Σ^+ and Λ_c^+ studies at the SPS with double crystal setup

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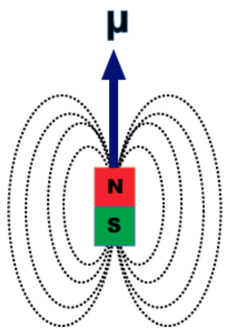
INTRODUCTION: Magnetic dipole moment (MDM) of short-living particles



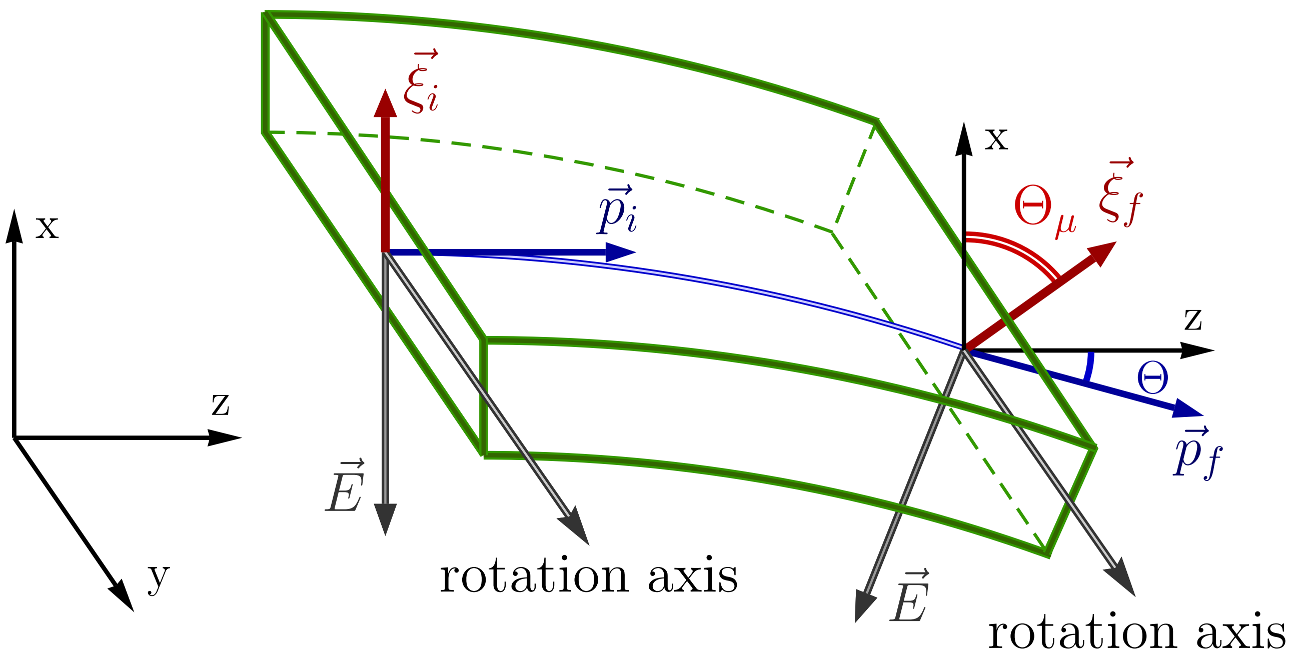
$$\vec{\mu} = \frac{g}{2}\,\frac{e}{m}\,\vec{S}, \qquad \vec{S} = \frac{\hbar}{2}\vec{\sigma}$$

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

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

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

Particle	$c\tau$	g-factor	Comments		Experiment
e^-		– 2.002 319 304 361 82 (52)	exp.	most accurate determinations of α	Harvard 2008
μ^-	659 m	– 2.002 331 8361 (10)	theor.	SM prediction	
		– 2.002 331 8418 (13)	exp.	3.4 σ deviation	BNL: E821 2006
τ^-	87 μm	– 2.002 354 42 (10)	theor.	SM prediction	
		– 2.036 (34)	exp.	$\sigma(e^+e^- \to e^+e^- \tau^+\tau^-)$	LEP2: DELPHI 2004
		– 2.002 (6)	*exp.*	*assuming $EDM_\tau = 0$*	*from LEP and SLD 2000*
		no direct measurement	exp.	Proposed in arxiv:1810.06699	
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	Fermilab 1992
Λ_c^+	60 μm	+ 1.90 (15)	theor.	assuming $g_c \approx 2$	
		not measured	exp.	Feasibility studies at LHC	



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

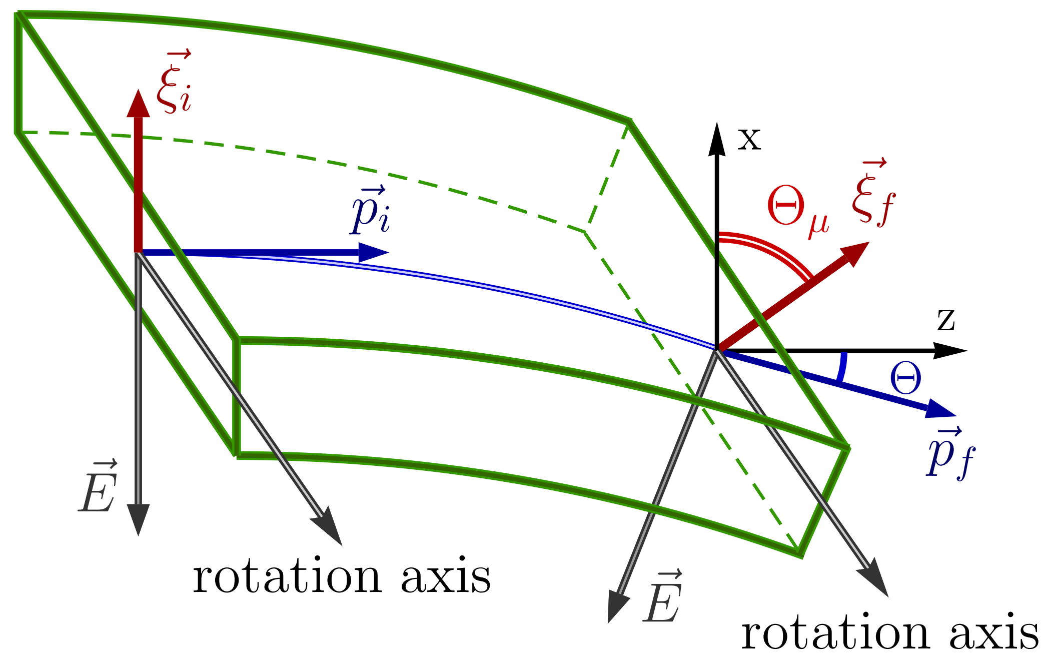
$$a = \frac{g-2}{2}, \qquad \Theta = \frac{L}{R}$$

$\overrightarrow{\xi}_i, \overrightarrow{\xi}_f$ – initial and final polarisations of Λ_c (before and after the crystal)

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

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

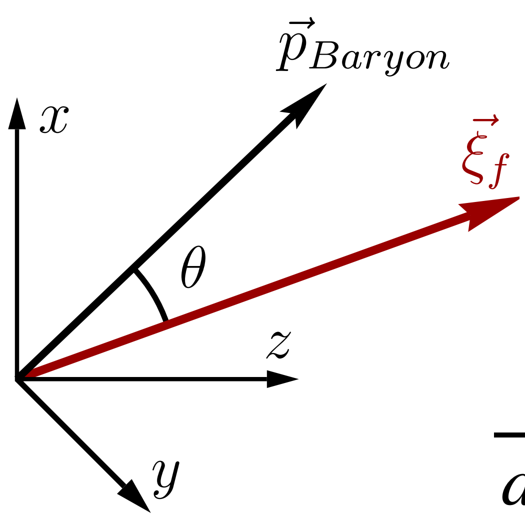
V.G. Baryshevsky, Sov. Tech. Phys. Lett. 5 (1979) 73.
V.L. Lyuboshits, Sov. J. Nucl. Phys. 31 (1980) 509.



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

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

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



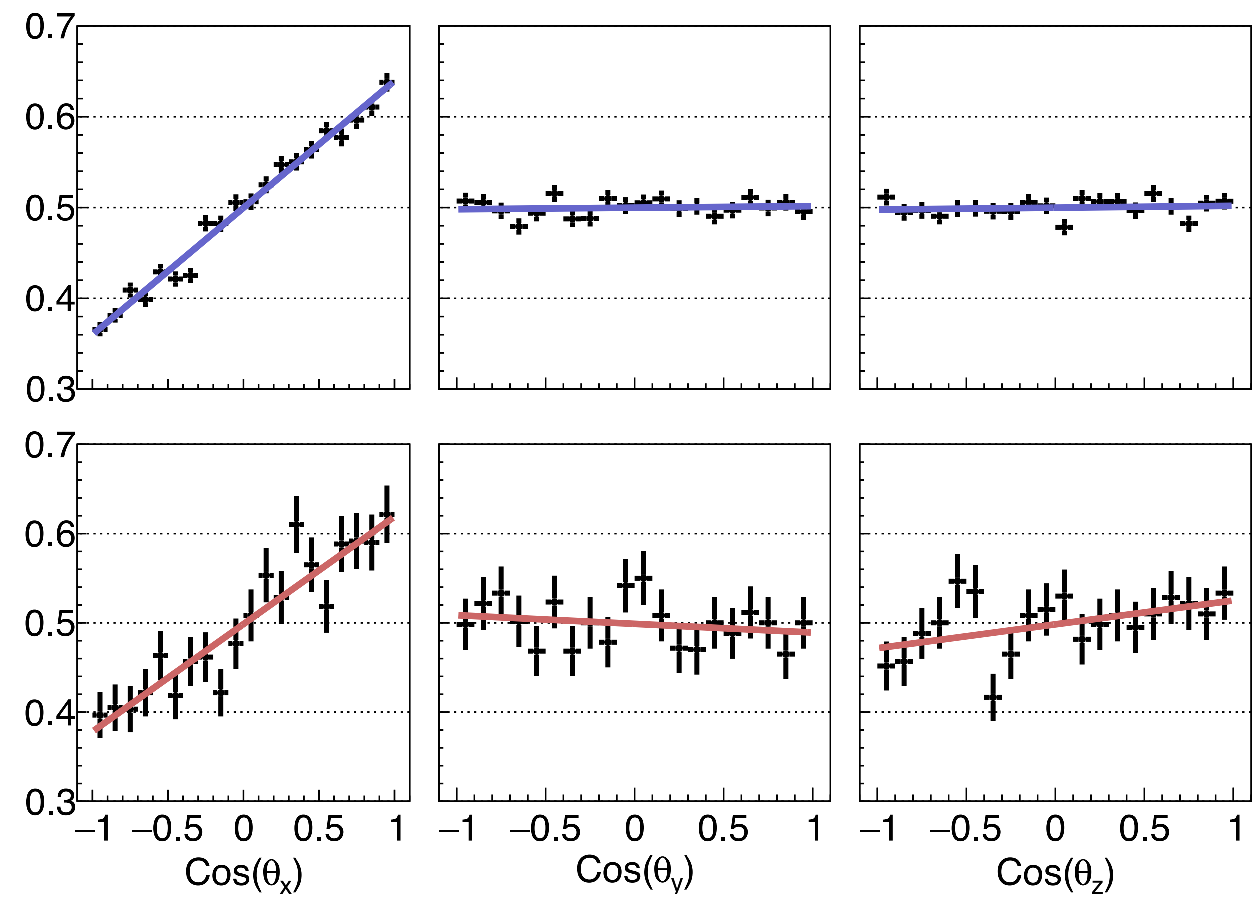
$$\Lambda_c^+ \rightarrow Meson + Baryon$$

$$\frac{dN}{d\cos\theta_k} = \frac{1}{2}\left(1 + \alpha\,\xi_k \cos\theta_k\right)$$

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

$\xi \neq 0$ – Λ_c polarisation at the production

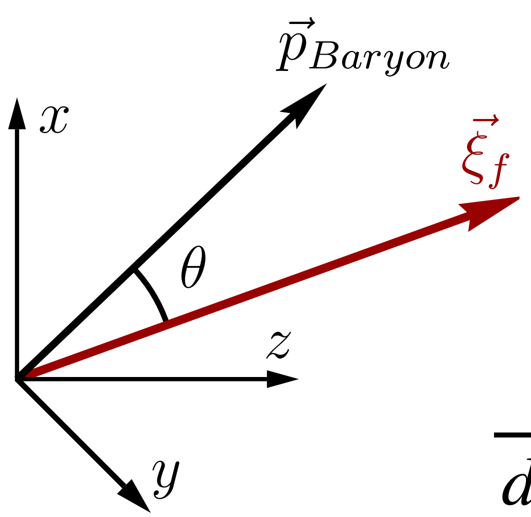
$\alpha \neq 0$ – reveals polarisation at the decay



$$\Lambda_c^+ \to \Lambda^0(p\pi^-)\,\pi^+ \qquad \alpha = 0.91\,(15) \qquad Br = 1.3 \cdot 0.64\,\%$$

$$\Lambda_c^+ \to \Delta^{++}(p\pi^+)\,K^- \qquad \alpha = 0.67\,(30) \qquad Br = 1.1\,\%$$

$$\Sigma^+ \to p\,\pi^0 \qquad \alpha = 0.98\,(2) \qquad Br = 52\,\%$$



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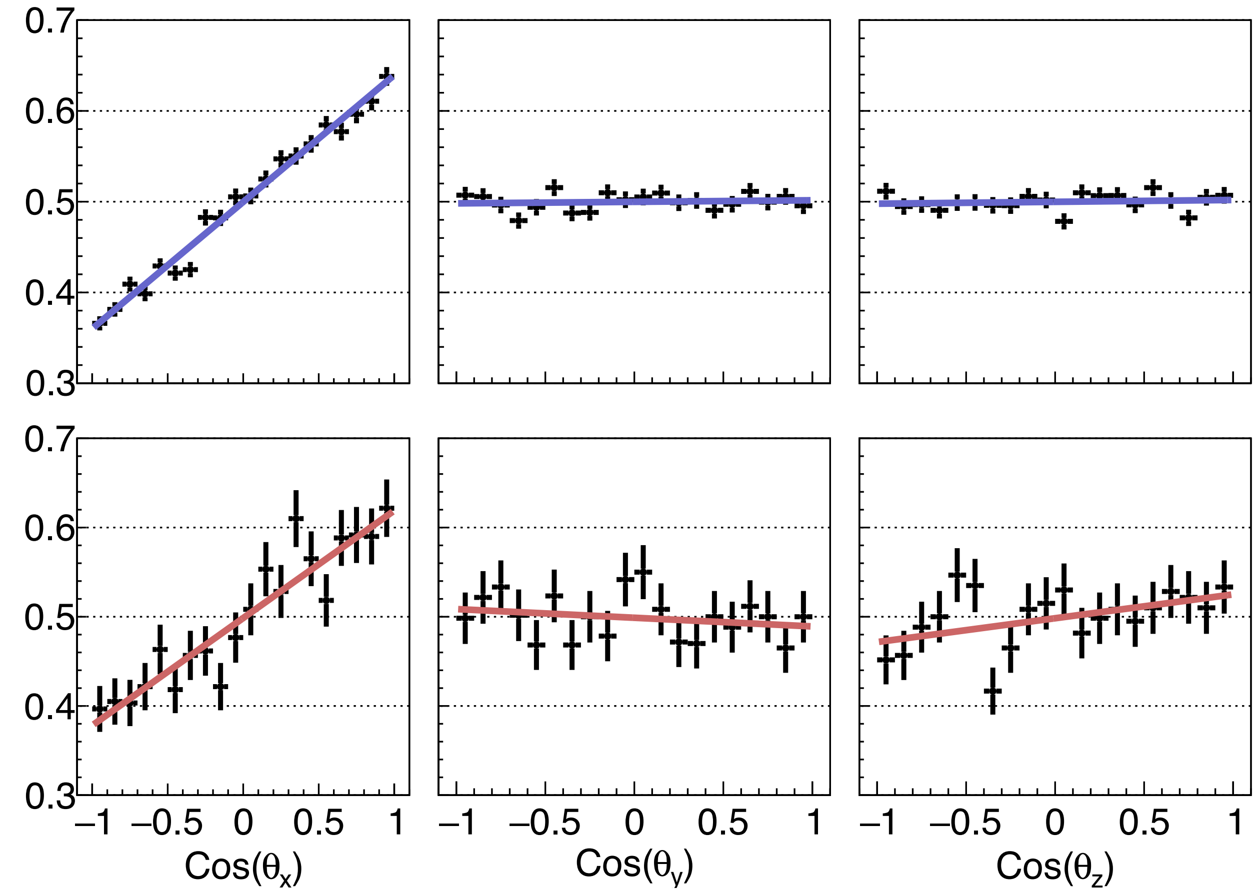

$\xi \neq 0$ – Λ_c polarisation at the production

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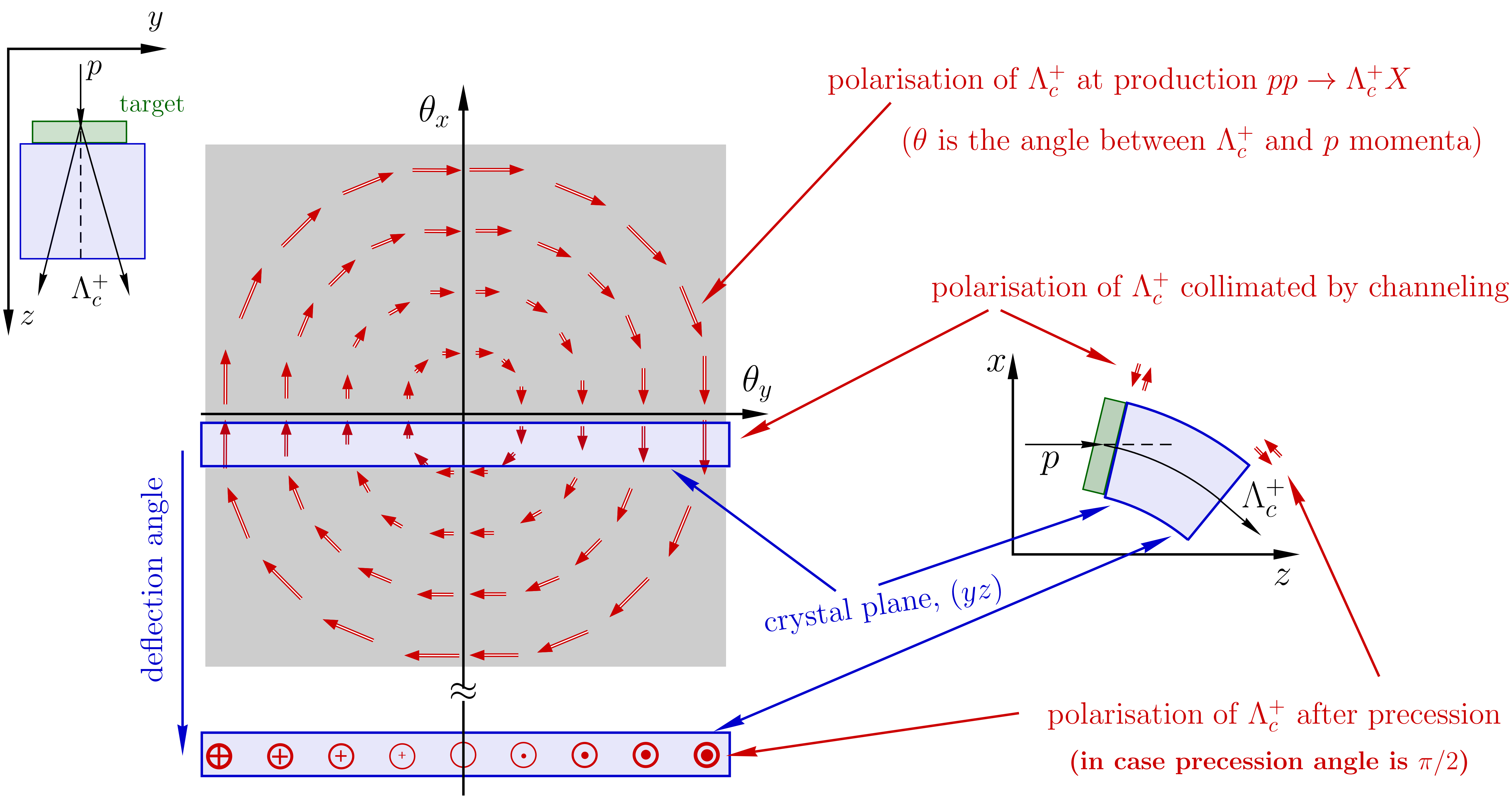
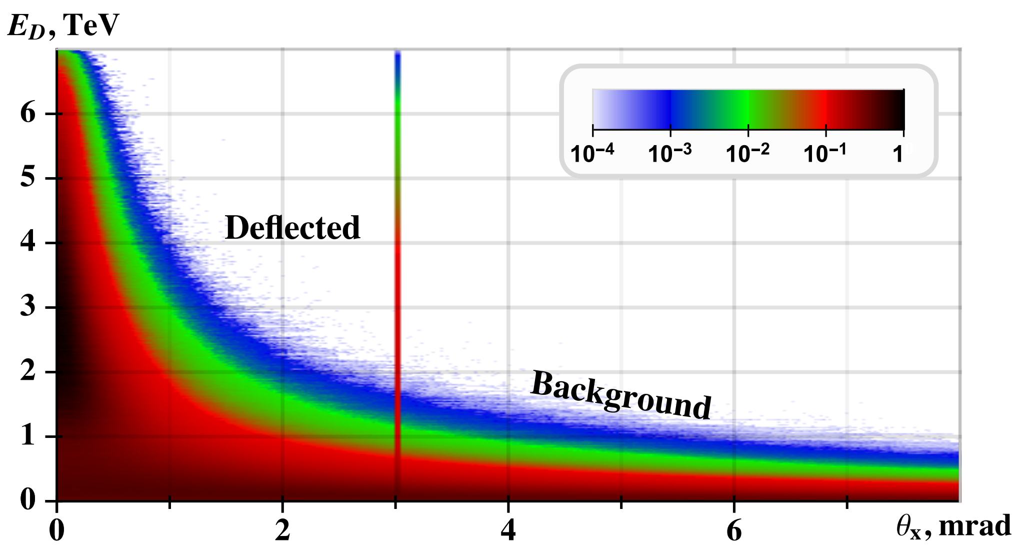


y
p
target
Λ_c^+
z
θ_x
θ_y
deflection angle
≈
polarisation of Λ_c^+ at production $pp \to \Lambda_c^+ X$
(θ is the angle between Λ_c^+ and p momenta)
polarisation of Λ_c^+ collimated by channeling
x
p
Λ_c^+
z
crystal plane, (yz)
polarisation of Λ_c^+ after precession
(in case precession angle is $\pi/2$)

$$\Delta g = \frac{2}{\alpha\ \xi\ \gamma\ \Theta}\sqrt{\frac{3}{N_{\Lambda_c}}}$$

Λ_c spectra →

$$\Delta g = \frac{2}{\alpha_j\ \xi\ \Theta}\sqrt{\frac{3}{\Phi\, t\, \frac{\Gamma_j}{\Gamma}\, \eta_{\mathrm{det}}^{(j)} \int \frac{\partial N_{\mathrm{tar+crys}}}{\partial \varepsilon}\, \gamma^2\, d\varepsilon}}$$

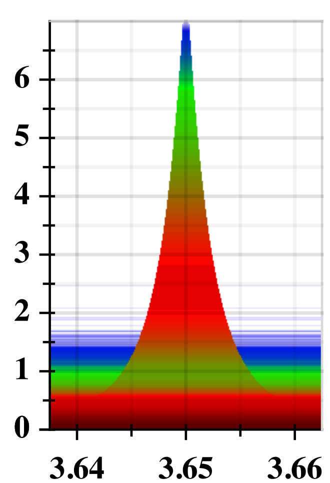


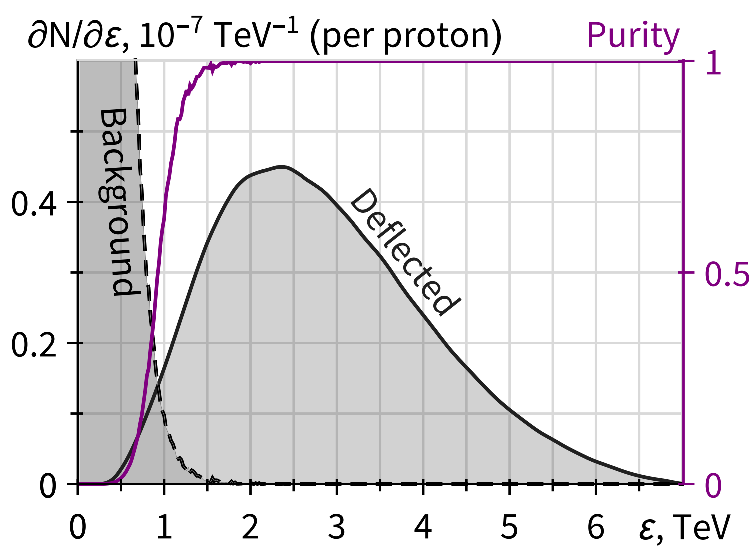
Spectra-Angular distribution of Λc (Pythia 8.2)

– p-p collision in fixed target at LHC

Λc spectra after the target

$$\frac{\partial N_{\mathrm{tar}}}{\partial \varepsilon} = \frac{\rho\, N_A\, A_{\mathrm{tar}}}{M_{\mathrm{tar}}}\, \sigma_{\Lambda_c}\, \frac{\partial N}{\partial \varepsilon} \int_0^{L_{\mathrm{tar}}} e^{-\frac{L}{c\,\tau\,\gamma}}\, dL$$





Λc spectra after the crystal

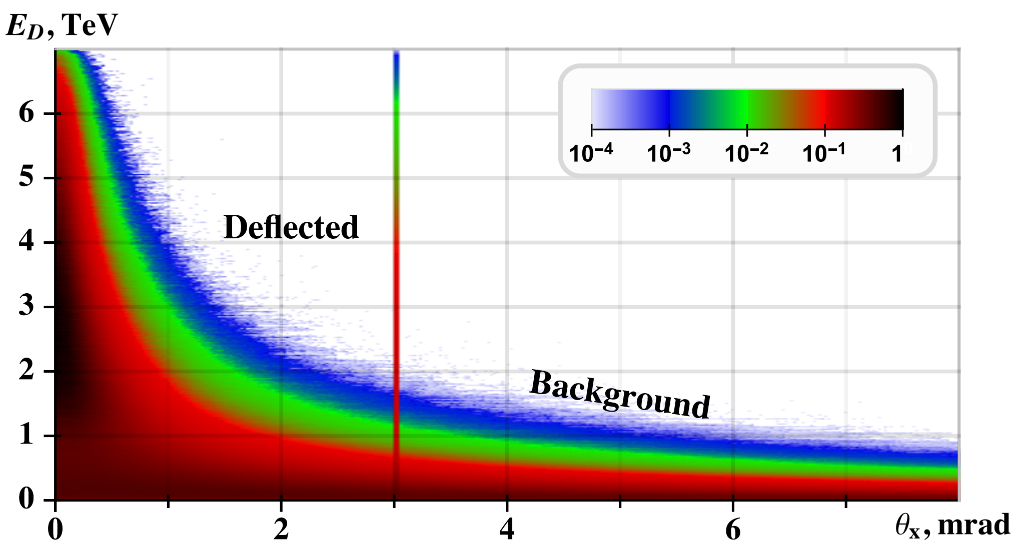
$$\frac{\partial N_{\mathrm{tar+crys}}}{\partial \varepsilon} = \frac{\partial N_{\mathrm{tar}}}{\partial \varepsilon}\, \eta_{\mathrm{def}}\, e^{-\frac{L_{\mathrm{crys}}}{c\,\tau\,\gamma}}$$

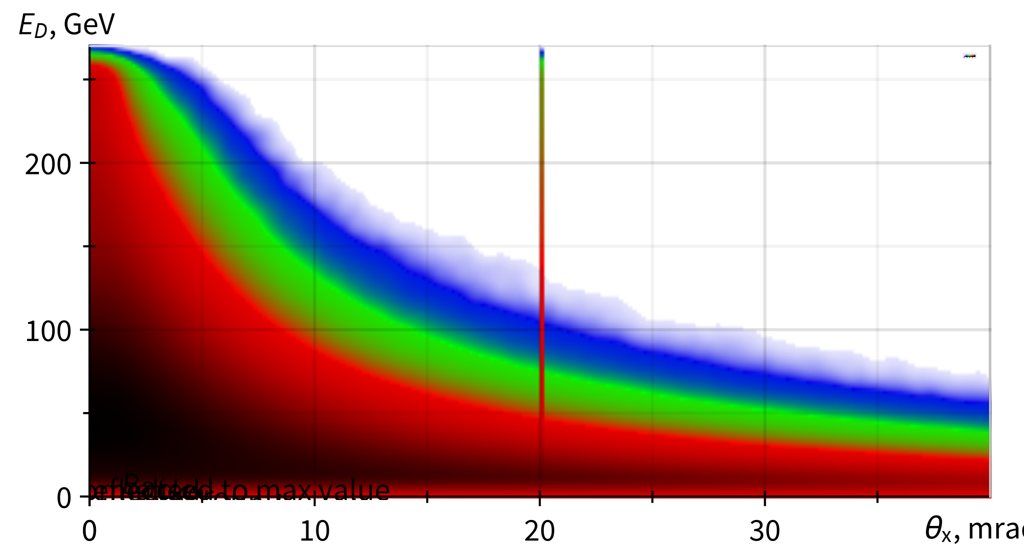
LHC

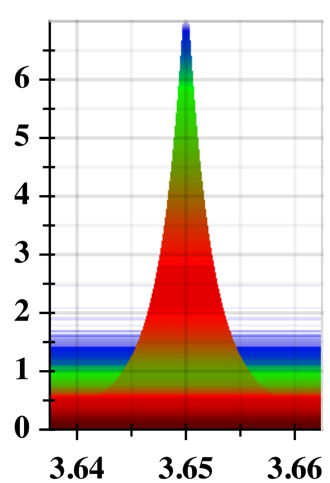
Θ = 3—6 mrad

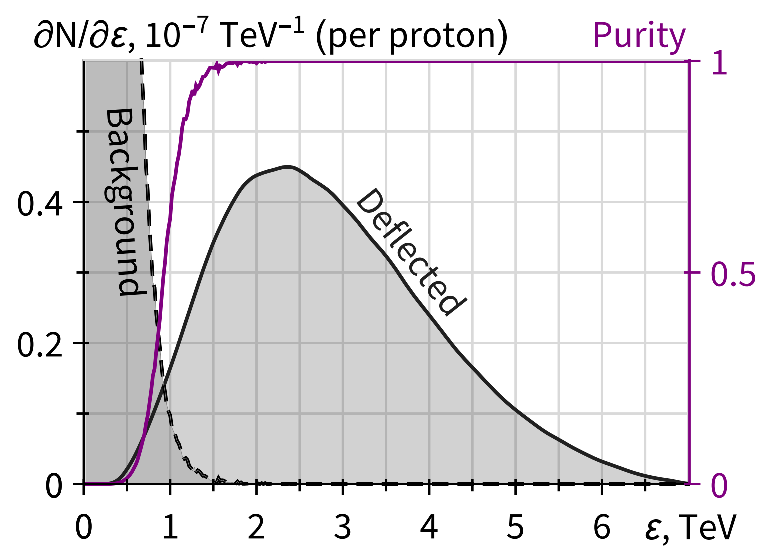
SPS

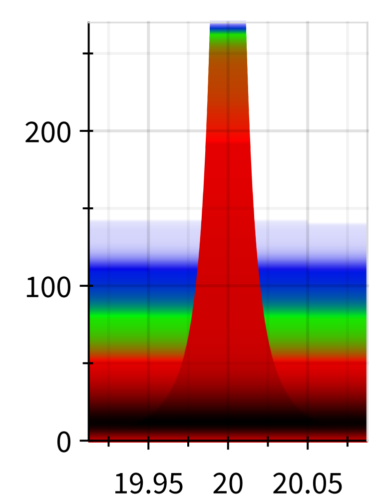
Θ = 15—20 mrad

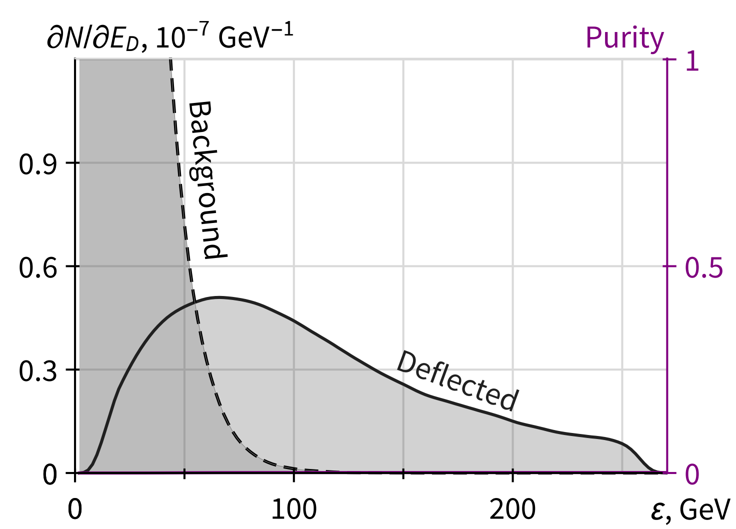








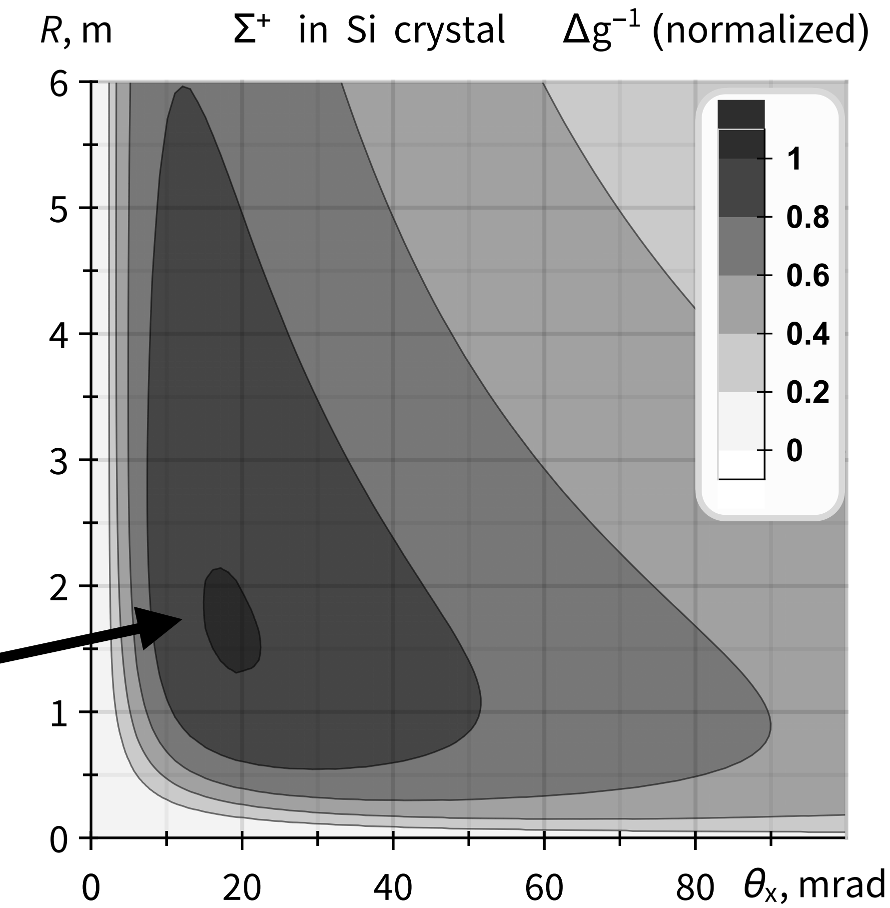




Optimal crystal parameters

$$\Delta g = \frac{1}{\alpha\,|P|\,\Theta}\sqrt{\frac{12}{\Phi\; t\; \eta_{\rm det}\; Br_j \int \frac{\partial N_{\rm tar+crys}}{\partial \varepsilon}\,\gamma^2\, d\varepsilon}}$$

$$\Delta g^{-1}_{\rm norm} = \frac{\Theta}{\Theta^0}\sqrt{\frac{\int \frac{\partial N_{\rm tar+crys}}{\partial \varepsilon}\,\gamma^2\, d\varepsilon}{\int \frac{\partial N^0_{\rm tar+crys}}{\partial \varepsilon}\,\gamma^2\, d\varepsilon}}$$



Optimal crystal:

θ_x = 10–30 mrad

R = 2 m, L = 2–6 cm

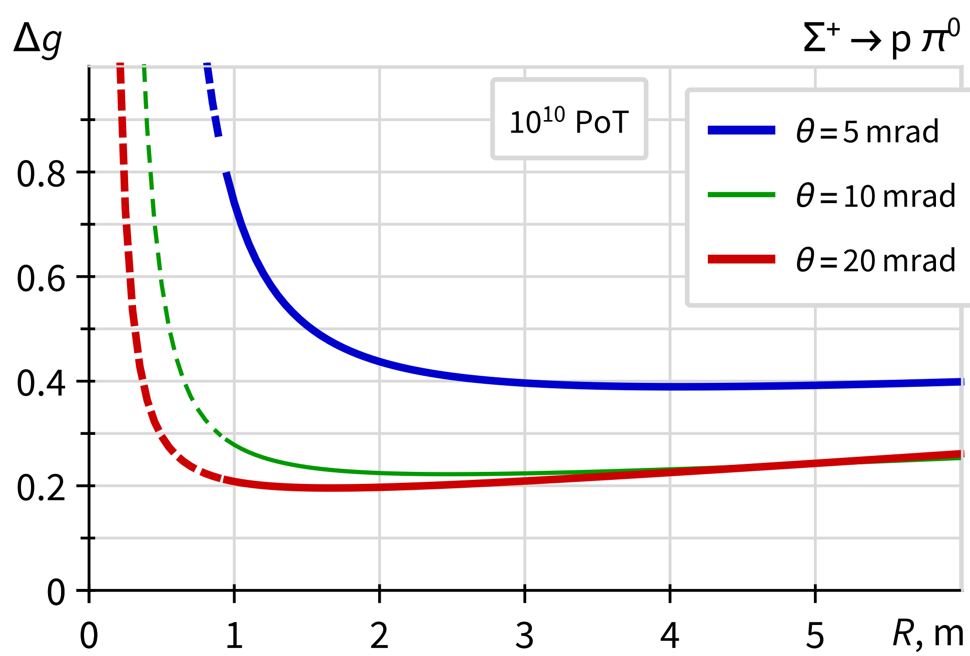
Other parameters:

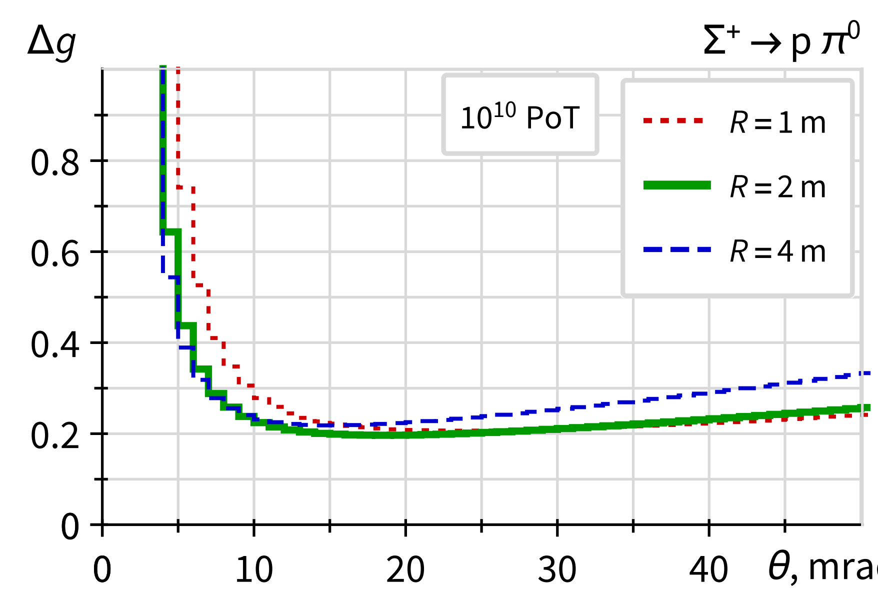
P = 0.12

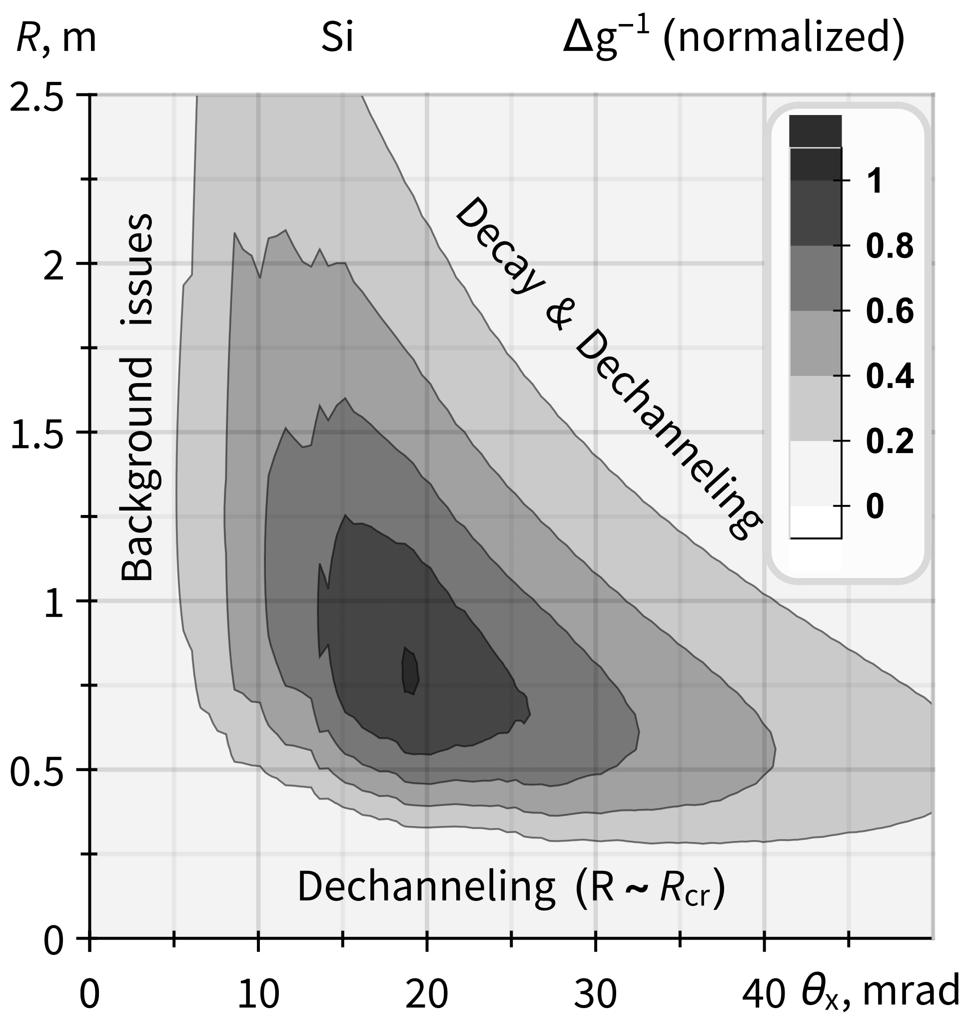
α = 0.98

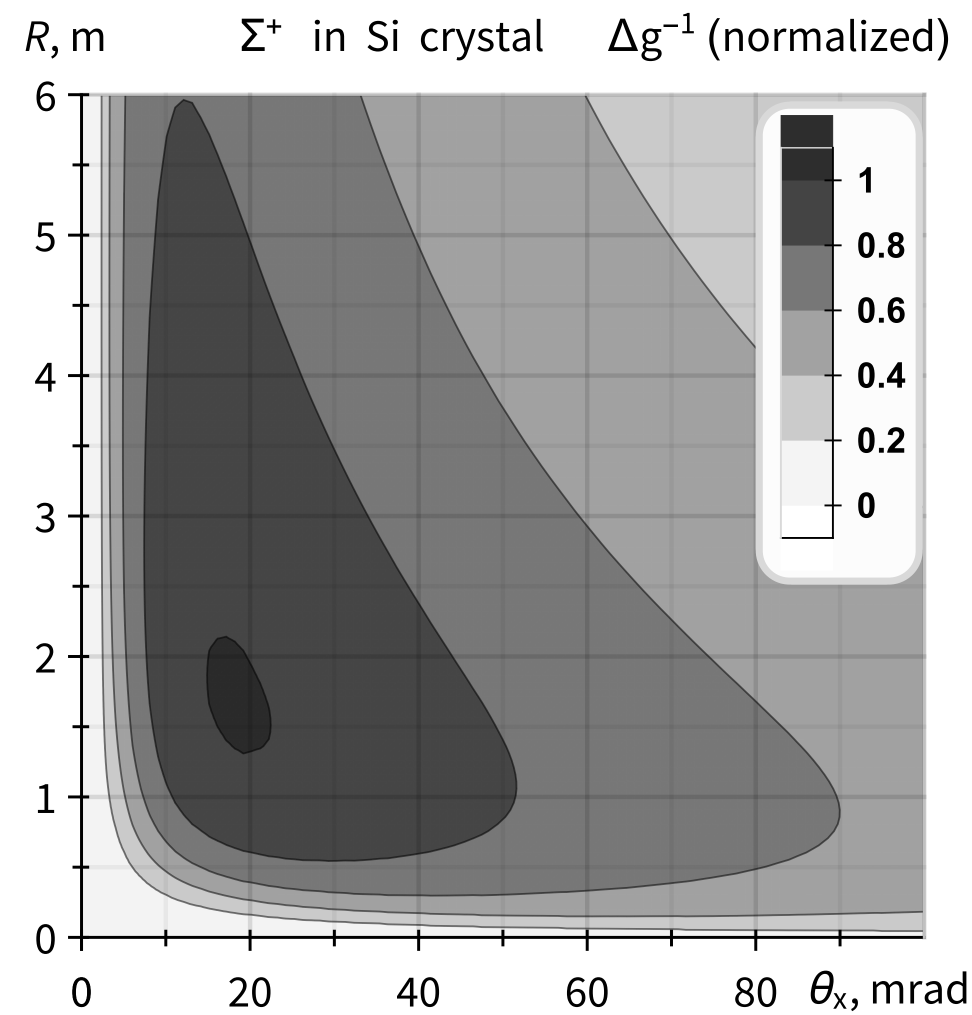
Br_j = 0.516

$\phi\; t\; \eta_{\rm det}$ = 10^{10} PoT









Optimal crystal for Λ_c^+

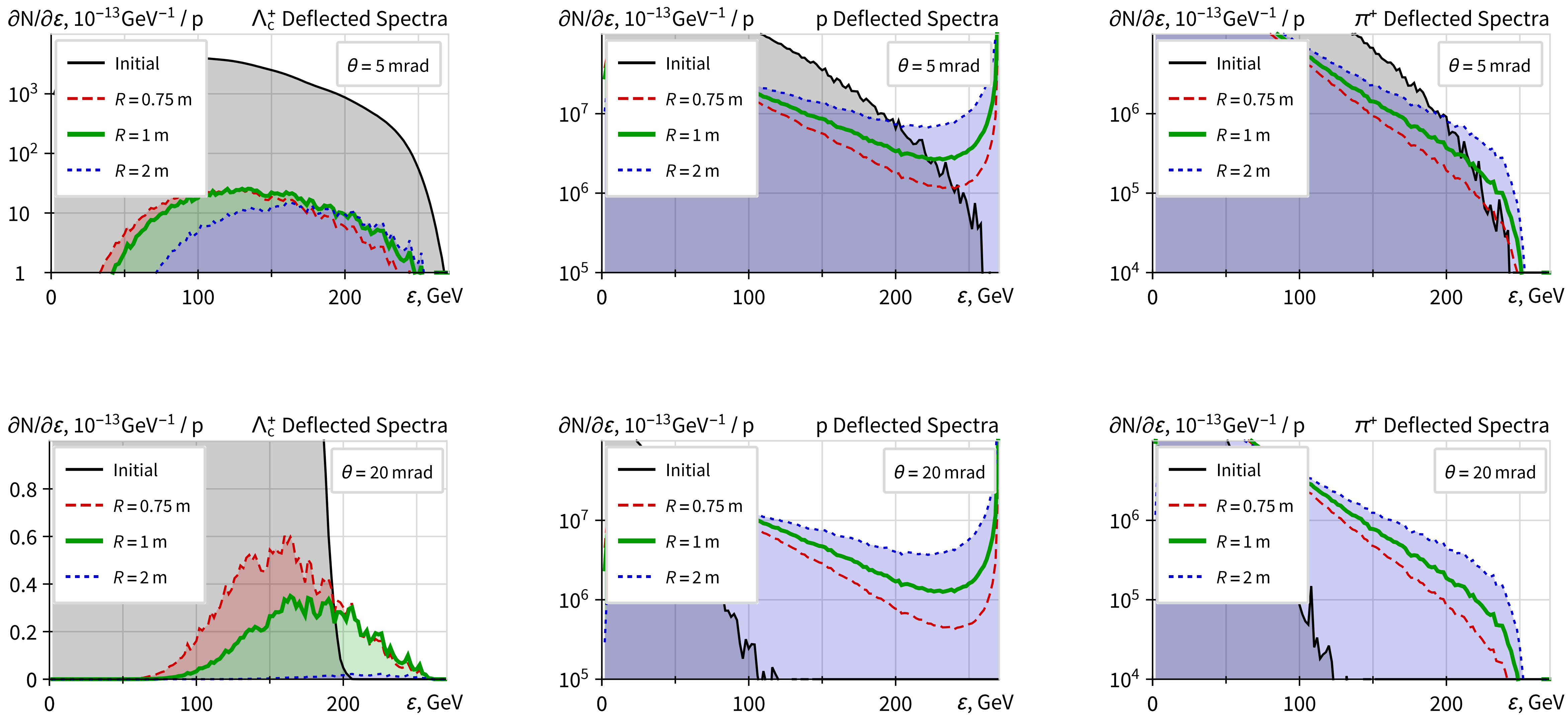
θ_x = 15–20 mrad

R = 1 m, L = 1.5–2 cm

Optimal crystal for Σ^+

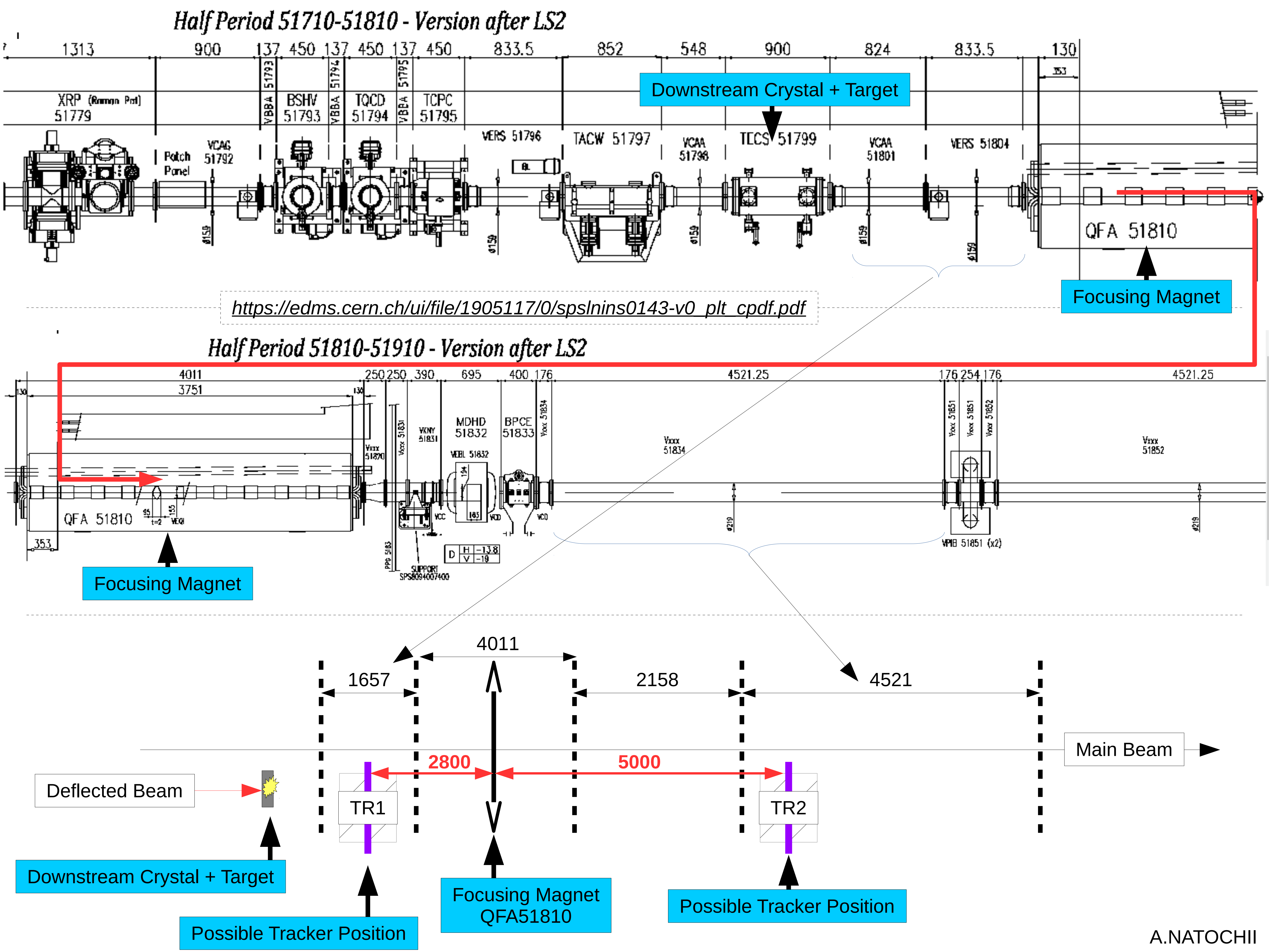
θ_x = 10–30 mrad

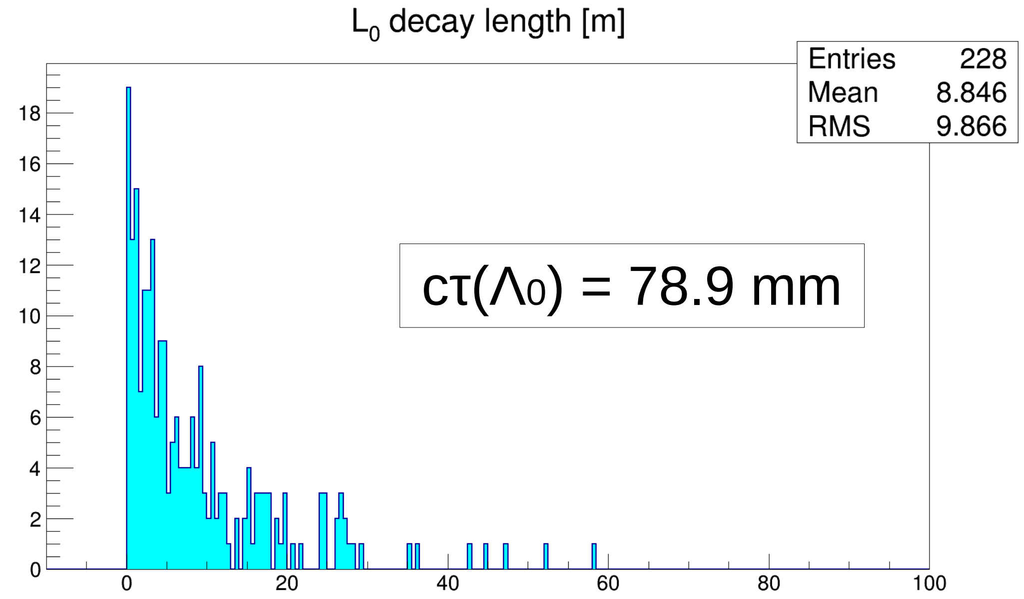
R = 2 m, L = 2–6 cm

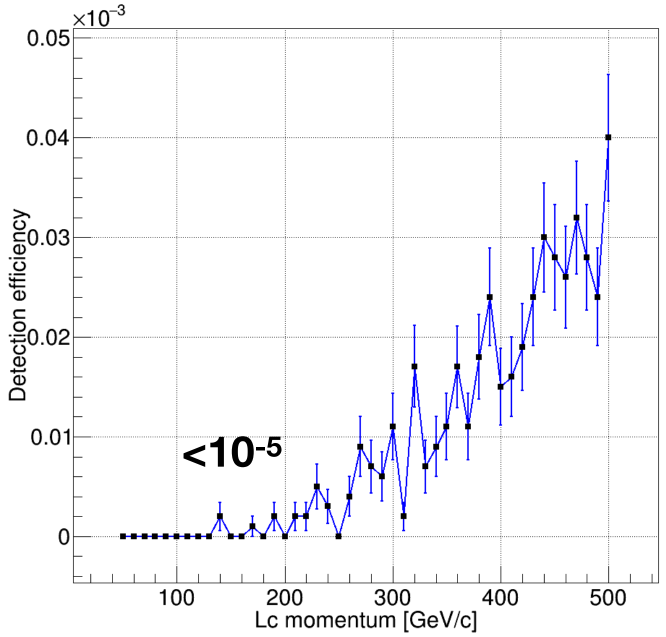


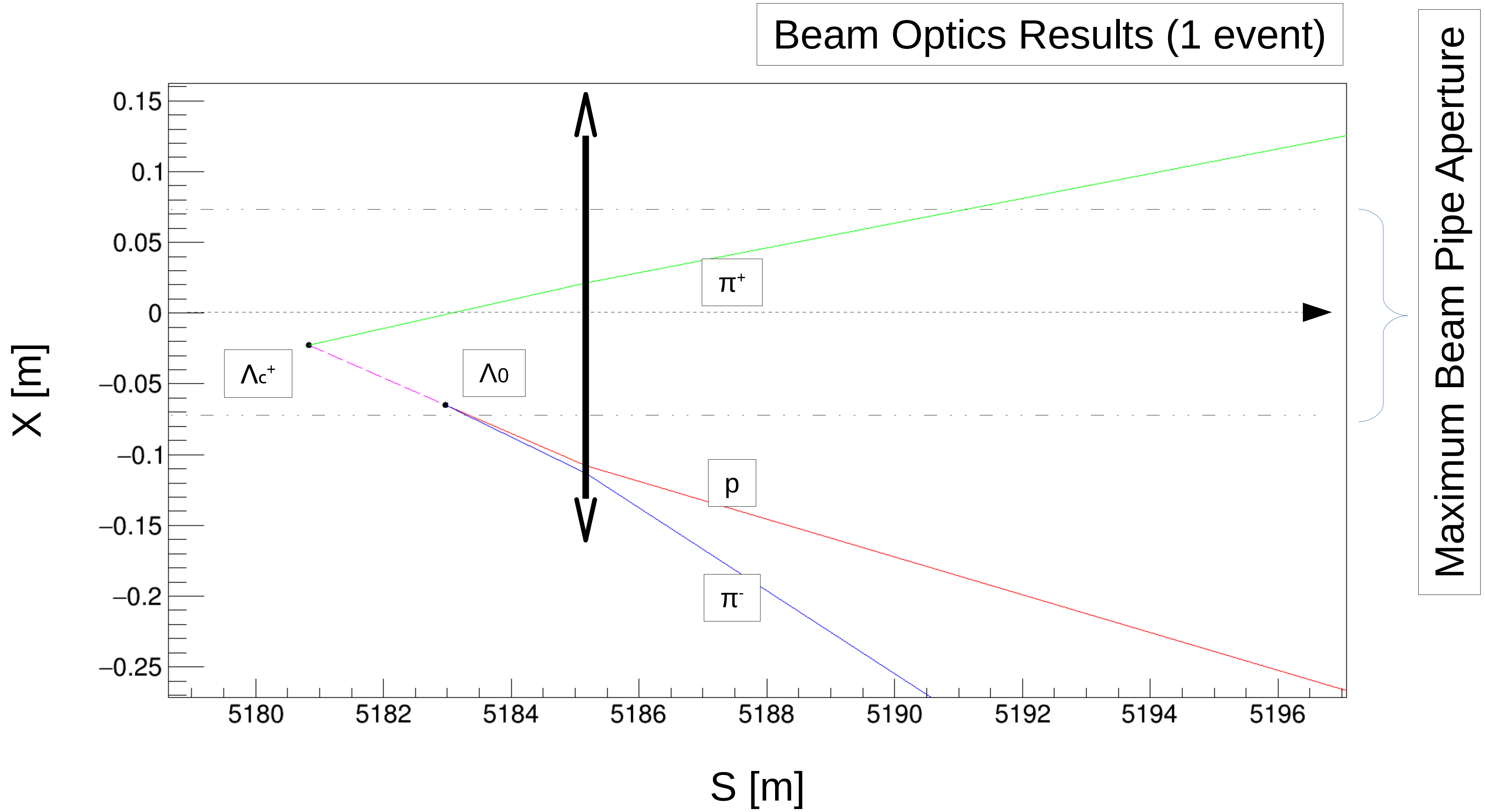
	Λ_c^+	p	π^+	K^+	Σ^+	energy
per initial p	3.2×10^{-5}	3.6	3.4	0.36	0.04	—
per produced Λ_c^+	1	1.1×10^{5}	1.1×10^{5}	1.1×10^{4}	1.2×10^{3}	—
per deflected Λ_c^+ (5 mrad)	1	2.0×10^{6}	0.8×10^{6}		$\sim10^{3}$	150 GeV
per deflected Λ_c^+ (20 mrad)	1	6.0×10^{6}	0.6×10^{6}		$\sim10^{3}$	200 GeV

POSSIBLE SETUP : Measuring the MDM of Λ_c at SPS



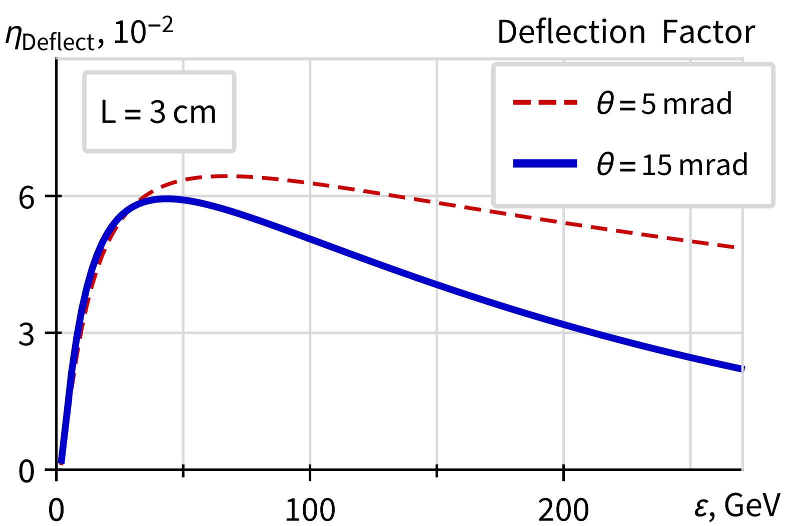

L0 decay length [m]
Entries 228
Mean 8.846
RMS 9.866
cτ(Λ0) = 78.9 mm

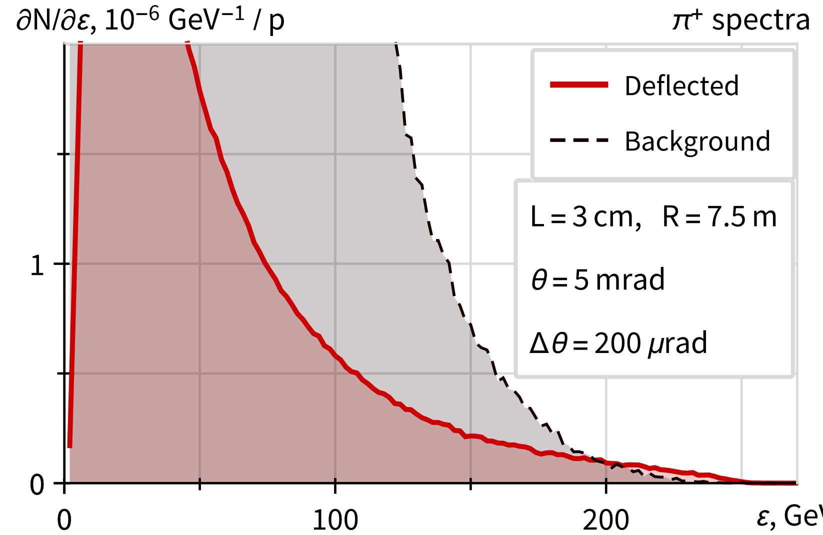

×10-3
Detection efficiency
Lc momentum [GeV/c]
<10-5

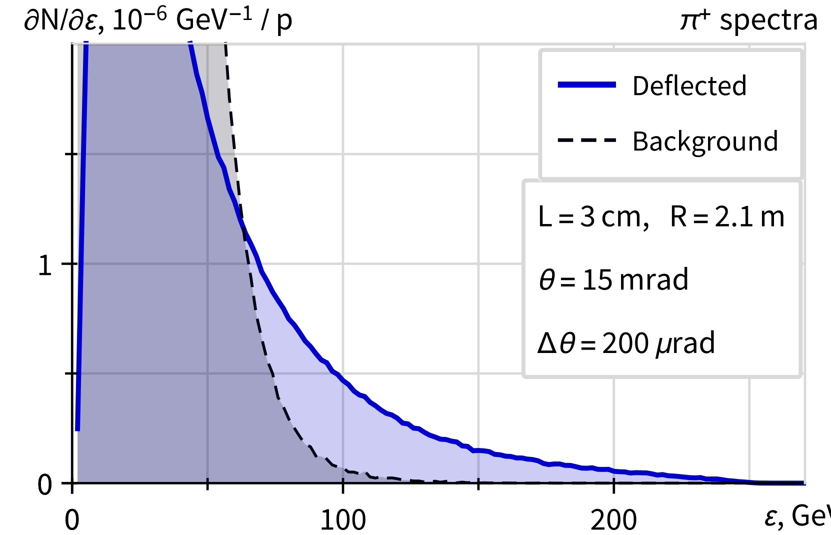

Beam Optics Results (1 event)
Maximum Beam Pipe Aperture
X [m]
S [m]
π+
Λc+
Λ0
p
π-
5

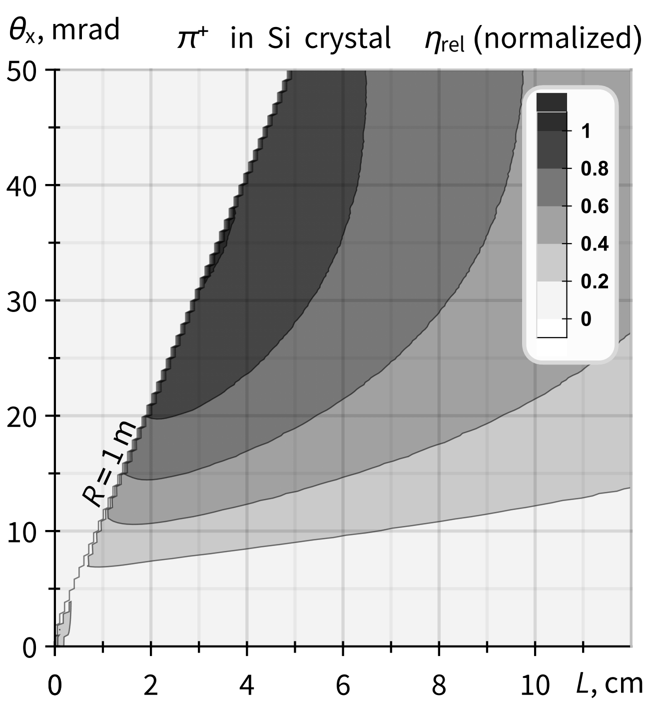
A.NATOCHII

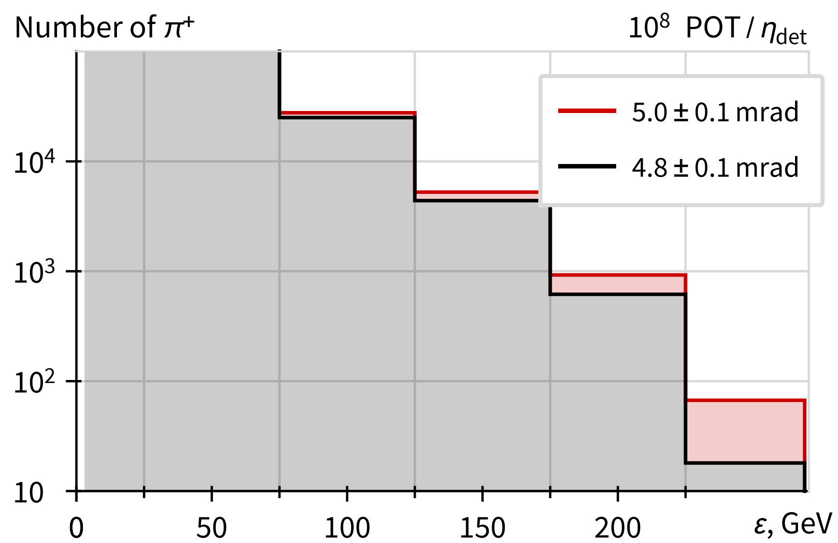
Channeling efficiency of π^+ produced in the target

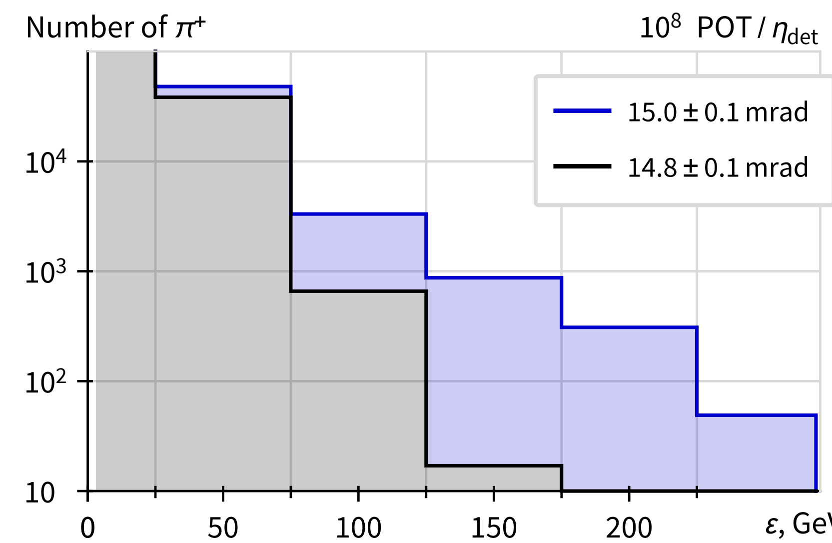












for Θ = 15 mrad

— the deflection efficiency is lower

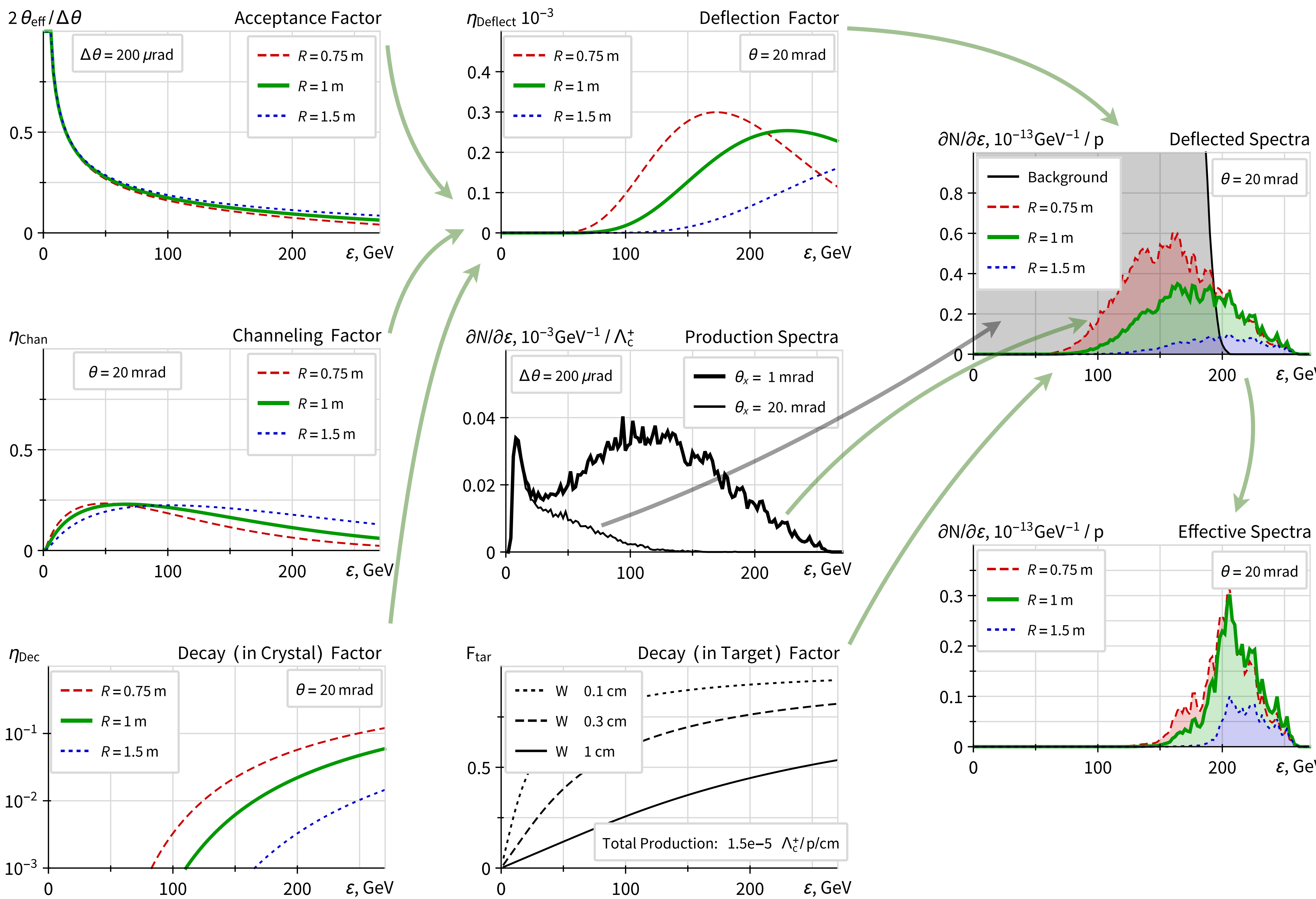
— but the BG separation is much better !

Efficiency of MDM measurement

Place	Process	Efficiency (per process)						
		π^+	$\Sigma^+ \to p\,\pi^0$	$\Lambda_c^+ \to \Lambda^0 \pi^+$		$\Lambda_c^+ \to \Delta^{++} K^-$		
		3cm, 2 m	2 cm, 2 m	1.5cm, 1m	1cm, 1.4m	8 cm, 20 m	7 cm, 5 m	crystal (L, R)
		270 GeV	270 GeV	270 GeV	270 GeV	7 TeV	7 TeV	*p* energy
target	production & decay	0.9	0.017	$3.0 \cdot 10^{-6}$	$3.0 \cdot 10^{-6}$	$0.5 \cdot 10^{-4}$	$0.5 \cdot 10^{-4}$	
crystal	collimation	0.05	0.004	0.0024	0.0028	0.007	0.0028	
	decay	—	—	0.017	0.06	0.21	0.07	
	deflection	0.09	0.24	0.16	0.3	0.27	0.06	
	Total (per *p*)	$0.4 \cdot 10^{-3}$	$1.4 \cdot 10^{-5}$	$2.0 \cdot 10^{-11}$	$1.7 \cdot 10^{-10}$	$2.2 \cdot 10^{-8}$	$0.7 \cdot 10^{-9}$	
detector	purity	0.5—1	0.4	0.13	—	0.5	0.5	
	BF · decay	—	0.2	0.002	0.0026	0.011	0.011	
	MDM	—	0.012	0.022	0.0021	0.18	0.4	
	MDM (per *p*)	—	10^{-8}	10^{-16}	10^{-15}	$2.1 \cdot 10^{-11}$	$1.3 \cdot 10^{-12}$	

$$\Delta g = \sqrt{\frac{1}{N_{\rm POT}\ \eta_{\rm det}\ \eta_{\rm MDM}}}$$

Thank you for your attention !


Acceptance Factor
$2\,\theta_{eff}/\Delta\theta$
$\Delta\theta = 200\ \mu$rad
$R = 0.75$ m
$R = 1$ m
$R = 1.5$ m
ε, GeV
Deflection Factor
$\eta_{Deflect}\ 10^{-3}$
$\theta = 20$ mrad
Deflected Spectra
$\partial N/\partial\varepsilon,\ 10^{-13}\mathrm{GeV}^{-1}$ / p
Background
Channeling Factor
η_{Chan}
Production Spectra
$\partial N/\partial\varepsilon,\ 10^{-3}\mathrm{GeV}^{-1} / \Lambda_c^+$
$\theta_x = 1$ mrad
$\theta_x = 20.$ mrad
Effective Spectra
Decay (in Crystal) Factor
η_{Dec}
Decay (in Target) Factor
F_{tar}
W 0.1 cm
W 0.3 cm
W 1 cm
Total Production: 1.5e−5 Λ_c^+/p/cm

D. Chen, et al. First Observation of Magnetic Moment Precession of Channeled Particles in Bent Crystals. Phys. Rev. Lett 69.3286 (1992)

$\Sigma^+ = u\uparrow u\uparrow s\downarrow$

Mass $m = 1189.37 \pm 0.07$ MeV (S = 2.2)
Mean life $\tau = (0.8018 \pm 0.0026) \times 10^{-10}$ s
$c\tau = 2.404$ cm
$(\tau_{\Sigma^+} - \tau_{\overline{\Sigma}^-}) / \tau_{\Sigma^+} = (-0.6 \pm 1.2) \times 10^{-3}$
Magnetic moment $\mu = 2.458 \pm 0.010\ \mu_N$ (S = 2.1)
$(\mu_{\Sigma^+} + \mu_{\overline{\Sigma}^-}) / \mu_{\Sigma^+} = 0.014 \pm 0.015$
$\Gamma(\Sigma^+ \to n\ell^+\nu)/\Gamma(\Sigma^- \to n\ell^-\overline{\nu}) < 0.043$

$\Lambda_C^+ = u\uparrow d\downarrow c\downarrow$

Mass $m = 2286.46 \pm 0.14$ MeV
Mean life $\tau = (200 \pm 6) \times 10^{-15}$ s
$c\tau = 59.9\ \mu$m

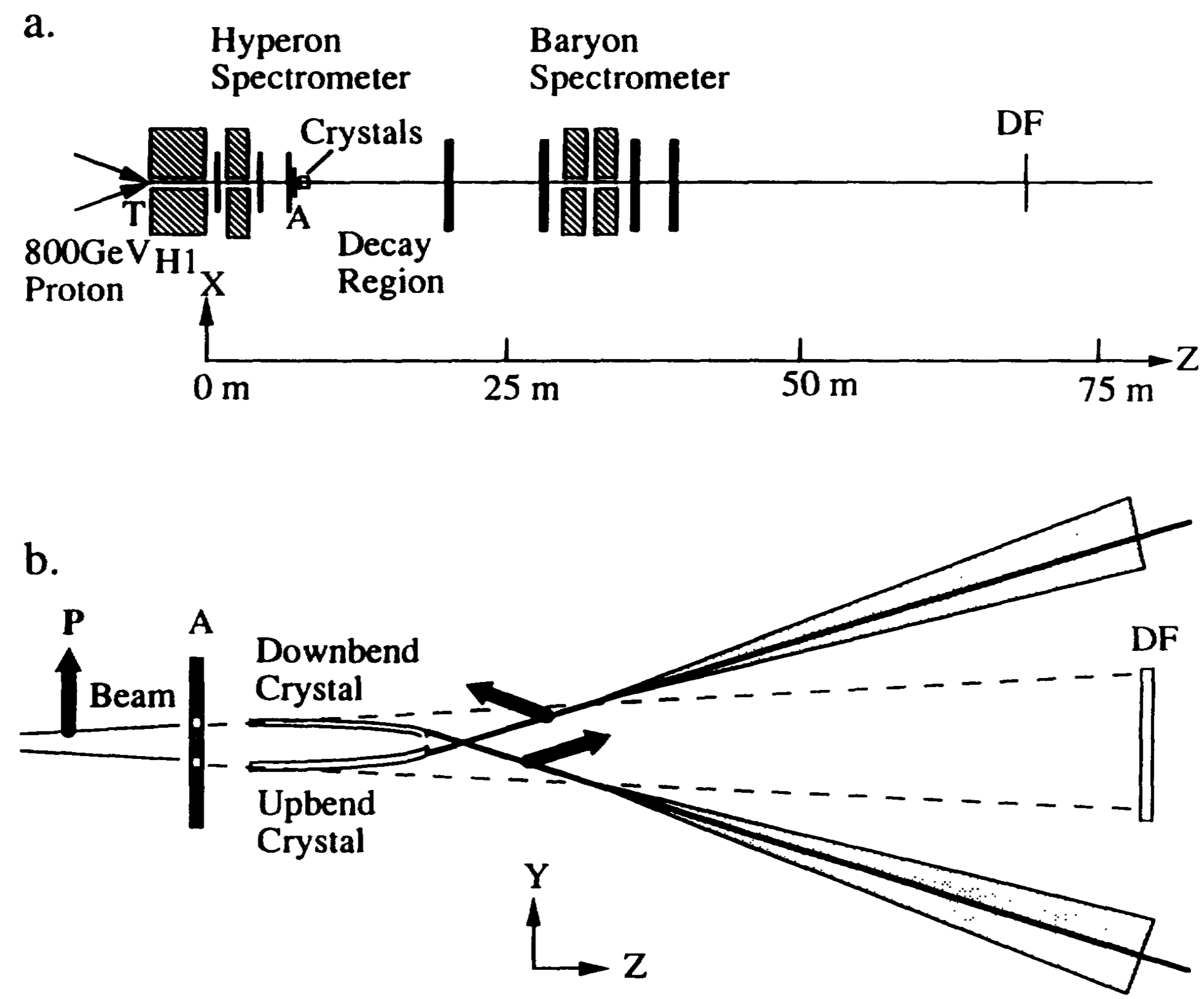
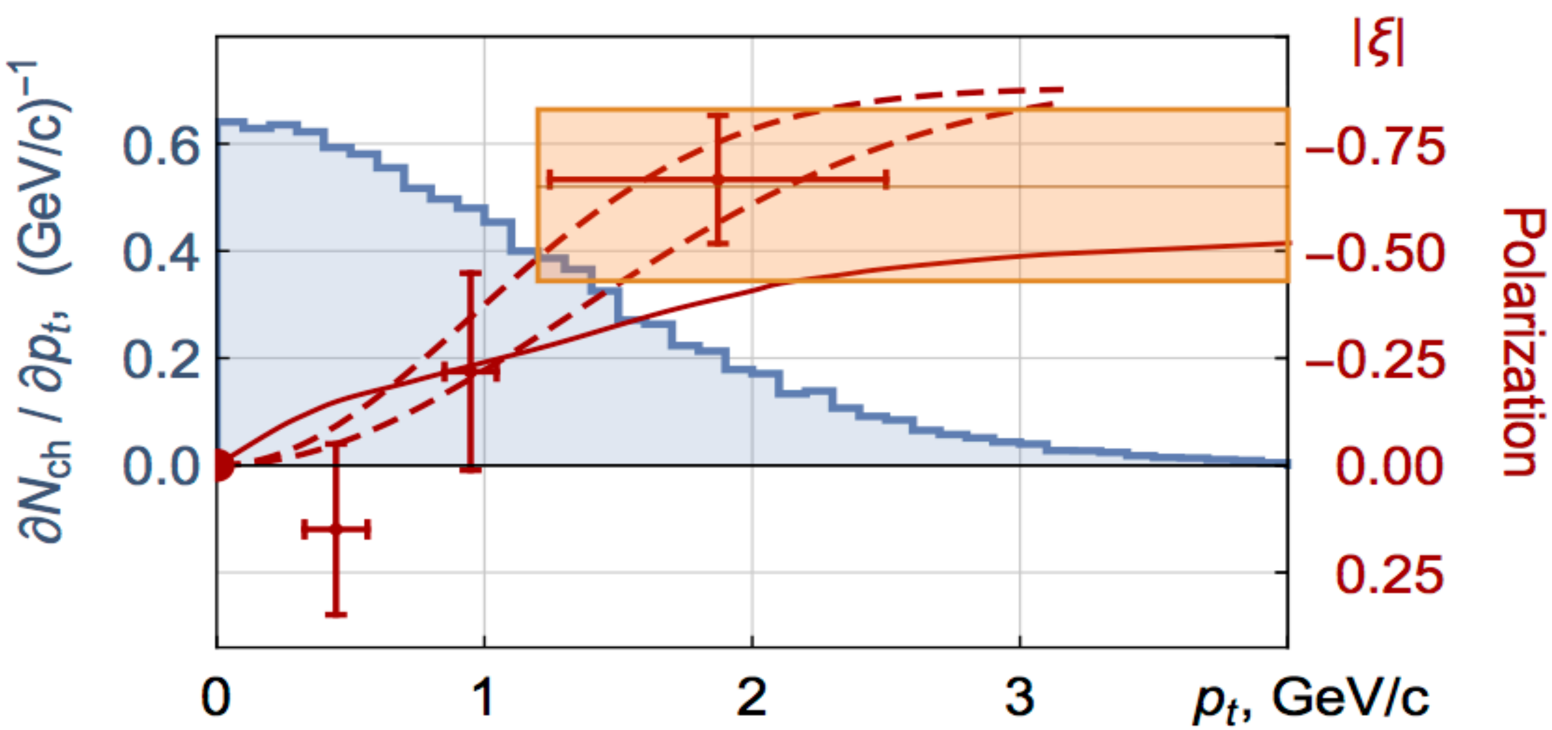


FIG. 1. (a) Plan view of the incident proton beam and spectrometer system. The horizontal scale (z) correctly illustrates the length of the apparatus, the vertical scale (x) is schematic only. (b) Elevation view of the channeling apparatus (not to scale). The arrows illustrate the spin precession in the crystals. Shaded areas depict the Σ^+ decay cone. The scintillation counters A and DF are part of the trigger and are described in the text.

$$\Delta g = \frac{1}{\alpha_j \, |\xi| \, \Theta} \sqrt{\frac{12}{\Phi \; t \; \frac{\Gamma_j}{\Gamma} \; \eta_{\rm det}^{(j)} \; \int \frac{\partial N_{\rm tar+crys}}{\partial \varepsilon} \, \gamma^2 \, d\varepsilon}}$$

$\xi_{th}^{(rms)} = -0.37$

$\xi_{ex}^{(rms)} = -0.40(5)$



J.G. Korner, *et al.*, Z. Phys., C2:117, 1979.

E.M. Aitala, *et al.*, Phys. Lett., B471:449, 2000

Fitted exp. data

G.R. Goldstein. FNAL, Batavia, Illinois, 1999.

$$\eta_{\rm def}\,(\varepsilon,\; R,\; L) = \eta_{\rm ang}\;\eta_{\rm ch}\;(1-\eta_{\rm dech})$$

– deflected fraction of secondary beam

Angular acceptance

$$\eta_{\rm ang} = {\rm erf}\left(\sqrt{2}\,\theta_{\rm acc}\,\gamma\right)$$

$$\theta_{\rm acc} = \sqrt{\frac{2\,U_{\rm eff}}{\varepsilon}}\left(1-\frac{\varepsilon}{R}\frac{1}{U'_x}\right)$$

Channeling acceptance

$$\eta_{\rm ch}\,(\varepsilon, R) = \frac{\eta_{\rm str}}{1+\left(\frac{\varepsilon}{R}\;\frac{1}{U'_x\,k_\theta}\right)^2}$$

Dechanneling probability

$$\eta_{\rm dech}(\varepsilon, R, L) = 1 - {\rm e}^{-\sqrt{\frac{L}{L_{\rm dech}(\varepsilon, R)}}}$$

Dechanneling length

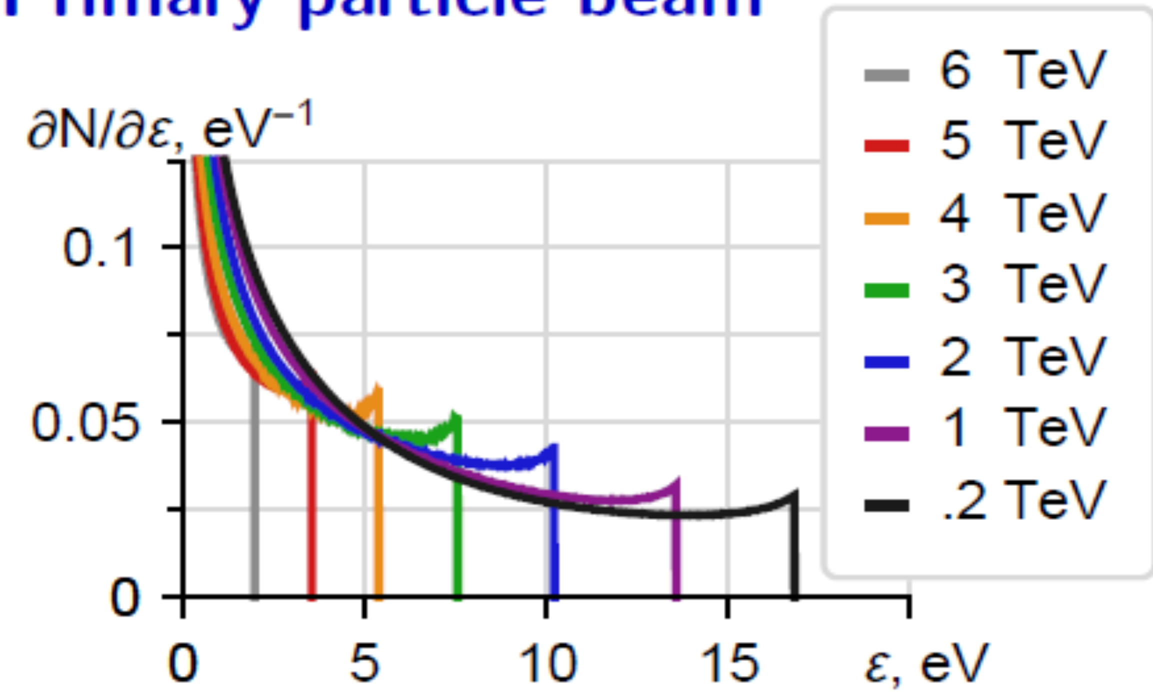
$$L_{\rm dech}(\varepsilon, R) = L_{\rm max}\frac{\varepsilon}{\varepsilon_{\rm max}}\;e^{1-\frac{\varepsilon}{\varepsilon_{\rm max}}}$$

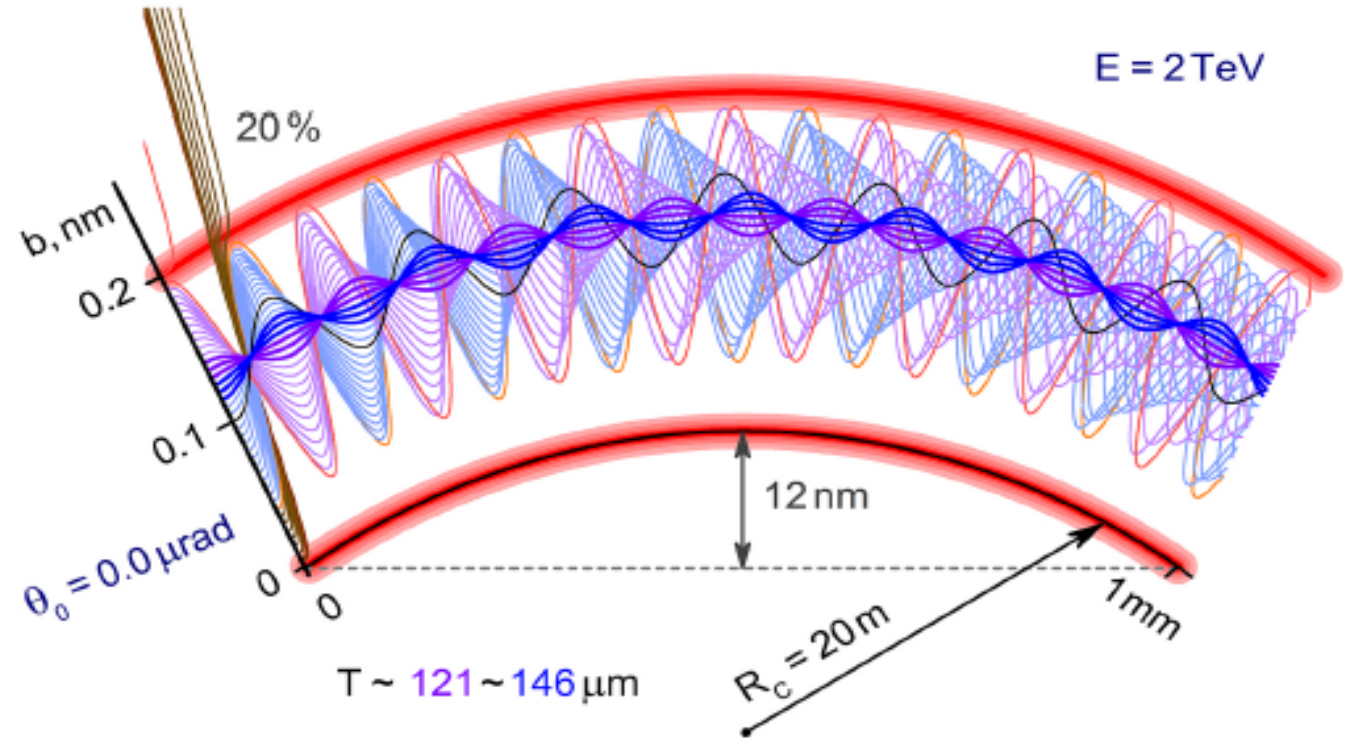
$$L_{\rm max} = k_{\rm dech}\,R\left(\frac{R_0}{R}\right)^{b_{\rm dech}}$$

$$\varepsilon_{\rm max} = R\;F_{\rm dech}$$

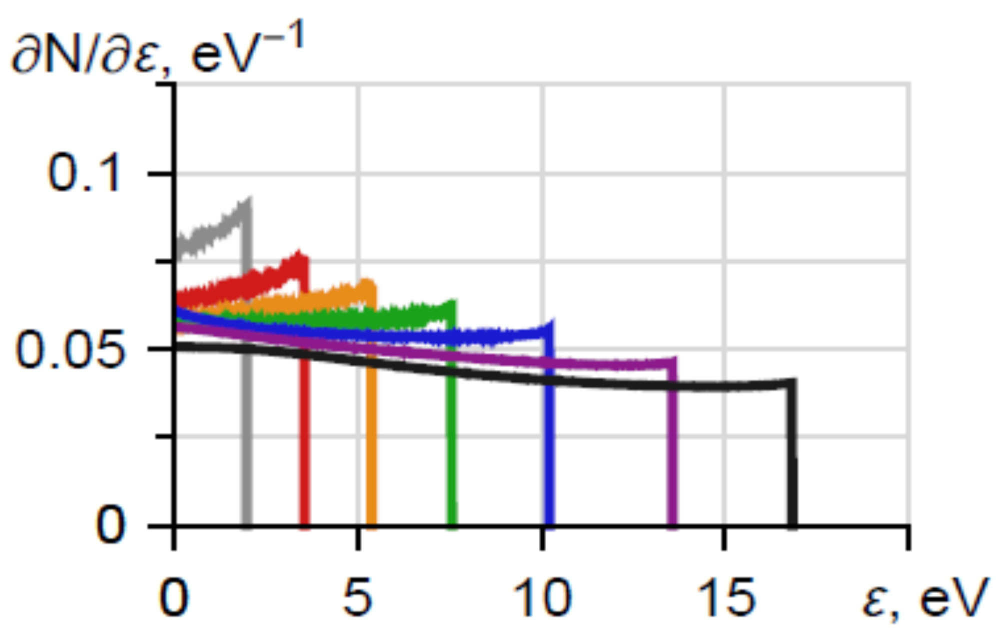
$U_{\rm eff}$, U'_x, $\eta_{\rm str}$, k_θ, $k_{\rm dech}$, R_0, $b_{\rm dech}$, $F_{\rm dech}$ were found for Si, Ge and Ge* crystals

Primary particle beam





Secondary particle beam



- Primary particle beam
  - Parallel beam
  - Monochromatic
- Secondary particle beam
  - Uniform angular distribution
  - Wide energy distribution
  - Populated high energy states