

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

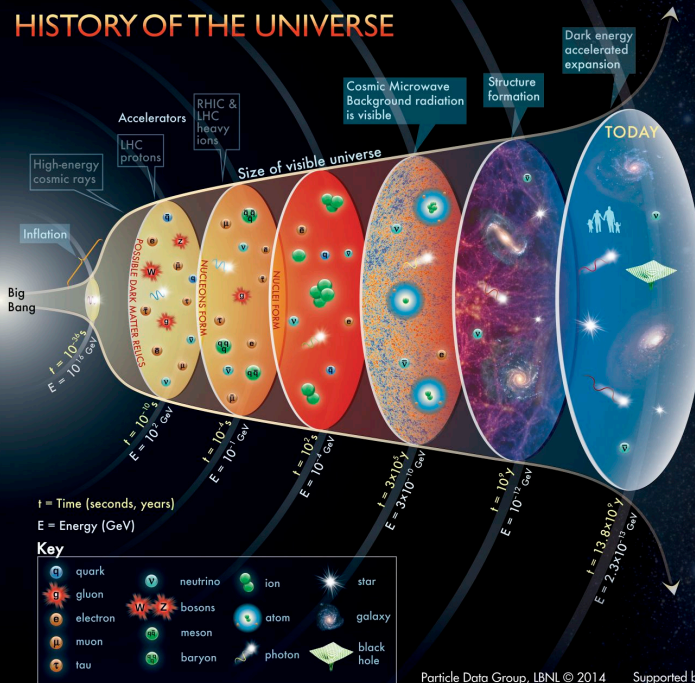
**Some things that will be
not addressed**

Figure about “Dark matter and assignment” omitted

Some questions that might hopefully be answered:

- 1 Why is ~~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 ~~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?

HISTORY OF THE UNIVERSE



Particle Data Group, LBNL © 2014

Supported by DOE

Matter Excess in the Universe

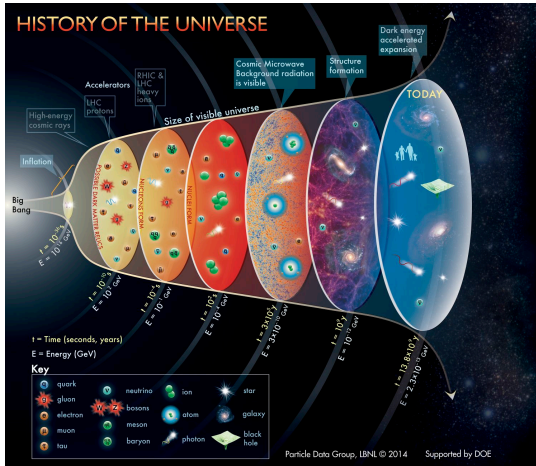


Fig. courtesy of PDG, LBNL © 2014

$$(*) \quad 2J_{\text{Jariskog}}^{\text{CKM}} (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2) \sim 10^{-18} M_{\text{EW}}^{12}$$

- 1 End of inflation: $n_B = n_{\bar{B}}$
- 2 Cosmic Microwave Bkgr.
 - SM(s) prediction: *
 $(n_B - n_{\bar{B}})/n_\gamma|_{\text{CMB}} \sim 10^{-18}$
 - WMAP+PLANCK ('13):
 $n_B/n_\gamma|_{\text{CMB}} = (6.05 \pm 0.07) 10^{-10}$

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

► in the SM?

CP violation and the Electric Dipole Moment (EDM)

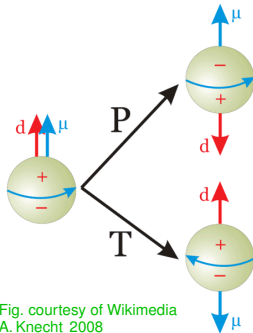


Fig. courtesy of Wikimedia
A. Knecht 2008

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

(polar) (axial)

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

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

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

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)
 $\hookrightarrow$ subatomic EDMs: “rear window” to CP violation in early universe
- Strongly suppressed in SM (CKM-matrix): $|d_n| \sim 10^{-31} \text{ e cm}$, $|d_e| \sim 10^{-38} \text{ e cm}$
- Current bounds: $|d_n| < 3^\circ / 1.6^\circ \cdot 10^{-26} \text{ e cm}$, $|d_p| < 2 \cdot 10^{-25} \text{ e cm}$, $|d_e| < 1 \cdot 10^{-28} \text{ e cm}$

n : Baker et al.(2006)[◊], p prediction: Dimitriev & Sen'kov (2003)^{*}, e : Baron et al.(2013)[†]

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

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

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

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

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Werner Bernreuther (2012)

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

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

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

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

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There are always vacuum polarizations with rich short-distance structure
($g-2$ of the electron and muon aren’t exactly zero either)

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‘What about the huge EDMs of H_2O or NH_3 molecules?’

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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 ~~T~~ nor ~~P~~ !

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The induced EDM is **quadratic** in the electric field and **neither** ~~P~~ **nor** ~~T~~

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

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State $|j^P\rangle$ can be 'elementary' particle (quark, charged lepton, $W^\pm$ boson, Dirac neutrino, ...) or a 'composite' neutron, proton, nucleus, atom, molecule.

If the interactions are described by an action which is

local, Lorentz-invariant, and hermitian

then **CPT** invariance holds: thus ~~T~~ $\iff$ ~~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

$$\mu_N = \frac{e}{2m_p} \sim 10^{-14} \text{ ecm}.$$

- A nonzero EDM requires

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

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

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

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

- In summary: $|d_N| \sim 10^{-7} \times 10^{-3} \times \mu_N \sim 10^{-24} \text{ ecm}$

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

$$\hookrightarrow |d_N^{\text{SM}}| \sim 10^{-7} \times 10^{-24} \text{ ecm} \sim 10^{-31} \text{ ecm}$$

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

$$10^{-24} \text{ ecm} > |d_N| > 10^{-30} \text{ ecm}.$$

Chronology of upper bounds on the neutron EDM

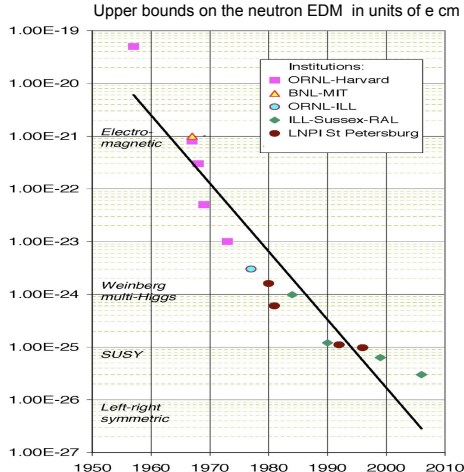


Fig. courtesy of N.N. Nikolaev

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

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

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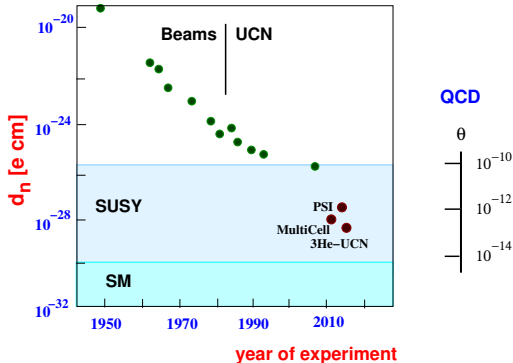
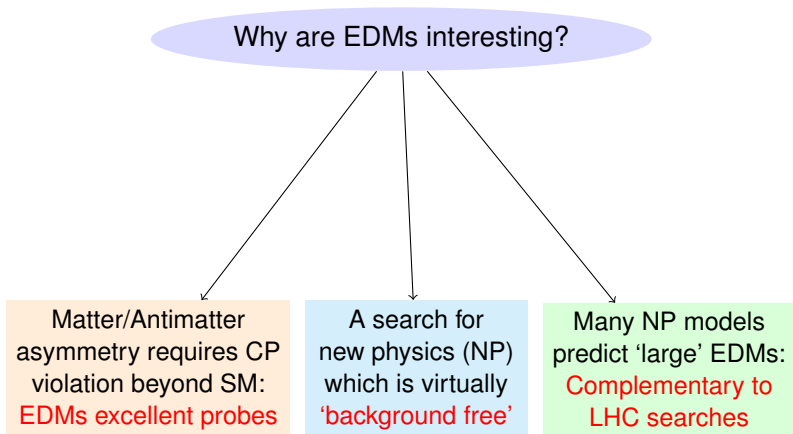


Fig. courtesy of U.-G. Meißner

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

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Three motivations for EDM searches



EDM bounds from neutral particles

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

current $d_n = (-0.21 \pm 1.82) \cdot 10^{-26} \text{ e cm}$

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

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

- Proton (and neutron) EDM inferred from **diamagnetic atoms**

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

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

$\rightarrow |d_p| < 2 \cdot 10^{-25} \text{ e cm} \quad \& \quad |d_n| < 1.6 \cdot 10^{-26} \text{ e cm}$

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

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

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

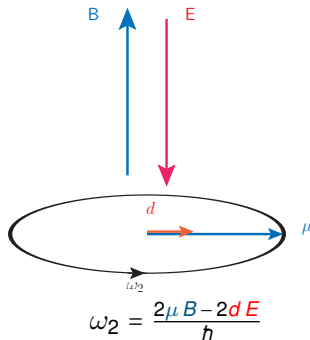
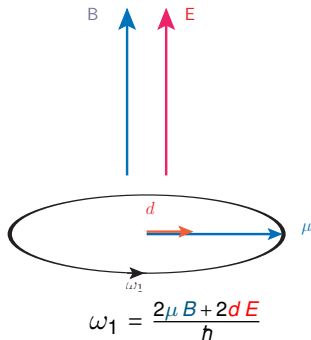
current $|d_e| < 8.7 \cdot 10^{-29} \text{ e cm} \quad (90\% \text{ C.L.})$

from polar ThO

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

EDM measurement of neutral particles in a nutshell

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

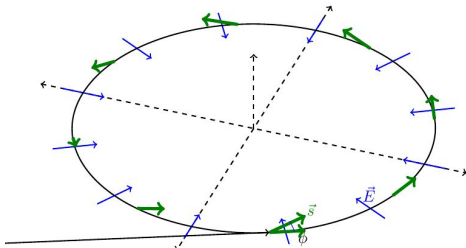


$$d = \frac{h(\omega_1 - \omega_2)}{4E}$$

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)

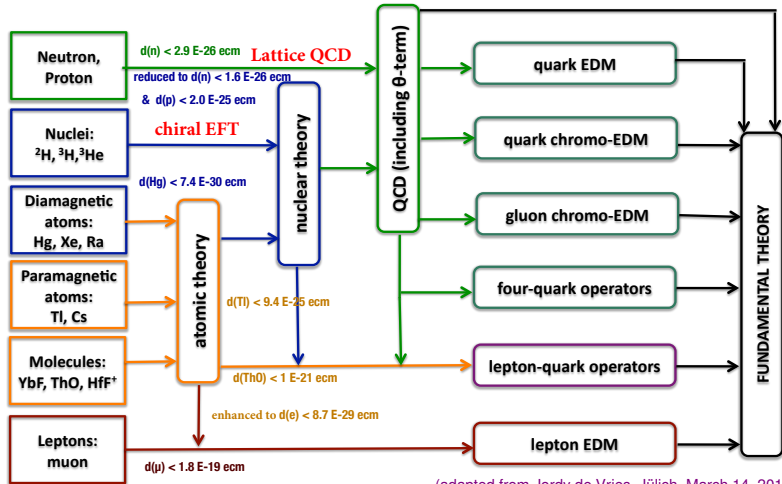
Limit on muon EDM: $d_\mu < 1.8 \cdot 10^{-19} \text{ e cm}$ (95 % C. L.) Bennett et al. (BNL g-2) *PRL* '09:

- Sensitivity of storage ring experiments $\sim 10^{-29} \text{ e cm}$
- But **systematical** errors $\sim ?$
- Precursor experiment $\gtrsim 10^{-(20 \dots 24)} \text{ e cm}$ for p or D planned at COSY@Jülich

Road map from EDM Measurements to EDM Sources

Experimentalist's point of view →

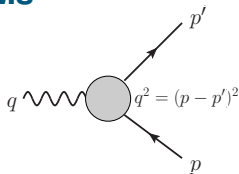
← Theorist's point of view



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

Calculation: from form factors to EDMs

$$\langle f(p') | J_{\text{em}}^\mu | f(p) \rangle = \bar{u}_f(p') \Gamma^\mu(q^2) u_f(p)$$



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

Dirac FF

Pauli FF

electric dipole FF (~~CP~~)

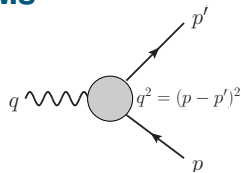
anapole FF (~~P~~)

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



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Dirac FF

Pauli FF

electric dipole FF (~~$\mathcal{CP}$~~)

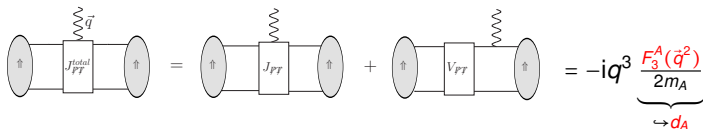
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$$\hookrightarrow d_f := \lim_{q^2 \rightarrow 0} \frac{F_3(q^2)}{2m_f} \quad \text{for } s = 1/2 \text{ fermion}$$



Nucleus A

$\langle \uparrow | J_{\vec{p}\vec{T}}^0(q) | \uparrow \rangle$
in Breit frame



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

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**
- $\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{gauge-fermion}} + \mathcal{L}_{\text{gauge-Higgs}} + \mathcal{L}_{\text{Higgs-fermion}}$ is CP inv.,
 - with the exception of the θ term of QCD (see later)

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

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

- V : 3×3 unitary quark-mixing matrix U : 3×3 unitary lepton-mixing matrix
(Cabibbo-Kobayashi-Maskawa matrix) (Pontecorvo-Maki-Nakagawa-Sakata m.)

3 angles + 1 $\cancel{\text{CP}}$ phase δ_{KM}

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

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

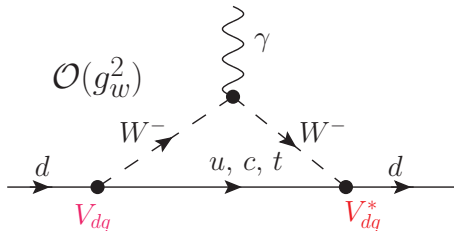
$$\propto \left(\frac{m_t^2 - m_c^2}{M_{EW}^2}\right) \left(\frac{m_c^2 - m_u^2}{M_{EW}^2}\right) \left(\frac{m_t^2 - m_u^2}{M_{EW}^2}\right) \cdot \left(\frac{m_b^2 - m_s^2}{M_{EW}^2}\right) \left(\frac{m_s^2 - m_d^2}{M_{EW}^2}\right) \left(\frac{m_b^2 - m_d^2}{M_{EW}^2}\right) \cdot J_{KM} \simeq 10^{-15}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

Jarlskog PRL '85

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

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

1 loop:



$$\rightarrow \text{CP phase } \delta_{KM} \text{ cancels} \rightarrow \text{prefactor real} \Rightarrow d_q^{1\text{-loop}} = 0$$

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

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

Jarlskog *PRL* '85

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

2 loops:

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

Shabalin *Sov.J.NP* '78

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

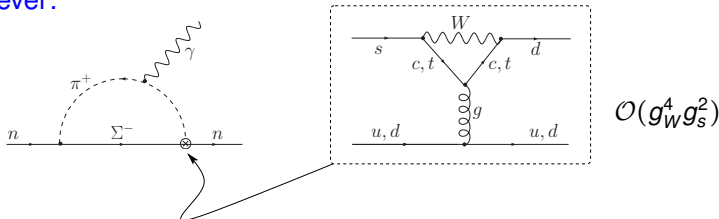
$$\propto \left(\frac{m_t^2 - m_c^2}{M_{EW}^2} \right) \left(\frac{m_c^2 - m_u^2}{M_{EW}^2} \right) \left(\frac{m_t^2 - m_u^2}{M_{EW}^2} \right) \cdot \left(\frac{m_b^2 - m_s^2}{M_{EW}^2} \right) \left(\frac{m_s^2 - m_d^2}{M_{EW}^2} \right) \left(\frac{m_b^2 - m_d^2}{M_{EW}^2} \right) \cdot J_{KM} \simeq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

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

however:



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

Gavela; Khriplovich & Zhitnitsky ('82)

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

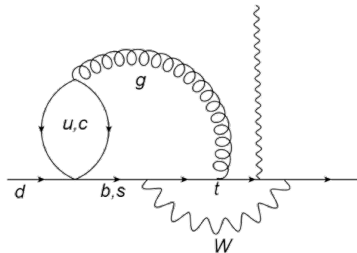
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EDM flavor-neutral $\Rightarrow$ KM predictions tiny: $\mathcal{O}(G_F^2) \sim \mathcal{O}(g_W^4)$

at ≥ 3 loops:



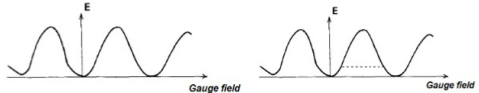
$$\mathcal{O}(g_W^4 g_s^2)$$

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

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** $\mathcal{P}$ & $\mathcal{T}$ $\leadsto$ **$\mathcal{CP}$** interaction with a new parameter θ :

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

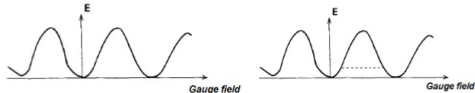
- **Anomalous** $U_A(1)$ quark-rotations induce mixing with 'mass' term

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

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

EDM sources: QCD θ -term of the SM

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

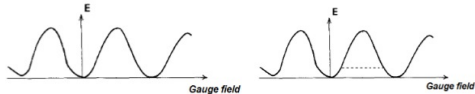
$$|d_n^{\bar{\theta}}| \sim \bar{\theta} \cdot \frac{m_q^*}{m_s} \cdot \frac{e}{2m_n} \sim \bar{\theta} \cdot 10^{-2} \cdot 10^{-14} \text{ e cm} \sim \bar{\theta} \cdot 10^{-16} \text{ e cm} \quad \text{with } \bar{\theta} \sim \mathcal{O}(1).$$

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

► **strong CP problem**

EDM sources: QCD θ -term of the SM

The topologically non-trivial vacuum structure of QCD



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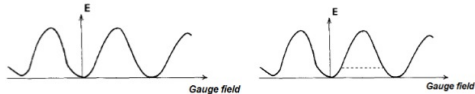
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$10^{-10} > |\bar{\theta}| > 10^{-14}$ eventually measurable via nonzero EDM, but because of $\Lambda_{\chi SB} \ll \Lambda_{EWSB}$ it doesn't explain the cosmic matter surplus.

EDM sources: QCD θ -term of the SM

The topologically non-trivial vacuum structure of QCD



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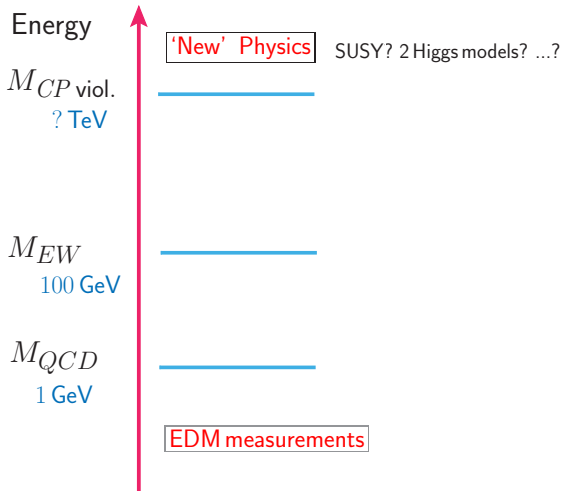
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Thus $\mathcal{CP}$ by new physics (NP) (*i.e.* dimension ≥ 6 sources beyond SM) needed to explain the cosmic matter-antimatter asymmetry.

How to handle CP-violating sources beyond the SM?

Running through the scales

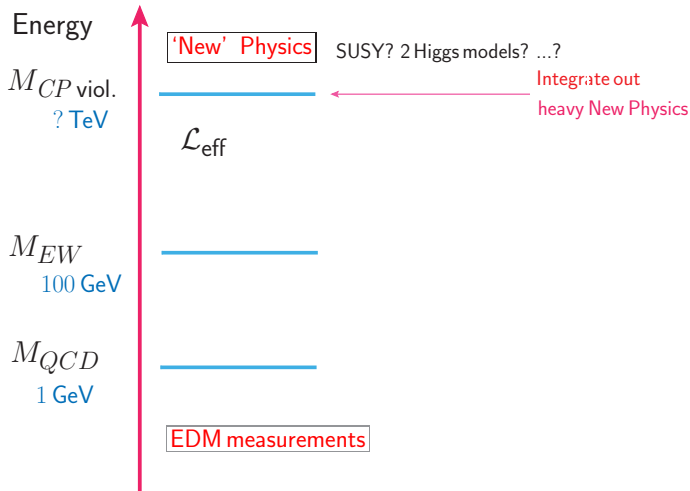
W. Dekens & J. de Vries, *JHEP* '13
recall talk by Vincenzo Cirigliano on 09/13/16



How to handle CP-violating sources beyond the SM?

Running through the scales

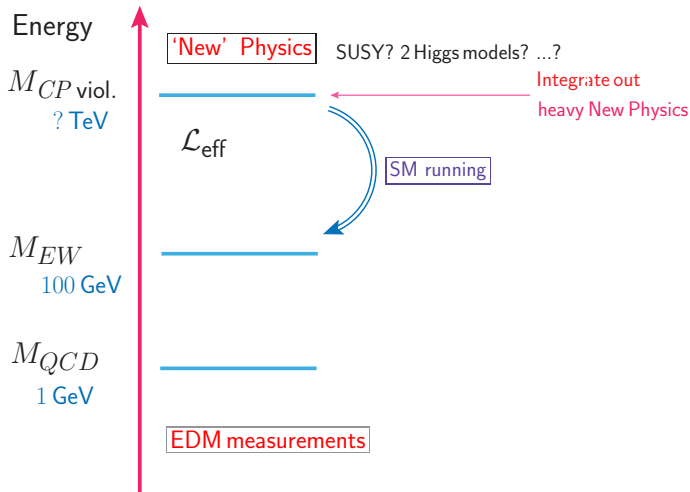
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How to handle CP-violating sources beyond the SM?

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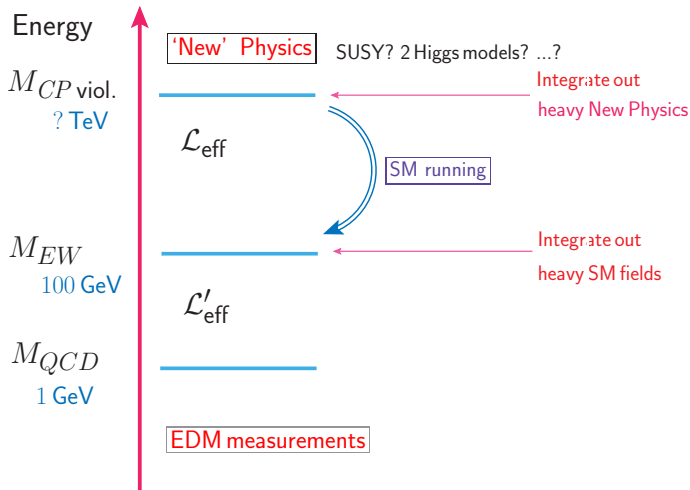
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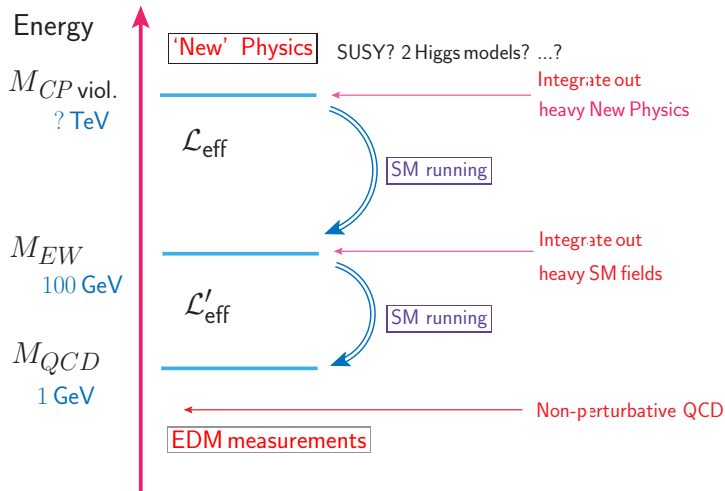
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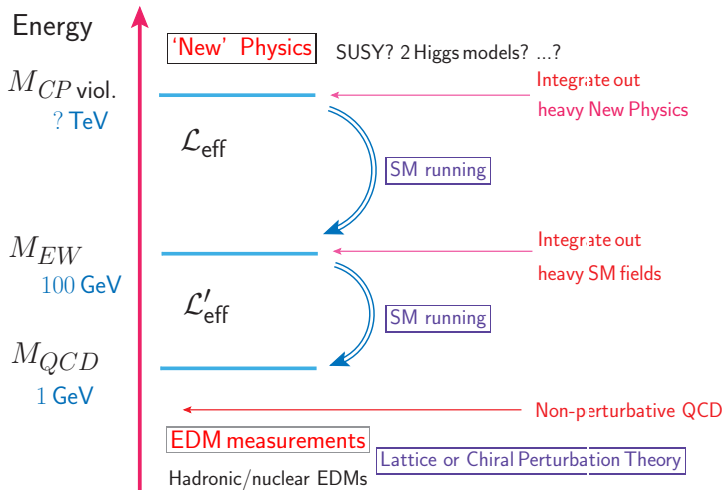
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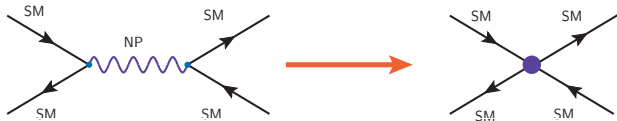
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How to handle CP-violating sources beyond the SM?

New interactions as higher dimensional operators

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



- The new interactions appear as higher dimensional operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_5^{(i)}}{M_{\chi}} \mathcal{O}_5^{(i)} + \sum_i \frac{c_6^{(i)}}{M_{\chi}^2} \mathcal{O}_6^{(i)} + \dots$$

where M_{χ} 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

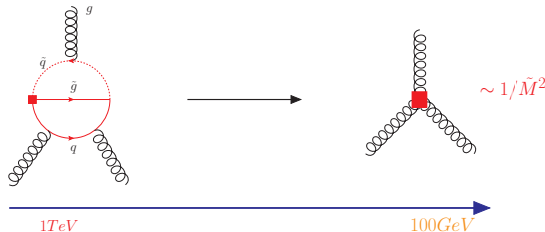
Not of dim. 5 because of **Higgs insertion** (chiral symm.) at **high** (low) scales

How to handle CP-violating sources beyond the SM?

Evaluation in Effective Field Theory (EFT) approach

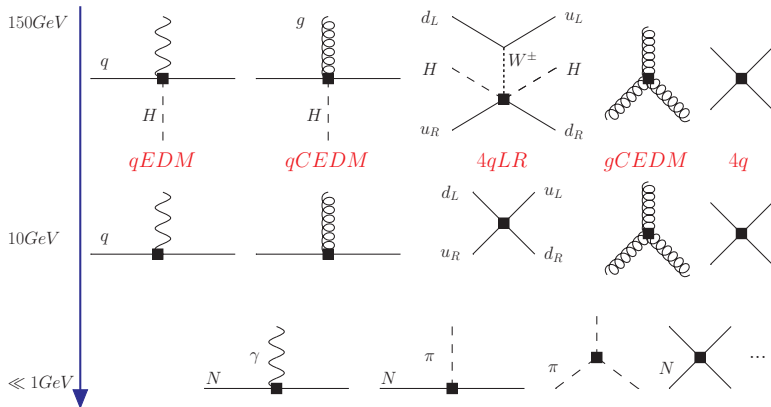
► EFT

- All degrees of freedom *beyond NP (EW) scale* are integrated out:
 $\hookrightarrow$ Only SM degrees of freedom remain: $q, g, (H, Z, W^\pm, \dots)$
- 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

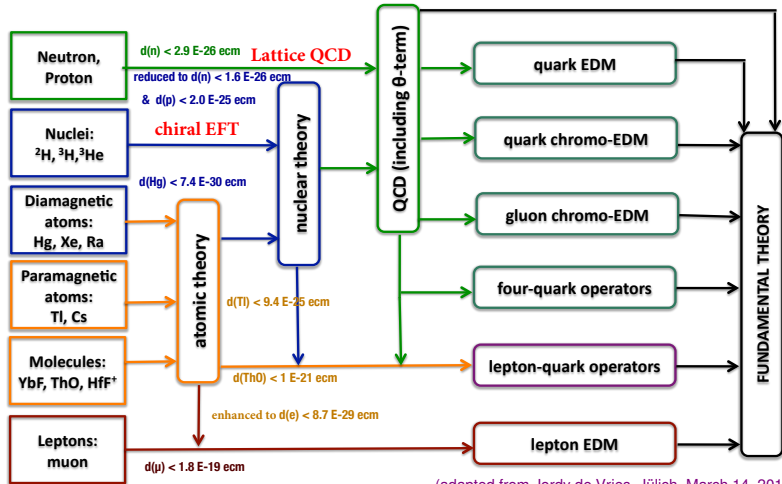


$$\begin{aligned} \text{Total \#} &= 1(\bar{\theta}) + 2(qEDM) + 2(qCEDM) + 1(4qLR) + 1(gCEDM) + 2(4q) \quad [+3(\text{semi}) + 1(\text{lept})] \\ &= 1(\text{dim-four}) + 8(\text{dim-six}) \quad [+3+1] \quad [\text{Caveat: } m_s \gg m_u, m_d \text{ \& } m_\mu \gg m_e \text{ assumed}] \end{aligned}$$

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



Dirk VorderstraBe

EDM Translator

from 'quarkish/machine' to 'hadronic/human' language?



3-CPO & R2-D2  Dirk Vorderstraße

→ 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 $\mathcal{CP}$ hadronic vertices

from θ to BSM sources

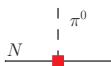
$g_0: \mathcal{CP}, I$

$g_1: \mathcal{CP}, I$

$d_0, d_1: \mathcal{CP}, I + I$

$(m_N \Delta): \mathcal{CP}, I$

$\mathcal{L}_{\text{EFT}}^{\mathcal{CP}}$:



θ -term:

$\mathcal{O}(1)$

$\mathcal{O}(M_\pi/m_N)$

$\mathcal{O}(M_\pi^2/m_N^2)$

$\mathcal{O}(M_\pi^2/m_N^2)$

qEDM:

$\mathcal{O}(\alpha_{EM}/(4\pi))$

$\mathcal{O}(\alpha_{EM}/(4\pi))$

$\mathcal{O}(1)$

$\mathcal{O}(\alpha_{EM}/(4\pi))$

qCEDM:

$\mathcal{O}(1)$

$\mathcal{O}(1)$

$\mathcal{O}(M_\pi^2/m_N^2)$

$\mathcal{O}(M_\pi^2/m_N^2)$

4qLR:

$\mathcal{O}(M_\pi^2/m_n^2)$

$\mathcal{O}(1)$

$\mathcal{O}(M_\pi^2/m_N^2)$

$\mathcal{O}(M_\pi/m_n)$

gCEDM:

$\mathcal{O}(M_\pi^2/m_N^2)^*$

$\mathcal{O}(M_\pi^2/m_N^2)^*$

$\mathcal{O}(1)$

$\mathcal{O}(M_\pi^2/m_N^2)$

4q:

$\mathcal{O}(M_\pi^2/m_N^2)^*$

$\mathcal{O}(M_\pi^2/m_N^2)^*$

$\mathcal{O}(1)$

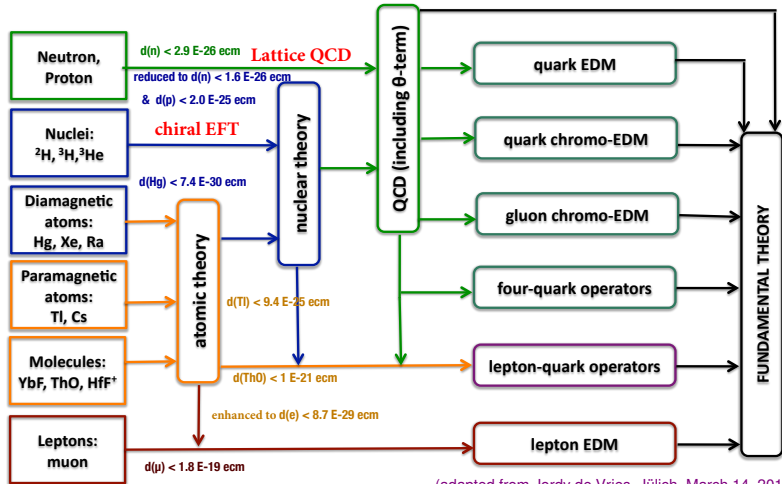
$\mathcal{O}(M_\pi^2/m_N^2)$

*: Goldstone theorem $\rightarrow$ 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:



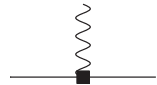
“controlled”

isovector

$\approx$

$\ll$

isoscalar



two “unknown” coefficients

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

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

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

$$g_\theta^{\text{isovector}} = \frac{(m_n - m_p)^{\text{strong}} (1 - \epsilon^2)}{4F_\pi \epsilon} \bar{\theta} \approx (-0.016 \pm 0.002) \bar{\theta} \quad (\text{where } \epsilon \equiv \frac{m_u - m_d}{m_u + m_d})$$

$$\hookrightarrow d_N^{\text{isovector}}|_{\text{loop}} \sim (1.8 \pm 0.3) \cdot 10^{-16} \bar{\theta} \text{ ecm} \quad \text{Bsaisou et al., } EPJA \text{'13 \& } JHEP \text{'15} \quad \text{details}$$

θ -Term Induced Nucleon EDM

single nucleon EDM:



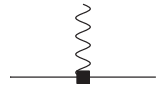
“controlled”

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

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

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

$$\hookrightarrow d_N^{\text{isovector}}|_{\text{loop}} \sim (1.8 \pm 0.3) \cdot 10^{-16} \bar{\theta} \text{ ecm} \quad \text{Bsaisou et al., } EPJA'13 \text{ \& } JHEP'15 \quad \text{details}$$

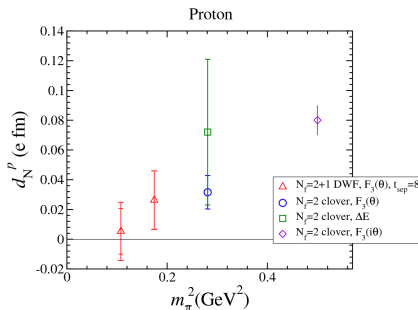
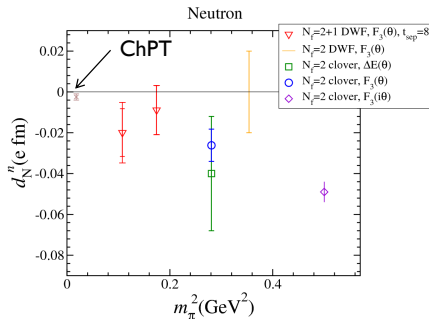
But what about the two “unknown” coefficients of the contact terms?

Preliminary Lattice (full QCD) results

neutron EDM

and

proton EDM



$\theta \equiv 1 !$

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

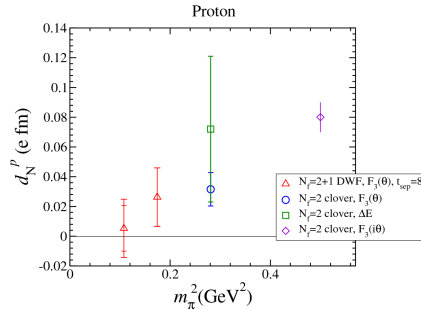
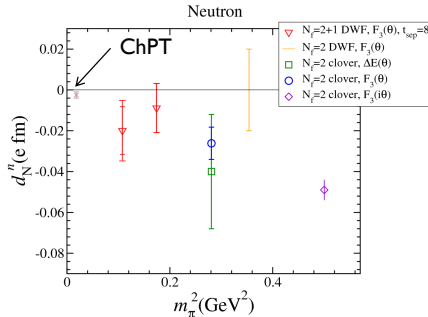
no systematical errors!

Preliminary Lattice (full QCD) results

neutron EDM

and

proton EDM



$\theta \equiv 1 !$

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

no systematical errors!

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

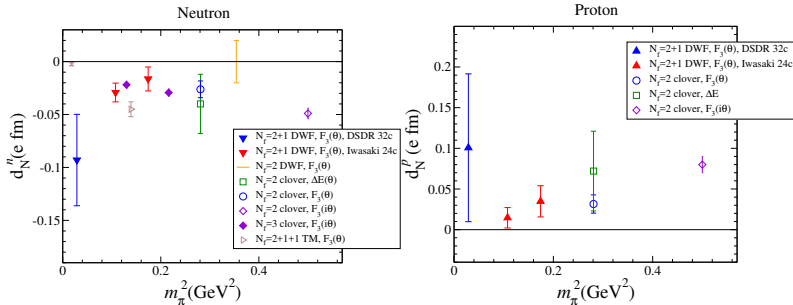
Akan, Guo & Meißner, *PLB* **736** (2014); see also $d_n = \bar{\theta} (-3.9 \pm 0.2 \pm 0.9) 10^{-3} \text{e fm}$ Guo et al., *PRL* **115** (2015)

Preliminary Lattice (full QCD) results

neutron EDM

and

proton EDM



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

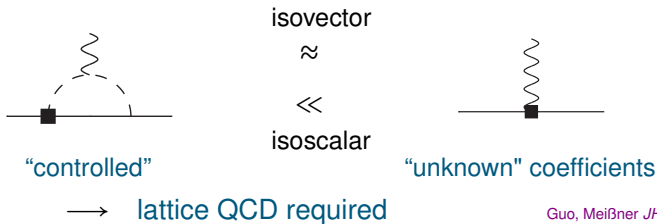
Eigo Shintani et al., *Phys. Rev. D* **93**, 094503 (2016) $M_\pi = 170, 330, 420, 530$ MeV

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:



Guo, Meißner *JHEP*'12

two nucleon EDM:

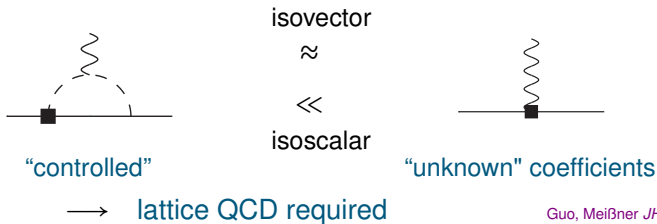
Sushkov, Flambaum, Khriplovich *Sov.Phys. JETP*'84



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:



Guo, Meißner *JHEP*'12

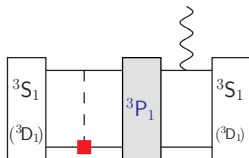
two nucleon EDM:

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

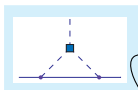


EDM of the Deuteron at LO: CP-violating π exchange

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



LO: $\cancel{g_0 N^\dagger \vec{\pi} \cdot \vec{\tau} N}$ ($\mathcal{CP}, I$) $\rightarrow 0$ (Isospin filter!)
 NLO: $g_1 N^\dagger \pi_3 N$ ($\mathcal{CP}, I$) $\rightarrow$ "LO" in D case



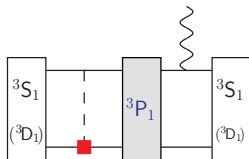
term	N ² LO ChPT	Av ₁₈	CD-Bonn	units
d_n^D	0.939 ± 0.009	0.914	0.927	d_n
d_p^D	0.939 ± 0.009	0.914	0.927	d_p
g_1	0.183 ± 0.017	0.186	0.186	g_1 e fm
Δf_{g_1}	-0.748 ± 0.138	-0.703	-0.719	Δ e fm

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

BSM $\mathcal{CP}$ sources: g_1 πNN vertex is of LO in qCEDM and 4qLR case

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

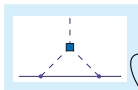
$$\mathcal{L}_{\cancel{CP}}^{\pi N} = -d_n N^\dagger (1 - \tau^3) S^\mu v^\nu N F_{\mu\nu} - d_p N^\dagger (1 + \tau_3) S^\mu v^\nu N F_{\mu\nu} \\ + (m_N \Delta) \pi^2 \pi_3 + \cancel{g_0 N^\dagger \vec{\pi} \cdot \vec{\tau} N} + \cancel{g_1 N^\dagger \pi_3 N} \\ + \cancel{C_1 N^\dagger N D_\mu (N^\dagger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



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

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

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

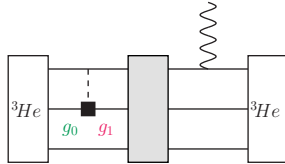


term	N ² LO ChPT	Av ₁₈	CD-Bonn	units
d_n^D	0.939 ± 0.009	0.914	0.927	d_n
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BSM $\cancel{CP}$ sources: g_1 πNN vertex is of LO in qCEDM and 4qLR case

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



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

LO: θ -term, qCEDM

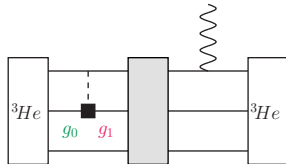
N²LO: 4qLR

$$g_1 N^\dagger \pi_3 N \quad (\text{CP}, I)$$

LO: qCEDM, 4qLR

NLO: θ term

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



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

LO: θ -term, qCEDM

N²LO: 4qLR

$g_1 N^\dagger \pi_3 N$ (CP, I)

LO: qCEDM, 4qLR

NLO: θ term

term	A	N ² LO ChPT	$\Lambda\chi_1 + \text{UIX}$	CD-Bonn+TM	units
d_n	^3He	0.904 ± 0.013	0.875	0.902	d_n
	^3H	-0.030 ± 0.007	-0.051	-0.038	
d_p	^3He	-0.029 ± 0.006	-0.050	-0.037	d_p
	^3H	0.918 ± 0.013	0.902	0.876	
Δ	^3He	-0.017 ± 0.006	-0.015	-0.019	Δ efm
	^3H	-0.017 ± 0.006	-0.015	-0.019	
g_0	^3He	0.111 ± 0.013	0.073	0.087	g_0 efm
	^3H	-0.108 ± 0.013	-0.073	-0.085	
g_1	^3He	0.142 ± 0.019	0.142	0.146	g_1 efm
	^3H	0.139 ± 0.019	0.142	0.144	
Δf_{g_1}	^3He	-0.608 ± 0.142	-0.556	-0.586	Δ efm
	^3H	-0.598 ± 0.141	-0.564	-0.576	
C_1	^3He	-0.042 ± 0.017	-0.0014	-0.016	C_1 efm ⁻²
	^3H	0.041 ± 0.016	0.0014	0.016	
C_2	^3He	0.089 ± 0.022	0.0042	0.033	C_2 efm ⁻²
	^3H	-0.087 ± 0.022	-0.0044	-0.032	

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

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

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Δ	^3He	-0.017 ± 0.006	-0.015	-0.019	Δ efm
	^3H	-0.017 ± 0.006	-0.015	-0.019	
g_0	^3He	0.111 ± 0.013	0.073	0.087	g_0 efm
	^3H	-0.108 ± 0.013	-0.073	-0.085	
g_1	^3He	0.142 ± 0.019	0.142	0.146	g_1 efm
	^3H	0.139 ± 0.019	0.142	0.144	
Δf_{g_1}	^3He	-0.608 ± 0.142	-0.556	-0.586	Δ efm
	^3H	-0.598 ± 0.141	-0.564	-0.576	
C_1	^3He	-0.042 ± 0.017	-0.0014	-0.016	C_1 efm ⁻²
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Discriminating between three scenarios at 1 GeV

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

- 1 The Standard Model + $\bar{\theta}$

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

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

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

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

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

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

matched on

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

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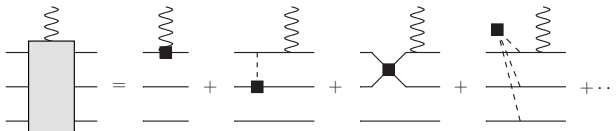
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matched on



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

$$d_{3\text{He}} - 0.9d_n = -\bar{\theta} \left(1.01 \pm 0.31_{\text{had}} \pm 0.29^*_{\text{nuc1}} \right) \cdot 10^{-16} \text{e cm}$$

Extraction of $\bar{\theta}$

* includes ± 0.20 uncertainty from 2N contact terms

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Extraction of $\bar{\theta}$

$$d_D - 0.94(d_n + d_p) = \bar{\theta} \left(0.89 \pm 0.29_{\text{had}} \pm 0.08_{\text{nuc1}} \right) \cdot 10^{-16} \text{e cm}$$

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

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(& triton EDM): $d_D^{\text{Nuc1}} \approx -d_{3\text{He}}^{\text{Nuc1}} \approx \frac{1}{2} d_{3\text{H}}^{\text{Nuc1}}$

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

*includes ± 0.20 uncertainty from 2N contact terms

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

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

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



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

Extraction of Δ^{LR}

* includes ± 0.1 uncertainty from 2N contact terms

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$$d_D - 0.94(d_n + d_p) \simeq d_D = -(2.1 \pm 0.5^*) \Delta^{LR} \text{ efm}$$

Extraction of Δ^{LR}

$$d_{^3\text{He}} - 0.9d_n \simeq d_{^3\text{He}} = -(1.7 \pm 0.5^*) \Delta^{LR} \text{ efm}$$

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

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Testing strategies: minimal LR symmetric Model

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

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

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

* 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
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Measurement of the deuteron
and nucleon EDMs

$$d_D - 0.94(d_n + d_p) = [(0.18 \pm 0.02)g_1 - (0.75 \pm 0.14)\Delta] \text{ efm}$$

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)

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

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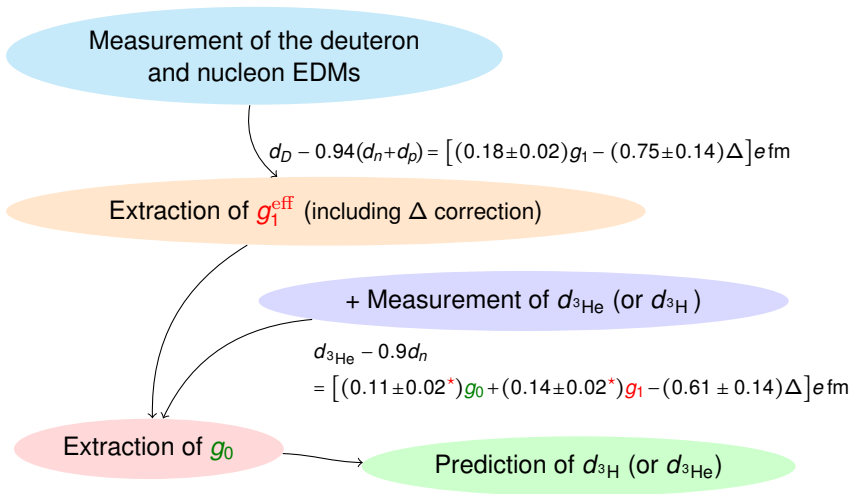
$$\begin{aligned} d_{^3\text{He}} - 0.9d_n \\ = [(0.11 \pm 0.02^*)g_0 + (0.14 \pm 0.02^*)g_1 - (0.61 \pm 0.14)\Delta] \text{ e fm} \end{aligned}$$

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)



*includes ± 0.01 uncertainty from 2N contact terms

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 $d_{^3\text{He}/^3\text{H}} = 0.9d_{n/p}$
- **gCEDM, 4quark χ singlet**: controlled calculation difficult (lattice ?)
- Ultimate progress may eventually come from **Lattice QCD**
 $\hookrightarrow \mathcal{CP}$ $N\pi$ 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: $|d_{199\text{Hg}}| < 7.4 \cdot 10^{-30} \cdot e \cdot \text{fm}$

Graner et al. *PRL* '16

- The **atomic** part of the calculation is well under control

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

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

S_{Hg} : Nuclear Schiff moment

- But the **nuclear** part isn't ...

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

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 $\leadsto$ 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) CP**
- EDM measurements are characteristically of **low-energy nature**:
 - non-leptonic predictions have to be in the *language of hadrons*
 - only systematical methods: **ChPT/EFT** and **Lattice QCD**
- EDMs of light nuclei provide **independent information** to nucleon ones and may be even larger and, moreover, even **simpler**

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

Many thanks to my colleagues

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

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

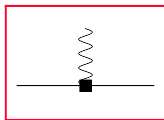
and: Werner Bernreuther, Bira van Kolck, and Kolya Nikolaev

References:

- 1** J. Baisou, 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].
- 2** J. Baisou, C. Hanhart, S. Liebig, D. Minossi, U.-G. Meißner, A. Nogga and A.W.,
Electric dipole moments of light nuclei, JHEP **03**, 104 (05,083) (2015), arXiv:1411.5804.
- 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. Baisou, 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. Baisou, 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

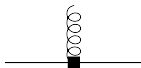
If $\bar{\theta}$ -term tests fail, then effective BSM dim. 6 sources de Vries et al.(2011)



$qEDM$

$$d_D \approx d_p + d_n$$

$$d_{3He} \approx d_n$$



$qCEDM$

$$d_D > d_p + d_n$$

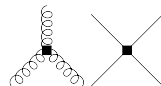
$$d_{3He} > d_n$$



$4qLR$

$$d_D > d_p + d_n$$

$$d_{3He} > d_n$$



$gCEDM + 4qEDM$

$$d_D \sim d_p + d_n$$

$$d_{3He} \sim d_n$$

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

$2N$ contribution suppressed by photon loop!

here: only absolute values considered

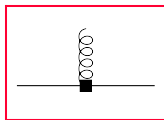
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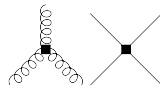
$$d_{3He} > d_n$$



$4qLR$

$$d_D > d_p + d_n$$

$$d_{3He} > d_n$$



$gCEDM + 4qEDM$

$$d_D \sim d_p + d_n$$

$$d_{3He} \sim d_n$$

→ g_0, g_1 dominant and of the same order

$2N$ contribution enhanced!

here: only absolute values considered

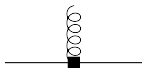
If $\bar{\theta}$ -term tests fail, then effective BSM dim. 6 sources de Vries et al.(2011)



$qEDM$

$$d_D \approx d_p + d_n$$

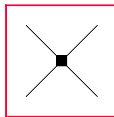
$$d_{3He} \approx d_n$$



$qCEDM$

$$d_D > d_p + d_n$$

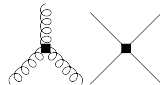
$$d_{3He} > d_n$$



$4qLR$

$$d_D > d_p + d_n$$

$$d_{3He} > d_n$$



$gCEDM + 4qEDM$

$$d_D \sim d_p + d_n$$

$$d_{3He} \sim d_n$$

→ $g_1 \gg g_0$; 3π -coupling (unsuppressed in 3He)

isospin-breaking $2N$ contribution enhanced!

here: only absolute values considered

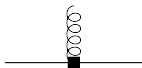
If $\bar{\theta}$ -term tests fail, then effective BSM dim. 6 sources de Vries et al.(2011)



$qEDM$

$$d_D \approx d_p + d_n$$

$$d_{3He} \approx d_n$$



$qCEDM$

$$d_D > d_p + d_n$$

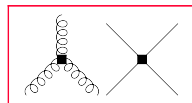
$$d_{3He} > d_n$$



$4qLR$

$$d_D > d_p + d_n$$

$$d_{3He} > d_n$$



$gCEDM + 4qEDM$

$$d_D \sim d_p + d_n$$

$$d_{3He} \sim d_n$$

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

$2N$ contribution difficult to assess!

here: only absolute values considered

Generic features of a permanent EDM

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

Generic features of a permanent EDM

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

- 1 For any non-zero EDM, $\mathcal{CP}$ 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: $\frac{1}{2}(\mathbf{1} - \gamma_5)f \equiv f_L \leftrightarrow f_R \equiv \frac{1}{2}(\mathbf{1} + \gamma_5)f$

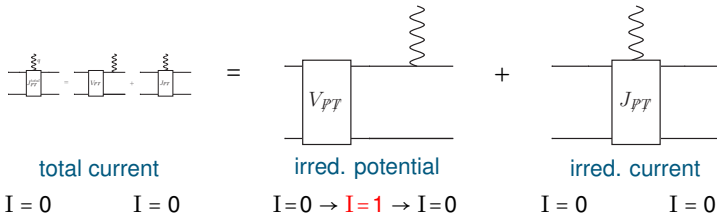
$$\mathcal{L}_{\text{EDM}} = -i \frac{d_f}{2} \bar{f} \sigma_{\mu\nu} \gamma_5 f F^{\mu\nu} = -i \frac{d_f}{2} \bar{f}_L \sigma_{\mu\nu} f_R F^{\mu\nu} + i \frac{d_f}{2} \bar{f}_R \sigma_{\mu\nu} f_L F^{\mu\nu}$$
 $\Rightarrow$ fermion mass m_f insertion (e.g. via Higgs mechanism) needed:
 $d_f \propto m_f^n, \quad n = 1, 2, 3$ (depending on the model of $\mathcal{CP}$)
 $\hookrightarrow \mathcal{CP}$ beyond SM: $\mathcal{L}_{\text{BSM}}^{\mathcal{CP}} = \frac{1}{M_{\text{BSM}}} \mathcal{L}^{\dim 5} + \frac{1}{M_{\text{BSM}}^2} \mathcal{L}^{\dim 6} + \dots$

EDM of the Deuteron:

Deuteron (D) as Isospin Filter

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

2N-system: $I + S + L = \text{odd}$



isospin selection rules!

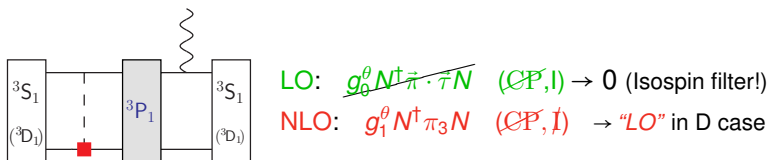


~~$g_0^\theta N^\dagger \vec{\pi} \cdot \vec{\tau} N$~~ at leading order (LO)



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

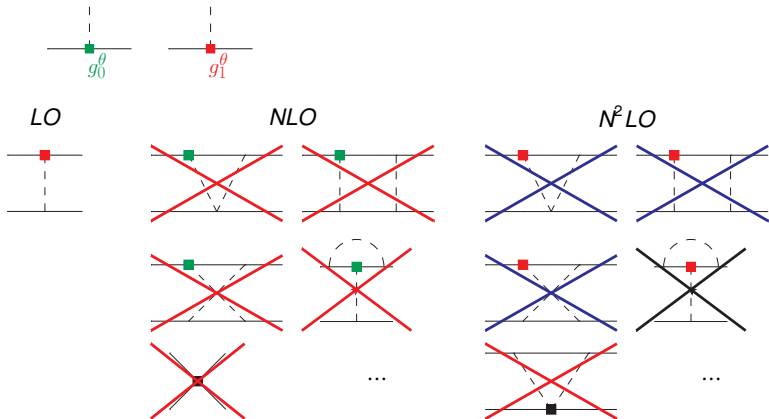


Reference	potential	result [$g_1 g_{\pi NN}$ e fm]
Liu & Timmermans (2004)	Av_{18}	1.43×10^{-2}
Afnan & Gibson (2010)	Reid 93	1.53×10^{-2}
Song et al. (2013)	Av_{18}	1.45×10^{-2}
JBC (2014)*	Av_{18}	1.45×10^{-2}
Bsaisou et al. (2013) $^\diamond$	CD Bonn	1.52×10^{-2}
JBC (2014)*	ChPT (N^2LO)	$(1.43 \pm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

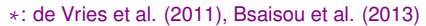
* unpublished, $^\diamond$ Eur. Phys. J. A **49** (2013) 31 [arXiv:1209.6306]

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

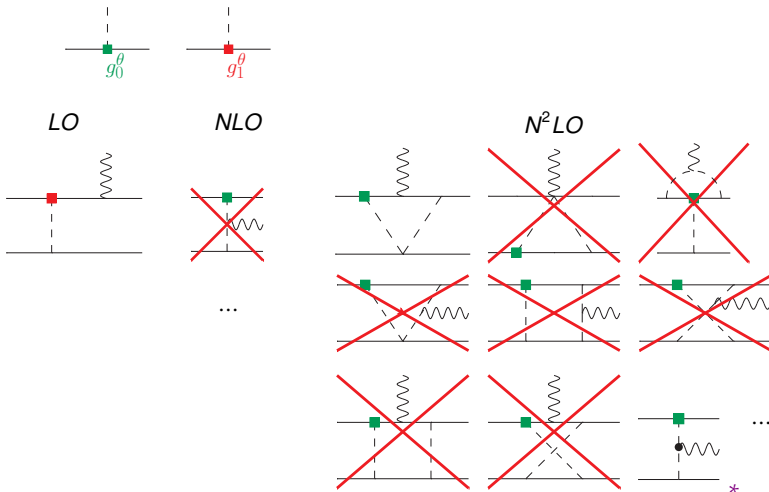
EDM of the Deuteron: NLO - and N^2LO -Potentials



- $\times$: vanishing by selection rules, $\times$: sum of diagrams vanishes
- $\times$: vertex correction



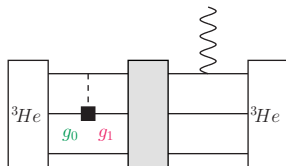
EDM of the Deuteron: NLO - and N^2LO -Currents



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

- $\times$: vanishing by selection rules, $\times$: sum of diagrams vanishes

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



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

LO: θ -term, qCEDM

$N^2\text{LO}$: 4qLR

$$g_1 N^\dagger \pi_3 N \quad (\text{CP}, I)$$

LO: qCEDM, 4qLR

NLO: θ term

Reference	potential	result [$g_0 g_{\pi NN}$ efm]	result [$g_1 g_{\pi NN}$ efm]
Stetcu et al.(2008)	A_{V18} UIX	$1.20 \times 10^{-2} / 2^\diamond$	$2.20 \times 10^{-2} / 2^\diamond$
Song et al.(2013)	A_{V18} UIX	0.55×10^{-2}	1.06×10^{-2}
JBC (2014) $^\diamond$	A_{V18} 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 ($N^2\text{LO}$)	$(0.86 \pm 0.11) \times 10^{-2}$	$(1.11 \pm 0.14) \times 10^{-2}$

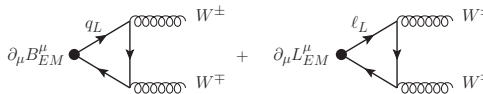
$^\diamond$ unpublished

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:



$$\begin{aligned}
 & \partial_\mu B_{EM}^\mu \quad + \quad \partial_\mu L_{EM}^\mu \quad \propto N_c \cdot (Q_u + Q_d) + (0 - 1) = 1 - 1 = 0 \\
 & \hookrightarrow \Delta(Q_B + Q_L) = 0 \text{ (charge conservation!)}
 \end{aligned}$$

EW Baryogenesis: Standard Model

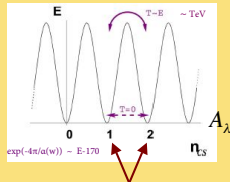
Conservation of the Baryon–Lepton current under $(L - R)$ interactions:

$$\begin{aligned}
 & \partial_\mu B^\mu \quad \begin{array}{c} \nearrow q_L \\ \searrow \end{array} \begin{array}{c} \text{-----} W^\pm \\ \text{-----} W^\mp \end{array} \\
 & \quad \quad \quad - \quad \partial_\mu L^\mu \quad \begin{array}{c} \nearrow \ell_L \\ \searrow \end{array} \begin{array}{c} \text{-----} W^\pm \\ \text{-----} W^\mp \end{array} \quad \propto N_C \cdot 1/3 - 1 = 1 - 1 = 0 \\
 & \quad \quad \quad \hookrightarrow \Delta(B - L) = 0 \quad \text{but} \quad \Delta(B + L) \neq 0 !
 \end{aligned}$$

Sakharov criteria

- 1 B violation ✓
($\Delta(B+L) \neq 0$ sphaleron transitions)
- 2 C & CP violation ✗
(CKM determinant)
- 3 Nonequilibrium dynamics ✗
(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

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

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

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

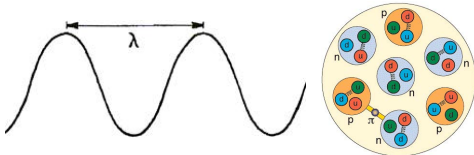
$$d_p = \lambda_u^p d_u + \lambda_d^p d_d = \frac{4}{3} d_u - \frac{1}{3} d_d \quad \text{such that} \quad d_p - d_n = \frac{N_c+2}{3} (d_u - d_d)$$

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

What are Effective Field Theories (EFT)?

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

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



Effective Field Theory: Weinberg's conjecture

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

Weinberg 1979

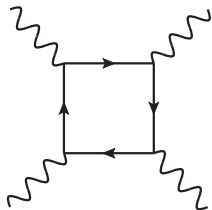
To calculate the S-matrix for any theory below some scale,
simply use the **most general effective Lagrangian** consistent with
these principles in terms of the **appropriate asymptotic states**
(i.e. the general S-matrix can be obtained by perturbation theory using some
effective lagrangian from the 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 $\leadsto$ estimate of **uncertainty** possible

EFT example: light-by-light scattering

Euler, Heisenberg, Kockel (1935/6)



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

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

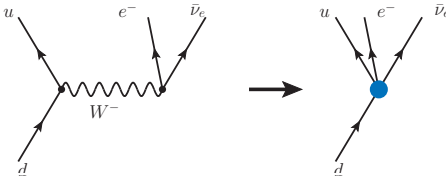
- calculation from the underlying theory, QED, yields $7a = b = 14/45$
- energy **power law** expansion: $(\omega/m_e)^{2n}$
- $\mathcal{L}_{\text{eff}}$ more efficient than full QED for calculating cross sections etc.

◀ back

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

Weak decays:

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



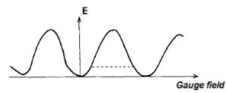
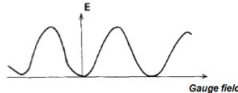
$$\frac{e^2}{8 \sin \theta_w} \times \frac{1}{M_W^2 - q^2} \xrightarrow{q^2 \ll M_W^2} \underbrace{\frac{e^2}{8 M_W^2 \sin \theta_w}}_{G_F / \sqrt{2}} \left(1 + \frac{q^2}{M_W^2} + \dots \right) + \mathcal{O}(q^2/M_W^2)$$

↪ Fermi's current-current interaction

◀ back

θ vacua in strong interaction physics

The topologically non-trivial vacuum structure of QCD



induces **winding number n** and **strong gauge transformation (instanton)**

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

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

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

$\leadsto$ **Theta vacuum:**

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

Note

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

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

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

θ term

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

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

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

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

◀ back

Strong CP problem: Peccei-Quinn symmetry and axions

R. Peccei & H. Quinn (1977)

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

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

- 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 make mass term real again)

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

→ or instead $G\tilde{G}$ term becomes: $(-\theta - \arg \det \mathcal{M} + a/f_a) \frac{g_s^2}{16\pi^2} \text{tr } G\tilde{G}$

- Make the trivial U(1) shift $a \rightarrow a + (\theta + \arg \det \mathcal{M}) \times f_a$.
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 !

◀ back

Axions and EDMs: generic effective Lagrangian of the axion

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

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

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

δ_{KM} = Kobayashi-Maskawa phase in the PQ-invariant SM

δ_{BSM} = $\mathcal{CP}$ phase in PQ-invariant BSM at the scale m_{BSM}

δ_{UV} = $\mathcal{CP}$ phase in explicit PQ-breaking sector at $m_{UV} \sim M_{\text{Planck}}$

$$V_{\text{QCD}} \sim \underbrace{f_\pi^2 m_\pi^2}_{10^{-14}} \cos(a/f_a) \quad (\text{expl. PQ-breaking by low-energy QCD})$$

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

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

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

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

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

→ 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 $\sim 10^{-10}$.

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

likely dominated by $\bar{\theta}_{\text{UV}}$ induced by $\mathcal{CP}$ in the PQ sector @ $m_{\text{UV}} (\sim M_{\text{Pl}})$, 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

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

and let the **axion decay constant** f_a be in the window

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

→ Axions in our galaxy *spatially* constant over a scale of $\lesssim 500 \text{ km} \times (f_a / M_{\text{GUT}})$:

↪ Ansatz: $a(t, \vec{x}) \approx a(t) = a_0 \cos(m_a t)$ in the lab.

- Equating $\frac{1}{2} m_a^2 a_0^2 \sim \rho_{\text{local DM}} \approx (0.3 \pm 0.1) \text{ GeV/cm}^3$ gives as **axion amplitude**

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

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

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

Non-relativistic reduction of

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

$$- \int d^3x \frac{a_f}{2} \bar{\psi}_f \sigma^{ij} \psi_f F_{ij} + \dots$$

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

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

$$\rightarrow a_f \int d^3x \bar{\psi}_f \vec{\sigma} \psi_f \cdot \vec{B}$$

$$= a_f \langle \vec{\sigma} \rangle \cdot \vec{B}$$

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

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

$$i \int d^3x \frac{d_f}{2} \bar{\psi}_f \sigma^{0i} \gamma_5 \psi_f F_{0i} \times 2 + \dots$$

$$\rightarrow i d_f \int d^3x \bar{\psi}_f i \begin{pmatrix} 0 & \sigma_i \\ \sigma_i & 0 \end{pmatrix} \gamma_5 \psi_f F^{i0}$$

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

$$\rightarrow i^2 d_f \int d^3x \bar{\psi}_f \vec{\sigma} \psi_f \cdot \vec{E}$$

$$= -d_f \langle \vec{\sigma} \rangle \cdot \vec{E}$$

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

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

Transformation Properties of the Form Factor Γ^μ

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

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

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

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

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**:

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

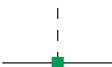
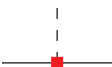
where M_U & M_D are **3×3 unitary matrices**

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

- M unitary $n_G \times n_G$ matrix for n_G quark generations $\leadsto$ **n_G^2 real parameters**.
- $2n_G - 1$ of these can be absorbed by the relative phases of the quark wave functions $\leadsto$ **$(n_G - 1)^2$** 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: $\leadsto$ 3 angles plus 3 $\cancel{CP}$ phases
- If phase(s) present, M complex matrix, whereas CP invariance $\leadsto M^* = M$!

Hierarchy among the sources at the hadronic EFT level

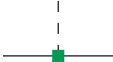
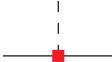
Each source transforms differently under chiral and isospin symmetry

$\mathcal{CP}, I$	$\mathcal{CP}, I$	$\mathcal{CP}, I + \bar{I}$
$\mathcal{L}_{\text{EFT}}^{\mathcal{CP}} = g_0 N^\dagger \vec{\pi} \cdot \vec{\tau} N$ $\Downarrow$ 	$g_1 N^\dagger \pi_3 N$ $\Downarrow$ 	$N^\dagger (d_0 + d_1 \tau_3) S^{\mu\nu} F_{\mu\nu} N$ $\Downarrow$ 
dominant for $\bar{\theta}$ term	suppressed for $\bar{\theta}$ term	suppressed by $\mathcal{O}(M_\pi^2)$

- $\mathcal{L}_{\text{QCD}}^\theta = \bar{\theta} m_q^* \sum_f \bar{q}_f i \gamma_5 q_f$: $\mathcal{CP}, I$ $m_q^* = \frac{m_u m_d}{m_u + m_d}$
 $\rightarrow \bar{\theta}$ source breaks chiral symmetry ($\propto m_q^*$) but conserves the isospin one:
 - $\rightarrow |g_0^\theta| \gg |g_1^\theta|$: 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

Hierarchy among the sources at the hadronic EFT level

Each source transforms differently under chiral and isospin symmetry

$\mathcal{CP}, I$	$\mathcal{CP}, I$	$\mathcal{CP}, I + I$
$\mathcal{L}_{\text{EFT}}^{\mathcal{CP}} = g_0 N^\dagger \vec{\pi} \cdot \vec{\tau} N$	$+ g_1 N^\dagger \pi_3 N$	$+ N^\dagger (d_0 + d_1 \tau_3) S^{\mu\nu} v^\nu F_{\mu\nu} N + \dots$
$\Downarrow$ 	$\Downarrow$ 	$\Downarrow$ 
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 $\leadsto$ Goldstone theorem respected
- **4quark Left-Right EDM**: **explicit** breaking of **chiral & isospin** symmetries because of underlying W boson exchange $\leadsto$ Goldstone th. doesn't apply

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Hierarchy among the sources at the hadronic EFT level

Each source transforms differently under chiral and isospin symmetry

$\mathcal{CP}, I$	$\mathcal{CP}, I$	$\mathcal{CP}, I + I$
$\mathcal{L}_{\text{EFT}}^{\mathcal{CP}} = g_0 N^\dagger \vec{\pi} \cdot \vec{\tau} N$	$+ g_1 N^\dagger \pi_3 N$	$+ N^\dagger (d_0 + d_1 \tau_3) S^{\mu\nu} v^\nu F_{\mu\nu} N + \dots$
$\Downarrow$ 	$\Downarrow$ 	$\Downarrow$ 
suppressed for quark EDM source	suppressed for quark EDM source	dominating for quark EDM source

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

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θ -term: $\mathcal{CP}$ πNN vertices determined from LECs

Leading g_0^θ coupling (from c_5)

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

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

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

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

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

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

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

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

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

g_1^θ : $\pi_3 NN$ -vertex

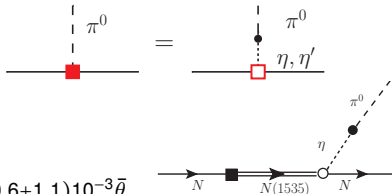
$$\epsilon := (m_u - m_d)/(m_u + m_d)$$

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

1 $c_1 \longleftrightarrow \sigma_{\pi N}$: $c_1 = (-1.0 \pm 0.3) \text{ GeV}^{-1}$

Compilation: Baru et al. (2011)

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



$$g_1^\theta(c_1) = (2.8 \pm 1.1) 10^{-3} \bar{\theta} \quad \& \quad \bar{g}_1^\theta = (0.6 \pm 1.1) 10^{-3} \bar{\theta}$$

$$\leadsto g_1^\theta = (3.5 \pm 1.5) \cdot 10^{-3} \bar{\theta}$$

Bsaisou et al. '13, '15

$$\frac{g_1^\theta}{g_0^\theta} = -0.22 \pm 0.10 \sim \frac{M_\pi}{m_N}$$

Bsaisou et al. '13, '15

$$\gg \epsilon \frac{M_\pi^2}{m_N^2} \sim -0.01 \quad (\text{NDA})$$

de Vries et al. (2011)

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

◀ back

◀ BACK

◀ back loop

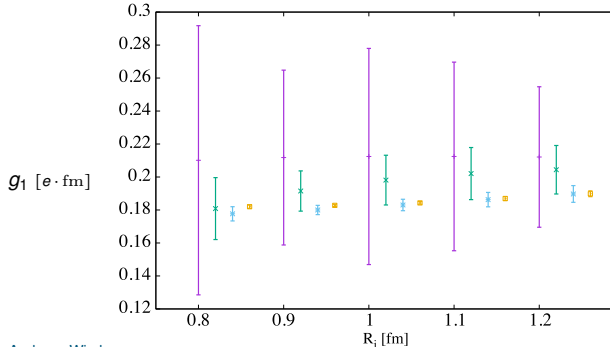
Deuteron Quantities in ChPT from NLO to N4LO

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

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

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	0.6 GeV	0.6 GeV	0.6 GeV	0.5 GeV	0.4 GeV



NLO, N2LO, N3LO, N4LO

$(0.183 \pm 0.017) g_1 \text{ efm}$

$\hookrightarrow (0.1815 \pm 0.0025) g_1 \text{ efm}$

◀ back

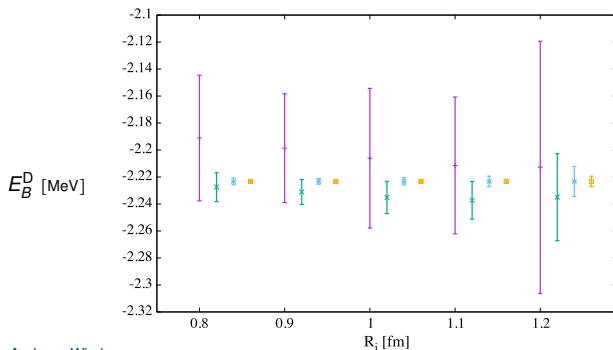
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R_i	0.8 fm	0.9 fm	1.0 fm	1.1 fm	1.2 fm
Λ_b^i	0.6 GeV	0.6 GeV	0.6 GeV	0.5 GeV	0.4 GeV



NLO, N2LO, N3LO, N4LO

(-2.2233 ± 0.0004) MeV

← back

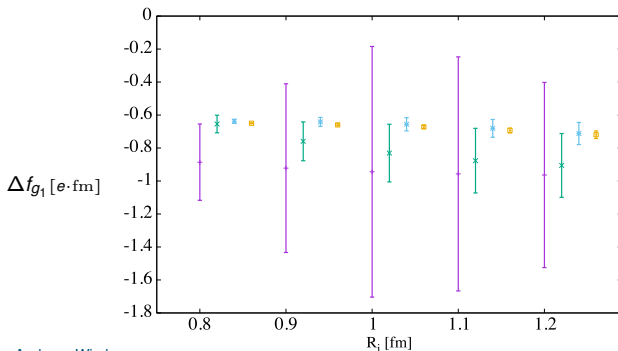
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$$\Delta X^{\text{NLO}}(p) = Q^{n+2} \cdot \max \left[\left| X^{\text{LO}}(p) \right|, \frac{\left| X^{\text{NLO}}(p) - X^{\text{LO}}(p) \right|}{Q^2}, \frac{\left| X^{\text{N2LO}}(p) - X^{\text{NLO}}(p) \right|}{Q^3}, \frac{\left| X^{\text{N3LO}}(p)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

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	0.6 GeV	0.6 GeV	0.6 GeV	0.5 GeV	0.4 GeV



NLO, N2LO, N3LO, N4LO

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

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

◀ back

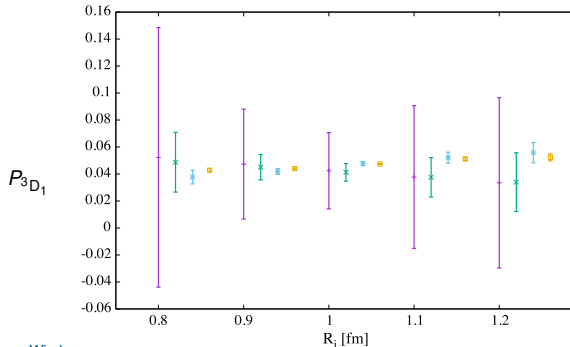
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$$d_{n,p}^D = (0.939 \pm 0.009) d_n$$

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

◀ back

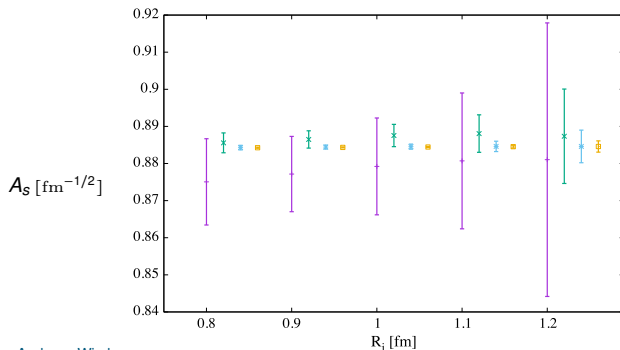
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NLO, N2LO, N3LO, N4LO

$(0.8844 \pm 0.0001) \text{ fm}^{-1/2}$

◀ back

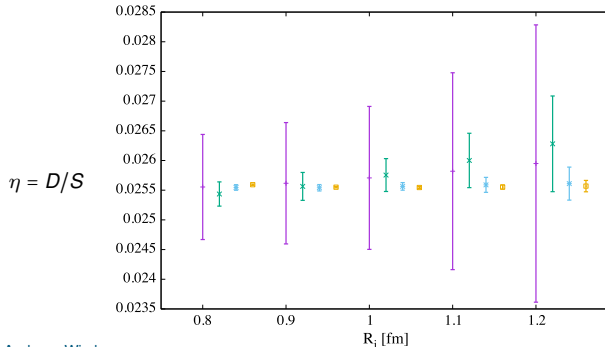
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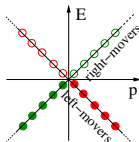
NLO, N2LO, N3LO, N4LO

(0.02555 ± 0.00001)

← back

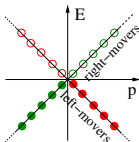
$U_A(1)$ anomaly in 1+1 D

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



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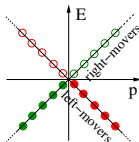
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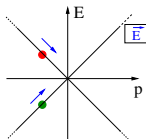
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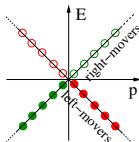
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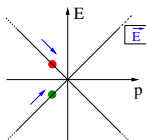
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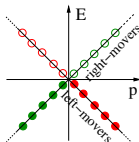
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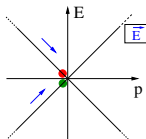
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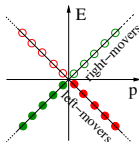
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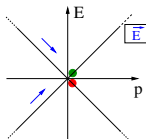
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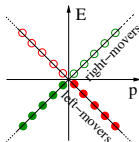
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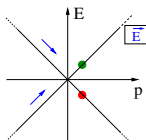
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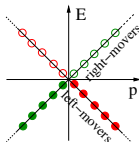
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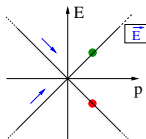
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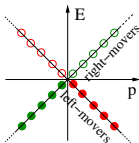
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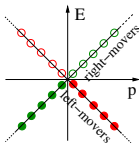


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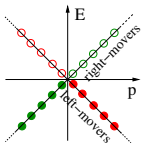
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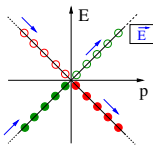
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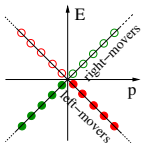
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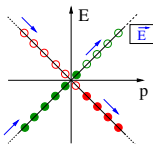
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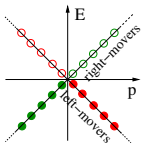
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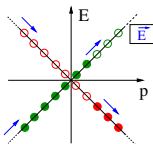
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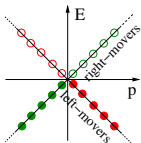
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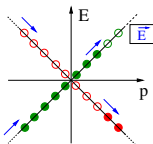
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The symmetries of QCD

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

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

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

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

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

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

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

Hidden Symmetry and Goldstone Bosons

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

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

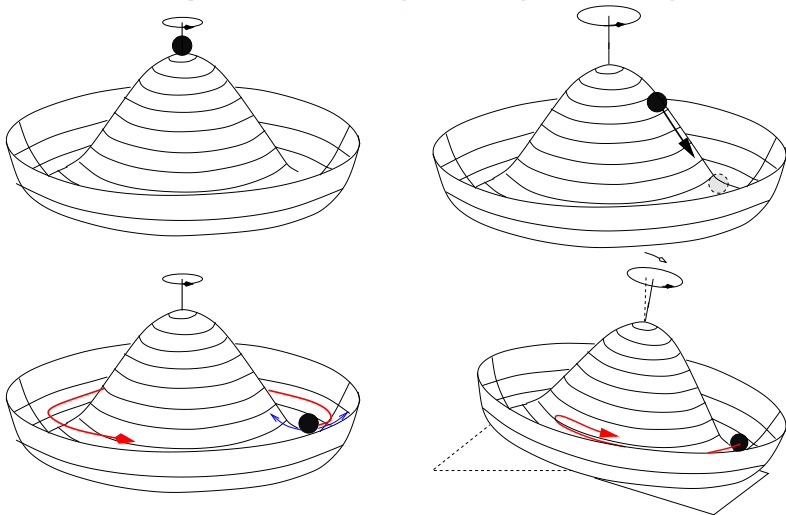
- Consequence: $e^{-iQ_A^a}|0\rangle \neq |0\rangle$ is not the vacuum, but

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

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

Illustration: spontaneous symmetry breaking (SSB)



◀ back

Decoupling theorem of Goldstone bosons

Goldstone bosons do not interact at zero energy/momentum

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

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

A_b^μ axial current

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

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

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

$$i\mathcal{A}^\mu = \text{diagram 1} + \text{diagram 2}$$

diagram 1: wavy line labeled A_μ enters a grey circle, with two outgoing lines.

diagram 2: wavy line labeled A_μ enters a blue circle, which is connected by a dashed line labeled π to a red circle, with two outgoing lines from the red circle.

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

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

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