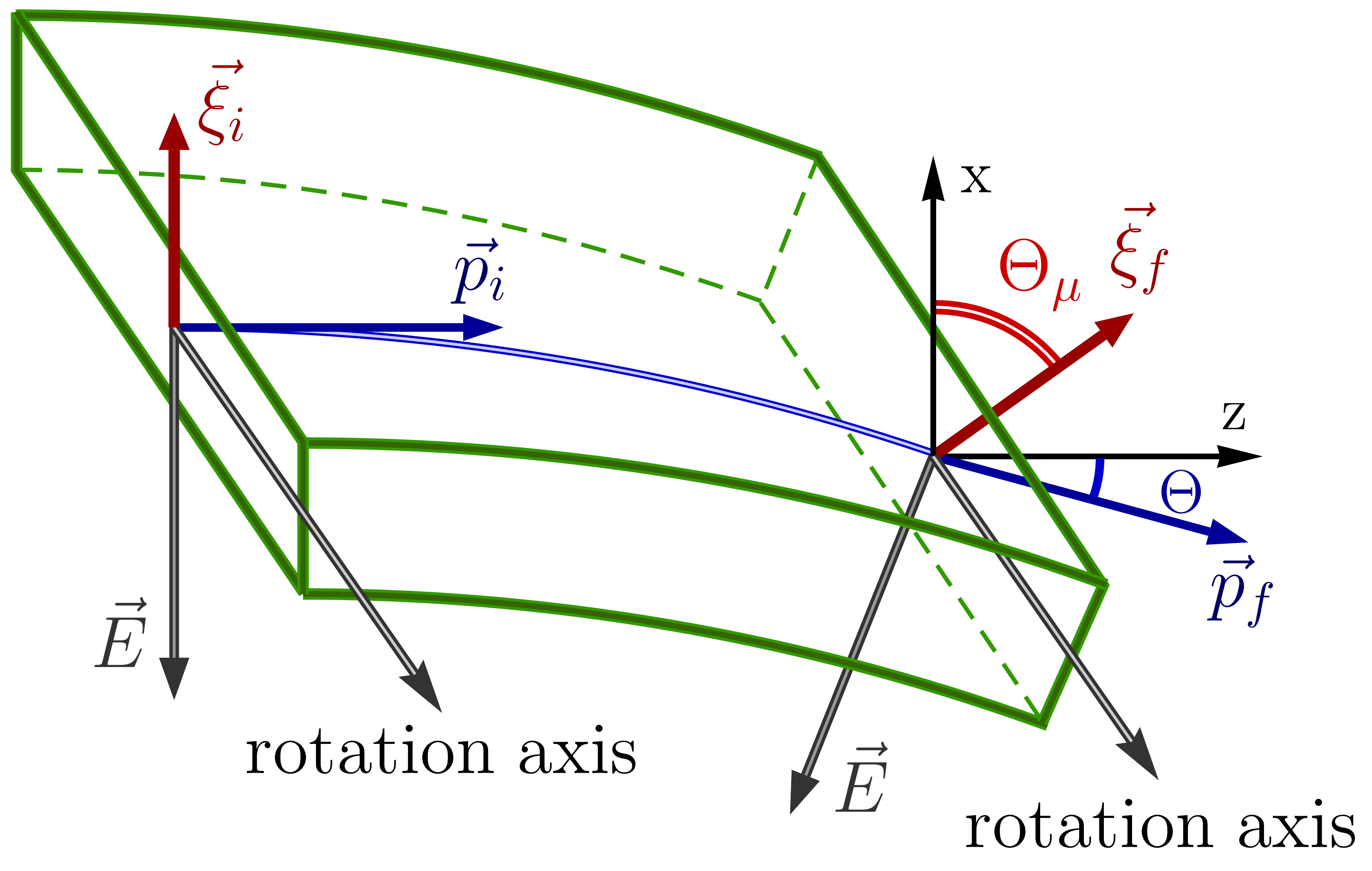
A nonzero value is forbidden by both:
T invariance and P invariance.

Particle	$\|\delta\|$, 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

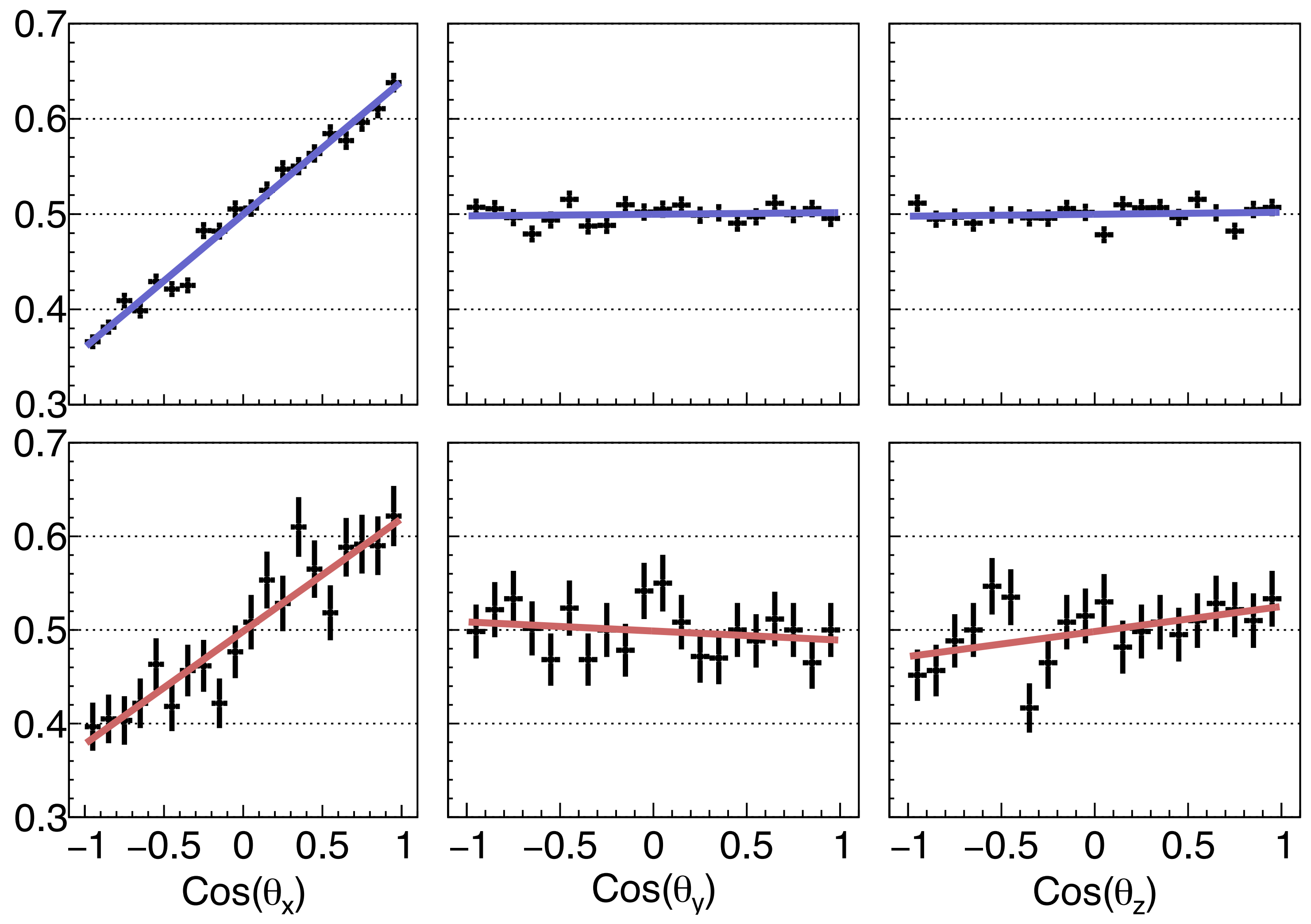
$\Theta,\ L,\ R$ – deflecting angle, length, curvature radius of the crystal

Initial Polarisation:

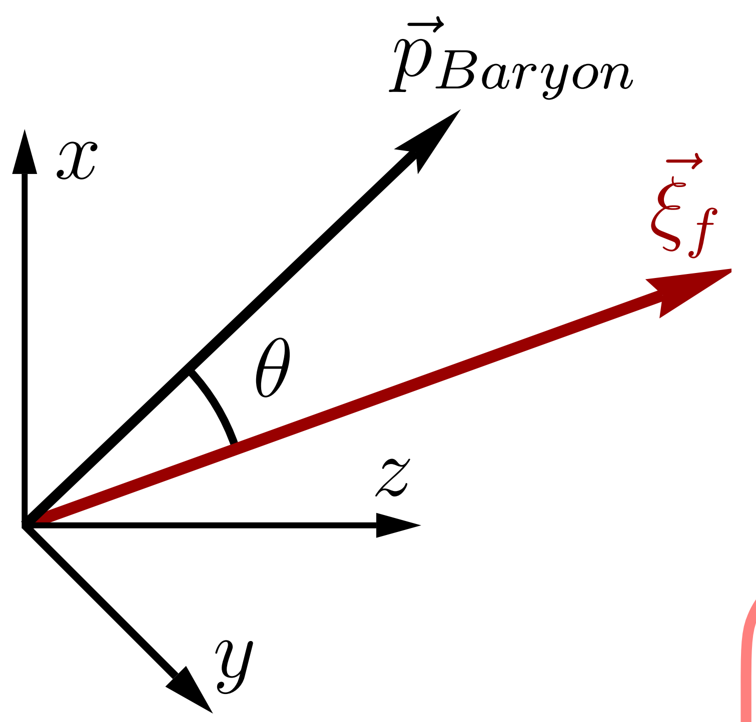
$$\vec{\xi}_i = \xi\,(\ 1\ ,\ 0\ ,\ 0\ )$$

Final polarisation

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



$$\Lambda_c^+ \to Meson + Baryon$$



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

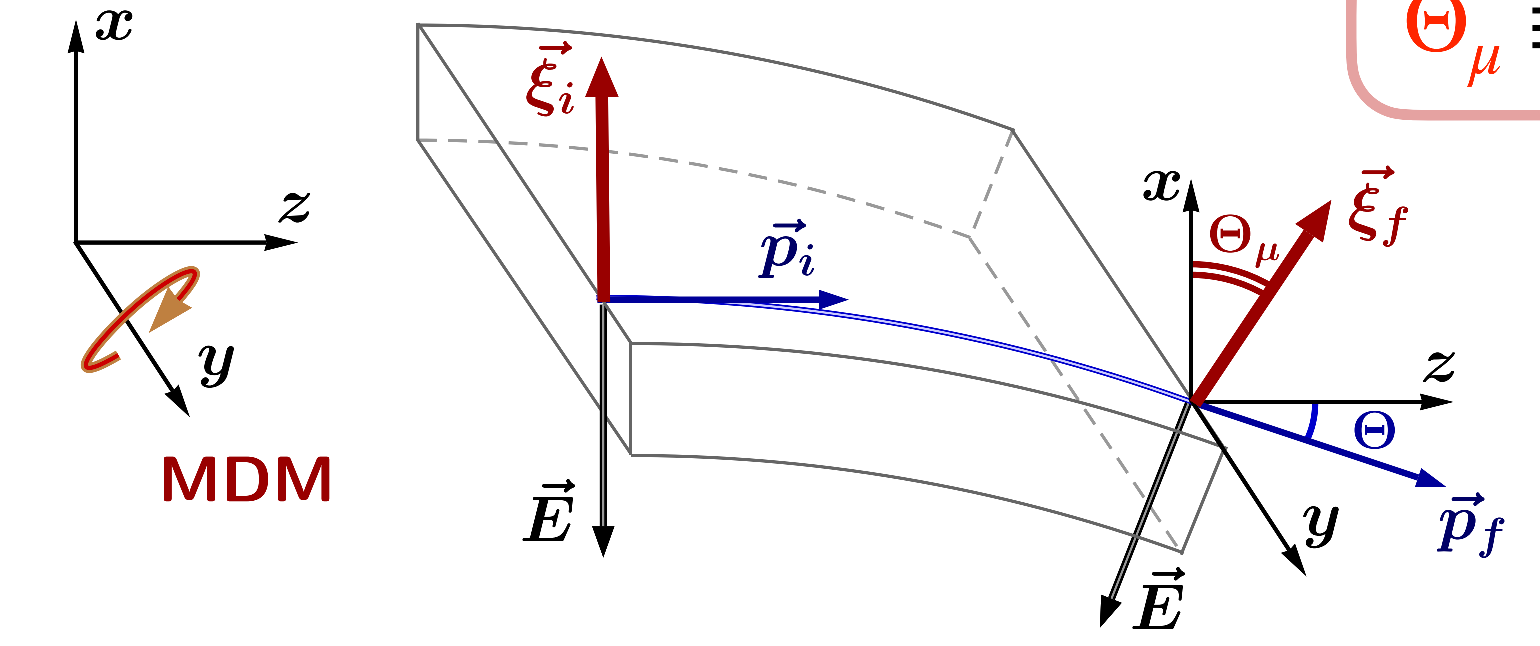
$$b \equiv \alpha\,\xi\,\Theta_\mu \qquad \Delta b = \sqrt{\frac{3}{N}}$$

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

Optimal crystal orientation for MDM and EDM measurements

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

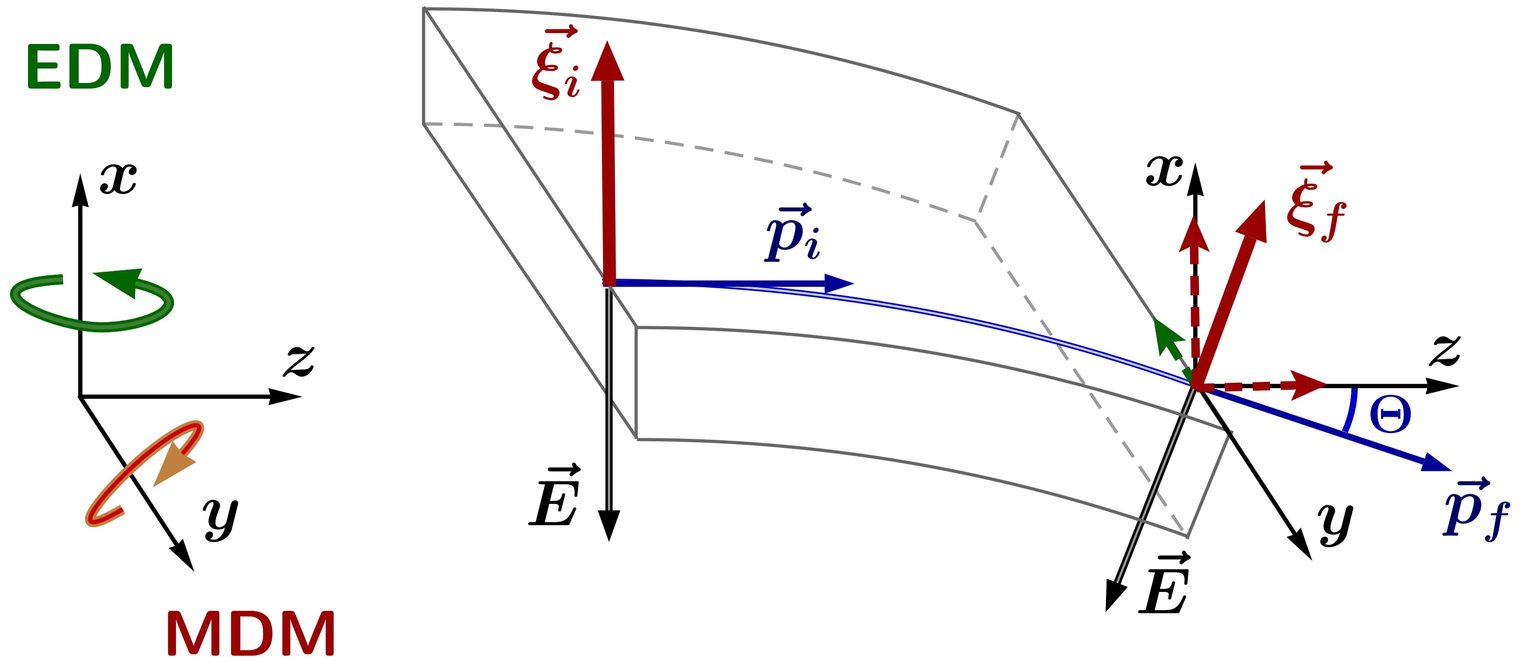
V.L. Lyuboshits,
Sov. J. Nucl. Phys. 31 (1980) 509
[inSPIRE].



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

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

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

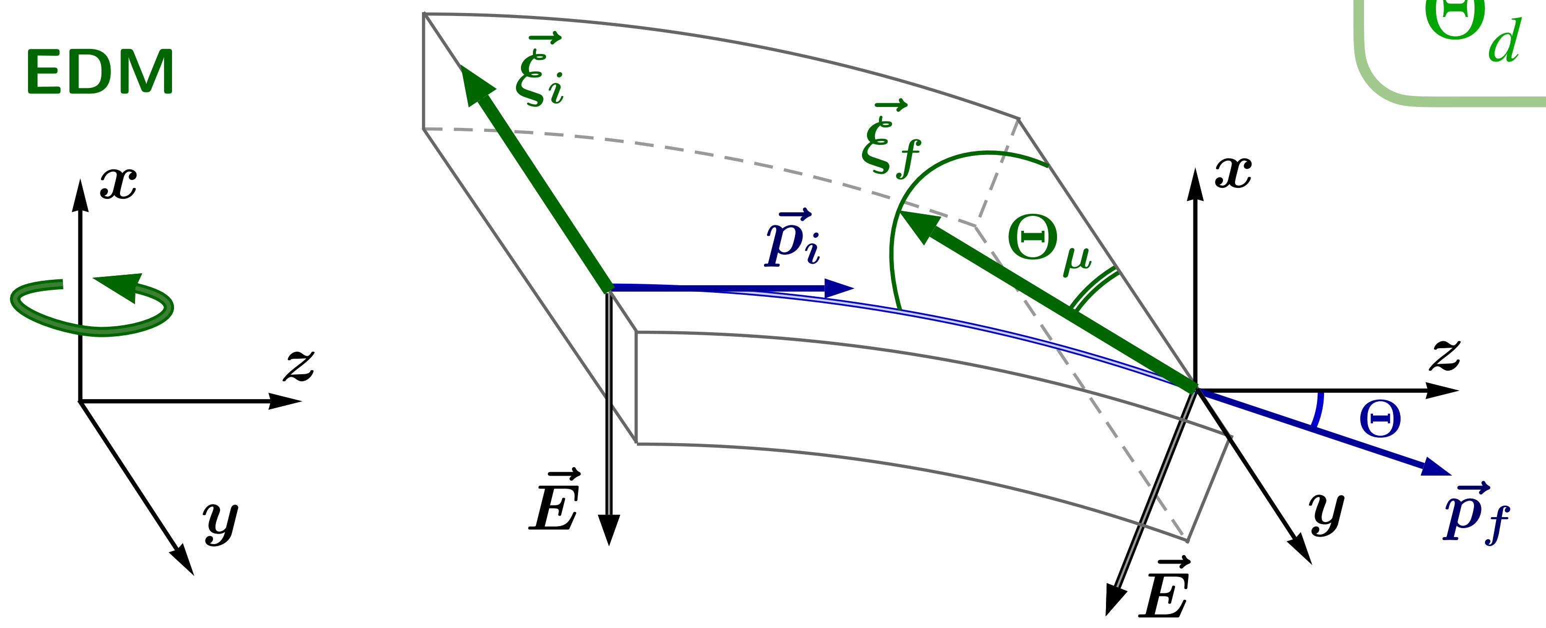


$$\frac{\Delta f}{\Delta g} = \frac{2\,\gamma a}{\Theta\,(1 + \gamma a)^2}$$

effect is suppressed by a small bending angle

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

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



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

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

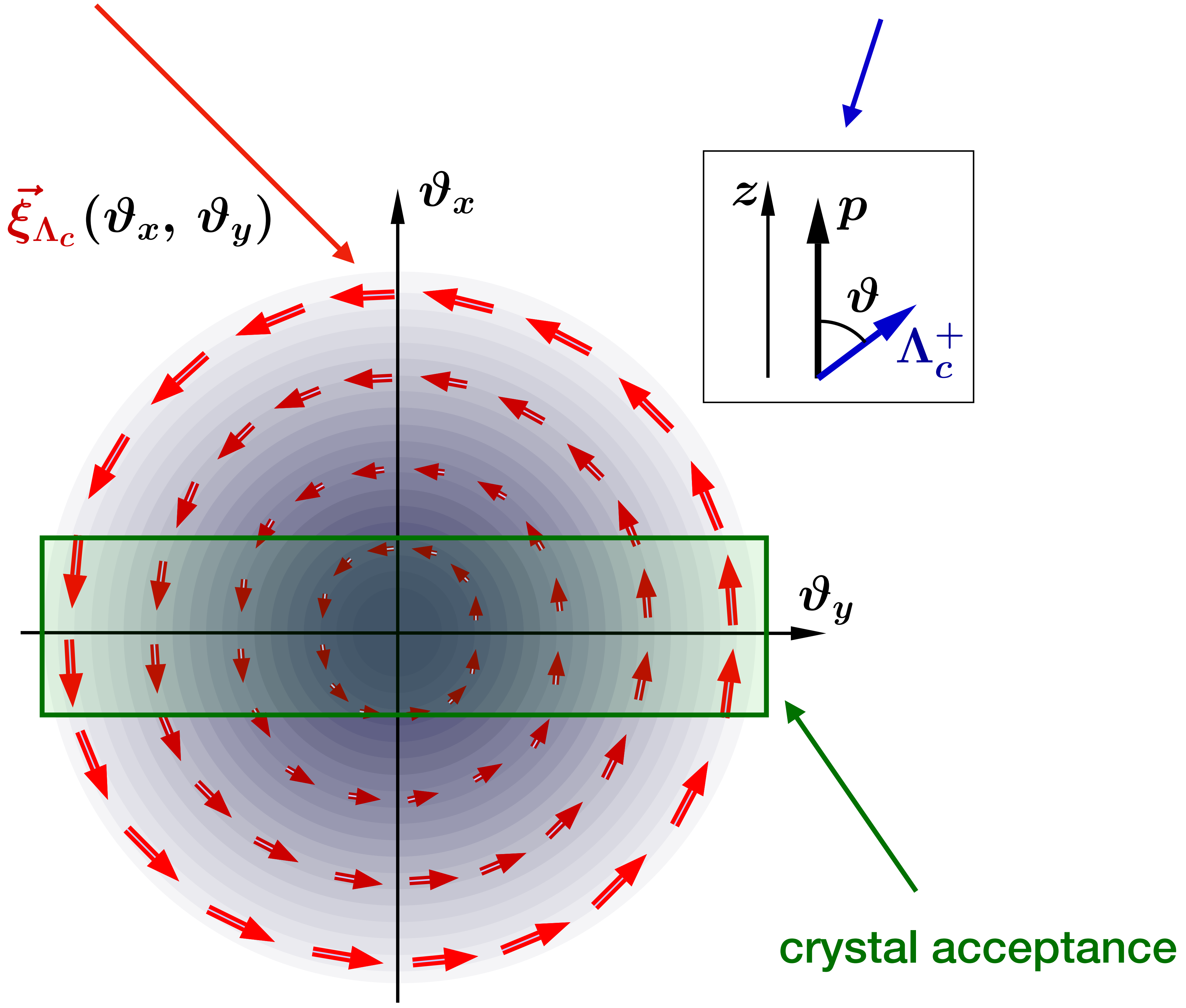
Optimal crystal orientation for EDM measurement: Initial polarisation

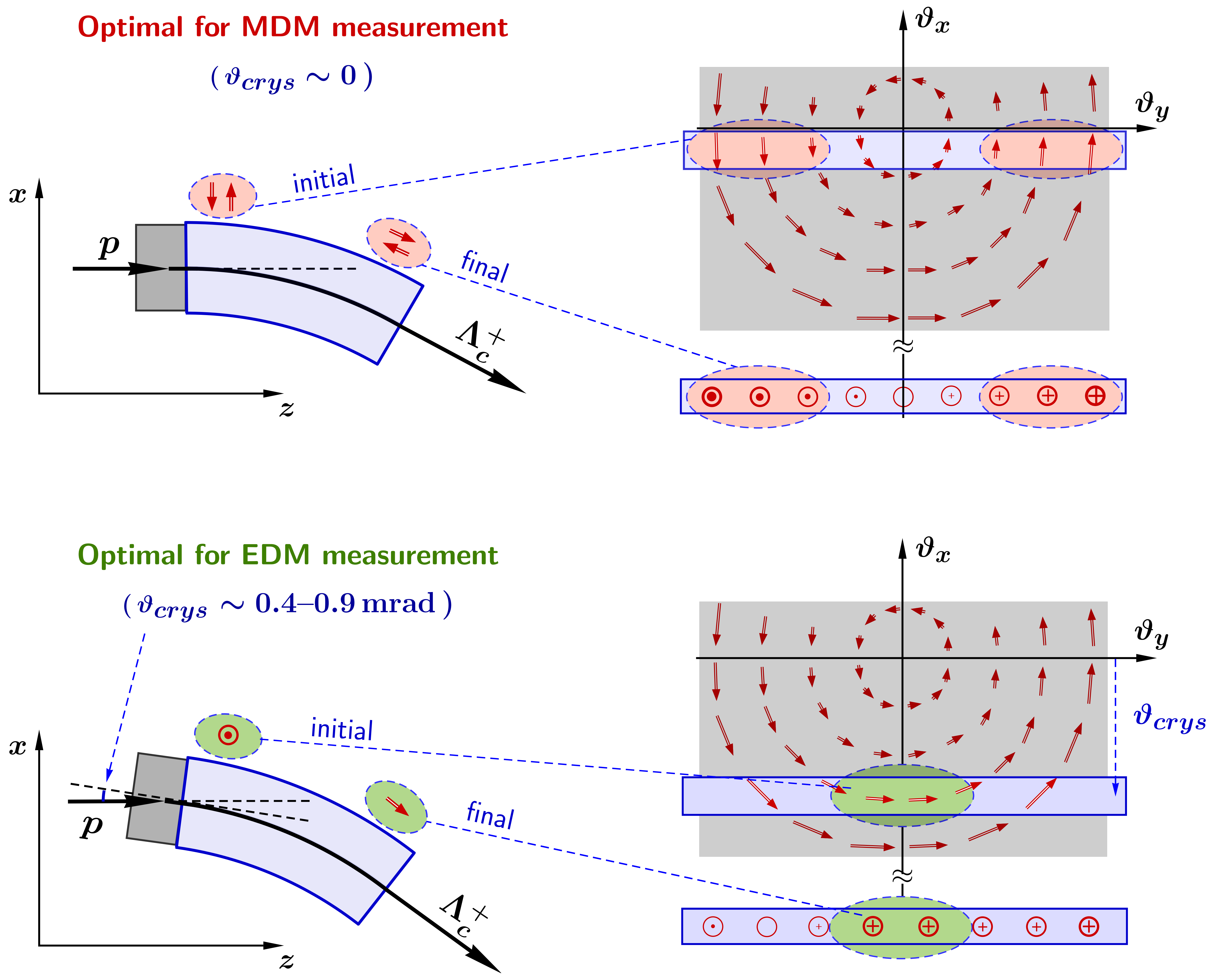
A. Fomin et al. Eur. Phys. J. C (2020) 80:358 [1909.04654]

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

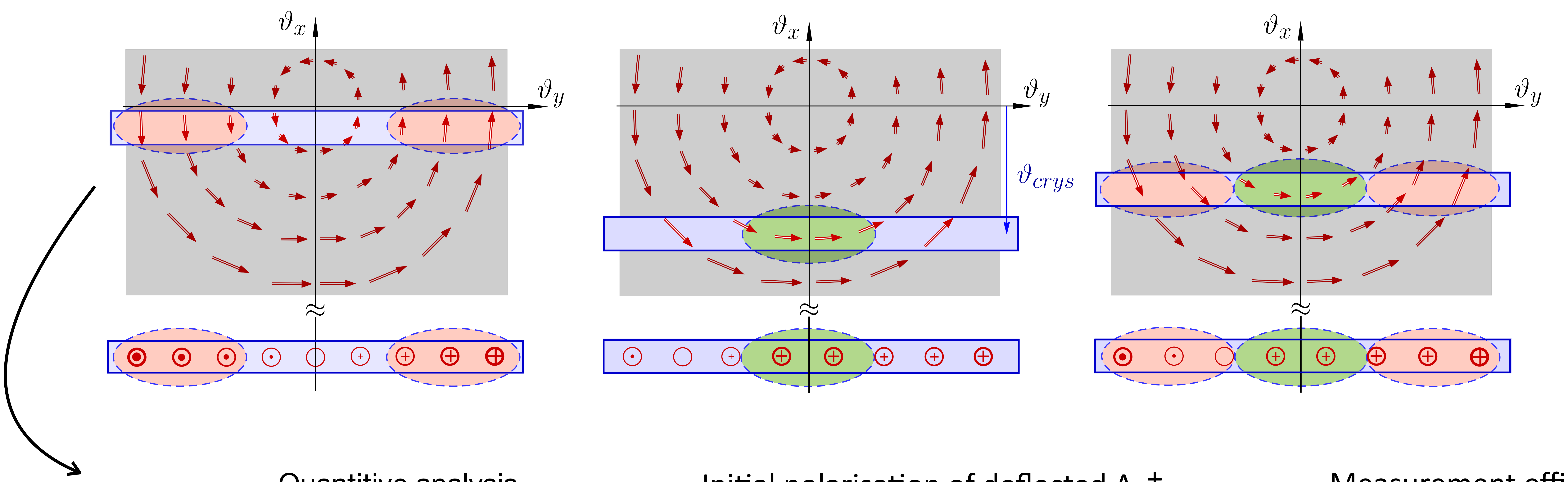
Due to the space-inversion symmetry of the strong interaction

Λ_c^+ polarisation is perpendicular to the reaction plane



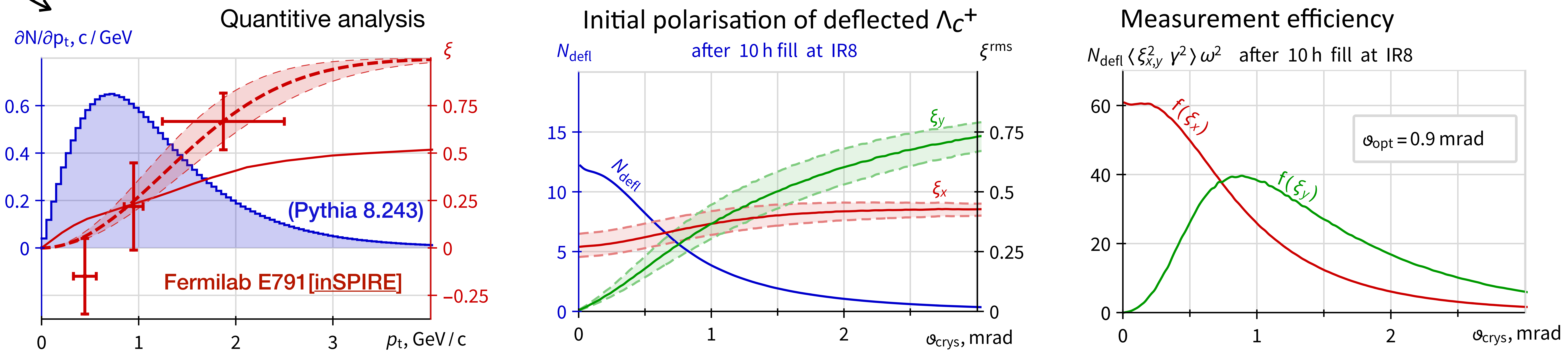


Optimal crystal orientation for EDM measurement: Quantitive analysis

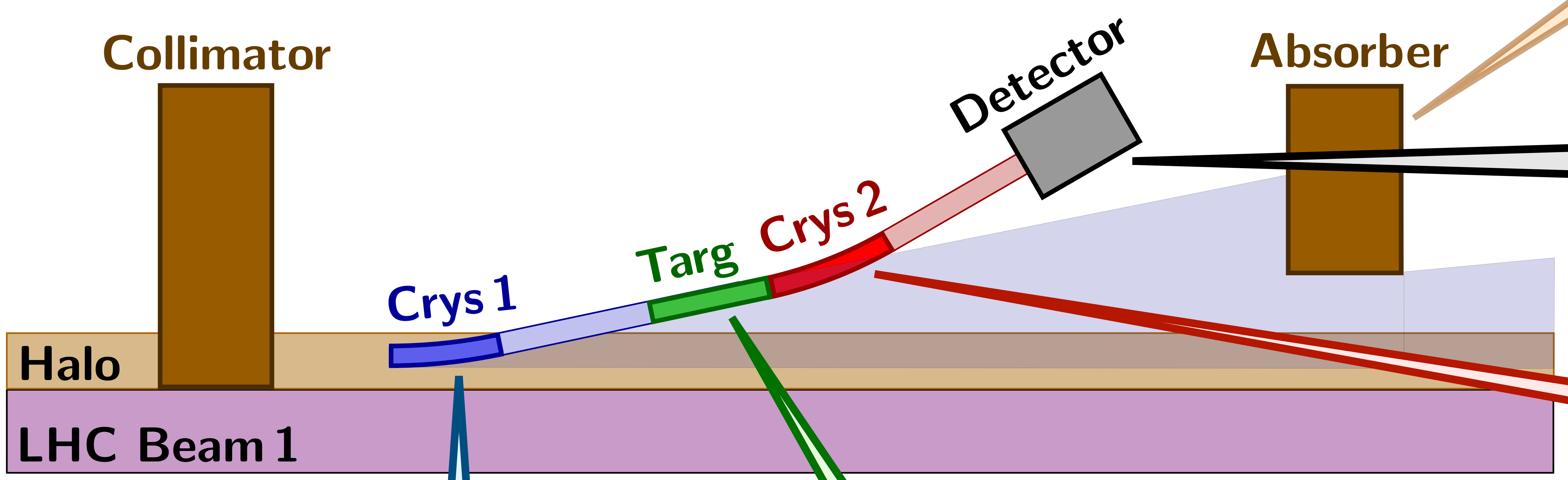


$$\Delta g = \frac{2}{\alpha \langle \xi_x \gamma \rangle \Theta} \sqrt{\frac{3}{N}}$$

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



- 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**.



Beam halo particles that do not interact with the Target+Crys2 assembly are intercepted by 4 double-sided LHC-type collimators

In the Detector the final polarisation of Λc is reconstructed from the distribution of decay products

The second Crystal deflects Λc with specific initial polarisation.

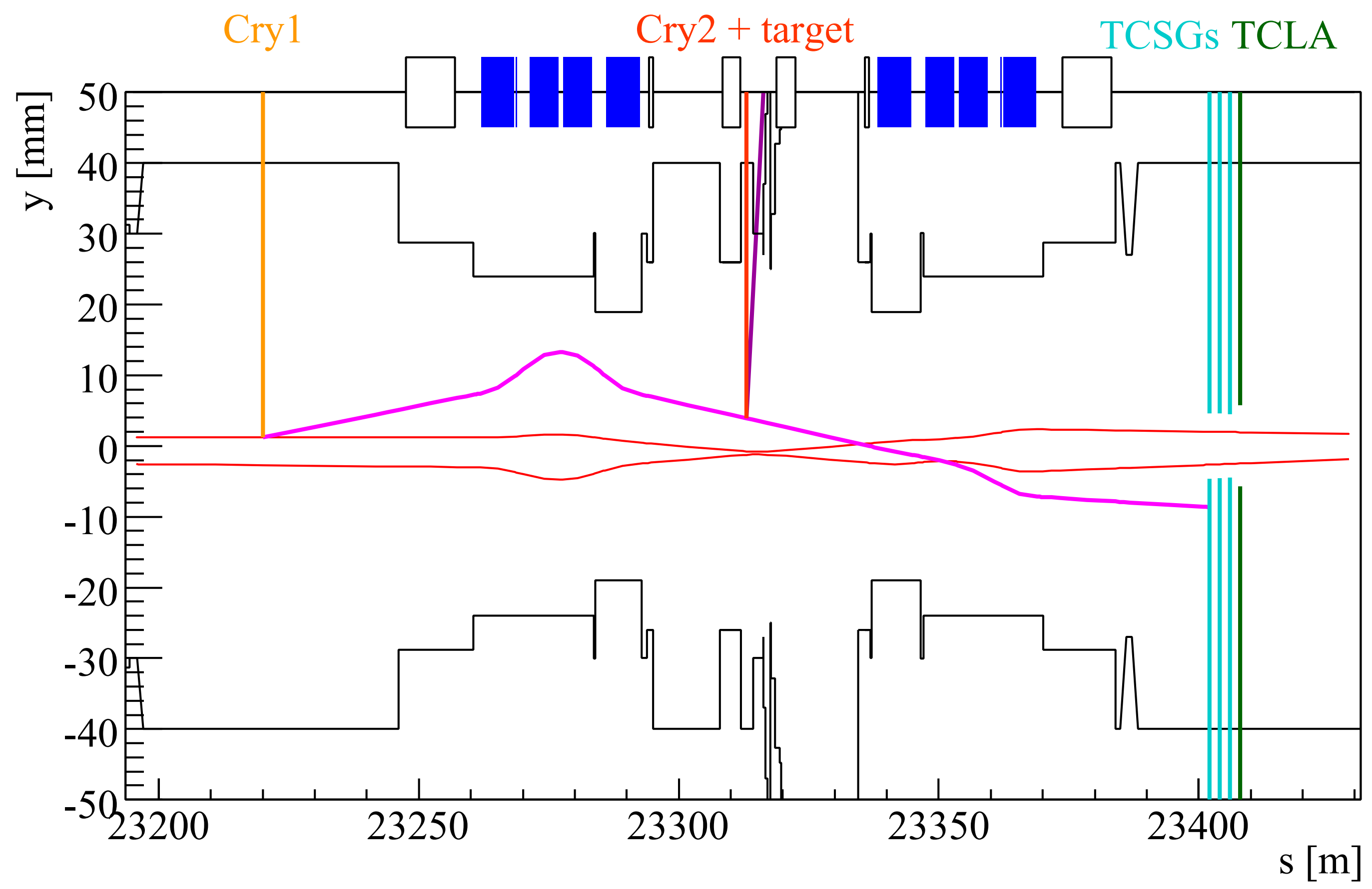
Λc spin precession in the electric field of crystal planes is proportional to MDM (or EDM)

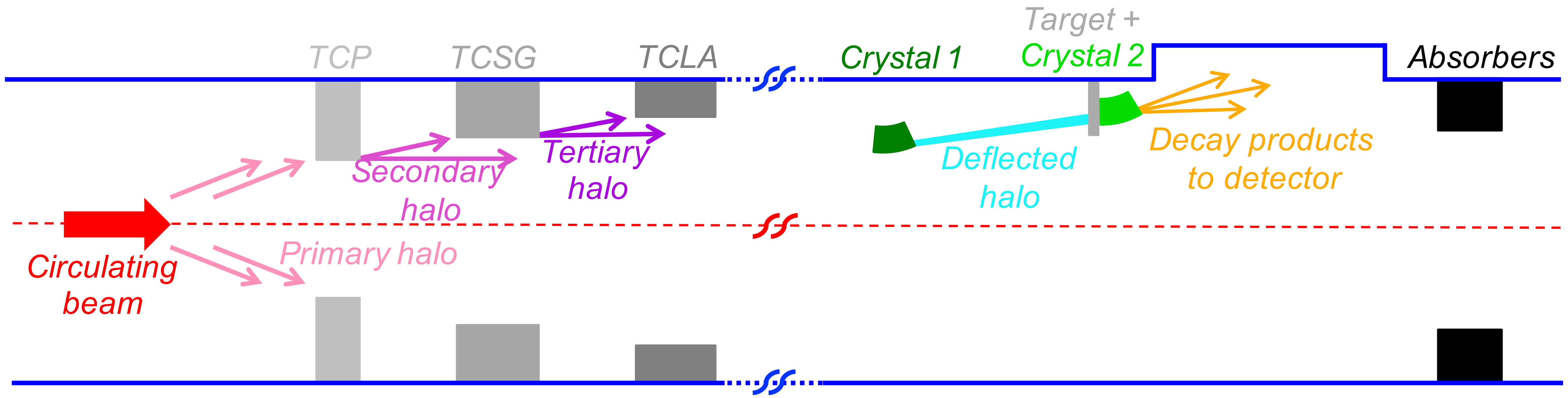
The first Crystal deflects protons from the LHC beam halo onto the Target

In the Target protons are converted to polarised Λc

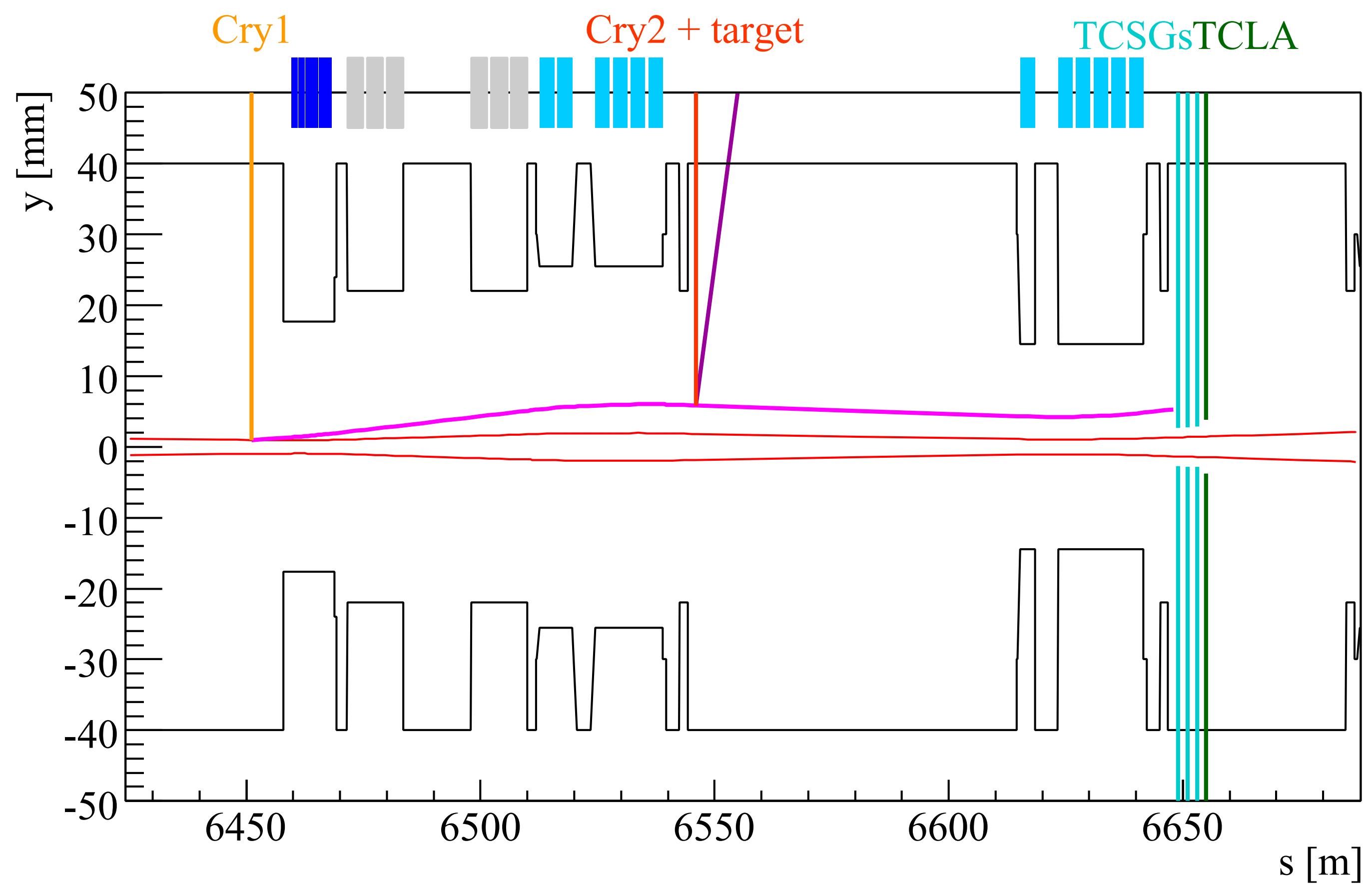
Performance assessment of layouts in IR3 and IR8 of LHC

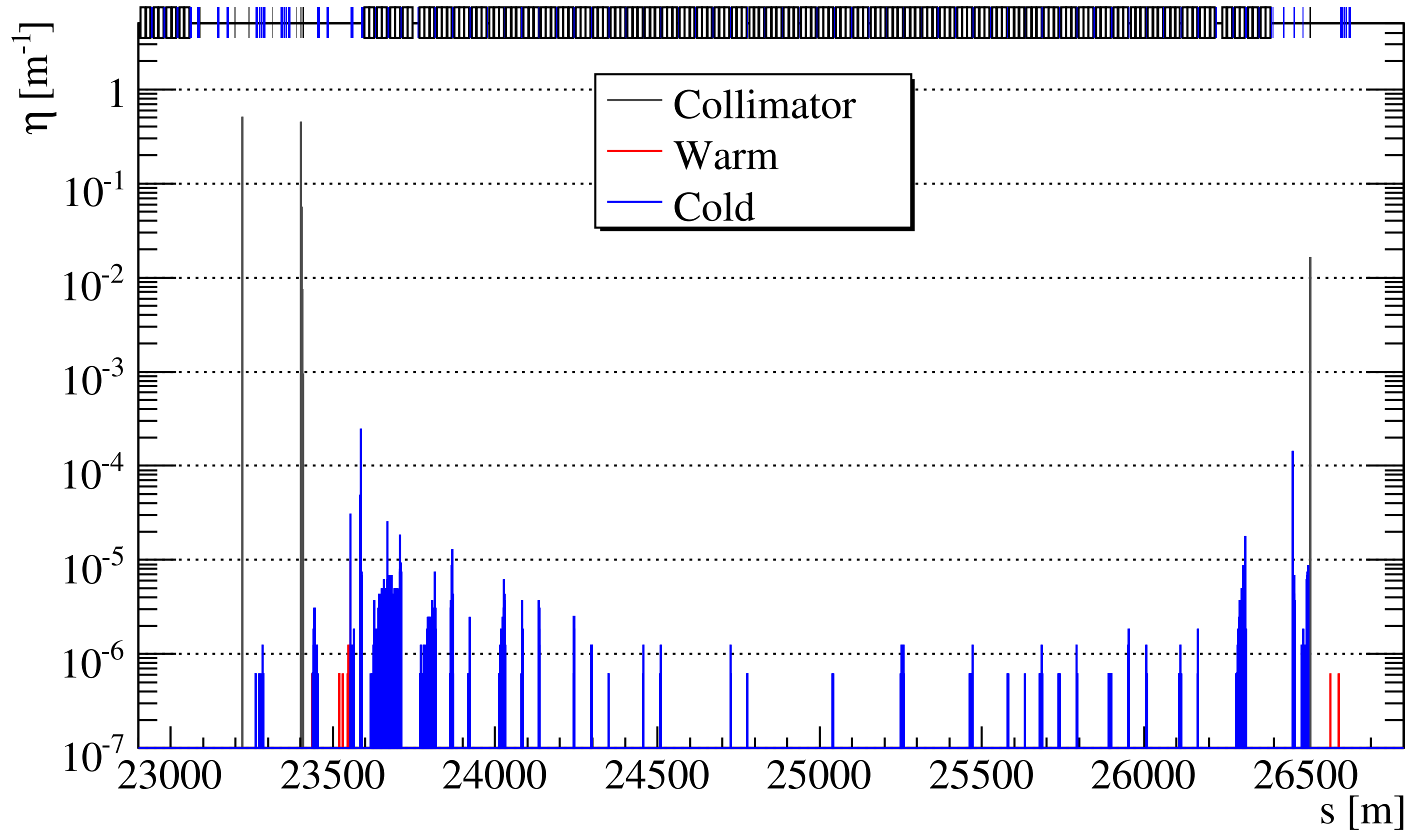
D. Mirarchi et al. Eur. Phys. J. C 80 (2020) 10, 929

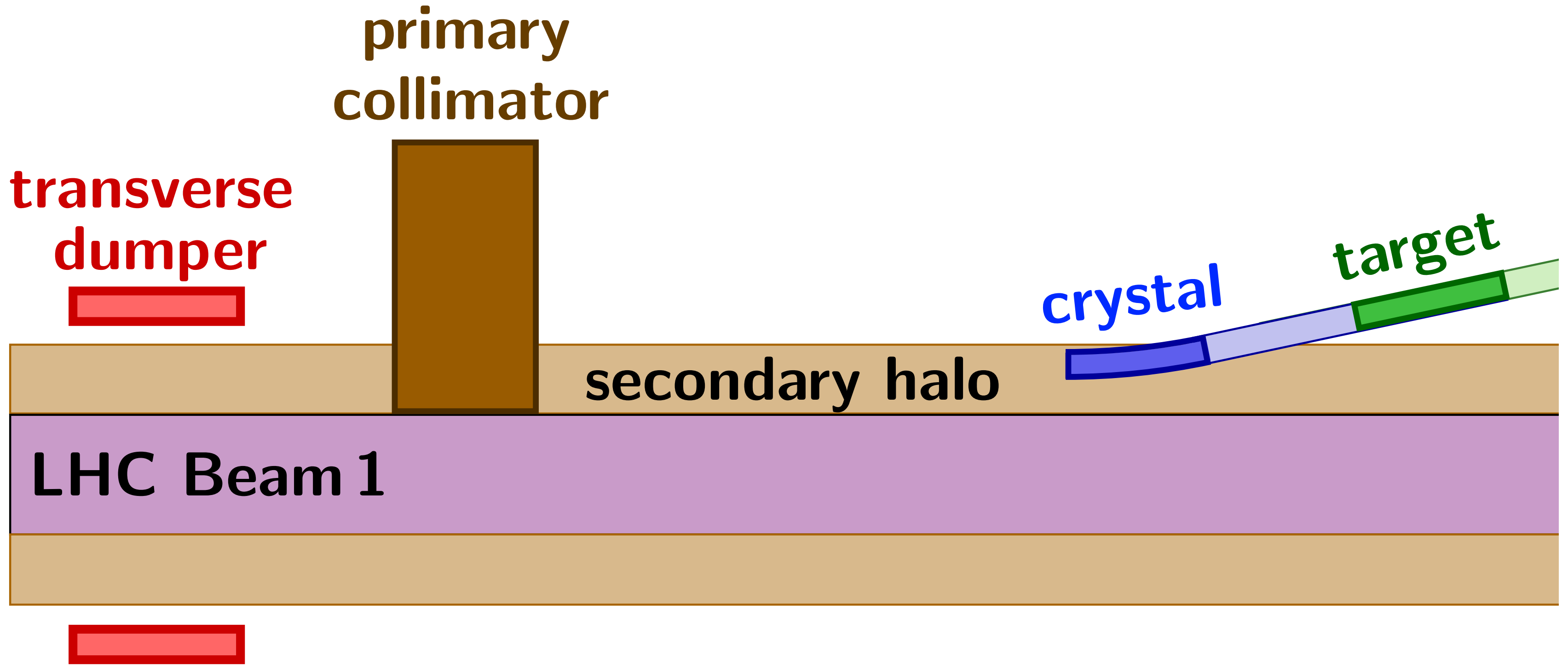




- impact on the machine
- optimisation of Crystal 1 and Absorbers positions
- running experiment in a parasitic mode
- layout in front of LHCb (IR8) **4.3×10^{10} POT/fill**
- alternative layout at IR3 **3.0×10^{10} POT/fill**
- restriction on Crystal 2 bending radius



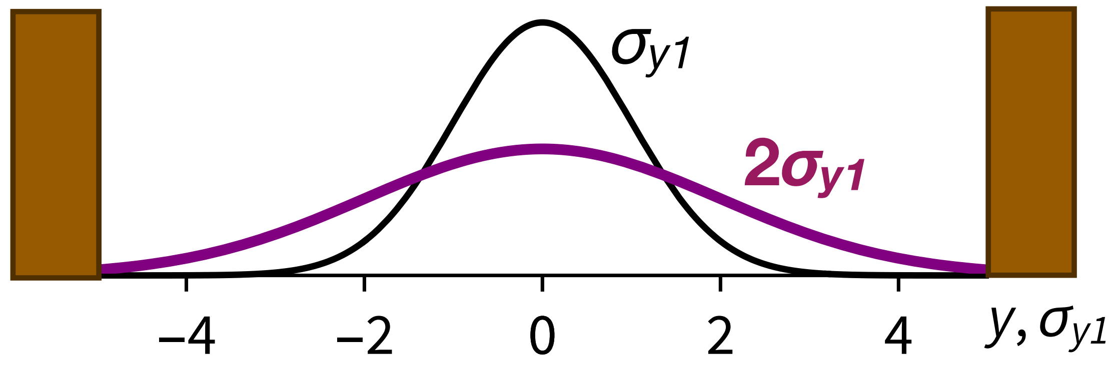




General idea

- apply random noise excitations with the **transverse damper** when a selected trains of bunches pass by

→ **emittance grow** of these bunches



→ increase the loss rate in **primary collimators** at IR7

→ enrich the **secondary halo** of the beam

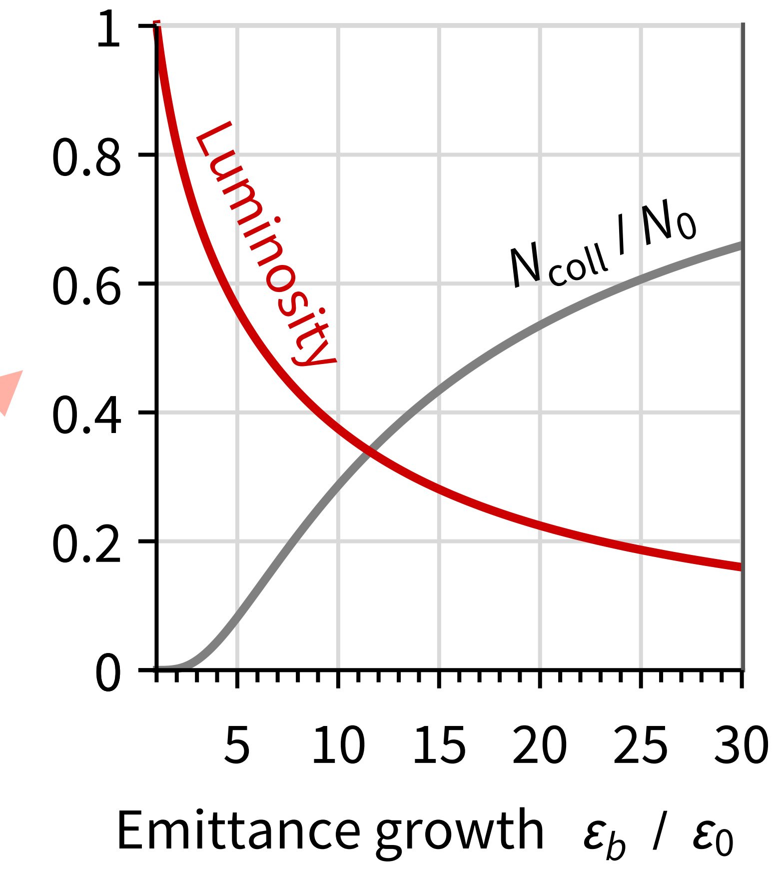
→ increase the flux on the **crystal** → increase the deliverable rates of **PoT**

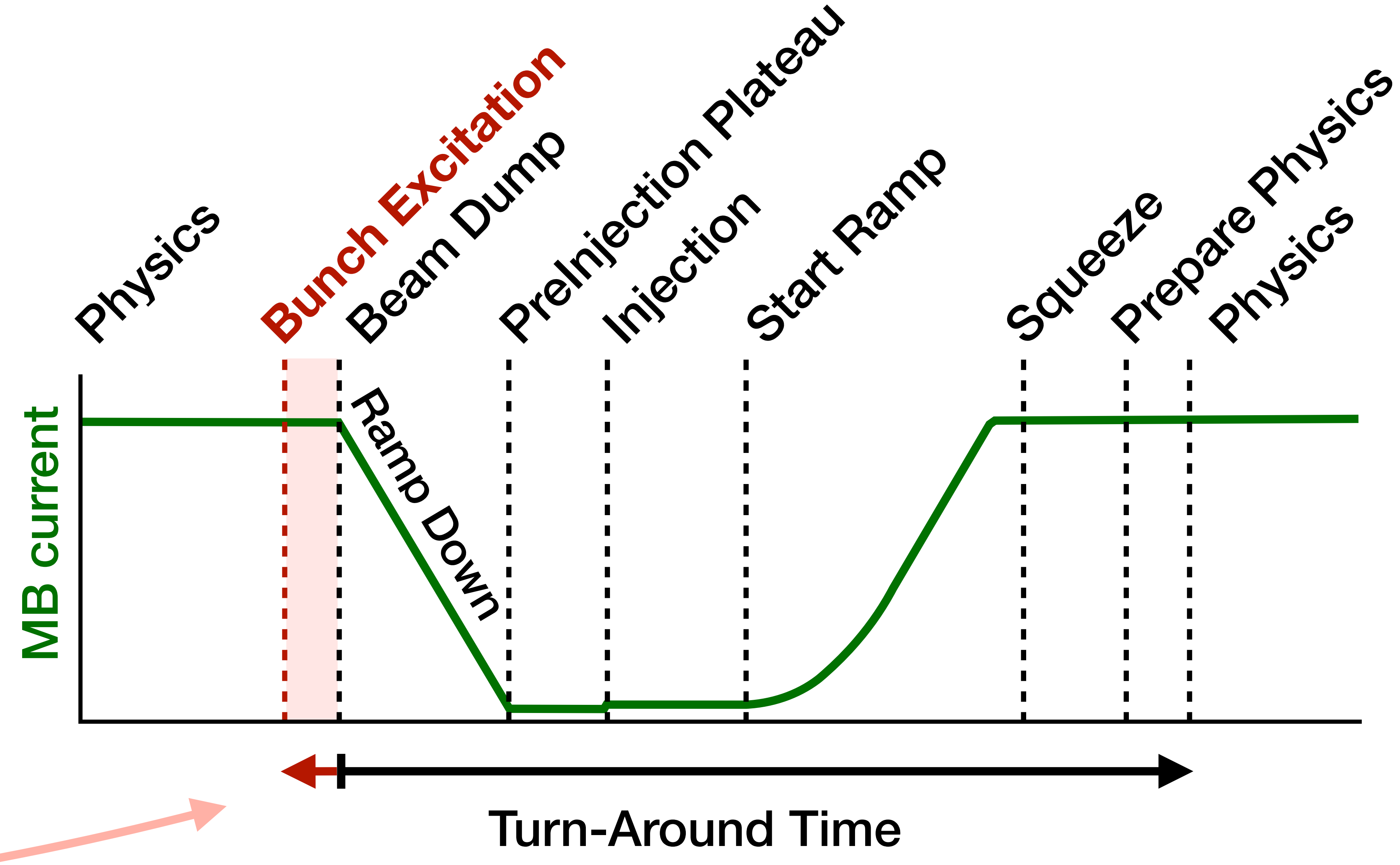
Transverse damper is currently used in LHC

- corrects the trajectory of the bunches during the fill
- increase the loss rate during alignment of collimators

Drawback — reduction of total luminosity

- excitation during the fill → higher emittance
- excitation before dumping → longer turn-around time





Maximum achievable PoT due to beam excitation (based on 2018 run data)

The **gain factor** in PoT from the beam excitation with respect to the “Baseline” (no excitation):

$$\eta_{\mathrm{exc}} = \frac{N_{\mathrm{PoT}}^{(\mathrm{ex})}}{N_{\mathrm{PoT}}^{(\mathrm{BL})}}$$

too high rates of PoT per bunch crossing (~49 @LHCb)

					200 kW in coll. system		3.5 p / bunch X @ LHCb		
					after collisions			after collis.	during collis.
Beam excitation	N_{coll}	N_{PoT} (IR3)	N_{PoT} (IR8)	η_{exc}	*t, h*	*ΔL / L*	t, h	ΔL / L	**ΔL / L**
No excitation (“Baseline”)	1.7×10^{15}	4.7×10^{12}	6.8×10^{12}	1	*1908*	*0*	1908	0	0
All fills (3–2556b) (no limit on Δt)	4.7×10^{15}	2.6×10^{13}	3.8×10^{13}	**5.6**	*8*	*> 0.4 %*	167	8.7 %	**2.9 %**
Selected fills (2556b), Δt < 1 hour	2.5×10^{15}	1.4×10^{13}	2.0×10^{13}	**3.0**	-	-	54	2.8 %	**1.2 %**

The most efficient scenario:

The gradual excitation of bunches (3.5 p/bunch X) at the end of the fills with 2556 bunches, with duration under 1 hour:

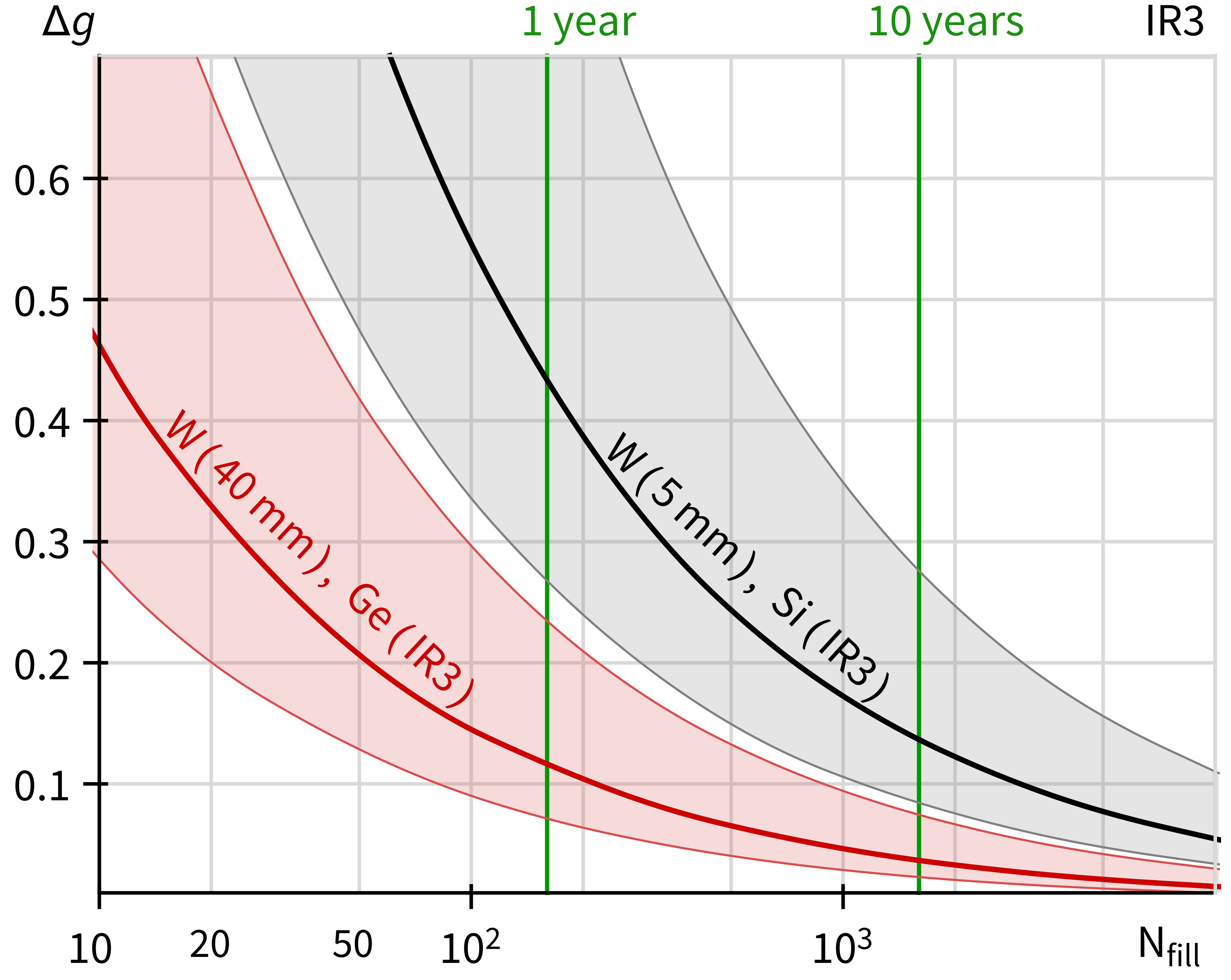
⇨ delivers **3 times more PoT** w.r.t. “Baseline”

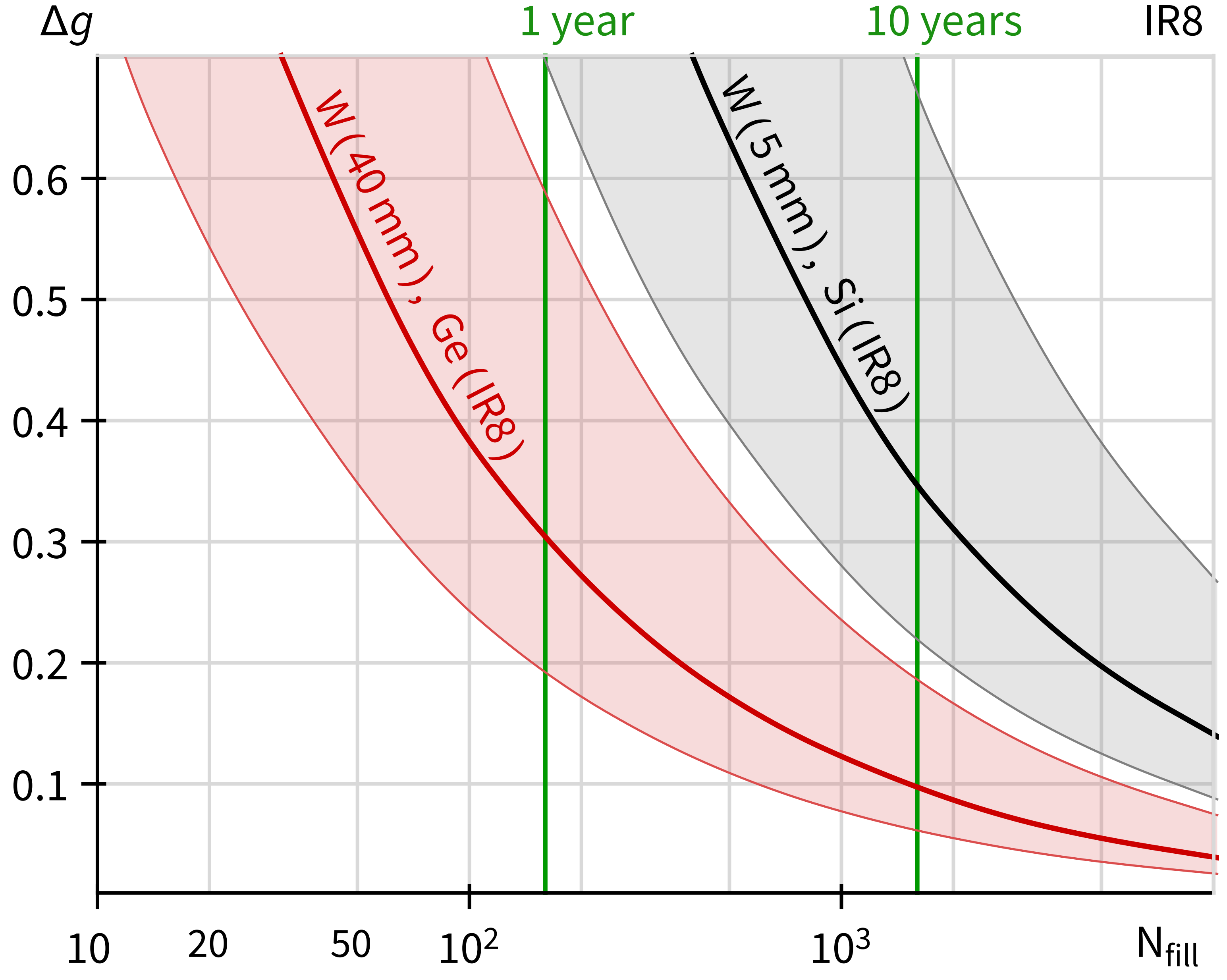
⇨ reduces the total luminosity at ATLAS and CMS by **~1.2%**

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	**4**
Crystal	silicon → germanium	**4**
Detector	LHCb (IR8) → dedicated at IR3	**5**
Beam exitation	additional to parasitic scenario	**3**

- **10 years** 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**
- **10 years** at **LHCb**, ~7×10^{13} POT, **40mm**, **Ge** → Δd ~ **2.6 10^{-16} e cm**
  (optimal orientation → data taking time reduced by ~170)
- big uncertainty (×10) due to α parameter
  → significant improvement in PhD thesis of Elisabeth Neil

Questions ?

thank you