Improved experimental layout with **focusing crystals**

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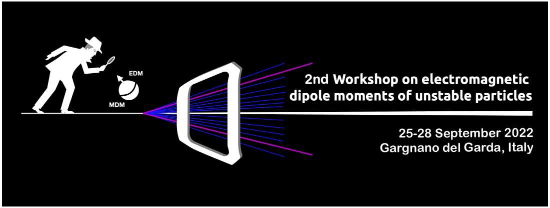
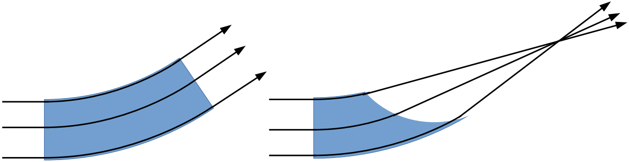
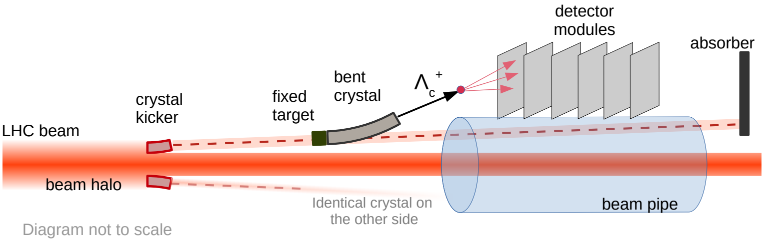
based on: *Improved experimental layout for dipole moment measurements at the LHC*;
Valery Biryukov, JRV; EPJC 82 (2022) 2, 149; arXiv:2110.00845



Crystal lens



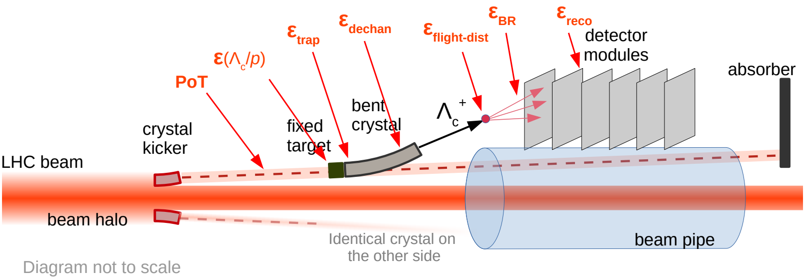
Experimental layout at the LHC



Sensitivity with two years of data taking (10^{13} PoT)
updated in Phys.Rev.D 103 (2021) 7, 072003

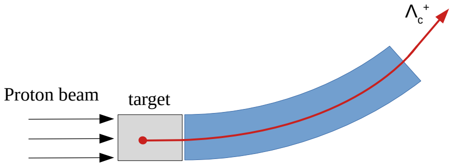
- **EDM** sensitivity $\sigma_\delta \approx 4 \cdot 10^{-16} e\mathrm{cm}$
- First measurement of Λ_c^+ **magnetic moment**, $\sigma_{g-2} \approx 2 \times 10^{-2}$

Experiment (in)efficiencies



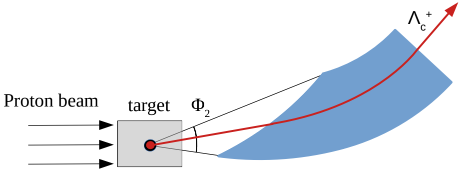
- Sensitivity dominated by statistics
- Bottleneck: **trapping efficiency** $\varepsilon_{\mathrm{trap}}$
- Trapped particles: small Λ_c^+ aperture angle

Trapping (qualitative)



Plain crystal:

- Λ_c^+ from whole target volume
- in few directions (horizontal)

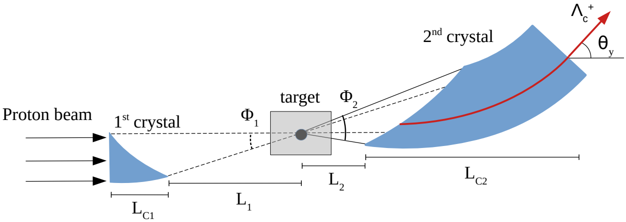


Crystal lens:

- Λ_c^+ from small target volume ($\sim$ focal point)
- in **all directions**

Double-lens scheme **(qualitative)**

V.M. Biryukov, JRV, arXiV:2110.00845

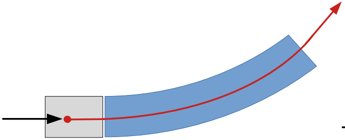


Double-lens scheme:

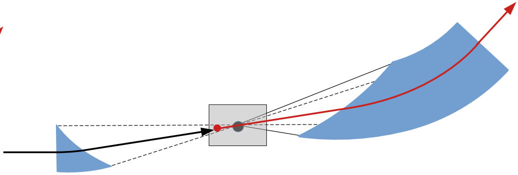
- Additional crystal focusing protons onto the target
- More Λ_c^+ produced at the focal point, or passing through it

Seeing the gain geometrically

If the Λ_c^+ angle wrt proton $<$ Lindhard angle, it is trapped



if and only if



just **if**

In the double-lens scheme, in addition, the particles produced at the focal point are always trapped, independently of the angle.

Overview (rest of the talk)

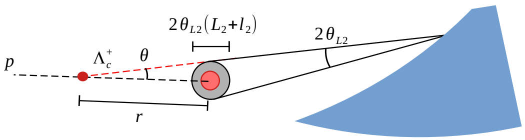
- Define **new trapping condition**
  - Plain crystal
  - Focusing crystal (aligned and misaligned)
- Analytical method to evaluate **trapping efficiency**
- **Setup parameters**
- Results
- Technical limitations

Trapping condition

- **Plain crystal:** Λ_c^+ aperture below Lindhard angle $|\theta| < \theta_{L2}$

$$P = \{(r,\theta) \ : \ (|r| \leq 1\text{cm}, \ |\theta| \leq \theta_{L2})\} \ .$$

- **Crystal lens:** Λ_c^+ path should overlap with focal "point"



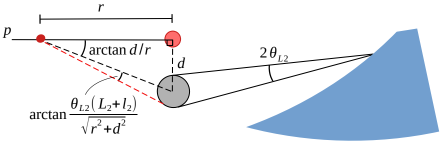
$$|r\tan\theta| < w_{F2}/2$$
$$|r\tan\theta| < \theta_{L2}(L_2 + l_2)$$
$$|\theta| \lesssim \theta_{L2}\frac{(L_2 + l_2)}{|r|}$$

Condition depends on Λ_c^+ aperture angle θ **and production point *r***

$$R = \{(r,\theta) \ : \ (|r| \leq 1\text{cm}, \ |\theta| \leq \theta_{L2}(L_2 + l_2)/|r|)\} \ .$$

Trapping condition (misaligned)

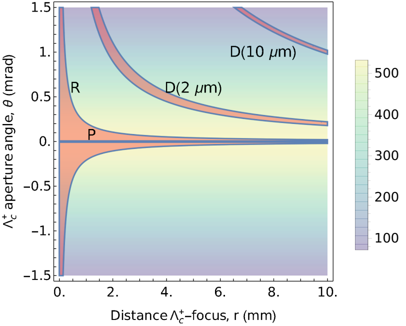
- If the first crystal is *sending* protons above or below the focal point, by distance d



$$|\theta - \arctan\frac{d}{r}| \leq \arctan\frac{\theta_{L2}L_2}{\sqrt{d^2+r^2}} \ ,$$

$$D(d) = \{(r,\theta) \ : \ (|r| \leq 1\text{cm}, \ \textit{condition on } \theta(r;d)\} \ .$$

Method to extract efficiency



- *Background:* Distribution of Λ_c^+ aperture angle

$$G(\theta;\ \mu, \sigma)$$

- Trapping efficiency: integral over $\{R, P, D\}$

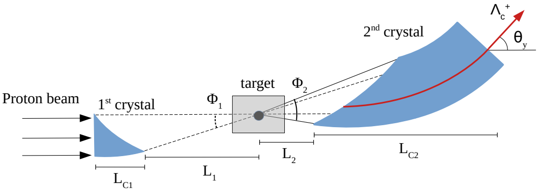
$$\int_{\{R,P,D\}} G(\theta;\ 0,\ 1.5\ \text{mrad})\ dr\ d\theta\ .$$

- Regions on the phase space:
  - Plain-crystal scheme - P
  - Double-lens aligned - R
  - Double-lens misaligned by d - D(d)

Beam pipe constraints & layout parameters

- After the focal point, the protons start diverging
- They should not touch the beam pipe before reaching the absorber
- Estimated maximum *beam spot* of 1 cm after 60 m

$$\Phi_1 \lesssim (1\text{cm}/60\,\mathrm{m}) \approx 170\,\mu\text{rad}$$



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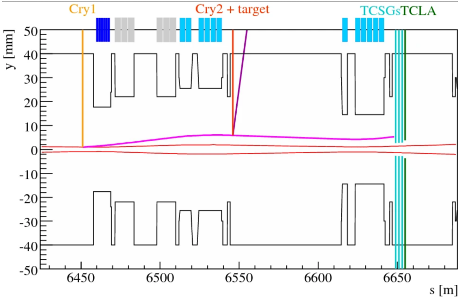

Eur.Phys.J.C 80 (2020) 10, 929

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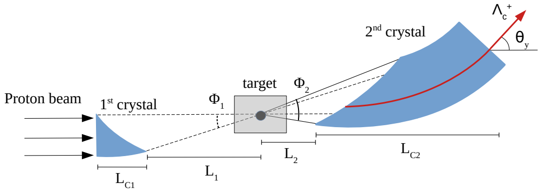
- Other parameters of the setup (with $\sigma_{\rm beam} \approx 50\,\mu$m)

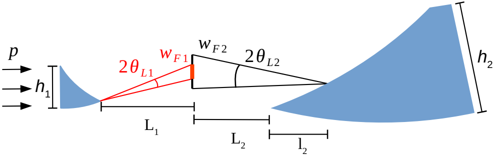
$$L_1 = \sigma_{\rm beam}/\Phi_1 = 30\text{cm}$$
$$\Phi_2 = \Phi_1 + (3\,\text{mrad}) \approx 3.2\,\text{mrad}$$
$$L_2 = 3\text{cm}$$

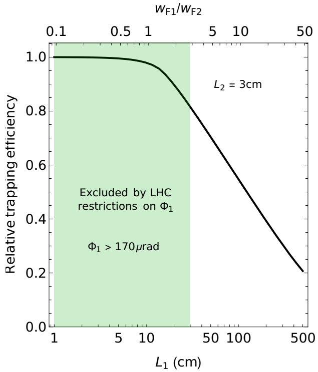


Dilution of protons at the focal point

- Smaller focusing angle Φ_1
  $\rightarrow$ larger distance to focus protons L_1
  $\rightarrow$ dilution of protons in w_{F1}
- Dilution $\sim$ small vertical misalignments of y (average over w_{F1})

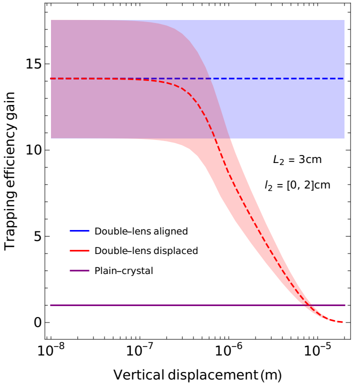
$$N(d_0) = \frac{1}{w_{F1}} \int_{-w_{F1}/2}^{w_{F1}/2} N_{D(d_0+y)}\, \mathrm{d}y \quad ,$$





- Beam pipe constraint $\rightarrow$ small effect (82%)

Results - double lens scheme

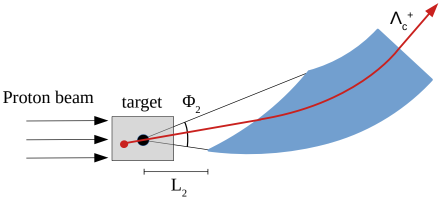


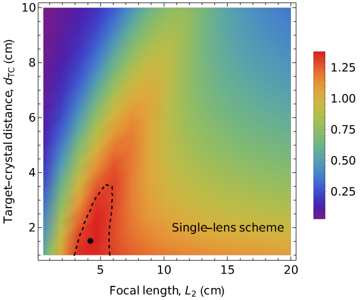
- Large **improvement in trapping efficiency**
  - Nominal target thickness 2 cm: **factor 15**
  - Optimized target thickness 0.5 cm: **factor 35**
- Adding first-lens efficiency ($\sim 80\%$) and extra target-crystal distance of $+1$cm ($\sim 70\%$):

  Gain factor of x20

- Sensitive to vertical misalignment
  - From 0.3 μm – maximum gain
  - to 10 μm – no gain wrt plain crystal
- Avoidable with nanometer-accuracy piezoelectric motors

Results - Single lens scheme





- Protons on the target directly (no first lens)
- Vertical spread of protons $\sigma_{\mathrm{beam}} \approx 50\,\mu$m (instead of w_{F1})
- Highly dependent on final σ_{beam}
- Much easier alignment
- **Gain of 40%** wrt to plain crystal

Technical limitations ...

Crystal alignment

- Trapping efficiency sensitive to vertical **displacement of focal points**
  Interplay of
  - Vertical positioning of crystals
  - Angular precision (goniometers)

- Precise **piezoelectric motors** to control **relative vertical position** of both crystals
  Scan to find best efficiency $\rightarrow$ no need for high angular precision

- If scan only possible in the **angle of the second crystal**
  To achieve maximum gain: need goniometer with precision

$$\delta(\text{angle}) = (0.3\,\mu\text{m})/(3\text{cm}) \approx 10\,\mu\text{rad}$$

Crystal dimensions & shape (I)

- Trap the divergent Λ_c^+
  - within $\Phi_2 = 3.2\,\text{mrad}$,
  - at a distance $L_2 = 3\text{cm}$ of the focal point
- They enter the crystal lens in a vertical range

$$h_2 \approx L_2 \Phi_2 \approx 100\,\mu\text{m}$$

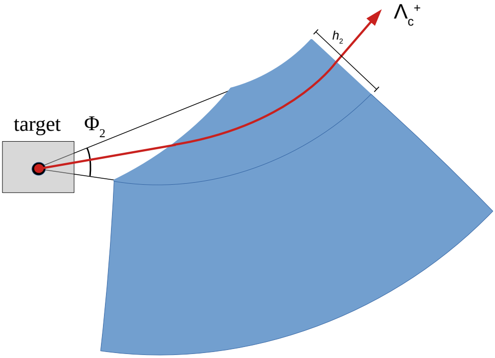
- Extremely **thin crystal**

- Or... thicker crystal where only h_2 is *active*
  - Focusing angle Φ_2 grows with thickness h_2
    (theoretical) limit at maximum crystal bending – **triangular crystal**

$$h_2^{\text{limit}} = L_2 \theta_{C2} \approx 0.6\,\text{mm}$$

Crystal dimensions & shape (II)

- Or... combination: **plain face + focusing face**
  - Extended plain crystal allows "arbitrary thickness" for manufacturers
  - Focusing face: Cut starting at the middle of the crystal face



target / crystal dimensions not to scale (evidently...)

Different Channels

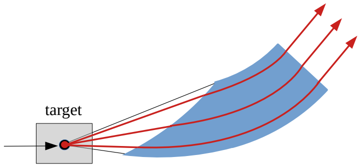
Angle of proton-Λ_c^+ determines:

Deflection angle

- Different entry angle $\rightarrow$ different total deflection $\rightarrow$ different spin precession
- Enough knowing the average precession? Potentially large systematics.
- Need **information on the channel** followed by each Λ_c^+

Polarization

- Need information on the initial polarization
  $\rightarrow$ Need **information on the channel**



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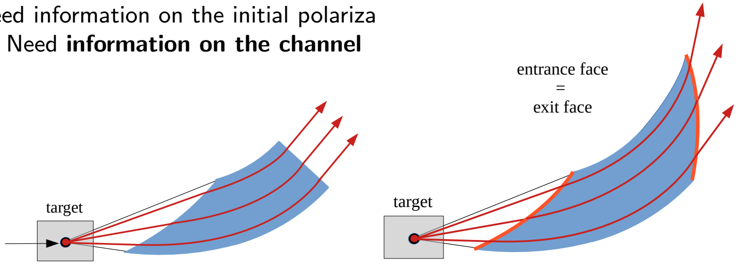


Possible solutions: increase resolution on Λ_c^+ position or change exit face

Conclusions

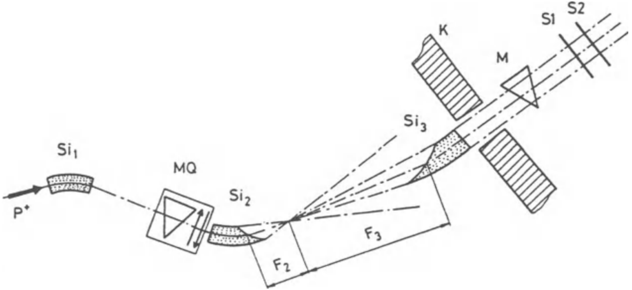
Single lens scheme

- Potential gain of 40% just replacing plain crystal by crystal lens
- High dependence on beam spot $\sigma_{\mathrm{beam}} \approx 50\,\mu$m

Double-lens scheme

- Large potential gain of a factor 15 (35) for 2cm (0.5cm) target
- Technical limitations to be addressed in detail

Backup

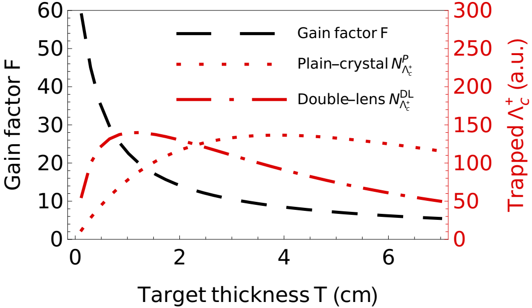


- Focusing crystals tested at IHEP Protvino
- 70-GeV proton beam

First results from a study of a 70 GeV proton beam being focused, Nucl. Instrum. Meth. B 69 (1992) 382

Denisov, Smirnov, Baranov, Chesnokov, Kotov

Target optimization



- Number of produced-survived-and-trapped Λ_c^+ baryons in the double-lens scheme as $N^{DL}_{\Lambda_c^+}(T) \propto F(T)\ N^{P}_{\Lambda_c^+}(T)$
- Optimal target thickness: 5 mm for double-lens scheme