Theory overview of heavy baryon EDMs

Joan Ruiz-Vidal

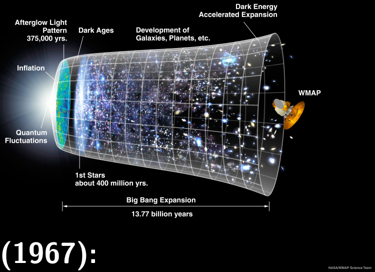
Division of Particle and Nuclear Physics
Department of Physics
Lund University

December 11, 2023

LUND UNIVERSITY

3rd workshop on electromagnetic dipole moments of unstable particles
IJCLab, Orsay

Matter-antimatter imbalance



Sakharov conditions (1967):

Ingredients to generate matter-antimatter imbalance:

- **Baryon number violation**

  $X \to X' + B$

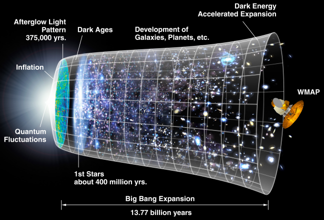
- **C and CP violation**

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

- **Out of thermal equilibrium**

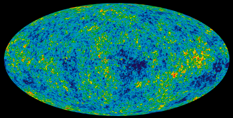
  $X \to X' + B \neq X' + B \to X$

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 dipole moments

Classical EDM

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

Quantum mechanics

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

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

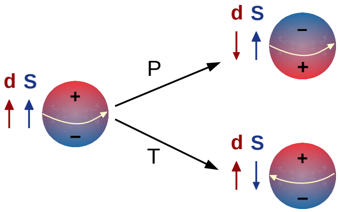
QFT

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

Interaction with **E**

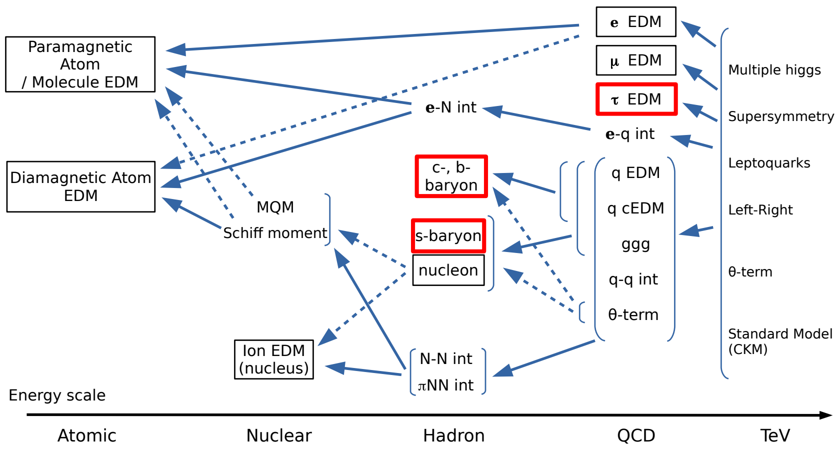
$$H = -\boldsymbol{\delta} \cdot \boldsymbol{E} \quad \xrightarrow{T} \quad +\boldsymbol{\delta} \cdot \boldsymbol{E}$$

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

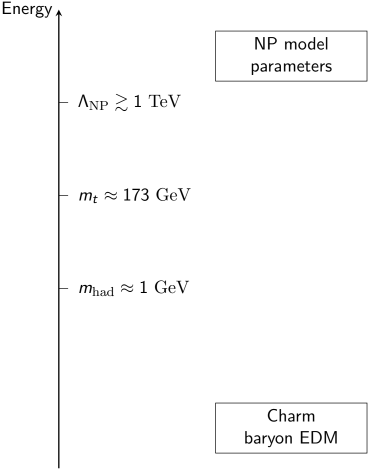


The EDM violates separately T and P $\Rightarrow$ **CP violation**

Map of the EDM field

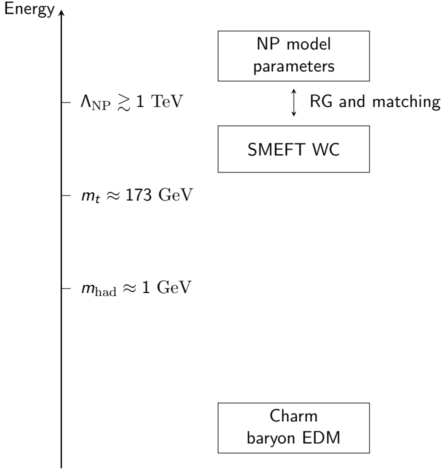


Big picture



Connection New Physics to heavy baryon EDM

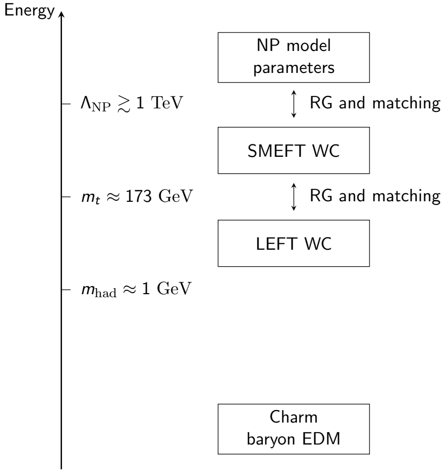
Big picture



Connection New Physics to heavy baryon EDM

- NP particles integrated out below Λ_{NP}
- Wilson coefficients (WC) of the SM Effective Field Theory (SMEFT) capture the high-energy dynamics

Big picture



Connection New Physics to heavy baryon EDM

- NP particles integrated out below Λ_{NP}
- Wilson coefficients (WC) of the SM Effective Field Theory (SMEFT) capture the high-energy dynamics

- Same for Low Energy EFT (LEFT)
- Strictly, different EFT below each mass threshold

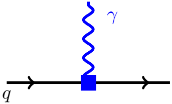
- Contributions to EDMs: **flavour-diagonal CP-violating effective operators**

Effective operators

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

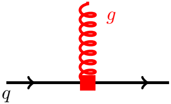
charm EDM

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



charm chromo-EDM

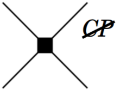
$$\tilde{d}_q \, \bar{q} i \sigma^{\mu\nu} \gamma_5 t_a q \, G^a_{\mu\nu}$$



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

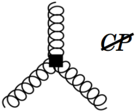
4 quark op.

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



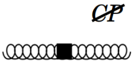
Weinberg op.

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



θ-QCD

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



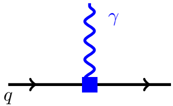
(non-perturbative)

Effective operators

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

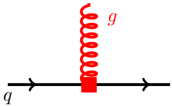
charm EDM

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



charm chromo-EDM

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



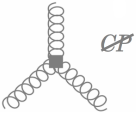
- Other contributions are **suppressed** (higher-order or ruled out by nEDM)

4 quark op.

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

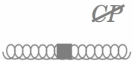
Weinberg op.

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



θ-QCD

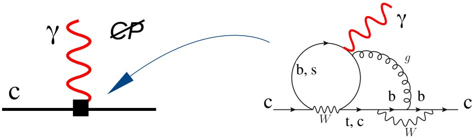
$-\bar{\theta} \frac{g^2}{64\pi^2} \epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}$



(non-perturbative)

Charm EDM in BSM theories

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



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

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

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

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)

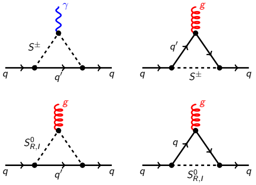
- New scalars with colour charge (8,2,1/2)

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

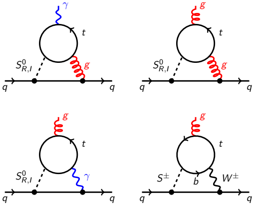
- Predictive theory. Motivated by MFV and GUTs
- Quark (C)EDMs at 1-loop in [Martinez, Valencia, 1612.00561]
- Quark (C)EDMs at 2-loop in [Gisbert, Miralles, JRV, 2111.09397]
- Parameter constraints w/o the nEDM, [X.Q.Li et al., 1504.00839] [Eberhardt, Miralles, Pich, 2106.12235] allow maximum value

$$d_b \sim 10^{-19} \text{ecm} \; , \quad d_c \sim 10^{-21} \text{ecm}$$

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

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

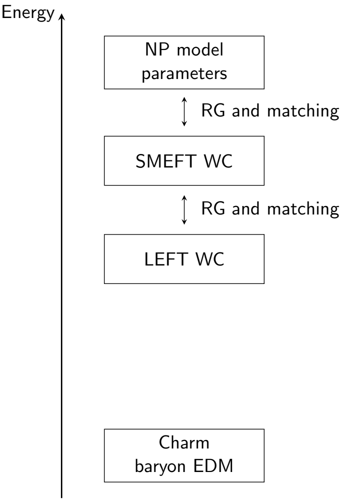
BLMSSM

- 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

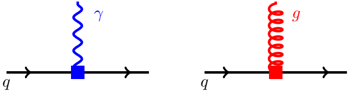
$$d_c \sim 10^{-17} \;\to d_c \sim 10^{-19} \text{ecm}$$

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

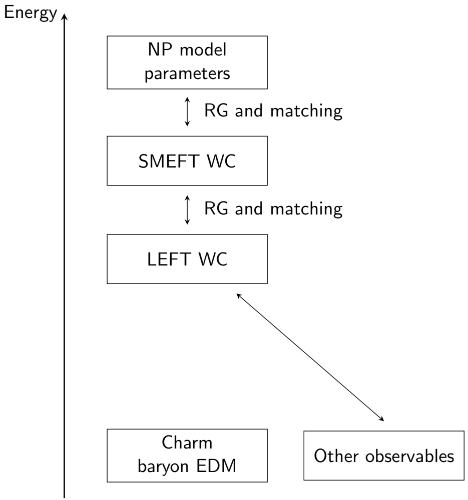
Indirect bounds on charm EDM



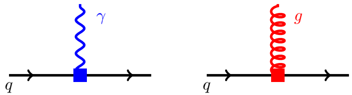
- **What is the maximum d_c allowed, regardless of the NP model?**



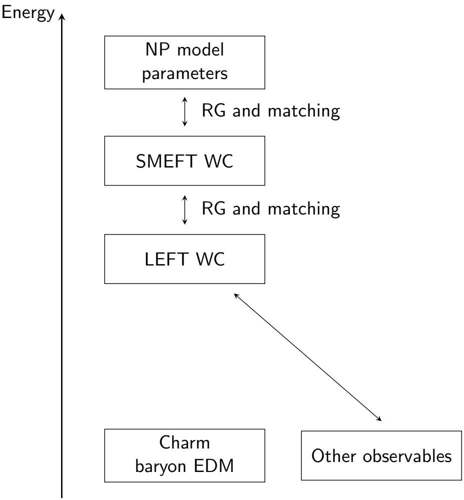
Indirect bounds on charm EDM



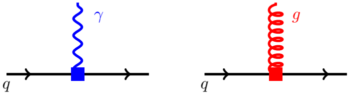
- **What is the maximum d_c allowed, regardless of the NP model?**



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]



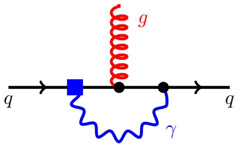
$|d_c| < 4.4 \times 10^{-17} e\text{cm}$ $\quad |\tilde{d}_c| < 1.0 \cdot 10^{-22}\text{cm}$

- 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

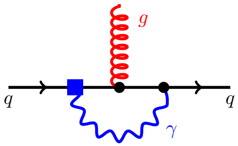
$$\mu \frac{d}{d\mu} \vec{C}(\mu) = \hat{\gamma}^T \vec{C}(\mu) \qquad \vec{C} = \begin{pmatrix} d_q \\ \tilde{d}_q \end{pmatrix}$$

$$\hat{\gamma} = \begin{pmatrix} 8C_F & 0 \\ 8C_F & 16C_F - 4N \end{pmatrix}$$

Bounds on charm EDM

[Gisbert, JRV, 1905.02513]

EDM may contribute to CEDM?



Renormalization group equations

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

$$\gamma_s^{(0)} = \begin{pmatrix} 8C_F & 0 \\ 8C_F & 16C_F - 4N \end{pmatrix}$$

- Expansion of the anomalous dimension matrix

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

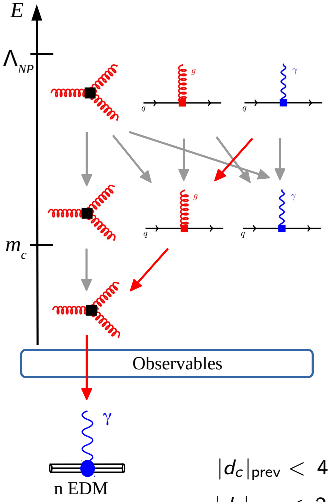
- First nonzero term at $\mathcal{O}(\alpha_e)$.

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

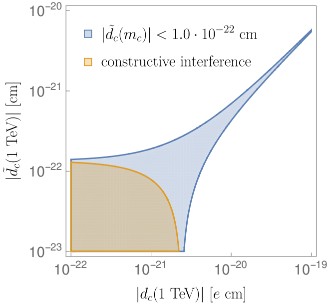
*: negligible wrt $\mathcal{O}(\alpha_s)$

Bounds on charm EDM

[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

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

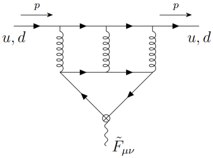
Bounds on charm EDM II

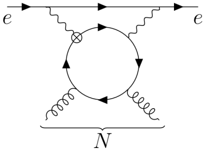
Limits from light quark EDM and eN interaction

[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)





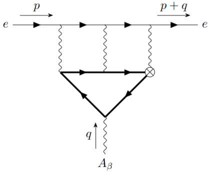
$$|d_c| < 6 \times 10^{-22}\ ecm$$

Limits from electron EDM

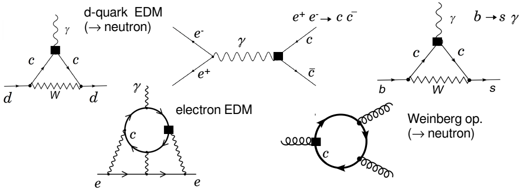
[Ema, Gao, Pospelov, 2207.01679]

Contribution of d_c

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

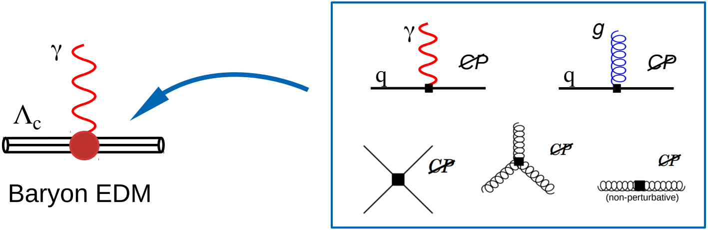


Other limits

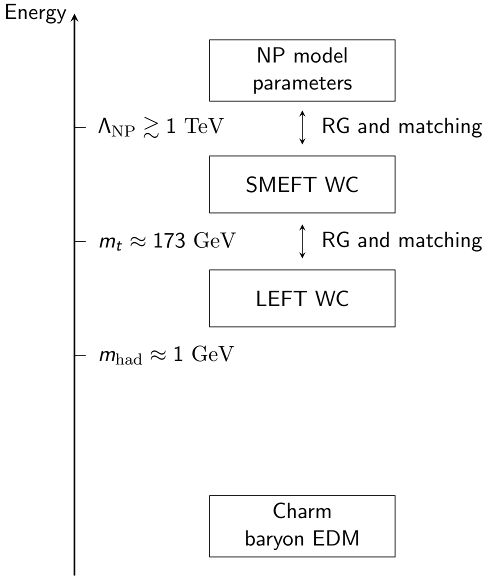


Bound	Ref.	Measurement	Method
$\|d_c\| < 8.9 \times 10^{-17}$ ecm	[Escribano:1993xr]	$\Gamma(Z \to c\bar{c})$	Measurement at the Z peak (LEP). Weights electic (d_c) and weak (d_c^w) dipole moments through model-dependent relations.
$\|d_c\| < 5 \times 10^{-17}$ ecm	[Blinov:2008mu]	$e^+e^- \to c\bar{c}$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

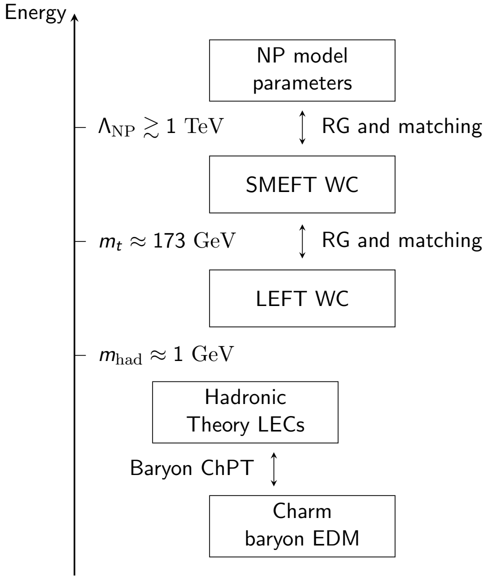
Baryon EDM in non-perturbative QCD



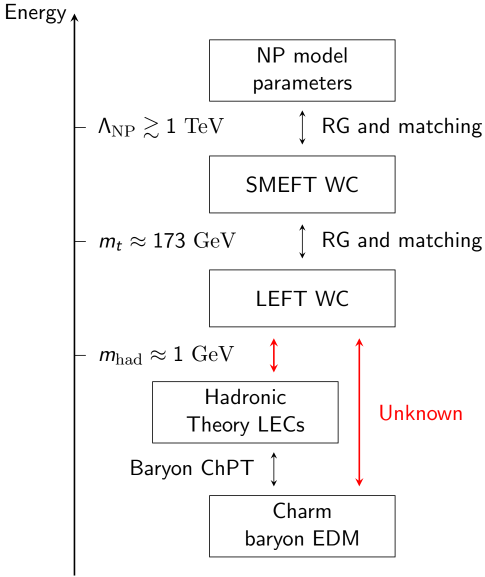
Baryon EDM in non-perturbative QCD



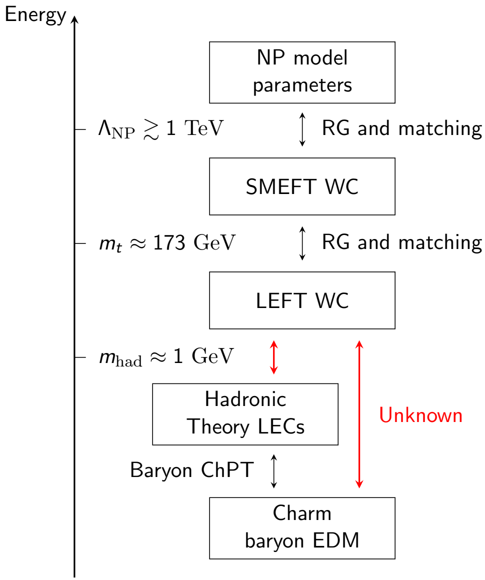
Baryon EDM in non-perturbative QCD



Baryon EDM in non-perturbative QCD



Baryon EDM in non-perturbative QCD



- Connection to quark EDM

$$¿d_{\Lambda_c^+} = d_c?$$

- 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

Nonperturbative QCD methods I

Quark constituent model

- Precursor of QCD. Sea quarks and gluons dressing the *quarks*, $m_{u,d} \approx 300\mathrm{MeV}$ ($\neq$ quarks of QCD)
- Phenomenological successes *e.g.* $\mu_n = -\frac{2}{3}\mu_p$
- Charm baryon EDM: $d_{\Lambda_c^+} = d_c$

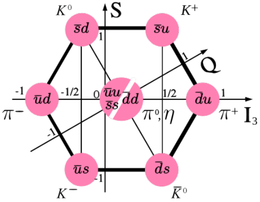
Naive Dimensional Analysis (NDA)

- Dimensionality of couplings + loop suppression factors
- Estimations **within an order of magnitude**
- Charm baryon EDM: $d_{\Lambda_c^+} \sim \pm\, d_c \pm \frac{e}{4\pi}\tilde{d}_c$

Nonperturbative QCD methods II

Chiral Perturbation Theory

- EFT based on the **symmetries of QCD**
  $SU(3)_C$, $SU(3)_L \times SU(3)_R^{\ddagger}$, $\mathcal{P}$, $\mathcal{C}$
  ‡ provided $m_q \to 0$



- Chiral symmetry spontaneously broken ($m_q \neq 0$):
  Octet mesons as Goldstone bosons

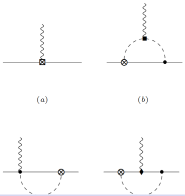
$$SU(3)_L \times SU(3)_R \longrightarrow SU(3)_V$$

- Extensions
  - **Adding resonances**
  - **Adding baryons**
  - **Adding heavy quarks**
  - **Adding CPV interactions**

Remarkable success describing **meson-octet interactions**

- 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 (loops ⟶)
  then estimated these with NDA



Nonperturbative QCD methods III

[Georgi, Phys.Lett.B 240 (1990) 447]

Heavy Quark Effective Theory

[Eichten, Hill, Phys.Lett.B 234 (1990) 511]

- Considers heavy quark $m_Q \to \infty$ with constant 4-velocity v^μ
- Consequences on angular momentum of hadron components. Antiquark described by different field $\to$ new spin-flavour symmetries
- High predictive power: spectrum, masses, decays

Sum Rules

[Introduction: de Rafael, hep-ph/9802448]

- Hadronic form factors from quark interactions. Needs:
  dispersion relation   optical theorem   something else
- No general recipe
- 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

Nonperturbative QCD methods IV

Lattice QCD

- Numerical method to solve the functional integral of QCD
- Discretize space time and simulate extended wave functions
- **Challenging for charm baryons**
  - Large lattice to fit the baryon
  - Small spacing to resolve small c quark wave function
- State-of-the-art computations
  - Huge simulations and data analyses
  - Extrapolation to the continuum limit
  - Physical masses
  - Rigorous systematic uncertainties
- nEDM: Uncertainty improvement wrt sum rules *e.g.* [Cirgliano et al, 1808.07597]

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

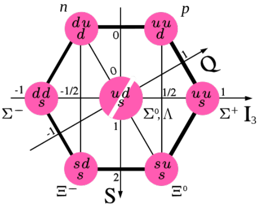
- Charm baryon EDM *"doable if there is interest..."*

EDM of strange Λ hyperon

- General discussion on the theory interpretation applies
- Current Λ EDM limit
  [Fermilab, Phys. Rev. D23 (1981) 814]

$$|d_\Lambda| < 1.8 \cdot 10^{-16} \text{ecm}$$

- Enhanced strange quark contribution, $d_\Lambda = d_s$ (quark model)



- Strange EDM also contributes to neutron EDM
  [Cirgliano et al, 1808.07597]

$$d_n = (0.784 \pm 0.030) d_d - (0.204 \pm 0.015) d_u + (0.0027 \pm 0.0016) d_s$$

- neutron EDM constraint
  [PSI-nEDM, 2001.11966]

$$|d_n| < 1.8 \cdot 10^{-26} \text{ecm}$$

- Improved accuracy on Λ, Σ^+, Ω^- **MDM very valuable** to test NLO in different QCD approaches

Conclusions

- Charm baryon EDM **never tested before**. Sensitivity of this experiment $\delta(d_{\Lambda_c^+}) \approx 10^{-17} e\text{cm}$ [2010.11902]
- **Interpretation in terms of NP** needs advanced **hadronic methods**
  Theory uncertainty key to assess the restrictive power

- nEDM experiments have a 70-year lead on us
- Challenging to beat indirect bounds on charm quark EDM

- **Charm baryon MDM** at the few % will provide answers to the validity of different QCD methods

- Long way for charm EDM... the first step is the most important one