Feasibility of measuring the magnetic dipole moments of the charm baryons at the LHC using bent crystals

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Outline

1. Magnetic dipole moment of charm baryons
   - Introduction
   - Principals of measurement
2. Deflection by a bent crystal
   - Planar channeling
   - Computational model
   - Phenomenological formula
3. Sensitivity study
   - Error of measured g-factor
   - Crystal parameters optimization
   - Data taking time

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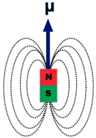
Λ_c^+ magnetic dipole moment measurement

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



Particle	g-factor
electron	−2.002 319 304 361 82(52)
muon	−2.002 331 84 18(13)
neutron	−3.826 085 45(90)
proton	+5.585 694 702(17)
$\Sigma+$	+2.458(10)

not measured for charmed, beauty baryons

- $|g| \approx 2 \;\rightarrow\;$ a point-like (Dirac particle)
- $|g| \not\approx 2 \;\rightarrow\;$ a composite structure
- $g\left(\Lambda_c^+(u,d,c)\right) \approx g_c$
- $g_c = 2 \;\rightarrow\; g\left(\Lambda_c^+\right) = 1.80\text{–}2.05$

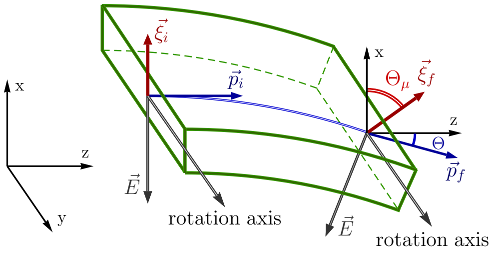
How? Induce the precession of the polarization vector by the strong magnetic field

Problem: $c\,\tau(\Lambda_c^+) \sim 60\ \mu\text{m}$ — far too short for measuring

Solution: conventional $\vec{B}$ replaced by bent crystal

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

Precession of magnetic dipole moment: principals of measurement



$$\Theta_\mu \approx \gamma \left(\frac{g}{2} - 1\right) \Theta$$

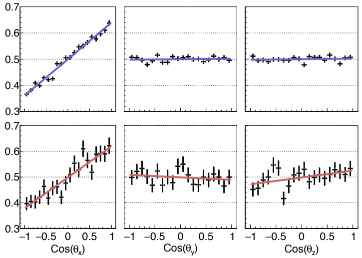
$$\Theta = \frac{L_{\text{crys}}}{R}$$

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

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

Angular distribution of decay products:

$$\frac{1}{N}\frac{dN}{d\cos\vartheta_k} = \frac{1}{2}\left(1 + \alpha\,\xi_k \cos\vartheta_k\right)\Big|_{k=x,y,z}$$



Need:

$\xi \neq 0$ — Λ_c^+ polarized at the production

$\alpha \neq 0$ — keep polarization at the decay

Precession of magnetic dipole moment: angular analysis

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

$|\xi|$ – polarization

Φ – proton flux

t – data taking time

- Decay channel dependent

  α_j – weak-decay parameter

  Γ_j/Γ – branching fraction

  $\eta_{\rm det}^{(j)}$ – detection efficiency

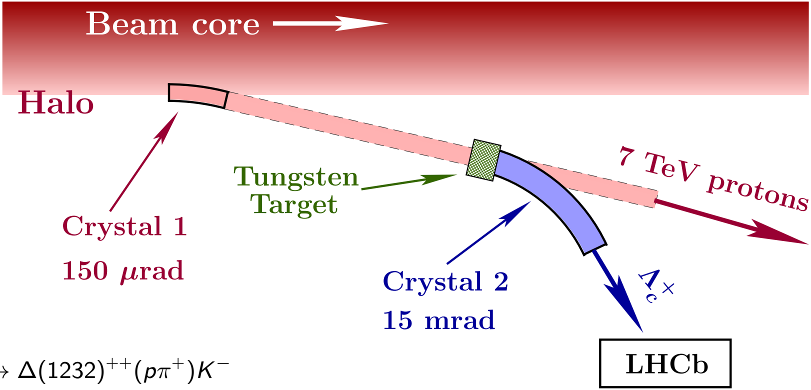
- Crystal dependent

  Θ – deflection angle

  $\frac{\partial N_{\rm tar+crys}}{\partial \varepsilon}$ – normalized spectra of deflected particles (per incident proton)

Λ_c^+ magnetic dipole moment measurement: Exp. setup

This double crystal scheme is now under study with a 2 years program by UA9 at SPS.



$\Lambda_c^+ \to \Delta(1232)^{++}(p\pi^+)K^-$

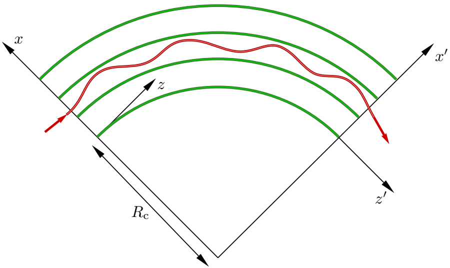
$\Lambda_c^+ \to + + -$

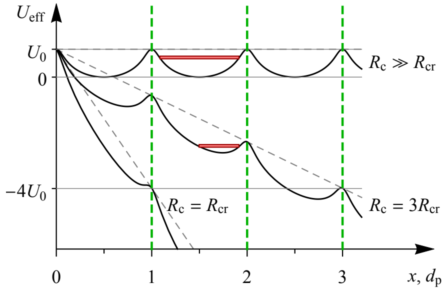
EOI (CERN 2016): L. Burmistrov *et al.*, Tech. Rep. CERN-SPSC-2016-030. SPSC-EOI-012;

Physics Beyond Colliders Kickoff Workshop (CERN 2016): A. Stocchi *et al.*; W. Scandale *et al.*

Outline

Channeling in a bent crystal





Effective potential

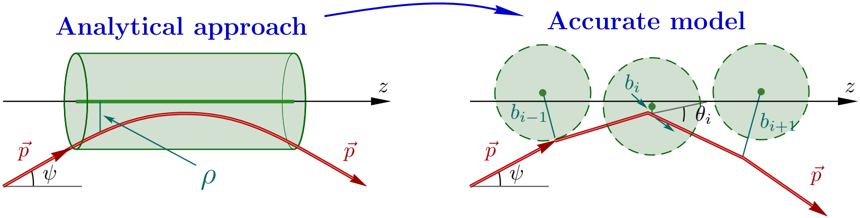
$$U_{\text{eff}}(x) = U^{\pm}(x) - x\,\frac{\varepsilon}{R_c}$$

Critical radius

$$R_{\text{cr}} = \frac{\varepsilon}{U'_x} \approx d_p\,\frac{\varepsilon}{4\,U_0}$$

Acceptance angle

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



Binary collision model (scattering on atoms)

- Most natural way of taking into account the thermal vibration of atoms
- Deflection angle of particle is calculated on each consequent atom
- Displacement of nearest atom due to the thermal vibration is drawn by normal distribution

Aggregate collisions model (scattering on electrons)

- Multiple scattering with modified radiation length

Computational model

Binary collision model

Deflection angle of particle on each consequent atom:

$$\Delta\vec{\vartheta}_{\mathrm{a}}(\vec{r}) = \frac{Z\,e^2\,\vec{r}}{\varepsilon\,r^2}\sum_{i=1}^{3}\alpha_i\,\beta_i^2\,K_0(\beta_i\,r), \quad \Delta\vec{\vartheta}_n = \sum_{k=1}^{N}\Delta\vec{\vartheta}_a(\vec{r}_k).$$

Displacement of nearest atom due to the thermal vibration:

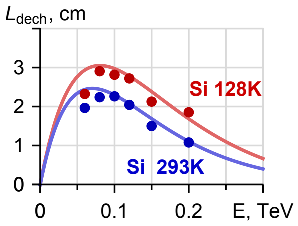
$$P(u_x)\,du_x = \frac{1}{\sqrt{2\,\pi\,\overline{u_x^2}}}\exp\left(-\frac{u_x^2}{2\,\overline{u_x^2}}\right)du_x$$

Aggregate collisions model

Multiple scattering on the electron subsystem

$$\sqrt{\overline{\vartheta_x^2}} = \frac{13.6\ \mathrm{MeV}}{\varepsilon}\sqrt{\frac{\Delta l}{X_0}}\left[1 + 0.038\ln\left(\frac{\Delta l}{X_0}\right)\right],$$

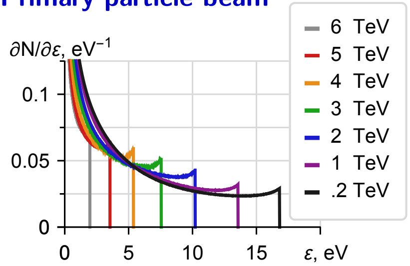
$$\frac{\Delta l}{X_0} = \frac{4\,e^6}{m^2}\ln(m\,d_{\mathrm{p}})\int_0^{\Delta l}\bar{n}_e(l)\,dl.$$

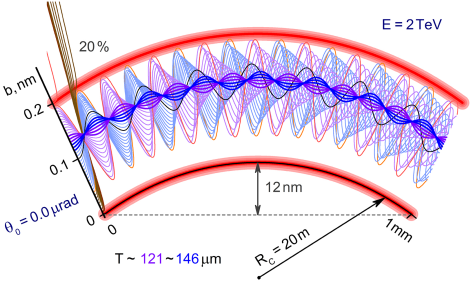


Forster J S et al.
Nucl. Phys. B 318 301 (1989)

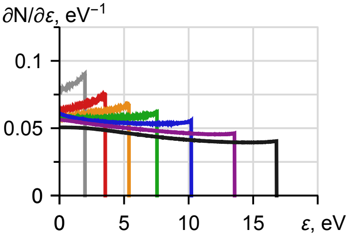
Channeling in a bent crystal: primary vs secondary beams

Primary particle beam

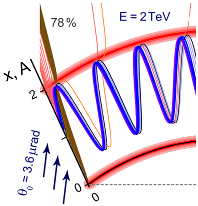




Secondary particle beam



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



Deflection efficiency: phenomenological formula

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

– 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

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

Dechanneling probability

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

Dechanneling length

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

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

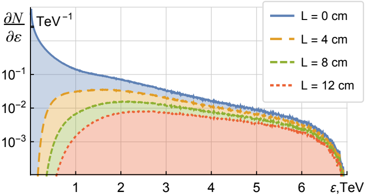
$$\varepsilon_{\rm max} = R\ F_{\rm dech}$$

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

Spectra of deflected Λ_c^+ produced by 7 TeV protons

Initial spectra (Pythia v8.1)

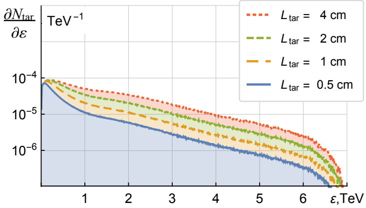
- credit to Leonid Burmistrov
- p - N collision in a fixed target
- normalized to one produced Λ_c^+



Spectra after the target

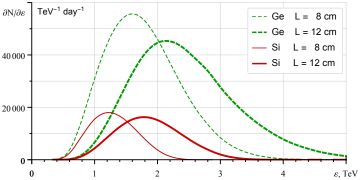
$$\frac{\partial N_{\mathrm{tar}}}{\partial \varepsilon} = \frac{\rho\, N_{\mathrm{A}}\, A_{\mathrm{tar}}}{M_{\mathrm{tar}}} \sigma_{\Lambda_c} \frac{\partial N}{\partial \varepsilon} \int_0^{L_{\mathrm{tar}}} e^{-\frac{L}{c\tau\gamma}}\, dL$$

- normalized to one initial proton



Spectra of deflected Λ_c^+

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



Outline

Sensitivity study: error of measured g-factor. List of parameters.

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

$|\xi|$ – polarization

Φ – proton flux

t – data taking time

- Decay channel dependent

  α_j – weak-decay parameter

  Γ_j/Γ – branching fraction

  $\eta_{\rm det}^{(j)}$ – detection efficiency

- Crystal dependent

  Θ – deflection angle

  $\frac{\partial N_{\rm tar+crys}}{\partial \varepsilon}$ – normalized spectra of deflected particles (per incident proton)

Optimization of the crystal parameters

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

Relative crystal efficiency:

$$\eta_{\mathrm{rel}} = \frac{t_0}{t} = \frac{\Theta^2 \int \frac{\partial N_{\mathrm{tar+crys}}}{\partial \varepsilon} \; \gamma^2 \, d\varepsilon}{\Theta_0^2 \int \frac{\partial N_{\mathrm{tar+crys},\,0}}{\partial \varepsilon} \; \gamma^2 \, d\varepsilon}$$

t – data taking time ('0' indicates the reference crystal)

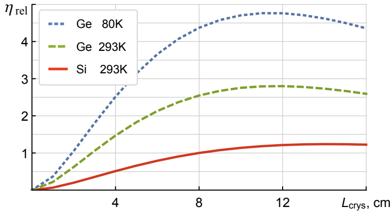
Θ – deflection angle

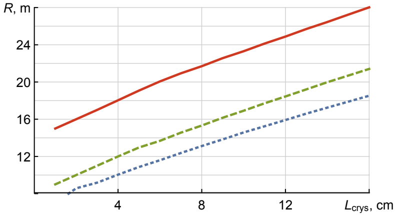
$\frac{\partial N_{\mathrm{tar+crys}}}{\partial \varepsilon}$ – normalized spectra of deflected particles (per incident proton)

Optimal crystal for measuring the MDM of Λ_c^+

Relative crystal efficiency

$$\eta_{\mathrm{rel}} = \frac{t_0}{t} = \frac{\Theta^2 \displaystyle\int \frac{\partial N_{\mathrm{tar+crys}}}{\partial \varepsilon} \gamma^2 \, d\varepsilon}{\Theta_0^2 \displaystyle\int \frac{\partial N_{\mathrm{tar+crys,\,0}}}{\partial \varepsilon} \gamma^2 \, d\varepsilon}$$





Optimal Length: $L_{\mathrm{crys}} = 8\text{–}11$ cm

Optimal Curvature:

Si 293K $R = 22$ m $\Theta_0 \approx 3.6$ mrad

Ge 293K $R = 15$ m $\Theta \approx 5.3$ mrad

Ge 80K $R = 13$ m $\Theta \approx 6.2$ mrad

Optimal Crystal:

$\frac{\eta_{\mathrm{rel}}\,(\mathbf{Ge})}{\eta_{\mathrm{rel}}\,(\mathbf{Si})} \approx$ **2.5 !!** $\qquad$ $\frac{\eta_{\mathrm{rel}}\,(\mathbf{Ge})}{\eta_{\mathrm{rel}}\,(\mathbf{Si})} \approx$ **4.5 !!!!**

Optimal crystal for measuring the MDM of Λ_c^+ at LHCb

Relative crystal efficiency

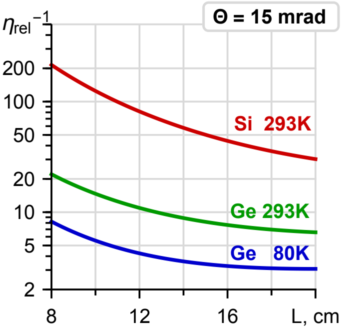
$$\eta_{\rm rel} = \frac{t_0}{t} = \frac{\Theta^2 \displaystyle\int \frac{\partial N_{\rm tar+crys}}{\partial \varepsilon} \gamma^2 \, d\varepsilon}{\Theta_0^2 \displaystyle\int \frac{\partial N_{\rm tar+crys,\,0}}{\partial \varepsilon} \gamma^2 \, d\varepsilon}$$

relative to the reference Si configuration:

– Si 293K $L = 8$ cm $\Theta_0 \approx 3.6$ mrad

But:

- silicon is more mature technology
- 8 cm is possible (difficulties with longer crystals)
- Acceptance of "LHCb" ~ 15 mrad



work is ongoing

$\eta_{\rm rel}^{-1}$ (**Si**) $\approx 50-200$ $\eta_{\rm rel}^{-1}$ (**Ge**) $\approx 8-22$ $\eta_{\rm rel}^{-1}$ (**Ge**) $\approx 3-8$

Absolute statistical error of measured g-factor.

Decay channel parameters

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

$c\tau(\Lambda) \approx 8$ cm

Decay channel	Weak-decay parameter α_j	Branching fraction Γ_j/Γ, %	Detection efficiency $\eta_{\rm det}^{(j)}$, %
$\Lambda_c^+ \to \boldsymbol{\Lambda}(p\,\pi^-)\,\pi^+$	$-0.91(15)$	0.7(2)	0.2
$\Lambda_c^+ \to \boldsymbol{\Lambda}(p\,\pi^-)\,e^+(\mu^+)\,\nu_{e(\mu)}$	$-0.86(04)$	1.3(4)	0.2
$\Lambda_c^+ \to \boldsymbol{\Delta(1232)^{++}}(p\,\pi^+)\,K^-$	$-0.67(30)$	0.9(3)	3
$\Lambda_c^+ \to \boldsymbol{\overline{K}^*(892)^0}(K^-\pi^+)\,p$	$-0.55(35)$	1.6(5)	3
$\Lambda_c^+ \to \boldsymbol{\Lambda(1520)}(p\,K^-)\,\pi^+$	$-0.11(60)$	0.8(3)	3

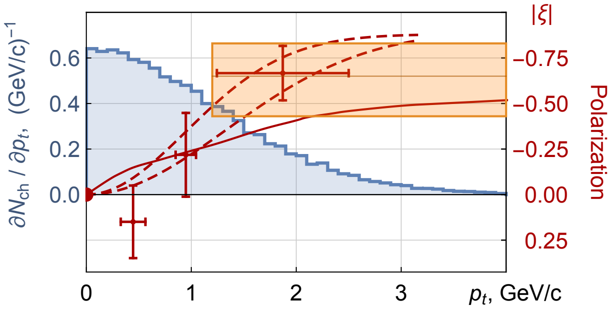
Absolute statistical error of measured g-factor.

Polarization as a function of transverse momentum.

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

$$\sqrt{|\xi|^2_{\mathrm{th}}} = -\,0.37$$

$$\sqrt{|\xi|^2_{\mathrm{ex}}} = -\,0.40(5)$$



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

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

Fitted exp. data

Gary R. Goldstein. FNAL, Batavia, Illinois, p.132–136, 1999.

Absolute statistical error of measured g-factor

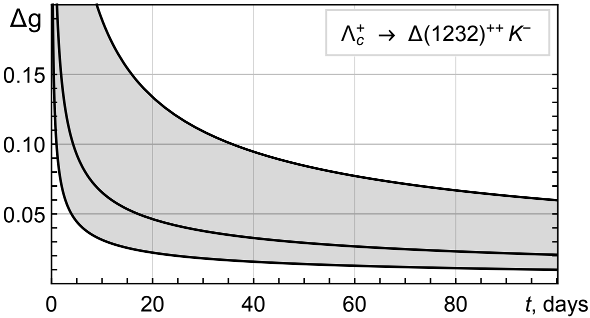
as a function of data taking time

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

Reference crystal:

Si $L = 8$ cm

$R = 22$ m



$\Delta g = 0.1$

$t \sim 1 - 30$ days

$\bar{t} \sim 5$ days

This proposal is now considered in LHCb and so we use the required parameters

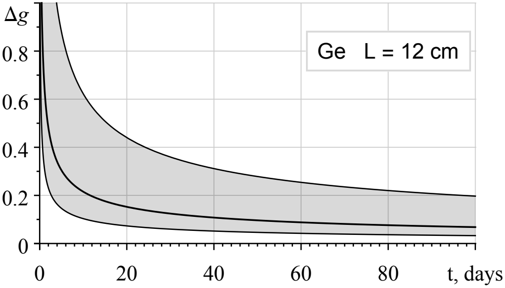
Absolute statistical error of measured g-factor

as a function of data taking time

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

Ge $\quad L = 12$ cm

$R = 8$ m



$\Delta g = 0.3$

$t \sim 1 - 40$ days

$\bar{t} \sim 5$ days

Work is going on both UA9 and LHCb