Fixed-target experiments at LHC with bent crystals.

MDM measurement of short lived particles.

Alex Fomin

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Fixed-target experiments at LHC with bent crystals. MDM of short lived particles.

Introduction

- Electromagnetic moments of short lived particles
- Spin precession in a bent crystal

Optimal crystal orientation for MDM and EDM measurement

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

Performance assessment of layouts in IR2, IR3 and IR8 of LHC

- Double and single crystal layouts at LHC [3,4,5]
- Precision of measurement [1]
- Possible improvements [1,3]
- Direct measurement of τ-lepton MDM and EDM [6]

[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

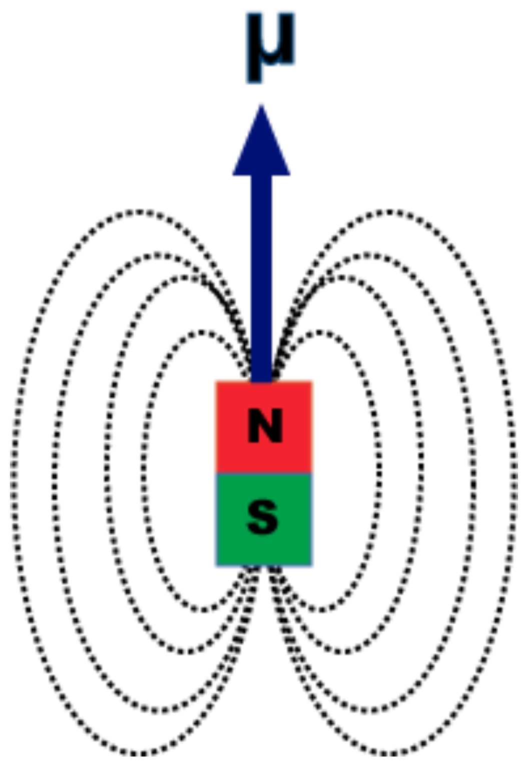
[4] CERN Yellow Reports: Monographs, 4/2020

[5] M. Patecki et al. Eur. Phys. J. C (2023) 83, 1053

[6] A.S. Fomin et al. JHEP 1903 (2019) 156

MDM and EDM of short lived particles

Magnetic Dipole Moment:



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

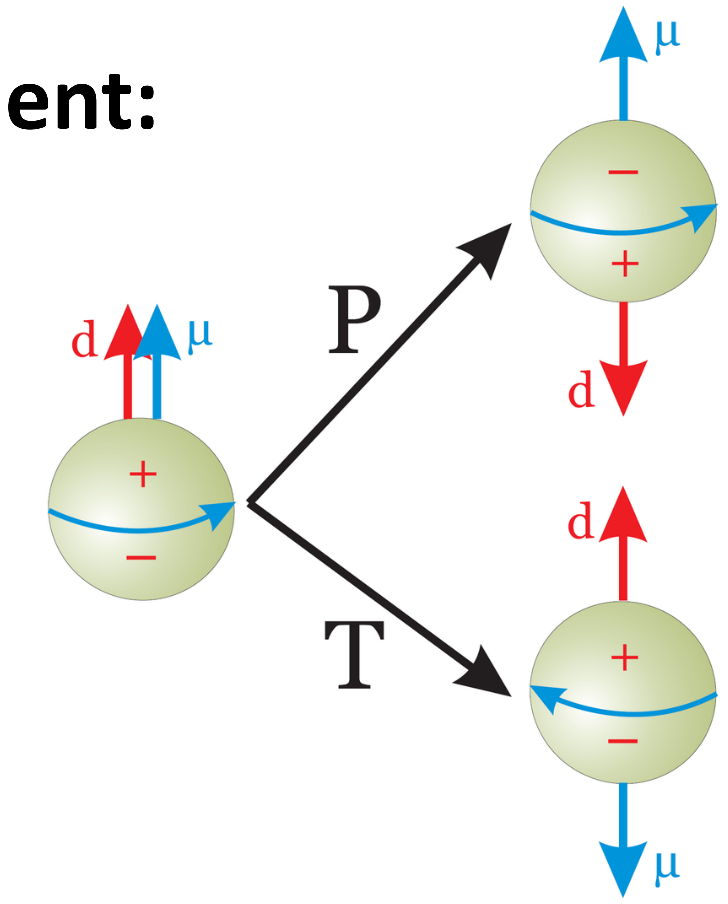
$|g| = 2$ → a point-like Dirac particle

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

$|g| \not\approx 2$ → a composite structure or NP

Particle	cτ	g-factor	Comments
e –		– 2.002 319 304 361 82 (52)	exp. most accurate determinations of α (Harvard 2008)
μ –	659 m	– 2.002 331 8361 (10) – 2.002 331 84110 (43 stat, 19 syst)	theor. SM prediction (diff. from lattice gauge theory) exp. running (3/6 year of data taking at Fermilab 2021)
τ –	87 μm	– 2.002 354 42 (10) – 2.036 (34) – 2.002 (6) no direct measurement	theor. SM prediction exp. σ (e+e– → e+e– τ+τ–) (LEP2: DELPHI 2004) exp. assuming EDM τ = 0 (from LEP and SLD 2000) exp. Feasibility studies at **LHC**
p n	∞ ~∞	+ 5.585 694 702 (17) – 3.826 085 45 (90)	exp. exp.
Σ+	2.4 cm	+ 6.233 (25) + 6.1 (1.2)stat (1.0)syst	exp. world-average value exp. using **Bent Crystals** (at Fermilab 1990)
Λ_c^+	60 μm	+ 1.90 (15) not measured	theor. assuming $g_c \approx 2$ exp. Feasibility studies at **LHC**

Electric Dipole Moment:



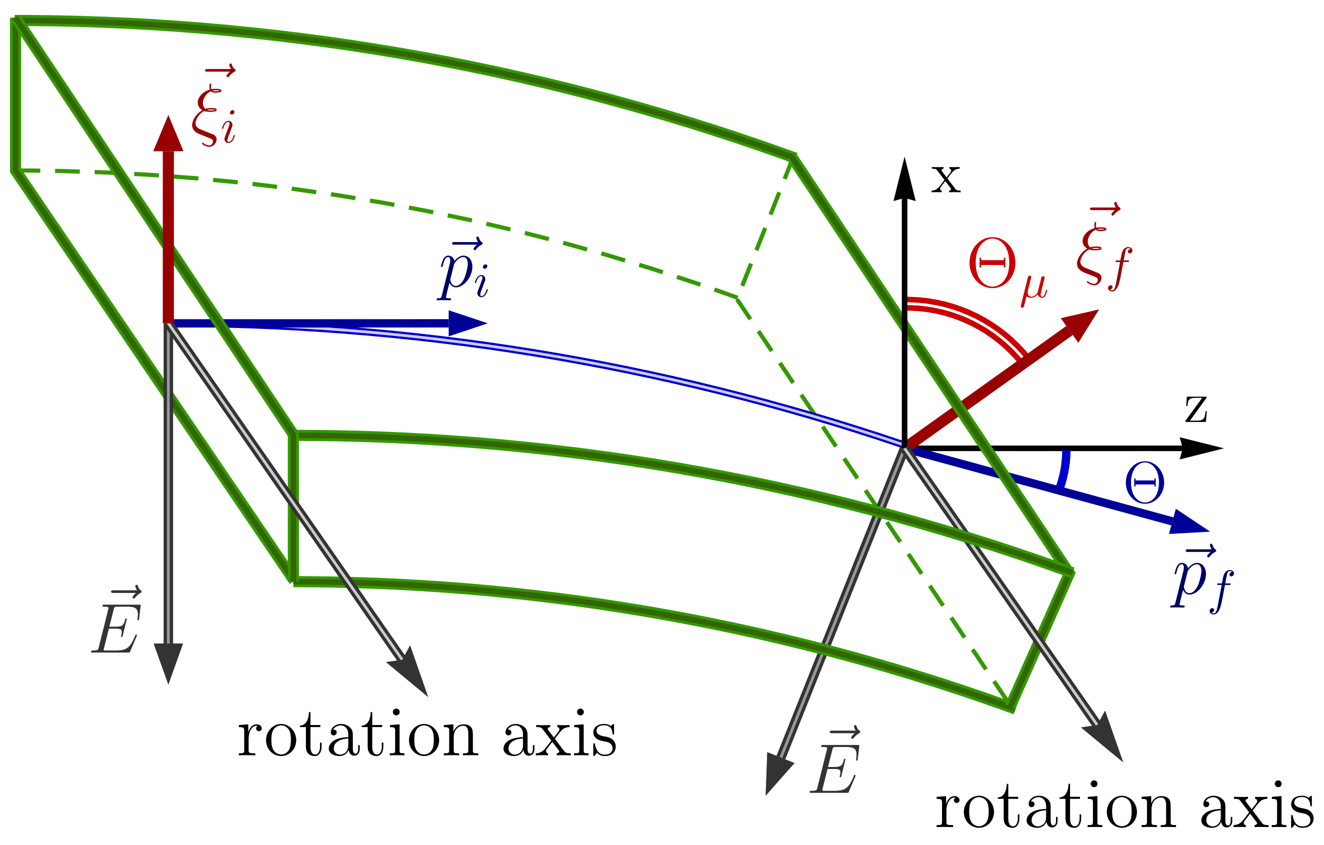
$$\vec{\delta} = \frac{f}{2}\frac{e}{m}\vec{S}, \quad \vec{S} = \frac{\hbar}{2}\vec{\sigma}$$

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].



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

γ, g, a — Lorentz factor, g-factor, anomalous MDM of Λ_c

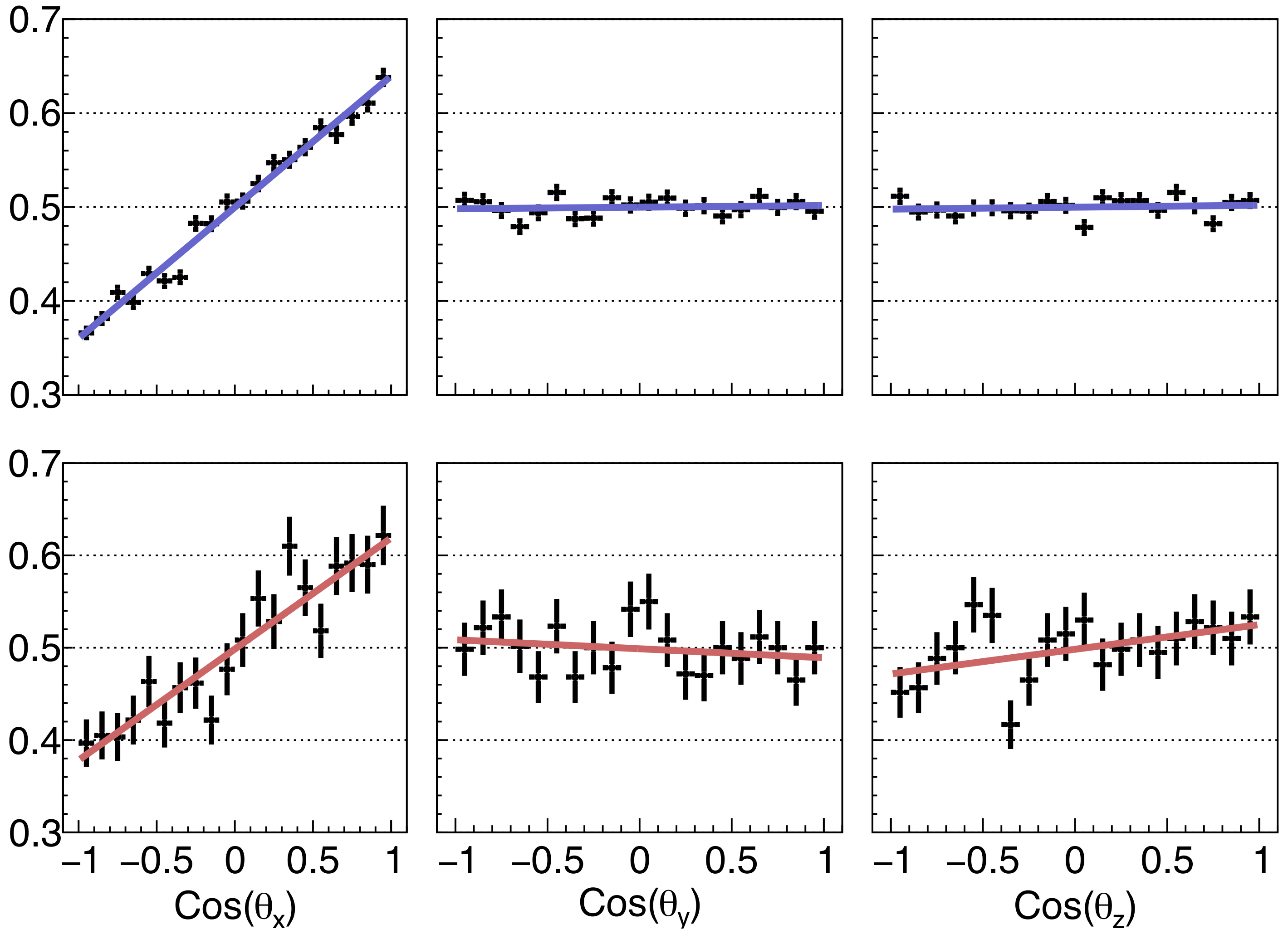
Θ, L, R — deflecting angle, length, curvature radius of the crystal

Initial polarisation

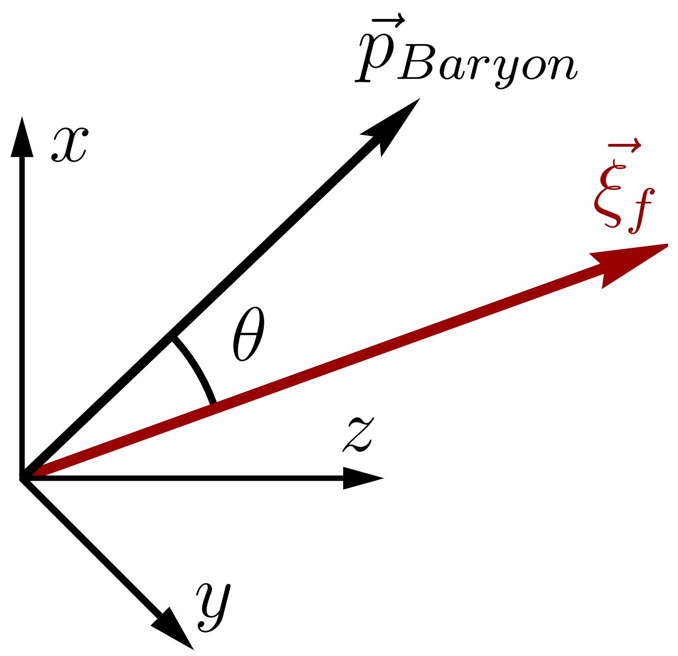
$$\vec{\xi}_i = \xi\,(\;1\;,\,0\,,\;0\;)$$

Final polarisation

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



$$\Lambda_c^+ \rightarrow Meson + Baryon$$



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

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

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

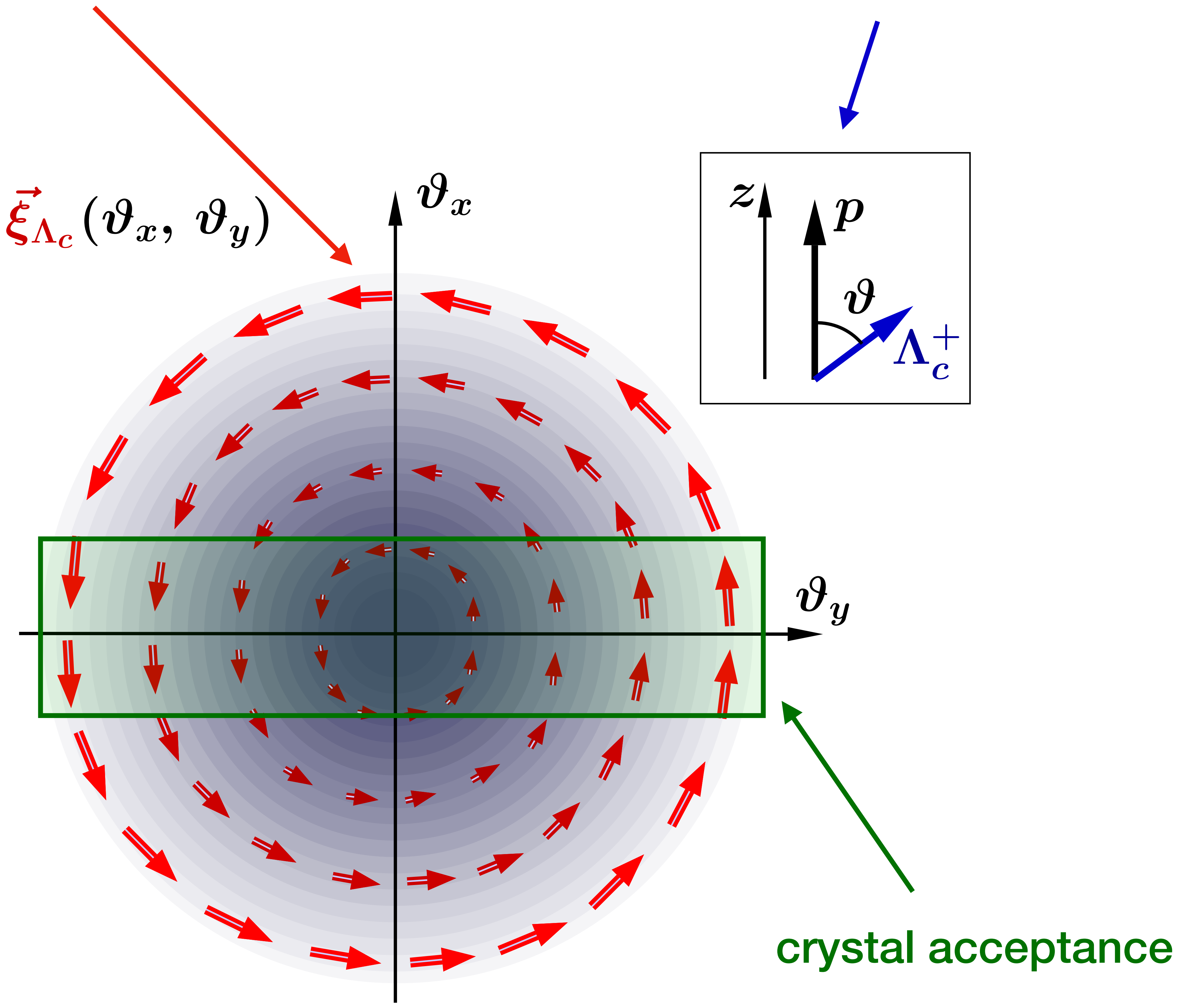
Optimal crystal orientation for MDM and EDM measurements

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

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

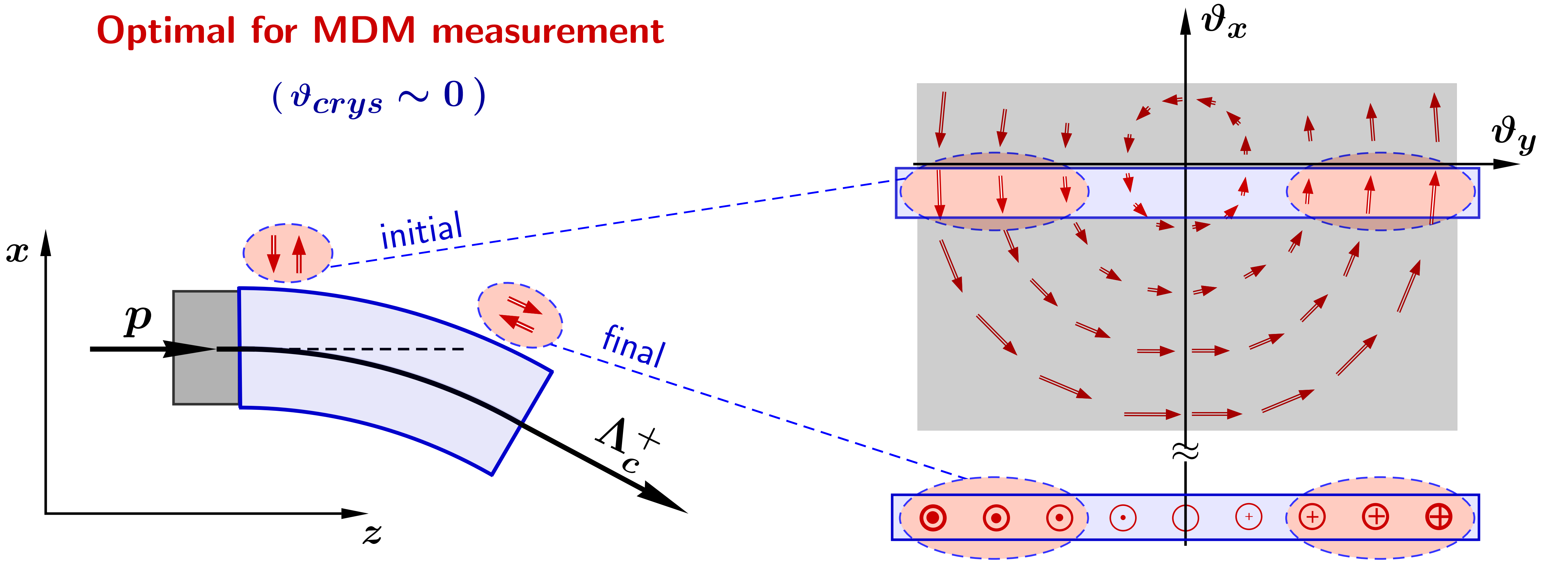
Due to the space-inversion symmetry of the strong interaction

Λ_c^+ polarisation is perpendicular to the reaction plane



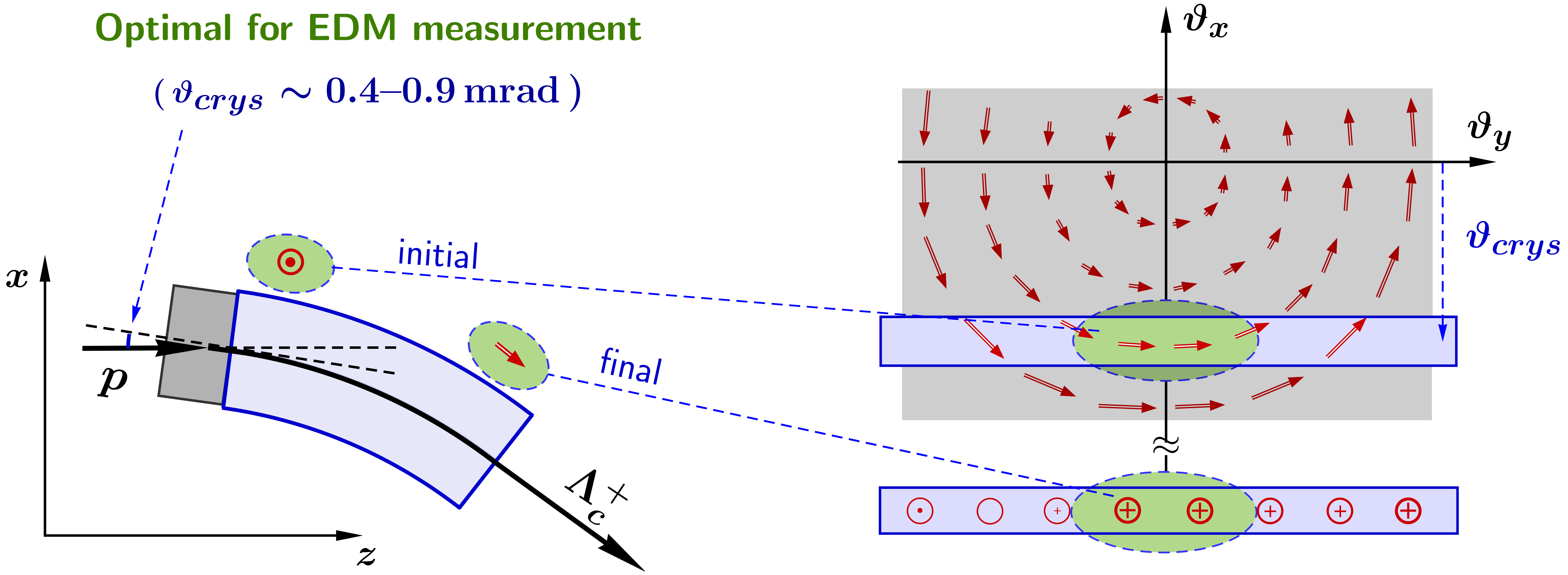
Optimal for MDM measurement

$(\vartheta_{crys} \sim 0)$

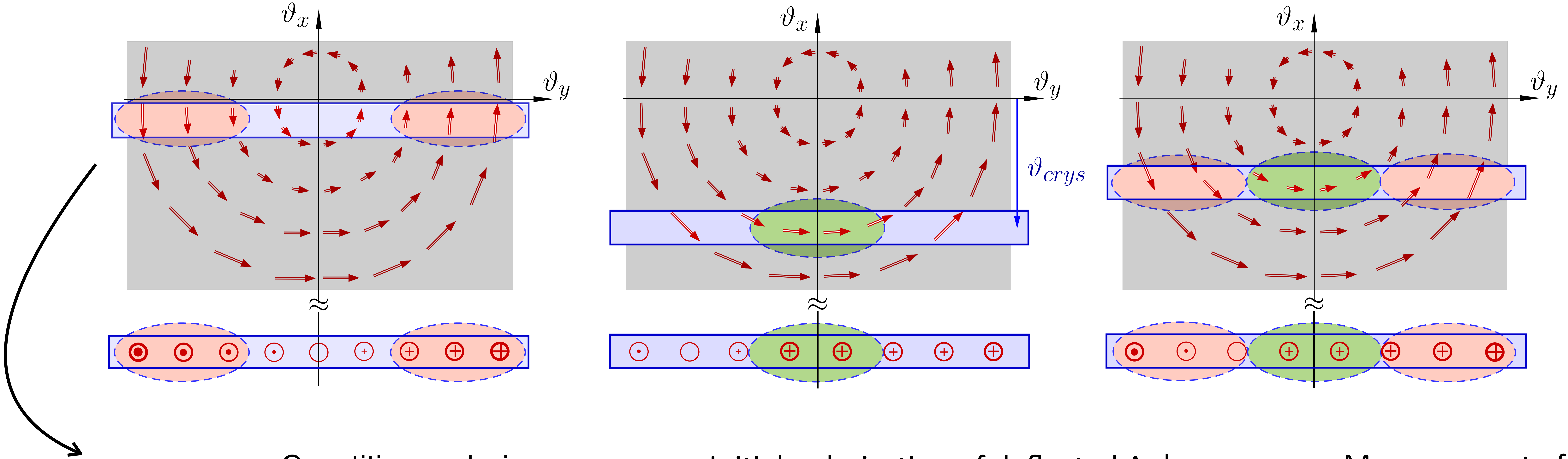


Optimal for EDM measurement

$(\vartheta_{crys} \sim 0.4\text{–}0.9\,\text{mrad})$



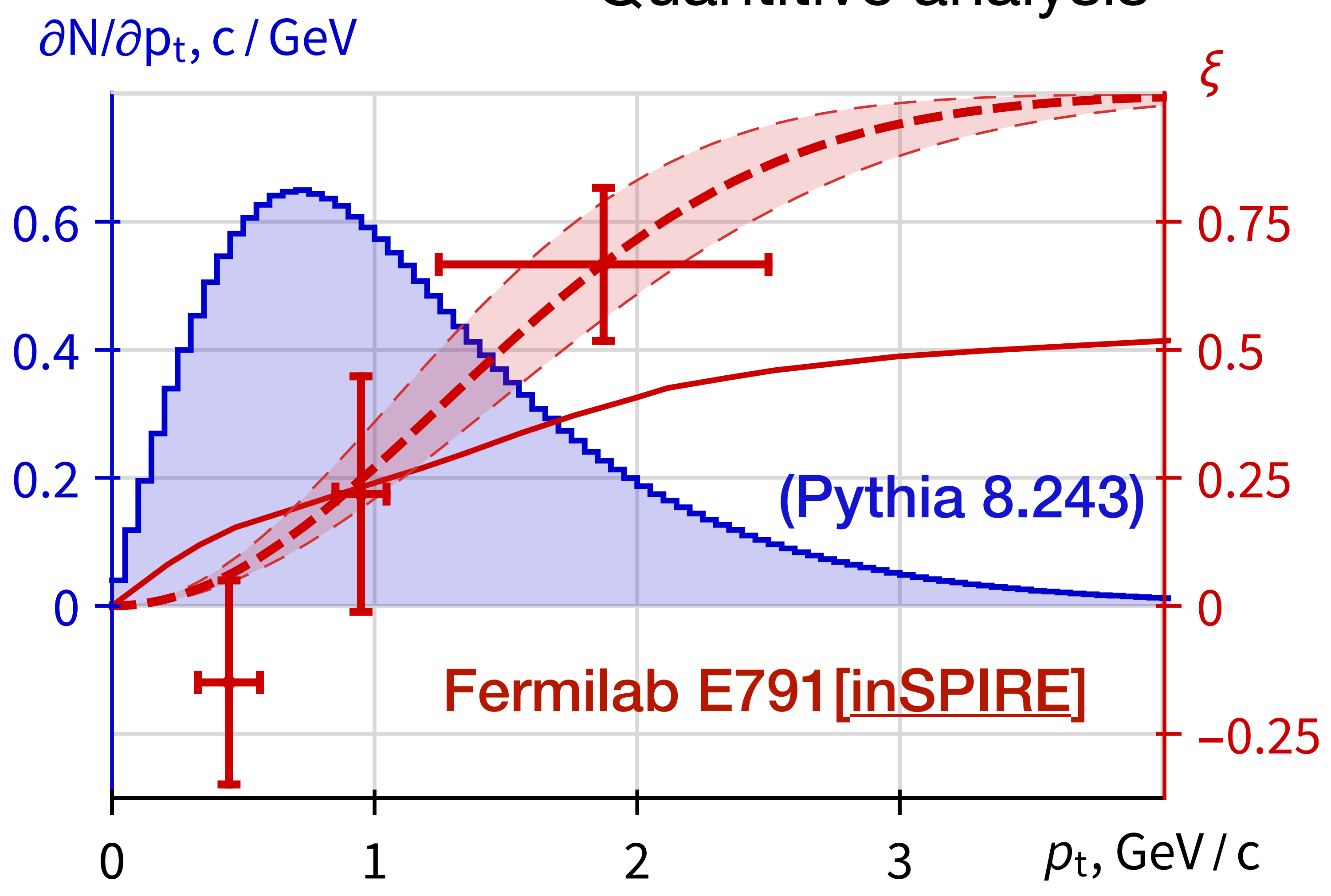
Optimal crystal orientation for EDM measurement: Quantitive analysis



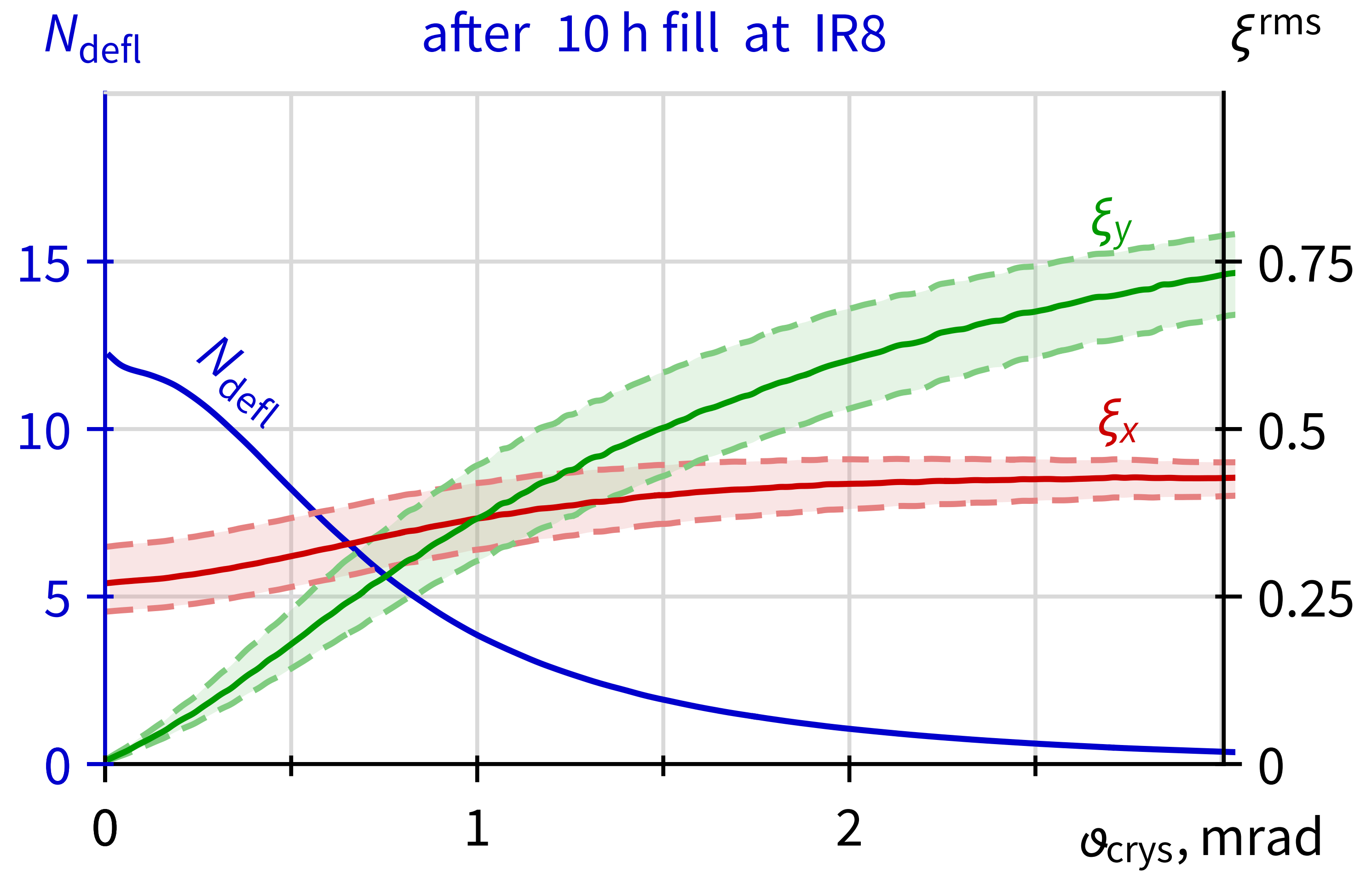
$$\Delta g = \frac{2}{\alpha \langle \xi_x \gamma \rangle \Theta} \sqrt{\frac{3}{N}}$$

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

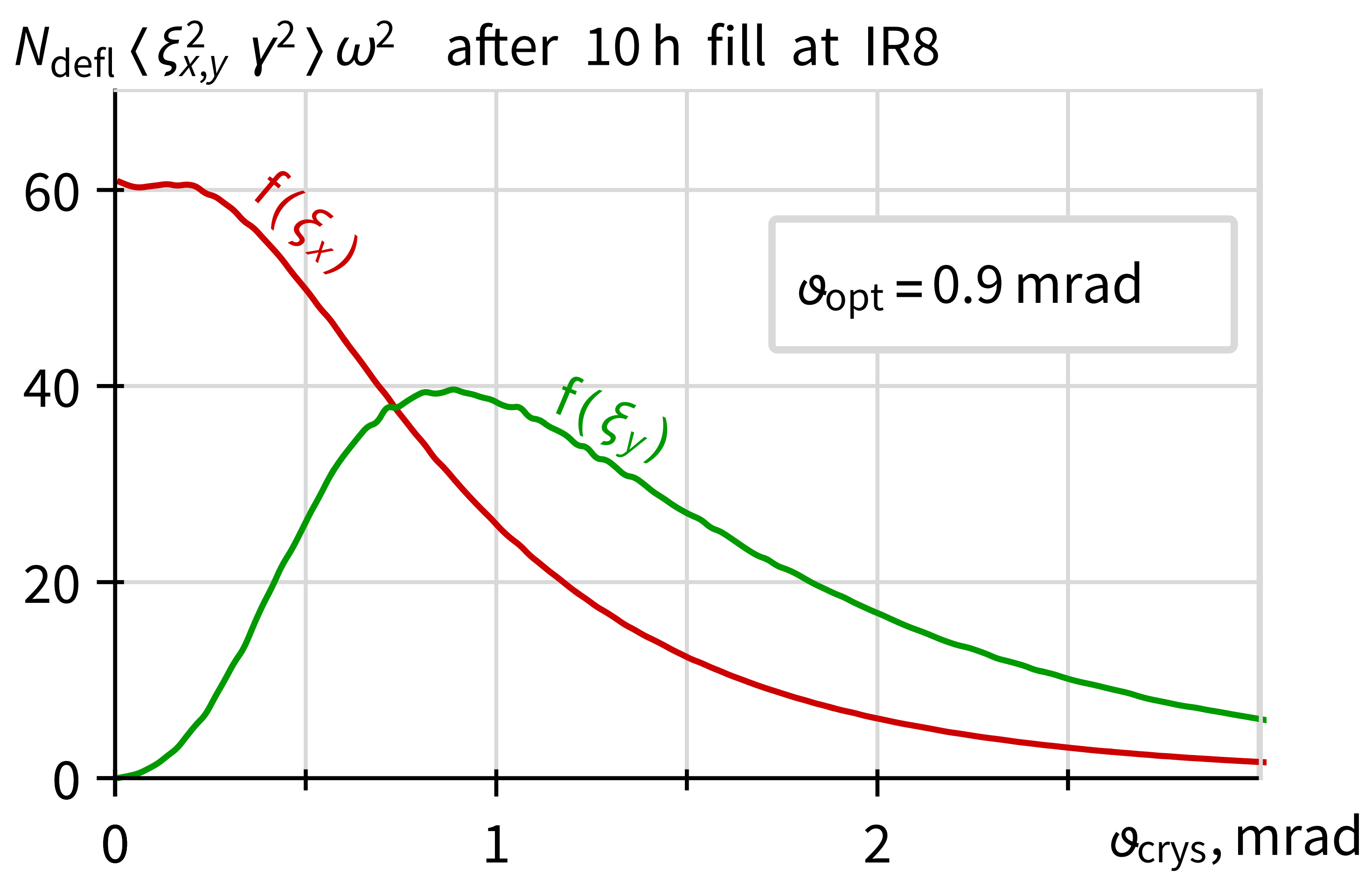
Quantitive analysis



Initial polarisation of deflected Λ_c^+

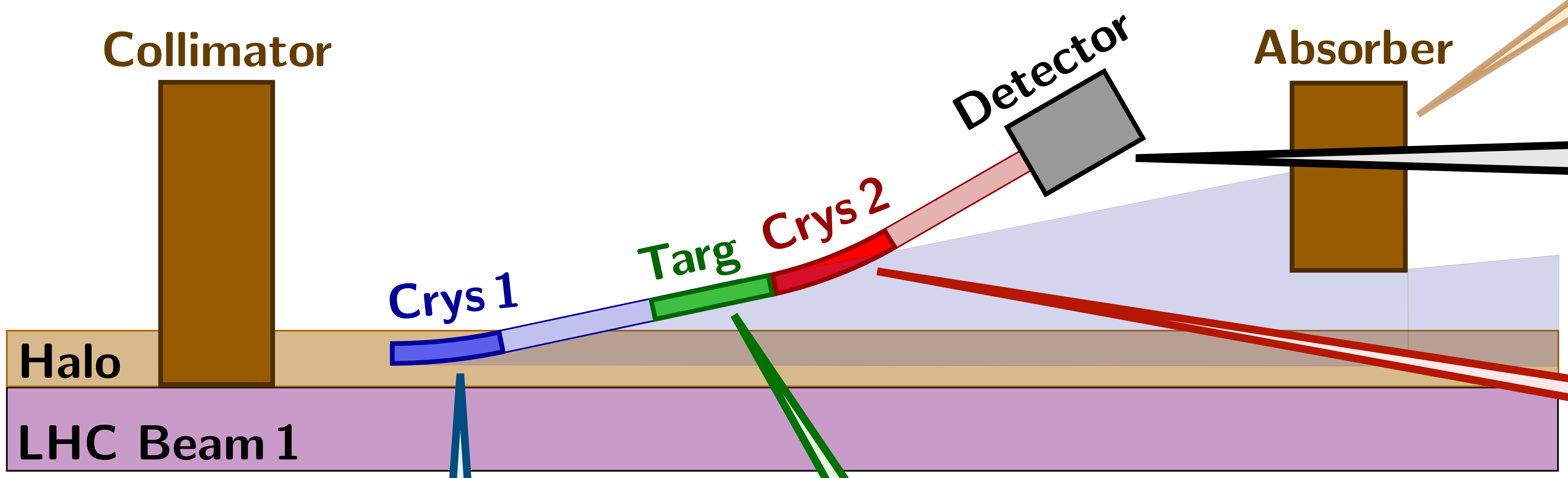


Measurement efficiency



MDM 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**.



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.

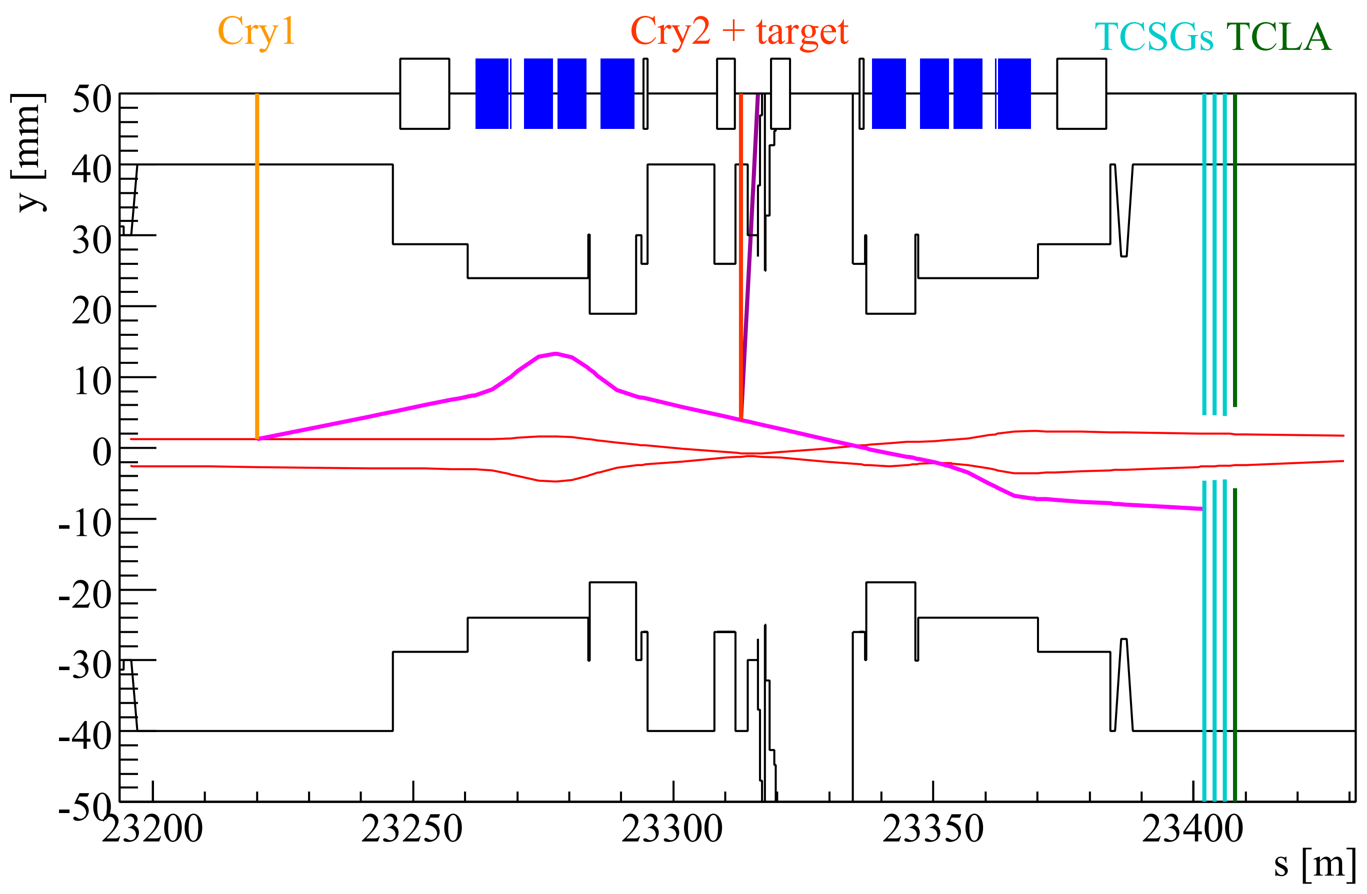
Λc spin precession in the electric field of crystal planes is proportional to MDM (or EDM)

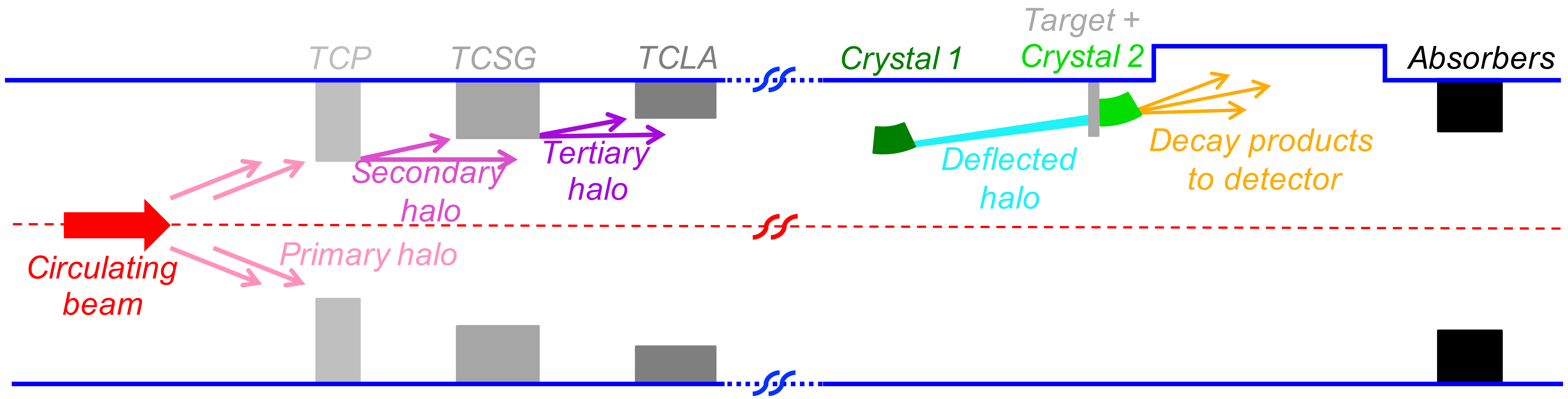
The first Crystal deflects protons from the LHC beam halo onto the Target

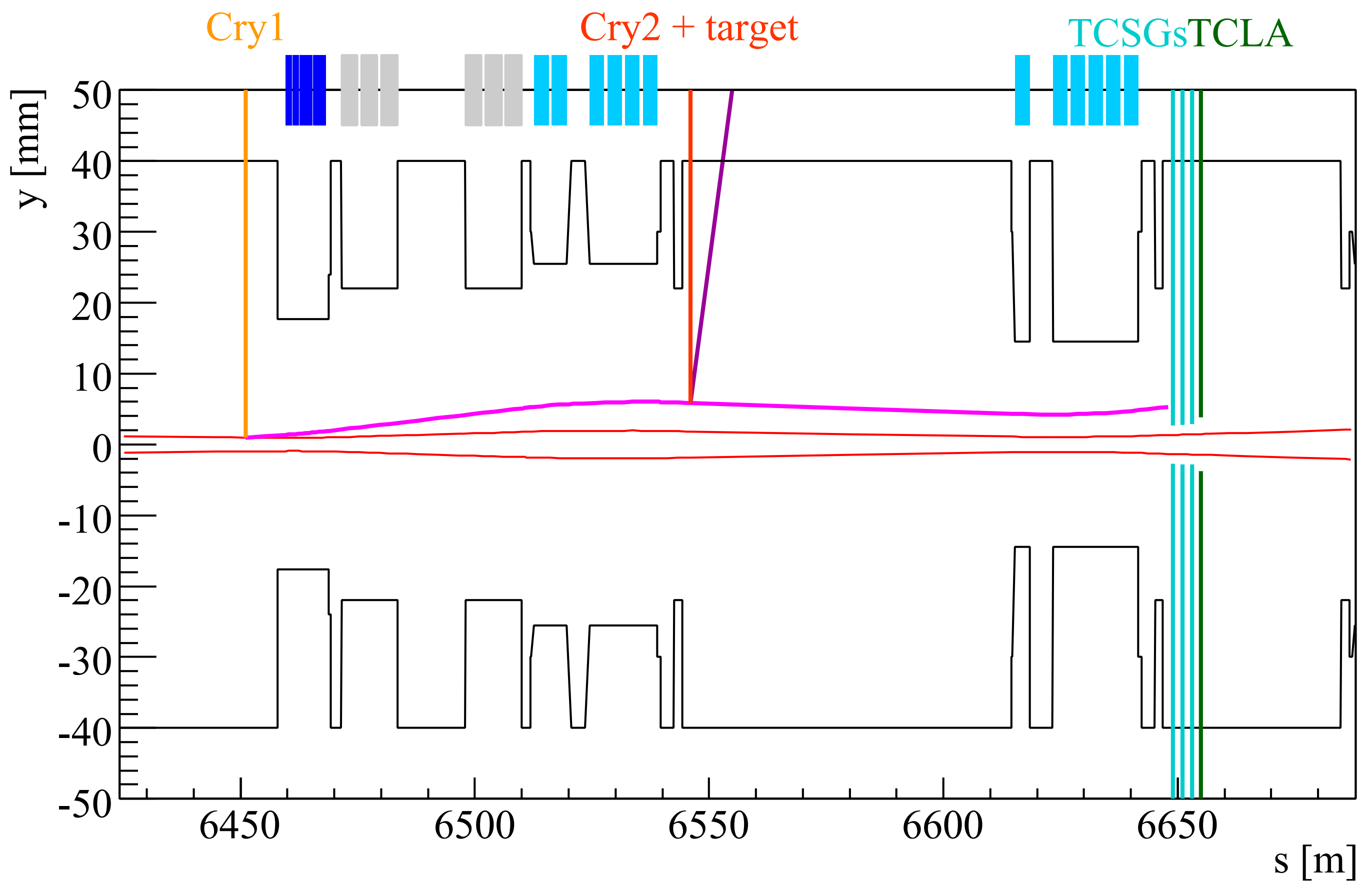
In the Target protons are converted to polarised Λc

Performance assessment of layouts in IR3 and IR8 of LHC

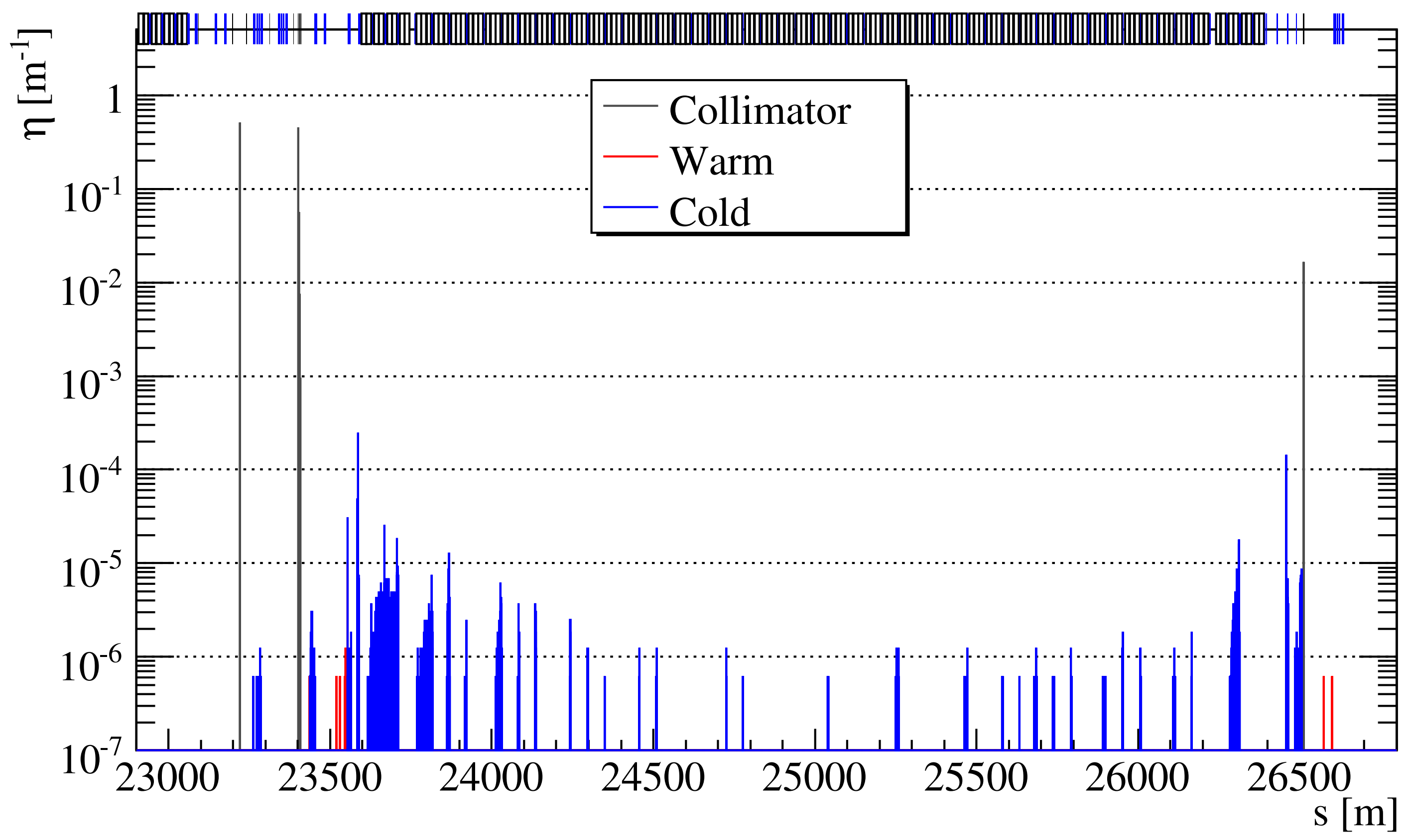
D. Mirarchi et al. Eur. Phys. J. C 80 (2020) 10, 929







- 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**

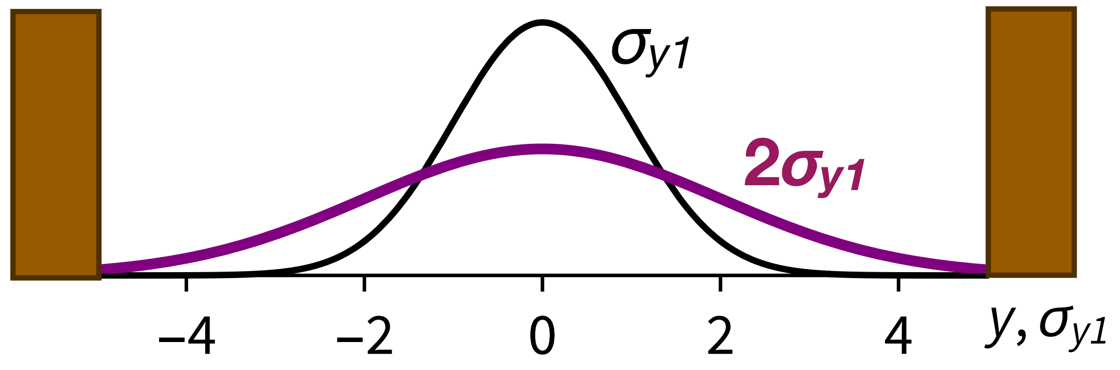


Increasing the PoT through active bunch excitation

General idea

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

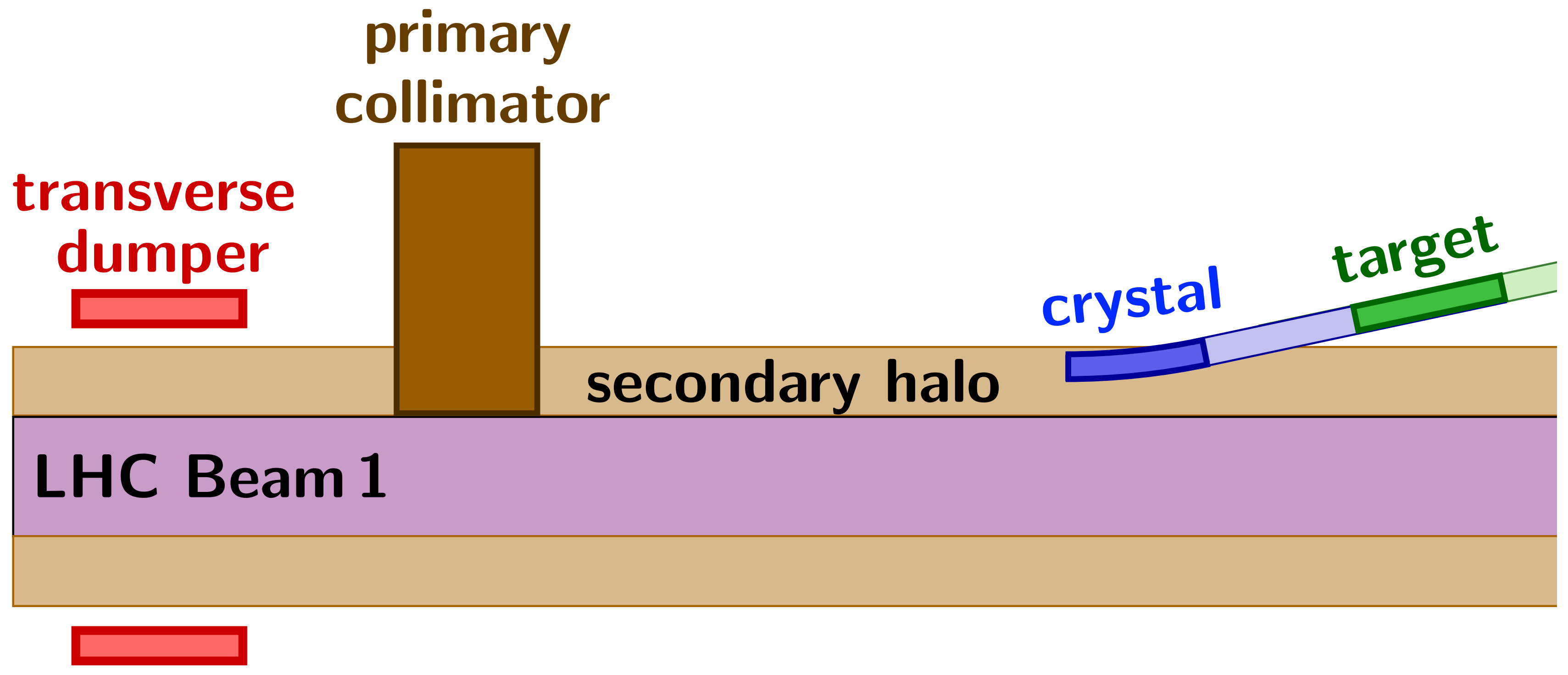
→ **emittance grow** of these bunches



→ 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**

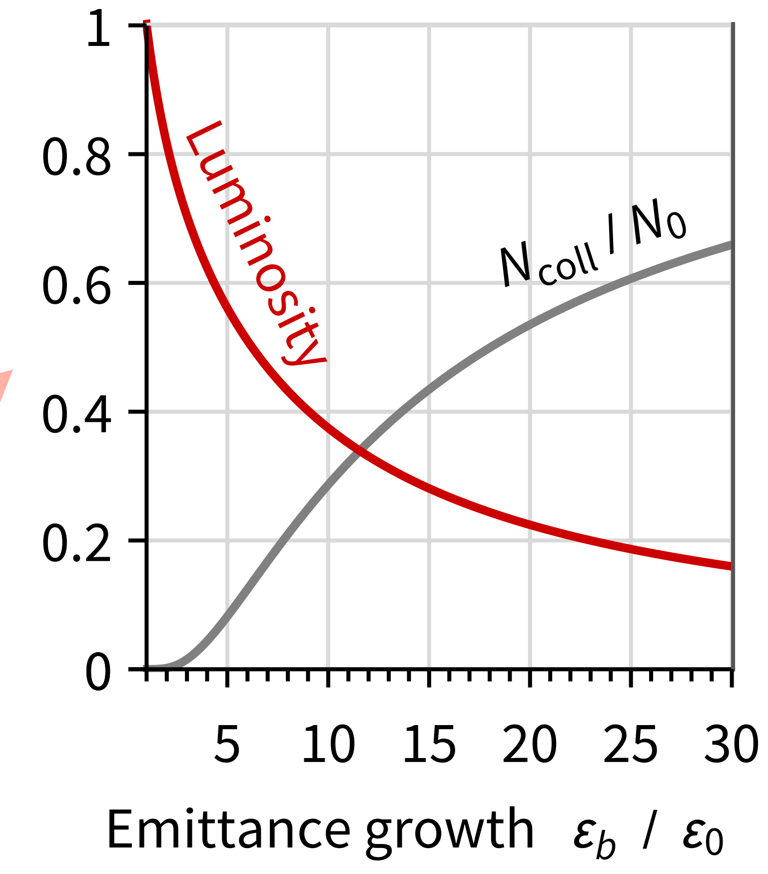


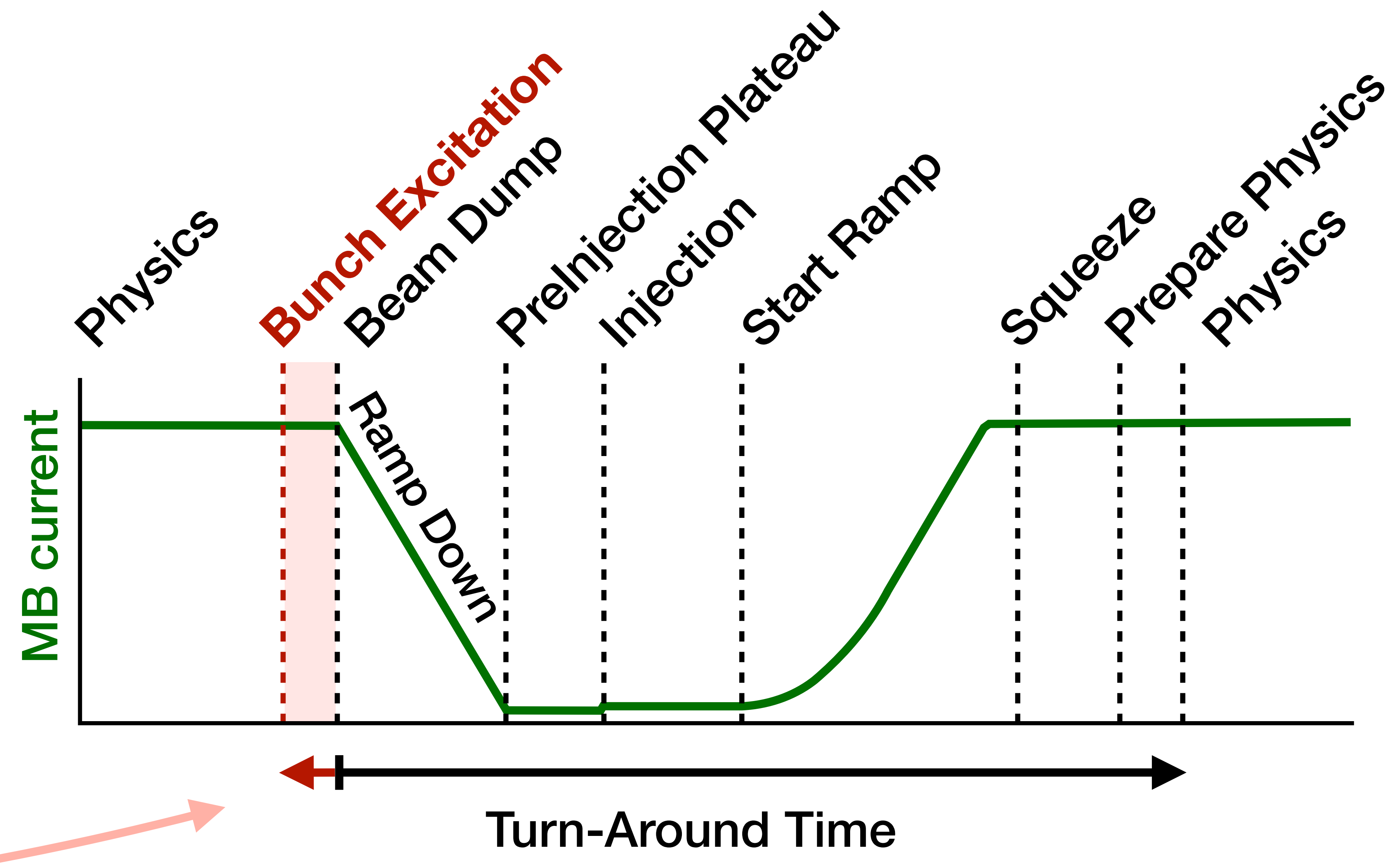
Transverse damper is currently used in LHC

- 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

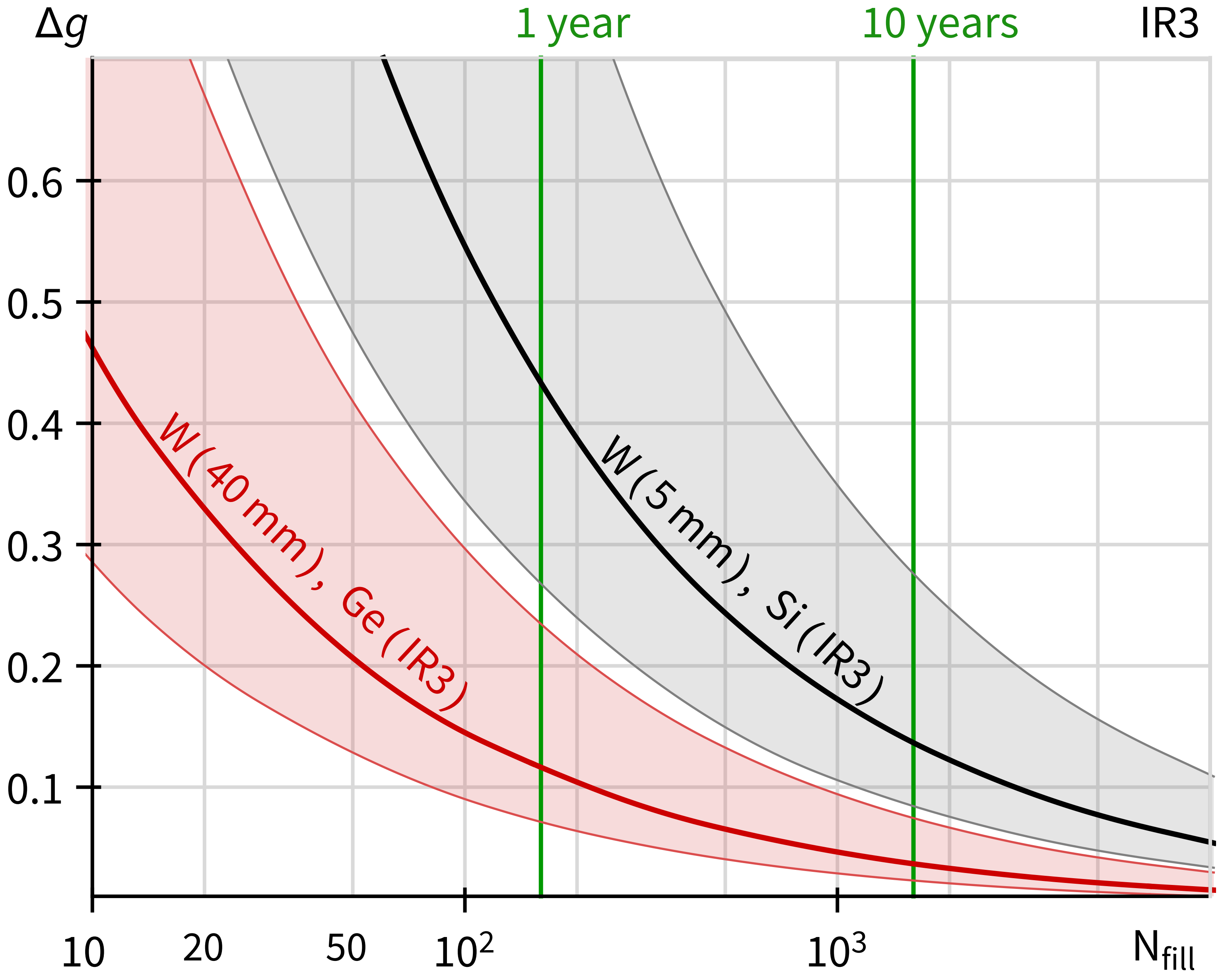


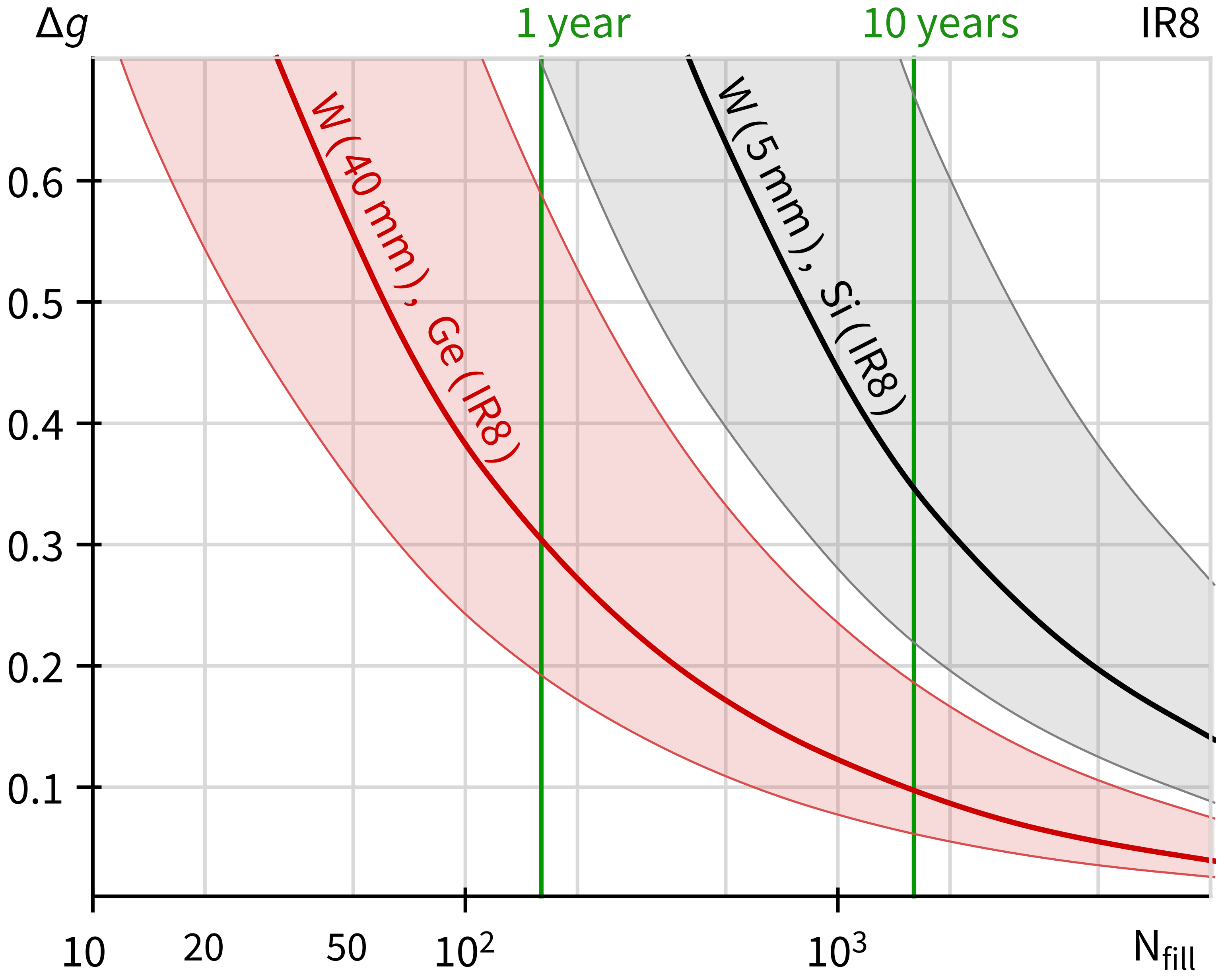


Performance assessment of layouts in IR3 and IR8: possible improvements

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	4

- **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

MDM of τ-lepton. Double-crystal setup.

A.S. Fomin et al. JHEP 1903 (2019) 156

Crystal 1:

Ge: L = 3 cm R = 10 m

Si: L = 4.5 cm R = 15 m

θ_D = 3 mrad

θ_p = 0.1 mrad

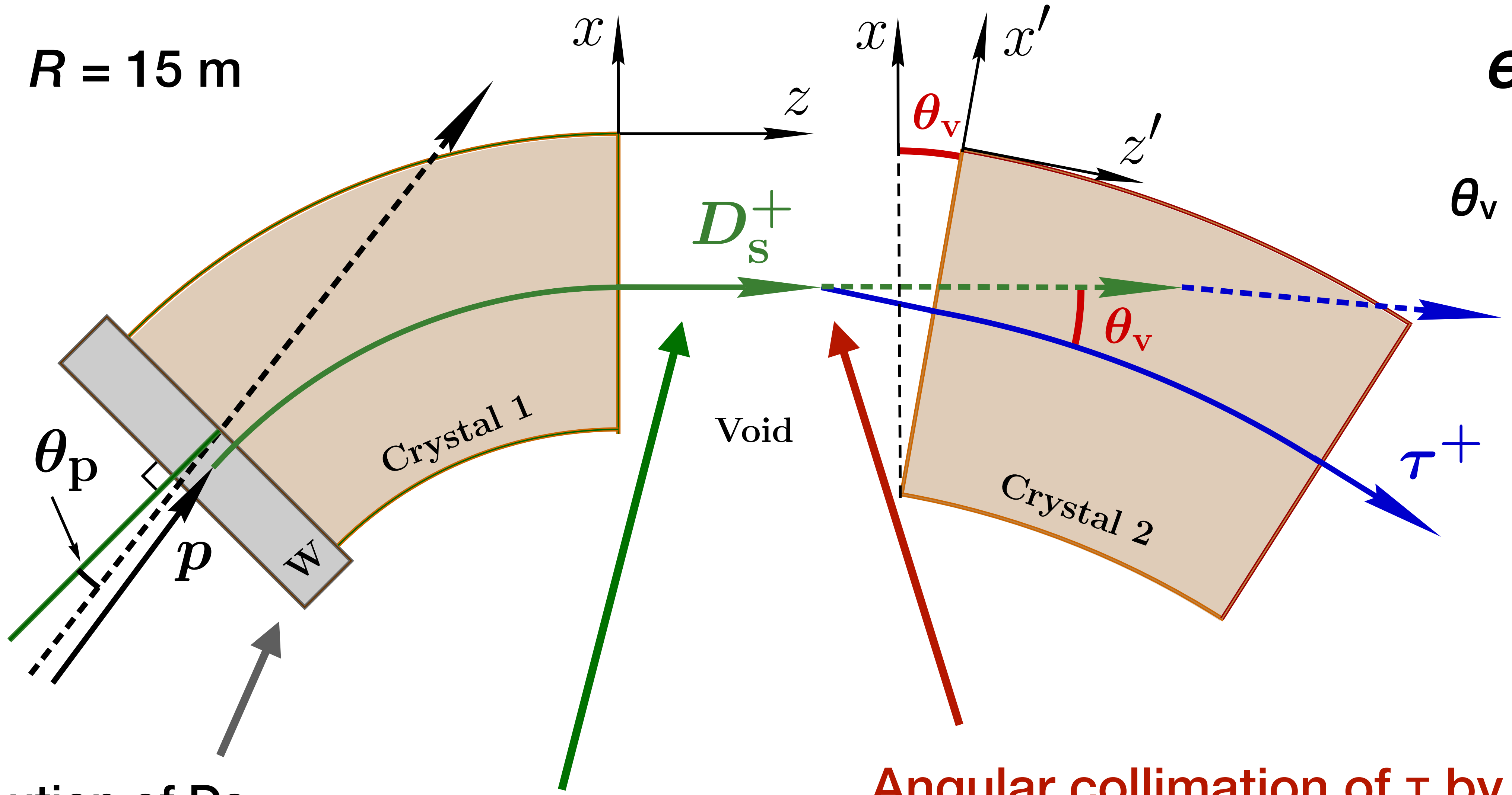
Crystal 2:

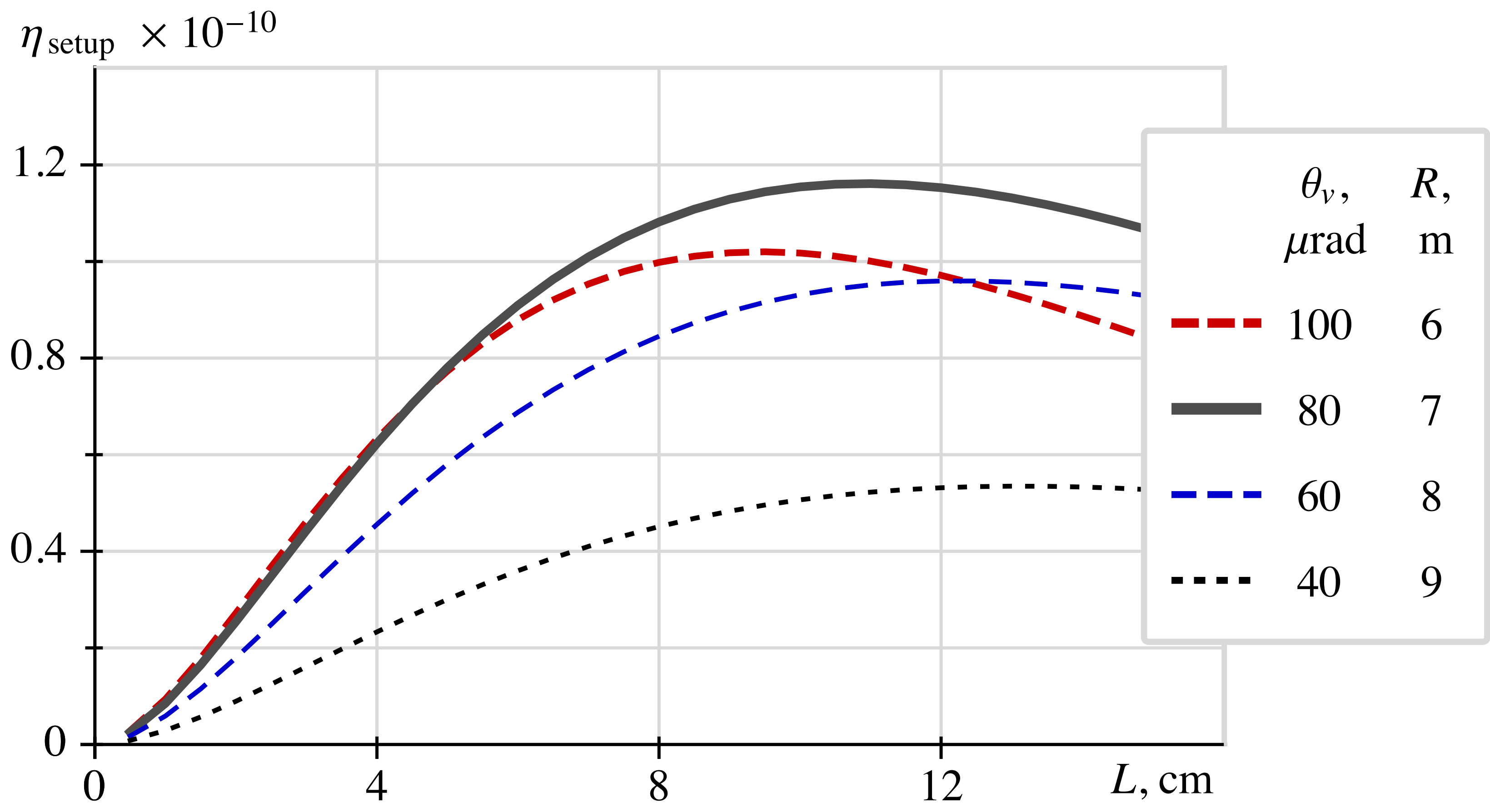
Ge: L = 10 cm R = 7 m

Θ_τ = 14 mrad

θ_v = 0.08 mrad

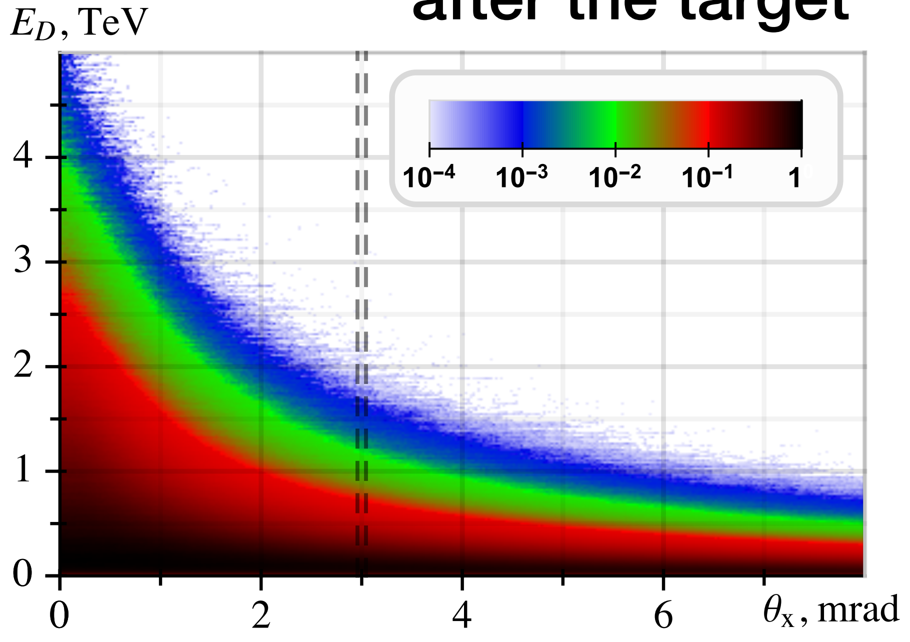
L_v = 10 cm



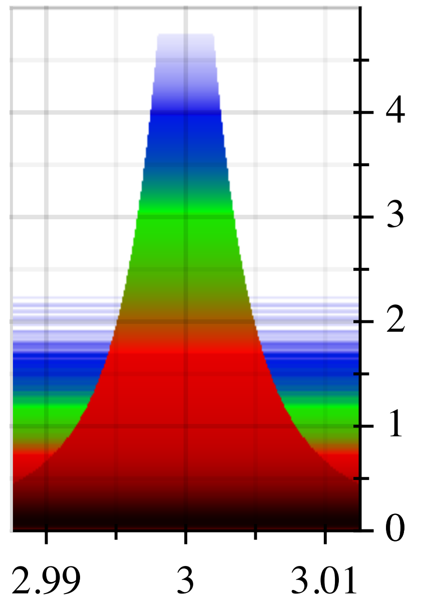


Sp.-ang. distribution of Ds

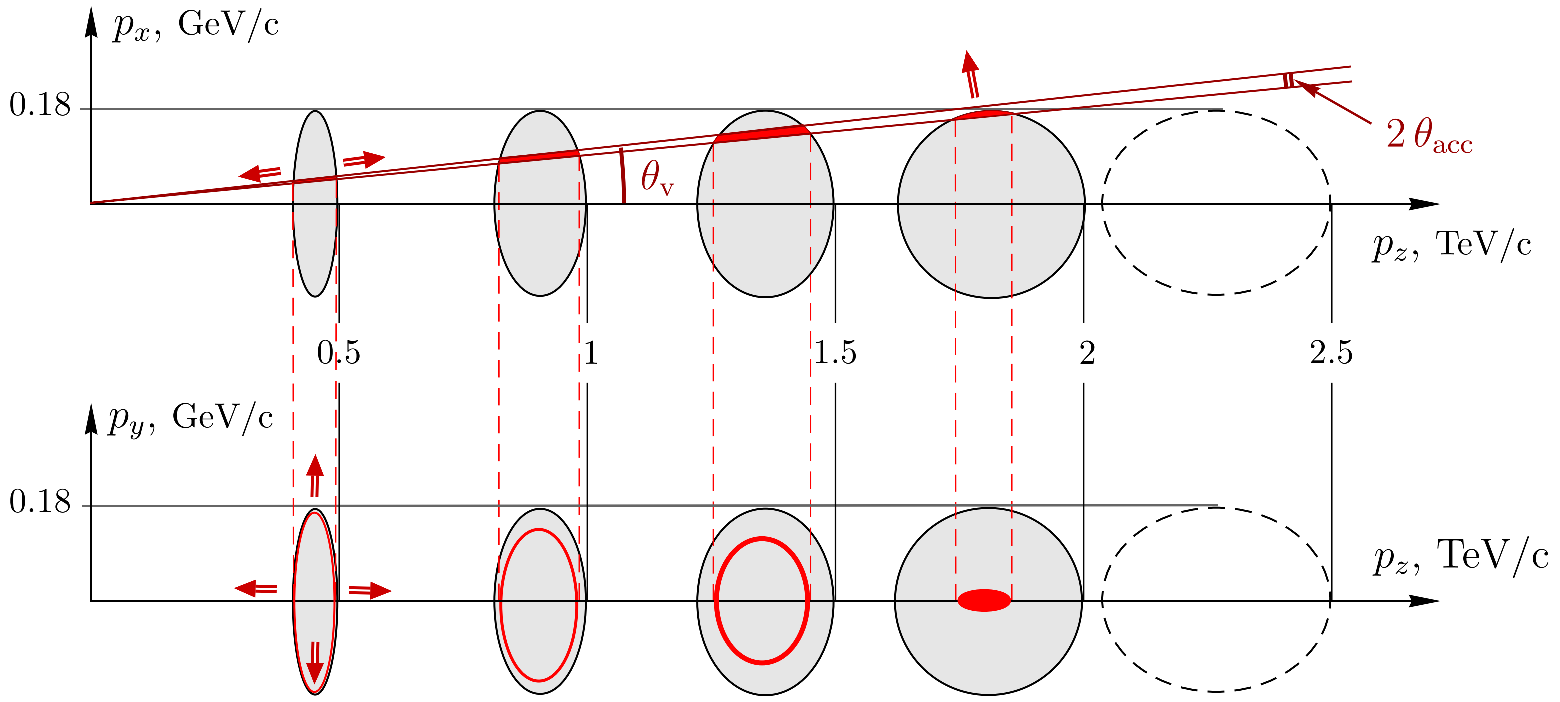
after the target

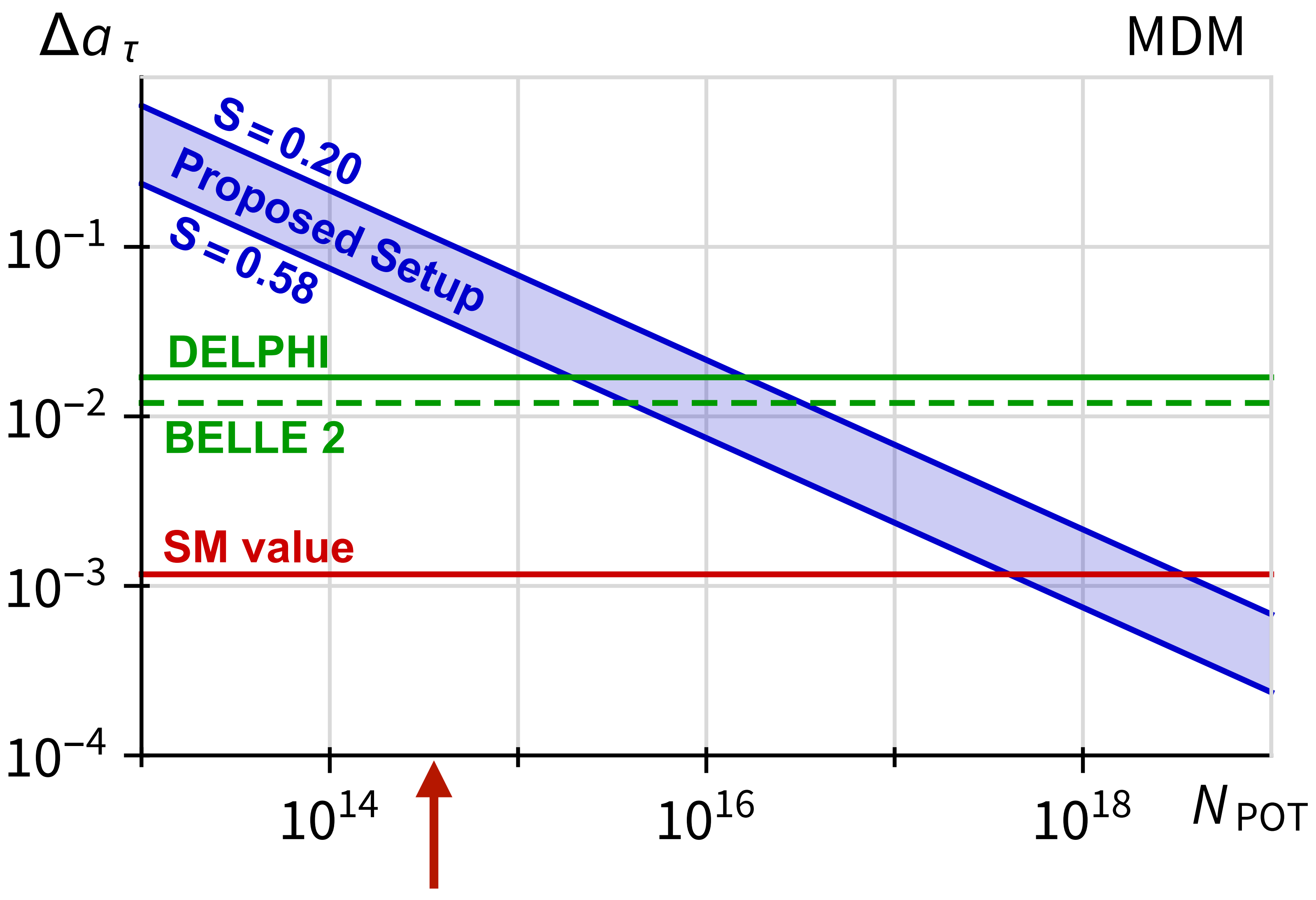


after Crystal 1



Angular collimation of τ by Crystal 2





too many PoT needed !

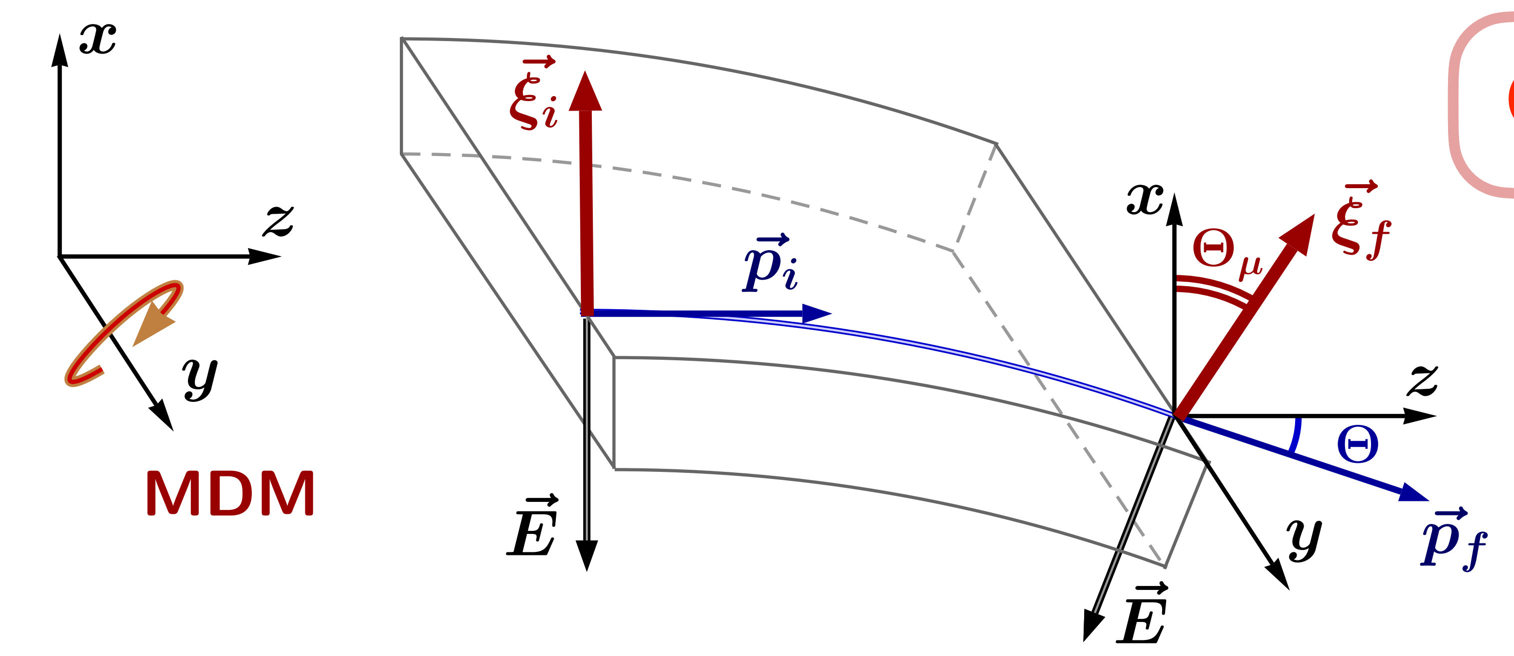
Fixed-target experiments at LHC with bent crystals. MDM of short lived particles.

τhank you

Optimal crystal orientation for MDM and EDM measurements

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

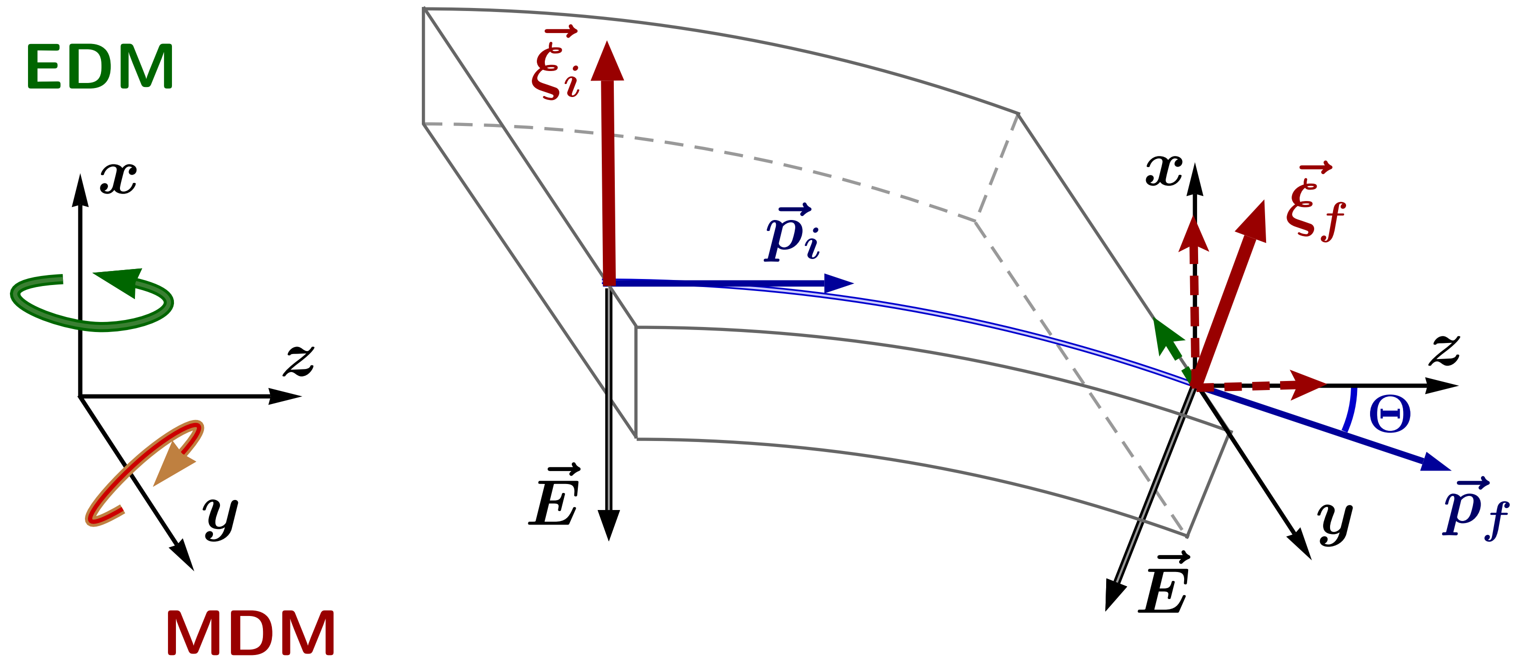
V.L. Lyuboshits,
Sov. J. Nucl. Phys. 31 (1980) 509
[inSPIRE].



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

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

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

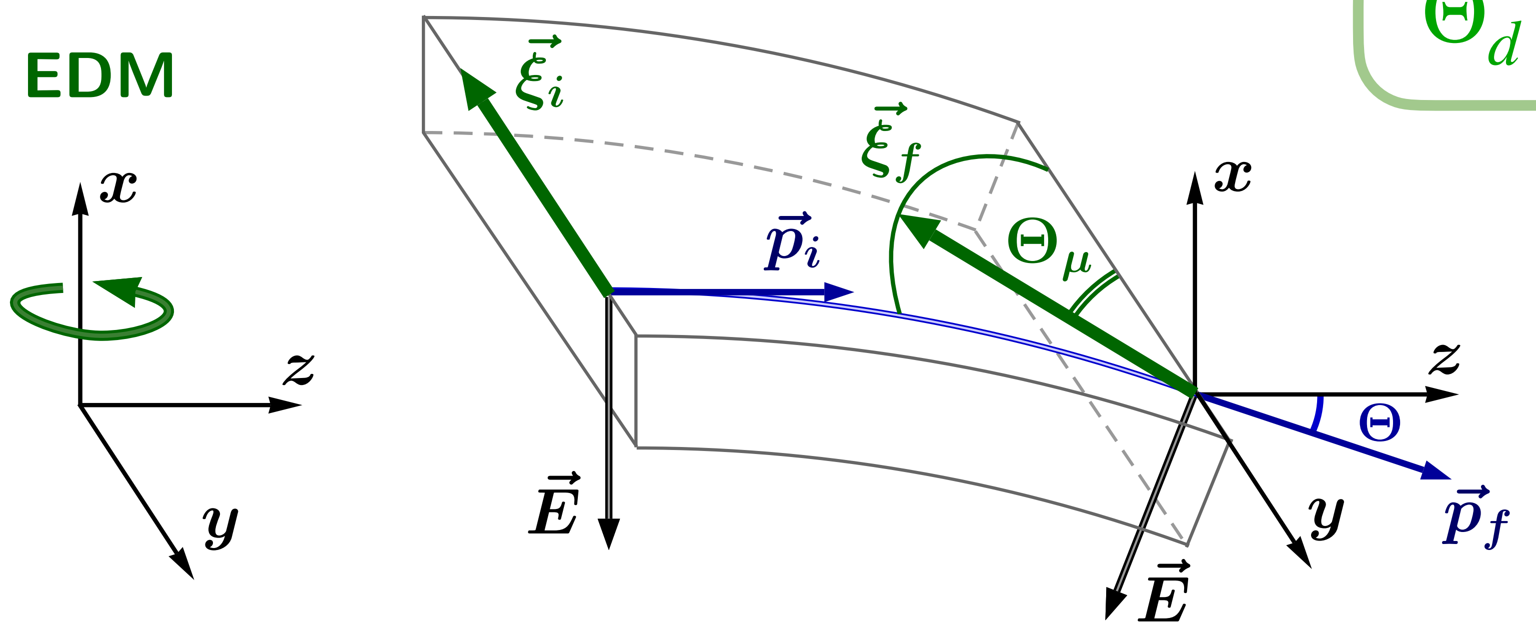


$$\frac{\Delta f}{\Delta g} = \frac{2\,\gamma a}{\Theta\left(1+\gamma a\right)^2}$$

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]



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

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

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

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

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

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:

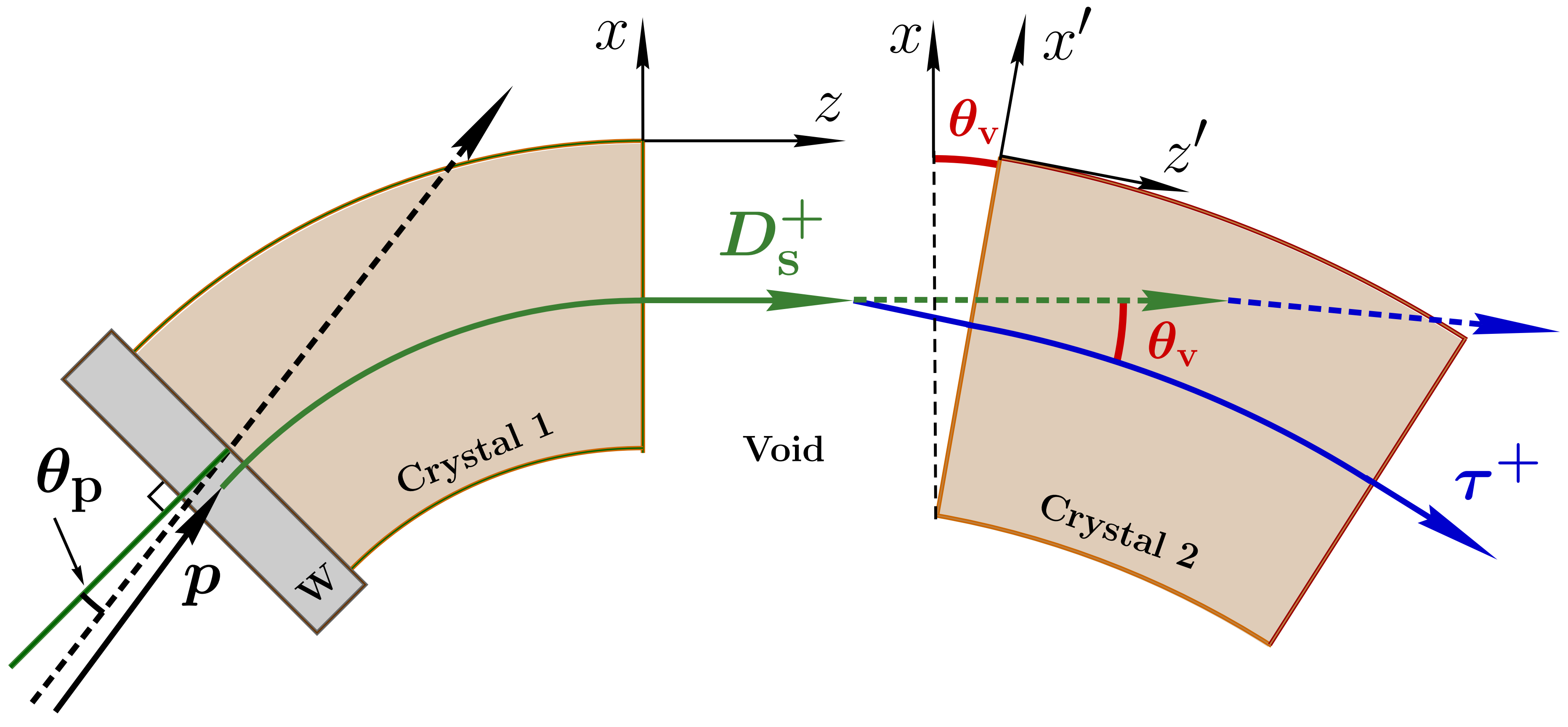
The gradual excitation of bunches (3.5 p/bunch X) at the end of the fills with 2556 bunches, with duration under 1 hour:

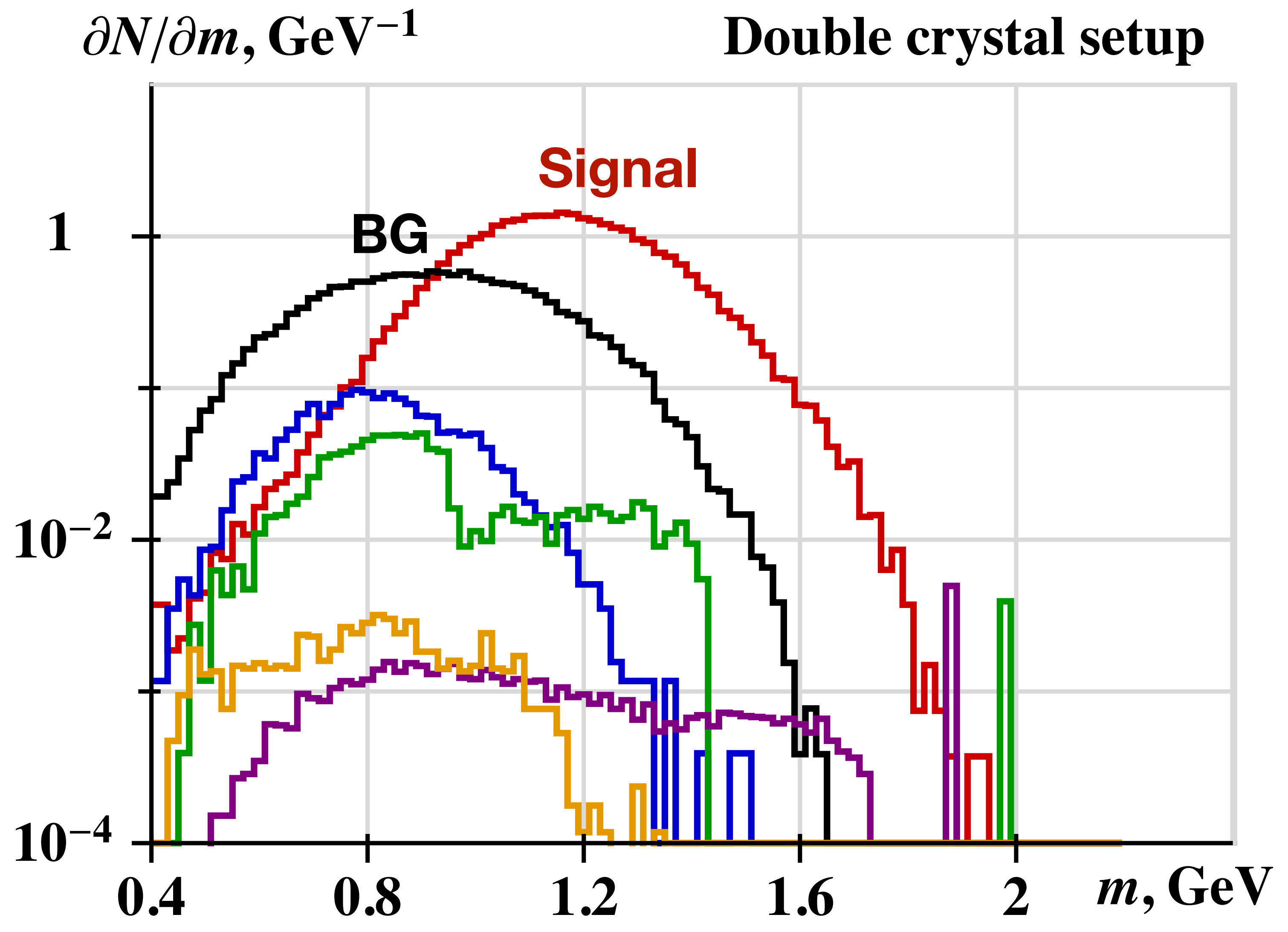
⇨ delivers **3 times more PoT** w.r.t. “Baseline”

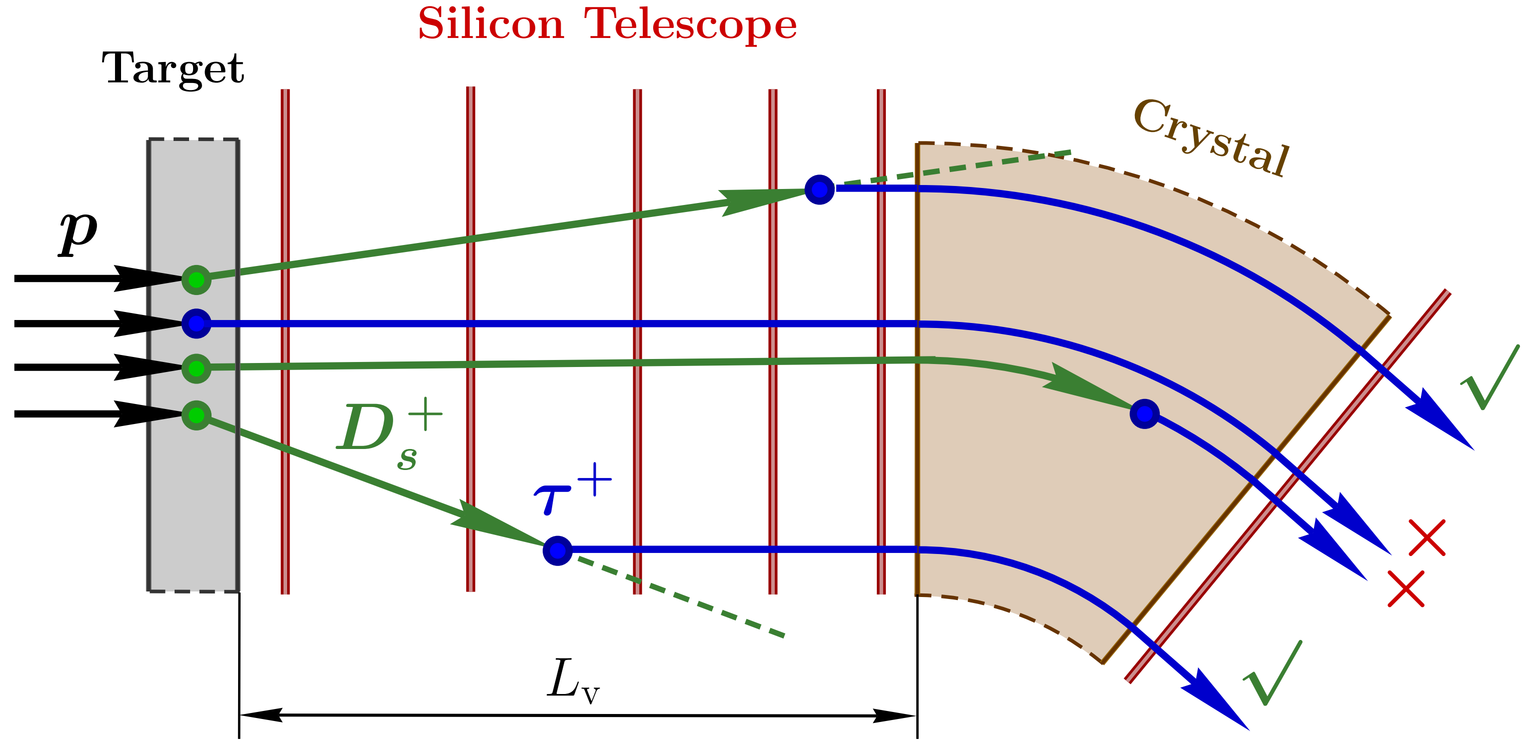
⇨ reduces the total luminosity at ATLAS and CMS by **~1.2%**

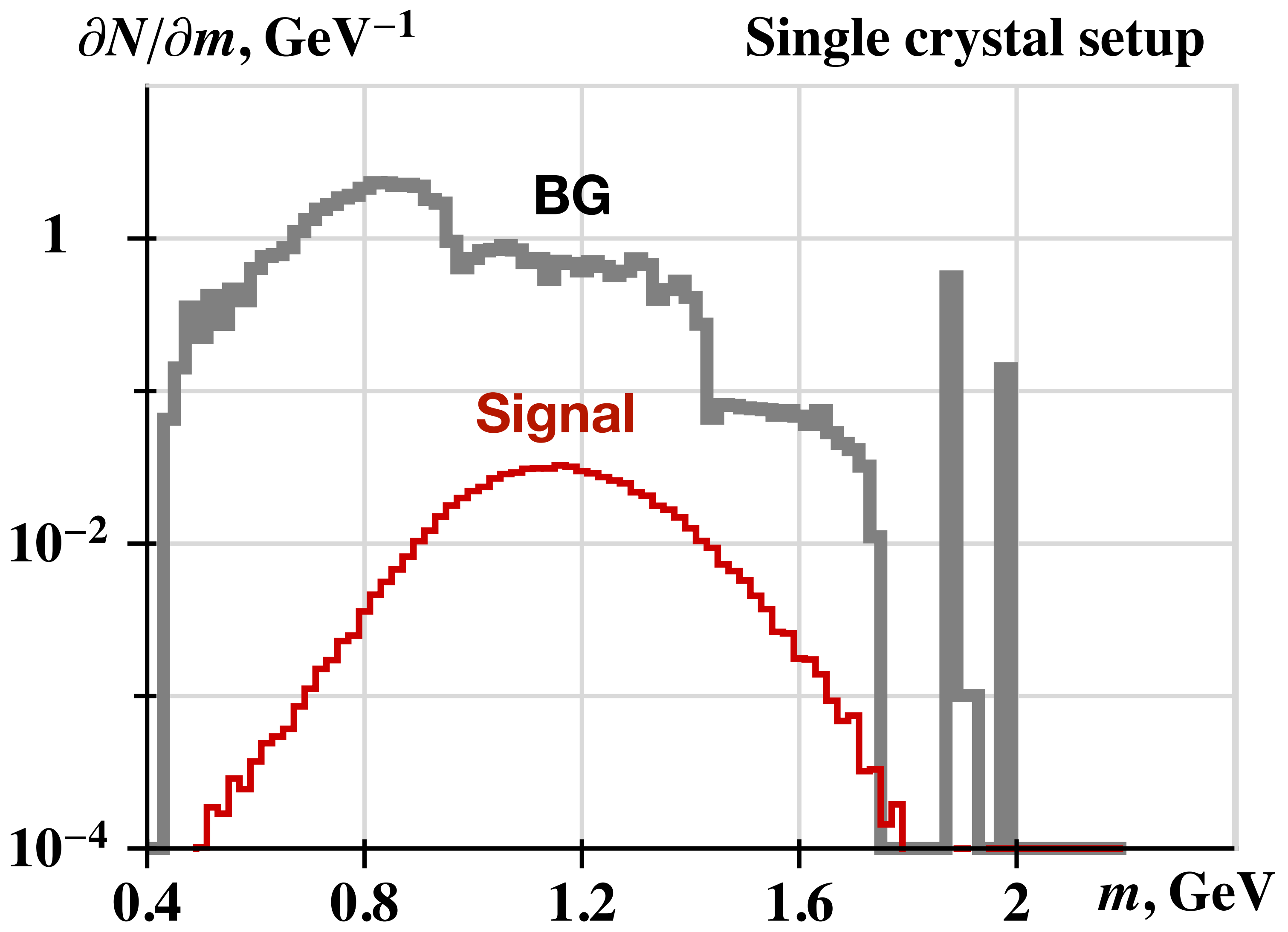
MDM of τ-lepton. Background from other decay channels

A.S. Fomin et al. JHEP 1903 (2019) 156









- 🟥 $D_s^+ \to \tau^+ \nu_\tau, \quad \tau^+ \to \pi^+\pi^+\pi^- \bar{\nu}_\tau$
- ⬛ $D_s^+ \to \tau^+ \nu_\tau, \quad \tau^+ \to \pi^+\pi^+\pi^- \pi^0 \bar{\nu}_\tau$
- 🟦 $D_s^+ \to \tau^+ \nu_\tau, \quad \tau^+ \to \pi^+\pi^+\pi^- \pi^0\pi^0 \bar{\nu}_\tau$
- ▬ $D_s^+,\ D^+,\ \Lambda_c^+ \to \pi^+\pi^+\pi^- X^0$
- 🟩 $B^+ \to D_s^+ X, \quad D_s^+ \to \pi^+\pi^+\pi^- X^0$
- 🟪 $B^+ \to D^+ X, \quad D^+ \to \pi^+\pi^+\pi^- X^0$
- 🟧 $B^+ \to \Lambda_c^+ X, \quad \Lambda_c^+ \to \pi^+\pi^+\pi^- X^0$