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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 $\cancel{CP}$ 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 $\cancel{CP}$?
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?

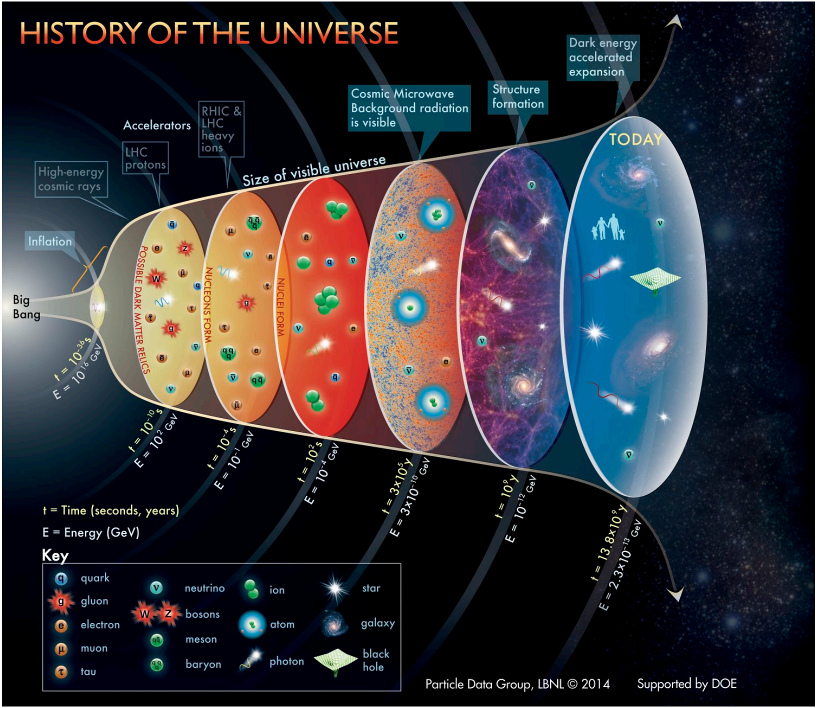

Fig. courtesy of PDG, LBNL © 2014

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Matter Excess in the Universe

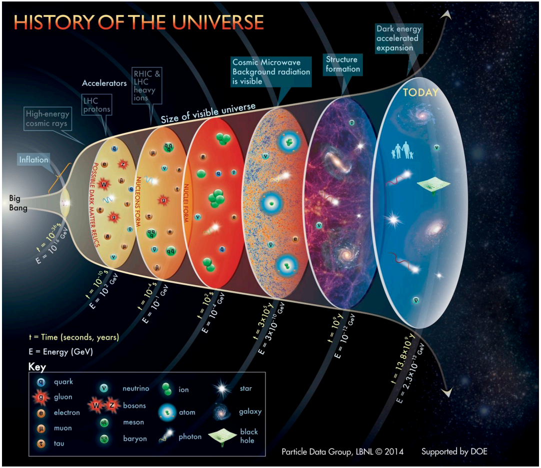

Fig. courtesy of PDG, LBNL ©2014

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

2 Cosmic Microwave Bkgr.

- SM(s) *prediction:**

  $(n_B - \cancel{n_{\bar{B}}})/n_\gamma|_{\rm CMB} \sim 10^{-18}$

- WMAP+PLANCK ('13):

  $n_B/n_\gamma|_{\rm CMB} = (6.05\pm 0.07)10^{-10}$

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

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

▸ in the SM?

CP violation and the Electric Dipole Moment (EDM)

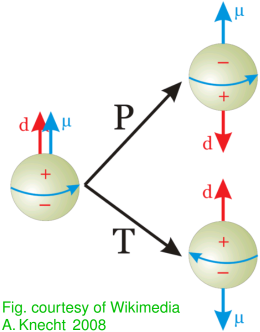

Fig. courtesy of Wikimedia
A. Knecht 2008

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)$^\diamond$, *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 specified parity P and nonzero spin j and

$$\vec{d} \to \mp \vec{d} \quad \& \quad \vec{J} \to \pm \vec{J} \quad \text{under} \quad \begin{cases} \text{space reflection}, \\ \text{time reversal}. \end{cases}$$

If $d \neq 0$ and $|j^{\mathrm{P}}\rangle$ has *no* degeneracy (besides rotational), *then* $\cancel{P}$ & $\cancel{T}$.

* *non*-selfconjugate particle is *not* its own antiparticle ⇒ at least one "charge" *non*-zero

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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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 $\cancel{T}$ nor $\cancel{P}$!

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

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'But what about the induced EDM (polarization)?'

The induced EDM is *quadratic* in the electric field and *neither* $\cancel{P}$ nor $\cancel{T}$

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 $\cancel{T} \iff \cancel{CP}$

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 $\sim 10^{-7}$

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

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

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

- 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

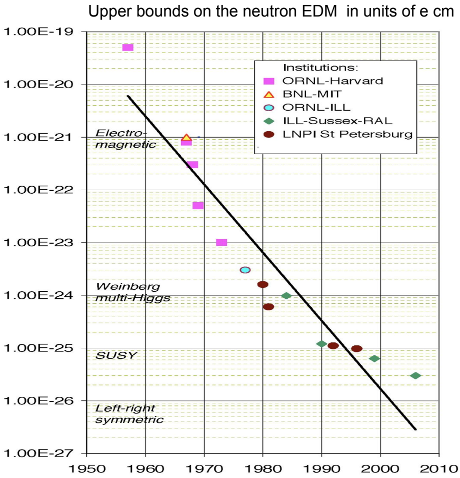

Fig. courtesy of N.N. Nikolaev

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

↪ 5 to 6 orders above SM predictions which are out of reach !

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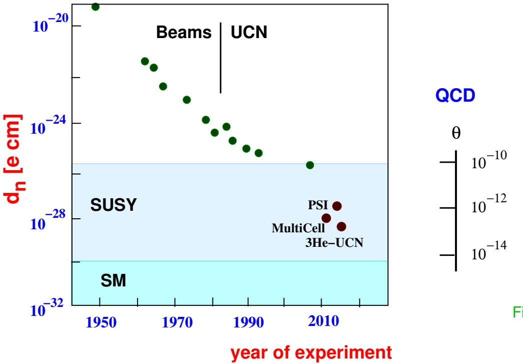

Fig. courtesy of U.-G. Meißner

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

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

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

- Proton (and neutron) EDM inferred from diamagnetic atoms

  current $\quad |d(^{199}\mathrm{Hg})| < 7.4 \cdot 10^{-30}\, e\,\mathrm{cm}$ (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:

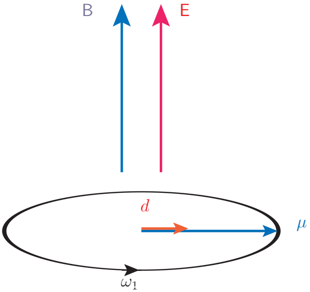
  current $\quad |d_e| < 8.7 \cdot 10^{-29}\, e\,\mathrm{cm}$ (90% C.L.)

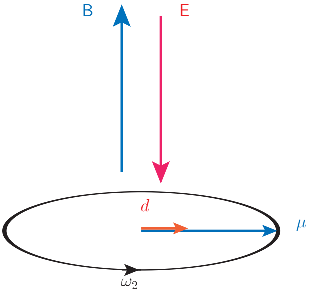
  from polar ThO

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

EDM measurement of neutral particles in a nutshell

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





$$\omega_1 = \frac{2\mu B + 2d E}{\hbar} \qquad \omega_2 = \frac{2\mu B - 2d E}{\hbar}$$

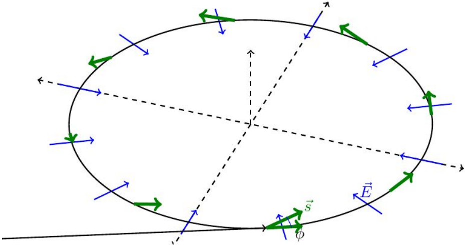
$$d = \frac{\hbar(\omega_1 - \omega_2)}{4E}$$

Direct EDM searches with charged particles

in storage rings

General idea:

Farley et al. *PRL* '04



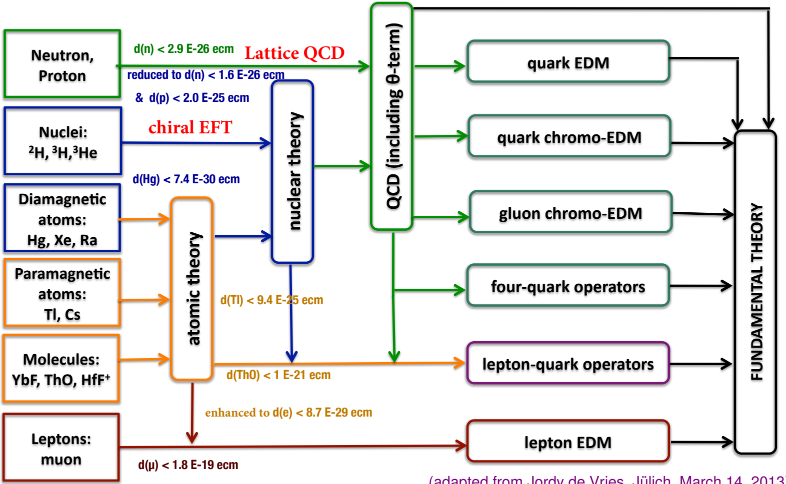
Initially longitudinally polarized particles interact with radial $\vec{E}$ field
$\hookrightarrow$ build-up of vertical polarization (measured with a polarimeter)

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

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

Road map from EDM Measurements to EDM Sources

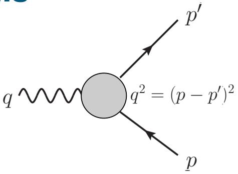
Experimentalist's point of view → ← Theorist's point of view



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

Calculation: from form factors to EDMs

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



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

Dirac FF | Pauli FF | electric dipole FF ($\cancel{CP}$) | anapole FF ($\cancel{P}$)

$$\hookrightarrow \quad d_f := \lim_{q^2 \to 0} \frac{F_3(q^2)}{2m_f}$$ for $s = 1/2$ fermion

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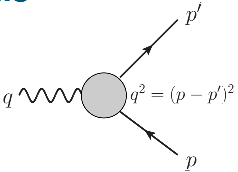

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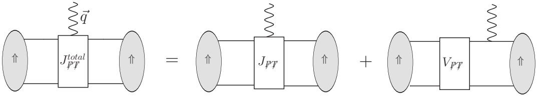
$$\hookrightarrow \quad d_f := \lim_{q^2\to 0} \frac{F_3(q^2)}{2m_f} \qquad \text{for } s = 1/2 \text{ fermion}$$

Nucleus A

$\langle\Uparrow|J^0_{\cancel{P}\cancel{T}}(q)|\Uparrow\rangle$

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 $\cancel{CP}$ phase δ_{KM}

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

    3 angles +1(3) $\cancel{CP}$ phase(s) for Dirac (Majorana) ν_i's

$\cancel{CP}$ and EDMs and in the SM with $J_{\mathrm{KM}} = \mathrm{Im}(V_{tb}V_{td}^{*}V_{cd}V_{cb}^{*}) \simeq 3 \cdot 10^{-5}$

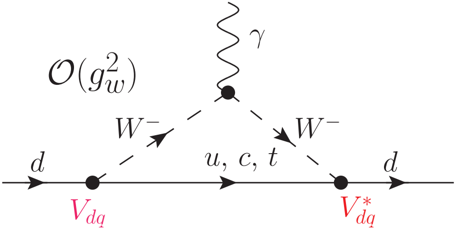
$$\propto \left(\frac{m_t^2-m_c^2}{M_{EW}^2}\right)\left(\frac{m_c^2-m_u^2}{M_{EW}^2}\right)\left(\frac{m_t^2-m_u^2}{M_{EW}^2}\right)\cdot\left(\frac{m_b^2-m_s^2}{M_{EW}^2}\right)\left(\frac{m_s^2-m_d^2}{M_{EW}^2}\right)\left(\frac{m_b^2-m_d^2}{M_{EW}^2}\right)\cdot J_{\mathrm{KM}} \simeq 10^{-15} J_{\mathrm{KM}},$$

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: $\mathcal{O}(G_F^2) \sim \mathcal{O}(g_W^4)$

1 loop:



$\hookrightarrow$ $\cancel{CP}$ phase δ_{KM} cancels $\to$ prefactor real $\Rightarrow$ $\boxed{d_q^{\text{1-loop}} = 0}$

$\cancel{CP}$ 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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2 loops:

$$d^{\text{2-loop}}_{\text{quark}} = d^{\text{2-loop}}_{\text{chromo q}} = 0$$

Shabalin *Sov.J.NP* '78

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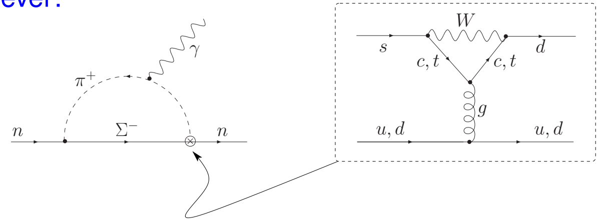
however:



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

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

Gavela; Khriplovich & Zhitnitsky ('82)

$\cancel{CP}$ and EDMs and in the SM with $J_{\mathbf{KM}} = \mathbf{Im}(V_{tb}V_{td}^* V_{cd} V_{cb}^*) \simeq 3 \cdot 10^{-5}$

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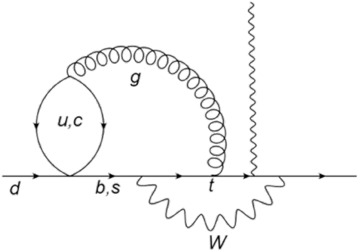
EDM flavor-neutral $\Rightarrow$ KM predictions tiny: $\mathcal{O}(G_F^2) \sim \mathcal{O}(g_W^4)$

at $\geq$ 3 loops:



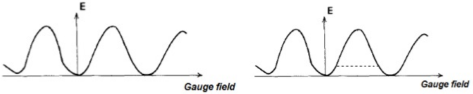
$\mathcal{O}(g_W^4 g_s^2)$

$d_n^{\mathrm{KM}} \simeq 10^{-34} \ldots 10^{-31} e\,\mathrm{cm}$ $\quad (d_e^{\mathrm{KM}} \sim 10^{-38} \ldots 10^{-40} e\,\mathrm{cm}$ 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 $\cancel{P}\&\cancel{T} \rightsquigarrow \cancel{CP}$ 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 $\boxed{\bar\theta = \theta + \arg\det \mathcal{M}_{\text{quark}}}$

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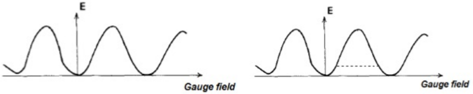

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- Naive Dimensional Analysis (NDA) estimate of $\bar\theta$-induced n EDM:

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

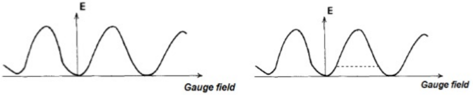
$$|d_n^{emp}| < 2.9 \cdot 10^{-26} e\,\text{cm} \rightsquigarrow \boxed{|\bar\theta| < 10^{-10}}$$

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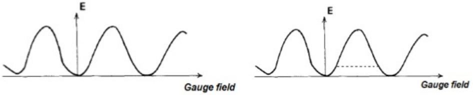
$10^{-10} > |\bar{\theta}| > 10^{-14}$ eventually measurable via nonzero EDM, but because of $\Lambda_{\chi SB} \ll \Lambda_{EWSB}$ it doesn't explain the cosmic matter surplus.

EDM sources: QCD θ-term of the SM

The topologically non-trivial vacuum structure of QCD



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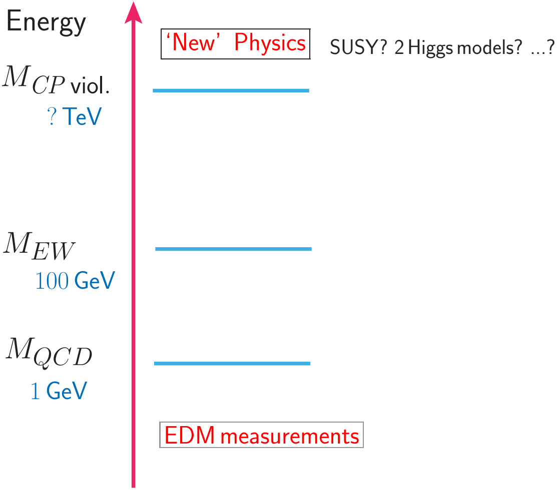
Thus $\cancel{CP}$ by new physics (NP) (*i.e.* dimension ≥ 6 sources beyond SM) needed to explain the cosmic matter-antimatter asymmetry.

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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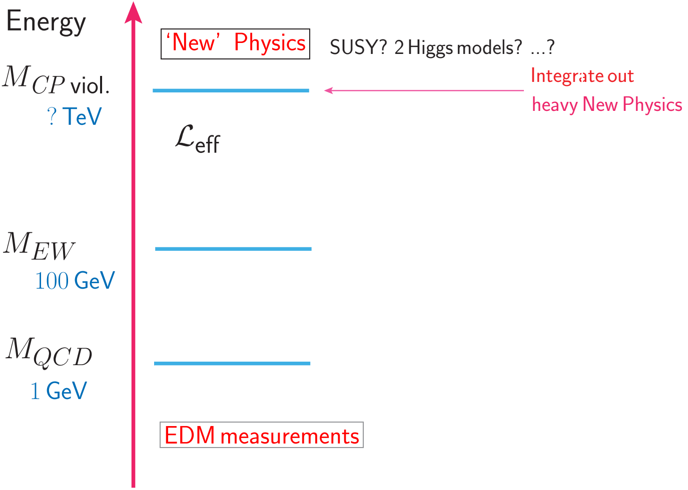

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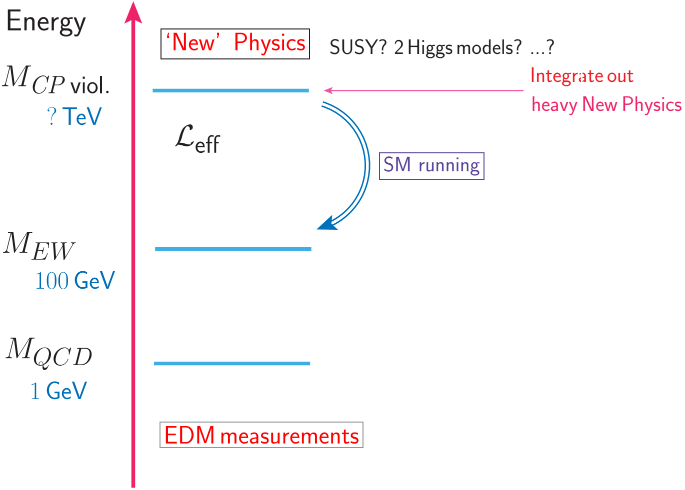

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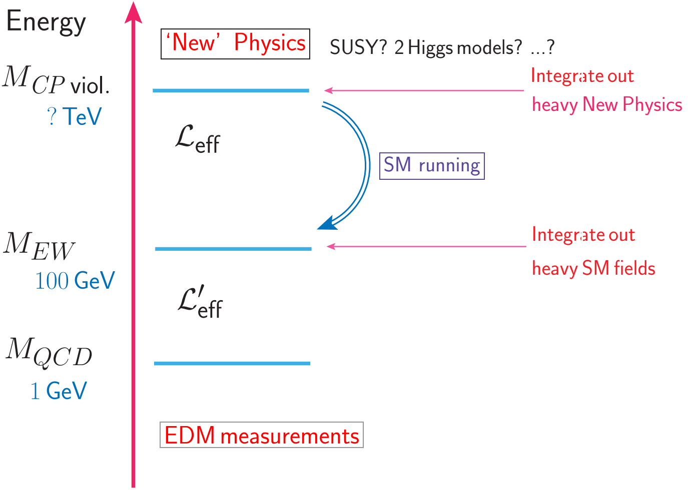

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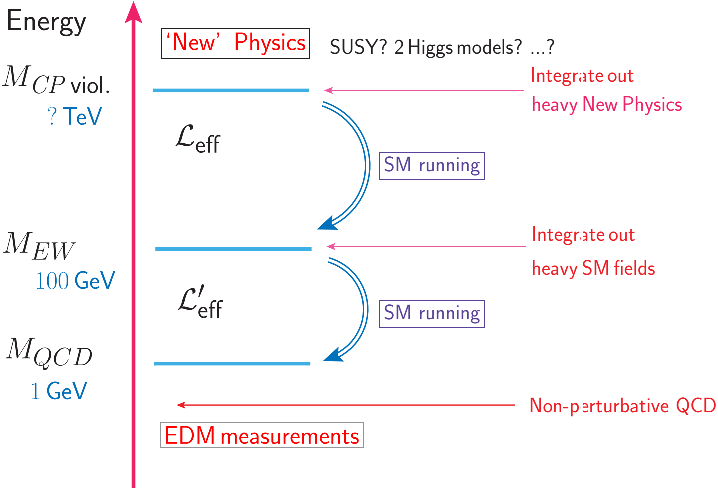

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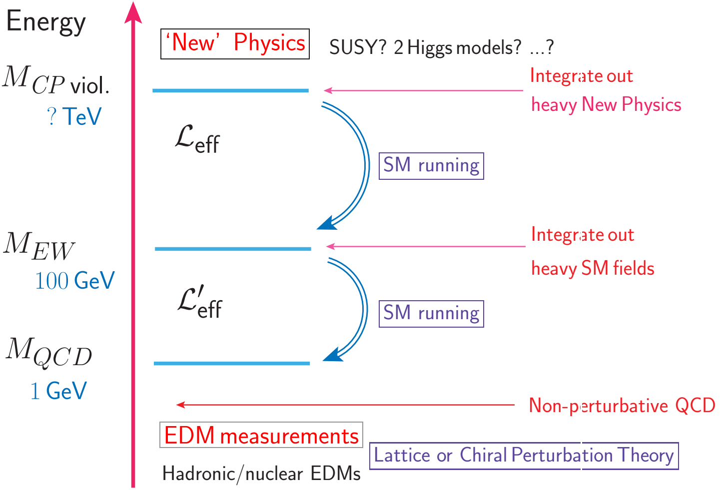
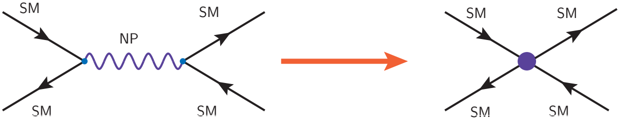


How to handle CP-violating sources beyond the SM?

New interactions as higher dimensional operators

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



- The new interactions appear as higher dimensional operators

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

  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

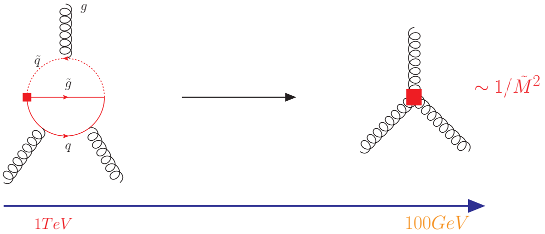
  Not of dim. 5 because of Higgs insertion (chiral symm.) at high (low) scales

How to handle CP-violating sources beyond the SM?

Evaluation in Effective Field Theory (EFT) approach

▸ EFT

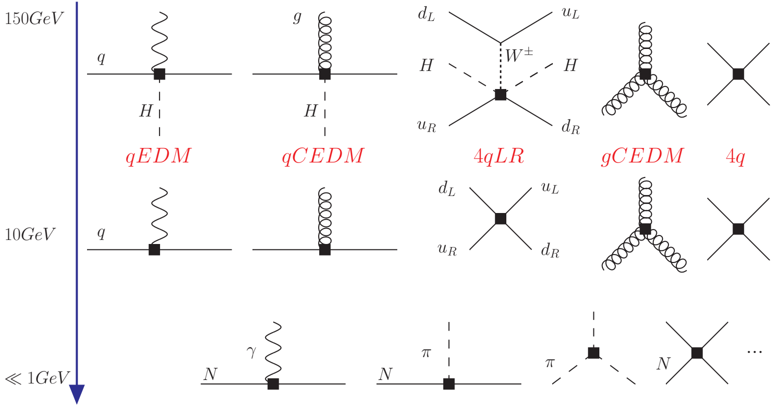
- All degrees of freedom *beyond NP (EW) scale* are integrated out:
  ↪ Only SM degrees of freedom remain: q, g, (H, Z, $W^\pm$, ...)
- Write down *all* interactions for these *active* degrees of freedom that *respect the* SM+ Lorentz *symmetries*: here dim. 6 or higher order
- Need a *power-counting 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

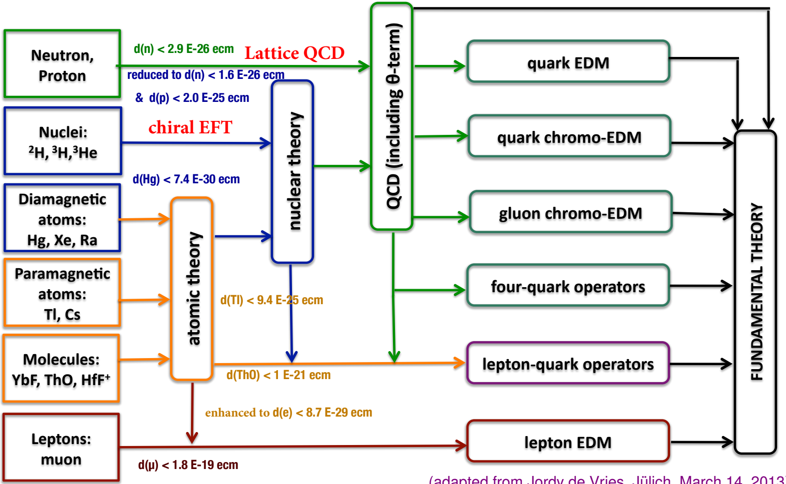


$$\text{Total \#} = 1(\bar\theta) + 2(qEDM) + 2(qCEDM) + 1(4qLR) + 1(gCEDM) + 2(4q) \;\; [+3(\text{semi}) + 1(\text{lept})]$$

$$= \underbrace{1(\text{dim-four}) + 8(\text{dim-six})}_{\hookrightarrow \text{ 5 discriminable classes}} \; [+3+1] \quad [\text{Caveat: } m_s \gg m_u, m_d \text{ (\& } m_\mu \gg m_e) \text{ assumed}]$$

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

JÜLICH FORSCHUNGSZENTRUM

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 $\cancel{CP}$ hadronic vertices

from θ to BSM sources

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

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

Road map from EDM Measurements to EDM Sources

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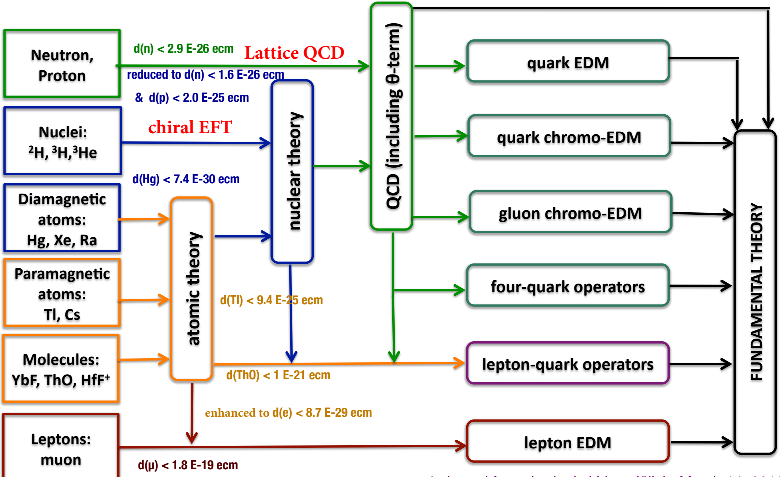
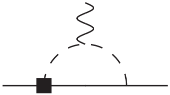


(adapted from Jordy de Vries, Jülich, March 14, 2013)

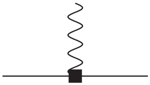
θ-Term Induced Nucleon EDM

single nucleon EDM:



"controlled"

isovector
$\approx$
$\ll$
isoscalar



two "unknown" coefficients

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

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

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

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

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

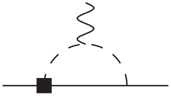
Bsaisou et al., *EPJA*'13 & *JHEP*'15

▸ details

JÜLICH
FORSCHUNGSZENTRUM

θ-Term Induced Nucleon EDM

single nucleon EDM:



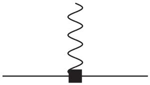
“controlled”

isovector

$\approx$

$\ll$

isoscalar



two “unknown” coefficients

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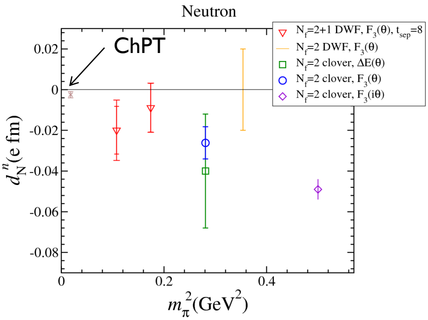
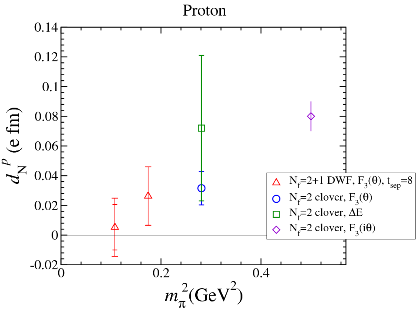
Bsaisou et al., *EPJA*’13 & *JHEP*’15 ▸ details

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

Preliminary Lattice (full QCD) results

neutron EDM and proton EDM





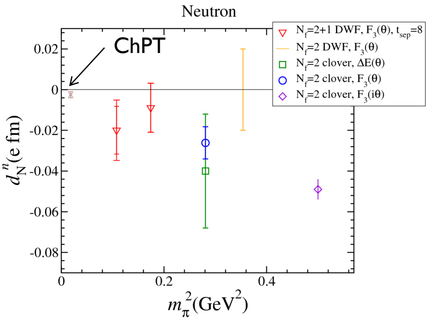
$\theta \equiv 1$!

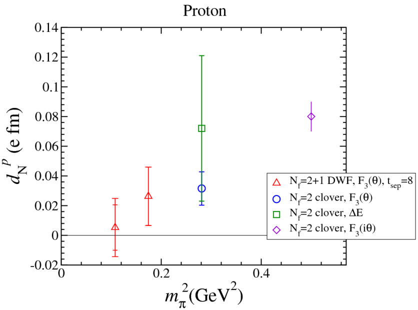
(adapted from Eigo Shintani (Mainz), *Lattice calculation of nucleon EDM*, Hirschegg, Jan. 14, 2014)

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)

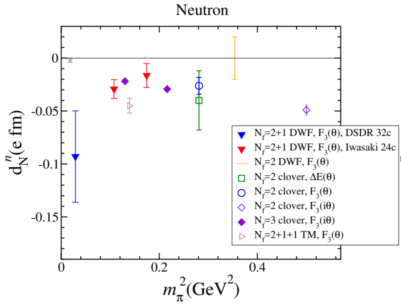
no systematical errors!

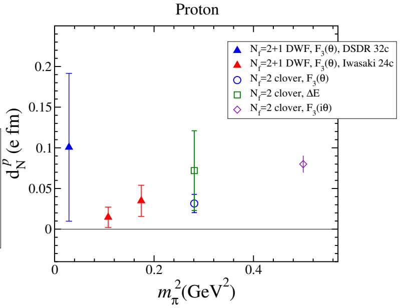
$$\hookrightarrow d_n = \bar\theta\,(-2.7 \pm 1.2)\cdot 10^{-3}\cdot e\,\mathrm{fm} \quad \text{and} \quad d_p = \bar\theta\,(2.1 \pm 1.2)\cdot 10^{-3}\cdot e\,\mathrm{fm}$$

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

Preliminary Lattice (full QCD) results

neutron EDM and proton EDM





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

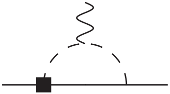
Eigo Shintani et al., *Phys. Rev. D* **93**, 094503 (2016) $M_\pi = 170, 330, 420, 530\,\mathrm{MeV}$

Don't mention the ... light nuclei

Single Nucleon Versus Nuclear EDM

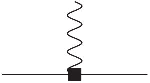
Crewther, di Vecchia, Veneziano, Witten *PLB*'79; Pich, de Rafael *NPB*'91; Ottnad et al. *PLB*'10

single nucleon EDM:



isovector $\approx$

$\ll$ isoscalar



"controlled"

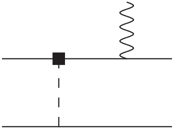
"unknown" coefficients

$\longrightarrow$ lattice QCD required

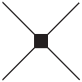
Guo, Meißner *JHEP*'12

two nucleon EDM:

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



$\gg$



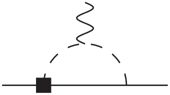
controlled

unknown coefficient

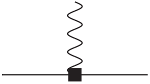
Single Nucleon Versus Nuclear EDM

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

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Guo, Meißner *JHEP*'12

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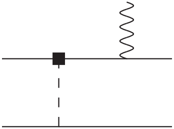
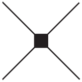


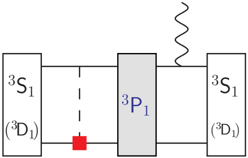
$\gg$



controlled | unknown coefficient

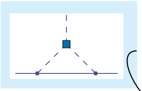
EDM of the Deuteron at LO: CP-violating π exchange

$$\begin{aligned}\mathcal{L}^{\pi N}_{\cancel{CP}} \;=\;& -d_n N^\dagger(1-\tau^3)S^\mu v^\nu N F_{\mu\nu} - d_p N^\dagger(1+\tau_3)S^\mu v^\nu N F_{\mu\nu}\\ &+ (m_N\Delta)\pi^2\pi_3 + \cancel{g_0 N^\dagger\vec{\pi}\cdot\vec{\tau}N} + g_1 N^\dagger\pi_3 N\\ &+ \cancel{C_1 N^\dagger N \mathcal{D}_\mu(N^\dagger S^\mu N)} + \cancel{C_2 N^\dagger\vec{\tau}N\cdot\mathcal{D}_\mu(N^\dagger\vec{\tau}S^\mu N)} + \cdots .\end{aligned}$$



LO: $\cancel{g_0 N^\dagger\vec{\pi}\cdot\vec{\tau}N}$ $(\cancel{CP}, I)$ $\to$ 0 (Isospin filter!)

NLO: $g_1 N^\dagger\pi_3 N$ $(\cancel{CP}, \cancel{I})$ $\to$ *"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 $\cancel{CP}$ 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

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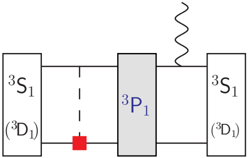
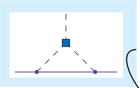


LO: $\cancel{g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N}$ $(\cancel{CP},\mathrm{I})$ $\to 0$ (Isospin filter!)

NLO: $g_1 N^\dagger \pi_3 N$ $(\cancel{CP},\cancel{\mathrm{I}})$ $\to$ *"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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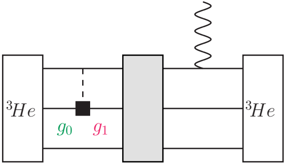
new

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



$g_0 N^\dagger \vec{\pi} \cdot \vec{\tau} N$ $(\cancel{CP}, \mathrm{I})$

LO: θ-term, qCEDM

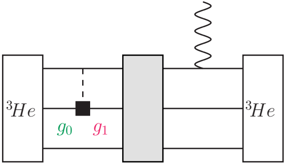
N^{2}LO: 4qLR

$g_1 N^\dagger \pi_3 N$ $(\cancel{CP}, \cancel{\mathrm{I}})$

LO: qCEDM, 4qLR

NLO: θ term

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



$g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N$ ($\cancel{CP}$, I)
LO: θ-term, qCEDM
N^2LO: 4qLR

$g_1 N^\dagger \pi_3 N$ ($\cancel{CP}$, $\cancel{I}$)
LO: qCEDM, 4qLR
NLO: θ term

term	A	N^2LO 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	-0.018	
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

$$
\begin{aligned}
\mathcal{L}^{\pi N}_{\cancel{CP}} \quad = \quad & -d_n N^\dagger(1-\tau^3)S^\mu v^\nu N F_{\mu\nu} - d_p N^\dagger(1+\tau_3)S^\mu v^\nu N F_{\mu\nu} \\
& + (m_N\Delta)\pi^2\pi_3 + g_0 N^\dagger\vec{\pi}\cdot\vec{\tau}N + g_1 N^\dagger\pi_3 N \\
& + C_1 N^\dagger N \mathcal{D}_\mu(N^\dagger S^\mu N) + C_2 N^\dagger\vec{\tau}N\cdot\mathcal{D}_\mu(N^\dagger\vec{\tau}S^\mu N) + \cdots .
\end{aligned}
$$

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	^{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	-0.018	
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	$C_1\, e\,\mathrm{fm}^{-2}$
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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	

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

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 $\tilde{d}_d \simeq 4 d_d \simeq 20 d_W$

matched on

$$\begin{aligned}\mathcal{L}^{\pi N}_{\cancel{CP}\,\mathrm{EFT}} \quad = \quad & -d_n N^\dagger(1-\tau^3)S^\mu v^\nu N F_{\mu\nu} - d_p N^\dagger(1+\tau_3)S^\mu v^\nu N F_{\mu\nu} \\ & + (m_N\Delta)\pi^2\pi_3 + g_0 N^\dagger\vec{\pi}\cdot\vec{\tau}N + g_1 N^\dagger\pi_3 N \\ & + C_1 N^\dagger N\mathcal{D}_\mu(N^\dagger S^\mu N) + C_2 N^\dagger\vec{\tau}N\cdot\mathcal{D}_\mu(N^\dagger\vec{\tau}S^\mu N) + \cdots .\end{aligned}$$

Discriminating between three scenarios at 1 GeV

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

1. The Standard Model + $\bar\theta$

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

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

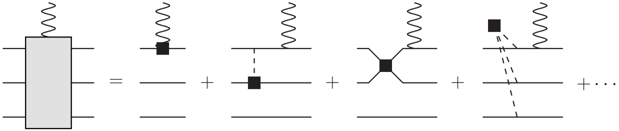
$$\mathcal{L}_{LR} = -\mathrm{i}\,\Xi\left[1.1(\bar u_R\gamma_\mu u_R)(\bar d_L\gamma^\mu d_L) + 1.4(\bar u_R t^a\gamma_\mu u_R)(\bar d_L t^a\gamma^\mu d_L)\right] + \text{h.c.}$$

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



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

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 $\bar{\theta}$

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

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

*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

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

Extraction of $\bar\theta$

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

Prediction for $d_D - 0.94(d_n + d_p)$

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

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

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

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

*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

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

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): $d_D \approx d_{^3\mathrm{He}} \approx d_{^3\mathrm{H}}$

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

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

*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

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

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

Testing strategies: aligned 2-Higgs Doublet Model

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

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

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

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Extraction of g_0

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

*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**
  $\hookrightarrow$ $\cancel{CP}$ $N\pi$ 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) $\not{C}\not{P}$**
- 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 ^3He 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

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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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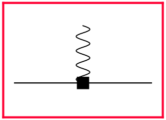
3. A.W., *Electric dipole moments of the nucleon and light nuclei* Nuclear Physics A **928**, 116-127 (2014), arXiv:1404.6131 [hep-ph].
4. W. Dekens, J. de Vries, J. Bsaisou, W. Bernreuther, C. Hanhart, U.-G. Meißner, A. Nogga and A.W., *Unraveling models of CP violation through electric dipole moments 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

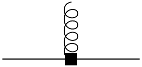
de Vries et al.(2011)



qEDM

$d_D \approx d_p + d_n$

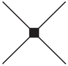
$d_{^3He} \approx d_n$



qCEDM

$d_D > d_p + d_n$

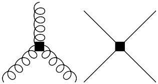
$d_{^3He} > d_n$



4qLR

$d_D > d_p + d_n$

$d_{^3He} > d_n$



gCEDM + 4qEDM

$d_D \sim d_p + d_n$

$d_{^3He} \sim d_n$

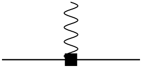
$$\longrightarrow \quad g_0,\, g_1 \propto \alpha/(4\pi)$$

2*N* contribution suppressed by photon loop!

here: only absolute values considered

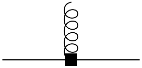
If $\bar{\theta}$-term tests fail, then effective BSM dim. 6 sources

de Vries et al.(2011)



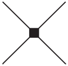
qEDM

$d_D \approx d_p + d_n$
$d_{^3He} \approx d_n$



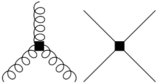
qCEDM

$d_D > d_p + d_n$
$d_{^3He} > d_n$



4qLR

$d_D > d_p + d_n$
$d_{^3He} > d_n$



gCEDM + 4qEDM

$d_D \sim d_p + d_n$
$d_{^3He} \sim d_n$

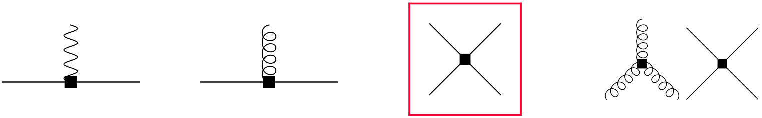
$\longrightarrow$ g_0, g_1 dominant and of the same order

2*N* 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*
$d_D \approx d_p + d_n$	$d_D > d_p + d_n$	$d_D > d_p + d_n$	$d_D \sim d_p + d_n$
$d_{^3He} \approx d_n$	$d_{^3He} > d_n$	$d_{^3He} > d_n$	$d_{^3He} \sim d_n$

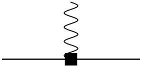
$\longrightarrow\; g_1 \gg g_0$; 3π-coupling (unsuppressed in ^{3}He)

isospin-breaking $2N$ contribution enhanced!

here: only absolute values considered

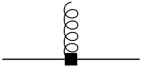
If $\bar{\theta}$-term tests fail, then effective BSM dim. 6 sources

de Vries et al.(2011)



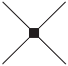
qEDM

$$d_D \approx d_p + d_n$$
$$d_{^3He} \approx d_n$$



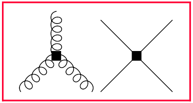
qCEDM

$$d_D > d_p + d_n$$
$$d_{^3He} > d_n$$



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

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

Generic features of a permanent EDM

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

1. For any non-zero EDM, ~~CP~~ must be flavor *diagonal*!

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

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

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

$\Rightarrow$ 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 ~~CP~~)

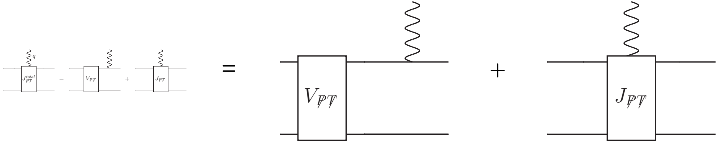
$\hookrightarrow$ ~~CP~~ beyond SM: $\mathcal{L}_{\text{BSM}}^{\cancel{CP}} = \cancel{\frac{1}{M_{\text{BSM}}}\mathcal{L}_{\dim 5}} + \frac{1}{M_{\text{BSM}}^2}\mathcal{L}_{\dim 6} + \ldots$

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

$\mathrm{I} = 0$ $\mathrm{I} = 0$ $\mathrm{I}=0 \rightarrow \mathrm{I}=1 \rightarrow \mathrm{I}=0$ $\mathrm{I} = 0$ $\mathrm{I} = 0$

isospin selection rules!

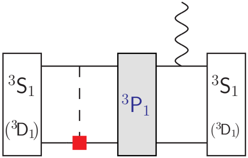
$\Downarrow$

$\cancel{g_0^\theta N^\dagger \vec{\pi}\cdot\vec{\tau} N}$ 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: $\cancel{g_0^\theta N^\dagger \vec{\pi}\cdot\vec{\tau} N}$ $(\cancel{CP}, \mathrm{I}) \to 0$ (Isospin filter!)

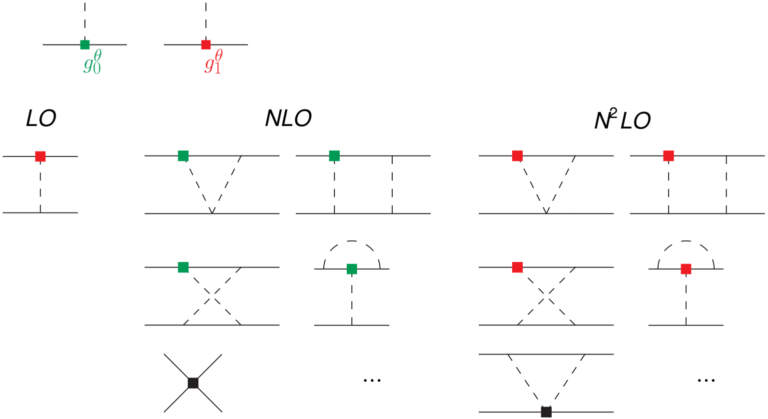
NLO: $g_1^\theta N^\dagger \pi_3 N$ $(\cancel{CP}, \cancel{\mathrm{I}})$ $\to$ *"LO"* in D case

Reference	potential	result [$g_1\, g_{\pi NN}\, e\,\mathrm{fm}$]
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)	$(1.43 \pm 0.13) \times 10^{-2}$

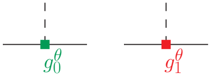
* unpublished, $^\diamond$ Eur. Phys. J. A **49** (2013) 31 [arXiv:1209.6306]

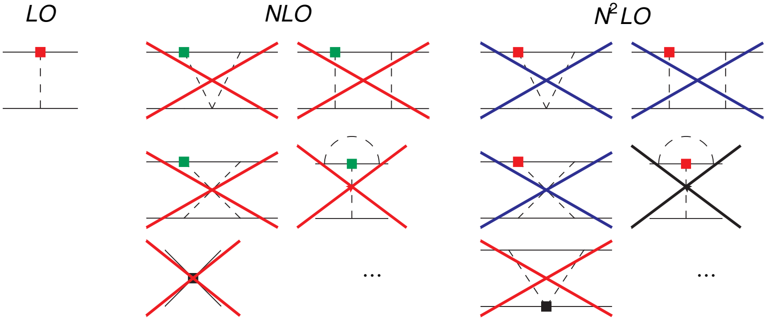
$\boxed{\text{BSM } \cancel{CP} \text{ sources:}}$ $g_1\ \pi NN$ vertex is of LO in qCEDM and 4qLR case

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



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

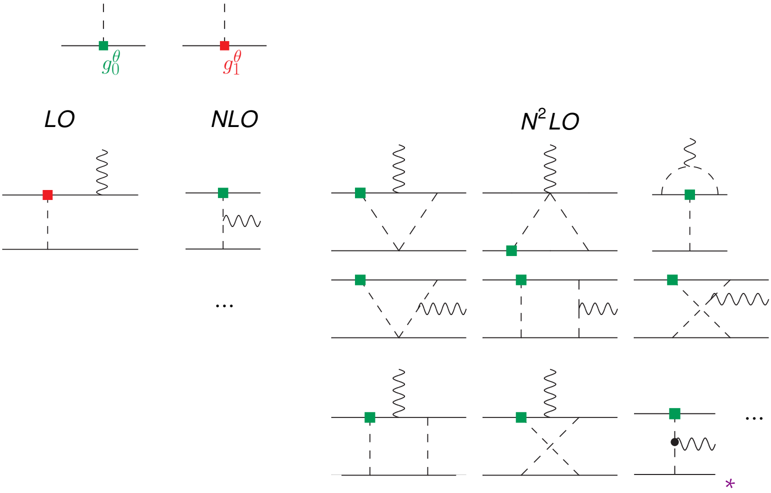




- ×: vanishing by selection rules, ×: sum of diagrams vanishes
  ×: vertex correction

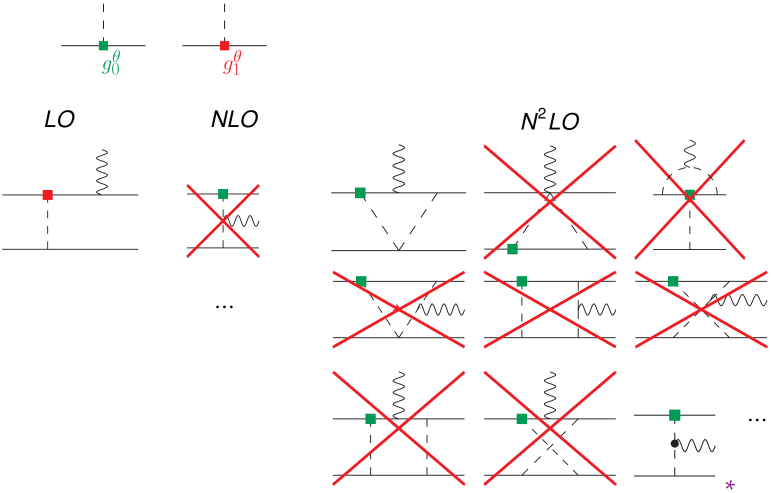
LO NLO N^{2}LO

EDM of the Deuteron: *NLO*- and *N²LO*-Currents



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

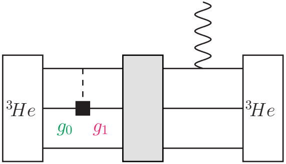
EDM of the Deuteron: *NLO*- and N^2LO-Currents



*: 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



$g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N$ ($\cancel{CP}$, I)
LO: θ-term, qCEDM
N^2LO: 4qLR

$g_1 N^\dagger \pi_3 N$ ($\cancel{CP}$, $\cancel{I}$)
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)	$(0.86 \pm 0.11) \times 10^{-2}$	$(1.11 \pm 0.14) \times 10^{-2}$

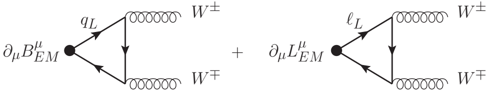
$^{\diamond}$ unpublished

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:

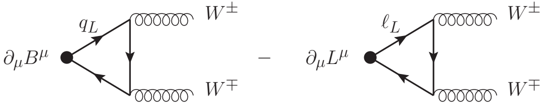


$$\propto\ N_c \cdot (Q_u + Q_d) + (0 - 1) = 1 - 1 = 0$$

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

EW Baryogenesis: Standard Model

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



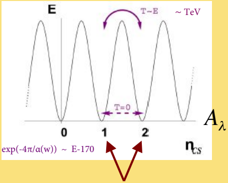
$\propto \; N_c \cdot 1/3 - 1 = 1 - 1 = 0$

$\hookrightarrow \Delta(B-L) = 0$ 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

$$\begin{aligned}
\langle n|\vec{J}_d|n\rangle &\equiv \langle p|\vec{J}_u|p\rangle \equiv \lambda_u^p\langle p|\vec{J}|p\rangle = \frac{N_c+5}{6}\langle p|\vec{J}|p\rangle \xrightarrow{N_c=3} \frac{4}{3}\langle p|\vec{J}|p\rangle \\
\langle n|\vec{J}_u|n\rangle &\equiv \langle p|\vec{J}_d|p\rangle \equiv \lambda_d^p\langle p|\vec{J}|p\rangle = -\frac{N_c-1}{6}\langle p|\vec{J}|p\rangle \xrightarrow{N_c=3} -\frac{1}{3}\langle p|\vec{J}|p\rangle
\end{aligned}$$

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

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

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

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

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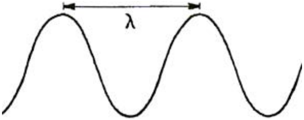
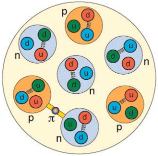
What are Effective Field Theories (EFT)?

- 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: $m_e \approx 0.511\,\mathrm{MeV} \ldots m_t \sim 180\,\mathrm{GeV}$ 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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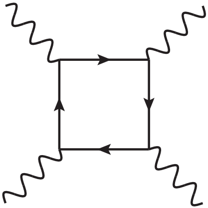
EFT example: light-by-light scattering

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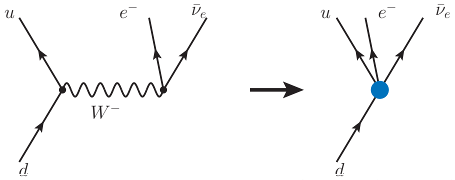
EFT example: weak interactions for $E \ll M_W$

Weak decays:

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



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

$\hookrightarrow$ Fermi's current-current interaction

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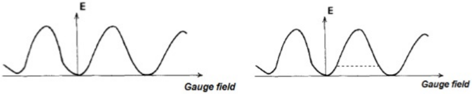
θ vacua in strong interaction physics

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

$\leadsto$ 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

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

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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 $q_f \to \mathrm{e}^{-\mathrm{i}\alpha\gamma_5/2} q_f \approx (1 - \mathrm{i}\frac{1}{2}\alpha\gamma_5) q_f$:

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

$$\hookrightarrow \mathcal{L}_{SM}^{\mathrm{str}\,\cancel{\mathrm{CP}}} = \mathcal{L}_{SM}^{\mathrm{CP}} + \bar{\theta} m^* \sum_f \bar{q}_f i\gamma_5 q_f \quad \text{with } \bar{\theta} = \theta + \arg\det \mathcal{M} \text{ and } m^* = \frac{m_u m_d}{m_u + m_d}$$

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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

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

- 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

  $$m_a \approx 0.5\, m_\pi f_\pi / f_a \quad \text{with} \quad f_a \gg \langle H\rangle = (\sqrt{2}G_F)^{-1/2} = 247\,\text{GeV}$$

- 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

$$\mathcal{L}_{\rm eff}(a) = \underbrace{\mathcal{L}_0}_{\text{indep. of } a} + \underbrace{\tfrac{1}{2}(\partial_\mu a)^2 + \frac{\partial_\mu a}{f_a}\tilde{J}^\mu(\bar\psi\ldots\psi,\phi)}_{\text{PQ-invariant}} + \underbrace{\frac{a}{f_a}\frac{N}{32\pi^2}G\tilde{G}}_{\text{expl. PQ-breaking by QCD anomaly}}$$
$$+ \underbrace{\Delta\mathcal{L}_{UV}\left(= -\epsilon m_{\rm UV}^4\cos(a/f_a+\delta_{\rm UV})\right)}_{a \text{ coupling from expl. PQ breaking at UV scale}}$$

$\bar\theta = \langle a\rangle/f_a$ is calculable in terms of the $\cancel{CP}$ angles (in presence of a!):

- $\delta_{\rm KM}$ = Kobayashi-Maskawa phase in the PQ-invariant SM
- $\delta_{\rm BSM}$ = $\cancel{CP}$ phase in PQ-invariant BSM at the scale $m_{\rm BSM}$
- $\delta_{\rm UV}$ = $\cancel{CP}$ 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 $\cancel{CP}$ in the $\cancel{PQ}$ 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 $\lesssim 500\,\mathrm{km} \times (f_a/M_{\mathrm{GUT}})$:
  $\hookrightarrow$ Ansatz: $a(t,\vec{x}) \approx a(t) = a_0 \cos(m_a t)$ in the lab.
- Equating $\frac{1}{2}m_a^2 a_0^2 \sim \rho_{\mathrm{local\,DM}} \approx (0.3\pm 0.1)\,\mathrm{GeV/cm}^3$ gives as axion amplitude

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

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 ?

Non-relativistic reduction of

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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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

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

$\bar q$ 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	$-\gamma^\mu$
$\gamma^\mu\gamma_5$	$-\gamma_\mu\gamma_5$	$\gamma^\mu\gamma_5$	$-\gamma_\mu\gamma_5$	$\gamma_\mu\gamma_5$	$-\gamma^\mu\gamma_5$
$\sigma^{\mu\nu}$	$\sigma_{\mu\nu}$	$-\sigma^{\mu\nu}$	$-\sigma_{\mu\nu}$	$-\sigma_{\mu\nu}$	$\sigma^{\mu\nu}$
$\sigma^{\mu\nu} q_\nu$	$\sigma_{\mu\nu} q^\nu$	$-\sigma^{\mu\nu} q_\nu$	$-\sigma_{\mu\nu} q^\nu$	$-\sigma_{\mu\nu} q^\nu$	$\sigma^{\mu\nu} q_\nu$
$\mathrm{i}\sigma^{\mu\nu} q_\nu$	$\mathrm{i}\sigma_{\mu\nu} q^\nu$	$-\mathrm{i}\sigma^{\mu\nu} q_\nu$	$-\mathrm{i}\sigma_{\mu\nu} q^\nu$	$\mathrm{i}\sigma_{\mu\nu} q^\nu$	$-\mathrm{i}\sigma^{\mu\nu} q_\nu$
$\sigma^{\mu\nu} q_\nu\gamma_5$	$-\sigma_{\mu\nu} q^\nu\gamma_5$	$-\sigma^{\mu\nu} q_\nu\gamma_5$	$\sigma_{\mu\nu} q^\nu\gamma_5$	$-\sigma_{\mu\nu} q^\nu\gamma_5$	$-\sigma^{\mu\nu} q_\nu\gamma_5$

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 $\rightsquigarrow$ $\boxed{n_G^2 \text{ real parameters}}$.
- $2n_G - 1$ of these can be absorbed by the relative phases of the quark wave functions $\rightsquigarrow$ $\boxed{(n_G - 1)^2}$ 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 $\cancel{CP}$ phase
- Lepton case: neutrinos may be Majoranas: $\rightsquigarrow$ 3 angles plus 3 $\cancel{CP}$ phases
- If phase(s) present, M complex matrix, whereas CP invariance $\rightsquigarrow$ $M^* = M$!

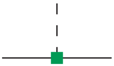
Hierachy among the sources at the hadronic EFT level

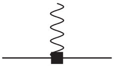
Each source transforms differently under chiral and isospin symmetry

$\cancel{CP}$, I | $\cancel{CP}$, $\cancel{\mathrm{I}}$ | $\cancel{CP}$, I + $\cancel{\mathrm{I}}$

$$\mathcal{L}^{\cancel{CP}}_{\mathrm{EFT}} = g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N \;+\; g_1 N^\dagger \pi_3 N \;+\; N^\dagger(d_0 + d_1\tau_3) S^\mu v^\nu F_{\mu\nu} N \;+\cdots$$

$\Downarrow$ | $\Downarrow$ | $\Downarrow$





…

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

- $\mathcal{L}^{\theta}_{QCD} = \bar\theta m_q^* \sum_f \bar q_f i\gamma_5 q_f$: $\cancel{CP}$, I $\qquad m_q^* = \frac{m_u m_d}{m_u + m_d}$

  $\hookrightarrow$ $\bar\theta$ 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

	$\cancel{CP}$, I		$\cancel{CP}$, $\cancel{I}$		$\cancel{CP}$, I + $\cancel{I}$	
$\mathcal{L}^{\cancel{CP}}_{\text{EFT}} =$	$g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N$	$+$	$g_1 N^\dagger \pi_3 N$	$+$	$N^\dagger(d_0+d_1\tau_3)S^\mu v^\nu F_{\mu\nu} N$	$+\cdots$
	$\Downarrow$		$\Downarrow$		$\Downarrow$	

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

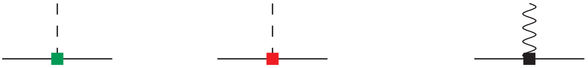
- chromo quark EDM: chiral symmetries are (& isospin ones may be) broken
  because of quark masses $\rightsquigarrow$ Goldstone theorem respected
- 4quark Left-Right EDM: **explicit** breaking of **chiral & isospin** symmetries
  because of underlying W boson exchange $\rightsquigarrow$ Goldstone th.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

back

Hierachy among the sources at the hadronic EFT level

Each source transforms differently under chiral and isospin symmetry

$$\begin{array}{cccccccc} & & \cancel{CP},\ \mathrm{I} & & \cancel{CP},\ \cancel{\mathrm{I}} & & \cancel{CP},\ \mathrm{I}+\cancel{\mathrm{I}} & \\ \mathcal{L}_{\mathrm{EFT}}^{\cancel{CP}} & = & g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N & + & g_1 N^\dagger \pi_3 N & + & N^\dagger(d_0+d_1\tau_3) S^\mu v^\nu F_{\mu\nu} N & +\cdots \\ & & \Downarrow & & \Downarrow & & \Downarrow & \end{array}$$



…

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 $\alpha_{\mathrm{em}}/(4\pi)$
- 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: $\cancel{CP}$ 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)

$\boxed{g_0^\theta: \quad N^\dagger \vec{\pi}\cdot\vec{\tau} N\text{-vertex}}$

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

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

$$\delta M_{np}^{em} \quad \rightarrow \quad \delta M_{np}^{str} = (2.44 \pm 0.18)\text{MeV}$$ 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)

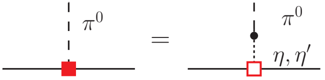
$\boxed{g_1^\theta: \quad \pi_3 NN\text{-vertex}}$

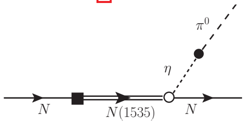
$$\epsilon := (m_u - m_d)/(m_u + m_d)$$

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

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

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





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

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

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

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

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

back BACK back loop

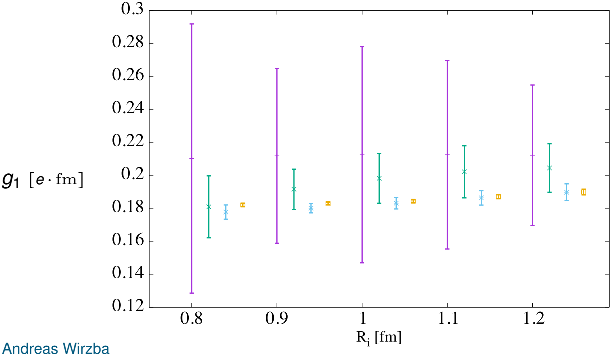
Deuteron Quantities in ChPT from NLO to N4LO

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

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

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

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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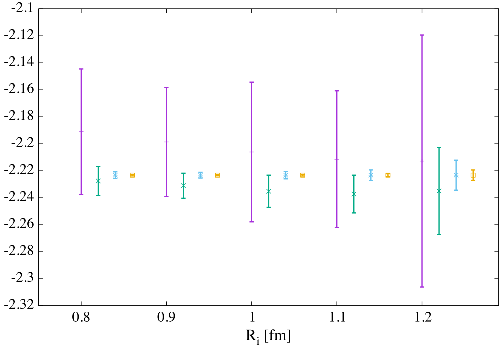
E_B^D [MeV]



NLO, N2LO, N3LO, N4LO

(-2.2233 ± 0.0004) MeV

back

Deuteron Quantities in ChPT from NLO to N4LO

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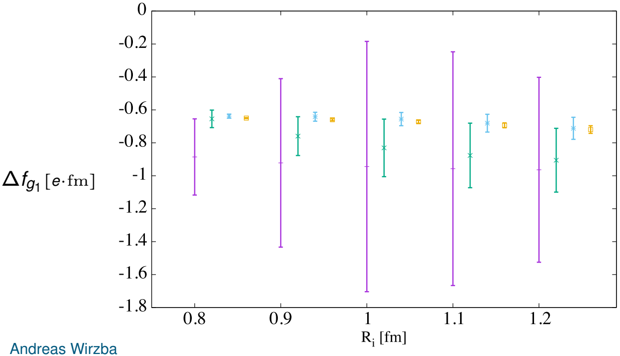
$$\Delta X^{\mathrm{N}} n\mathrm{LO}(p) \;=\; Q^{n+2} \cdot \max\left[\left|X^{\mathrm{LO}}(p)\right|, \frac{\left|X^{\mathrm{NLO}}(p) - X^{\mathrm{LO}}(p)\right|}{Q^2}, \frac{\left|X^{\mathrm{N2LO}}(p) - X^{\mathrm{NLO}}(p)\right|}{Q^3}, \frac{\left|X^{\mathrm{N3LO}}(p) - X^{\mathrm{N2LO}}(p)\right|}{Q^4}, \frac{\left|X^{\mathrm{N4LO}}(p) - X^{\mathrm{N3LO}}(p)\right|}{Q^5} \right] \quad \text{with} \quad Q = \max\left(\frac{|p|}{\Lambda_b^i}, \frac{M_\pi}{\Lambda_b^i}\right)$$

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

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

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

back

Deuteron Quantities in ChPT from NLO to N4LO

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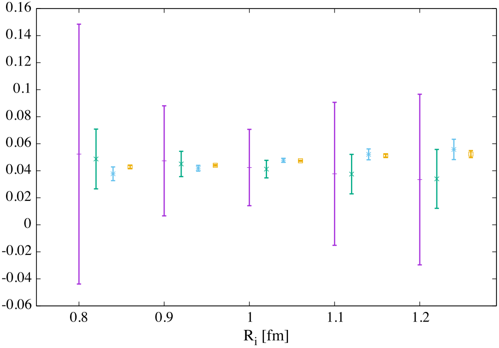
R_i	0.8 fm	0.9 fm	1.0 fm	1.1 fm	1.2 fm
Λ_b^i	0.6GeV	0.6GeV	0.6GeV	0.5GeV	0.4GeV

$P_{^3D_1}$



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

Deuteron Quantities in ChPT from NLO to N4LO

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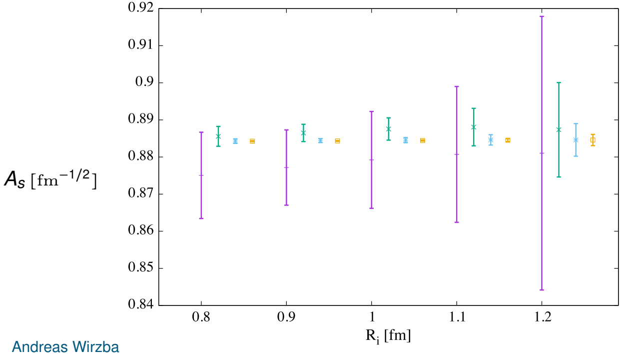

NLO, N2LO, N3LO, N4LO

(0.8844 ± 0.0001) fm$^{-1/2}$

back

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.*

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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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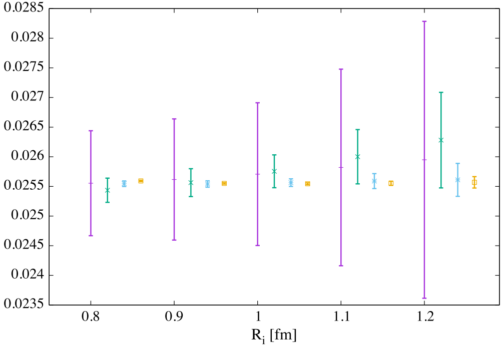
$\eta = D/S$



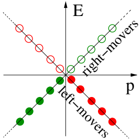
NLO, N2LO, N3LO, N4LO

(0.02555 ± 0.00001)

back

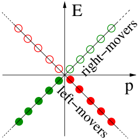
$U_A(1)$ anomaly in 1+1 D

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



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

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



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

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

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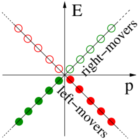

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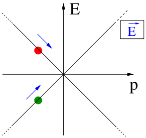

Nothing happens to single states,
except energy change.

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

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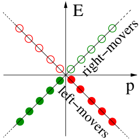

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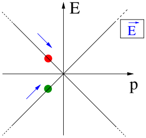

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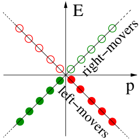

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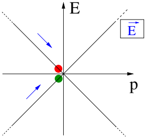

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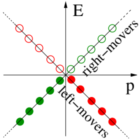

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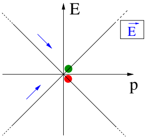

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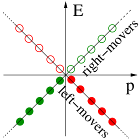

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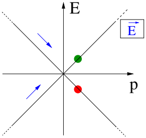

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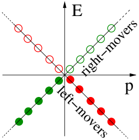

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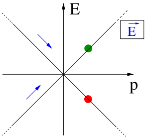

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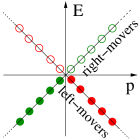

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$U_A(1)$ anomaly in 1+1 D

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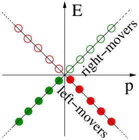

2. Add electric field
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Nothing happens to single states, except energy change.

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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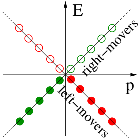

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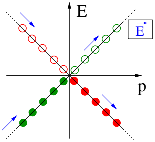

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$U_A(1)$ anomaly in 1+1 D

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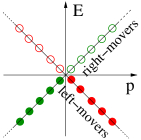

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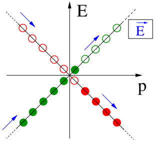

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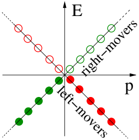

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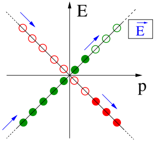

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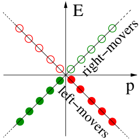

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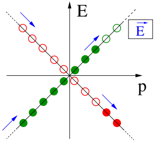

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The symmetries of QCD

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

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

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

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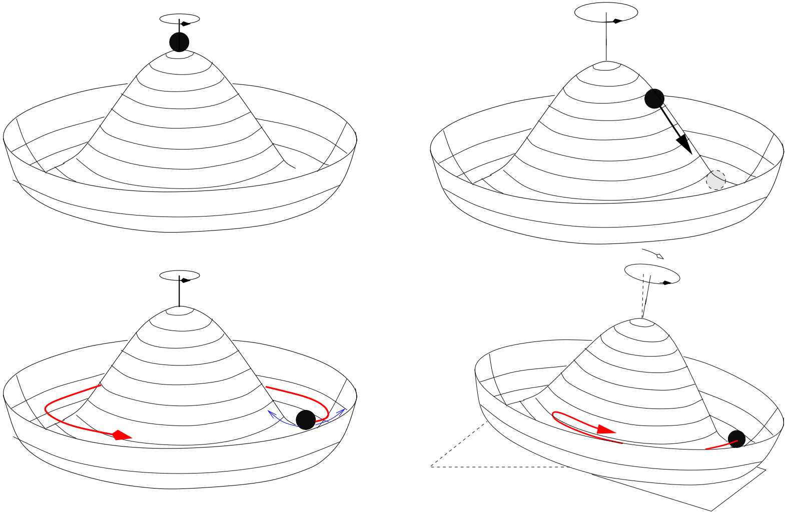
Illustration: spontaneous symmetry breaking (SSB)



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Decoupling theorem of Goldstone bosons

Goldstone bosons do not interact at zero energy/momentum

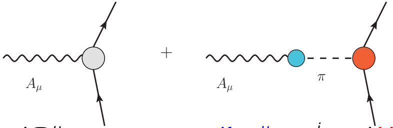
1. $Q_A^a|0\rangle \neq 0 \quad \Rightarrow \quad Q_A^a$ creates GB $\quad \Rightarrow \quad \langle \pi^a | Q_A^a | 0\rangle \neq 0.$
2. Lorentz invariance $\rightsquigarrow \langle \pi^a(q) | A_b^\mu(x) | 0 \rangle = -i f_\pi\, q^\mu\, \delta_b^a\, e^{iq\cdot x} \neq 0\,!$

   A_b^μ axial current

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

   (pion decay constant $f_\pi = 92\,\mathrm{MeV}$ from weak decay $\pi^+ \to \mu^+ \nu_\mu$)
3. Coupling of axial current A_μ to matter fields (and/or pions)

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



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

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

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