Electric dipole moments of heavy baryons and quarks

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2nd Workshop on EDMs of unstable particles

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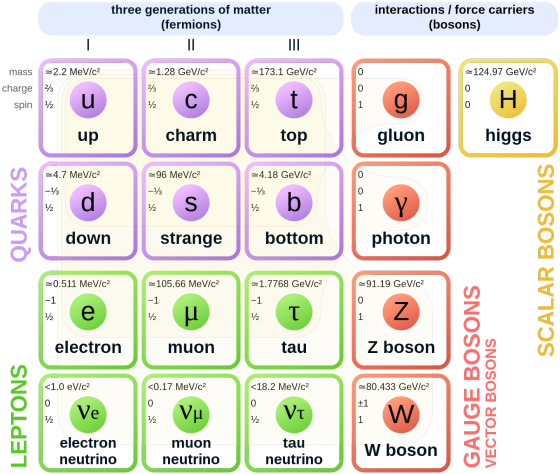
Standard Model of Elementary Particles



Nothing to see here...

Credit: wikipedia.org

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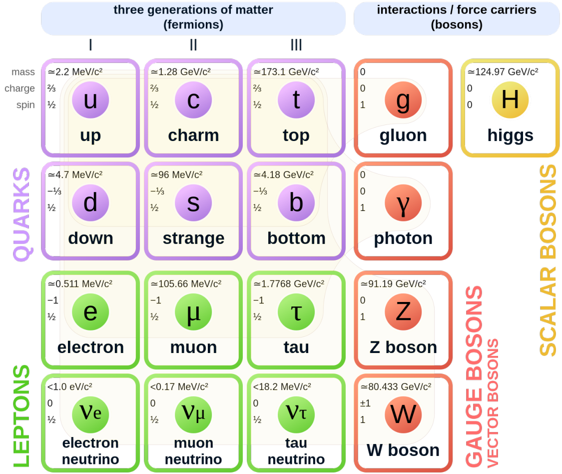


Credit: wikipedia.org

Nothing to see here...

*...just the **best** theory of particle physics today!*

- Looking for “non-standard physics”...
  - We know the Standard Model isn’t the full story
  - Many observations we can’t explain (yet)

Open Puzzles:

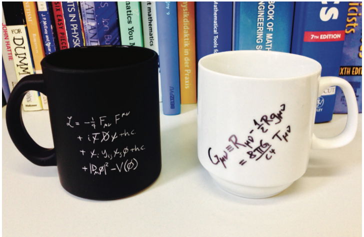
$\rightarrow$ Gravity?

$\rightarrow$ Neutrino masses?

$\rightarrow$ Dark matter?

$\rightarrow$ Matter-antimatter asymmetry?

$\rightarrow$ ...



Credit: Woithe *et al.* (2017)

Introduction and Motivation

- How to find "non-standard physics"?

Credit: CERN

Energy frontier:

→ New particles? SUSY?

→ Quantumgravity?

→ Extra dimensions?

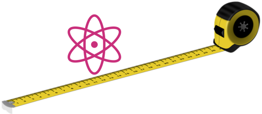
→ Strings?

Precision frontier:

→ Muon $(g-2)$?

→ Rare decays? $0\nu 2\beta$?

→ Electric dipole moments?

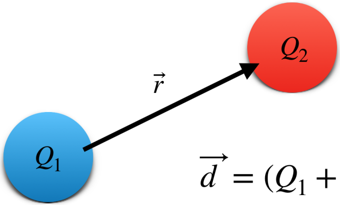


Electric dipole moments

- What is an electric dipole moment (EDM)?
  - Classical electro statics:

    $\rightarrow$ An EDM $\vec{d}$ appears when charges are separated

    $\rightarrow$ First order term in mutipole expansion



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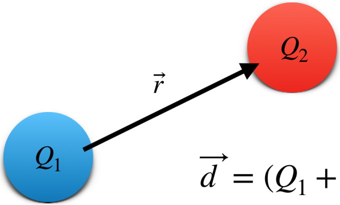

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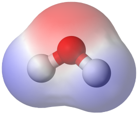

- Example in nature: water molecule

Credit: wikipedia.org

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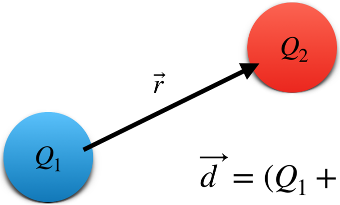

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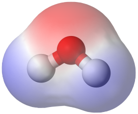


- Example in nature: water molecule
- What about (elementary) particles?

Credit: wikipedia.org

Electric dipole moments

- Consider a non-relativistic particle with spin $\vec{S}$:
  - magnetic moment: $\vec{\mu}$
  - electric dipole moment: $\vec{d}$
- Now, turn on external magnetic field $\vec{B}$ and electric field $\vec{E}$:

$$H_{EM} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

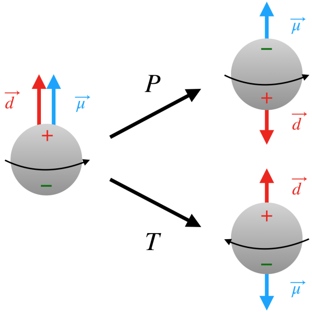
- From quantum mechanics we know:
  - mag. moment proportional to spin: $\vec{\mu} \propto \vec{S} \;\Rightarrow\; \vec{\mu} = \mu \vec{S}$
  - EDM must be aligned with $\vec{S}$, i.e.: $\vec{d} \sim \vec{\mu} \;\Rightarrow\; \vec{d} = d\vec{S}$

$$H_{EM} = -\mu \left(\vec{S} \cdot \vec{B}\right) - d \left(\vec{S} \cdot \vec{E}\right)$$

Electric dipole moments

- Behavior under discrete symmetries?
  - parity P, time reversal T, charge conjugation C
  - apply P or T to the Hamiltonian

$$H_{EM} \rightarrow H'_{EM} = -\mu \left(\vec{S} \cdot \vec{B}\right) + d \left(\vec{S} \cdot \vec{E}\right)$$



$\rightarrow$ permanent EDM violates both P and T symmetry!

$\rightarrow$ **CPT-Theorem:**

T-violation $\Leftrightarrow$ CP-violation

$\rightarrow$ CP-violation needed for matter-antimatter asymmetry!

(*one open puzzle...*)

Electric dipole moments

- Are EDMs “non-standard”?

Electric dipole moments

- Are EDMs “non-standard”? $\rightarrow$ *No!*

Electric dipole moments

- Are EDMs "non-standard"? $\rightarrow$ *No!*
- There are CP-violating effects in the Standard Model!
  - QED: **X**
  - Weak sector: ✓ $\rightarrow$ CKM-phase
  - Strong sector: **?** $\rightarrow$ QCD-Theta-Term
- Measuring EDMs helps us to find Standard Model parameters *...but there might be more!*

Electric dipole moments

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  - Strong sector: **?** $\rightarrow$ QCD-Theta-Term
- Measuring EDMs helps us to find Standard Model parameters *...but there might be more!*
- EDMs can also test “non-standard” physics!
- Beyond Standard Model (BSM) physics can induce CP-violation $\rightarrow$ matter-antimatter asymmetry!
- Various sources for BSM physics $\rightarrow$ here: strong sector!

Quantum Chromodynamics (QCD)

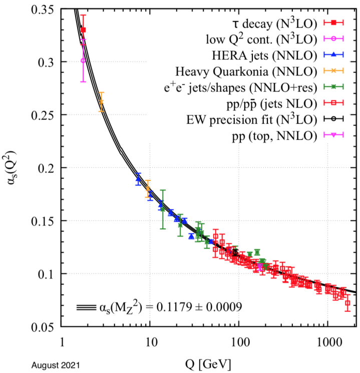
$$\mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu,\,a} + \sum_f \bar{q}_f \left(i \not{D} - m_f \right) q_f$$

- $f = (u, d, s, c, b, t)$
- $D_\mu = \partial_\mu - i g A^a_\mu \lambda^a / 2$
- $G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$
- Running coupling: $\alpha_s = \dfrac{g^2}{4\pi}$

$\Rightarrow \Lambda_{QCD} \approx 200\,\mathrm{MeV}$

non-perturbative at small energies!

- $m_{u,d,s} \ll \Lambda_{QCD}\ ,\ m_{c,b,t} \gg \Lambda_{QCD}$



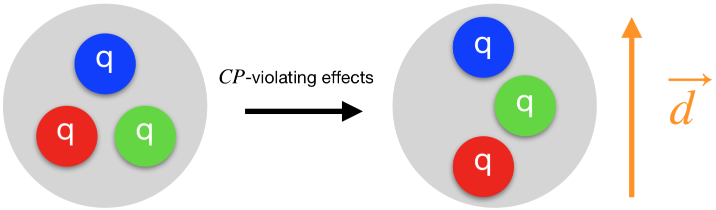
Credit: PDG

The QCD θ-term

- CP-violation in the strong sector is possible due to the QCD θ-term:

$$\mathcal{L}_{\text{strong-}\not{C}\not{P}} = \mathcal{L}_{QCD} + \theta \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu,\,a}$$

  - θ is unknown $\rightarrow$ must be measured!
  - θ-term induces permanent EDM in hadrons, like e.g. the neutron



The QCD θ-term and the neutron EDM

Measuring the neutron EDM:

- from EDM measurement of ^{199}Hg atoms

  [nEDM Collab. (2020)]
- upper bound: $|d_n| < 1.8 \times 10^{-26} e\,\mathrm{cm}$

  $\rightarrow$ implies very small theta parameter: $\theta < 10^{-10}$

  $\rightarrow$ *"strong CP-problem"*

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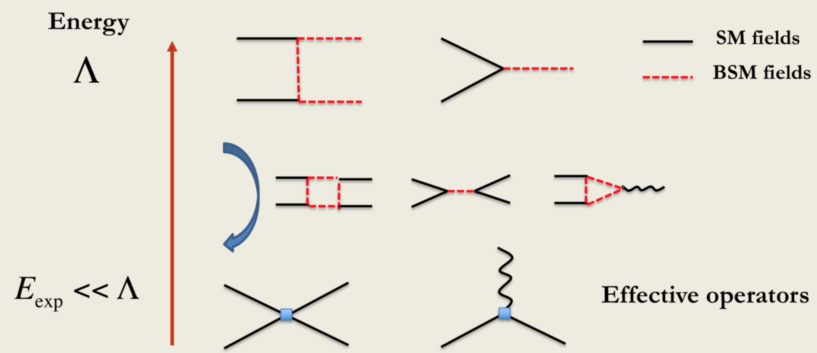
- What else might there be?
  - New heavy particles? SUSY? Dragons?
- How can we test these hypotheses model independently?

  $\rightarrow$ **Standard Model effective field theory (SMEFT)**

Standard Model effective field theory

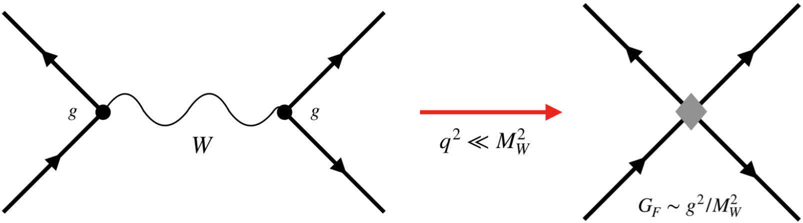
- **Basic idea:** SM is a low energy approximation of a more fundamental theory
  - $E \approx \Lambda$: new BSM particles and interactions
  - $E \ll \Lambda$: only SM particles and interactions



Credit: J. de Vries

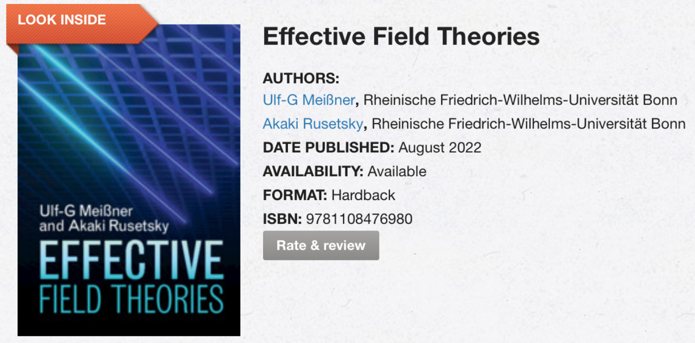
Standard Model effective field theory

- Well-known example: Fermi's Theory of β-decay
  - Below a certain energy the high-physics details (here the W-boson) do not matter
  - W-boson exchange looks effectively like a 4-fermion interaction
  - Integrate out heavy degrees of freedom to obtain effective field theory (EFT)



Standard Model effective field theory

- Now: Construct the effective field theory for SM
  - How to obtain the EFT if we don't know the high-energy theory?
  - What are the degrees of freedom?
- More on EFTs:



Standard Model effective field theory

- Constructing the Standard Model EFT Lagrangian
- Assume BSM physics appears at a scale $\Lambda \gg \Lambda_{EW}$ (electro-weak scale $\Lambda_{EW} \approx 250\,\text{GeV}$)
- Cooking recipe:
  (1) Degrees of freedom: Only Standard Model fields!
  (2) Symmetries: Lorentz and $SU(3)_C \times SU(2)_L \times U(1)_Y$
  (3) Write down all possible terms allowed by the symmetries!

SMEFT-Lagrangian:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \dots$$

Standard Model effective field theory

- **Goal:** Looking for CP-violating operators in the strong sector that can induce an EDM

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \cancel{\frac{1}{\Lambda}\mathcal{L}_5} + \frac{1}{\Lambda^2}\mathcal{L}_6 + \dots$$

$\rightarrow$ *only contributions from dimension-6 operators!*

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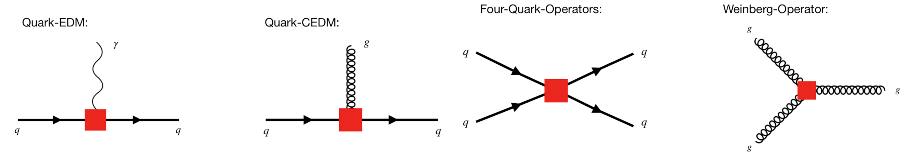
- Appearing structures:



Chiral Perturbation Theory

- *But wait a minute...*
  How do we calculate EDMs in the strong sector?
  - EDMs measured at low energies $\rightarrow$ QCD non-perturbative!
  - Single quarks not observed $\rightarrow$ Confinement!

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ChPT: [Weinberg, Gasser, Leutwyler, ...]

- **EFT** for the strong interaction
- D.o.f.: baryons & mesons
- quarks & gluons not resolvable at low energies

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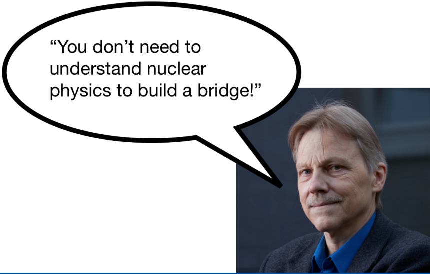

Construction of ChPT

- Three light quarks u, d and s (flavor $SU(3)$)
- Baryons B and light pseudo-scalar mesons ϕ

$$\mathcal{L}_{QCD} \mapsto \mathcal{L}_{\phi} + \mathcal{L}_{\phi B} + \mathcal{L}_{BB} + \ldots$$

- Quark masses $= 0 \Rightarrow SU(3)_L \times SU(3)_R$ symmetry!
  - spontaneously broken to $SU(3)_V$ (isospin)

    $\rightarrow \phi =$ Goldstone bosons!
  - explicit breaking due to quark masses

    $\rightarrow$ Goldstone boson masses!
- Systematic expansion over chiral symmetry breaking scale $\Lambda_\chi \approx 1\,\text{GeV}$: (p/Λ_χ), (M_π/Λ_χ), (M_K/Λ_χ), $\ldots$

Construction of ChPT

- Including heavy quarks also possible!
  - mesons or baryons containing heavy quarks can be included in ChPT
  - use heavy quark mass m_Q as additional expansion scale, i.e. (p/m_Q), (M_π/m_Q), ...
  - expansion with several large scales can cause difficulties!

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- *But now we can calculate EDMs... right?* $\rightarrow$ Yes!
- Consider baryons with bottom quarks:

  [Ünal, DS, de Vries, Hanhart, Meißner (2021)]
  - write down Lagrangian for b-baryons
  - include CP-violating terms explicitely

Constructing the b-baryon effective Lagrangian

- Degrees of freedom:
  - Bottom baryon states:

$$B_{\bar{3}} = \begin{pmatrix} 0 & \Lambda_b^0 & \Xi_b^0 \\ -\Lambda_b^0 & 0 & \Xi_b^- \\ -\Xi_b^0 & -\Xi_b^- & 0 \end{pmatrix}, \quad B_6 = \begin{pmatrix} \Sigma_b^+ & \frac{\Sigma_b^0}{\sqrt{2}} & \frac{\Xi_b'^0}{\sqrt{2}} \\ \frac{\Sigma_b^0}{\sqrt{2}} & \Sigma_b^- & \frac{\Xi_b'^-}{\sqrt{2}} \\ \frac{\Xi_b'^0}{\sqrt{2}} & \frac{\Xi_b'^-}{\sqrt{2}} & \Omega_b^- \end{pmatrix}$$

  - Goldstone boson octet:

$$\phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

Constructing the b-baryon effective Lagrangian

- Leading order Lagrangian:

$$\mathcal{L}^{(1)}_{\text{free}} = \frac{1}{2}\langle \bar{B}_{\bar{3}}(i\not{D} - m_{\bar{3}})B_{\bar{3}}\rangle + \langle \bar{B}_6(i\not{D} - m_6)B_6\rangle \,,$$

$$\mathcal{L}^{(1)}_{\text{int}} = \frac{g_1}{2}\langle \bar{B}_6 \not{u}\gamma_5 B_6\rangle + \frac{g_2}{2}\langle \bar{B}_6 \not{u}\gamma_5 B_{\bar{3}} + h.c.\rangle + \frac{g_3}{2}\langle \bar{B}_{\bar{3}} \not{u}\gamma_5 B_{\bar{3}}\rangle \,.$$

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- Sources of CP-violation:
  - θ-term: We know $\theta < 10^{-10}$ $\rightarrow$ **neglect!**
  - Dimension-6 terms containing *only* light quarks:

    Would contribute to neutron EDM, but $|d_n| < 10^{-26}$.

    Highly constrained! $\rightarrow$ **neglect!**
  - Dimension-6 terms containing b-quarks: $\rightarrow$ **include!**

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- **Now:** Build effective Lagrangian for the b-baryons

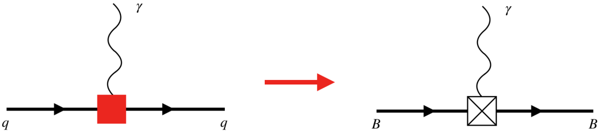
  from the dim.-6 operators!

Effective Lagrangian from dim.-6 operators

(1) *b*-quark EDM:

$$\mathcal{L}^{(6)}_{b,\mathrm{qEDM}} = d_b \bar{b}\, \sigma^{\mu\nu}\gamma_5 b\, F_{\mu\nu}$$

→ induces directly an EDM for *b*-baryons!



EFT-Lagrangian:

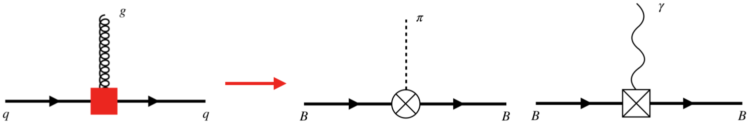
$$\mathcal{L}^{\mathrm{eff.}}_{qEDM} = c_1 \langle \bar{B}_{\bar{3}} \sigma^{\mu\nu}\gamma_5 F_{\mu\nu} B_{\bar{3}} \rangle + c_2 \langle \bar{B}_6 \sigma^{\mu\nu}\gamma_5 F_{\mu\nu} B_6 \rangle + \ldots$$

→ c_1 and c_2 low energy constants (LECs)

(2) ***b*-quark CEDM:**

$$\mathcal{L}^{(6)}_{b,\mathrm{qCEDM}} = \tilde{d}_b \bar{b}\, \sigma^{\mu\nu}\gamma_5 \lambda^a b\, G^a_{\mu\nu}$$

$\rightarrow$ induces indirectly an EDM for *b*-baryons!



EFT-Lagrangian:

$$\mathcal{L}^{\mathrm{eff.}}_{\mathrm{qCEDM}} = i\beta^+ \Big[b_1 \langle \bar{B}_{\bar{3}} \chi_+ \gamma_5 B_{\bar{3}} \rangle + b_2 \langle \bar{B}_6 \chi_+ \gamma_5 B_6 \rangle + b_3 \langle \bar{B}_6 \chi_+ \gamma_5 B_{\bar{3}} + h.c. \rangle \Big] + \ldots$$

Effective Lagrangian from dim.-6 operators

(3) **4-quark operators:**

$$\mathcal{L}^{(6)}_{b,4q} = i\mu_1^{ub}(\bar{u}u\bar{b}\gamma_5 b + \bar{u}\gamma_5 u\bar{b}b - \bar{b}\gamma_5 u\bar{u}b - \bar{b}u\bar{u}\gamma_5 b) + \ldots$$

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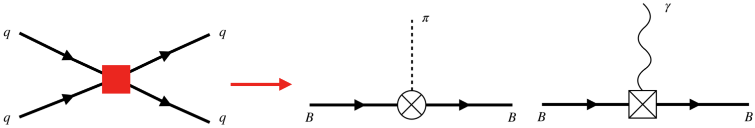


EFT-Lagrangian:

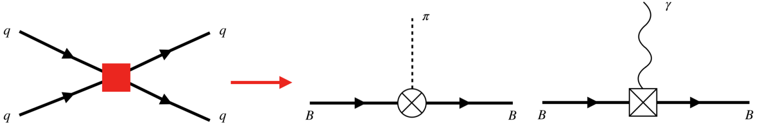
$$\mathcal{L}^{\text{eff.}}_{4q} = i\mu_1\langle \bar{B}_{\bar{3}}\tilde{\chi}_+\gamma_5 B_{\bar{3}}\rangle + i\mu_2\langle \bar{B}_6\tilde{\chi}_+\gamma_5 B_6\rangle + i\mu_3\langle \bar{B}_6\tilde{\chi}_+\gamma_5 B_{\bar{3}} + h.c.\rangle + \ldots$$

Effective Lagrangian from dim.-6 operators

(4) 4**-quark-left-right operators:**

$$\mathcal{L}^{(6)}_{b,4\mathrm{qLR}} = i\nu_1^{ub} V_{ub} (\bar{b}_L \gamma_\mu u_L \bar{u}_R \gamma^\mu b_R) + \ldots$$

$\rightarrow$ induces indirectly an EDM for b-baryons!



EFT-Lagrangian:

$$\mathcal{L}^{\mathrm{eff.}}_{4\mathrm{qLR}} = i\mathrm{Re}(V_{ub}) \Big[\nu_1 \langle \bar{B}_{\bar{3}} \hat{\tilde{\chi}}_- B_{\bar{3}} \rangle + \nu_2 \langle \bar{B}_6 \hat{\tilde{\chi}}_- B_6 \rangle + \nu_3 \langle \bar{B}_6 \hat{\tilde{\chi}}_- B_{\bar{3}} + h.c. \rangle \Big] + \ldots$$

EDMs of Baryons with bottom quarks

- Calculate the EDMs of the *b*-Baryons up to one-loop order: [Borasoy (2000)]

$$\langle B_b(p_f)\,|\,J_{\mathrm{EDM},\nu}\,|\,B_b(p_i)\rangle = D^{\gamma}_{B_b}(q^2)\,\bar{u}(p_f)\sigma_{\mu\nu}\gamma_5 q^{\mu}u(p_i)$$

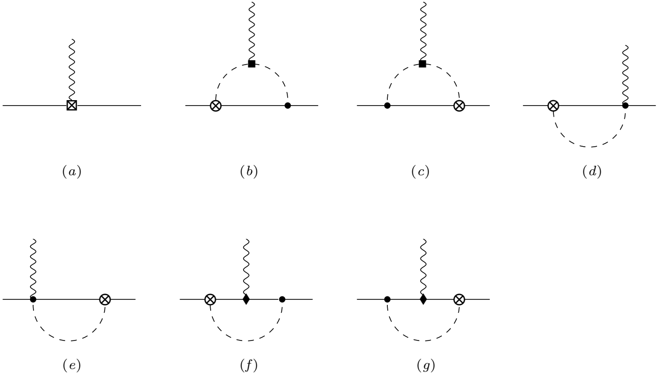
  with momentum transfer $q = p_f - p_i$
- The EDM is then given by

$$d^{\gamma}_{B_b} = D^{\gamma}_{B_b}(q^2 = 0)$$

- Draw all possible Feynman-graphs and calculate them...

EDMs of Baryons with bottom quarks

- Contributions to the EDMs of the b-baryons at one-loop order (chiral order $\mathcal{O}(\delta^2)$)



EDMs of Baryons with bottom quarks

- **Results:** example Λ_b^0-baryon

$$d^{\gamma}_{\Lambda_b^0} = 4c_1 - 4e\Big(b_{19} - \mu_{11}(\mu^{ub} - \mu^{db})$$
$$+ \mu_{14}(\mu^{ub} + \mu^{db}) - 2\mu_{20}(\mu^{ub} - \mu^{db} - \mu^{sb})$$
$$- \mathrm{Re}(V_{ub})(\nu_{11} - \nu_{14} + 2\nu_{20})\nu^{ub}\Big) + \text{loops}$$

- *Too many LECs...* $\rightarrow$ we need to fix this!
- How to determine LECs:
  - fundamental theory $\rightarrow$ not possible (maybe Lattice-QCD?)
  - experimental data $\rightarrow$ not yet available

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$\rightarrow$ **Idea:** Naive dimensional analysis (NDA)

Naive dimensional analysis (NDA)

- NDA: [Manohar & Georgi (1984), Weinberg (1989)]

  Set of rules to estimate the order of magnitude of unknown LECs from dimensional arguments

- Example: neutron EDM [Weinberg (1989)]

$$\mathcal{L}_{\mathrm{nEDM}} = d_n \bar{n}\, \sigma^{\mu\nu}\gamma_5 n\, F_{\mu\nu}\ , \quad \mathcal{L}_{\not{C}\not{P}} = \theta m_q \bar{q}\gamma_5 q$$

  - dimension of EDM: $[d_n] = -1$
  - NDA predicts: $d_n \sim e\theta m_q/\Lambda_\chi \approx 10^{-16} e\theta\,\mathrm{cm}$
  - with $\theta = 10^{-10}$, we get $d_n \approx 10^{-26} e\,\mathrm{cm}$

    $\rightarrow$ agrees with experimental upper bound!

Naive dimensional analysis (NDA)

- Use NDA to estimate the LECs in the b-baryon EDMs:
- Example: b-quark EDM

$$\mathcal{L}_{BEDM} = c_1 \langle \bar{B}_{\bar{3}} \sigma^{\mu\nu} \gamma_5 F_{\mu\nu} B_{\bar{3}} \rangle + c_2 \langle \bar{B}_6 \sigma^{\mu\nu} \gamma_5 F_{\mu\nu} B_6 \rangle + \ldots ,$$

$$\mathcal{L}^{(6)}_{b,\mathrm{qEDM}} = d_b \bar{b}\, \sigma^{\mu\nu} \gamma_5 b\, F_{\mu\nu}$$

  - dimension of BEDM: $[c_1] = [c_2] = -1$
  - NDA predicts:

$$c_{1,2} = \mathcal{O}\left(\frac{m_b}{\Lambda^2}\right)$$

  - with BSM scale $\Lambda = 1\,\mathrm{TeV}$, we get $c_{1,2} \approx 10^{-19}\, e\,\mathrm{cm}$

Results

- NDA predictions for the different contributions: (BSM scale $\Lambda = 1\,\text{TeV}$)
  - qEDM: $d^{\gamma}_{B_b} \approx 10^{-19}\,e\,\text{cm}$
  - qCEDM: $d^{\gamma}_{B_b} \approx 10^{-20}\,e\,\text{cm}$
  - 4q: $d^{\gamma}_{B_b} \approx 10^{-21}\,e\,\text{cm}$
  - 4qLR: $d^{\gamma}_{B_b} \approx 10^{-24}\,e\,\text{cm}$
- All EDMs scale with Λ^{-2}
- Future experiments can help to identify the sources of CP-violation

Summary and outlook

- EDMs are important observales for precision physics
  - $\rightarrow$ EDM $\Leftrightarrow$ CP-violation
  - $\rightarrow$ testing the Standard Model and beyond!
- EFT is a useful tool to describe phenomena in nature
  - $\rightarrow$ SMEFT for model independent approach for BSM physics
  - $\rightarrow$ ChPT for the strong interaction
- Calculation for b-baryons can be repeated for c-baryons (in progress)
- New experiments on the way
- New insights presented here

Summary and outlook

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...looking forward to this workshop!

Thank you for your attention!

My card

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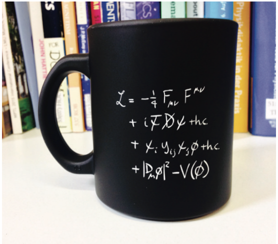
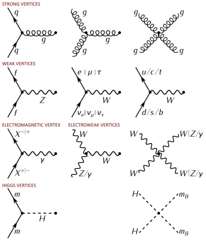
Spares

- The Standard Model of particle physics
  - Describing particle interactions since the 1950s
  - Strong- and electro-weak-force combined

    $\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry
  - Countless predictions and Nobel prizes...



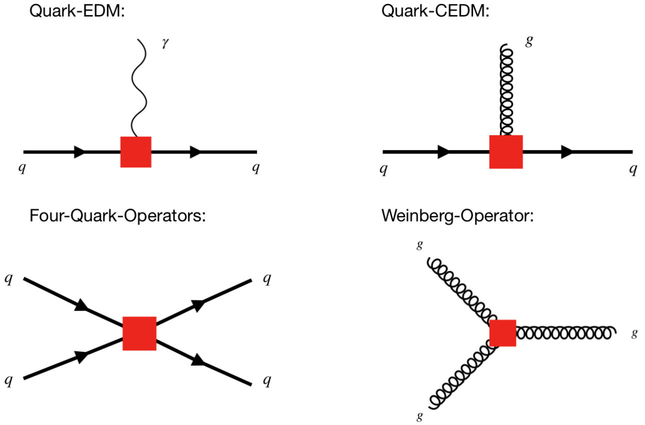
Credit: Woithe *et al.* (2017)



Credit: wikipedia.org

Dimension-6 operators

- Feynman-diagrams for the contributions from $\mathcal{L}_6$:



→ *Now we can calculate EDMs!*

EDMs of Baryons with bottom quarks

Results:

- We calculate the tree-level and one-loop contributions for all 3 antitriplet baryons $B_{\bar{3}}$ and all 6 sextet baryons B_6
- We find interesting patterns in the results
  $\rightarrow$ *can be used to test the theory!*

Patterns in the EDMs:

- qEDM: $\bar{3}$: $d_{B_{\bar{3}}} \sim c_1$, 6: $d_{B_6} \sim c_2$
- qCEDM: $\bar{3}$: $d^{\gamma}_{\Lambda^0_b} = d^{\gamma}_{\Xi^0_b}$,
  6: $d^{\gamma}_{\Sigma^-_b} + d^{\gamma}_{\Sigma^+_b} = 2d^{\gamma}_{\Sigma^0_b}$, $d^{\gamma}_{\Xi'^-_b} - (d^{\gamma}_{\Sigma^-_b} + d^{\gamma}_{\Omega^-_b})/2 = 0$
- 4qLR: $\bar{3}$: $d^{\gamma}_{\Lambda^0_b} - d^{\gamma}_{\Xi^0_b} =$ loops,
  6: $d^{\gamma}_{\Xi'^-_b} - (d^{\gamma}_{\Sigma^-_b} + d^{\gamma}_{\Omega^-_b})/2 = 0$