Exploring electric dipole moments of heavy flavors

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Seminar at JGU Mainz

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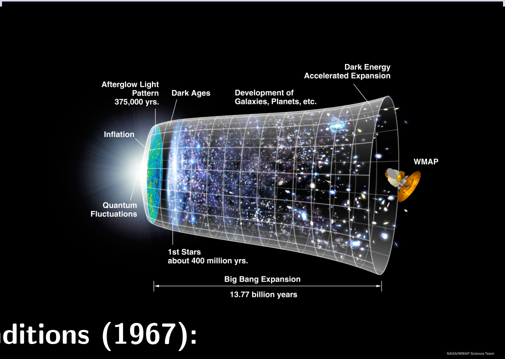
Overview

- Motivation: Electric dipole moments
- **Experimental proposal at the LHC**
  - Experiment Concept: charm baryons
  - Extensions and new ideas
  - Plans
- **Heavy quark EDM in BSM**
  - Heavy *baryon* EDMs
  - Indirect bounds
  - BSM scenarios
- Conclusions

Matter-antimatter imbalance



Sakharov conditions (1967):

Ingredients to generate matter-antimatter imbalance:

- **Baryon number violation**

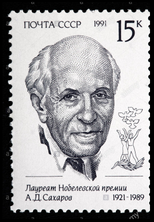
  $X \to X' + B$

- **C and CP violation**

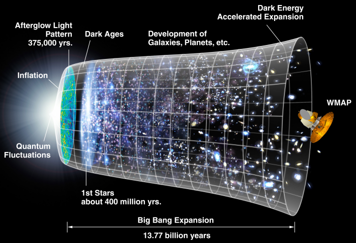
  $X \to X' + B \neq \bar{X} \to \bar{X}' + \bar{B}$

- **Out of thermal equilibrium**

  $X \to X' + B \neq X' + B \to X$

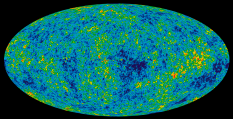


Matter-antimatter imbalance



- The SM has the three ingredients, but not the needed quantities

$$\left.\frac{n_B - n_{\bar{B}}}{n_\gamma}\right|_{\text{observed}} = 6 \cdot 10^{-10} \qquad \left.\frac{n_B - n_{\bar{B}}}{n_\gamma}\right|_{\text{SM}} \approx 10^{-18}$$

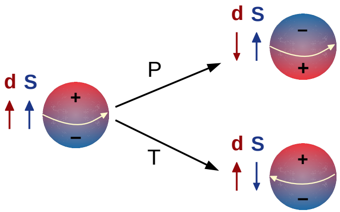


- **New sources of CP violation**
  $\Rightarrow$ Present in many BSM theories
  $\Rightarrow$ Tested in particle experiments through CPV observables

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

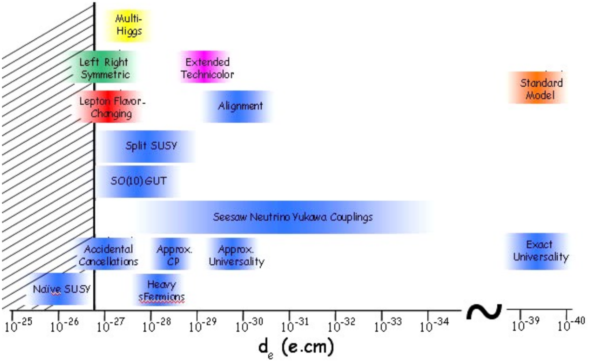
$$H = -\boldsymbol{\delta}\cdot\boldsymbol{E} - \boldsymbol{\mu}\cdot\boldsymbol{B} \quad \xrightarrow{T} \quad +\boldsymbol{\delta}\cdot\boldsymbol{E} - \boldsymbol{\mu}\cdot\boldsymbol{B}$$

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

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

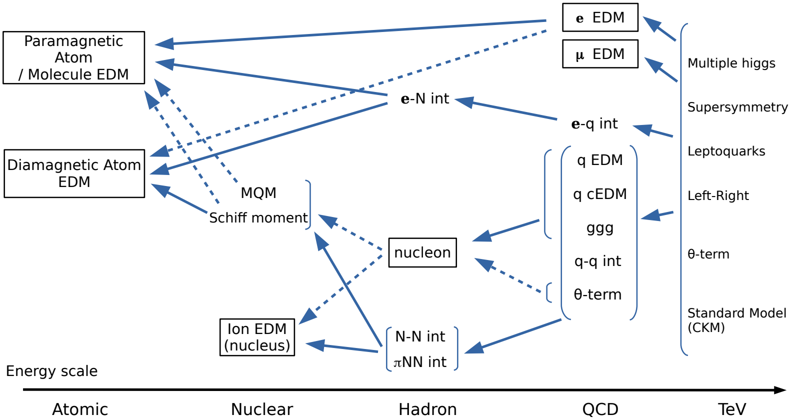
EDM searches of fundamental particles

- $\sim$ zero in the SM.
- Any signal of a nonzero EDM **is New Physics**



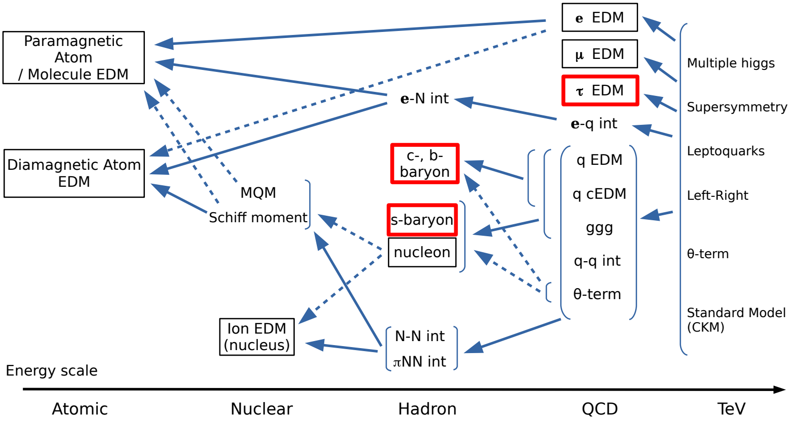
But **which** New Physics ?

Map of the EDM field



Based on N. Yamanaka. PhD Thesis (2014)

Map of the EDM field

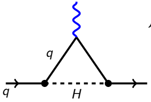


Based on N. Yamanaka. PhD Thesis (2014)

Valencia / Milano LHCb groups, EPJ C77 (2017) 181

Quark EDM: light vs heavy

- Stringent limits on **neutron EDM** $\rightarrow$ light quarks $d_{u,d} \lesssim 10^{-25}$
- Light quarks dominate constraints in models where $d_q \propto m_q$
- Models with non-trivial flavor structure:
  e.g. Yukawa couplings in 2HDM



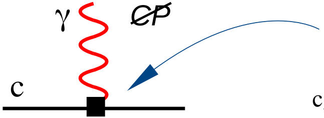
$$\mathcal{L}_Y \supset -\zeta_U \overline{Q}_{L_i} Y^u_{ij} u_{R_j} H$$

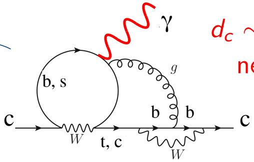
$$\zeta_U \quad \rightarrow \quad \begin{pmatrix} \zeta_U^u & 0 & 0 \\ 0 & \zeta_U^c & 0 \\ 0 & 0 & \zeta_U^t \end{pmatrix}$$

- **Heavy quark EDMs** are useful to constrain models with family-specific couplings

Predictions in BSM theories

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

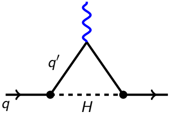


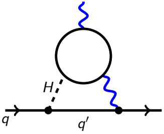


$d_c \sim 10^{-32}$ecm
negligible

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

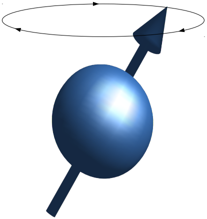
$d_c \sim 10^{-17}$ecm	EPJ C77 (2017), no.2 102	**BLMSSM**
$d_c \sim 10^{-17}$ecm	PRD 67 (2003) 036006	**MSSM**
$d_c \sim 10^{-19}$ecm	arXiv:hep-ph/0412360	**MSSM**
$d_c \sim 10^{-20}$ecm	PRD 95 (2017) 035041	**Colour-octet scalars**
$d_c \sim 10^{-21}$ecm	JHEP 1901 (2019) 069	**Scalar leptoquarks**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





How to measure EDMs?

- **Spin precession:**
  In the presence of an electromagnetic field, the spin-polarization rotates due to the magnetic moment. A change on the orthogonal direction signals the presence of an electric dipole moment.



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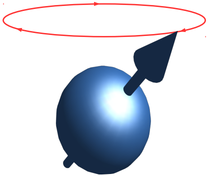

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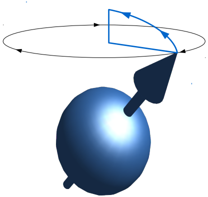


Experiment concept: requirements

- 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 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**

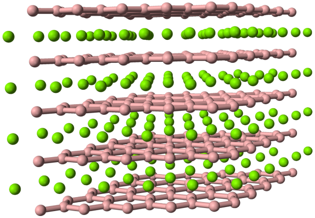
- A **detector** to measure the polarization

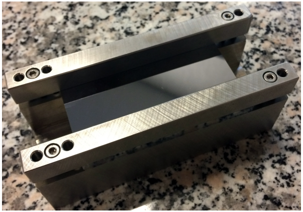
  Angular distribution of baryon decay
  products at **LHCb**

EPJ C77 (2017) 181

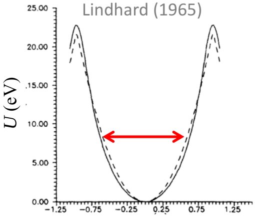
Channelling in bent crystals

- 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



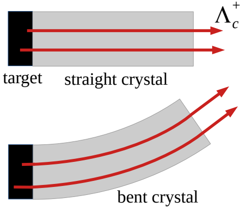


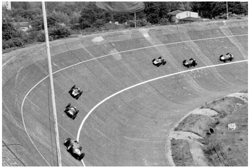
- Potential well between crystallographic planes
- Incident **positively-charged** particles can be **trapped** if their *transverse energy* is small
  $\Rightarrow$ **Small incident angle** w.r.t the crystal planes (few μrad)



Channelling in bent crystals

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



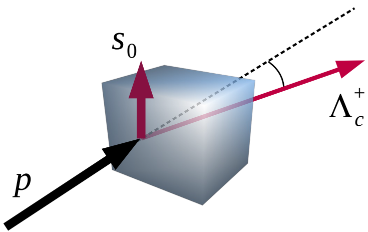


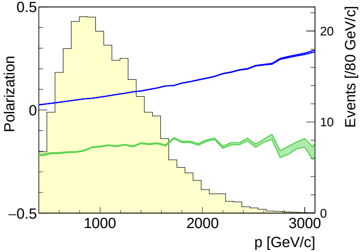
- The **E** field must compensate the *centrifugal force* which increases with the *momentum*
  $\Rightarrow$ The momentum determines a **critical bending radius** ($\sim$ 5 m)

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

Initial polarization

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





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

Spin precesion

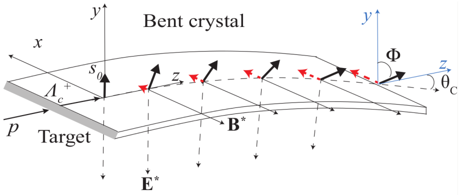
Spin-polarization vector equation of motion: T-BMT equation

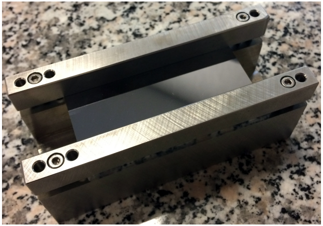
$$\frac{ds}{dt} = s \times \Omega, \quad \Omega = \Omega_{\mathrm{MDM}} + \Omega_{\mathrm{EDM}} + \Omega_{\mathrm{TH}},$$

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

Precession induced by the net EM field

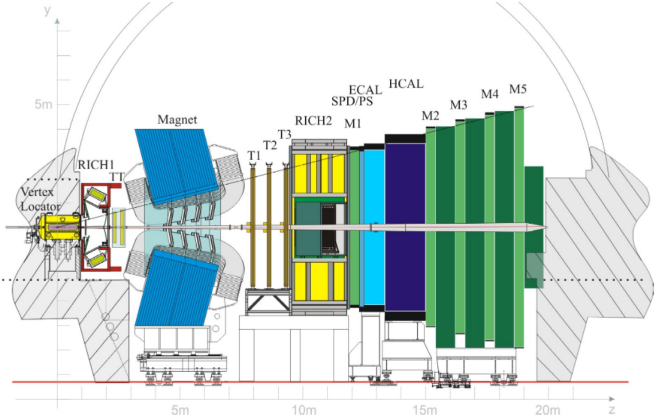
$$\boldsymbol{s} \approx s_0 \left(\frac{d}{g-2}(\cos\Phi - 1),\ \cos\Phi,\ \sin\Phi \right),\quad \Phi \approx \frac{g-2}{2}\gamma\theta_C \approx \pi$$





Reconstruction of the final polarization

- Angular analysis of $\Lambda_c^+ \to pK^-\pi^+$ decay
- LHCb detector
  - Fully instrumented in forward region $\to$ a **fixed-target-like geometry!**
  - Excellent particle identification
  - Closest tracking detectors to the LHC beam

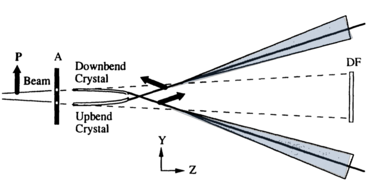


Proof of principle at E761

- 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



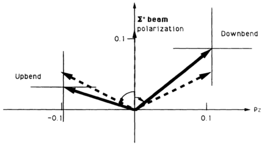
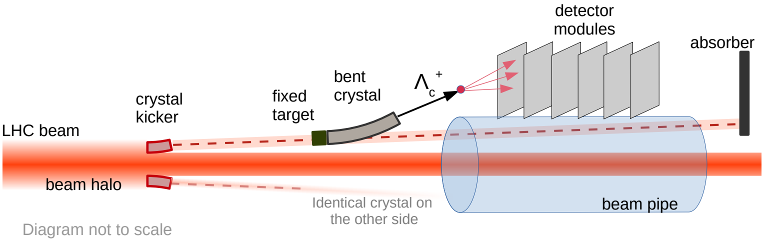


FIG. 3. Measured polarizations and uncertainties (1σ statistical errors) after spins have been precessed by the two crystals. The dashed arrows show the expected precessions.

Experimental setup at the LHC



- Setup specifications
  - Fixed-target + bent crystal in LHCb beam pipe
  - Incident protons (7 TeV) extracted from LHC beam halo with *crystal kickers*
  - Crystal length and bending (Ge): $(L, \theta_c) = (10\text{cm}, 16\text{mrad})$
  - Initial **transversal polarization** $s_0 \approx 50\%$

Physics Lett. B 758 (2016) 129
Eur.Phys.J.C 80 (2020) 10, 929
Phys. Lett. B 757 (2016) 426
CERN-SPSC-2016-030
EPJ C 77 (2017) 181
JHEP 1708 (2017) 120
EPJ C 77 (2017) 828

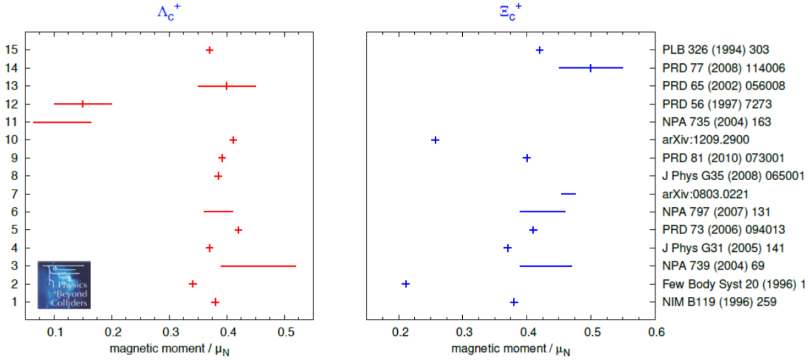
Sensitivity with **two years** of data taking (10^{13} PoT)

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

Charm baryon magnetic moments: predictions

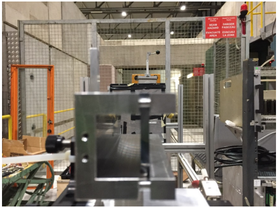
- Calculation of hadron magnetic moments not possible within pQCD (non-perturbative energy regime)
- Different models of strong interactions at low energy
- Measurement at the few % level discriminates between these approaches

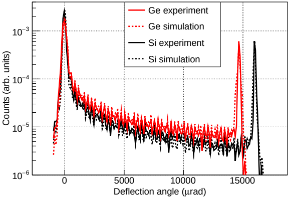
Phys. Rev. D73 (2006) 094013 Phys. Rev. D81 (2010) 073001 CERN-PBC-REPORT-2018-008



Major results so far

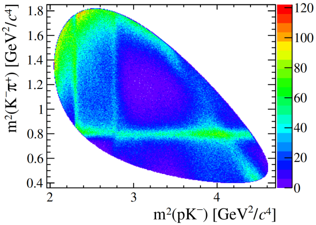
- Specific LHCb simulations prove the feasibility LHCb-INT-2017-013
  - Occupancies of the detector due to fixed target events
  - Reconstruction of $\Lambda_c^+ \to pK^-\pi^+$: resolutions and reconstruction efficiency
  - Main backgrounds under control
- Vacuum valve approved to be installed upstream of LHCb. Will allow quick target+crystal installation without breaking the VELO vacuum (during EYETS)
- Succesful test of LHC beam extraction Physics Lett. B 758 (2016) 129
- Maximum proton flux assesed with precise LHC machine optics simulations Eur.Phys.J.C 80 (2020) 10, 929
- Updated sensitivities and reconstruction strategy with state-of-the-art simulations Phys.Rev.D 103 (2021) 7, 072003
- First crystals with needed specs produced and tested on beam (Si: 8 cm, 16 mrad) (Ge: 5 cm, 15 mrad) Phys.Rev.D 103 (2021) 7, 072003

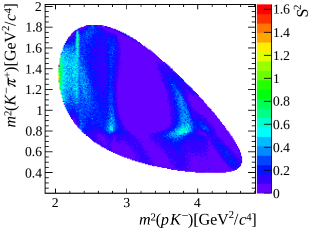




Preparatory measurements of $\Lambda_c^+ \to pK^-\pi^+$

- $\Lambda_c^+ \to pK^-\pi^+$ dominated by intermediate resonances
  $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) \approx \mathcal{B}(\Lambda_c^+ \to pK^*) + \mathcal{B}(\Lambda^*\pi^+) + \mathcal{B}(\Delta^{++}K^-)$
- Determination of polarization depends on the phase space
- Full amplitude analysis at LHCb (**close to publication!**)
  - Λ_c^+ **polarization from semileptonic decays** $\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu$
- Sensitivity to polarization parametrized through *event information* S^2

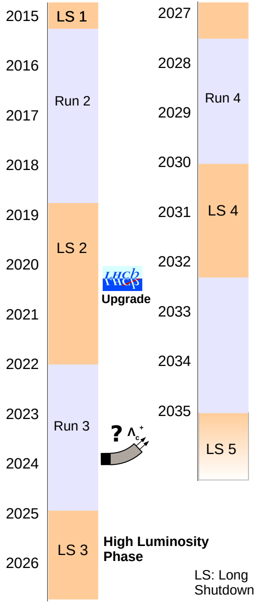




Phys.Rev.D 103 (2021) 7, 072003
D. Marangotto, PhD Thesis

- Analysis with SMOG data (*fixed target p*-gas)
  - Improved determination of the initial polarization at LHC energies

Prospects for **heavy baryon** EDMs at LHC



- Accurate studies for installation of device are currently under evaluation within the **LHCb Collaboration**
- Proposal included in the **Physics Beyond Colliders** study group

- The proposed experiment will greatly benefit from the ongoing **LHCb Upgrade**, planned for Run 3

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

Extensions of the proposal

- τ^+ **lepton** $(g-2)$ in a dedicated experiment
- Negative **b-baryons** Ξ_b^- through axial channeling
- Schemes with **new crystal geometry**

τ^+ lepton

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

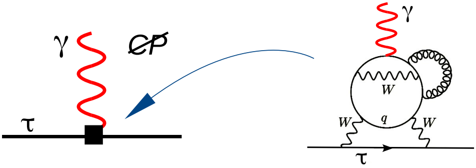
- Lepton $\to$ **free from hadronic uncertainties**

EDM of τ

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

PRD 89 (2014) 056006

PRL 125 (2020) 241802

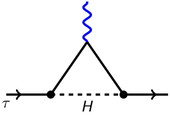


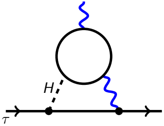
$d_\tau \sim 10^{-38} e\text{cm}$

negligible

Beyond SM predictions

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





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

Indirect bounds

$d_\tau < 4.5 \times 10^{-17} e\text{cm}$	Phys.Lett. B551 (2003) 16	$e^+e^- \to \tau^+\tau^-$, ang. dist.
$d_\tau \lesssim 5 \times 10^{-17} e\text{cm}$	Nuc.Phys.B 821 (2009) 285	d_e through lbl diagrams
$d_\tau < 3 \times 10^{-17} e\text{cm}$	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, $\boldsymbol{D_s^+ \to \tau^+ \nu_\tau}$
  (longitudinal polarization)

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

  Interatomic electric field
  in **bent crystals**

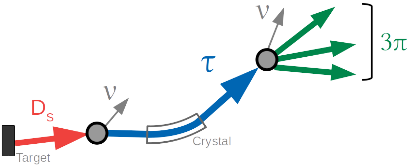
- A **detector** to measure the polarization

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

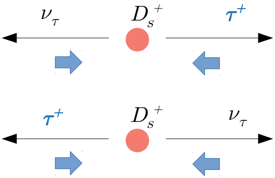
  PRL 123 (2019) 011801

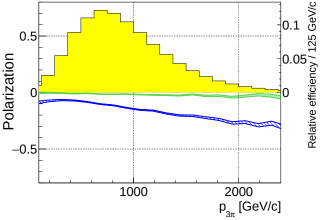
Production and initial polarization

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

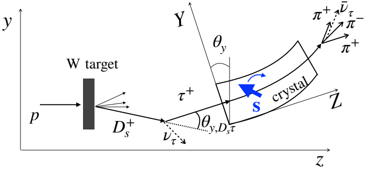


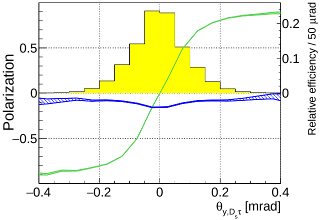


Longitudinal polarization, s_z

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

Transvere polarization, s_y

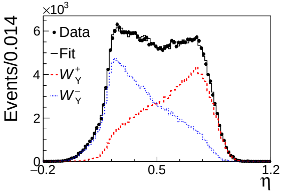




- The transverse polarization is highly **correlated to** $\theta_{\mathrm{y,D_s}\tau}$
- Variable in the **invisible part of the event** (only ν_τ associated to the vertex)
- Use the rest of the event to get statistical information on the D_s direction: $\theta_{\mathrm{y,D_s}}$**-tagging**
- Alternatively: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



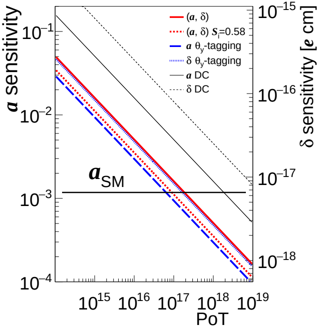
PRL 123 (2019) 011801

- Achieved event information

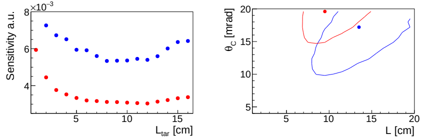
$$S_X \approx S_Y \approx 0.42\ , \quad S_Z \approx 0.23$$

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 $10^{-17}\,e\,\text{cm}$ with the same data set

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

b-baryons

Axial channeling

Planar channeling

- Repulsion of positive particles by (positive) atomic **planes**
- Well suited for Λ_c^+, Ξ_c^+. Not for Λ_b^0, Ξ_b^-
- Possible for antiparticles (Ξ_b^+). Production suppressed

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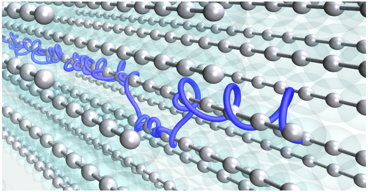
Axial channeling

- Attraction of negative particles to (positive) atomic **strings**
- Accessible with crystal orientation



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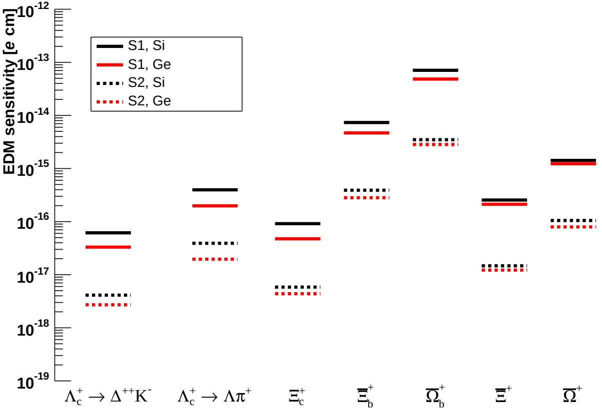
Axial channeling

- Attraction of negative particles to (positive) atomic **strings**
- Accessible with crystal orientation
- Spin precession for axial channeling possible EPJ C 77 (2017) 828
- Efficiencies with specific simulations under study

Sensitivities to other baryons

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

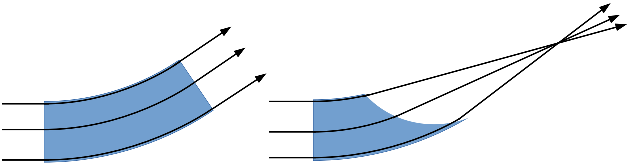


S1: Configuration at the LHCb
S2: Dedicated experiment at the LHC

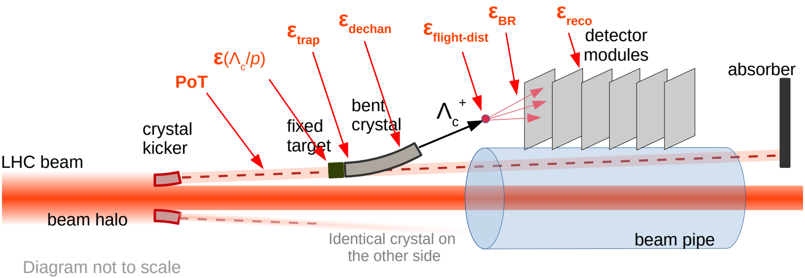
Material of the crystal:
→ **Silicon**
→ **Germanium**

Assumed 10^{15} PoT. Recently reported a maximum of 10^{13} PoT from beam optics simulations.

New crystal geometry

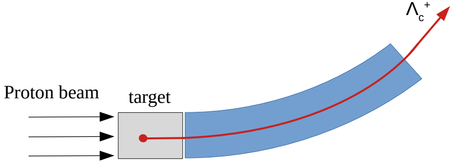


Experiment (in)efficiencies



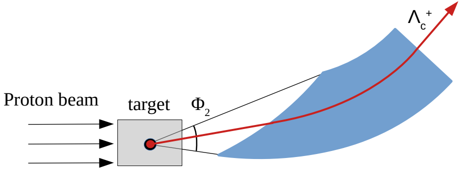
- Sensitivity dominated by statistics
- Bottlenecks: Protons on Target (PoT) and **trapping efficiency** $\varepsilon_{\text{trap}}$
- Trapped particles: small Λ_c^+ aperture angle

Trapping efficiency



Plain crystal:

- Λ_c^+ from the whole target
- In small range of directions (atomic planes horizontal)

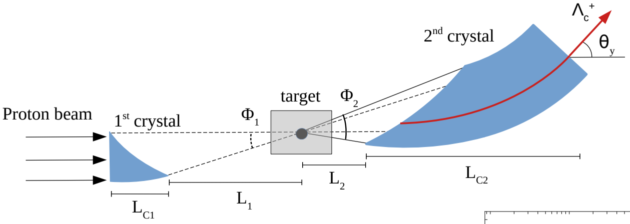


Crystal lens:

- Λ_c^+ from small volume of the target (focal point)
- In **all directions**

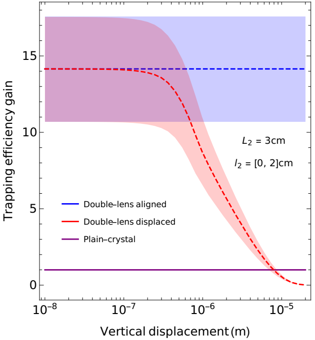
Double-lens scheme

V.M. Biryukov, JRV, arXiV:2110.00845



Double-lens scheme:

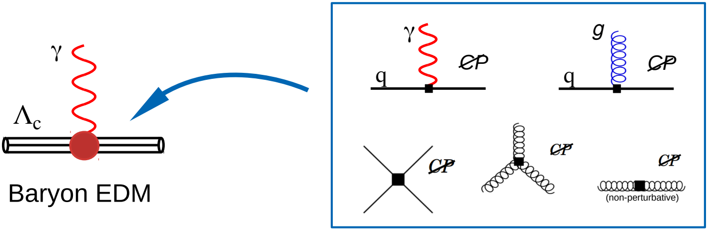
- Additional crystal focusing protons onto the target
- Λ_c^+ produced in a small vertical window
- Crystal lens trapping more Λ_c^+'s
- **Large efficiency gain** $\sim 15\times$
- Sensitive to crystal placement



Part II

- Implications of the measurement: sources of Λ_c^+ baryon EDM
- Indirect bounds
- Implications for BSM
- EDM phenomenology in colour-octet scalars

Baryon EDM in non-perturbative QCD



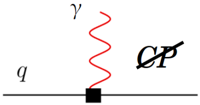
- No calculation in the lit. of EDM of Λ_c^+ (or c,b-baryons) from charm quarks (recently from θ-QCD term! Ünal, Meißner, 2008.01371)
- Estimations (NDA) point to $d_{\Lambda_c^+} \sim d_c \pm \frac{e}{4\pi}\tilde{d}_c$
- **Theoretical uncertainties** are key to understand the constraining power of heavy baryon EDM searches
- **Non-perturbative QCD methods**: chiral theories, sum rules, lattice QCD, ...

Effective operators

- **Quark dipole operators**. Λ_c^+ EDM uniquely sensitive to valence charm quarks

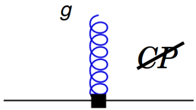
charm EDM

$d_q\, \bar{q} i \sigma^{\mu\nu} \gamma_5 q\, F_{\mu\nu}$



charm chromo-EDM

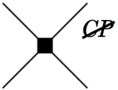
$\tilde{d}_q\, \bar{q} i \sigma^{\mu\nu} \gamma_5 t_a q\, G^a_{\mu\nu}$



- Other contributions are **suppressed** (higher-order or ruled out by nEDM)

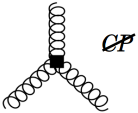
4 quark op.

$C_{ijkl}\, \bar{q}_i \Gamma q_j\, \bar{q}_k \Gamma' q_l$



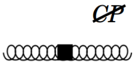
Weinberg op.

$\frac{C_W}{6} f_{abc} \varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\ \rho}_{\nu}$



θ-QCD

$-\bar{\theta} \frac{g^2}{64\pi^2} \epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}$



(non-perturbative)

Effective operators

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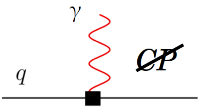
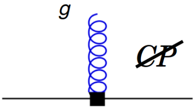


charm chromo-EDM
$\tilde{d}_q\, \bar{q} i \sigma^{\mu\nu} \gamma_5 t_a q\, G^a_{\mu\nu}$



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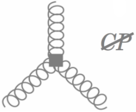
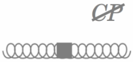


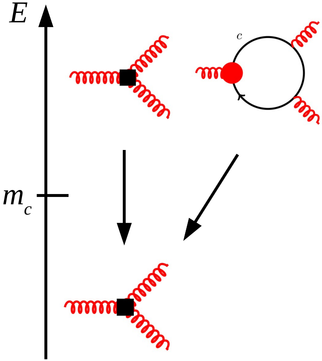
θ-QCD
$-\bar{\theta} \frac{g^2}{64\pi^2} \epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}$



(non-perturbative)

Bound on charm chromo-EDM

F.Sala, 1312.2589



Threshold contribution of chromo-EDM into Weinberg op.

$$C_W(m_c^-) = C_W(m_c^+) + \frac{g_s^3}{32\pi^2 m_c}\tilde{d}_c$$

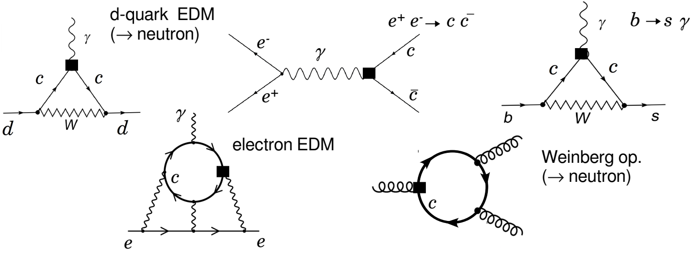
Contribution of Weinberg op. to neutron EDM

$$d_n = [\ldots]d_{u,d} + [\ldots]\tilde{d}_{u,d} + (22 \pm 10)\mathrm{MeV}\ e\ C_W(\mu_{had})$$

Assuming constructive interference (*i.e.* **neglecting cancellations**)

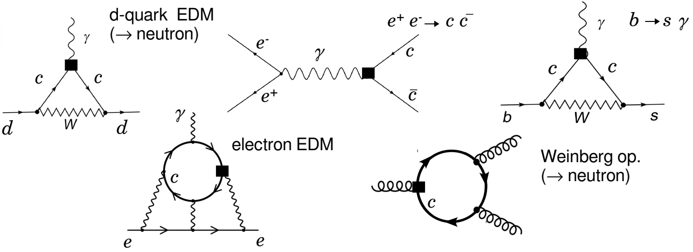
$$|\tilde{d}_c(m_c)| < 1.0 \cdot 10^{-22}\mathrm{cm}$$

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	$\mathrm{BR}(B \to X_s\gamma)$	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



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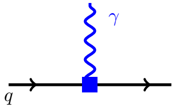
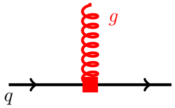
Bounds on charm EDM

H.Gisbert, JRV, 1905.02513

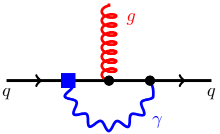


$|d_c| < 4.4 \times 10^{-17} e\,\mathrm{cm}$



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

EDM may contribute to CEDM?



Renormalization group

- Running of Wilson coefficiencts with the scale

$$\mu \frac{d}{d\mu} \vec{C}(\mu) = \hat{\gamma}^T \vec{C}(\mu) \qquad \vec{C} = \begin{pmatrix} d_q \\ \tilde{d}_q \end{pmatrix}$$

Bounds on charm EDM

$$\mu \frac{d}{d\mu} \vec{C}(\mu) = \hat{\gamma}^T \vec{C}(\mu) \qquad \vec{C} = \begin{pmatrix} d_q \\ \tilde{d}_q \end{pmatrix} \qquad \hat{\gamma} = \begin{pmatrix} 8C_F & 0 \\ 8C_F & 16C_F - 4N \end{pmatrix}$$

Bounds on charm EDM

H.Gisbert, JRV, 1905.02513

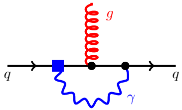
$$\mu \frac{d}{d\mu}\vec{C}(\mu) = \hat{\gamma}^T \vec{C}(\mu) \qquad \vec{C} = \begin{pmatrix} d_q \\ \tilde{d}_q \end{pmatrix} \qquad \gamma_s^{(0)} = \begin{pmatrix} 8C_F & 0 \\ 8C_F & 16C_F - 4N \end{pmatrix}$$

- Expansion of the anomalous dimension matrix

$$\hat{\gamma} = \frac{\alpha_s}{4\pi}\gamma_s^{(0)} + \left(\frac{\alpha_s}{4\pi}\right)^2 \gamma_s^{(1)} + \frac{\alpha_e}{4\pi}\gamma_e^{(0)} + \dots$$

- First nonzero term at $\mathcal{O}(\alpha_e)$.

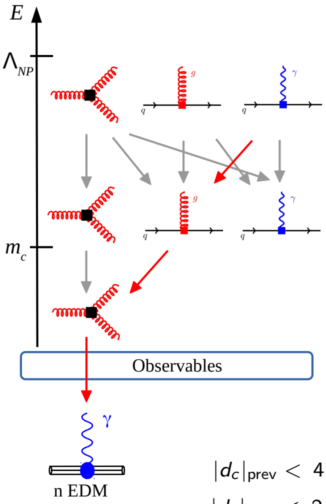
$$\gamma_e^{(0)} = \begin{pmatrix} * & 8 \\ * & * \end{pmatrix}$$



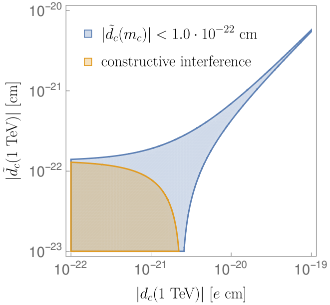
*: negligible wrt $\mathcal{O}(\alpha_s)$

Bounds on charm EDM

H.Gisbert, JRV, 1905.02513



$$\tilde{d}_c(m_c) = -0.04\frac{d_c(\Lambda_{NP})}{e} + 0.74\tilde{d}_c(\Lambda_{NP})$$



Fine tuning of 10^4 ? Assuming constructive interference

$$|d_c|_{\text{prev}} < 4.4 \times 10^{-17}\, e\,\text{cm} \rightarrow |d_c|_{\text{new}} < 1.5 \times 10^{-21}\, e\,\text{cm}\,,$$
$$|d_b|_{\text{prev}} < 2.0 \times 10^{-17}\, e\,\text{cm} \rightarrow |d_b|_{\text{new}} < 1.2 \times 10^{-20}\, e\,\text{cm}$$

Implications for BSM of the new bounds

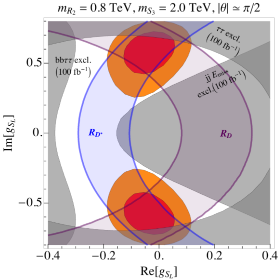
Implications for BSM: Leptoquarks

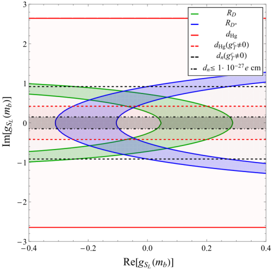
Scalar leptoquarks

- R_2 leptoquarks (3,2,7/6) couple left- and right-handed generating EDMs at 1 loop
- Included in $SU(5)$ GUT model (Bečirević et al., 1806.05689) which can explain both anomalies $b \to s\ell\bar{\ell}$ and $b \to c\tau\bar{\nu}_\tau$

$$\mathcal{L}_{\rm eff} \supset -\frac{4G_F}{\sqrt{2}} V_{cb}\; g_{S_L}(\bar{c}_R b_L)(\bar{\tau}_R \nu_\tau) \quad ,$$

- $\mathrm{Im}(g_{S_L})$ arises from the same LQ couplings that generates the charm EDM





- Stringent constraints from d_c. Will rule out the model if nEDM bound reaches $d_n \leq 10^{-27}\, e\,$cm (Dekens, de Vries, Jung, Vos, 1809.09114)

Implications for BSM: SUSY

MSSM

- Contributions at 1-loop level via gluino-, chargino-, or neutralino-squark loops
- Many works giving predictions above our bound
- Large charm EDM via gluino loops (hep-ph/0204238)
  - Updating this reference with LHC lower limits on the masses

$$d_c \approx 10^{-20} e\,\mathrm{cm}$$

BLMSSM

- MSSM where B and L local gauged symmetries break spontaneouly at the TeV scale.
- Phases $\theta_X,\ \theta_{m_B},\ \theta_{\mu_B}$ associated to new exotic superfields of this model (1610.07314)

$$d_c \in [10^{-17}, 10^{-20}] e\,\mathrm{cm} \;\; \text{accounting for curent } d_t \text{ bounds} \quad \rightarrow \quad d_c \approx 10^{-19} e\,\mathrm{cm}$$

- Recent analysis triggered by our bounds (1910.05868)

Implications for BSM: Coloured scalars

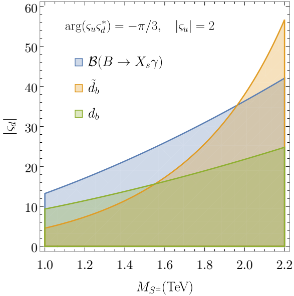
H.Gisbert, JRV, 1905.02513

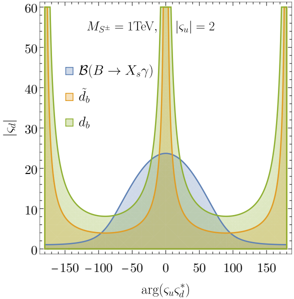
Color octet scalars (Manohar-Wise model)

- Respects MFV with (8,2,1/2)

$$\mathcal{L}_Y = -\sum_{i,j=1}^{3} \left[\zeta_U \, Y^d_{ij} \, \overline{Q}_{L_i} \, S \, d_{R_j} + \zeta_D \, Y^u_{ij} \, \overline{Q}_{L_i} \, \widetilde{S} \, u_{R_j} + \text{h.c.} \right]$$

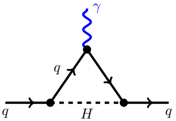
- Quark (C)EDMs at 1-loop calculated in (Martinez, Valencia, 1612.00561)
- Constraints on the $|\zeta_U \zeta_D| - M_S$ plane dominated by $\mathcal{B}(B \to X_s \gamma)$ (X.Q.Li et al., 1504.00839)
- Comparison with d_b after new bounds
- **New bounds dominate the constraints** in regions of the param. space



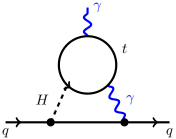


Implications for BSM

Minimal Flavor Violation



$d_q \propto m_q^3/m_H^2$



$d_q \propto m_q \frac{\alpha}{\pi}$

Restrictive power = experimental limit / size

$$\begin{pmatrix} d_u \\ d_d \\ d_s \\ d_c \\ d_b \\ d_t \end{pmatrix}_{\text{exp bound}} \lesssim \begin{pmatrix} 10^{-25} \\ 10^{-25} \\ 10^{-24} \\ 10^{-21} \\ 10^{-20} \\ 10^{-19} \end{pmatrix} \qquad \begin{pmatrix} d_u \\ d_d \\ d_s \\ d_c \\ d_b \\ d_t \end{pmatrix}_{size} \propto \begin{pmatrix} 5.5 \cdot 10^{-2} \\ 1 \cdot 10^{-3} \\ 0.2 \\ 3.2 \\ 100 \\ 5.2 \cdot 10^{3} \end{pmatrix} \tag{1}$$

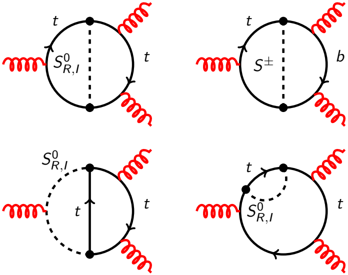
- Models with Yukawa couplings proportional to the quark mass
- Heavy quark (C)EDM compete with light quarks if $M_H \approx 400\mathrm{GeV}$
- Excluded for MW, $M_S \gtrsim 1\text{TeV}$ (Miralles, Pich, 1910.07947)
- **Needs full phenomenological analysis of EDMs in MW model**

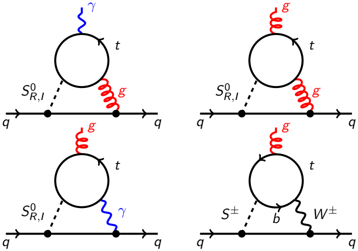
EDMs in models of coloured scalars (MW)

On arXiv next week

H.Gisbert, V.Miralles, JRV, arXiv:2111.09397

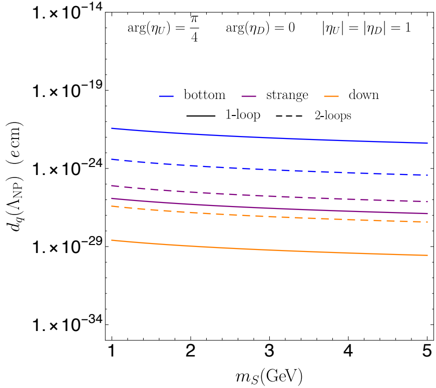
- *Full phenomenological analysis*: Contributions directly to the primary observables (neutron, mercury EDM). Possible **cancellations accounted for.**
- New two-loop contributions

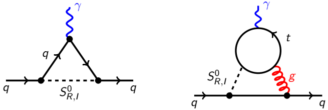




EDMs in MW: light and heavy quarks

H.Gisbert, V.Miralles, JRV, arXiv:2111.09397



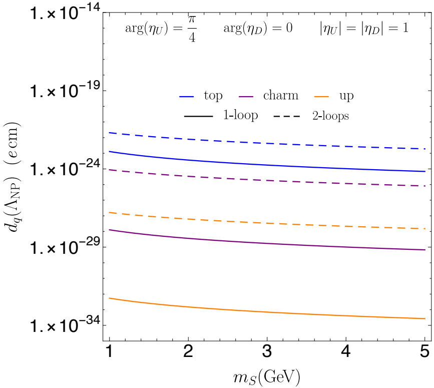


$d_q \propto m_q^3/m_S^2$ $\qquad$ $d_q \propto m_q \frac{\alpha}{\pi}$

Down-type quarks:

Hierarchy of one- and two-loop contributions as expected

H.Gisbert, V.Miralles, JRV, arXiv:2111.09397



Up-type quarks:
Top EDM also dominated by Barr-Zee...?

- Barr-Zee **enhanced** (wrt THDM)
- One-loop charged contr. **suppressed**
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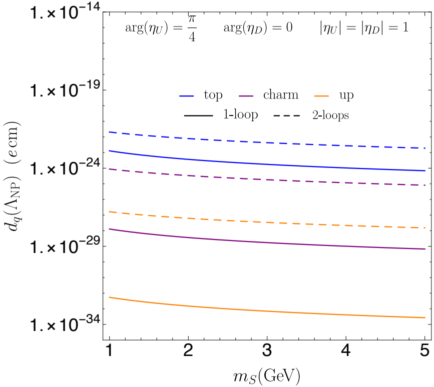

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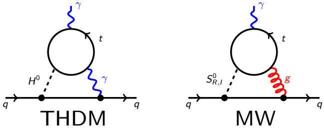

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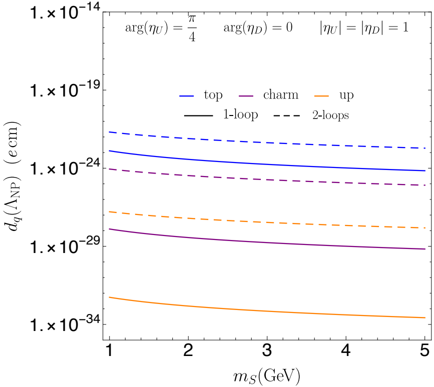

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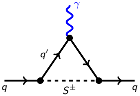

$$d_q \propto m_q m_{q'}^2 |V_{qq'}|^2$$

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EDMs in MW: light and heavy quarks

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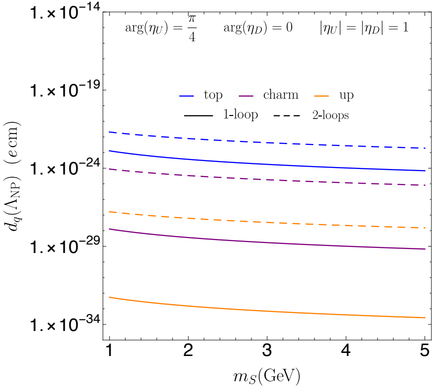

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Mass splitting (unitarity bounds):

$$|m_{S_R^0} - m_{S_I^0}| \leq 30\,\text{GeV}$$

EDMs in MW: light and heavy quarks

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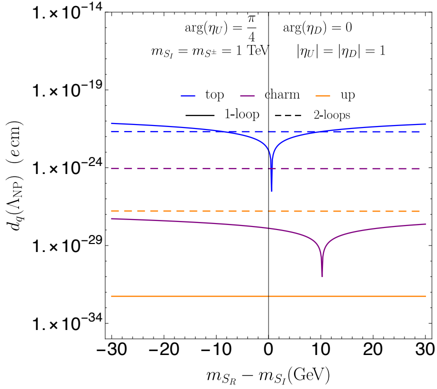

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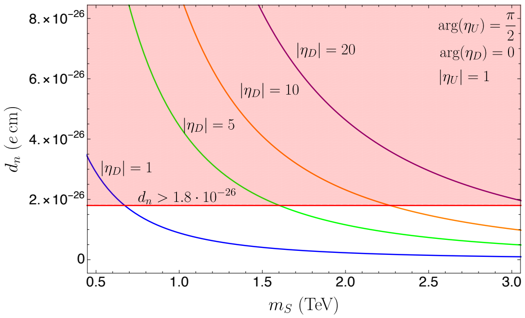
EDMs in MW: Neutron EDM

H.Gisbert, V.Miralles, JRV, arXiv:2111.09397

- Direct contributions only from light quarks and Weinberg op.

$$d_n = g_T^u\, d_u + g_T^d\, d_d + \tilde{g}_T^u\, e\, \tilde{d}_u + \tilde{g}_T^d\, e\, \tilde{d}_d + g_w\; e\, g_s\, w,$$

- Large predictions to neuton EDM, for reasonable parameters



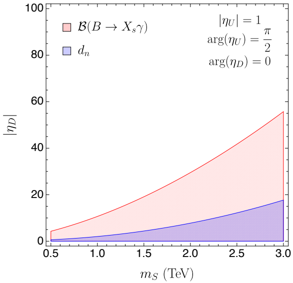
EDMs in MW: Constraints

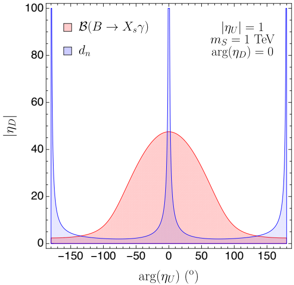
H.Gisbert, V.Miralles, JRV, arXiv:2111.09397

- Included all relevant contributions to the neutron EDM
- Stringent experimental limit by nEDM@PSI,

$$d_n < 1.8 \cdot 10^{-26} e\,\text{cm} \quad (90\%\ \text{CL})$$

- Light-quark (C)EDMs: even better than bottom EDM
- **Best restrictions from EDMs** if the phases $\neq 0$





Summary

Experiment

- Direct spin precession on **charm baryons**
  - Feasible with minimal additional instrumentation
  - **First EDM search**, at $\approx 4 \cdot 10^{-16}$ecm
  - **First measurement of magnetic moment**, at 12% accuracy level
- Estension 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
  - Ultimate sensitivity in a dedicated experiment

Phenomenology

- Indirect **bounds on heavy quark EDM** can be derived already
- Important **implications for BSM** theories

  ▹ Leptoquarks ▹ SUSY ▹ THDM ▹ MW
- Final restrictions to MW from light quarks

Backup