Experimental proposals for MDM/EDM of charm baryons and tau lepton at LHC

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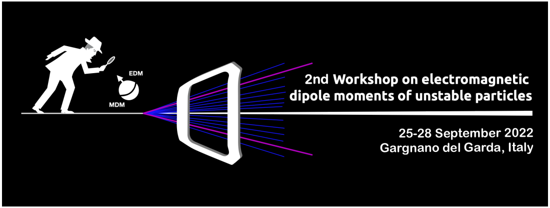
September 26, 2022



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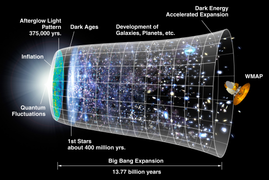
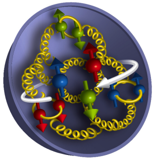
Electric Dipole Moment (EDM)

- Matter–antimatter asymmetry
- Sakharov conditions $\supset$ C and CP violation
- Sources of CP Violation: SM (not enough) and BSM
- A golden observable for new CPV sources:
  Electric Dipole Moment (EDM)





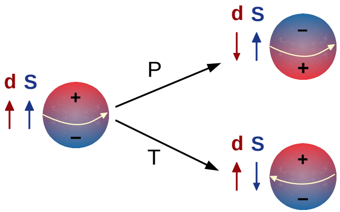
Magnetic Dipole Moment (MDM)

- Gives information on the baryon **spin structure**
- MDM of lowest-lying baryon octet (p, n, Λ, Σ, ...) was key to assess the quark model
- Baryon MDM nowadays: recurrent benchmark to compare **non-perturbative QCD** methods

Electric and magnetic dipole moments

Definition

$$\boldsymbol{\delta} = \int \boldsymbol{r}\rho(\boldsymbol{r})d^3r \qquad \boldsymbol{\mu} = \frac{1}{2}\int \boldsymbol{r}\times \boldsymbol{J}d^3r$$



Quantum systems

$$\boldsymbol{\delta} = d\mu_N\frac{\boldsymbol{S}}{2} \qquad \boldsymbol{\mu} = g\mu_N\frac{\boldsymbol{S}}{2}$$

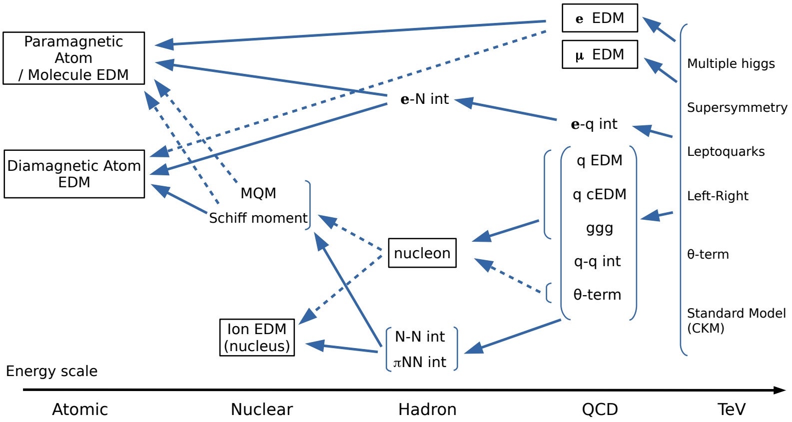
Energy of a system

$$H = -\boldsymbol{\delta}\cdot\boldsymbol{E} - \boldsymbol{\mu}\cdot\boldsymbol{B} \quad \xrightarrow{T} \quad +\boldsymbol{\delta}\cdot\boldsymbol{E} - \boldsymbol{\mu}\cdot\boldsymbol{B}$$

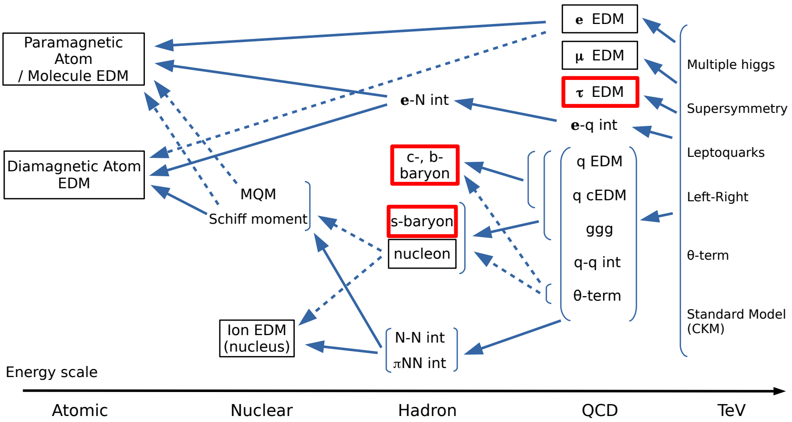
$$\xrightarrow{P} \quad +\boldsymbol{\delta}\cdot\boldsymbol{E} - \boldsymbol{\mu}\cdot\boldsymbol{B}$$

The EDM violates separately T and P $\Rightarrow$ **CP violation**

Map of the EDM field

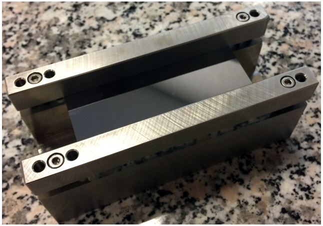


Map of the EDM field



EPJ C77 (2017) 181

Experiment concept



Requirements

- A source of **polarized particles**
- **Electromagnetic field** intense enough to induce precession
- A **detector** to measure the polarization

Requirements

Case of **short-lived charmed baryons**

Λ_c^+

- A source of **polarized particles**

  Strong production in a **fixed target**
  (transverse polarization)

- **Electromagnetic field** intense enough to induce precession

  Interatomic electric field
  in **bent crystals**

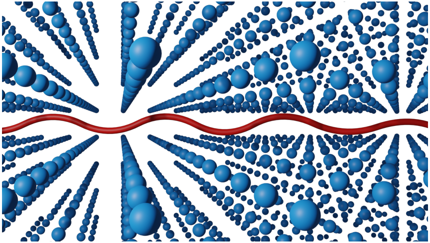
- A **detector** to measure the polarization

  Angular distribution of baryon decay
  products, at **LHCb** / **IR3** (dedicated)

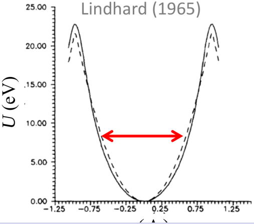
EPJ C77 (2017) 181

Channelling in bent crystals

- Very short-lived Λ_c^+ ($\sim$ 5cm) $\rightarrow$ need large EM field in small space ($\sim 10^3$ T)
- Electric field between atomic planes of a crystal

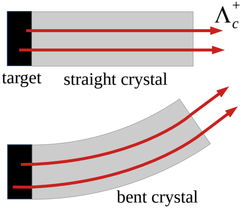


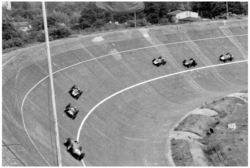
- Potential well between crystallographic planes
- Incident **positively-charged** particles can be **trapped** if their *transverse energy* is small
  $\Rightarrow$ **Small incident angle** w.r.t the crystal planes (few μrad)



Channelling in bent crystals

- To induce a net EM field, the crystal must be bent





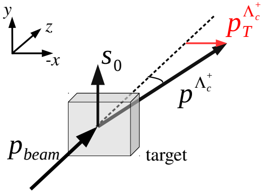
- The **E** field must compensate the *centrifugal force* which increases with the *momentum*
  $\Rightarrow$ The momentum determines a **critical bending radius** ($\sim$ 5 m)

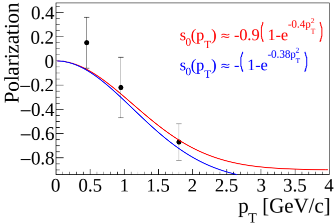
Several requirements for channeling $\rightarrow$ low efficiency $\sim 10^{-3}$

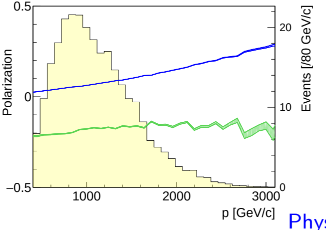
Initial polarization

- Perpendicular to the production plane ($\mathcal{P}$ conservation in strong inter.)
- Channeling in the horizontal $\rightarrow$ polarization vertical
- Magnitude depends on the Λ_c^+ p_T and x_F

Phys. Lett. B471 (2000) 449







Phys.Rev.D 103 (2021) 7, 072003

Spin precesion

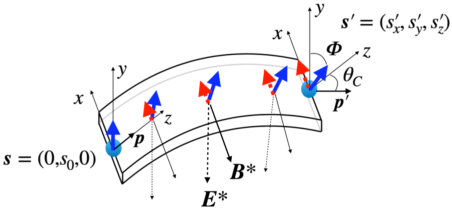
Spin-polarization vector equation of motion: T-BMT equation

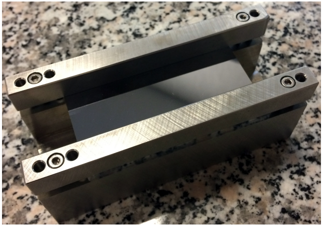
$$\frac{ds}{dt} = \mathsf{s} \times \Omega, \quad \Omega = \Omega_{\rm MDM} + \Omega_{\rm EDM} + \Omega_{\rm TH},$$

see *e.g.* EPJ C 77 (2017) 828

Precession induced by the net EM field

$$\boldsymbol{s} \approx s_0 \left(\frac{d}{g-2}(\cos\Phi - 1), \; \cos\Phi, \; \sin\Phi \right) , \quad \Phi \approx \frac{g-2}{2}\gamma\theta_C \approx \pi$$





Proof of principle at E761

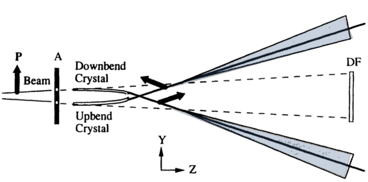
- E761 Fermilab experiment firstly observed spin precession in bent crystals and measured MDM of Σ^+

  Phys. Rev. Lett 69 (1992) 3286

- 350 GeV/c Σ^+ produced from 800 GeV/c proton beam on a Cu target
- Used up- and down-bend silicon crystals $L = 4.5cm$, $\theta_C = 1.6mrad$ to induce opposite spin precession

VOLUME 69, NUMBER 23 PHYSICAL REVIEW LETTERS 7 DECEMBER 1992

First Observation of Magnetic Moment Precession of Channeled Particles in Bent Crystals



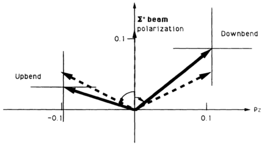
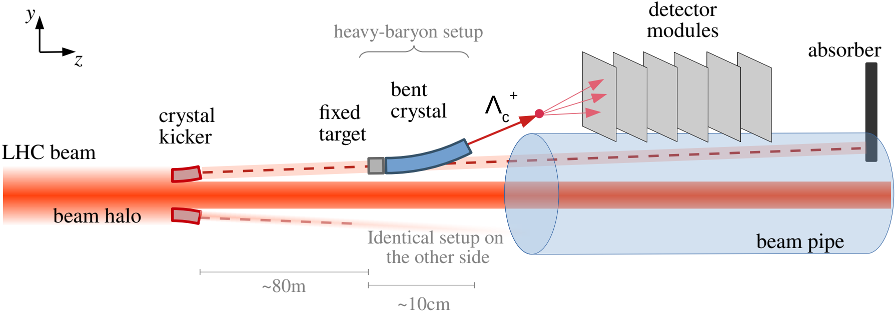


FIG. 3. Measured polarizations and uncertainties (1σ statistical errors) after spins have been precessed by the two crystals. The dashed arrows show the expected precessions.

Layout for the LHC



Sensitivity with **two years** of data taking (10^{13} PoT)

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

Phys.Rev.D 103 (2021) 7, 072003

Key factors

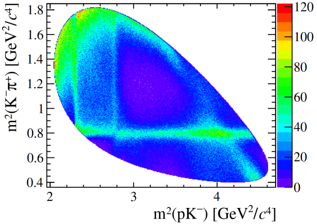
Measurement of final polarization

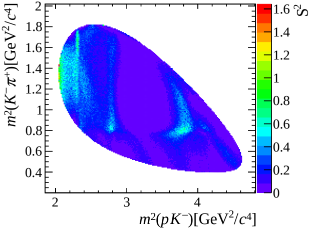
- $\Lambda_c^+ \to pK^-\pi^+$ dominated by intermediate resonances
  $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) \;\approx\; \mathcal{B}(\Lambda_c^+ \to pK^*) \;+\; \mathcal{B}(\Lambda^*\pi^+) \;+\; \mathcal{B}(\Delta^{++}K^-)$
- Initially considered exclusive quasi-two-body decays

$$\frac{dN}{d\Omega'} \propto 1 + \alpha_{\text{eff}}\, \boldsymbol{s} \cdot \hat{\boldsymbol{k}}$$

- New amplitude analysis: Λ_c^+ from semileptonic decays, LHCb arXiv:2208.03262
- Precise amplitude model allows sensitivity to the Λ_c^+ polarization across the phase space: **statistics x6**, Phys.Rev.D 103 (2021) 7, 072003

see talk by D. Marangotto





- Ongoing analysis with SMOG data (*fixed target p*-gas)

see talk by A. Merli

Target

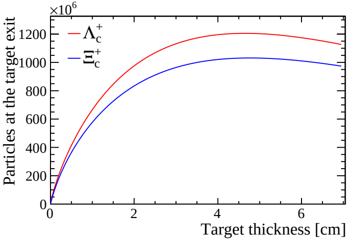
Number of Λ_c^+ as a function of target thickness

$$\frac{\mathrm{d}N_{\Lambda_c^+}}{\mathrm{d}z} = \frac{N_{\mathrm{PoT}}}{\lambda_{\mathrm{W},\Lambda_c^+}} e^{-z/\lambda_{\mathrm{W}}} - \frac{N_{\Lambda_c^+}}{\lambda'}$$

production of Λ_c^+ re-absorption and decay

$$1/\lambda' = 1/\lambda_{\mathrm{W}}^{(\Lambda_c^+)} + 1/(\beta\gamma c\tau)$$

Optimal point 2 cm: trade off between max $N_{\Lambda_c^+}$ and min occupancy/bkg



Nuclear interaction length $\lambda_{\mathrm{W}} \approx 8.87$cm: only one in every ~ 4 protons interacts

Crystal specifications and manufacturing

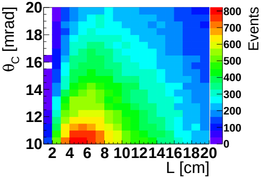
Crystal optimization

- Two parameters: crystal length L and bending θ_C
- Sensitivity evaluated as a function of (L, θ_C)

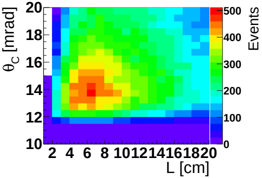
$$L \approx 10\text{cm} \quad \theta_C \approx 16\text{mrad} \quad \text{(LHCb)}$$
$$L \approx 7\text{cm} \quad \theta_C \approx 7\text{mrad} \quad \text{(dedicated)}$$

EPJ C 77 (2017) 828, PRD 103 (2021) 7, 072003

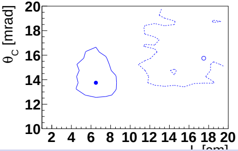
channelled



in acceptance

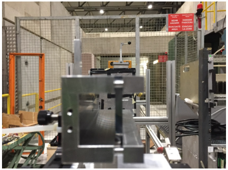


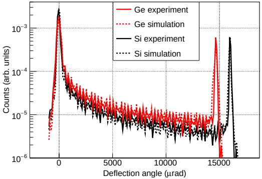
sensitivity



First prototypes

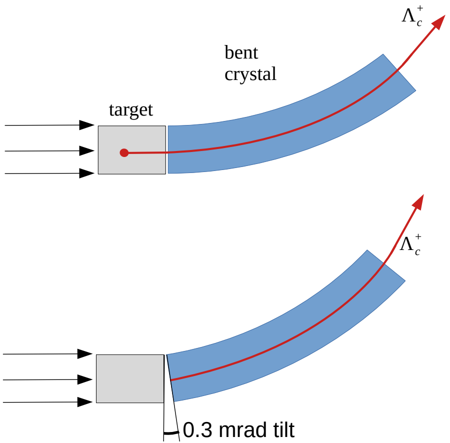
- Manufactured by INFN Ferrara; tested at CERN





PRD 103 (2021) 7, 072003

Crystal positioning and tilt



Tilt

- Crucial to increase sensitivity to EDM
  Need initial polarization component **not aligned** with E^*

Phys.Rev.D 103 (2021) 7, 072003

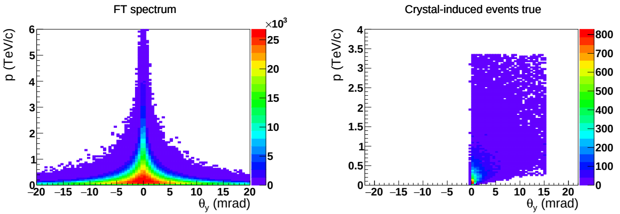
Angular position. Goniometers

- Crystal deflector, "kicker" of protons: accuracy below 2 μrad needed (Lindhard angle)
- Main precession crystal: accuracy limited by precision on crystal tilt, $\lesssim 20\,\mu\mathrm{rad}$

see talk by Q.J. Demassieux

Background rejection

Non-channeled Λ_c^+ backgrounds:



- Cuts: $p_{3\pi} > 800\text{GeV/c}$, $\theta_y \in \theta_C \pm 1.5\text{mrad}$, decay vertex after the crystal

Partially-channeled Λ_c^+ background

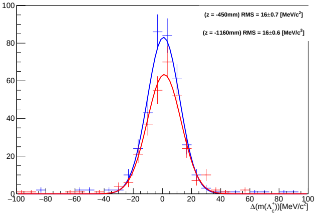
- Λ_c^+ produced inside the crystal, $p \lesssim 800\text{GeV}$
- Λ_c^+ decaying inside the crystal, $\theta_y < \theta_C$
- Λ_c^+ dechanneled $\theta_y < \theta_C$
- (Combinations of the above)

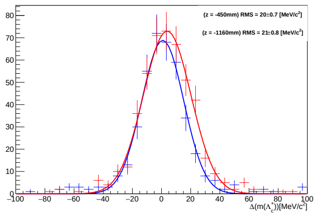
Leftover contamination is almost fully channeled $\rightarrow$ similar spin precession

Signal gain	Small precession bias
$+20\%$	$\approx 3\%$

Reconstruction efficiency and resolution

- Reconstruction of $\Lambda_c^+ \to pK^-\pi^+$ with **full simulations at LHCb**
- Λ_c^+-mass resolution of 16-20 MeV, for 1-2 TeV particles
  - Crucial to distinguish misidentified backgrounds, *e.g.* $D^+ \to K^-\pi^+\pi^+$ or $D_s \to K^+K^-\pi^+$
- Reconstruction efficiency at LHCb $\approx 30\,\%$.



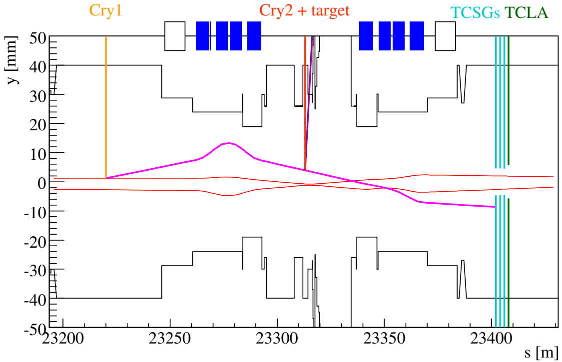


LHCb-INT-2017-011

see talk by J. Grabowski (reconstruction for IR3 test)

Proton flux

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



- Detailed simulations of beam optics to asses realistic proton flux of deflected beam
  - $\sim 10^6 p/s$

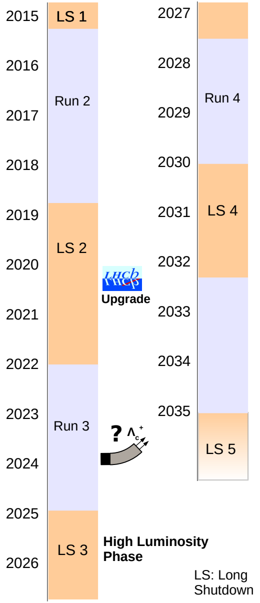
out of $\sim 10^{18} p/s$ (full LHC beam)

- Ocupancy and redout capabilities may limit the proton flux as well

see talk by D. Mirarchi

see talk by P. Hermes

Prospects for **heavy baryon** EDMs at LHC



- Proof-of-principle experimental **test at IR3** in preparation. Accelerator + target/crystal device + spectrometer Talks on Tuesday: E. Spadaro, Han Miao, J. Grabowski, V. Coco.
- Measurement with essentially same setup (and more beam time) Discussion on Letter of Intent: N. Neri
- Proposal included in the **Physics Beyond Colliders** study group

http://lhc-commissioning.web.cern.ch/lhc-commissioning

τ^+ lepton

JHEP 03 (2019) 156, PRL 123 (2019) 011801

Anomalous magnetic moment of τ

- Astonishing sensitivity on **electron and muon (g-2)**

$(g-2)/2_{\,e} = 0.00115965218091(26)$ $\qquad$ $(g-2)/2_{\,\mu} = 0.0011659209(6)$

- Never measured for the τ

$$-0.052 < (g-2)/2_{\,\tau} < 0.013$$

DELPHI through $e^+e^- \to e^+e^-\tau^+\tau^-$

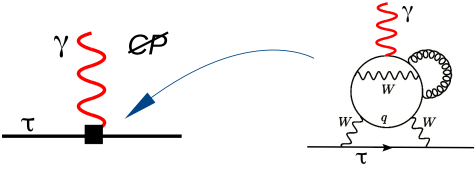
- Lepton $\to$ **free from hadronic uncertainties**

EDM of τ

Standard Model has its leading contribution at **4-loop** level

PRD 89 (2014) 056006

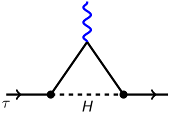
PRL 125 (2020) 241802

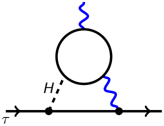


$d_\tau \sim 10^{-38} ecm$

negligible

Beyond SM predictions





$d_\tau \sim 10^{-17} ecm$	JHEP 1901 (2019) 069	**Scalar leptoquarks**
$d_\tau \sim 10^{-17} ecm$	J.Phys. G40 (2013) 035001	**331 models**
$d_\tau \sim 10^{-17} ecm$	Mod.Phys.Lett. A25 (2010) 703	**Little Higgs**
$d_\tau \sim 10^{-18} ecm$	Phys.Rev. D81 (2010) 033007	**Vector-like multiplets**
$d_\tau \sim 10^{-20} ecm$	EPJ C44 (2005) 411	**2HDM extra dim.**
...	...	

Caveats: non-perturbativity of large couplings; not full phenom. analyses

Indirect bounds

$d_\tau < 4.5 \times 10^{-17} ecm$	Phys.Lett. B551 (2003) 16	$e^+e^- \to \tau^+\tau^-$, ang. dist.
$d_\tau \lesssim 5 \times 10^{-17} ecm$	Nuc.Phys.B 821 (2009) 285	d_e through lbl diagrams
$d_\tau < 3 \times 10^{-17} ecm$	Nucl.Phys.Proc.S. 189 (2009) 257	$e^+e^- \to \tau^+\tau^-$, total σ

Experiment concept: requirements

- A source of **polarized particles**
- **Electromagnetic field** intense enough to induce precession
- A **detector** to measure the polarization

Experiment concept: requirements

Case of **short-lived** τ^+ **leptons**

- A source of **polarized particles**

  Weak decays of charmed mesons, $\boldsymbol{D_s^+ \rightarrow \tau^+ \nu_\tau}$
  (longitudinal polarization)

- **Electromagnetic field** intense enough to induce precession

  Interatomic electric field
  in **bent crystals**

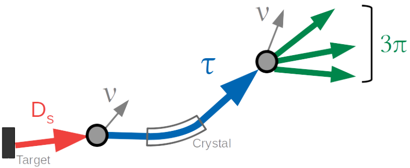
- A **detector** to measure the polarization

  Full kinematic information of the $3\pi^\pm$ system, $\tau^+ \rightarrow 3\pi^\pm \bar{\nu}$,
  in a multi-variate classifier. **Future dedicated experiment**

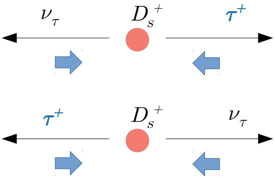
  PRL 123 (2019) 011801

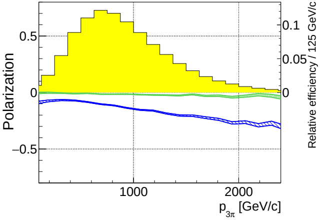
Production and initial polarization

PRL 123 (2019) 011801



- Production of τs in hadronic machines dominated by $D_s^+ \to \tau^+\nu_\tau$
- τ^+ polarization well defined in the D_s^+ rest frame.
- Not accessible from the lab frame due to missing energy
  $\to$ use kinematical constraints to enrich the polarization

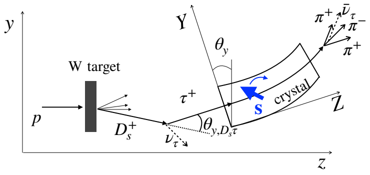


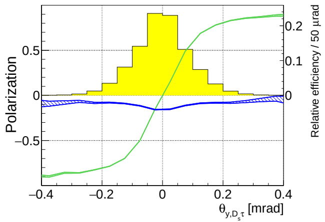


Longitudinal polarization, s_z

- Momentum cut (required for bkg separation) + channeling conditions $\rightarrow$ select a sample of τ's with $s_z \sim$ -18 %

Transvere polarization, s_y

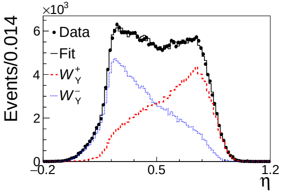




- The transverse polarization is highly **correlated to** $\theta_{y,D_s\tau}$
- Variable in the **invisible part of the event** (only ν_τ associated to the vertex)
- Use the rest of the event to get statistical information on the D_s direction: θ_{y,D_s}**-tagging**
- Alternatively: double-crystal scheme to fix D_s direction (JHEP 03 (2019) 156)

Polarization reconstruction

- Kinematics of the τ^+ decay cannot be fully reconstructed
  Known methods in the lit. do not apply
- Use a **multivariate classifier** with the available information.
  - angles between $p_{3\pi}$ in τ^+ rest frame and crystal axes
  - angles of 3π plane in 3π rest frame and crystal axes
  - $m(2\pi^\pm)$, $m(3\pi^\pm)$
- Training samples: Full ±1 polarization (on each axis, x3)



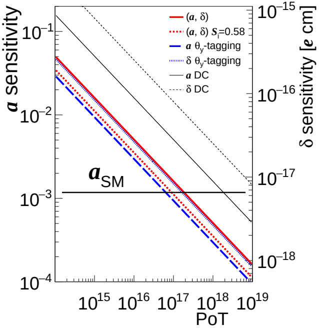
PRL 123 (2019) 011801

- Achieved event information

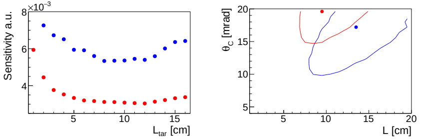
$$S_X \approx S_Y \approx 0.42\ , \quad S_Z \approx 0.23$$

Ideal case, with complete event kinematics, 0.58

Optimization and sensitivity



- Optimization of the setup for a dedicated experiment
  Small detector separated from the main LHC experiments

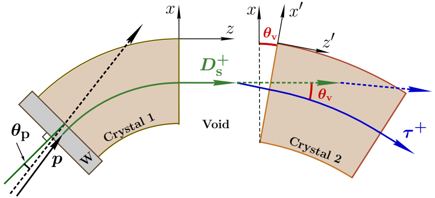


Sensitivity scans for crystals made of **Germanium** and **Silicon**

- The SM prediction of the τ MDM with 10^{17} protons on target
- EDM of the τ probed below $10^{-17} e\,\mathrm{cm}$ with the same data set

- 10^{17} protons $\approx$ 10% of LHC protons during a decade of operation

Layout with two crystals



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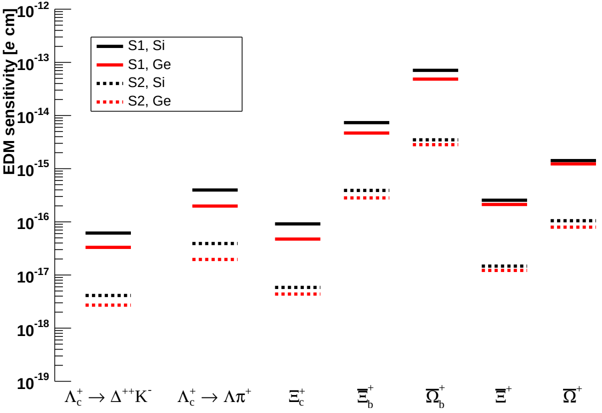
- Crystal to fix the direction of D_s^+. Exploits the longitudinal polarization
- Lower efficiency
- Advantages in terms of background rejection
- Larger absolute value of polarization
- Technically challenging

Sensitivities to other baryons

Extension to other baryons studied in EPJ C 77 (2017) 828



S1: Configuration at the LHCb
S2: Dedicated experiment at the LHC

Material of the crystal:
→ **Silicon**
→ **Germanium**

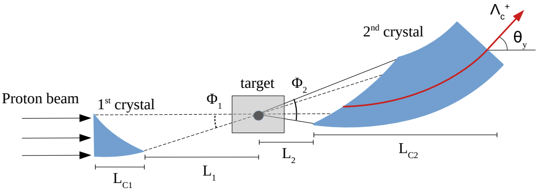
In figure assumed 10^{15} PoT. More realistic estimate → 10^{13} PoT.

New ideas

Focusing crystals

EPJC 82 no. 2, (2022) 149

- Increase channeling efficiency by a factor ~ 20
- Technical limitations



see my talk on Tuesday

High intensity magnet

- Replace crystal by magnet
- Allows to measure spin precession in neutral systems, *e.g.* Λ_b

see talks by A. Merli and M. Sorbi

Summary

- Direct spin precession on **charm baryons**
  - **First EDM search**, at $\approx 4 \cdot 10^{-16}$ecm
  - **First measurement of magnetic moment**, at 5% accuracy level

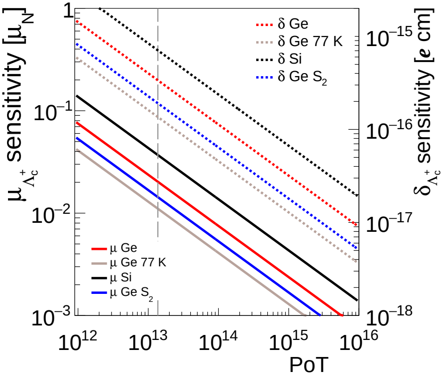
- Extension to other positively-charged baryons such as Ω^+, Ξ^+, ${\Xi_b}^+$, ...

- Also extended to τ^+ **leptons**
  - Test of the SM through $(g-2)_\tau$
  - (Even) more challenging than baryons

- Unique oportunity now at LHC
- Lots of progress on R&D; machine simulations; physics involved

Backup

Sensitivity estimates



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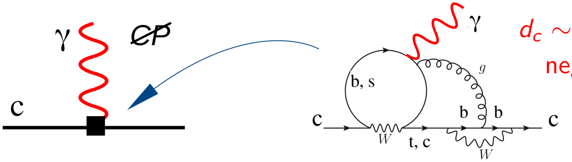
Refined estimations accounting for

- Dependence of spin information across the phase space
- Dependence of initial polarization with kinematics
- State-of-the-art channeling simulations
- Additional Λ_c^+ final states

Predictions in BSM theories

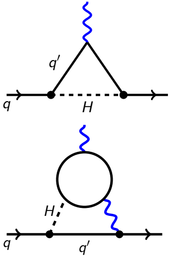
Standard Model has its leading contribution at **3-loop** level



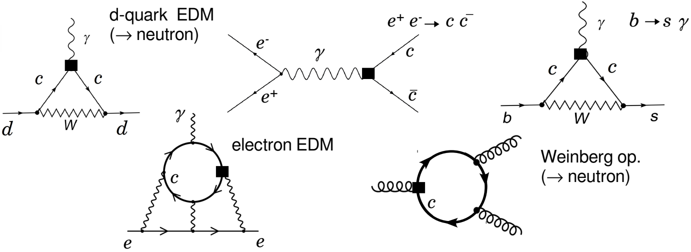
$d_c \sim 10^{-32} ecm$
negligible

Beyond SM contributions at **1,2 loops**

$d_c \sim 10^{-17} ecm$	EPJ C77 (2017), no.2 102	**BLMSSM**
$d_c \sim 10^{-17} ecm$	PRD 67 (2003) 036006	**MSSM**
$d_c \sim 10^{-19} ecm$	arXiv:hep-ph/0412360	**MSSM**
$d_c \sim 10^{-20} ecm$	PRD 95 (2017) 035041	**Colour-octet scalars**
$d_c \sim 10^{-21} ecm$	JHEP 1901 (2019) 069	**Scalar leptoquarks**
...	...	



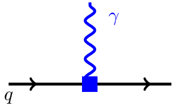
Bounds on charm EDM



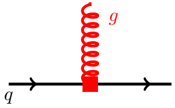
Bound	Ref.	Measurement	Method
$\lvert d_c \rvert < 4.4 \times 10^{-17}$ ecm	Sala:2013osa	neutron EDM	Considers threshold contributions of d_c into d_d via $W^{\pm}$ loops.
$\lvert d_c \rvert < 3.4 \times 10^{-16}$ ecm	Sala:2013osa	$BR(B \to X_s\gamma)$	Considers contributions from d_c to the Wilson coefficient C_7.
$\lvert d_c \rvert < 3 \times 10^{-16}$ ecm	Grozin:2009jq	electron EDM	Extracted from d_c threshold contribution to d_e through light-by-light scattering diagrams.
$\lvert d_c \rvert < 1 \times 10^{-15}$ ecm	Grozin:2009jq	neutron EDM	Similar approach than ref. Sala:2013osa. Evaluates contributions in two steps: c-quark → d-quark → neutron.
$\lvert d_c \rvert < 5 \times 10^{-17}$ ecm	Blinov:2008mu	$e^+e^- \to c\bar{c}$	The total cross section (LEP) can be enhanced by the charm qEDM vertex $c\bar{c}\gamma$.
$\lvert d_c \rvert < 8.9 \times 10^{-17}$ ecm	Escribano:1993xr	$\Gamma(Z \to c\bar{c})$	Measurement at the Z peak (LEP). Uses model dependent relationships to weight contributions from d_c and d_c^w.

Bounds on charm EDM

H.Gisbert, JRV, 1905.02513

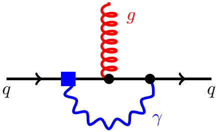


$|d_c| < 4.4 \times 10^{-17} e\,\text{cm}$



$|\tilde{d}_c| < 1.0 \cdot 10^{-22}\text{cm}$

EDM may contribute to CEDM?



Operators mix with the change of energy scale (RGE).

- Improvement of charm EDM limit

$$|d_c|_{\text{prev}} < \; 4.4 \times 10^{-17} \; e\,\text{cm} \quad \rightarrow \quad |d_c|_{\text{new}} < \; 1.5 \times 10^{-21} \; e\,\text{cm} \; ,$$