Electric Dipole Moments

of Hadrons and Light Nuclei

in chiral EFT

Frontiers in Nuclear Physics | KITP @ UCSB | September 15, 2016 | Andreas Wirzba

Figure about “Doesn’t matter” omitted

Some things that will be not addressed

Figure about “Dark matter and assignment” omitted

Some questions that might hopefully be answered:

1. Why is $\not{CP}$ beyond the Standard Model expected?
2. How can a point-particle (*e.g.* an electron) support an EDM?
3. Why don't the EDMs of certain molecules predict a strong $\not{CP}$?
4. What is the natural scale of a neutron EDM?
5. How large is the EDM window for *New Physics* searches?
6. How can the EDM-producing sources be discriminated?
7. Why is low-energy Effective Field Theory needed here?
8. Why deuteron and helion EDM measurements essential?

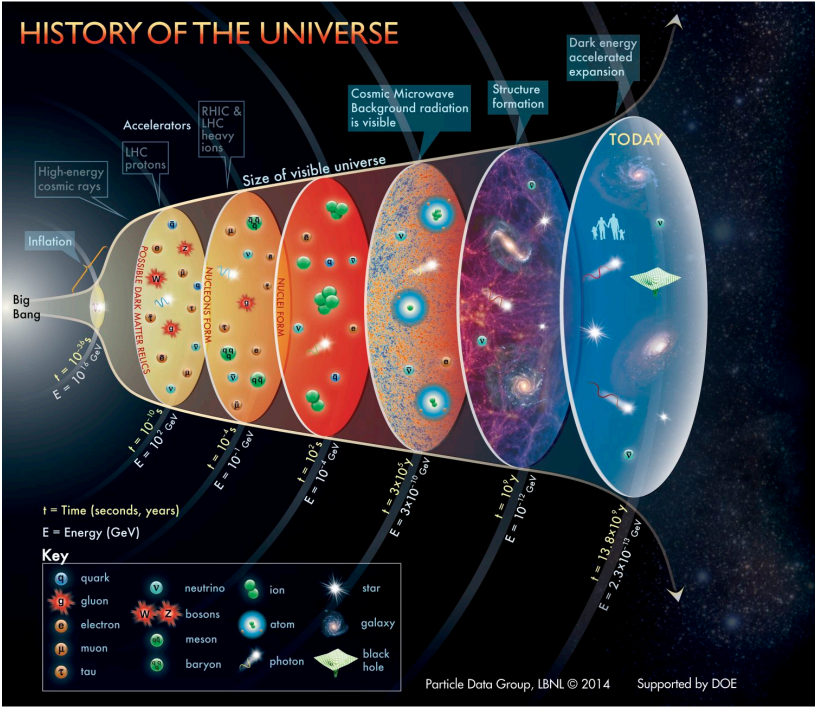

Fig. courtesy of PDG, LBNL © 2014

Matter Excess in the Universe

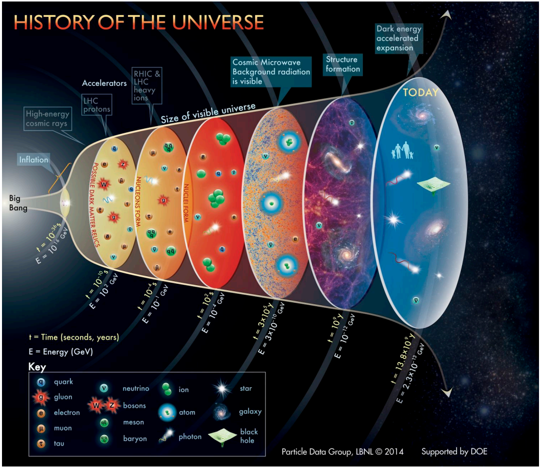

Fig. courtesy of PDG, LBNL ©2014

1 End of inflation: $n_B = n_{\bar{B}}$

2 Cosmic Microwave Bkgr.

- SM(s) *prediction:* *

  $(n_B - \not{n}_{\bar{B}})/n_\gamma|_{\rm CMB} \sim 10^{-18}$

- WMAP+PLANCK ('13):

  $n_B/n_\gamma|_{\rm CMB} = (6.05\pm0.07)10^{-10}$

Sakharov conditions ('67)
for dyn. generation of net B:

1 B violation to depart from initial B=0

2 C & CP violation
to distinguish B from $\bar{B}$ production rates

3 Either CPT violation or
out of thermal equilibrium
to dist. B production from back reaction
and to escape $\langle B\rangle$=0 if CPT holds

(*) $2J^{\rm CKM}_{\rm Jarlskog}(m_t^2-m_u^2)(m_t^2-m_c^2)(m_c^2-m_u^2)(m_b^2-m_d^2)(m_b^2-m_s^2)(m_s^2-m_d^2) \sim 10^{-18} M^{12}_{\rm EW}$

▸ in the SM?

CP violation and the Electric Dipole Moment (EDM)

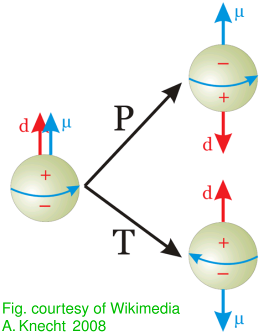

Fig. courtesy of Wikimedia
A. Knecht 2008

EDM: $\vec{d} = \sum_i \vec{r}_i\, e_i \xrightarrow[\text{particles}]{\text{subatomic}} d \cdot \vec{S}/|\vec{S}|$
(polar) (axial)

$$\mathcal{H} = -\mu \frac{\vec{S}}{S}\cdot\vec{B} - d\frac{\vec{S}}{S}\cdot\vec{E}$$

P: $\mathcal{H} = -\mu \frac{\vec{S}}{S}\cdot\vec{B} + d\frac{\vec{S}}{S}\cdot\vec{E}$

T: $\mathcal{H} = -\mu \frac{\vec{S}}{S}\cdot\vec{B} + d\frac{\vec{S}}{S}\cdot\vec{E}$

Any *non-vanishing EDM* of a **non-degenerate** (e.g. subatomic) particle violates **P** & **T**

- Assuming CPT to hold, CP is violated as well (flavor-diagonally)
  ↪ subatomic EDMs: "rear window" to CP violation in early universe
- Strongly suppressed in SM (CKM-matrix): $|d_n| \sim 10^{-31} e\,\text{cm}$, $|d_e| \sim 10^{-38} e\,\text{cm}$
- Current bounds: $|d_n| < 3^{\diamond}/1.6^{*} \cdot 10^{-26} e\,\text{cm}$, $|d_p| < 2 \cdot 10^{-25} e\,\text{cm}$, $|d_e| < 1 \cdot 10^{-28} e\,\text{cm}$

n: Baker et al. (2006)◇, p prediction: Dimitriev & Sen'kov (2003)*, e: Baron et al. (2013)†

* from $|d_{^{199}\text{Hg}}| < 7.4 \cdot 10^{-30} e\,\text{cm}$ bound of Graner et al. (2016)   † from polar ThO: $|d_{\text{ThO}}| \lesssim 10^{-21} e\,\text{cm}$

Theorem: Permanent EDMs of *non*-selfconjugate* particles *with* spin $j \neq 0$

Let $\langle j^{\mathrm{P}} | \vec{d} \, | j^{\mathrm{P}} \rangle = d \, \langle j^{\mathrm{P}} | \vec{J} \, | j^{\mathrm{P}} \rangle$ with $\vec{d} \equiv \int \vec{r} \rho(\vec{r}) \mathrm{d}^3 r$ be an EDM operator in a stationary state $|j^{\mathrm{P}}\rangle$ of definite parity P and nonzero spin j, such that

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If $d \neq 0$ and $|j^{\mathrm{P}}\rangle$ has *no* degeneracy (besides rotational), *then* $\not{P}$ & $\not{T}$.

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Werner Bernreuther (2012)

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It can be interpreted as a special case of the theorem:

Any *finite* quantum system without *explicit* symmetry breaking cannot have a spontaneously broken groundstate.

Keywords: *symmetric double-well* potential and *quantum tunneling* (instantons)

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How can such a particle be polarized and support an EDM?’

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There are always vacuum polarizations with rich short-distance structure

($g-2$ of the electron and muon aren’t exactly zero either)

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The ground states of these molecules at non-zero temperatures or strong E-fields are mixtures of at least 2 opposite parity states:

The theorem doesn't apply for degenerate states: neither $\not{T}$ nor $\not{P}$!

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‘But what about the induced EDM (polarization)?’

JÜLICH FORSCHUNGSZENTRUM

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The induced EDM is *quadratic* in the electric field and *neither* $\not{P}$ nor $\not{T}$

induced EDM	$\longleftrightarrow$	quadratic Stark effect ($\propto E^2$)
permanent EDM	$\longleftrightarrow$	linear Stark effect ($\propto E$)

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If the interactions are described by an action which is

local, Lorentz-invariant, and hermitian

then CPT invariance holds: thus $\not{T} \iff \not{CP}$

A *naive* estimate of the scale of the nucleon EDM

Khriplovich & Lamoreaux (1997); Kolya Nikolaev (2012)

- CP & P conserving magnetic moment $\sim$ nuclear magneton μ_N

$$\mu_N = \frac{e}{2m_p} \sim 10^{-14}\, e\,\mathrm{cm}\,.$$

- A nonzero EDM requires

  parity P violation: the price to pay is $\sim 10^{-7}$

  $\left(G_F \cdot F_\pi^2 \sim 10^{-7} \text{ with } G_F \approx 1.166 \cdot 10^{-5}\mathrm{GeV}^{-2} \right)$,

  and additionally **CP violation**: the price to pay is $\sim 10^{-3}$

  $\left(|\eta_{+-}| \equiv |\mathcal{A}(K_L^0 \to \pi^+\pi^-)| / |\mathcal{A}(K_S^0 \to \pi^+\pi^-)| = (2.232 \pm 0.011) \cdot 10^{-3} \right)$.

- In summary: $|d_N| \;\sim\; 10^{-7} \times 10^{-3} \times \mu_N \;\sim\; 10^{-24}\, e\,\mathrm{cm}$

- In SM (without θ term): extra $G_F F_\pi^2$ factor to *undo* flavor change

$$\hookrightarrow \quad \left| d_N^{\mathrm{SM}} \right| \sim 10^{-7} \times 10^{-24}\, e\,\mathrm{cm} \;\sim\; 10^{-31}\, e\,\mathrm{cm}$$

$\hookrightarrow$ *The empirical window* for search of physics BSM(θ=0) is

$$10^{-24}\, e\,\mathrm{cm} > |d_N| > 10^{-30}\, e\,\mathrm{cm}.$$

Chronology of upper bounds on the neutron EDM

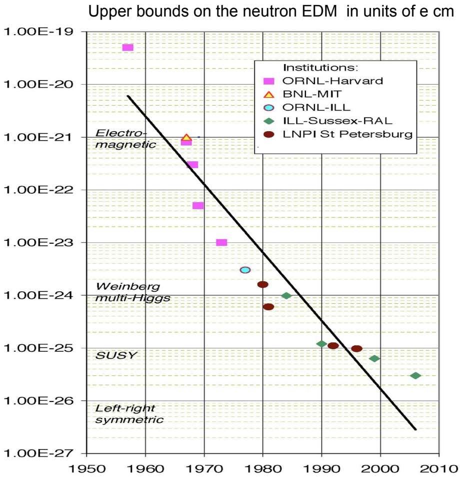

Fig. courtesy of N.N. Nikolaev

Smith, Purcell, Ramsey (1957) . . . . Baker et al. (2006)

$\hookrightarrow$ 5 to 6 orders above SM predictions which are out of reach !

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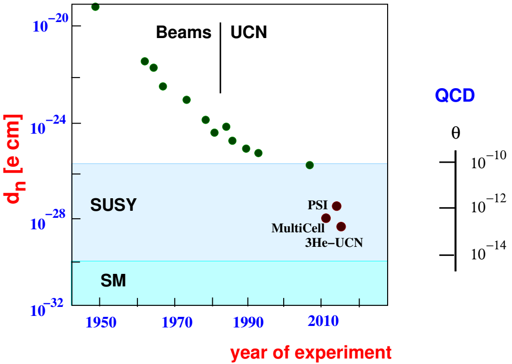

Fig. courtesy of U.-G. Meißner

Smith, Purcell, Ramsey (1957) . . . . Baker et al. (2006)

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Three motivations for EDM searches

Why are EDMs interesting?

- Matter/Antimatter asymmetry requires CP violation beyond SM: EDMs excellent probes
- A search for new physics (NP) which is virtually ‘background free’
- Many NP models predict ‘large’ EDMs: Complementary to LHC searches

EDM bounds from neutral particles

- Modern neutron EDM experiments at ILL, SNS, PSI, TRIUMF

  current $d_n = \left(-0.21 \pm 1.82\right) \cdot 10^{-26}\, e\,\mathrm{cm}$

  Baker et al. *PRL*'06 (ILL); Pendlebury et al. *PRD*'15

  proposed $\sim 10^{-28}\, e\,\mathrm{cm}$

- Proton (and neutron) EDM inferred from diamagnetic atoms

  current $|d(^{199}\mathrm{Hg})| < 7.4 \cdot 10^{-30}\, e\,\mathrm{cm}$ (95% C.L.)

  Graner et al. *PRL* '16(UW)

  $\hookrightarrow |d_p| < 2 \cdot 10^{-25}\, e\,\mathrm{cm}$ & $|d_n| < 1.6 \cdot 10^{-26}\, e\,\mathrm{cm}$

  Theory input from: Dimitriev & Sen'kov *PRL* '03

  ongoing experiments on Xe, Ra, (Rn) ...

- Electron EDM inferred from paramagnetic atoms or non-generate molecules:

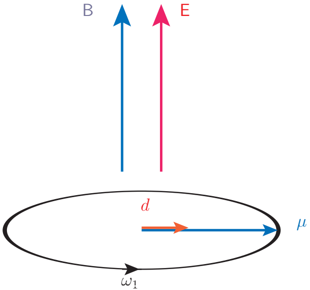
  current $|d_e| < 8.7 \cdot 10^{-29}\, e\,\mathrm{cm}$ (90% C.L.)

  from polar ThO

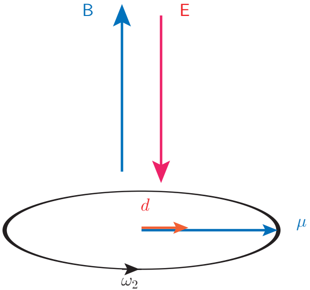
  Baron et al. *Science* '14 (ACME)

EDM measurement of neutral particles in a nutshell

ground state (here with $s = 1/2$):



$$\omega_1 = \frac{2\mu B + 2d E}{\hbar}$$



$$\omega_2 = \frac{2\mu B - 2d E}{\hbar}$$

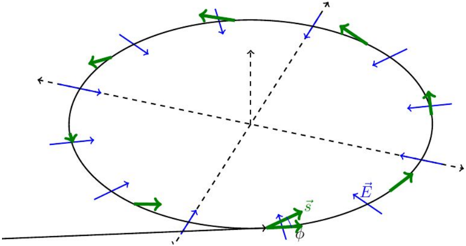
$$d = \frac{\hbar(\omega_1 - \omega_2)}{4E}$$

Direct EDM searches with charged particles

in storage rings

General idea:

Farley et al. *PRL* '04



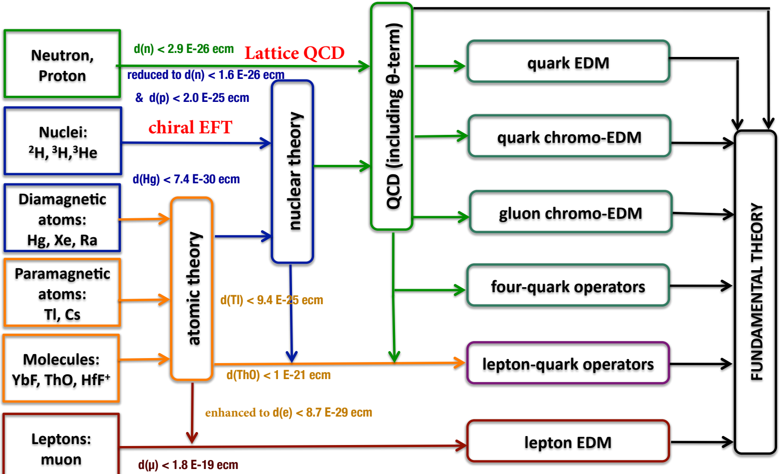
Initially longitudinally polarized particles interact with radial $\vec{E}$ field
$\hookrightarrow$ build-up of vertical polarization (measured with a polarimeter)

Limit on muon EDM: $d_\mu < 1.8 \cdot 10^{-19}\, e\,\text{cm}$ (95 % C. L.) Bennett et al. (BNL *g*-2) *PRL* '09:

- Sensitivity of storage ring experiments $\sim 10^{-29}\, e\,\text{cm}$
- But **systematical** errors ~?
- Precursor experiment $\gtrsim 10^{-(20\cdots24)}\, e\,\text{cm}$ for p or D planned at COSY@Jülich

Road map from EDM Measurements to EDM Sources

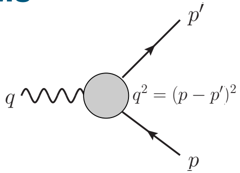
Experimentalist's point of view → ← Theorist's point of view



(adapted from Jordy de Vries, Jülich, March 14, 2013)

Calculation: from form factors to EDMs

$$\langle f(p')|J^\mu_{\rm em}|f(p)\rangle = \bar u_f(p')\,\Gamma^\mu(q^2)\,u_f(p)$$



$$\Gamma^\mu(q^2) = \gamma^\mu F_1(q^2) - \mathrm{i}\sigma^{\mu\nu} q_\nu \frac{F_2(q^2)}{2m_f} + \sigma^{\mu\nu} q_\nu \gamma_5 \frac{F_3(q^2)}{2m_f} + (\not{q}\, q^\mu - q^2\gamma^\mu)\gamma_5 \frac{F_a(q^2)}{m_f^2}$$

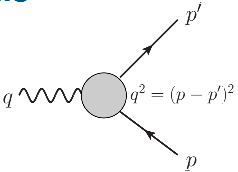
Dirac FF — Pauli FF — electric dipole FF ($\not{CP}$) — anapole FF ($\not{P}$)

$$\hookrightarrow \quad d_f := \lim_{q^2\to 0} \frac{F_3(q^2)}{2m_f}$$

for $s = 1/2$ fermion

Calculation: from form factors to EDMs

$$\langle f(p')|J^\mu_{\rm em}|f(p)\rangle = \bar u_f(p')\,\Gamma^\mu(q^2)\,u_f(p)$$



$$\Gamma^\mu(q^2) = \gamma^\mu F_1(q^2) - \mathrm{i}\sigma^{\mu\nu} q_\nu \frac{F_2(q^2)}{2m_f} + \sigma^{\mu\nu} q_\nu \gamma_5 \frac{F_3(q^2)}{2m_f} + (\not q\, q^\mu - q^2\gamma^\mu)\gamma_5 \frac{F_a(q^2)}{m_f^2}$$

Dirac FF — Pauli FF — electric dipole FF ($\not{CP}$) — anapole FF ($\not{P}$)

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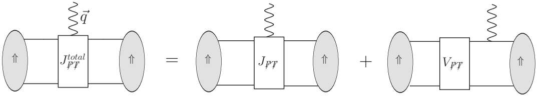
Nucleus A

$\langle \Uparrow | J^0_{\not{P}\not{T}}(q) | \Uparrow \rangle$

in Breit frame



$$= -\mathrm{i}q^3 \underbrace{\frac{F_3^A(\vec q^{\,2})}{2m_A}}_{\hookrightarrow d_A}$$

CP violation in the Standard Model

The conventional source: Kobayashi-Maskawa mechanism

Empirical facts: 3 generations of u/d quarks (& e/ν leptons)

- quarks & leptons in **mass** basis $\neq$ quarks & leptons in **weak**-int. basis
- $\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm gauge\text{-}fermion} + \mathcal{L}_{\rm gauge\text{-}Higgs} + \mathcal{L}_{\rm Higgs\text{-}fermion}$ is CP inv.,
  - with the exception of the θ term of QCD (see later)

    and the **charged-weak-current** interaction ($\subset \mathcal{L}_{\rm gauge\text{-}fermion}$)

$$\mathcal{L}_{\rm c\text{-}w\text{-}c} = -\frac{g_w}{\sqrt{2}} \sum_{ij=1}^{3} \bar{d}_{Li}\gamma^\mu V_{ij}\, u_{Lj}\, W_\mu^- - \frac{g_w}{\sqrt{2}} \sum_{ij=1}^{3} \bar{\ell}_{Li}\gamma^\mu U_{ij}\, \nu_{Lj}\, W_\mu^- + \text{h.c.}$$

  - V: 3×3 unitary quark-mixing matrix (Cabibbo-Kobayashi-Maskawa matrix)

    3 angles + 1 ~~CP~~ phase δ_{KM}

    U: 3×3 unitary lepton-mixing matrix (Pontecorvo-Maki-Nakagawa-Sakata m.)

    3 angles +1(3) ~~CP~~ phase(s) for Dirac (Majorana) ν_i's

$\not{CP}$ and EDMs and in the SM with $J_{\rm KM} = {\rm Im}(V_{tb}V_{td}^* V_{cd} V_{cb}^*) \simeq 3\cdot 10^{-5}$

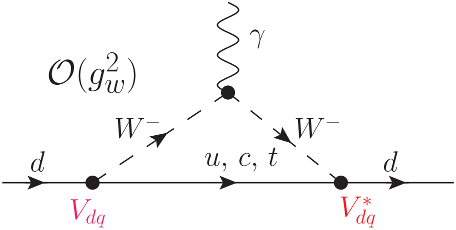
$$\propto \left(\frac{m_t^2-m_c^2}{M_{EW}^2}\right)\left(\frac{m_c^2-m_u^2}{M_{EW}^2}\right)\left(\frac{m_t^2-m_u^2}{M_{EW}^2}\right)\cdot\left(\frac{m_b^2-m_s^2}{M_{EW}^2}\right)\left(\frac{m_s^2-m_d^2}{M_{EW}^2}\right)\left(\frac{m_b^2-m_d^2}{M_{EW}^2}\right)\cdot J_{\rm KM} \simeq 10^{-15} J_{\rm KM},$$

Jarlskog *PRL* '85

$\hookrightarrow$ $(n_B - n_{\bar B})/n_\gamma|^{\rm SM}_{T\sim 20\,\rm MeV} \sim 10^{-20}$ and $d_n^{\rm SM} \sim 10^{-20}\cdot 10^{-14}\,e\,{\rm cm} \sim 10^{-34}\,e\,{\rm cm}$

EDM flavor-neutral $\Rightarrow$ KM predictions tiny: $\mathcal{O}(G_{\rm F}^2) \sim \mathcal{O}(g_W^4)$

1 loop:



$\hookrightarrow$ $\not{CP}$ phase $\delta_{\rm KM}$ cancels $\rightarrow$ prefactor real $\Rightarrow$ $d_q^{\text{1-loop}} = 0$

JÜLICH FORSCHUNGSZENTRUM

$\not{CP}$ and EDMs and in the SM with $J_{\mathrm{KM}} = \mathrm{Im}(V_{tb}V_{td}^* V_{cd} V_{cb}^*) \simeq 3\cdot 10^{-5}$

$$\propto \left(\frac{m_t^2-m_c^2}{M_{EW}^2}\right)\left(\frac{m_c^2-m_u^2}{M_{EW}^2}\right)\left(\frac{m_t^2-m_u^2}{M_{EW}^2}\right)\cdot\left(\frac{m_b^2-m_s^2}{M_{EW}^2}\right)\left(\frac{m_s^2-m_d^2}{M_{EW}^2}\right)\left(\frac{m_b^2-m_d^2}{M_{EW}^2}\right)\cdot J_{\mathrm{KM}} \simeq 10^{-15} J_{\mathrm{KM}},$$

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EDM flavor-neutral $\Rightarrow$ KM predictions tiny: $\mathcal{O}(G_F^2) \sim \mathcal{O}(g_W^4)$

2 loops:

$$d_{\mathrm{quark}}^{\text{2-loop}} = d_{\text{chromo q}}^{\text{2-loop}} = 0$$

Shabalin *Sov.J.NP* ’78

$\not{CP}$ and EDMs and in the SM with $J_{KM} = \mathrm{Im}(V_{tb}V_{td}^* V_{cd} V_{cb}^*) \simeq 3\cdot 10^{-5}$

$$\propto \left(\frac{m_t^2-m_c^2}{M_{EW}^2}\right)\left(\frac{m_c^2-m_u^2}{M_{EW}^2}\right)\left(\frac{m_t^2-m_u^2}{M_{EW}^2}\right)\cdot\left(\frac{m_b^2-m_s^2}{M_{EW}^2}\right)\left(\frac{m_s^2-m_d^2}{M_{EW}^2}\right)\left(\frac{m_b^2-m_d^2}{M_{EW}^2}\right)\cdot J_{KM} \simeq 10^{-15} J_{KM},$$

Jarlskog *PRL* '85

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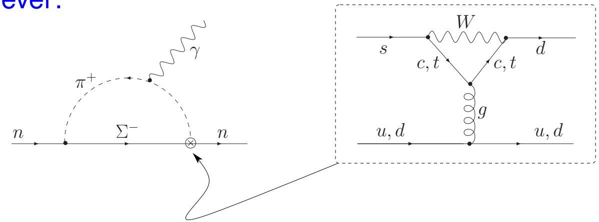
EDM flavor-neutral $\Rightarrow$ KM predictions tiny: $\mathcal{O}(G_F^2) \sim \mathcal{O}(g_W^4)$

however:



$\mathcal{O}(g_W^4 g_s^2)$

$d_n^{KM} \simeq 10^{-32}\,e\,\mathrm{cm}$ because of long-range pion & 'strong penguin'

Gavela; Khriplovich & Zhitnitsky ('82)

$\not{CP}$ and EDMs and in the SM with $J_{\mathrm{KM}} = \mathrm{Im}(V_{tb} V_{td}^* V_{cd} V_{cb}^*) \simeq 3 \cdot 10^{-5}$

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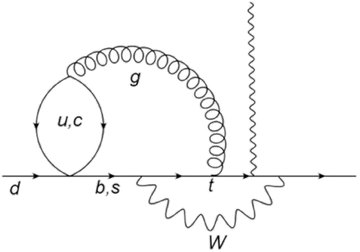
Jarlskog *PRL* '85

$\hookrightarrow$ $(n_B - n_{\bar{B}})/n_\gamma|^{\mathrm{SM}}_{T\sim 20\mathrm{MeV}} \sim 10^{-20}$ and $d_n^{\mathrm{SM}} \sim 10^{-20} \cdot 10^{-14}\, e\,\mathrm{cm} \sim 10^{-34}\, e\,\mathrm{cm}$

EDM flavor-neutral $\Rightarrow$ KM predictions tiny: $\mathcal{O}(G_F^2) \sim \mathcal{O}(g_W^4)$

at $\geq$ 3 loops:



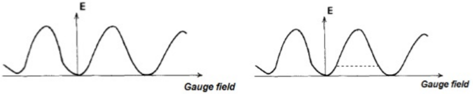
$\mathcal{O}(g_W^4 g_s^2)$

$d_n^{\mathrm{KM}} \simeq 10^{-34} \ldots 10^{-31} e\,\mathrm{cm}$ ($d_e^{\mathrm{KM}} \sim 10^{-38} \ldots 10^{-40} e\,\mathrm{cm}$ since 4 loops & $\mathcal{O}(g_W^6 g_s^2)$)

Khriplovich (1986); Czarnecki & Krause ('97) (Khriplovich & Pospelov (1991))

EDM sources: QCD θ-term of the SM

The topologically non-trivial vacuum structure of QCD



induces a direct $\not{P}\&\not{T} \leadsto \not{CP}$ interaction with a new parameter θ:

$$\mathcal{L}_{QCD} = \mathcal{L}_{QCD}^{CP} - \theta \frac{g_s^2}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} \quad (\text{note: } \epsilon^{0123} = -\epsilon_{0123} \ \& \ \text{dim} = 4)$$

- Anomalous $U_A(1)$ quark-rotations induce mixing with 'mass' term

$$-\theta \frac{g_s^2}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} \xrightarrow{U_A(1)} \bar{\theta} m_q^* \sum_f \bar{q}_f i\gamma_5 q_f \quad (m_q^* = \frac{m_u m_d}{m_u+m_d} \text{ reduced mass})$$

$\hookrightarrow$ *additional* coupling constant is actually $\bar{\theta} = \theta + \arg\det \mathcal{M}_{\text{quark}}$

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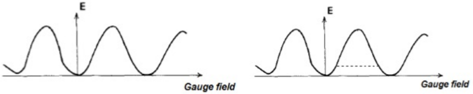

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- Naive Dimensional Analysis (NDA) estimate of $\bar\theta$-induced n EDM:

$$|d_n^{\bar\theta}| \sim \bar\theta \cdot \frac{m_q^*}{m_s} \cdot \frac{e}{2m_n} \sim \bar\theta \cdot 10^{-2} \cdot 10^{-14} e\,\text{cm} \sim \bar\theta \cdot 10^{-16} e\,\text{cm} \quad \text{with } \bar\theta \sim \mathcal{O}(1).$$

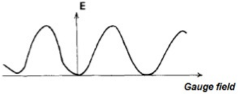
$$|d_n^{emp}| < 2.9 \cdot 10^{-26} e\,\text{cm} \rightsquigarrow |\bar\theta| < 10^{-10}$$

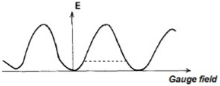
strong CP problem

Baker et al. *PRL* '06

EDM sources: QCD θ-term of the SM

The topologically non-trivial vacuum structure of QCD





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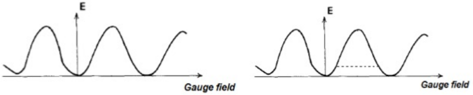
$10^{-10} > |\bar\theta| > 10^{-14}$ eventually measurable via nonzero EDM, but because of $\Lambda_{\chi SB} \ll \Lambda_{EWSB}$ it doesn't explain the cosmic matter surplus.

EDM sources: QCD θ-term of the SM

The topologically non-trivial vacuum structure of QCD



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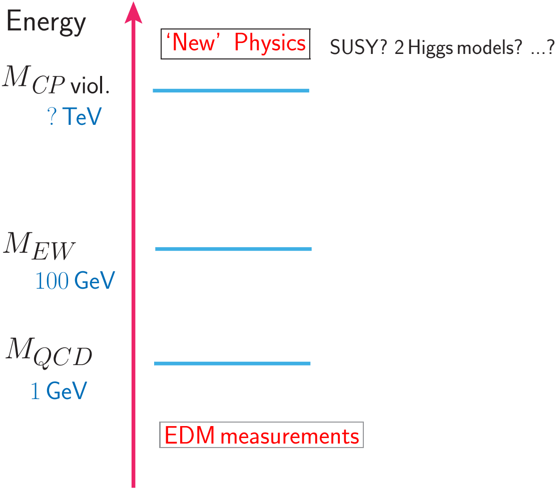
Thus $\not{CP}$ by new physics (NP) (*i.e.* dimension ≥ 6 sources beyond SM) needed to explain the cosmic matter-antimatter asymmetry.

How to handle CP-violating sources beyond the SM?

Running through the scales

W. Dekens & J. de Vries, *JHEP* '13
recall talk by Vincenzo Cirigliano on 09/13/16



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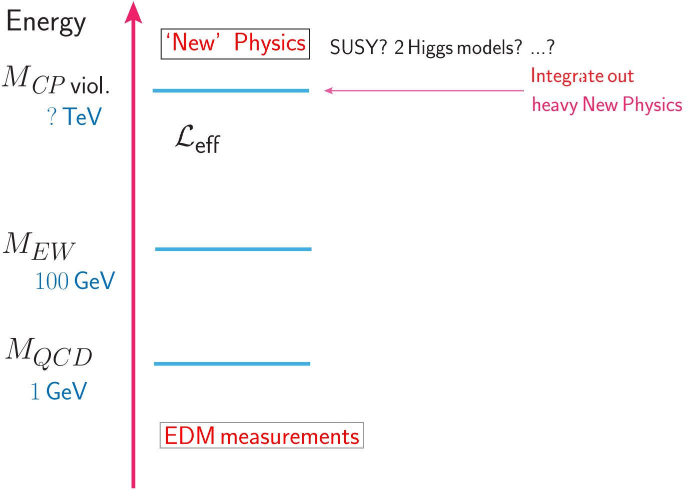

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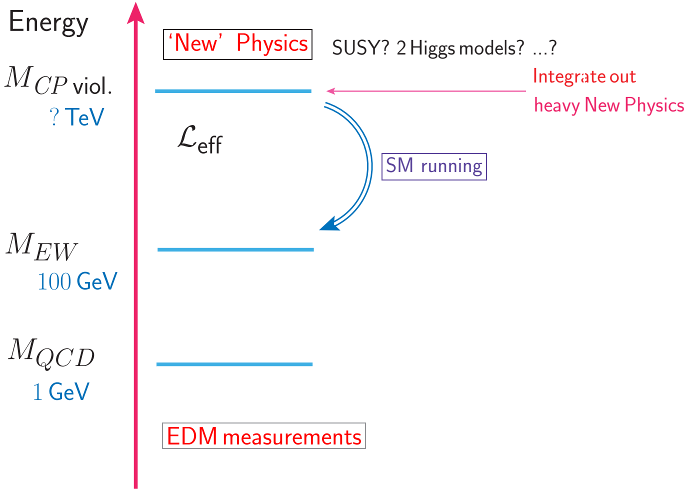

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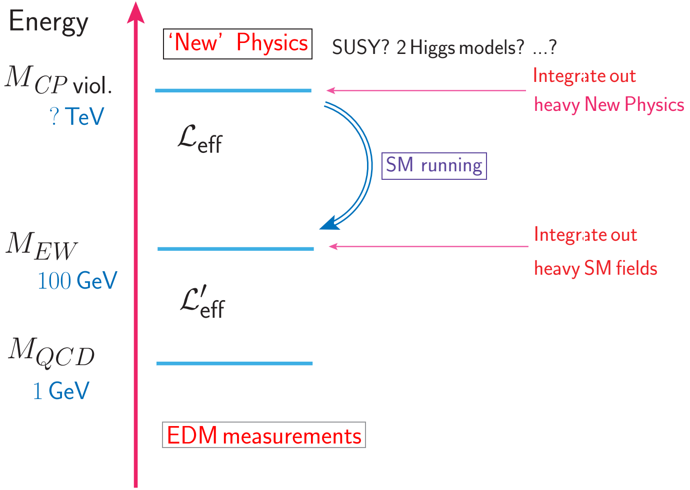

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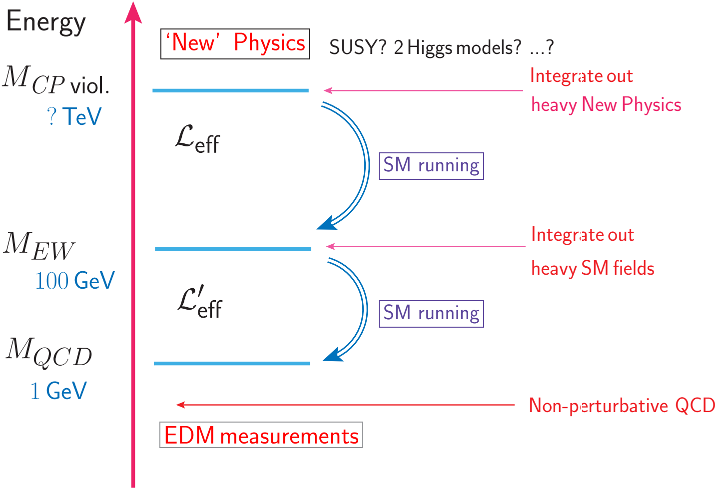

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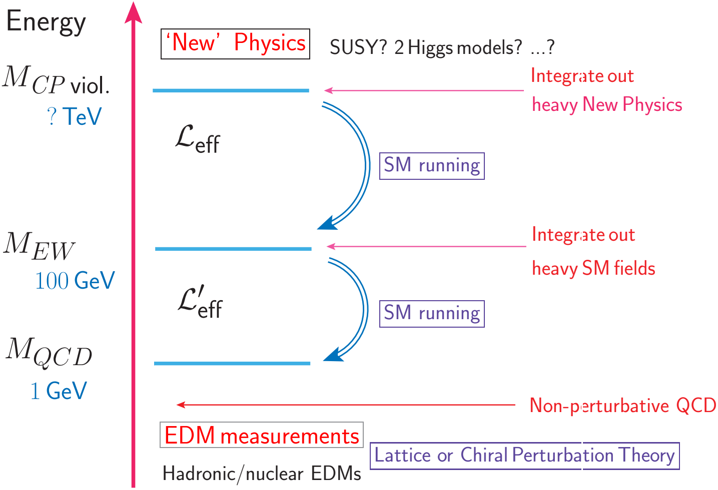
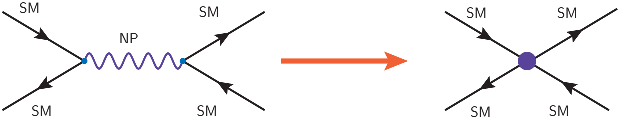


How to handle CP-violating sources beyond the SM?

New interactions as higher dimensional operators

- Add to the SM **all possible** effective interactions



- The new interactions appear as higher dimensional operators

$$\mathcal{L}_{\text{eft}} = \mathcal{L}_{SM} + \sum_i \frac{c_5^{(i)}}{M_{\not T}} \mathcal{O}_5^{(i)} + \sum_i \frac{c_6^{(i)}}{M_{\not T}^2} \mathcal{O}_6^{(i)} + \ldots$$

  where $M_{\not T}$ is the scale of the *New Physics* particles
- Only the lowest dimensional operators should be important
- Hadronic EDMs: non-leptonic CP-violating operators of dim. 6

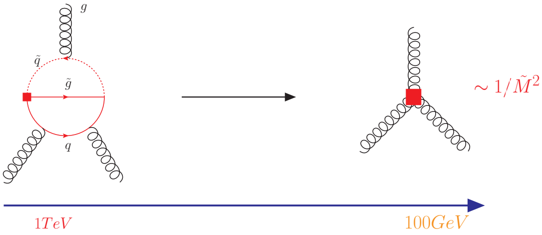
  Not of dim. 5 because of Higgs insertion (chiral symm.) at high (low) scales

How to handle CP-violating sources beyond the SM?

Evaluation in Effective Field Theory (EFT) approach

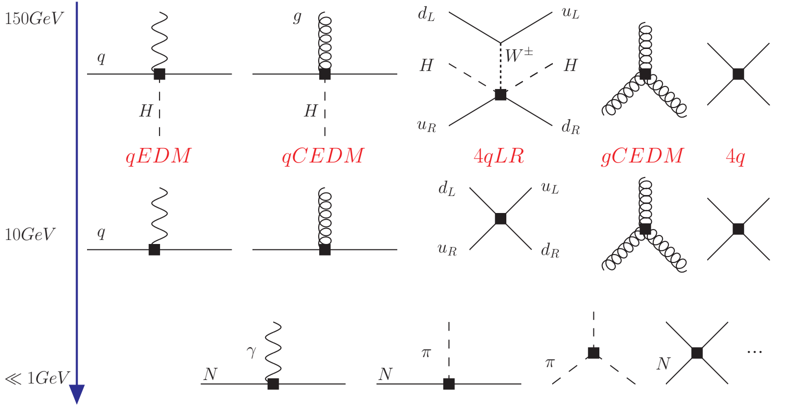
▸ EFT

- All degrees of freedom *beyond NP (EW) scale* are integrated out:
  ↪ Only SM degrees of freedom remain: q, g, (H, Z, $W^{\pm}$, ...)
- Write down *all* interactions for these *active* degrees of freedom that *respect the* SM+ Lorentz *symmetries*: here dim. 6 or higher order
- Need a *power-counting scheme* to order these infinite # interactions
- Relics of eliminated BSM physics 'remembered' by the values of the low-energy constants (LECs) of the CP-violating contact terms, e.g.



CP-violating BSM sources of dimension 6 from above EW scale to their hadronic equivalents below 1 GeV

W. Dekens & J. de Vries *JHEP* '13



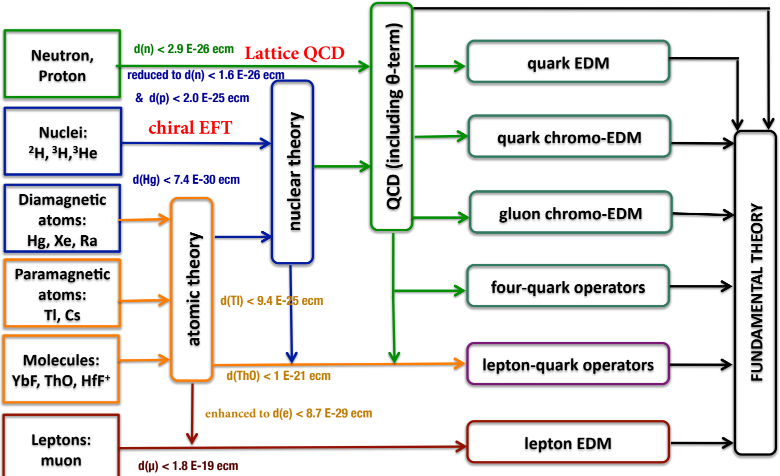
Total # $=$ 1$(\bar\theta)$ + 2(qEDM) + 2(qCEDM) + 1(4qLR) + 1(gCEDM) + 2(4q) [+3(semi)+1(lept)]

$=$ 1(dim-four) + 8(dim-six) [+3+1] [Caveat: $m_s \gg m_u, m_d$ (& $m_\mu \gg m_e$) assumed]

↪ 5 discriminable classes

Road map from EDM Measurements to EDM Sources

Experimentalist's point of view → ← Theorist's point of view



(adapted from Jordy de Vries, Jülich, March 14, 2013)

EDM Translator
from ‘quarkish/machine’ to ‘hadronic/human’ language?

3-CPO & R2-D2

EDM Translator

from ‘quarkish/machine’ to ‘hadronic/human’ language?

3-CPO & R2-D2

Symmetries (esp. chiral one) plus Goldstone Theorem

↪ Low-Energy Effective Field Theory with External Sources

i.e. Chiral Perturbation Theory (suitably extended)

Summary of scalings of $\not{CP}$ hadronic vertices

from θ to BSM sources

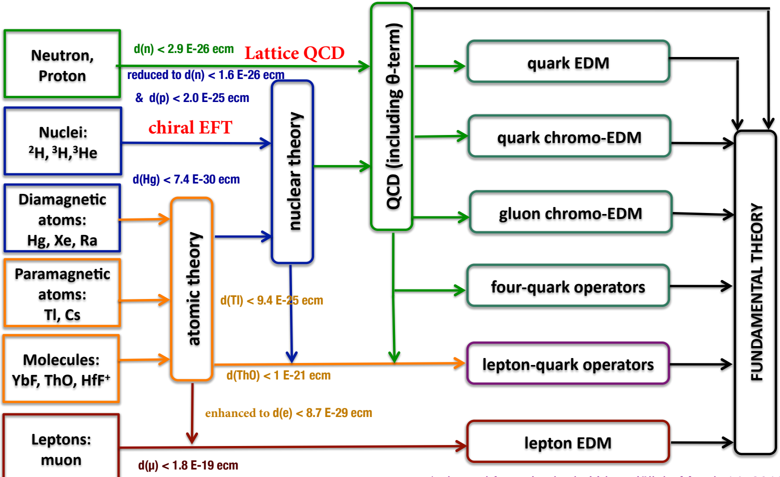
$\mathcal{L}_{\text{EFT}}^{\not{CP}}$:

	g_0: $\not{CP}$, I	g_1: $\not{CP}$, $\not{I}$	d_0, d_1: $\not{CP}$, I + $\not{I}$	$(m_N\Delta)$: $\not{CP}$, $\not{I}$
θ-term:	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi/m_N)$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(M_\pi^2/m_N^2)$
qEDM:	$\mathcal{O}(\alpha_{EM}/(4\pi))$	$\mathcal{O}(\alpha_{EM}/(4\pi))$	$\mathcal{O}(1)$	$\mathcal{O}(\alpha_{EM}/(4\pi))$
qCEDM:	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(M_\pi^2/m_N^2)$
4qLR:	$\mathcal{O}(M_\pi^2/m_n^2)$	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(M_\pi/m_n)$
gCEDM:	$\mathcal{O}(M_\pi^2/m_N^2)^*$	$\mathcal{O}(M_\pi^2/m_N^2)^*$	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi^2/m_N^2)$
4q:	$\mathcal{O}(M_\pi^2/m_N^2)^*$	$\mathcal{O}(M_\pi^2/m_N^2)^*$	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi^2/m_N^2)$

*: Goldstone theorem → relative $\mathcal{O}(M_\pi^2/m_n^2)$ suppression of $N\pi$ interactions

Road map from EDM Measurements to EDM Sources

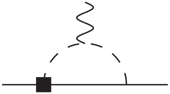
Experimentalist's point of view → ← Theorist's point of view



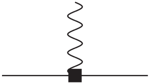
(adapted from Jordy de Vries, Jülich, March 14, 2013)

θ-Term Induced Nucleon EDM

single nucleon EDM:



isovector $\approx$ $\ll$ isoscalar



"controlled"

two "unknown" coefficients

Guo & Meißner *JHEP*'12: also in SU(3) case

$$d_N\big|^{\text{isovector}}_{\text{loop}} = -e\frac{g_{\pi NN}\, g_0^\theta}{4\pi^2}\,\frac{\ln(m_N^2/M_\pi^2)}{2m_N} \sim \bar\theta\, M_\pi^2 \ln M_\pi^2 \qquad (e>0)$$

Crewther, di Vecchia, Veneziano & Witten *PLB*'79; Pich & de Rafael *NPB*'91; Ottnad et al. *PLB*'10

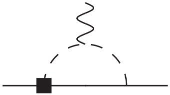
$$g_0^\theta = \frac{(m_n - m_p)^{\text{strong}}(1-\epsilon^2)}{4F_\pi\epsilon}\,\bar\theta \approx (-0.016\pm 0.002)\bar\theta \qquad \left(\text{where } \epsilon \equiv \frac{m_u-m_d}{m_u+m_d}\right)$$

$$\hookrightarrow d_N\big|^{\text{isovector}}_{\text{loop}} \sim (1.8\pm 0.3)\cdot 10^{-16}\,\bar\theta\, e\,\text{cm}$$

Bsaisou et al., *EPJA*'13 & *JHEP*'15 ▸ details

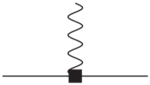
θ-Term Induced Nucleon EDM

single nucleon EDM:



isovector
$\approx$

$\ll$
isoscalar



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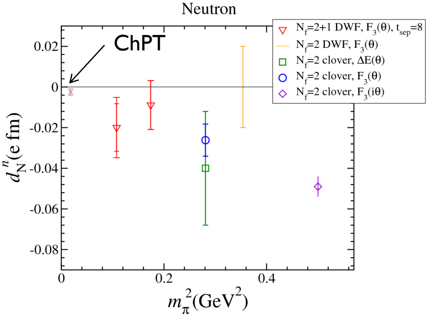
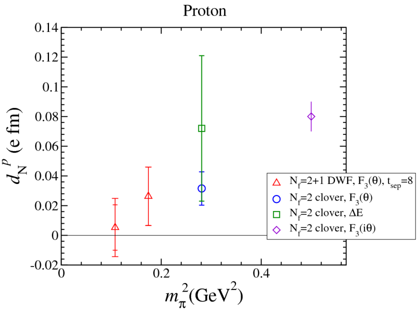
Bsaisou et al., *EPJA*'13 & *JHEP*'15 ▸ details

But what about the two "unknown" coefficients of the contact terms?

Preliminary Lattice (full QCD) results

neutron EDM and proton EDM





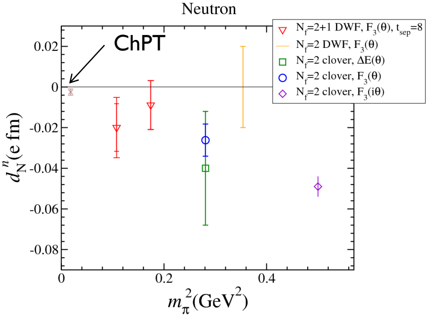
$\theta \equiv 1$!

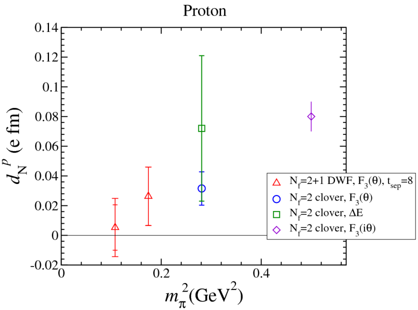
(adapted from Eigo Shintani (Mainz), *Lattice calculation of nucleon EDM*, Hirschegg, Jan. 14, 2014)

no systematical errors!

Preliminary Lattice (full QCD) results

neutron EDM and proton EDM





$\theta \equiv 1$! (adapted from Eigo Shintani (Mainz), *Lattice calculation of nucleon EDM*, Hirschegg, Jan. 14, 2014)

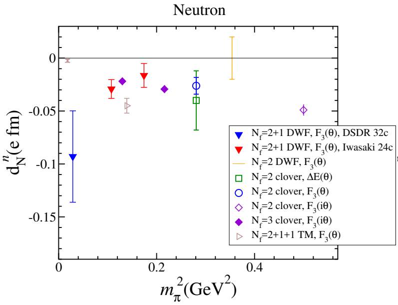
no systematical errors!

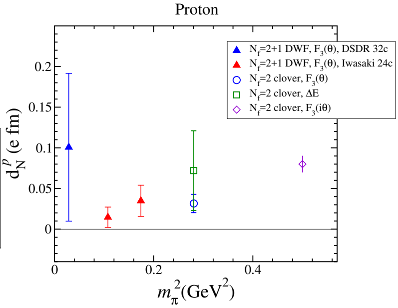
$$\hookrightarrow d_n = \bar{\theta}\,(-2.7 \pm 1.2) \cdot 10^{-3} \cdot e\,\text{fm} \quad \text{and} \quad d_p = \bar{\theta}\,(2.1 \pm 1.2) \cdot 10^{-3} \cdot e\,\text{fm}$$

Akan, Guo & Meißner, *PLB* **736** (2014); see also $d_n = \bar{\theta}(-3.9 \pm 0.2 \pm 0.9)10^{-3}\,e\,\text{fm}$ Guo et al., *PRL* **115** (2015)

Preliminary Lattice (full QCD) results

neutron EDM and proton EDM





$\bar{\theta} \equiv 1$!

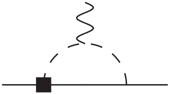
Eigo Shintani et al., *Phys. Rev. D* **93**, 094503 (2016) $M_\pi = 170, 330, 420, 530\,\text{MeV}$

Don't mention the ... light nuclei

Single Nucleon Versus Nuclear EDM

Crewther, di Vecchia, Veneziano, Witten *PLB*'79; Pich, de Rafael *NPB*'91; Ottnad et al. *PLB*'10

single nucleon EDM:

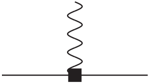


isovector

$\approx$

$\ll$

isoscalar



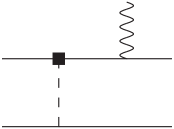
"controlled"   "unknown" coefficients

$\longrightarrow$ lattice QCD required

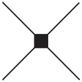
Guo, Meißner *JHEP*'12

two nucleon EDM:

Sushkov, Flambaum, Khriplovich *Sov.Phys. JETP*'84



$\gg$



controlled   unknown coefficient

Single Nucleon Versus Nuclear EDM

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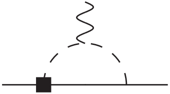
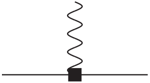


isovector $\approx$

$\ll$ isoscalar



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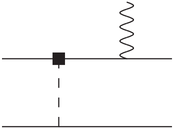

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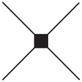
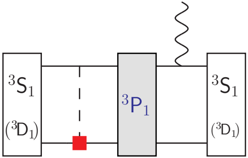


controlled | unknown coefficient

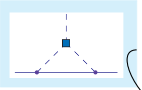
EDM of the Deuteron at LO: CP-violating π exchange

$$\mathcal{L}^{\pi N}_{\not{CP}} = -d_n N^\dagger(1-\tau^3)S^\mu v^\nu N F_{\mu\nu} - d_p N^\dagger(1+\tau_3)S^\mu v^\nu N F_{\mu\nu}$$
$$+ (m_N \Delta)\pi^2\pi_3 + \cancel{g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N} + g_1 N^\dagger \pi_3 N$$
$$+ \cancel{C_1 N^\dagger N \mathcal{D}_\mu (N^\dagger S^\mu N)} + \cancel{C_2 N^\dagger \vec{\tau} N \cdot \mathcal{D}_\mu (N^\dagger \vec{\tau} S^\mu N)} + \cdots .$$



LO: $\cancel{g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N}$ $(\not{CP}, I)$ $\rightarrow$ 0 (Isospin filter!)

NLO: $g_1 N^\dagger \pi_3 N$ $(\not{CP}, \not{I})$ $\rightarrow$ *"LO"* in D case



term	N^2LO ChPT	Av_{18}	CD-Bonn	units
d_n^D	0.939 ± 0.009	0.914	0.927	d_n
d_p^D	0.939 ± 0.009	0.914	0.927	d_p
g_1	0.183 ± 0.017	0.186	0.186	$g_1\, e\,\mathrm{fm}$
Δf_{g_1}	-0.748 ± 0.138	-0.703	-0.719	$\Delta\, e\,\mathrm{fm}$

Bsaisou, dissertation, Univ. Bonn (2014); Bsaisou et al., *JHEP* **03** (2015)

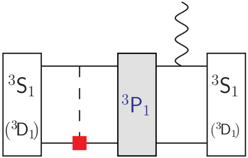
BSM $\not{CP}$ sources: g_1 πNN vertex is of LO in qCEDM and 4qLR case

$(\Lambda_{LS}, \Lambda_{SFR}) = \{(0.45, 0.5); (0.6, 0.5); (0.55, 0.6); (0.45, 0.7); (0.6, 0.7)\}$ GeV

new

EDM of the Deuteron at LO: CP-violating π exchange

$$
\begin{aligned}
\mathcal{L}^{\pi N}_{\not{CP}} = & -d_n N^\dagger(1-\tau^3)S^\mu v^\nu N F_{\mu\nu} - d_p N^\dagger(1+\tau_3)S^\mu v^\nu N F_{\mu\nu} \\
& + (m_N \Delta)\pi^2\pi_3 + \cancel{g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N} + g_1 N^\dagger \pi_3 N \\
& + \cancel{C_1 N^\dagger N \mathcal{D}_\mu (N^\dagger S^\mu N)} + \cancel{C_2 N^\dagger \vec{\tau} N \cdot \mathcal{D}_\mu (N^\dagger \vec{\tau} S^\mu N)} + \cdots .
\end{aligned}
$$



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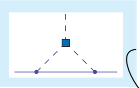
NLO: $g_1 N^\dagger \pi_3 N$ $(\not{CP}, \not{I})$ $\rightarrow$ *"LO"* in D case

Yamanaka & Hiyama, *PRC* **91** (2015): $d_N^D = \left(1 - \frac{3}{2} P_{^3D_1}\right) d_N$



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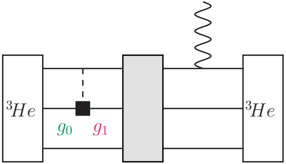
▸ new

^{3}*He* EDM: results for CP-violating π exchange



$g_0 N^\dagger \vec{\pi} \cdot \vec{\tau} N$ ($\not{CP}$, I)

LO: θ-term, qCEDM

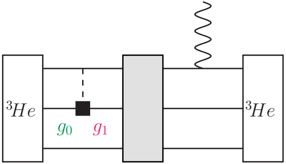
N^{2}LO: 4qLR

$g_1 N^\dagger \pi_3 N$ ($\not{CP}$, $\not{I}$)

LO: qCEDM, 4qLR

NLO: θ term

^3He EDM: results for CP-violating π exchange



$g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N$ ($\not{CP}$, I)
LO: θ-term, qCEDM
N^{2}LO: 4qLR

$g_1 N^\dagger \pi_3 N$ ($\not{CP}$, $\not{I}$)
LO: qCEDM, 4qLR
NLO: θ term

term	A	N^{2}LO ChPT	Av_{18}+UIX	CD-Bonn+TM	units
d_n	^{3}He	0.904 ± 0.013	0.875	0.902	d_n
	^{3}H	−0.030 ± 0.007	−0.051	−0.038	
d_p	^{3}He	−0.029 ± 0.006	−0.050	−0.037	d_p
	^{3}H	0.918 ± 0.013	0.902	0.876	
Δ	^{3}He	−0.017 ± 0.006	−0.015	−0.019	$\Delta\, e\,$fm
	^{3}H	−0.017 ± 0.006	−0.015	−0.019	
g_0	^{3}He	0.111 ± 0.013	0.073	0.087	$g_0\, e\,$fm
	^{3}H	−0.108 ± 0.013	−0.073	−0.085	
g_1	^{3}He	0.142 ± 0.019	0.142	0.146	$g_1\, e\,$fm
	^{3}H	0.139 ± 0.019	0.142	0.144	
Δf_{g_1}	^{3}He	−0.608 ± 0.142	−0.556	−0.586	$\Delta\, e\,$fm
	^{3}H	−0.598 ± 0.141	−0.564	−0.576	
C_1	^{3}He	−0.042 ± 0.017	−0.0014	−0.016	$C_1\, e\,\mathrm{fm}^{-2}$
	^{3}H	0.041 ± 0.016	0.0014	0.016	
C_2	^{3}He	0.089 ± 0.022	0.0042	0.033	$C_2\, e\,\mathrm{fm}^{-2}$
	^{3}H	−0.087 ± 0.022	−0.0044	−0.032	

Bsaisou, dissertation, Univ. Bonn (2014); Bsaisou et al., *JHEP* **03** (2015)

^3He EDM: results for CP-violating π exchange

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$$+ C_1 N^\dagger N \mathcal{D}_\mu(N^\dagger S^\mu N) + C_2 N^\dagger\vec{\tau}N\cdot\mathcal{D}_\mu(N^\dagger\vec{\tau}S^\mu N) + \cdots .$$

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Discriminating between three scenarios at 1 GeV

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

1 The Standard Model + $\bar\theta$

$$\mathcal{L}_{\rm SM}^{\theta} = \mathcal{L}_{\rm SM} + \bar\theta m_q^* \bar q i\gamma_5 q$$

2 The left-right symmetric model — with two 4-quark operators:

$$\mathcal{L}_{LR} = -\mathrm{i}\,\Xi\left[1.1(\bar u_R\gamma_\mu u_R)(\bar d_L\gamma^\mu d_L) + 1.4(\bar u_R t^a\gamma_\mu u_R)(\bar d_L t^a\gamma^\mu d_L)\right] + \text{h.c.}$$

3 The aligned two-Higgs-doublet model — with the dipole operators:

$$\mathcal{L}_{a2HM} = -e\frac{d_d}{2}\,\bar d\,\mathrm{i}\sigma_{\mu\nu}\gamma_5 d\,F^{\mu\nu} - \frac{\tilde d_d}{4}\,\bar d\,\mathrm{i}\sigma_{\mu\nu}\gamma_5\lambda^a d\,G^{a\,\mu\nu} + \frac{d_W}{3}\,f_{abc}\tilde G^{a\,\mu\nu}G^b_{\mu\rho}G^{c\rho}_{\ \ \nu}$$

— with the hierarchy $\tilde d_d \simeq 4d_d \simeq 20d_W$

matched on

$$\begin{aligned}\mathcal{L}^{\pi N}_{\not{CP}\,\mathrm{EFT}} \;=\;& -d_n N^\dagger(1-\tau^3)S^\mu v^\nu N F_{\mu\nu} - d_p N^\dagger(1+\tau_3)S^\mu v^\nu N F_{\mu\nu}\\ &+ (m_N\Delta)\pi^2\pi_3 + g_0 N^\dagger\vec\pi\cdot\vec\tau N + g_1 N^\dagger\pi_3 N\\ &+ C_1 N^\dagger N\mathcal{D}_\mu(N^\dagger S^\mu N) + C_2 N^\dagger\vec\tau N\cdot\mathcal{D}_\mu(N^\dagger\vec\tau S^\mu N) + \cdots .\end{aligned}$$

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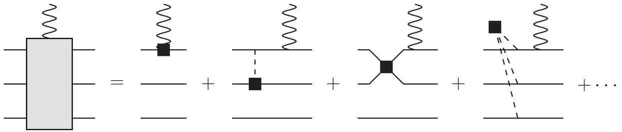
— with the hierarchy $\tilde{d}_d \simeq 4 d_d \simeq 20 d_W$

matched on



Testing strategies: SM + $\bar{\theta}$

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the helion and neutron EDMs

Testing strategies: SM + $\bar{\theta}$

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the helion and neutron EDMs

$$d_{^3\mathrm{He}} - 0.9 d_n = -\bar{\theta}\left(1.01 \pm 0.31_{\mathrm{had}} \pm 0.29^{\star}_{\mathrm{nucl}}\right) \cdot 10^{-16}\, e\,\mathrm{cm}$$

Extraction of $\bar{\theta}$

*includes ± 0.20 uncertainty from 2N contact terms

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Extraction of $\bar{\theta}$

$$d_D - 0.94(d_n + d_p) = \bar{\theta}\left(0.89 \pm 0.29_{\text{had}} \pm 0.08_{\text{nucl}}\right) \cdot 10^{-16}\, e\,\text{cm}$$

Prediction for $d_D - 0.94(d_n + d_p)$
(& triton EDM): $d_D^{\text{Nucl}} \approx -d_{^3\text{He}}^{\text{Nucl}} \approx \frac{1}{2} d_{^3\text{H}}^{\text{Nucl}}$

*includes ± 0.20 uncertainty from 2N contact terms

Testing strategies: SM + $\bar{\theta}$

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the helion and neutron EDMs

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(& triton EDM): $d_D^{\mathrm{Nucl}} \approx -d_{^3\mathrm{He}}^{\mathrm{Nucl}} \approx \frac{1}{2} d_{^3\mathrm{H}}^{\mathrm{Nucl}}$

$$g_0^\theta = \frac{(m_n - m_p)^{\mathrm{strong}}(1-\epsilon^2)}{4F_\pi\,\epsilon}\bar{\theta} = (-16\pm 2)10^{-3}\bar{\theta}$$

$$\frac{g_1^\theta}{g_0^\theta} \approx \frac{8c_1(M^2_{\pi^\pm} - M^2_{\pi^0})^{\mathrm{strong}}}{(m_n - m_p)^{\mathrm{strong}}}, \quad \epsilon \equiv \frac{m_u - m_d}{m_u + m_d}$$

$g_1^\theta / g_0^\theta \approx -0.2$

* includes ± 0.20 uncertainty from 2N contact terms

Testing strategies: minimal LR symmetric Model

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the deuteron
and nucleon EDMs

Testing strategies: minimal LR symmetric Model

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

$$d_D - 0.94(d_n + d_p) \simeq d_D = -\left(2.1 \pm 0.5^{\star}\right)\Delta^{LR}\, e\,\mathrm{fm}$$

Extraction of Δ^{LR}

* includes ± 0.1 uncertainty from 2N contact terms

Testing strategies: minimal LR symmetric Model

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

$$d_D - 0.94(d_n + d_p) \simeq d_D = -\left(2.1 \pm 0.5^{\star}\right)\Delta^{LR}\, e\,\mathrm{fm}$$

Extraction of Δ^{LR}

$$d_{^3\mathrm{He}} - 0.9 d_n \simeq d_{^3\mathrm{He}} = -(1.7 \pm 0.5^{\star})\Delta^{LR}\, e\,\mathrm{fm}$$

Prediction for the helion EDM

(& triton EDM): $d_D \approx d_{^3\mathrm{He}} \approx d_{^3\mathrm{H}}$

*includes ± 0.1 uncertainty from 2N contact terms

Testing strategies: minimal LR symmetric Model

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

$d_D - 0.94(d_n + d_p) \simeq d_D = -(2.1 \pm 0.5^{\star})\Delta^{LR} e\,\text{fm}$

Extraction of Δ^{LR}

$d_{^3\text{He}} - 0.9 d_n \simeq d_{^3\text{He}} = -(1.7 \pm 0.5^{\star})\Delta^{LR} e\,\text{fm}$

Prediction for the helion EDM (& triton EDM): $d_D \approx d_{^3\text{He}} \approx d_{^3\text{H}}$

$$g_1^{LR} = 8 c_1 m_N \Delta^{LR} = (-7.5 \pm 2.3)\Delta^{LR},$$
$$g_0^{LR} = \frac{(m_n - m_p)^{\text{str}} m_N}{M_\pi^2} \Delta^{LR} = (0.12 \pm 0.02)\Delta^{LR}$$

$-g_1^{LR}/g_0^{LR} \gg 1$ (!)

*includes ± 0.1 uncertainty from 2N contact terms

Testing strategies: aligned 2-Higgs Doublet Model

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

Testing strategies: aligned 2-Higgs Doublet Model

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

$$d_D - 0.94(d_n + d_p) = \left[(0.18 \pm 0.02)\, g_1 - (0.75 \pm 0.14)\,\Delta\right] e\,\text{fm}$$

Extraction of g_1^{eff} (including Δ correction)

Testing strategies: aligned 2-Higgs Doublet Model

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

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Extraction of g_1^{eff} (including Δ correction)

+ Measurement of $d_{^3\text{He}}$ (or $d_{^3\text{H}}$)

Testing strategies: aligned 2-Higgs Doublet Model

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

$$d_D - 0.94(d_n + d_p) = \left[(0.18 \pm 0.02) g_1 - (0.75 \pm 0.14)\Delta\right] e\,\text{fm}$$

Extraction of g_1^{eff} (including Δ correction)

+ Measurement of $d_{^3\text{He}}$ (or $d_{^3\text{H}}$)

$$d_{^3\text{He}} - 0.9 d_n$$
$$= \left[(0.11 \pm 0.02^{\star}) g_0 + (0.14 \pm 0.02^{\star}) g_1 - (0.61 \pm 0.14)\Delta\right] e\,\text{fm}$$

Extraction of g_0

*includes ± 0.01 uncertainty from 2N contact terms

Testing strategies: aligned 2-Higgs Doublet Model

Dekens et al. *JHEP* **07** (2014); Bsaisou et al. *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

$$d_D - 0.94(d_n + d_p) = \left[(0.18\pm0.02)g_1 - (0.75\pm0.14)\Delta\right] e\,\text{fm}$$

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Extraction of g_0

Prediction of $d_{^3\text{H}}$ (or $d_{^3\text{He}}$)

*includes ±0.01 uncertainty from 2N contact terms

JÜLICH
FORSCHUNGSZENTRUM

Summary

- *D* EDM might **distinguish** between $\bar{\theta}$ and other scenarios and allows **extraction** of the g_1 coupling constant via $d_D - 0.94(d_n + d_p)$. (The prefactor of $(d_n + d_p)$ stands for a 4% probability of the $^3D_1$ state.)
- ^3He (or ^3H) EDM necessary for a **proper test** of $\bar{\theta}$ and LR scenarios:
- Deuteron & helion work as complementary isospin filters of EDMs
- 2N contact terms **cannot be neglected** for nuclei beyond *D*
- a2HDM case: ^3He *and* ^3H EDMs would be needed for a proper test
- pure qCEDM: similar to a2HDM scenario
- pure qEDM: $d_D = 0.94(d_n + d_p)$ and $d_{^3He/^3H} = 0.9 d_{n/p}$
- gCEDM, 4quark χ singlet: controlled calculation difficult (lattice ?)
- Ultimate progress may eventually come from **Lattice QCD**
  $\hookrightarrow$ $\not{C}\not{P}$ $N\pi$ couplings g_0 & g_1 may be accessible even for dim-6 case

Traditional atomic EDMs

- Why can't we get **this info** from EDMs of Hg, Ra, Rn, … ?

  Strong bound on atomic EDM: $|d_{^{199}\mathrm{Hg}}| < 7.4 \cdot 10^{-30} \cdot e \cdot \mathrm{fm}$

  Graner et al. *PRL*'16

- The atomic part of the calculation is well under control

  $$d_{^{199}\mathrm{Hg}} = (2.8 \pm \underbrace{\cancel{0.6}}_{0.3})\, S_{\mathrm{Hg}} \cdot 10^{-4} \cdot \mathrm{fm}^{-2}$$

  Dzuba et al. *PRA*'02, '09, *IJMPE*'12

  S_{Hg}: Nuclear Schiff moment

- But the nuclear part isn't …

  $$S_{^{199}\mathrm{Hg}} = \left[(0.4 \pm 0.4) g_0 + (0.4 \pm 0.8) g_1\right] e \cdot \mathrm{fm}^3$$

  Engel et al. *PPNP*'13

- There is **no power counting** for nuclei with so many nucleons
- Short-range 4N contributions not even considered
- The CP-violating 3π contribution Δf_{g_1} to g_1 grows linearly with momentum transfer $\rightsquigarrow$ more important for heavier systems
- Hadronic uncertainties of g_0 and g_1 are underestimated too

Conclusions

- EDMs **probe** *New CP-odd Physics* (at similar energy scales as LHC)
- The **first** non-vanishing EDM might be detected in a charge-neutral case: *neutrons* or *dia-/ paramagnetic atoms* or *molecules* ⋯
- However, measurements of **light ion EDMs** can play a key role in **disentangling the *sources* of (flavor-diagonal) $\not{CP}$**
- EDM measurements are characteristically of **low-energy nature:**
  ↪ non-leptonic predictions have to be in the *language of hadrons*
  ↪ only systematical methods: *ChPT/EFT* and *Lattice QCD*
- EDMs of light nuclei provide independent information to nucleon ones and may be even larger and, moreover, even **simpler**

At least the EDMs of *p*, *n*, *D*, and ^{3}*He* would be needed
to have a **realistic** chance to disentangle the underlying physics

Many thanks to my colleagues

in Jülich: Jan Bsaisou, Christoph Hanhart, Susanna Liebig, Ulf-G. Meißner, David Minossi, Andreas Nogga, and Jordy de Vries

in Bonn: Feng-Kun Guo, Bastian Kubis, Ulf-G. Meißner

and: Werner Bernreuther, Bira van Kolck, and Kolya Nikolaev

References:

1. J. Bsaisou, U.-G. Meißner, A. Nogga and A.W., *P- and T-Violating Lagrangians in Chiral Effective Field Theory and Nuclear Electric Dipole Moments*, Annals of Physics **359**, 317-370 (2015), arXiv:1412.5471 [hep-ph].
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3. A.W., *Electric dipole moments of the nucleon and light nuclei* Nuclear Physics A **928**, 116-127 (2014), arXiv:1404.6131 [hep-ph].
4. W. Dekens, J. de Vries, J. Bsaisou, W. Bernreuther, C. Hanhart, U.-G. Meißner, A. Nogga and A.W., *Unraveling models of CP violation through electric dipole moments of light nuclei,* JHEP **07**, 069 (2014), arXiv:1404.6082 [hep-ph].
5. J. Bsaisou, C. Hanhart, S. Liebig, U.-G. Meißner, A. Nogga and A.W., *The electric dipole moment of the deuteron from the QCD θ-term,* Eur. Phys. J. A **49**, 31 (2013), arXiv:1209.6306 [hep-ph].

Backup slides

If $\bar{\theta}$-term tests fail, then effective BSM dim. 6 sources de Vries et al.(2011)

qEDM	qCEDM	4qLR	gCEDM + 4qEDM
$d_D \approx d_p + d_n$	$d_D > d_p + d_n$	$d_D > d_p + d_n$	$d_D \sim d_p + d_n$
$d_{^3He} \approx d_n$	$d_{^3He} > d_n$	$d_{^3He} > d_n$	$d_{^3He} \sim d_n$

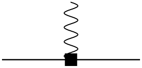
$\longrightarrow \quad g_0,\, g_1 \propto \alpha/(4\pi)$

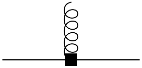
$2N$ contribution suppressed by photon loop!

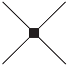
here: only absolute values considered

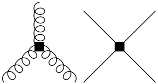
If $\bar{\theta}$-term tests fail, then effective BSM dim. 6 sources

de Vries et al.(2011)









qEDM	qCEDM	4qLR	gCEDM + 4qEDM
$d_D \approx d_p + d_n$	$d_D > d_p + d_n$	$d_D > d_p + d_n$	$d_D \sim d_p + d_n$
$d_{^3He} \approx d_n$	$d_{^3He} > d_n$	$d_{^3He} > d_n$	$d_{^3He} \sim d_n$

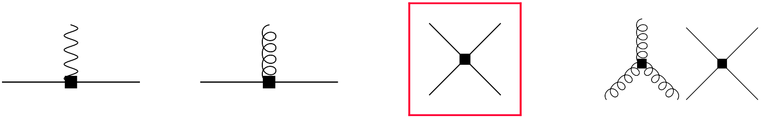
$\longrightarrow$ g_0, g_1 dominant and of the same order

$2N$ contribution enhanced!

here: only absolute values considered

If $\bar{\theta}$-term tests fail, then effective BSM dim. 6 sources

de Vries et al.(2011)



$qEDM$	$qCEDM$	$4qLR$	$gCEDM + 4qEDM$
$d_D \approx d_p + d_n$	$d_D > d_p + d_n$	$d_D > d_p + d_n$	$d_D \sim d_p + d_n$
$d_{^3He} \approx d_n$	$d_{^3He} > d_n$	$d_{^3He} > d_n$	$d_{^3He} \sim d_n$

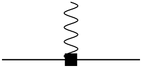
$\longrightarrow$ $g_1 \gg g_0$; 3π-coupling (unsuppressed in ^{3}He)

isospin-breaking $2N$ contribution enhanced!

here: only absolute values considered

If $\bar{\theta}$-term tests fail, then effective BSM dim. 6 sources

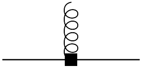
de Vries et al.(2011)



$qEDM$

$d_D \approx d_p + d_n$

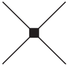
$d_{^3He} \approx d_n$



$qCEDM$

$d_D > d_p + d_n$

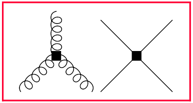
$d_{^3He} > d_n$



$4qLR$

$d_D > d_p + d_n$

$d_{^3He} > d_n$



$gCEDM + 4qEDM$

$d_D \sim d_p + d_n$

$d_{^3He} \sim d_n$

$\longrightarrow$ g_1, g_0, $4N$ – coupling on the same footing

$2N$ contribution difficult to asses!

here: only absolute values considered

Generic features of a permanent EDM

$$\mathcal{H}_{\text{eff}} = \mathrm{i}\frac{d_f}{2}\,\bar{f}\sigma^{\mu\nu}\gamma_5 f\, F_{\mu\nu} \xrightarrow{\text{non-rel.}} -d_f\,\langle\boldsymbol{\sigma}\rangle\cdot\mathbf{E} \longrightarrow$$ *linear* Stark effect

Generic features of a permanent EDM

$$\mathcal{H}_{\rm eff} = \mathrm{i}\frac{d_f}{2}\,\bar f \sigma^{\mu\nu}\gamma_5 f\, F_{\mu\nu} \stackrel{\text{non-rel.}}{\longrightarrow} -d_f\,\langle \boldsymbol{\sigma}\rangle \cdot \mathbf{E} \longrightarrow$$ ▸ *linear* Stark effect

1. For any non-zero EDM, $\not{C}\!\not{P}$ must be flavor *diagonal*!

2. Sum of the mass dimension of the fields: $\frac{3}{2}+\frac{3}{2}+2=5$:
   ↪ $\dim(d_f) = e \times \text{mass}^{-1} = e \times \text{length}$ (such that $\int d^4x\,\mathcal{L} \sim \text{mass}^0$)
   ↪ non-renormalizable *effective* interaction

3. fermion EDMs flip chirality: $\frac{1}{2}(\mathbb{1}-\gamma_5)f \equiv f_L \longleftrightarrow f_R \equiv \frac{1}{2}(\mathbb{1}+\gamma_5)f$

$$\mathcal{L}_{\rm EDM} = -\mathrm{i}\frac{d_f}{2}\,\bar f\sigma_{\mu\nu}\gamma_5 f\,F^{\mu\nu} = -\mathrm{i}\frac{d_f}{2}\,\bar f_L\,\sigma_{\mu\nu} f_R\,F^{\mu\nu} + \mathrm{i}\frac{d_f}{2}\,\bar f_R\,\sigma_{\mu\nu} f_L\,F^{\mu\nu}$$

⇒ fermion mass m_f insertion (e.g. via Higgs mechanism) needed:

$$d_f \propto m_f^n\,, \qquad n = 1, 2, 3$$ (depending on the model of $\not{C}\!\not{P}$)

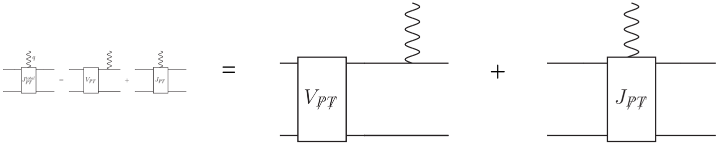
↪ $\not{C}\!\not{P}$ beyond SM: $\mathcal{L}^{\not{C}\not{P}}_{\rm BSM} = \cancel{\frac{1}{M_{\rm BSM}}\mathcal{L}_{\dim 5}} + \frac{1}{M^2_{\rm BSM}}\mathcal{L}_{\dim 6} + \ldots$

EDM of the Deuteron:

Deuteron (D) as Isospin Filter

note:  $= \frac{ie}{2}(1+\tau_3)$

2N-system: $I + S + L$=odd



total current — irred. potential — irred. current

$\mathrm{I}=0$ $\quad \mathrm{I}=0$ $\quad \mathrm{I}=0 \to \mathrm{I}=1 \to \mathrm{I}=0$ $\quad \mathrm{I}=0$ $\quad \mathrm{I}=0$

isospin selection rules!

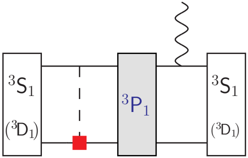
$\Downarrow$

~~$g_0^\theta N^\dagger \vec{\pi}\cdot\vec{\tau} N$~~ at leading order (LO)

$\Downarrow$

subleading (NLO) $g_1^\theta N^\dagger \pi_3 N$ acts as *'new'* leading order (LO) for D

EDM of the Deuteron at LO: CP-violating π exchange



LO: $\cancel{g_0^\theta N^\dagger \vec{\pi}\cdot\vec{\tau} N}$ $(\not{CP},\mathrm{I}) \to 0$ (Isospin filter!)

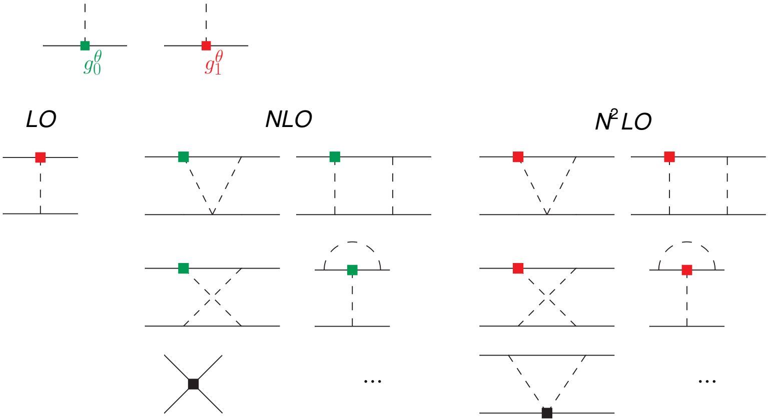
NLO: $g_1^\theta N^\dagger \pi_3 N$ $(\not{CP},\not{\mathrm{I}})$ $\to$ *"LO"* in D case

Reference	potential	result [$g_1\, g_{\pi NN}\, e\,$fm]
Liu & Timmermans (2004)	Av_{18}	1.43×10^{-2}
Afnan & Gibson (2010)	Reid 93	1.53×10^{-2}
Song et al. (2013)	Av_{18}	1.45×10^{-2}
JBC (2014)*	Av_{18}	1.45×10^{-2}
Bsaisou et al. (2013)$^\diamond$	CD Bonn	1.52×10^{-2}
JBC (2014)*	ChPT (N^2LO)	$(1.43 \pm 0.13) \times 10^{-2}$

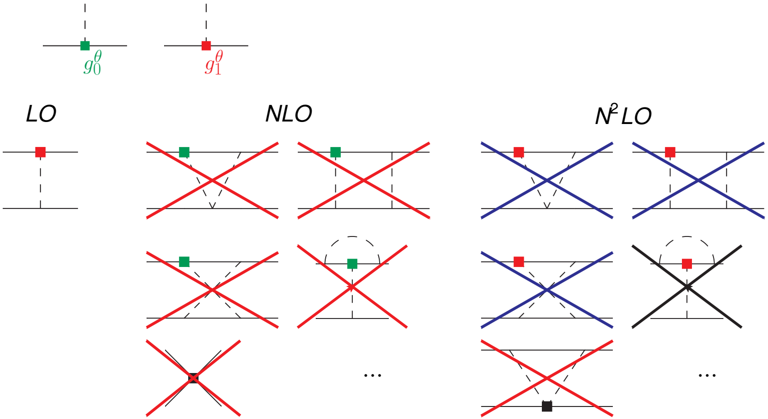
* unpublished, $^\diamond$ Eur. Phys. J. A **49** (2013) 31 [arXiv:1209.6306]

BSM $\not{CP}$ sources: g_1 πNN vertex is of LO in qCEDM and 4qLR case

EDM of the Deuteron: *NLO*- and N^2LO-Potentials



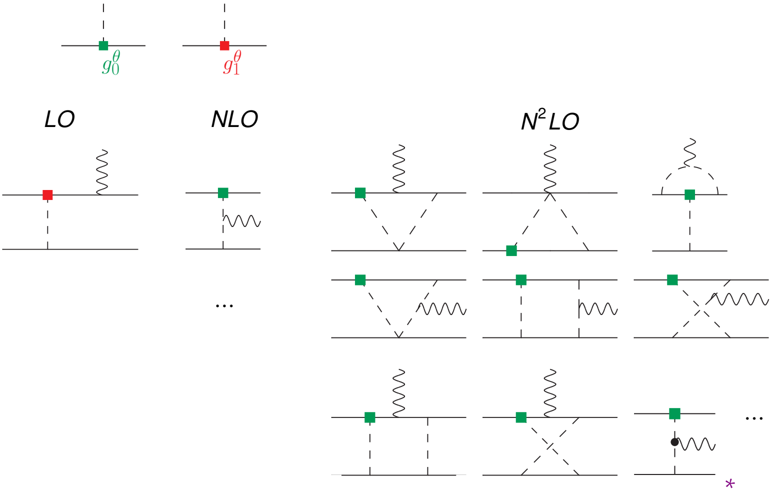
EDM of the Deuteron: *NLO*- and N^2LO-Potentials



- ×: vanishing by selection rules, ×: sum of diagrams vanishes
  ×: vertex correction

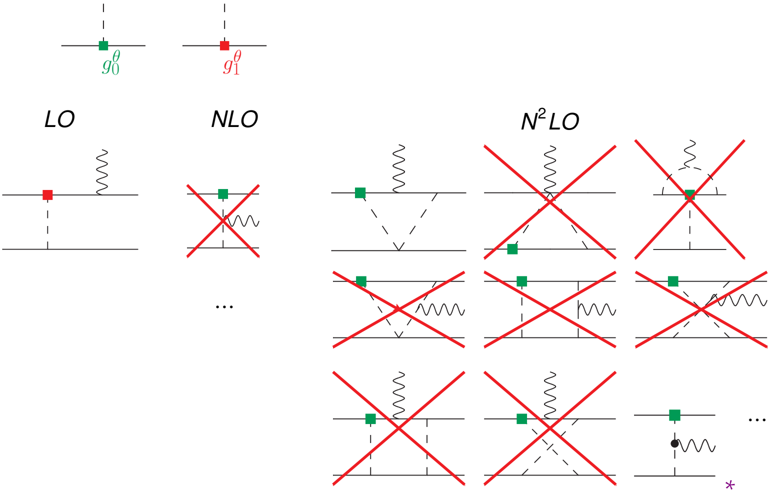
LO NLO N^2LO

EDM of the Deuteron: *NLO*- and N^2LO-Currents



*: de Vries et al. (2011), Bsaisou et al. (2013)

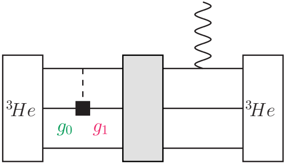
EDM of the Deuteron: *NLO*- and N^2LO-Currents



$\ast$: de Vries et al. (2011), Bsaisou et al. (2013)

- ×: vanishing by selection rules, ×: sum of diagrams vanishes

^3He EDM: results for CP-violating π exchange



$g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N$ ($\not{CP}$, I)
LO: θ-term, qCEDM
N^{2}LO: 4qLR

$g_1 N^\dagger \pi_3 N$ ($\not{CP}$, $\not{I}$)
LO: qCEDM, 4qLR
NLO: θ term

Reference	potential	result [$g_0 g_{\pi NN}\, e\,$fm]	result [$g_1 g_{\pi NN}\, e\,$fm]
Stetcu et al.(2008)	Av_{18} UIX	$1.20 \times 10^{-2}/2^{\diamond}$	$2.20 \times 10^{-2}/2^{\diamond}$
Song et al.(2013)	Av_{18}UIX	0.55×10^{-2}	1.06×10^{-2}
JBC (2014)$^\diamond$	Av_{18}UIX	0.57×10^{-2}	1.11×10^{-2}
JBC (2014)$^\diamond$	CD BONN TM	0.68×10^{-2}	1.14×10^{-2}
JBC (2014)$^\diamond$	ChPT (N^2LO)	$(0.86 \pm 0.11) \times 10^{-2}$	$(1.11 \pm 0.14) \times 10^{-2}$

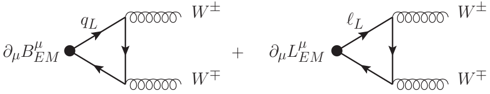
$^\diamond$ unpublished

Results for $^3H(g_i) \approx (-1)^{1+i} \times {}^3He(g_i)$ ones

Jump slides

EW Baryogenesis: Standard Model

Conservation of the EM current under weak $(L - R)$ interactions:

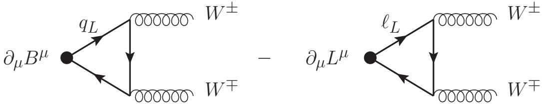


$$\propto N_c \cdot (Q_u + Q_d) + (0 - 1) = 1 - 1 = 0$$

$\hookrightarrow \Delta(Q_B + Q_L) = 0$ (charge conservation!)

EW Baryogenesis: Standard Model

Conservation of the Baryon−Lepton current under $(L-R)$ interactions:



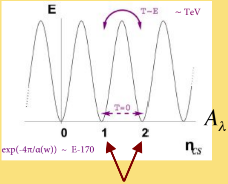
$\propto N_c \cdot 1/3 - 1 = 1 - 1 = 0$

$\hookrightarrow \Delta(B-L) = 0$ but $\Delta(B+L) \neq 0$!

Sakharov criteria

1. B violation ✓
   ($\Delta(B{+}L) \neq 0$ sphaleron transitions)
2. C & CP violation *x*
   (CKM determinant)
3. Nonequilibrium dynamics *x*
   (only fast cross over for $\mu_{chem} = 0$)

Anomalous Processes



Different vacua: $\Delta(B{+}L) = \Delta N_{CS}$

Sphaleron Transitions

Naive Quark Model results for a nucleon with N_c quarks

A proton (neutron) with isospin $I = \frac{1}{2}$ and spin $J = \frac{1}{2}$ contains $\frac{N_c+1}{2}$ quarks of u (d) flavor and $\frac{N_c-1}{2}$ quarks of d (u) flavor.

Because of spin-flavor *symmetry* the total spin $\vec{J}_u$ ($\vec{J}_d$) of all u (d) quarks satisfies $J_u = \frac{N_c+1}{4}$ ($J_d = \frac{N_c-1}{4}$) s.t. $J_z = \pm(J_u - J_d) = \pm\frac{1}{2}$ and

$$\langle n|\vec{J}_d|n\rangle \equiv \langle p|\vec{J}_u|p\rangle \equiv \lambda_u^p\langle p|\vec{J}|p\rangle = \frac{N_c+5}{6}\langle p|\vec{J}|p\rangle \xrightarrow{N_c=3} \frac{4}{3}\langle p|\vec{J}|p\rangle$$

$$\langle n|\vec{J}_u|n\rangle \equiv \langle p|\vec{J}_d|p\rangle \equiv \lambda_d^p\langle p|\vec{J}|p\rangle = -\frac{N_c-1}{6}\langle p|\vec{J}|p\rangle \xrightarrow{N_c=3} -\frac{1}{3}\langle p|\vec{J}|p\rangle$$

$$\hookrightarrow \frac{\mu_n}{\mu_p} = \frac{\left[\frac{2e}{3}\lambda_u^n - \frac{e}{3}\lambda_d^n\right]}{\left[\frac{2e}{3}\lambda_u^p - \frac{e}{3}\lambda_d^p\right]} = \frac{\left[\frac{2e}{3}\frac{-1}{3} - \frac{e}{3}\frac{4}{3}\right]}{\left[\frac{2e}{3}\frac{4}{3} - \frac{e}{3}\frac{-1}{3}\right]} = -\frac{2}{3}\ (!) \quad \left(-\frac{(N_c+1)^2-4}{(N_c+1)^2+2} \text{ in general}\right),$$

$$g_A^p = \lambda_u^p - \lambda_d^p = \frac{4}{3} - \frac{-1}{3} = \lambda_u^n - \lambda_d^n = g_A^n = \frac{5}{3} \quad \left(\frac{N_c+2}{3} \text{ in general}\right),$$

$$d_p = \lambda_u^p d_u + \lambda_d^p d_d = \frac{4}{3}d_u - \frac{1}{3}d_d \quad \text{such that } \boxed{d_p - d_n = \frac{N_c+2}{3}(d_u - d_d)}$$

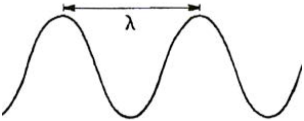
$$d_n = \lambda_u^n d_u + \lambda_d^n d_d = -\frac{1}{3}d_u + \frac{4}{3}d_d \quad \text{and only } \boxed{d_p + d_n = d_u + d_d}.$$

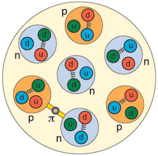
◂ back

What are Effective Field Theories (EFT)?

- Different areas in physics describe phenomena at very disparate scales (of length, time, energy, mass)
- Very intuitive idea: scales much smaller / much bigger than the ones of interest shouldn't matter much
  - *e.g.* masses in particle physics: $m_e \approx 0.511\,\text{MeV} \ldots m_t \sim 180\,\text{GeV}$ range nearly six orders of magnitude (even without neutrinos)
  - still hydrogen atom spectrum can be calculated very precisely without knowing m_t at all

$\hookrightarrow$ Separation of scales: $1/k = \lambda \gg R_{\text{substructure}}$





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Effective Field Theory: Weinberg's conjecture

Quantum Field Theory has no content besides
unitarity, analyticity, cluster decomposition and symmetries

Weinberg 1979

To calculated the S-matrix for any theory below some scale, simply use the most general effective Lagrangian consistent with these principles in terms of the appropriate asymptotic states
(*i.e.* the general S-matrix can be obtained by perturbation theory using some effective lagrangian from the free theory — Witten (2001))

Power-law expand the amplitudes in *energy(momentum) / scale.*

- Physics at specific energy scale described by active d.o.f.s
- Unresolved substructure incorporated via low-energy const(s)
- Systematic approach $\rightsquigarrow$ estimate of uncertainty possible

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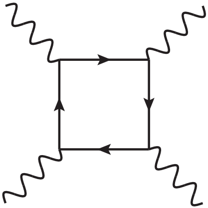
EFT example: light-by-light scattering

Euler, Heisenberg, Kockel (1935/6)



- only one scale: m_e
- consider energies $\omega \ll m_e$
- $\mathcal{L}_{QED}[\underbrace{\psi, \bar{\psi}}_{\text{matter}}, \underbrace{A_\mu}_{\text{light}}] \to \mathcal{L}_{\text{eff}}[A_\mu]$
- invariants: $F_{\mu\nu}F^{\mu\nu} \propto \vec{E}^2 - \vec{B}^2$ & $F_{\mu\nu}\tilde{F}^{\mu\nu} \propto \vec{E}\cdot\vec{B}$

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}\left(\vec{E}^2 - \vec{B}^2\right) + \frac{e^4}{16\pi^2 m_e^4}\left[a\left(\vec{E}^2 - \vec{B}^2\right)^2 + b\left(\vec{E}\cdot\vec{B}\right)^2\right] + \ldots$$

- calculation form the underlying theory, QED, yields $7a = b = 14/45$
- energy power law expansion: $(\omega/m_e)^{2n}$
- $\mathcal{L}_{\text{eff}}$ more efficient than full *QED* for calculating cross sections etc.

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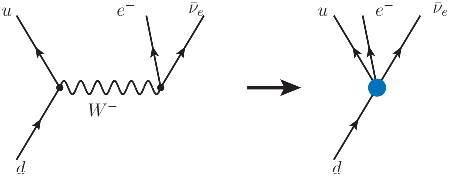
EFT example: weak interactions for $E \ll M_W$

Weak decays:

- mediated by the $W^{\pm}$ boson, $M_W \approx 80\,\text{GeV}$
- energy release in neutron decay: $\approx 1\,\text{MeV}$
- energy release in kaon decays: $\approx$ few $100\,\text{MeV}$



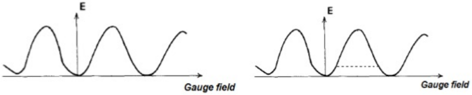
$$\frac{e^2}{8\sin\theta_W} \times \frac{1}{M_W^2 - q^2} \xrightarrow{q^2 \ll M_W^2} \underbrace{\frac{e^2}{8M_W^2\sin\theta_w}}_{G_F/\sqrt{2}}\underbrace{\left(1 + \frac{q^2}{M_W^2} + \ldots\right)}_{+\ \mathcal{O}(q^2/M_W^2)}$$

$\hookrightarrow$ Fermi's current-current interaction

back

θ vacua in strong interaction physics

The topologically non-trivial vacuum structure of QCD



induces winding number n and strong gauge transformation (instanton)

$$\Omega_1 : |n\rangle \to |n+1\rangle$$

Naive vacuum therefore *unstable* (and violates *cluster decomposition*).

Thus true vacuum must be a superposition of the various $|n\rangle$ vacua
$\rightsquigarrow$ Theta vacuum:

$$|vac\rangle_\theta = \sum_{n=-\infty}^{+\infty} e^{in\theta}|n\rangle \qquad \text{with} \quad \Omega_1 : |vac\rangle_\theta \to e^{-i\theta}|vac\rangle_\theta \quad \text{(only phase shift !)}$$

Note

$$_{\theta'}\langle vac|e^{-iHt}|vac\rangle_\theta = \delta_{\theta-\theta'} \times {}_\theta\langle vac|e^{-iHt}|vac\rangle_\theta$$

such that θ **unique** parameter of strong interaction physics which can be incorporated into the effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L} - \frac{\theta}{16\pi^2 g^2} \text{Tr}\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right)$$

back

θ term

$$\mathcal{L}_{QCD} = \mathcal{L}_{QCD}^{\mathrm{CP}} - \theta \frac{g_s^2}{32\pi^2} \tilde{G}^a_{\mu\nu} G^{a,\mu\nu} = \mathcal{L}_{QCD}^{\mathrm{CP}} - \theta \frac{g_s^2}{32\pi^2} \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\alpha\beta}$$

- Under $U_A(1)$ rotation of the quark fields $q_f \to \mathrm{e}^{-\mathrm{i}\alpha\gamma_5/2} q_f \approx (1 - \mathrm{i}\frac{1}{2}\alpha\gamma_5) q_f$:

$$\mathcal{L}_{QCD} \quad \to \quad \mathcal{L}_{QCD}^{\mathrm{CP}} + \alpha \sum_f m_f \bar{q} i\gamma_5 q - (\theta - N_f\alpha) \frac{g_s^2}{32\pi^2} \tilde{G}^a_{\mu\nu} G^{a,\mu\nu}$$

$\hookrightarrow \mathcal{L}_{SM}^{\mathrm{str}\,\not{\mathrm{CP}}} = \mathcal{L}_{SM}^{\mathrm{CP}} + \bar{\theta} m^* \sum_f \bar{q}_f i\gamma_5 q_f$ with $\bar{\theta} = \theta + \arg\det\mathcal{M}$ and $m^* = \frac{m_u m_d}{m_u + m_d}$

back

Strong CP problem: Peccei-Quinn symmetry and axions

R. Peccei & H. Quinn (1977)

Consider adding a new field a (the axion field) to the QCD action

$$\mathcal{L}_{\rm axion} = \bar\psi(\mathcal{M}e^{-ia/f_a})\psi + \tfrac{1}{2}\partial_\mu a\,\partial^\mu a$$

- The axion arises as Goldstone boson of the new broken U(1) symmetry of the quark sector and the Higgs sector.
- Perform further axial U(1) transformation on quark fields to eliminate the $G\tilde{G}$ term entirely (or to to make mass term real again)

  $\hookrightarrow$ new phase of quark mass term: $e^{i(\theta+\arg\det\mathcal{M}-a/f_a)}$

  $\hookrightarrow$ or instead $G\tilde{G}$ term becomes: $(-\theta - \arg\det\mathcal{M} + a/f_a)\,\frac{g_s^2}{16\pi^2}\,\mathrm{tr}\, G\tilde{G}$
- Make the trivial U(1) shift $a \to a + (\theta + \arg\det\mathcal{M}) \times f_a$. The kinetic term is invariant under this shift (axion massless to LO)
- At higher order, the axion acquires its mass as

  $$m_a \approx 0.5\, m_\pi f_\pi / f_a \quad \text{with} \quad f_a \gg \langle H\rangle = (\sqrt{2}G_F)^{-1/2} = 247\,\mathrm{GeV}$$
- New Problem: find a (light) axion !

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Axions and EDMs: generic effective Lagrangian of the axion

Kiwoon Choi (Daejeon, Korea), Bethe-Lectures, Bonn, March 2015

$$\mathcal{L}_{\rm eff}(a) = \underbrace{\mathcal{L}_0}_{\text{indep. of } a} + \underbrace{\tfrac{1}{2}(\partial_\mu a)^2 + \frac{\partial_\mu a}{f_a}\tilde{J}^\mu(\bar{\psi}...\psi,\phi)}_{\text{PQ-invariant}} + \underbrace{\frac{a}{f_a}\frac{N}{32\pi^2}G\tilde{G}}_{\text{expl. PQ-breaking by QCD anomaly}}$$

$$+ \underbrace{\Delta\mathcal{L}_{UV}\left(= -\epsilon m_{\rm UV}^4 \cos(a/f_a + \delta_{\rm UV})\right)}_{a \text{ coupling from expl. PQ breaking at UV scale}}$$

$\bar{\theta} = \langle a\rangle/f_a$ is calculable in terms of the $\not{CP}$ angles (in presence of a!):

- $\delta_{\rm KM}$ = Kobayashi-Maskawa phase in the PQ-invariant SM
- $\delta_{\rm BSM}$ = $\not{CP}$ phase in PQ-invariant BSM at the scale $m_{\rm BSM}$
- $\delta_{\rm UV}$ = $\not{CP}$ phase in explicit PQ-breaking sector at $m_{\rm UV} \sim M_{\rm Planck}$

$$V_{\rm QCD} \sim f_\pi^2 m_\pi^2 \cos(a/f_a) \quad \text{(expl. PQ-breaking by low-energy QCD)}$$

$$V_{\rm KM} \sim f_\pi^2 m_\pi^2 \times \overbrace{G_F^2 f_\pi^4}^{10^{-14}} \times \overbrace{10^{-5}\sin\delta_{\rm KM}}^{\text{Jarlskog inv.}} \times \sin(a/f_a)$$

$$V_{\rm BSM} \sim f_\pi^2 m_\pi^2 \times \underbrace{\left(10^{-2} - 10^{-3}\right)}_{\text{loop suppression}} \times \frac{f_\pi^2}{m_{\rm BSM}^2} \sin\delta_{\rm BSM} \times \sin(a/f_a)$$

$$V_{\rm UV} \sim \epsilon m_{\rm UV}^4 \sin\delta_{\rm UV} \sin(a/f_a)$$

$\bar{\theta} = \langle a \rangle / f_a$ and contributions to the nucleon EDM

$$\bar{\theta} \;\sim\; 10^{-19}\sin\delta_{\rm KM} + \overbrace{\left(10^{-10} - 10^{-11}\right)}^{(10^{-2}\text{–}10^{-3})\times f_\pi^2/\text{TeV}^2} \times \left(\frac{\text{TeV}}{m_{\rm BSM}}\right)^2 \sin\delta_{\rm BSM}$$
$$+\; \epsilon\,\frac{m_{\rm UV}^4}{f_\pi^2 m_\pi^2}\,\sin\delta_{\rm UV} \quad \left(\text{with } \epsilon < 10^{-10}\, f_\pi^2 m_\pi^2/m_{\rm UV}^4 \sim 10^{-88} \text{ for } m_{\rm UV}\sim M_{\rm Pl}\right)$$

$\hookrightarrow$ Regardless of the existence of BSM physics near the TeV scale, $\bar{\theta} = \langle a \rangle / f_a$ can have *any value* below the present bound $\sim 10^{-10}$.

$$d_N \;\sim\; \frac{e}{m_N}\left[\frac{m^*}{m_N}\bar{\theta} + G_F^2 f_\pi^4 \times 10^{-5}\sin\delta_{\rm KM} + \left(10^{-2} - 10^{-3}\right)\times\frac{f_\pi^2}{m_{\rm BSM}^2}\sin\delta_{\rm BSM} + \left(10^{-2} - 10^{-3}\right)\times\frac{f_\pi^2}{m_{\rm UV}^2}\sin\delta_{\rm UV}\right]$$

$$\sim\; \frac{e}{m_N}\left[\overbrace{\frac{m^*}{m_N}}^{\sim 10^{-2}} \times \overbrace{\bar{\theta}_{\rm UV}}^{\frac{\epsilon m_{\rm UV}^4 \sin\delta_{\rm UV}}{f_\pi^2 m_\pi^2}} + \left(10^{-2} - 10^{-3}\right)\times\frac{f_\pi^2}{m_{\rm BSM}^2}\sin\delta_{\rm BSM}\right]$$

likely dominated by $\bar{\theta}_{\rm UV}$ induced by $\not{CP}$ in the $\not{PQ}$ sector @ $m_{\rm UV}(\sim M_{\rm Pl})$, and/or by the BSM contribution near the TeV scale.

kHz to MHz Dark Matter Axions or Axion-Like Particles

P.W. Graham & S. Rajendran, PRD 84 (2011) & 88 (2013)

Apply

$$\mathcal{L}_{axion} = \frac{a}{f_a}\frac{g_s^2}{16\pi^2}\mathrm{tr}\, G\tilde{G} + \tfrac{1}{2}\partial_\mu a\,\partial^\mu a - \tfrac{1}{2}m_a^2 a^2 \quad \text{with} \quad m_a \approx 0.5\, m_\pi f_\pi / f_a$$

and let the axion decay constant f_a be in the window

$$10^{16}\,\mathrm{GeV} \sim M_{\mathrm{GUT}} \lesssim f_a \lesssim M_{\mathrm{Planck}} \sim 10^{19}\,\mathrm{GeV}\,.$$

- Axions in our galaxy *spatially* constant over a scale of $\lesssim 500\,\mathrm{km} \times (f_a/M_{\mathrm{GUT}})$:
  ↪ Ansatz: $a(t,\vec{x}) \approx a(t) = a_0 \cos(m_a t)$ in the lab.
- Equating $\frac{1}{2}m_a^2 a_0^2 \sim \rho_{\mathrm{local\,DM}} \approx (0.3\pm0.1)\,\mathrm{GeV/cm}^3$ gives as axion amplitude

$$\theta_a \equiv \frac{a_0}{f_a} \sim \frac{\sqrt{\rho_{\mathrm{local\,DM}}}}{0.5\, m_\pi f_\pi} \sim 3\times10^{-19} \xrightarrow[\text{independently of } f_a]{d_n \approx 10^{-16}\theta_a e\,\mathrm{cm}} d_n \approx 4\times10^{-35}\cos(m_a t)\, e\,\mathrm{cm}$$

with $m_a \approx$ 1 kHz $[M_{\mathrm{Planck}}/f_a]$ to 1 MHz $[M_{\mathrm{GUT}}/f_a]$ oscillations.

- Bounds on oscillating Axions or ALPs from storage ring EDM searches ?

JÜLICH FORSCHUNGSZENTRUM

Non-relativistic reduction of

$$\mathcal{H}_{\rm eff} = -\frac{a_f}{2}\bar f \sigma^{\mu\nu} f\, F_{\mu\nu}, \quad a_f = \frac{F_2(0)}{2m_f}$$

$$-\int d^3x\, \frac{a_f}{2}\, \bar\psi_f\, \sigma^{ij}\psi_f\, F_{ij} + \ldots$$

$$\to \quad -\frac{a_f}{2}\int d^3x\, \bar\psi_f\, \epsilon^{ijk}\begin{pmatrix}\sigma^k & 0\\ 0 & \sigma^k\end{pmatrix}\psi_f\, F_{ij}$$

$$= \quad -\frac{a_f}{2}\int d^3x\, \bar\psi_f \begin{pmatrix}\sigma^k & 0\\ 0 & \sigma^k\end{pmatrix}\psi_f\, \underbrace{\epsilon^{ijk} F_{ij}}_{-2B^k}$$

$$\to \quad a_f \int d^3x\, \bar\psi_f\, \vec\sigma\, \psi_f \cdot \vec B$$

$$= \quad a_f \langle\vec\sigma\rangle \cdot \vec B$$

$$= \quad a_f\, g\, \langle\vec S\rangle\cdot\vec B, \qquad g = 2$$

$$\mathcal{H}_{\rm eff} = \mathrm{i}\,\frac{d_f}{2}\bar f \sigma^{\mu\nu}\gamma_5 f\, F_{\mu\nu}, \quad d_f \equiv \frac{F_3(0)}{2m_f}$$

$$\mathrm{i}\int d^3x\, \frac{d_f}{2}\, \bar\psi_f\, \sigma^{0i}\gamma_5\, \psi_f\, F_{0i} \times 2 + \ldots$$

$$\to \quad \mathrm{i} d_f \int d^3x\, \bar\psi_f\, \mathrm{i}\begin{pmatrix}0 & \sigma_i\\ \sigma^i & 0\end{pmatrix}\gamma_5\, \psi_f\, F^{i0}$$

$$= \quad \mathrm{i} d_f \int d^3x\, \bar\psi_f\, \mathrm{i}\begin{pmatrix}\sigma^i & 0\\ 0 & \sigma^i\end{pmatrix}\psi_f\, \underbrace{F^{i0}}_{E^i}$$

$$\to \quad \mathrm{i}^2 d_f \int d^3x\, \bar\psi_f\, \vec\sigma\, \psi_f \cdot \vec E$$

$$= \quad -d_f \langle\vec\sigma\rangle\cdot\vec E$$

$$= \quad -d_f \langle\vec S/S\rangle\cdot\vec E \quad \text{(linear Stark term)}$$

$$\mathcal{H}_{\rm eff} = \mathrm{i}\,\frac{d_f}{2}\bar f\sigma^{\mu\nu}\gamma_5 f\, F_{\mu\nu} = \mathrm{i}\,\frac{d_f}{2}\bar f_L \sigma^{\mu\nu} f_R\, F_{\mu\nu} - \mathrm{i}\,\frac{d_f}{2}\bar f_R\sigma^{\mu\nu} f_L\, F_{\mu\nu} \rightsquigarrow \text{fermion mass insertion}$$

back1 back2

Transformation Properties of the Form Factor Γ^μ

$A_\mu \langle f(p')|J^\mu_{\rm em}|f(p)\rangle = A_\mu\, \bar{u}_f(p')\,\Gamma^\mu(q^2)\,u_f(p)$ with

$$\Gamma^\mu(q^2) = \gamma^\mu F_1(q^2) + i\sigma^{\mu\nu}q_\nu \frac{F_2(q^2)}{2m_f} + \sigma^{\mu\nu}q_\nu\gamma_5 \frac{F_3(q^2)}{2m_f} + (\not{q}\, q^\mu - q^2\gamma^\mu)\gamma_5 F_a(q^2)/m_f^2$$

$\bar{q}$ Op.q	P	C	CP	T	CPT
A_μ	A^μ	$-A_\mu$	$-A^\mu$	A^μ	$-A_\mu$
γ^μ	γ_μ	$-\gamma^\mu$	$-\gamma_\mu$	γ_μ	$-\gamma^\mu$
$\gamma^\mu\gamma_5$	$-\gamma_\mu\gamma_5$	$\gamma^\mu\gamma_5$	$-\gamma_\mu\gamma_5$	$\gamma_\mu\gamma_5$	$-\gamma^\mu\gamma_5$
$\sigma^{\mu\nu}$	$\sigma_{\mu\nu}$	$-\sigma^{\mu\nu}$	$-\sigma_{\mu\nu}$	$-\sigma_{\mu\nu}$	$\sigma^{\mu\nu}$
$\sigma^{\mu\nu}q_\nu$	$\sigma_{\mu\nu}q^\nu$	$-\sigma^{\mu\nu}q_\nu$	$-\sigma_{\mu\nu}q^\nu$	$-\sigma_{\mu\nu}q^\nu$	$\sigma^{\mu\nu}q_\nu$
$i\sigma^{\mu\nu}q_\nu$	$i\sigma_{\mu\nu}q^\nu$	$-i\sigma^{\mu\nu}q_\nu$	$-i\sigma_{\mu\nu}q^\nu$	$i\sigma_{\mu\nu}q^\nu$	$-i\sigma^{\mu\nu}q_\nu$
$\sigma^{\mu\nu}q_\nu\gamma_5$	$-\sigma_{\mu\nu}q^\nu\gamma_5$	$-\sigma^{\mu\nu}q_\nu\gamma_5$	$\sigma_{\mu\nu}q^\nu\gamma_5$	$-\sigma_{\mu\nu}q^\nu\gamma_5$	$-\sigma^{\mu\nu}q_\nu\gamma_5$

For EDMs of charged particles both $F_1(q^2)$ and $F_3(q^2)$ are present at the same time $\rightsquigarrow$ mixing

back

Construction of the CKM matrix

Since weak interactions do not respect the global flavor symmetry, there is mixing within the groups of quarks with the same charge:

$$U \equiv \begin{pmatrix} u \\ c \\ t \end{pmatrix} \to \tilde{U} = M_U U\,, \qquad D \equiv \begin{pmatrix} d \\ s \\ b \end{pmatrix} \to \tilde{D} = M_D D\,,$$

where M_U & M_D are 3×3 unitary matrices

$\hookrightarrow$ charged weak current: $J_\mu = \bar{\tilde{U}}^\mu \gamma_\mu (1-\gamma_5) \tilde{D}^\mu = \bar{U} \gamma_\mu (1-\gamma_5) \underbrace{M_U^\dagger M_D}_{\text{CKM matrix } M} D\,.$

- M unitary $n_G \times n_G$ matrix for n_G quark generations $\rightsquigarrow$ n_G^2 real parameters.
- $2n_G - 1$ of these can be absorbed by the relative phases of the quark wave functions $\rightsquigarrow$ $(n_G-1)^2$ remaining parameters:

  $n_G = 2$: one remaining real parameter: *Cabibbo angle*
  $n_G = 3$: $O(3)$ matrix with $\frac{1}{2} 3 \cdot (3-1) =$ 3 angles *plus* 1 ~~CP~~ phase
- Lepton case: neutrinos may be Majoranas: $\rightsquigarrow$ 3 angles plus 3 ~~CP~~ phases
- If phase(s) present, M complex matrix, whereas CP invariance $\rightsquigarrow$ $M^* = M$!

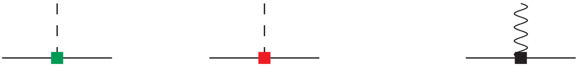
Hierachy among the sources at the hadronic EFT level

Each source transforms differently under chiral and isospin symmetry

$\not{CP}$, I | $\not{CP}$, $\not{I}$ | $\not{CP}$, I + $\not{I}$

$$\mathcal{L}_{EFT}^{\not{CP}} = g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N + g_1 N^\dagger \pi_3 N + N^\dagger(d_0 + d_1\tau_3) S^\mu v^\nu F_{\mu\nu} N + \cdots$$

$\Downarrow$ $\Downarrow$ $\Downarrow$



...

dominant for $\bar\theta$ term | suppressed for $\bar\theta$ term | suppressed by $\mathcal{O}(M_\pi^2)$

- $\mathcal{L}_{QCD}^{\theta} = \bar\theta m_q^* \sum_f \bar q_f i\gamma_5 q_f$: $\not{CP}$, I $\quad m_q^* = \frac{m_u m_d}{m_u+m_d}$

  $\hookrightarrow$ $\bar\theta$ source breaks chiral symmetry ($\propto m_q^*$) but conserves the isospin one:

  $\hookrightarrow$ $|g_0^\theta| \gg |g_1^\theta|$: NDA estimate: $g_1^\theta/g_0^\theta \sim \mathcal{O}(M_\pi^2/m_n^2)$ de Vries et al. *PRC* '11

  ChPT LECs predict: $g_1^\theta/g_0^\theta \sim \mathcal{O}(M_\pi/m_n)$! Bsaisou et al. *EPJA* '13

Hierachy among the sources at the hadronic EFT level

Each source transforms differently under chiral and isospin symmetry

$\not{CP}$, I — $\not{CP}$, $\not{I}$ — $\not{CP}$, I + $\not{I}$

$$\mathcal{L}_{\rm EFT}^{\not{CP}} = g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N \;+\; g_1 N^\dagger \pi_3 N \;+\; N^\dagger (d_0 + d_1 \tau_3) S^\mu v^\nu F_{\mu\nu} N \;+ \cdots$$

dominant for chromo qEDM source	dominant for chromo qEDM source	$\mathcal{O}(m_\pi^2)$ suppressed for chromo qEDM source

- chromo quark EDM: chiral symmetries are (& isospin ones may be) broken because of quark masses $\rightsquigarrow$ Goldstone theorem respected
- 4quark Left-Right EDM: **explicit** breaking of **chiral & isospin** symmetries because of underlying W boson exchange $\rightsquigarrow$ Goldstone th. doesn't apply

◂ back

Hierachy among the sources at the hadronic EFT level

Each source transforms differently under chiral and isospin symmetry

	$\not{CP}$, I		$\not{CP}$, $\not{I}$		$\not{CP}$, I + $\not{I}$	
$\mathcal{L}_{\text{EFT}}^{\not{CP}} =$	$g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N$	$+$	$g_1 N^\dagger \pi_3 N$	$+$	$N^\dagger (d_0 + d_1 \tau_3) S^\mu v^\nu F_{\mu\nu} N$	$+\cdots$
	$\Downarrow$		$\Downarrow$		$\Downarrow$	

suppressed for quark EDM source	suppressed for quark EDM source	dominating for quark EDM source

- quark EDM: $N\pi$ (and NN) interactions are **suppressed** by $\alpha_{\text{em}}/(4\pi)$
- gluon color EDM (and chiral-4quark EDM): **relative** $\mathcal{O}(M_\pi^2)$ **suppression** of $N\pi$ interactions because of Goldstone theorem

◂ back

θ-term: $\not{CP}$ πNN vertices determined from LECs

Leading g_0^θ coupling (from c_5)

Crewther et al. (1979); Ottnad et al. (2010); Mereghetti et al. (2011); de Vries et al. (2011); Bsaisou et al. (2013)

g_0^θ: $N^\dagger \vec{\pi}\cdot\vec{\tau} N$-vertex

$$\mathcal{L}_{\pi N} = \ \ldots + \ c_5 2B\, N^\dagger \left((m_u - m_d)\,\tau_3 + \frac{2m^*\bar{\theta}}{F_\pi}\vec{\pi}\cdot\vec{\tau} \right) N \ + \ldots$$

$$\delta M_{np}^{str} = 4B(m_u - m_d)c_5 \quad \rightarrow \quad g_0^\theta = \bar{\theta}\,\delta M_{np}^{str}\,(1-\epsilon^2)\frac{1}{4F_\pi \epsilon}$$

$$\delta M_{np}^{em} \ \rightarrow \ \delta M_{np}^{str} = (2.44 \pm 0.18)\mathrm{MeV}$$ Walker-Loud ('13); Borsányi et al.('14)

$$\& \quad m_u/m_d = 0.46 \pm 0.03$$ Flag Working Group ('14)

$$\longrightarrow \boxed{g_0^\theta = (15.5 \pm 1.9)\cdot 10^{-3} \cdot \bar{\theta}}$$ Bsaisou et al. ('15)

$$\epsilon = (m_u - m_d)/(m_u + m_d)\,, \quad 4Bm^* = M_\pi^2(1-\epsilon^2), \quad m^* = \frac{m_u m_d}{m_u + m_d}$$

θ-term: subleading g_1^θ coupling (from c_1 LEC)

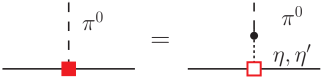
g_1^θ: $\pi_3 NN$-vertex

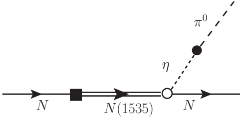
$\epsilon := (m_u - m_d)/(m_u + m_d)$

$$\mathcal{L}_{\pi N} = \quad \ldots + \quad c_1 4B\, N^\dagger \left((m_u + m_d) + \frac{(\delta M_\pi^2)_{QCD}(1-\epsilon^2)\,\bar\theta}{2BF_\pi \epsilon} \pi_3 \right) N \quad + \ldots$$

1 $c_1 \longleftrightarrow \sigma_{\pi N}$: $c_1 = (-1.0 \pm 0.3)\ \mathrm{GeV}^{-1}$ — Compilation: Baru et al. (2011)

2 $(\delta M_\pi^2)_{QCD} \approx \dfrac{\epsilon^2}{4} \dfrac{M_\pi^4}{M_K^2 - M_\pi^2}$





$g_1^\theta(c_1) = (2.8 \pm 1.1) 10^{-3} \bar\theta$ & $\bar g_1^\theta = (0.6 \pm 1.1) 10^{-3} \bar\theta$

$\rightsquigarrow$ $g_1^\theta = (3.5 \pm 1.5) \cdot 10^{-3} \bar\theta$ — Bsaisou et al. '13, '15

$$\frac{g_1^\theta}{g_0^\theta} = -0.22 \pm 0.10 \sim \frac{M_\pi}{m_N} \gg \epsilon \frac{M_\pi^2}{m_N^2} \sim -0.01 \quad \text{(NDA)}$$

Bsaisou et al. '13, '15 — de Vries et al. (2011)

$g_0^\theta(\delta M_{np}^{str})$ is unnaturally small !

back BACK back loop

Deuteron Quantities in ChPT from NLO to N4LO

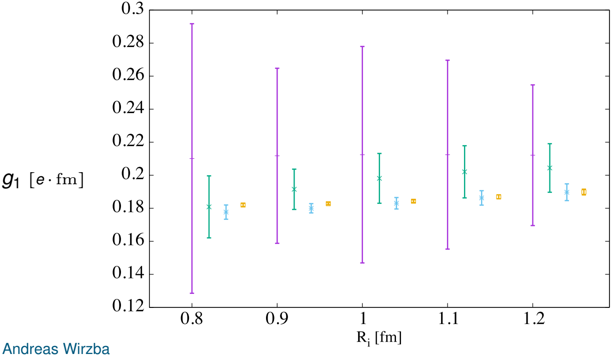
Epelbaum, Krebs, Meißner, *EPJA* **51** & *PRL* **115** (2015); Binder et al., *PRC* **93** (2016); *and* A. Nogga, *priv. comm.*

$$\Delta X^{\mathrm{N}n\mathrm{LO}}(p) = Q^{n+2}\cdot\max\Bigg[\left|X^{\mathrm{LO}}(p)\right|, \frac{\left|X^{\mathrm{NLO}}(p)-X^{\mathrm{LO}}(p)\right|}{Q^2}, \frac{\left|X^{\mathrm{N2LO}}(p)-X^{\mathrm{NLO}}(p)\right|}{Q^3}, \frac{\left|X^{\mathrm{N3LO}}(p)-X^{\mathrm{N2LO}}(p)\right|}{Q^4}, \frac{\left|X^{\mathrm{N4LO}}(p)-X^{\mathrm{N3LO}}(p)\right|}{Q^5}\Bigg]$$

with $Q=\max\left(\frac{|p|}{\Lambda_b^i},\frac{M_\pi}{\Lambda_b^i}\right)$

and $f(\frac{r}{R_i}) = \left[1-\exp\left(-\frac{r^2}{R_i^2}\right)\right]^6$ with

R_i	0.8 fm	0.9 fm	1.0 fm	1.1 fm	1.2 fm
Λ_b^i	0.6GeV	0.6GeV	0.6GeV	0.5GeV	0.4GeV



NLO, N2LO, N3LO, N4LO

$(0.183 \pm 0.017)g_1\,e\mathrm{fm}$

$\hookrightarrow (0.1815 \pm 0.0025)g_1\,e\mathrm{fm}$

back

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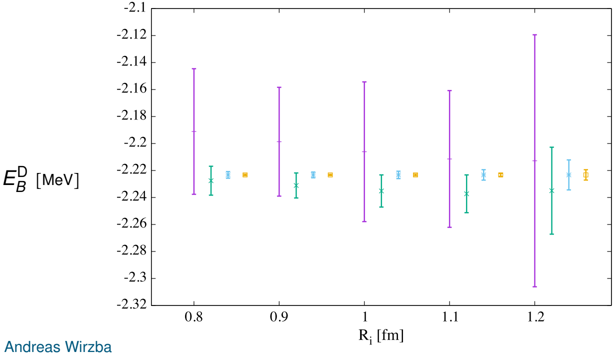

NLO, N2LO, N3LO, N4LO

(-2.2233 ± 0.0004) MeV

back

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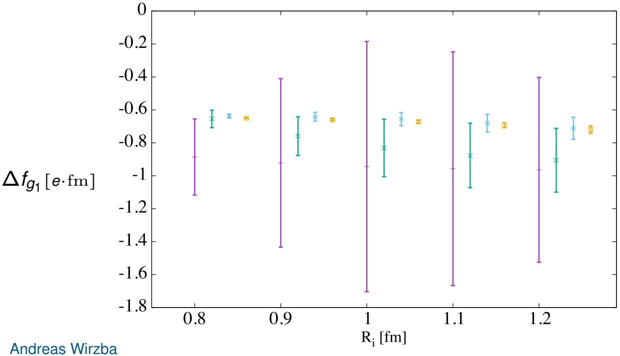

NLO, N2LO, N3LO, N4LO

$(-0.748 \pm 0.138)\Delta e\mathrm{fm}$

$\hookrightarrow (-0.646 \pm 0.023)\Delta e\mathrm{fm}$

back

Deuteron Quantities in ChPT from NLO to N4LO

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R_i	0.8 fm	0.9 fm	1.0 fm	1.1 fm	1.2 fm
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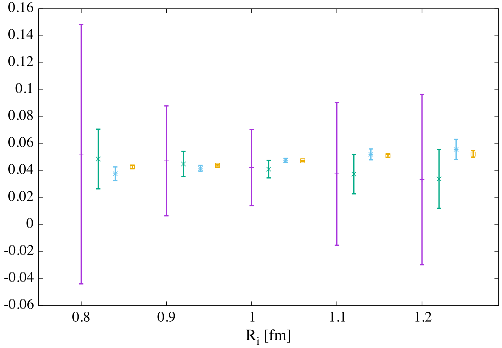
$P_{^3D_1}$



NLO, N2LO, N3LO, N4LO

$d^D_{n,p} = (0.939 \pm 0.009)\, d_n$

$\hookrightarrow d^D_{n,p} = (0.936 \pm 0.008)\, d_n$

back

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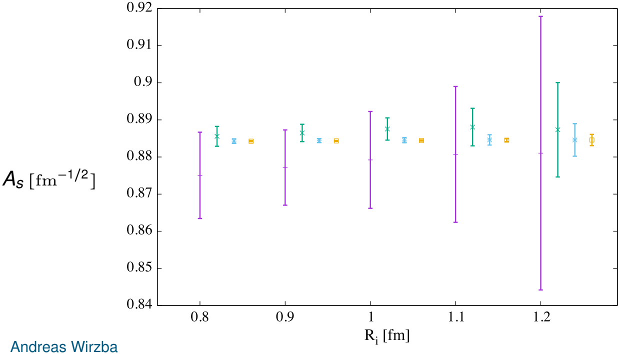

NLO, N2LO, N3LO, N4LO

(0.8844 ± 0.0001) fm$^{-1/2}$

back

Deuteron Quantities in ChPT from NLO to N4LO

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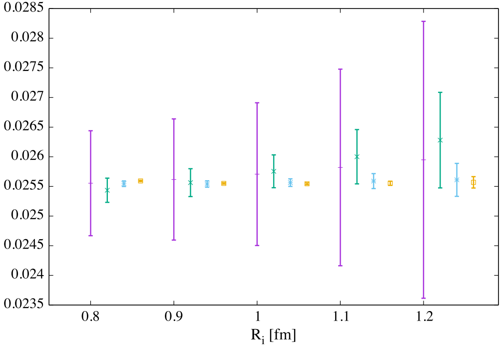
$\eta = D/S$



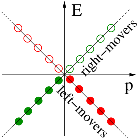
NLO, N2LO, N3LO, N4LO

(0.02555 ± 0.00001)

back

$U_A(1)$ anomaly in 1+1 D

1. Dispersion for massless fermions in 1+1 D:



$U_A(1)$ anomaly in 1+1 D

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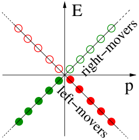

2. Add electric field
   to a single right/left-movers:

$U_A(1)$ anomaly in 1+1 D

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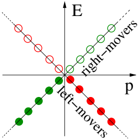

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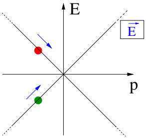

Nothing happens to single states, except energy change.

$U_A(1)$ anomaly in 1+1 D

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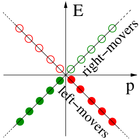

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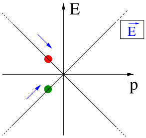

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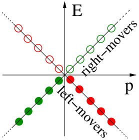

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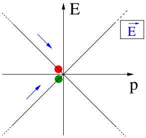

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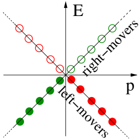

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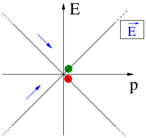

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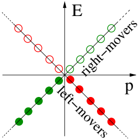

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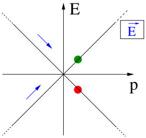

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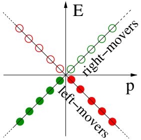

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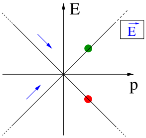

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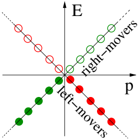

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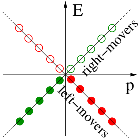

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3. However, for *infinite mode sums* the level shifts induce a surplace of right-movers:

$U_A(1)$ anomaly in 1+1 D

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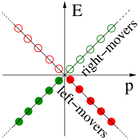

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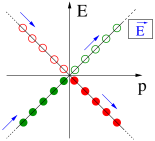

$$\dot{Q}_V = \dot{Q}_R + \dot{Q}_L = 0$$

(vector charge still conserved)

$$\dot{Q}_A = \dot{Q}_R - \dot{Q}_L \neq 0$$

(axial charge not conserved)

$U_A(1)$ anomaly in 1+1 D

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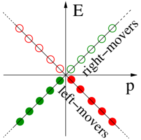

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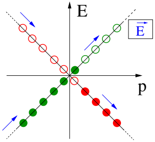

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$U_A(1)$ anomaly in 1+1 D

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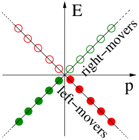

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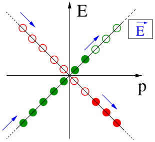

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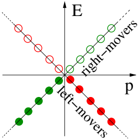

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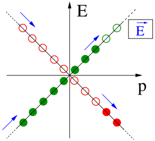

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The symmetries of QCD

$$\mathcal{L}_{\rm QCD} = -\tfrac{1}{2}\mathrm{Tr}\,(G_{\mu\nu}G^{\mu\nu}) + \sum_f \bar{q}_f(\mathrm{i}\not{D} - m_f)q_f + \ldots$$

$$D_\mu = \partial_\mu - igA_\mu \equiv \partial_\mu - igA_\mu^a\frac{\lambda^a}{2}\,, \qquad G_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - ig[A_\mu, A_\nu]$$

- Lorentz-invariance, P, C, T invariance, $\mathrm{SU}(3)_c$ gauge invariance
- The masses of the u, d, s quarks are small: $m_{u,d,s} \ll 1\,\mathrm{GeV} \approx \Lambda_{\rm hadron}$.
- Chiral decomposition of quark fields:

$$q = \tfrac{1}{2}(1-\gamma_5)q + \tfrac{1}{2}(1+\gamma_5)q = q_L + q_R\,.$$

- For massless fermions: left-/right-handed fields do not interact

$$\mathcal{L}[q_L, q_R] = i\bar{q}_L\not{D}q_L + i\bar{q}_R\not{D}q_R - m\,(\bar{q}_Lq_R + \bar{q}_Rq_L)$$

and $\mathcal{L}^0_{QCD}$ invariant under (global) chiral $\mathrm{U}(3)_L\times\mathrm{U}(3)_R$ transformations:

$\hookrightarrow$ rewrite $\mathrm{U}(3)_L \times \mathrm{U}(3)_R = \mathrm{SU}(3)_V \times \mathrm{SU}(3)_A \times \mathrm{U}(1)_V \times \mathrm{U}(1)_A$.

- $\mathrm{SU}(3)_V = \mathrm{SU}(3)_{R+L}$: still conserved for $m_u = m_d = m_s > 0$
- $\mathrm{U}(1)_V = \mathrm{U}(1)_{R+L}$: quark or baryon number is conserved
- $\mathrm{U}(1)_A = \mathrm{U}(1)_{R-L}$: broken by quantum effects ($\mathrm{U}(1)_A$ anomaly + instantons)

Hidden Symmetry and Goldstone Bosons

$$[Q_V^a, H] = 0, \quad \text{and} \quad e^{-iQ_V^a}|0\rangle = |0\rangle \Leftrightarrow Q_V^a|0\rangle = 0 \quad \text{(Wigner-Weyl realization)}$$

$$[Q_A^a, H] = 0, \quad \text{but} \quad e^{-iQ_A^a}|0\rangle \neq |0\rangle \Leftrightarrow Q_A^a|0\rangle \neq 0 \quad \text{(Nambu-Goldstone realiz.)}$$

- Consequence: $e^{-iQ_A^a}|0\rangle \neq |0\rangle$ is not the vacuum, but

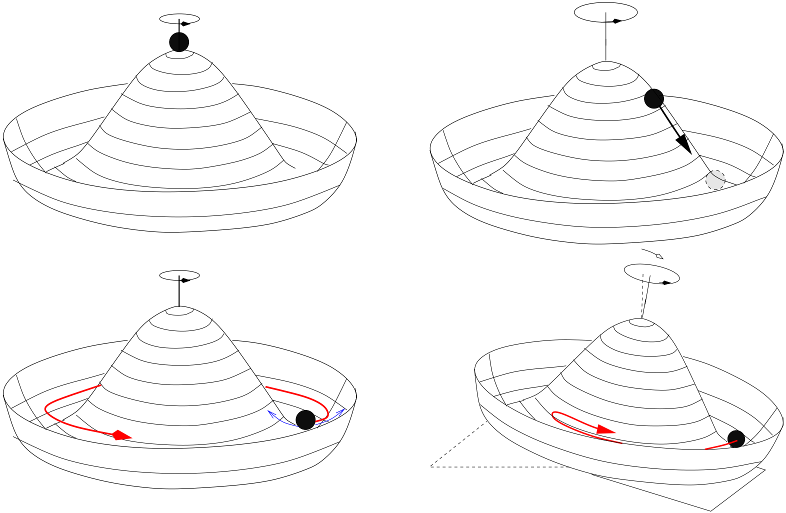
$$H\, e^{-iQ_A^a}|0\rangle = e^{-iQ_A^a} H|0\rangle = 0 \quad \text{is a massless state!}$$

Goldstone theorem: *continuous* global symmetry that does *not* leave the ground state invariant ('hidden' or 'spontaneously broken' symm.)

- mass- and spinless particles, "Goldstone bosons" (GBs)
- number of GBs = number of broken symmetry generators
- axial generators broken $\Rightarrow$ GBs should be pseudoscalars
- finite masses via (small) quark masses
  $\hookrightarrow$ 8 lightest hadrons: $\pi^\pm$, π^0, $K^\pm$, K^0, $\bar{K}^0$, η (not η')
- Goldstone bosons decouple (non-interacting) at vanishing energy

back

Illustration: spontaneous symmetry breaking (SSB)



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Decoupling theorem of Goldstone bosons

Goldstone bosons do not interact at zero energy/momentum

1. $Q_A^a|0\rangle \neq 0 \quad \Rightarrow \quad Q_A^a$ creates GB $\quad \Rightarrow \quad \langle \pi^a | Q_A^a | 0 \rangle \neq 0.$

2. Lorentz invariance $\rightsquigarrow \langle \pi^a(q)|A_b^\mu(x)|0\rangle = -i f_\pi \, q^\mu \, \delta_b^a \, e^{iq\cdot x} \neq 0\,!$

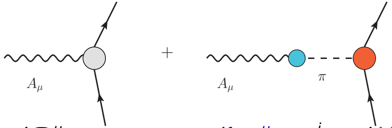
   A_b^μ axial current

   $\hookrightarrow f_\pi \neq 0$ necessary for SSB (order parameter)

   (pion decay constant $f_\pi = 92\,\text{MeV}$ from weak decay $\pi^+ \to \mu^+ \nu_\mu$)

3. Coupling of axial current A_μ to matter fields (and/or pions)

$i\mathcal{A}^\mu =$



$= \quad i\mathcal{R}^\mu$ (non-sing.) $\; + \; -i f_\pi \, q^\mu \, \frac{i}{q^2 - m_\pi^2 + i\epsilon} \, i\,V$ (V: coupling of GB to matter fields)

4. Conservation of axial current $\partial_\mu A_b^\mu(x) = 0$: $\Rightarrow m_\pi^2 = 0$ and $q_\mu \mathcal{A}^\mu = 0$:

$$0 = q_\mu \mathcal{R}^\mu - f_\pi \frac{q^2}{q^2} V \;\xrightarrow{q\to 0}\; 0 = -f_\pi \lim_{q\to 0} V \;\xrightarrow{f_\pi \neq 0}\; \lim_{q\to 0} V = 0 \;\Rightarrow\; \text{decoupling!}$$