Updates on charm baryon dipole moments

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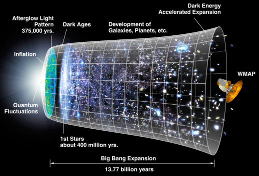
March 5, 2024

Probing baryon weak decays - from experiment to lattice QCD
Warsaw, 4 – 5 March 2024

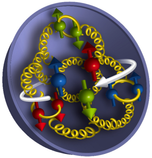
Electric and magnetic dipole moments

Electric Dipole Moment (EDM)

- Matter–antimatter asymmetry
- Sakharov conditions $\supset$ C and CP violation
- Sources of CP Violation: SM (not enough) and BSM
- SM-background free search for 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 dipole moments

Classical EDM

$$\boldsymbol{\delta} = \int \boldsymbol{r}\rho(\boldsymbol{r})d^3r$$

Quantum mechanics

$$\boldsymbol{\delta} = d\boldsymbol{S}/S$$

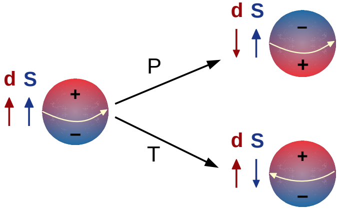
*with $H = -\boldsymbol{\delta}\cdot\boldsymbol{E}$

QFT

$$\mathcal{L} = -d\frac{i}{2}\,\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi\,F_{\mu\nu}$$

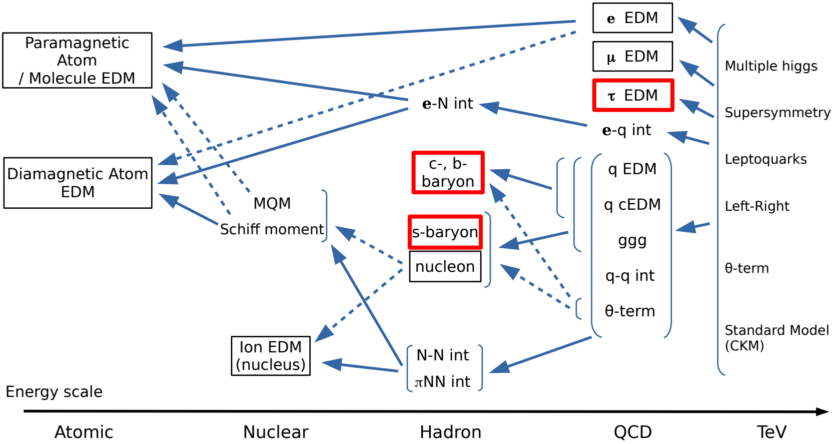
Interaction with **E**

$$H = -\boldsymbol{\delta}\cdot\boldsymbol{E} \quad \begin{array}{l} \xrightarrow{T} \quad +\boldsymbol{\delta}\cdot\boldsymbol{E} \\ \xrightarrow{P} \quad +\boldsymbol{\delta}\cdot\boldsymbol{E} \end{array}$$



The EDM violates separately T and P ⇒ **CP violation**

Map of the EDM field



Experiment concept

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How to measure EDMs?

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

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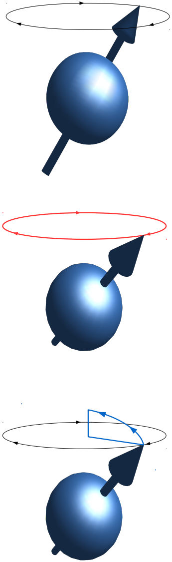
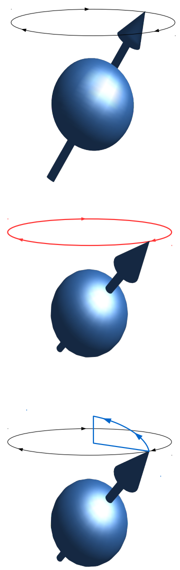


Experiment concept

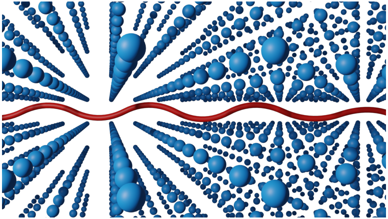
How to measure EDMs?

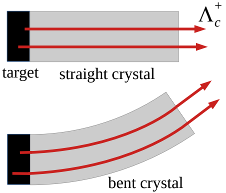
- **Spin precession:**
  In the presence of an electromagnetic field, the spin-polarization rotates due to the magnetic dipole moment. A change on the orthogonal direction signals the presence of an electric dipole moment.
- **Requirements:**
  Polarized particles   EM field   Detector



Bent crystals

- Very short-lived Λ_c^+ ($\sim$ 5cm) → need large EM field in small space ($\sim 10^3$ T)
- **E** field between atomic planes



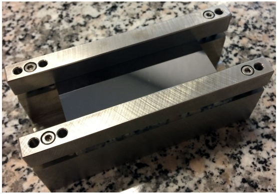


- Precession induced by the net EM field

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

$$\Phi \approx \frac{g-2}{2}\gamma\theta_C \approx \pi$$

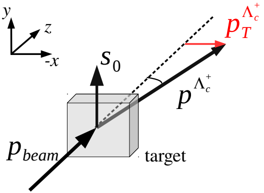
see *e.g.* EPJ C 77 (2017) 828

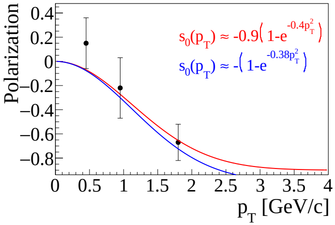


Initial Λ_c^+ polarization

- Perpendicular to the production plane ($\mathcal{P}$ conservation)
- Magnitude depends on the Λ_c^+ p_T and x_F
- Extrapollation from phenomenological models based on Λ production.

Phys. Lett. B471 (2000) 449





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

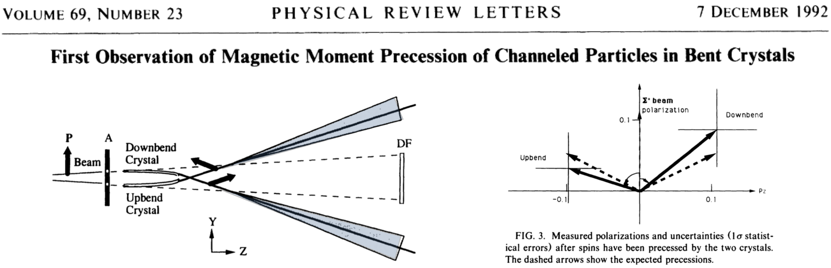
- Ongoing LHCb analysis with SMOG data (p-gas $\rightarrow$ $\Lambda_c^+ \rightarrow pK^-\pi^+$)
  Valuable information although in different kinematical range

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 $L = 4.5\,\mathrm{cm}$, $\theta_C = 1.6\,\mathrm{mrad}$ to induce opposite spin precession

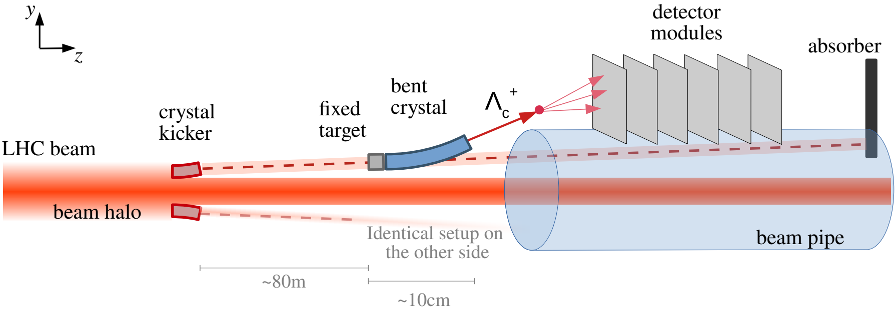


VOLUME 69, NUMBER 23 PHYSICAL REVIEW LETTERS 7 DECEMBER 1992

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 processed 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)

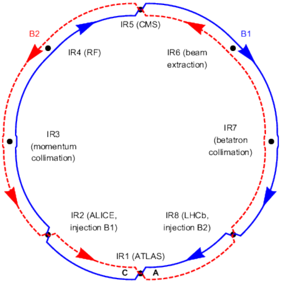
- **EDM** sensitivity $\sigma_\delta \approx 4 \cdot 10^{-16} e\mathrm{cm}$
- First measurement of Λ_c^+ (Ξ_c^+) **magnetic moment**, $\sigma_{g-2} \approx 2 \times 10^{-2}$

PRD 103 (2021) 7, 072003

Towards the realization

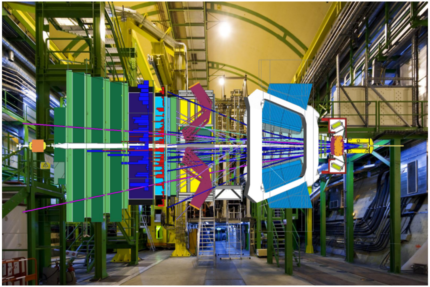
CERN, IFIC Valencia, IJCLab, NSC KIPT Kharkov,
Univ. of Bonn, UCAS, Lund Univ., INFN (Ferrara, Genova,
Milano, Milano Bicocca, Padova, Pisa)

Location



- Point 8: LHCb spectrometer, less instrumentation, potential interference (studied)
- Interaction Region IR3: New spectrometer, higher flexibility/control

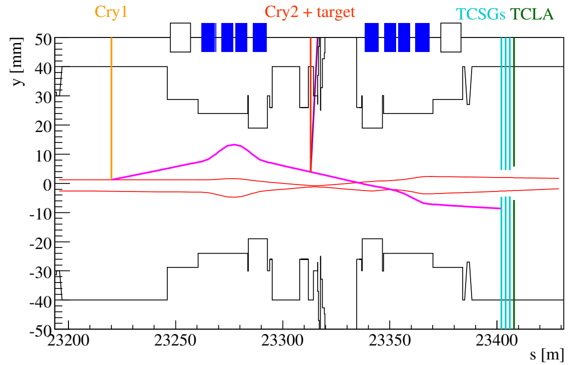
LHCb



IR3

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

Measurement of final polarization

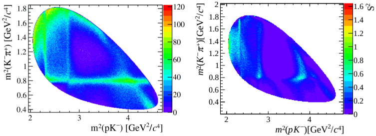
- $\Lambda_c^+ \to pK^-\pi^+$ dominated by intermediate resonances
- Initially considered exclusive quasi-two-body decays

$$\Lambda_c^+ \to \Delta^{++} K^- \quad , \qquad \frac{dN}{d\Omega'} \propto 1 + \alpha_{\text{eff}}\, \boldsymbol{s} \cdot \hat{\boldsymbol{k}}$$

- Precise amplitude model allows sensitivity to the Λ_c^+ polarization across the phase space: **statistics x6**,

LHCb analysis

Phys.Rev.D 108 (2023) 1, 012023



Λ_c^+ final state	$\mathcal{B}$ (%)	$\epsilon_{3\text{trk}}$	$\mathcal{B}_{\text{eff}}$ (%)
$pK^-\pi^+$	6.28 ± 0.32	0.99	6.25
$\Sigma^+\pi^-\pi^+$	4.50 ± 0.25	0.54	2.43
$\Sigma^-\pi^+\pi^+$	1.87 ± 0.18	0.71	1.33
$p\pi^-\pi^+$	0.461 ± 0.028	1.00	0.46
$\Xi^-K^+\pi^+$	0.62 ± 0.06	0.73	0.45
$\Sigma^+K^-K^+$	0.35 ± 0.04	0.51	0.18
pK^-K^+	0.106 ± 0.006	0.98	0.11
$\Sigma^+\pi^-K^+$	0.21 ± 0.06	0.54	0.11
$pK^-\pi^+\pi^0$	4.46 ± 0.30	0.99	4.43
$\Sigma^+\pi^-\pi^+\pi^0$	3.20	0.54	1.72
$\Sigma^-\pi^+\pi^+\pi^0$	2.1 ± 0.4	0.71	1.49
$\Sigma^+[p\pi^0]\pi^-\pi^+$	2.32	0.46	1.06
$\Sigma^+[p\pi^0]K^-K^+$	0.18	0.46	0.08
$\Sigma^+[p\pi^0]\pi^-K^+$	0.11	0.46	0.05
All	-	-	20.2

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

- Combined with other Λ_c^+ decay channels

Crystal specifications and manufacturing

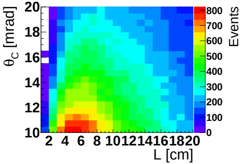
Crystal optimization

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

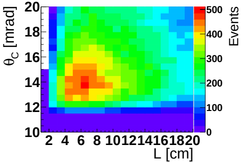
$$L \approx 10\text{cm} \quad \theta_C \approx 16\text{mrad} \quad \text{(LHCb)}$$
$$L \approx 7\text{cm} \quad \theta_C \approx 7\text{mrad} \quad \text{(dedicated)}$$

EPJ C 77 (2017) 828

channelled

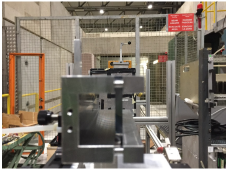


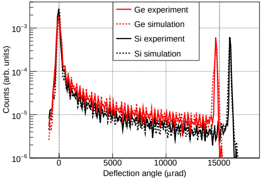
in acceptance



First prototypes

- Manufactured by INFN Ferrara; tested at CERN





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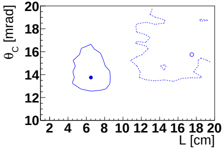
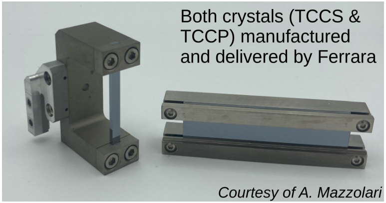
Optimal sensitivity EDM/MDM



Goniometers

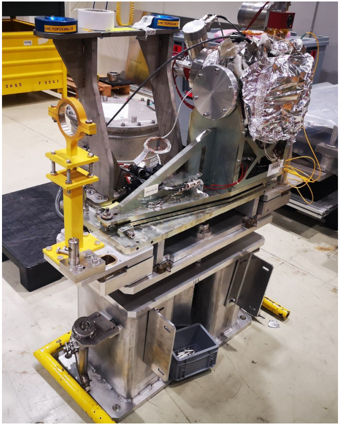
- Insert and retract target and crystal. Tune crystal orientation
- Two crystals/goniometers
  - **Beam splitter**: short crystal, 50μrad bending. Goniometer (TCCS) from previous LHC machine tests with crystals
  - **Spin precession crystal**: long, 7mrad bending Goniometer (TCCP) in construction



Both crystals (TCCS & TCCP) manufactured and delivered by Ferrara

Courtesy of A. Mazzolari

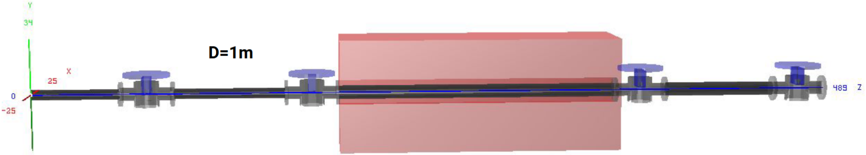
TCCS



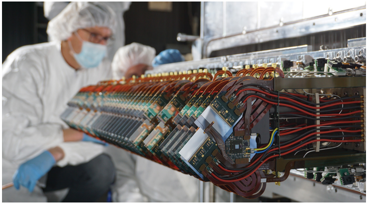
3rd workshop on EDM of unstable particles; P.Hermes

Spectrometer

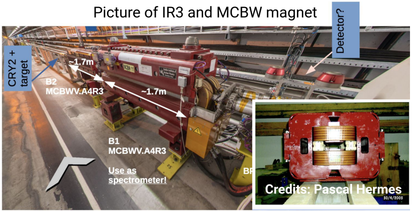
3rd workshop on EDM of unstable particles; E.Spadaro



- Layout optimization ongoing with **full simulations**
- Concrete experimental solutions identified
  - **Tracker**: Tiles of VELOpix (LHCb)
  - **Magnet**: Re-use orbit correction MCBW (1.1T) or dedicated (~ 5T)
  - **Roman pot** (beam pipe access): re-use ATLAS/ALFA, TOTEM (CMS)
  - Also under study: PID with dedicated RICH for TeV-particles (!)



Picture of IR3 and MCBW magnet

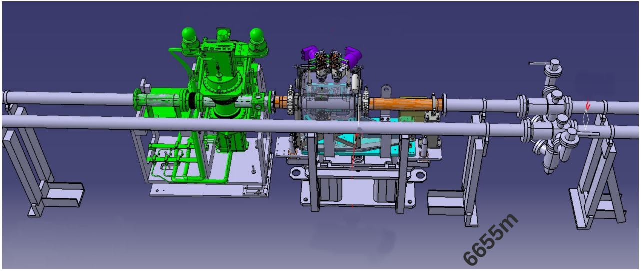


3rd workshop on EDM of unstable particles: S.Cesare, E. Matheson, N.Neri, S.Jakobsen, M.Sorbi, R.Forty ...

Proof of principle
TWOCRYST

Machine test

- Long crystals tested at 180 GeV. Prove channelling in TeV range
- Validate two-crystal setup (beam splitter/kicker + precession crystal)
- Operational feasibility

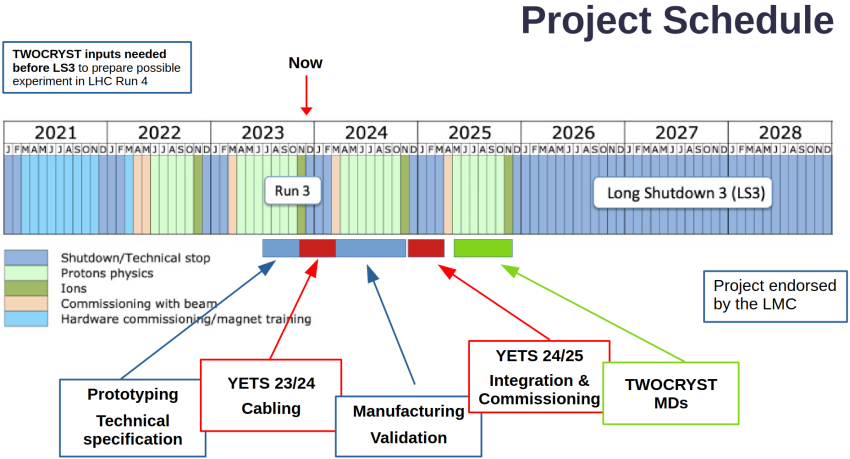


3rd workshop on EDM of unstable particles:

P.Hermes, K.Dewhurst, E.Matheson, H.Havlikova, S.Jakobsen, ...

Timeline

3rd workshop on EDM of unstable particles; P.Hermes



Project Schedule

TWOCRYST inputs needed before LS3 to prepare possible experiment in LHC Run 4

Now

Project endorsed by the LMC

Prototyping

Technical specification

YETS 23/24

Cabling

Manufacturing

Validation

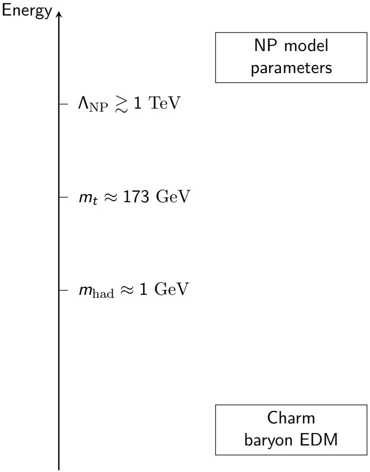
YETS 24/25

Integration & Commissioning

TWOCRYST MDs

Theory status

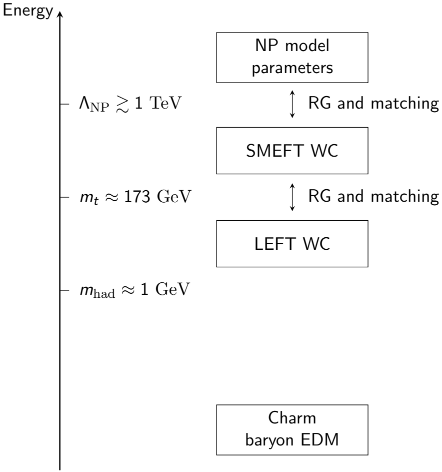
Big picture



RG: Renormalization group
WC: Wilson Coefficients
LEFT: Low-energy effective field theory

Connection New Physics to heavy baryon EDM

Big picture



Energy

NP model parameters

$\Lambda_{\mathrm{NP}} \gtrsim 1\ \mathrm{TeV}$

RG and matching

SMEFT WC

$m_t \approx 173\ \mathrm{GeV}$

RG and matching

LEFT WC

$m_{\mathrm{had}} \approx 1\ \mathrm{GeV}$

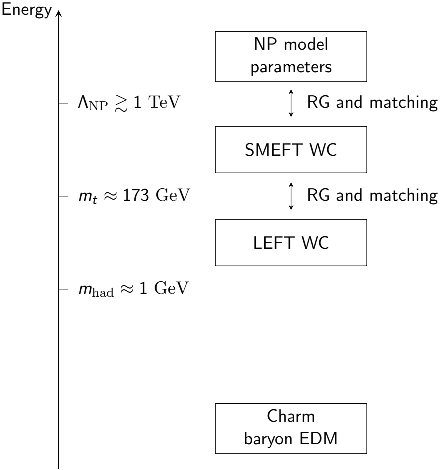
Charm baryon EDM

RG: Renormalization group
WC: Wilson Coefficients
LEFT: Low-energy effective field theory

Connection New Physics to heavy baryon EDM

- Effective theories capture high-energy dynamics and are model-independent
- Contributions to EDMs: **flavour-diagonal CP-violating effective operators**

Big picture



Energy

NP model parameters

$\Lambda_{\mathrm{NP}} \gtrsim 1$ TeV — RG and matching

SMEFT WC

$m_t \approx 173$ GeV — RG and matching

LEFT WC

$m_{\mathrm{had}} \approx 1$ GeV

Charm baryon EDM

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Connection New Physics to heavy baryon EDM

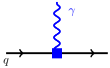
- Effective theories capture high-energy dynamics and are model-independent
- Contributions to EDMs: **flavour-diagonal CP-violating effective operators**
- **Quark dipole operators**. Λ_c^+ EDM uniquely sensitive to valence charm quarks

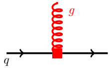
charm EDM

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

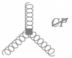
chromo-EDM

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



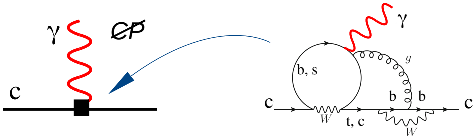


4 quark op. Weinberg op. θ-QCD



Charm EDM in BSM theories

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



$d_c \sim 10^{-32} e\text{cm}$
negligible

Generic New Physics

Size of dipole operators of dimension 5, originating from NP ($\Lambda_{\mathrm{NP}} = 1\mathrm{TeV}$)

$$-d_c \frac{i}{2}\,\bar{c}\sigma^{\mu\nu}\gamma_5 c\, F_{\mu\nu} \quad\rightarrow\quad d_c \sim \frac{vev}{\Lambda_{\mathrm{NP}}^2} e \sim 10^{-18} e\text{cm}$$

In concrete NP theories, with phenomenological and theoretical constraints, different story ... Let's see some examples

Charm EDM in BSM theories II

Colour octet scalars (Manohar-Wise model)

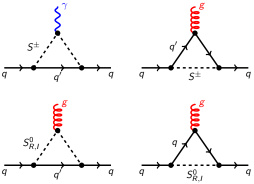
- New scalars with colour charge (8,2,1/2)

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

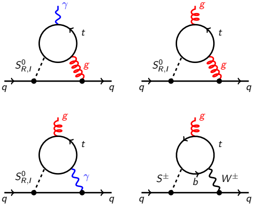
- Predictive theory. Motivated by MFV and GUTs
- Quark (C)EDMs at 1-loop in [Martinez, Valencia, 1612.00561]
- Quark (C)EDMs at 2-loop in [Gisbert, Miralles, JRV, 2111.09397]
- Parameter constraints w/o the nEDM, [X.Q.Li et al., 1504.00839] [Eberhardt, Miralles, Pich, 2106.12235] allow maximum value

$$d_b \sim 10^{-19} e\text{cm}\ , \quad d_c \sim 10^{-21} e\text{cm}$$

One loop



Two loops



Charm EDM in BSM theories III

Scalar leptoquarks

- R_2 leptoquarks (3,2,7/6) generate EDMs at 1 loop
- Solution to $b \to c\tau\bar{\nu}_\tau$ and (old) $b \to s\ell\bar{\ell}$ anomalies [Bečirević et al., 1806.05689]
- Charm EDM extremely relevant to assess the CPV in connection to $R_{D^{(*)}}$ [Dekens, de Vries, Jung, Vos, 1809.09114]

$$d_c \sim 10^{-21} \text{ ecm}$$

Minimal Supersymmetric model (MSSM)

- Large charm EDM via gluino loops [Aydin, Erkarslan, hep-ph/0204238]
  - Updating this reference with LHC lower limits on the masses

$$d_c \sim 10^{-17} \ \to \ d_c \sim 10^{-20} \text{ecm}$$

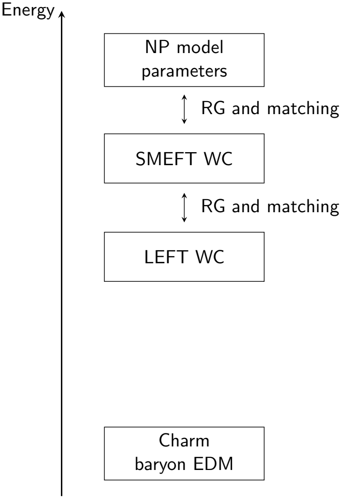
BLMSSM

- MSSM where B and L gauged symmetries break spontaneously at the TeV scale.
- Many new CPV phases. Charm and top EDM studied in [Zhao, Feng et al., 1610.07314]
  - Accounting for current d_t bounds

$$d_c \sim 10^{-17} \ \to d_c \sim 10^{-19} \text{ecm}$$

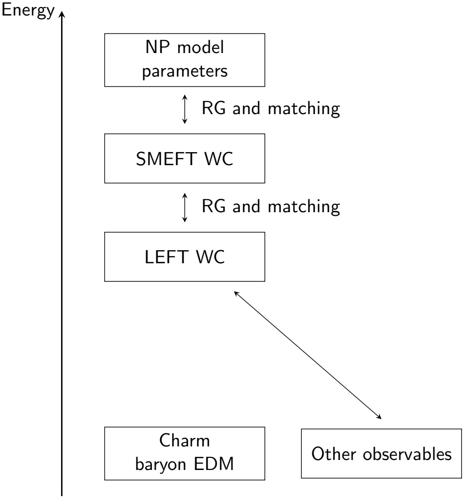
- Recent analysis [Yang, Feng et al., 1910.05868]

Indirect bounds on charm EDM



- **What is the maximum d_c allowed, regardless of the NP model?**

Indirect bounds on charm EDM



NP model parameters

RG and matching

SMEFT WC

RG and matching

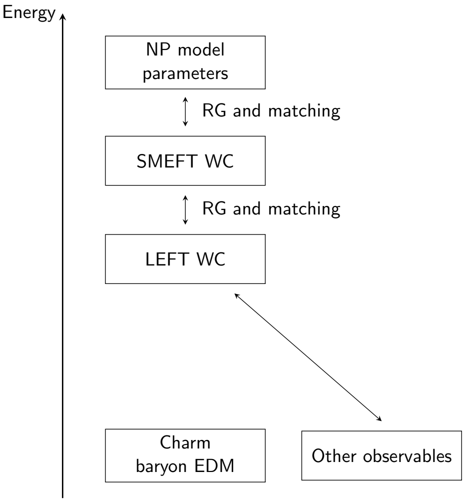
LEFT WC

Charm baryon EDM

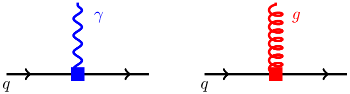
Other observables

- **What is the maximum d_c allowed, regardless of the NP model?**

Indirect bounds on charm EDM



- **What is the maximum d_c allowed, regardless of the NP model?**
- Up to 2019, best in the literature [Sala, 1312.2589]

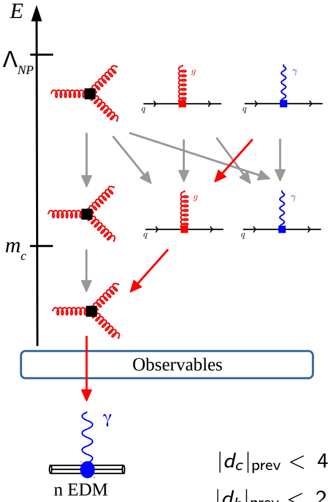


$|d_c| < 4.4 \times 10^{-17} e\text{cm}$ $\quad$ $|\tilde{d}_c| < 1.0 \cdot 10^{-22}\text{cm}$

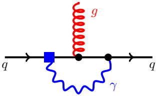
- Connection to nEDM is (more) straightforward from chromo-EDM

Bounds on charm EDM

[Gisbert, JRV, 1905.02513]



EDM may contribute to CEDM?



Renormalization group equations

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

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

* First nonzero mixing EDM → CEDM

Assuming constructive interference

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

$$|d_b|_{\text{prev}} < 2.0 \times 10^{-17} \text{ ecm} \quad \rightarrow \quad |d_b|_{\text{new}} < 1.2 \times 10^{-20} \text{ ecm}$$

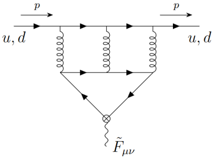
Bounds on charm EDM II

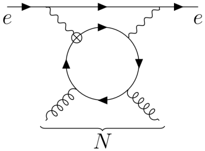
Limits from light quark EDM and eN interaction

[Ema, Gao, Pospelov, 2205.11532]

Contribution of d_c

- To $3g$-1γ operators, to light-quark EDM, to neutron EDM
- To 2γ-$2g$ operators, to electron-nucleon, to paramagnetic molecule ThO (used for d_e)





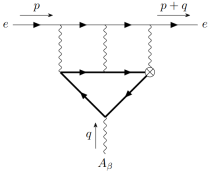
$$|d_c| < 6 \times 10^{-22} \text{ ecm}$$

Limits from electron EDM

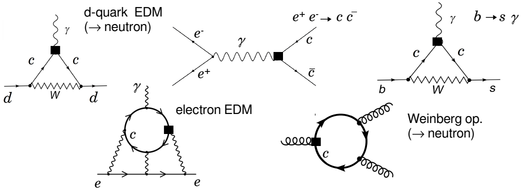
[Ema, Gao, Pospelov, 2207.01679]

Contribution of d_c

- To 4γ operators (light-by-light scattering), to electron EDM

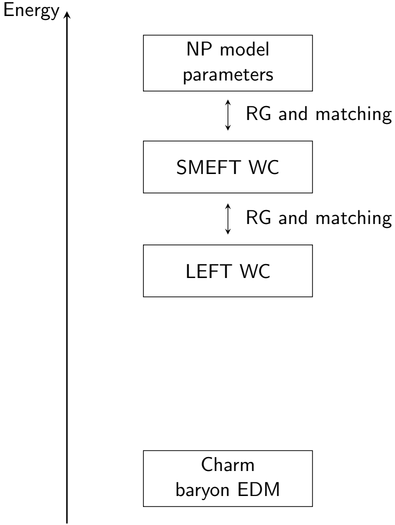


Other limits



Bound	Ref.	Measurement	Method
$\lvert d_c \rvert < 8.9 \times 10^{-17}$ ecm	[Escribano:1993xr]	$\Gamma(Z \to c\bar{c})$	Measurement at the Z peak (LEP). Weights electic (d_c) and weak (d_c^w) dipole moments through model-dependent relations.
$\lvert d_c \rvert < 5 \times 10^{-17}$ ecm	[Blinov:2008mu]	$e^+e^- \to c\bar{c}$	The total cross section (from the LEP combination [ALEPH:2006bhb]) is enhanced by the charm EDM vertex $c\bar{c}\gamma$.
$\lvert d_c \rvert < 3 \times 10^{-16}$ ecm	[Grozin:2009jq]	electron EDM	Considers contribution of d_c into d_e through light-by-light scattering (three-loop) diagrams.
$\lvert d_c \rvert < 1 \times 10^{-15}$ ecm	[Grozin:2009jq]	neutron EDM	Similar approach than Ref. [Sala:2013osa] with different treatment of diverging integrals and more conservative assumptions.
$\lvert d_c \rvert < 4.4 \times 10^{-17}$ ecm	[Sala:2013osa]	neutron EDM	Considers contribution of d_c into d_d via $W^{\pm}$ loops. Expressions from Ref. [CorderoCid:2007uc].
$\lvert d_c \rvert < 3.4 \times 10^{-16}$ ecm	[Sala:2013osa]	$\mathrm{BR}(B \to X_s\gamma)$	Considers contributions of d_c into the Wilson coefficient C_7.
$\lvert d_c \rvert < 1.5 \times 10^{-21}$ ecm	[Gisbert:2019ftm]	neutron EDM	Renormalization group mixing of d_c into $\tilde{d}_c$.
$\lvert d_c \rvert < 6 \times 10^{-22}$ ecm	[Ema:2022pmo]	neutron EDM	Contribution of d_c to $3g$-1γ operators, to light-quark, to neutron EDM
$\lvert d_c \rvert < 1.3 \times 10^{-20}$ ecm	[Ema:2022pmo]	electron EDM	Contribution of d_c to 2γ-$2g$ operators, to electron-nucleon, to paramagnetic molecule ThO

Baryon EDM in non-perturbative QCD



Energy

NP model parameters

RG and matching

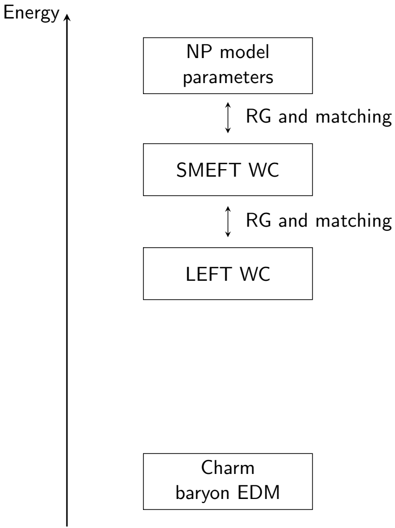
SMEFT WC

RG and matching

LEFT WC

Charm baryon EDM

Baryon EDM in non-perturbative QCD



Quark constituent model

- Sea quarks and gluons dressing the *"quarks"*, $m_{u,d} \approx 300\mathrm{MeV}$
- Phenomenological success *e.g.* $\mu_n = -\frac{2}{3}\mu_p$

$$d_{\Lambda_c^+} = d_c$$

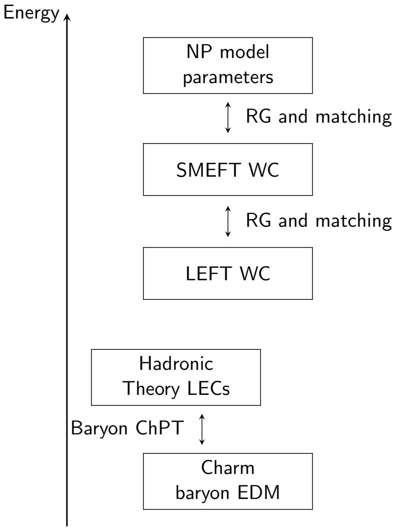
Naive Dimensional Analysis (NDA)

- Dimensionality of couplings + loop suppression factors

$$d_{\Lambda_c^+} \sim \quad \pm \; d_c \; \pm \; \frac{e}{4\pi}\tilde{d}_c$$

- Estimates not always reliable. See *e.g.* $\Delta A_{CP}(D \to \pi\pi, KK)$
- **Theoretical uncertainties** are key to understand the constraining power of heavy baryon EDM searches

Baryon EDM in non-perturbative QCD (II)


Energy

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RG and matching

LEFT WC

Hadronic Theory LECs

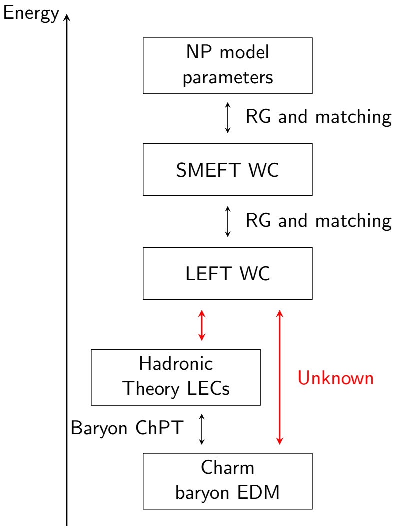
Baryon ChPT

Charm baryon EDM

Chiral Perturbation Theory

- EFT based on the **symmetries of QCD** with hadrons as degrees of freedom
  $SU(3)_C$, $SU(3)_L \times SU(3)_R^{\ddagger}$, $\mathcal{P}$, $\mathcal{C}$
  ‡ provided $m_q \to 0$
- Systematic frameworks developed. Many new interactions and unknown **Low Energy Constants** (LECs)
- Bottom baryons [de Vries, Hanhart, Severt, Ünal, Meißner, 2111.13000]
  Charm baryons [Ünal, 2306.03639]
  → Baryon EDM in terms of LECs
  then estimated these with NDA

Baryon EDM in non-perturbative QCD (II)



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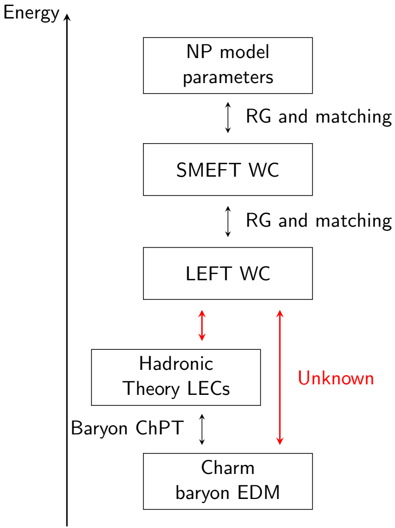


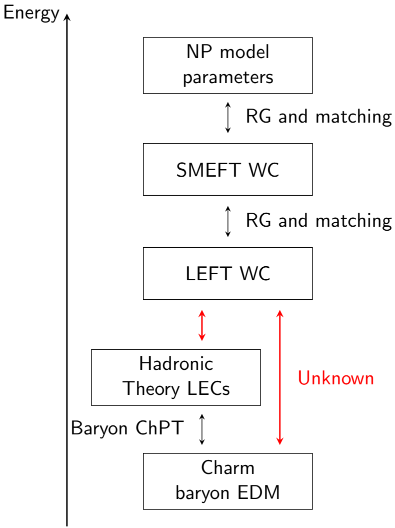
Heavy Quark Effective Theory

- Considers heavy quark $m_Q \to \infty$ with constant 4-velocity v^μ
- High predictive power: spectrum, masses, decays

Sum Rules

- Neutron EDM from QCD Sum Rules. Reference for many years [Pospelov, Ritz, hep-ph/0010037]
  $$d_n = (1 \pm 0.5)(1.4(d_d - 0.25 d_u) \\ + 1.1e(\tilde{d}_d + 0.5\tilde{d}_u))$$
- Allows systematic treatment of uncertainties

Baryon EDM in non-perturbative QCD (III)



Energy

NP model parameters

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SMEFT WC

RG and matching

LEFT WC

Hadronic Theory LECs

Unknown

Baryon ChPT

Charm baryon EDM

Lattice QCD

- Numerical method to solve the functional integral of QCD
- Discretize space time and simulate extended wave functions
- nEDM: Uncertainty improvement wrt sum rules *e.g.* [Cirgliano et al, 1808.07597]

$$d_n = (0.784 \pm 0.030) d_d - (0.204 \pm 0.015) d_u + \ldots$$

- Charm baryon EDM *"doable if there is interest..."*

Conclusions

- Charm baryon EDM **never tested before**. Sensitivity of this experiment $\delta(d_{\Lambda_c^+}) \approx 10^{-17} e\text{cm}$ 2010.11902
- Efforts towards a dedicated experiment for Run 4. Letter of Intent coming soon
- **Proof-of-principle TWOCRYST** (without magnet) to be installed at the end of 2024
- **Interpretation in terms of NP** needs advanced **hadronic methods**
  Theory uncertainty key to assess the restrictive power

- Challenging to beat indirect bounds on charm quark EDM

- **Charm baryon MDM** at the few % will test the validity of different low-energy QCD methods at the charm scale