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JÜLICH FORSCHUNGSZENTRUM

Two lectures on

Low-energy consequences of physics beyond the SM with special emphasis on electric dipole moments

Graduiertenkolleg School | Bad Honnef | August 25-29, 2014 | Andreas Wirzba

Some questions that will hopefully be answered:

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

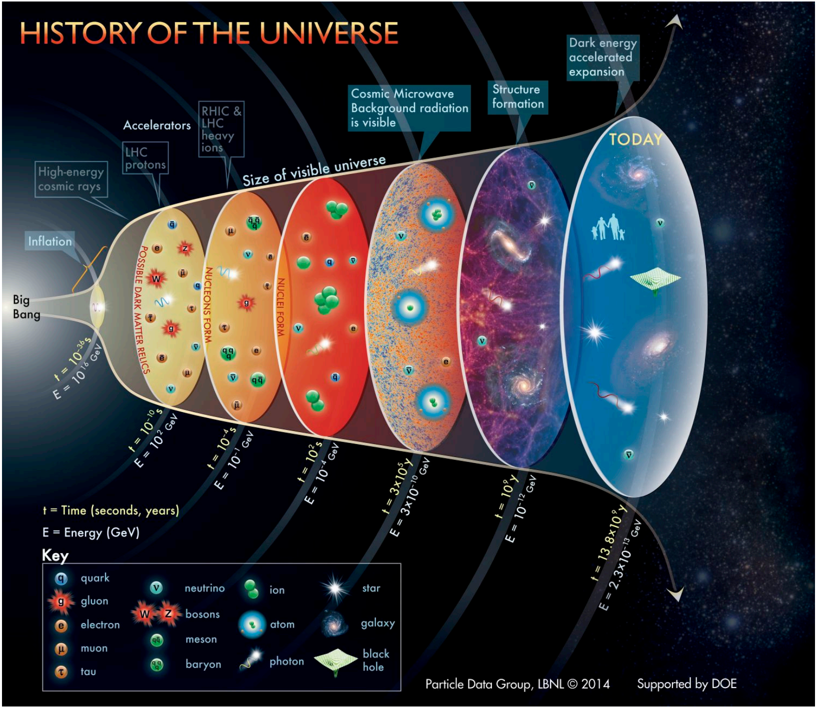

Fig. courtesy of PDG, LBNL © 2014

Matter Excess in the Universe

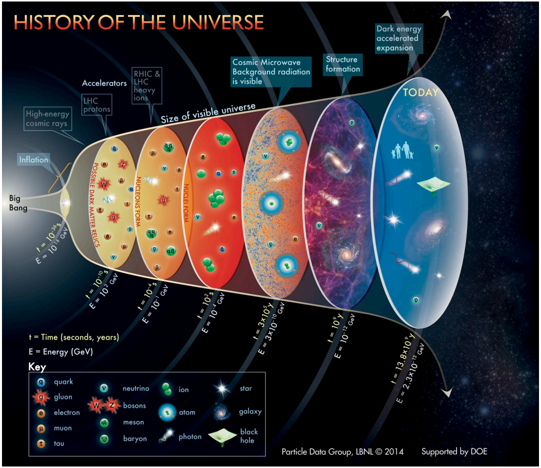

Fig. courtesy of PDG, LBNL ©2014

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

2 Cosmic Microwave Bkgr.

- SM(s) *prediction:* *

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

- WMAP+COBE (2012):

  $n_B/n_\gamma|_{\text{CMB}} = (6.08 \pm 0.09) 10^{-10}$

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 and $\bar{B}$ production rates

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

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

▸ in the SM?

CP violation and the Electric Dipole Moment (EDM)

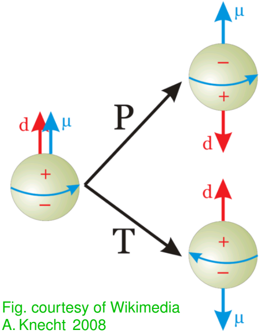

Fig. courtesy of Wikimedia
A. Knecht 2008

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-deg. (subatomic) particle violates **P** & **T**

- Assuming CPT to hold, CP is violated as well
  ↪ subatomic EDMs: "rear window" to CP violation in early universe
- Strongly suppressed in SM (CKM-matrix): $|d_n| \sim 10^{-31} e\,\mathrm{cm}$, $|d_e| \sim 10^{-38} e\,\mathrm{cm}$
- Current bounds: $|d_n| < 3 \cdot 10^{-26} e\,\mathrm{cm}$, $|d_p| < 8 \cdot 10^{-25} e\,\mathrm{cm}$, $|d_e| < 1 \cdot 10^{-28} e\,\mathrm{cm}$

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

  * from $|d_{^{199}\mathrm{Hg}}| < 3.1 \cdot 10^{-29} e\,\mathrm{cm}$ bound of Griffith et al. (2009) † from polar ThO: $|d_{ThO}| \lesssim 10^{-21} e\,\mathrm{cm}$

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 $\vec{d} \equiv \int \vec{r}\rho(\vec{r}) \mathrm{d}^3 r$ 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~~.

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

Werner Bernreuther (2012)

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

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There are always vacuum polarizations with rich short-distance structure

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

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

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

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

The induced EDM is *quadratic* in the electric field and *not* ~~P~~ or ~~T~~

induced EDM	⟷	quadratic Stark effect ($\propto E^2$)
permanent EDM	⟷	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 $\boxed{\not{T} \iff \not{CP}}$

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

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

- CP & P conserving magnetic moment ~ nuclear magneton μ_N

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

- A nonzero EDM requires

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

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

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

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

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

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

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

$\hookrightarrow$ *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

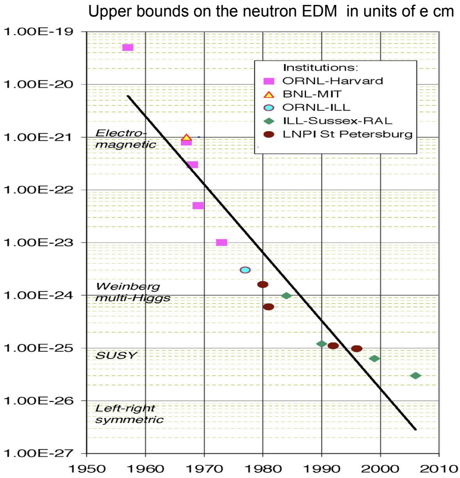

Fig. courtesy of N.N. Nikolaev

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

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

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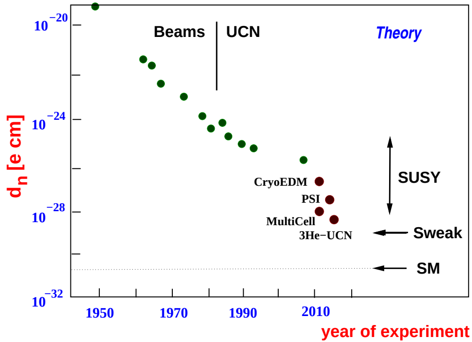

Fig. courtesy of U.-G. Meißner

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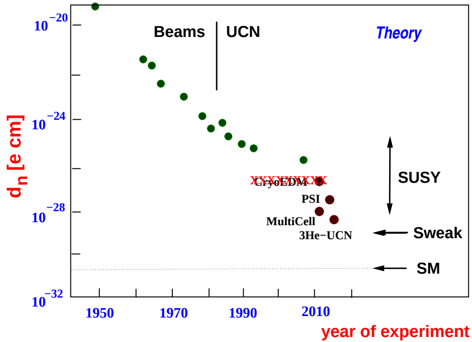

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Three motivations for EDM searches

Why are EDMs interesting to measure?

A search for new physics which is *'background free'*

Many beyond-the-SM models predict large EDMs: *Complementary to LHC search*

Matter/Antimatter asymmetry requires more CPV: *EDMs are excellent probes*

courtesy of J. de Vries

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EDM bounds from neutral particles

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

current $d_n = \big(0.2 \pm 1.5(\text{stat.}) \pm 0.7(\text{sys.})\big) \cdot 10^{-26}\, e\,\text{cm}$

Baker et al. *PRL*'06 (ILL)

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

- Proton (and neutron) EDM inferred from diamagnetic atoms

current $|d(^{199}\text{Hg})| < 3.1 \cdot 10^{-29}\, e\,\text{cm}$ (95% C.L.)

Griffith et al. *PRL* '09 (UW)

$\hookrightarrow |d_p| < 7.9 \cdot 10^{-25}\, e\,\text{cm}$

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

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

- Electron EDM inferred from paramagnetic atoms or molecules:

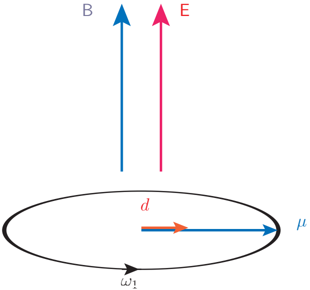
current $|d_e| < 8.7 \cdot 10^{-29}\, e\,\text{cm}$ (90% C.L.)

from polar ThO

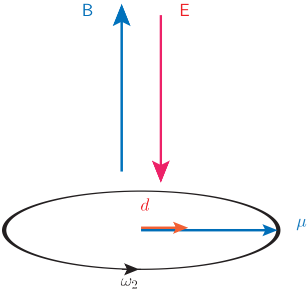
Baron et al. *Science* '14 (ACME)

EDM measurement of neutral particles in a nutshell

ground state with $s = 1/2$:



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



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

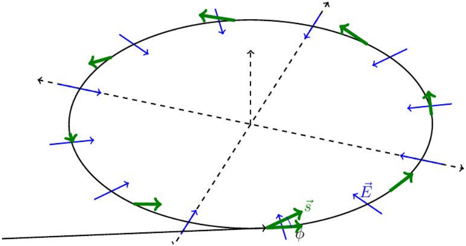
$$\omega_1 - \omega_2 = \frac{4d E}{\hbar}$$

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
↪ build-up of vertical polarization (measured with a polarimeter)

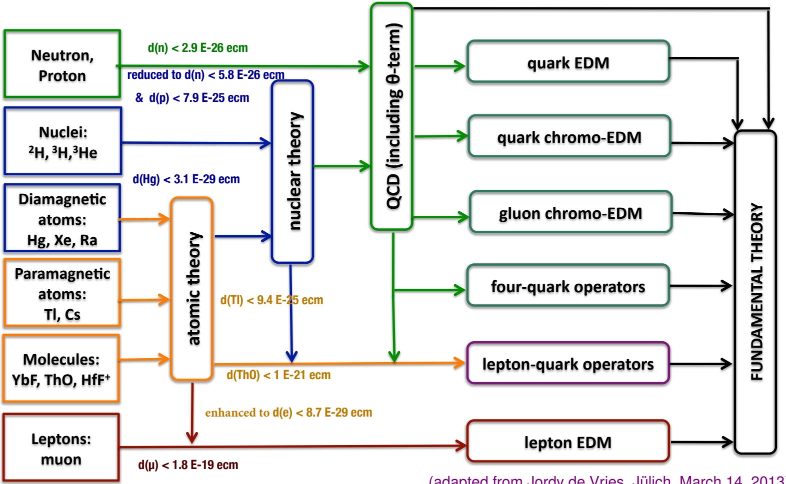
Limit on muon EDM: $d_\mu < 1.8 \cdot 10^{-19} e\,\mathrm{cm}$ (95 % C. L.) Bennett et al. (BNL *g*-2) *PRL* '09:

Proposed storage ring experiments ($\sim 10^{-29} e\,\mathrm{cm}$):

- Counter-circling proton ring at Brookhaven (srEDM) or Fermilab (Project X) ?
- All-purpose ring for proton, deuteron (and helion) in Jülich (JEDI) ?
- ↪ Precursor experiment ($\gtrsim 10^{-24} e\,\mathrm{cm}$) for p or D at COSY@Jülich !

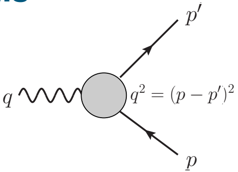
Road map from EDM Measurements to EDM Sources

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



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

Calculation: from form factors to EDMs



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

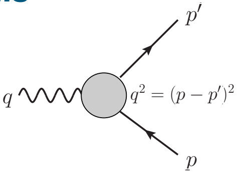
$$\Gamma^\mu(q^2) = \gamma^\mu F_1(q^2) - \mathrm{i}\sigma^{\mu\nu} q_\nu \frac{F_2(q^2)}{2m_f} + \sigma^{\mu\nu} q_\nu \gamma_5 \frac{F_3(q^2)}{2m_f} + (\not{q}\, q^\mu - q^2\gamma^\mu)\gamma_5 \frac{F_a(q^2)}{m_f^2}$$

Dirac FF | Pauli FF | electric dipole FF ($\not{C}\!\not{P}$) | anapole FF ($\not{P}$)

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

Calculation: from form factors to EDMs

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



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

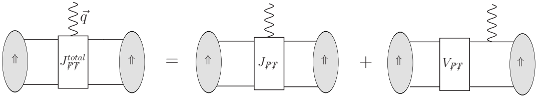
Dirac FF — Pauli FF — electric dipole FF ($\not{CP}$) — anapole FF ($\not{P}$)

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

Nucleus A

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

in Breit frame



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

CP violation in the Standard Model

The conventional source: Kobayashi-Maskawa mechanism

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

- $\boxed{u:}$ $m_u < m_c < m_t$, $\boxed{d:}$ $m_d < m_s < m_b$, and $\boxed{l:}$ $m_e < m_\mu < m_\tau$
- quarks & leptons in **mass** basis ≠ 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 (Cabibbo-Kobayashi-Maskawa m.)

    3 angles + 1 ~~CP~~ phase δ_{KM}

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

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

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

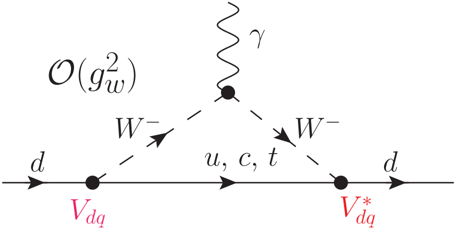
$$\propto \left(\frac{m_t^2 - m_c^2}{M_{EW}^2}\right)\left(\frac{m_c^2 - m_u^2}{M_{EW}^2}\right)\left(\frac{m_t^2 - m_u^2}{M_{EW}^2}\right)\cdot\left(\frac{m_b^2 - m_s^2}{M_{EW}^2}\right)\left(\frac{m_s^2 - m_d^2}{M_{EW}^2}\right)\left(\frac{m_b^2 - m_d^2}{M_{EW}^2}\right)\cdot J_{\mathrm{KM}} \simeq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

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:



$\hookrightarrow$ $\not{C}\not{P}$ phase δ_{KM} cancels $\rightarrow$ prefactor real $\Rightarrow$ $d_q^{\text{1-loop}} = 0$

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2 loops:

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

Shabalin *Sov.J.NP* '78

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

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Jarlskog *PRL* '85

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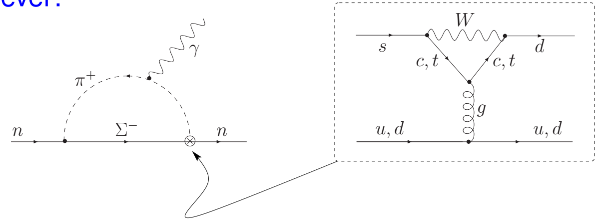
EDM flavor-neutral $\Rightarrow$ KM predictions tiny: $\mathcal{O}(G_F^2) \sim \mathcal{O}(g_W^4)$

however:



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

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

Gavela; Khriplovich & Zhitnitsky ('82)

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

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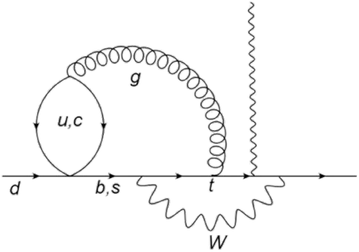
EDM flavor-neutral $\Rightarrow$ KM predictions tiny: $\mathcal{O}(G_F^2) \sim \mathcal{O}(g_W^4)$

at $\geq$ 3 loops:



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

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

Khriplovich (1986); Czarnecki & Krause ('97) (Khriplovich & Pospelov (1992))

Mitglied der Helmholtz-Gemeinschaft

JÜLICH FORSCHUNGSZENTRUM

Two lectures on

Low-energy consequences of physics beyond the SM with special emphasis on electric dipole moments

Graduiertenkolleg School | Bad Honnef | August 25-29, 2014 | Andreas Wirzba

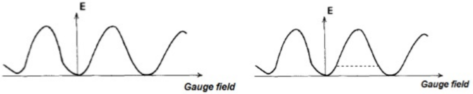
Some questions that hopefully are or will be answered:

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

JÜLICH FORSCHUNGSZENTRUM

EDM sources: QCD θ-term of the SM

The topologically non-trivial vacuum structure of QCD



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

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

- ▸ Anomalous $U_A(1)$ quark-rotations induce mixing with ‘mass’ term

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

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

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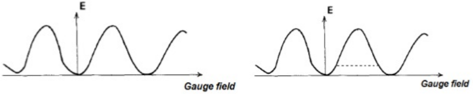

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- Naive Dimensional Analysis (NDA) estimate of $\bar{\theta}$-induced n EDM:

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

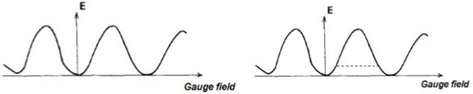
$$|d_n^{emp}| < 2.9 \cdot 10^{-26}\, e\,\text{cm} \rightsquigarrow \boxed{|\bar{\theta}| < 10^{-10}}$$

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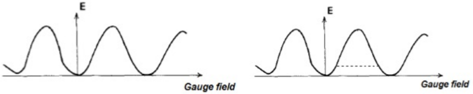
$10^{-10} > |\bar\theta| > 10^{-14}$ eventually measurable via nonzero EDM, but because of $\Lambda_{\chi SB} \ll \Lambda_{EWSB}$ it doesn't explain the cosmic matter surplus.

EDM sources: QCD θ-term of the SM

The topologically non-trivial vacuum structure of QCD



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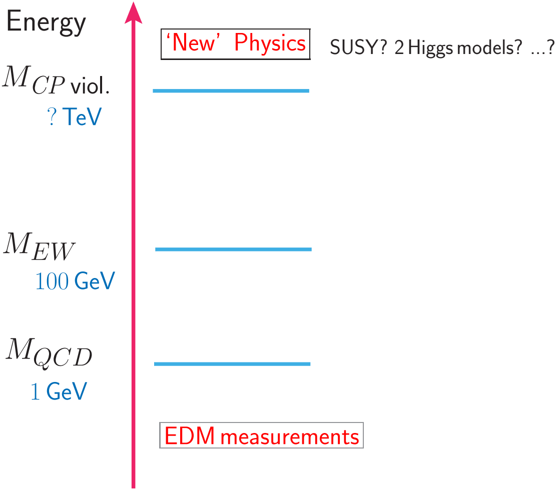
Thus $\not{CP}$ by new physics (NP) (*i.e.* dimension ≥ 6 sources beyond SM) needed to explain the cosmic matter-antimatter asymmetry.

How to handle CP-violating sources beyond the SM?

Running through the scales

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



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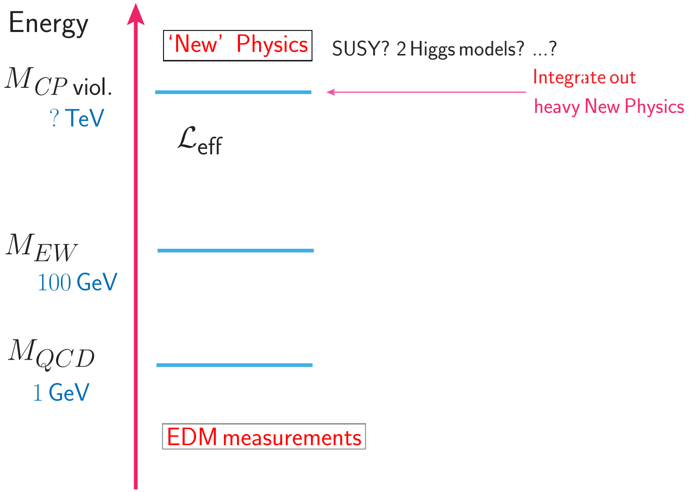

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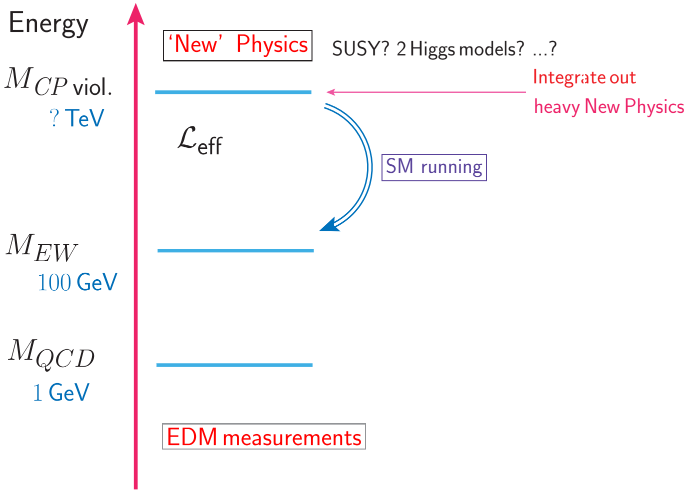

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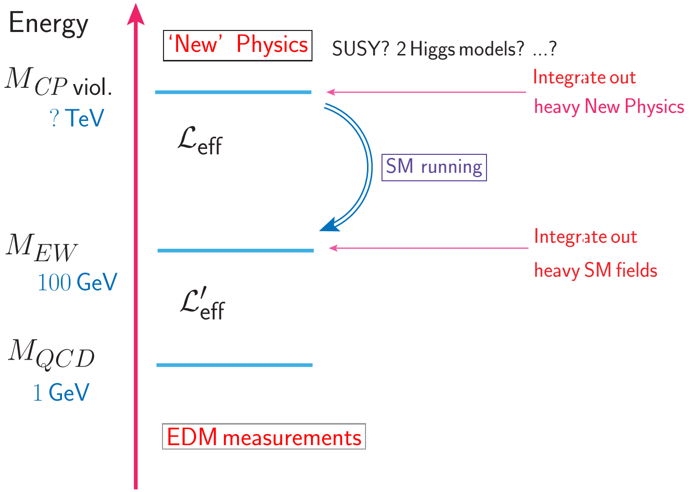

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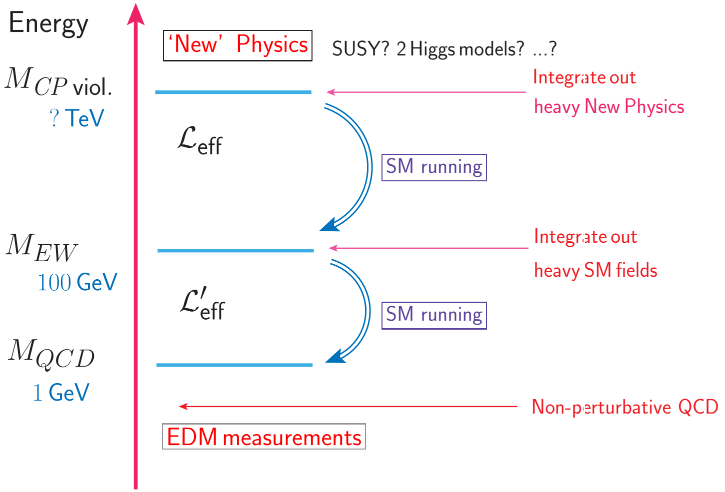

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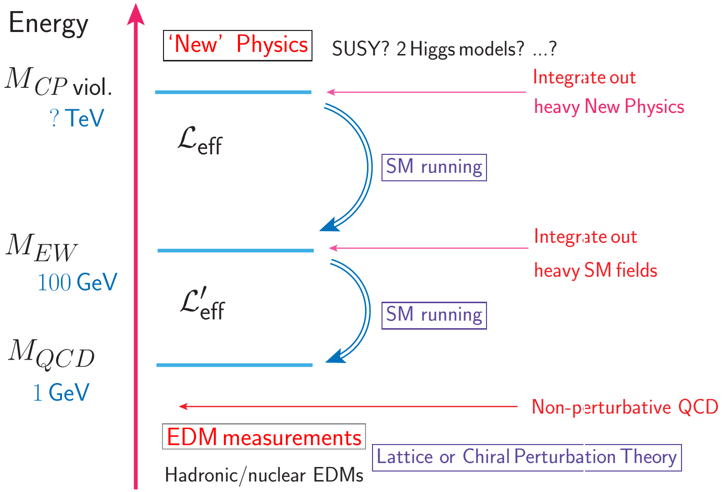
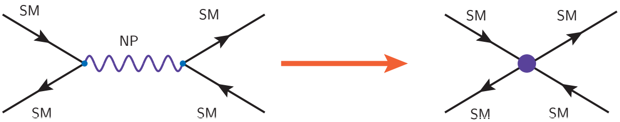


How to handle CP-violating sources beyond the SM?

New interactions as higher dimensional operators

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



- The new interactions appear as higher dimensional operators

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

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

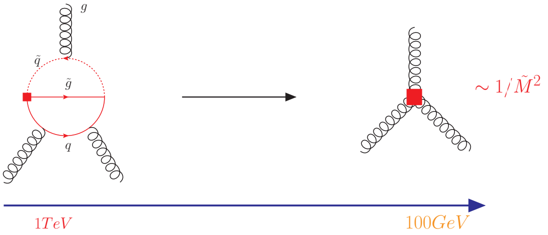
Not of dim. 5 because of Higgs insertion (chiral symm.) at high (low) scales

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.



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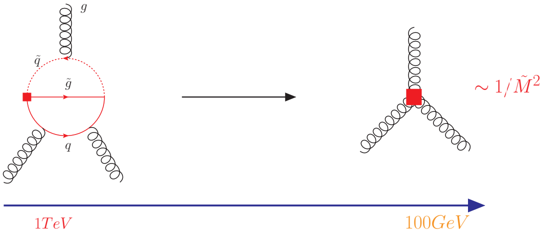

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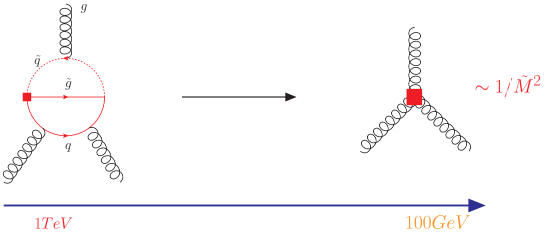

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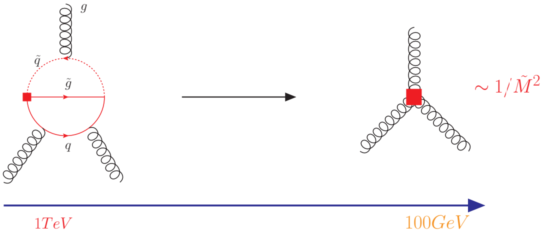
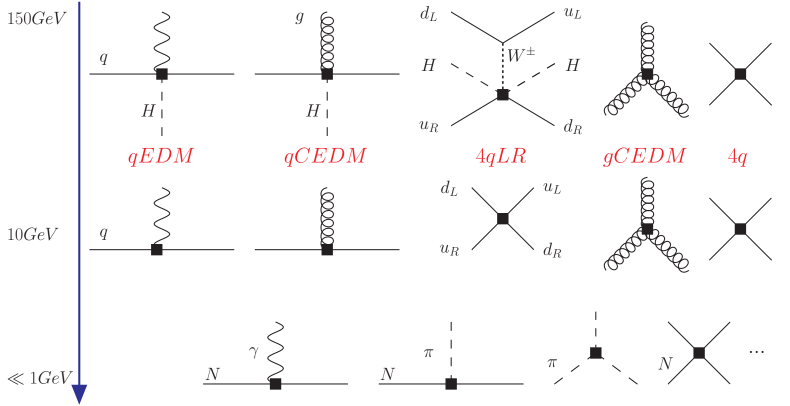


CP-violating BSM sources of dimension 6 from above EW scale to their hadronic equivalents below 1 GeV

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

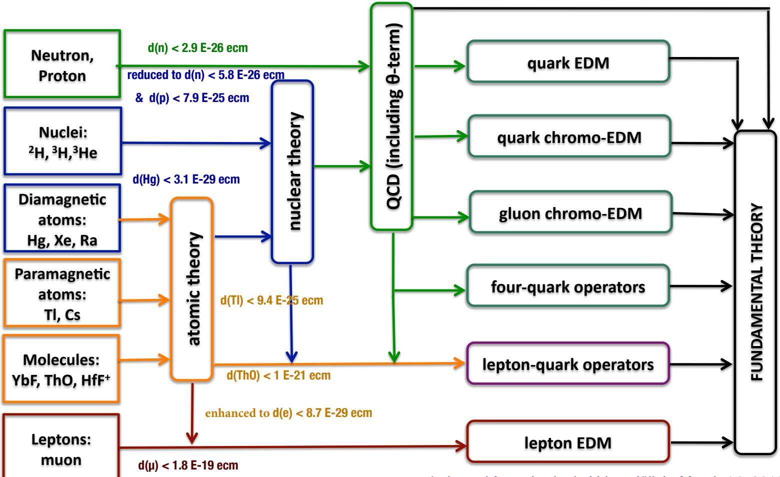


$$\text{Total \#} = 1(\bar{\theta}) + 2(qEDM) + 2(qCEDM) + 1(4qLR) + 1(gCEDM) + 2(4q) \ [+3(\text{semi-lept})]$$
$$= \underbrace{1(\text{dim-four}) + 8}_{\text{5 different classes}}[+3](\text{dim-six})$$

[Caveat: implicitly $m_s \gg m_u, m_d$ assumed]

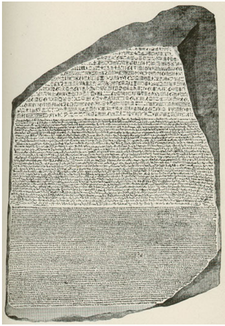
Road map from EDM Measurements to EDM Sources

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



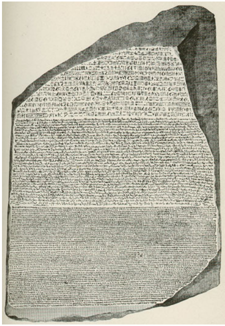
(adapted from Jordy de Vries, Jülich, March 14, 2013)

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



EDM Rosetta Stone

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



$\hookrightarrow$

Symmetries (esp. chiral one) plus Goldstone Theorem
Low-Energy Effective Field Theory with External Sources
i.e. Chiral Perturbation Theory (suitably extended)

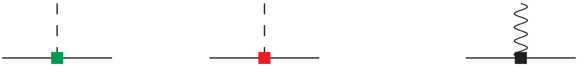
Hierachy among the sources at the hadronic EFT level

Each source transforms differently under chiral and isospin symmetry

$\not{C}\not{P}$, I — $\not{C}\not{P}$, $\not{I}$ — $\not{C}\not{P}$, I + $\not{I}$

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

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



...

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

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

  $\hookrightarrow$ $\bar{\theta}$ 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

$$\underbrace{\not{CP},\ \mathrm{I}}_{} \qquad \not{CP},\ \not{\mathrm{I}} \qquad \not{CP},\ \mathrm{I} + \not{\mathrm{I}}$$

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

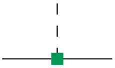
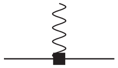
$$\Downarrow \qquad\qquad \Downarrow \qquad\qquad \Downarrow$$

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 theorem does not apply

Hierachy among the sources at the hadronic EFT level

Each source transforms differently under chiral and isospin symmetry

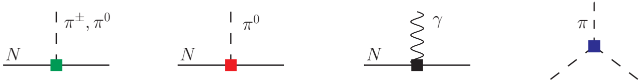
	$\not{CP}$, I		$\not{CP}$, $\not{I}$		$\not{CP}$, I + $\not{I}$	
$\mathcal{L}_{\mathrm{EFT}}^{\not{CP}} =$	$g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N$	$+$	$g_1 N^\dagger \pi_3 N$	$+$	$N^\dagger(d_0+d_1\tau_3)S^\mu v^\nu F_{\mu\nu} N$	$+\cdots$
	$\Downarrow$		$\Downarrow$		$\Downarrow$	
						…
	suppressed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

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

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

from θ to BSM sources

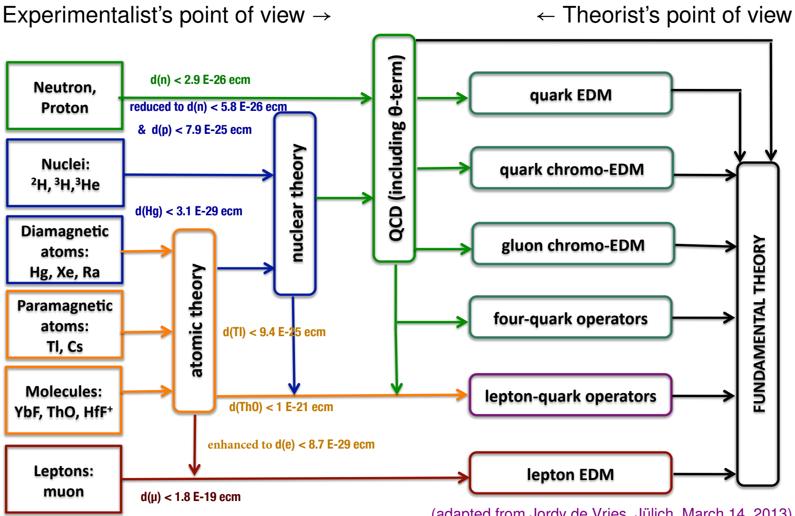
$\mathcal{L}^{\not{CP}}_{\text{EFT}}$:



	g_0: $\not{CP}$, I	g_1: $\not{CP}$, $\not{I}$	d_0, d_1: $\not{CP}$, I + $\not{I}$	$m_N\Delta_{3\pi}$: $\not{CP}$, $\not{I}$
θ-term:	**$\mathcal{O}(1)$**	**$\mathcal{O}(M_\pi/m_N)$**	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(M_\pi^2/m_N^2)$
qEDM:	$\mathcal{O}(\alpha_{EM}/(4\pi))$	$\mathcal{O}(\alpha_{EM}/(4\pi))$	**$\mathcal{O}(1)$**	$\mathcal{O}(\alpha_{EM}/(4\pi))$
qCEDM:	**$\mathcal{O}(1)$**	**$\mathcal{O}(1)$**	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(M_\pi^2/m_N^2)$
4qLR:	$\mathcal{O}(M_\pi^2/m_n^2)$	**$\mathcal{O}(1)$**	$\mathcal{O}(M_\pi^2/m_N^2)$	**$\mathcal{O}(M_\pi/m_n)$**
gCEDM:	$\mathcal{O}(M_\pi^2/m_N^2)^*$	$\mathcal{O}(M_\pi^2/m_N^2)^*$	**$\mathcal{O}(1)$**	$\mathcal{O}(M_\pi^2/m_N^2)$
4q:	$\mathcal{O}(M_\pi^2/m_N^2)^*$	$\mathcal{O}(M_\pi^2/m_N^2)^*$	**$\mathcal{O}(1)$**	$\mathcal{O}(M_\pi^2/m_N^2)$

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

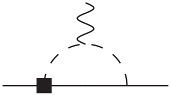
Road map from EDM Measurements to EDM Sources



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

θ-Term Induced Nucleon EDM

single nucleon EDM:

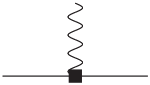


isovector

$\approx$

$\ll$

isoscalar



"controlled"

two "unknown" coefficients

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

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

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

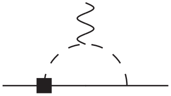
$$g_0^\theta = \frac{(m_n - m_p)^{\text{strong}}(1-\epsilon^2)}{4F_\pi \epsilon}\,\bar\theta \approx (-0.018 \pm 0.007)\bar\theta \qquad \left(\text{where } \epsilon \equiv \frac{m_u - m_d}{m_u + m_d}\right)$$

$$\hookrightarrow d_N\Big|^{\text{isovector}}_{\text{loop}} \sim (2.1 \pm 0.9)\cdot 10^{-16}\,\bar\theta\,\mathrm{e\,cm}$$

Ottnad et al. *PLB*'10; Bsaisou et al. *EPJA*'13

θ-Term Induced Nucleon EDM

single nucleon EDM:

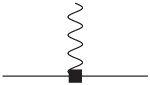


isovector

$\approx$

$\ll$

isoscalar



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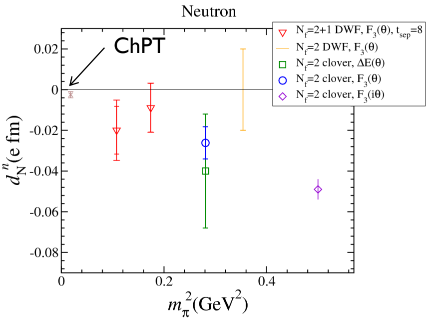
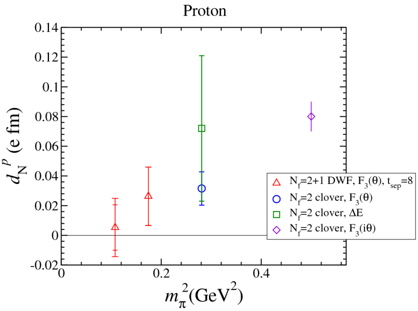
Ottnad et al. *PLB*'10; Bsaisou et al. *EPJA*'13

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

Lattice (full QCD) results

neutron EDM and proton EDM





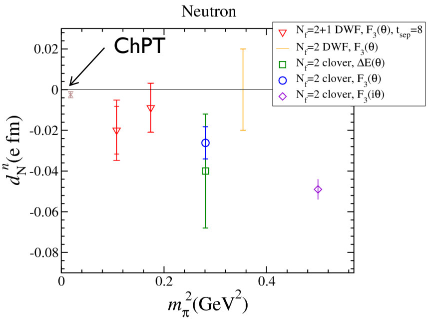
$\theta \equiv 1$!

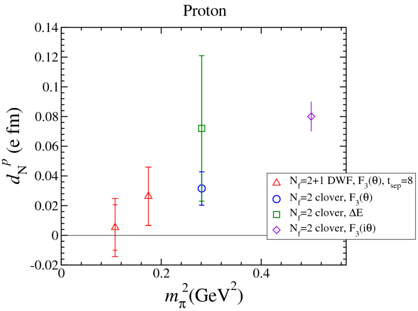
(adapted from Eigo Shintani (Mainz), *Lattice calculation of nucleon EDM*, Hirschegg, Jan. 14, 2014)

no systematical errors!

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)

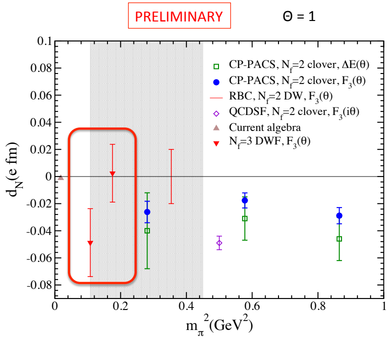
no systematical errors!

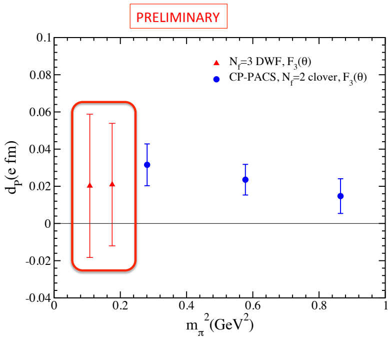
$\hookrightarrow d_n = \bar{\theta}\,(-2.7 \pm 1.2) \cdot 10^{-3} \cdot e \cdot fm$ and $d_p = \bar{\theta}\,(2.1 \pm 1.2) \cdot 10^{-3} \cdot e \cdot fm$

Akan, Guo, Meißner *PLB*'14

Lattice (full QCD) results

neutron EDM and proton EDM





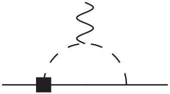
(adapted from Taku Izubuchi (BNL), *Lattice-QCD calculations for EDMs*, Fermilab, Feb. 14, 2013)

Don't mention the ... light nuclei

Single Nucleon Versus Nuclear EDM

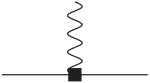
Crewther, di Vecchia, Veneziano, Witten *PLB*'79; Pich, de Rafael *NPB*'91; Ottnad et al. *PLB*'10

single nucleon EDM:



isovector $\approx$

isoscalar $\ll$



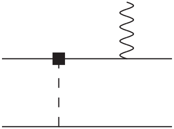
"controlled" "unknown" coefficients

$\longrightarrow$ lattice QCD required

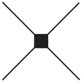
Guo, Meißner *JHEP*'12

two nucleon EDM:

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



$\gg$



controlled unknown coefficient

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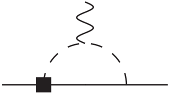
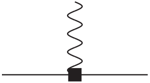


isovector $\approx$ / isoscalar $\ll$



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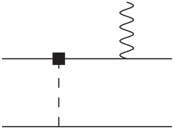
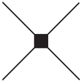


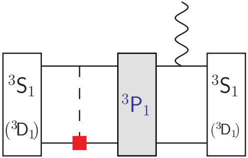
$\gg$



controlled unknown coefficient

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

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



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

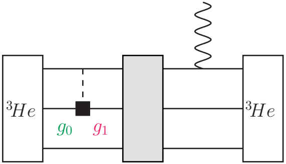
NLO: $g_1^\theta N^\dagger \pi_3 N$ $(\not{CP}, \not{I})$ $\rightarrow$ *"LO"* in D case

term	N^2LO ChPT	Av_{18}	CD-Bonn	units
d_n	1.00	1.00	1.00	d_n
d_p	1.00	1.00	1.00	d_p
g_1	0.183 ± 0.017	0.186	0.186	$g_1\, e\,\mathrm{fm}$

Bsaisou, dissertation, Univ. Bonn (2014); Bsaisou et al., in preparation

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

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



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

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

term	A	N^{2}LO ChPT	Av$_{18}$+UIX	CD-Bonn+TM	units
d_n	^{3}He	0.904 ± 0.013	0.875	0.902	d_n
	^{3}H	-0.030 ± 0.007	-0.051	-0.038	d_n
d_p	^{3}He	-0.029 ± 0.006	-0.050	-0.037	d_p
	^{3}H	0.918 ± 0.013	0.902	0.876	d_p
g_0	^{3}He	0.111 ± 0.013	0.073	0.087	$g_0\, e\,\mathrm{fm}$
	^{3}H	-0.108 ± 0.013	-0.073	-0.085	$g_0\, e\,\mathrm{fm}$
g_1	^{3}He	0.142 ± 0.019	0.142	0.146	$g_1\, e\,\mathrm{fm}$
	^{3}H	0.139 ± 0.019	0.142	0.144	$g_1\, e\,\mathrm{fm}$
$\Delta_{3\pi}$	^{3}He	...	...	...	$\Delta_{3\pi}\, e\,\mathrm{fm}$
	^{3}H	...	...	...	$\Delta_{3\pi}\, e\,\mathrm{fm}$

Bsaisou, dissertation, Univ. Bonn (2014); Bsaisou et al., in preparation

Discriminating between three scenarios at 1 GeV

Dekens, de Vries, Bsaisou, Bernreuther et al. *JHEP* **07** '14

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:

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

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

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

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

matched on

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

Discriminating between three scenarios at 1 GeV

Dekens, de Vries, Bsaisou, Bernreuther et al. *JHEP* **07** '14

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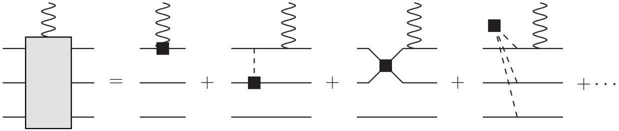

Testing strategies: SM + $\bar{\theta}$

Measurement of the helion and neutron EDMs

Wouter Dekens (Groningen) 2014

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

Measurement of the helion and neutron EDMs

$$d_{^3\mathrm{He}} - 0.9 d_n = (1.35 \pm 0.75_{\mathrm{had}} \pm 0.21_{\mathrm{nucl}}) \cdot 10^{-3} \cdot e \cdot \mathrm{fm}$$

Extraction of $\bar{\theta}$

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$$d_D - d_n - d_p = (0.59 \pm 0.26_{\mathrm{had.}} \pm 0.01_{\mathrm{nucl.}}) \cdot 10^{-3} \cdot e \cdot \mathrm{fm}$$

Prediction for $d_D - (d_n + d_p)$ (and triton EDM)

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Prediction for $d_D - (d_n + d_p)$ (and triton EDM)

$$g_0^\theta = \frac{(m_n - m_p)^{\mathrm{strong}}(1-\epsilon^2)}{4F_\pi \epsilon}\bar{\theta} \quad \text{and} \quad \frac{g_1^\theta}{g_0^\theta} \approx \frac{8c_1(M_{\pi^\pm}^2 - M_{\pi^0}^2)^{\mathrm{strong}}}{(m_n - m_p)^{\mathrm{strong}}} \quad \text{with} \quad \epsilon = \frac{m_u - m_d}{m_u + m_d}$$

Testing strategies: mLRSM

Measurement of the deuteron and nucleon EDMs

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Testing strategies: mLRSM

Measurement of the deuteron and nucleon EDMs

$$d_D - (d_n + d_p) \simeq d_D = (0.18 \pm 0.02)\, \bar{g}_1^{\mathrm{LR}} e \text{ fm}$$

Extraction of $\bar{g}_1$

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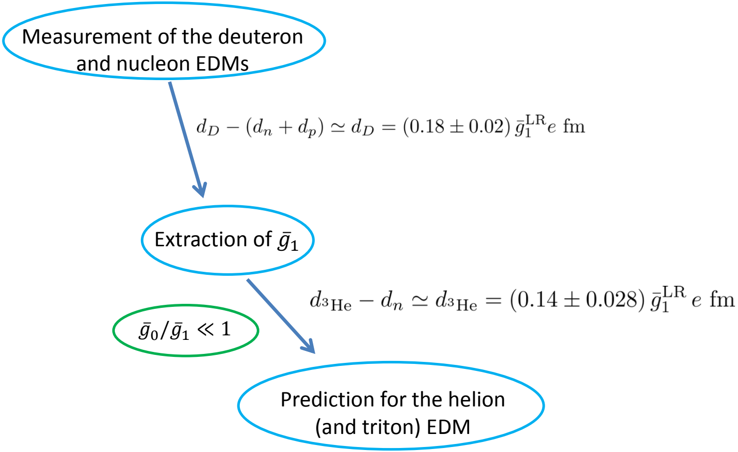
Testing strategies: mLRSM



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Testing strategies: mLRSM

Measurement of the deuteron and nucleon EDMs

$$d_D - (d_n + d_p) \simeq d_D = (0.18 \pm 0.02)\, \bar{g}_1^{\mathrm{LR}} e\ \mathrm{fm}$$

Extraction of $\bar{g}_1$

$\bar{g}_0 / \bar{g}_1 \ll 1$

$$d_{^3\mathrm{He}} - d_n \simeq d_{^3\mathrm{He}} = (0.14 \pm 0.028)\, \bar{g}_1^{\mathrm{LR}}\, e\ \mathrm{fm}$$

Prediction for the helion (and triton) EDM

Caveat: 3-pion interaction

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Testing strategies: a2HDM

Measurement of the deuteron and nucleon EDMs

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Testing strategies: a2HDM

Measurement of the deuteron and nucleon EDMs

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Extraction of $\bar{g}_1$

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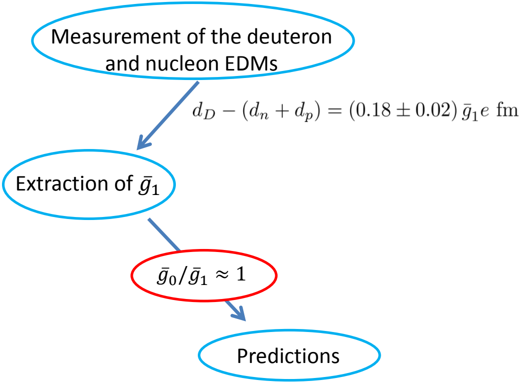
Testing strategies: a2HDM



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Testing strategies: a2HDM

Measurement of the deuteron and nucleon EDMs

$$d_D - (d_n + d_p) = (0.18 \pm 0.02)\,\bar{g}_1 e \text{ fm}$$

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Measurement of the helion or triton EDM

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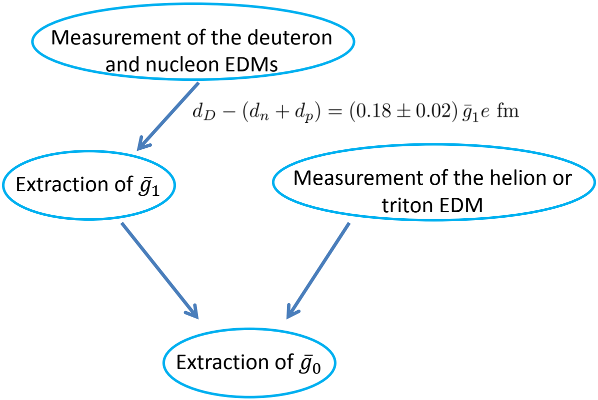
Testing strategies: a2HDM



$$
\begin{aligned}
d_{^3\mathrm{He}} &= \quad 0.88\, d_n - 0.047\, d_p + [(0.097 \pm 0.025)\, \bar{g}_0 + (0.14 \pm 0.028)\, \bar{g}_1]\; e\,\mathrm{fm}\;, \\
d_{^3\mathrm{H}} &= -0.050\, d_n + 0.90\, d_p - [(0.096 \pm 0.024)\, \bar{g}_0 - (0.14 \pm 0.028)\, \bar{g}_1]\; e\,\mathrm{fm}
\end{aligned}
$$

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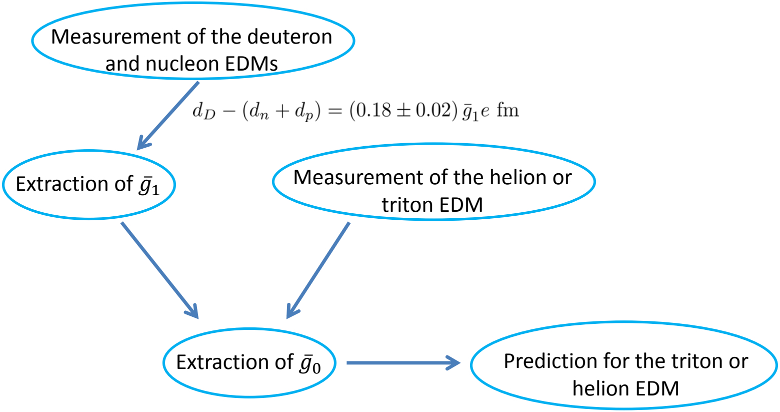
Testing strategies: a2HDM



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\end{aligned}
$$

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JÜLICH FORSCHUNGSZENTRUM

Summary

- ^{2}H EDM might distinguish between $\bar{\theta}$ and other scenarios and allows extraction of the g_1 coupling constant through $d_D - (d_n + d_p)$
- ^{3}He (or ^{3}H) EDM necessary for a proper test of $\bar{\theta}$ and LR scenarios
- a2HDM scenario: both helion & triton EDMs would be needed
- Deuteron & helion work as independent isospin filters of EDMs
- gCEDM, 4quark chiral singlet:

  controlled calculation/disentanglement difficult (lattice ?)
- Ultimate progress may eventually come from Lattice QCD
  $\hookrightarrow$ $\not{C}\not{P}$ $N\pi$ couplings g_0 & g_1 may be accessible even for dim-6 case

Traditional atomic EDMs

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

  Strong bound on atomic EDM: $|d_{^{199}\mathrm{Hg}}| < 3.1 \cdot 10^{-29} \cdot e \cdot \mathrm{fm}$

  Griffiths et al. *PRL*'09

- The atomic part of the calculation is well under control

  $d_{^{199}\mathrm{Hg}} = (2.8 \pm 0.6)\, S_{\mathrm{Hg}} \cdot e \cdot \mathrm{fm}^{-2}$ Dzuba et al. *PRA*'02,'09

  S_{Hg}: Nuclear Schiff moment

- But the nuclear part isn't ...

  $S_{^{199}\mathrm{Hg}} = \left[(0.3 \pm 0.4) g_0 + (0.4 \pm 0.8) g_1\right]\, e \cdot \mathrm{fm}^3$ Engel et al. *PPNP*'13

- There is **no power counting** for nuclei with so many nucleons

- Hadronic uncertainties of g_0 and g_1 are underestimated too

Conclusions

- EDMs are very good probes of New CP-odd Physics
- Probe 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 will play a key role in disentangling the *sources* of $\not{C}\not{P}$
- 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 ^{3}He are needed
to have a realistic chance to disentangle the underlying physics

Many thanks to my colleagues

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

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

References:

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- A.W., *Electric dipole moments of the nucleon and light nuclei* Nuclear Physics A 928 (2014) 116-127 [arXiv:404.6131 [hep-ph]].
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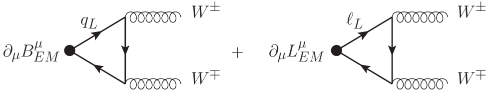
- J. Bsaisou, C. Hanhart, S. Liebig, U.-G. Meißner, A. Nogga and A.W., *The electric dipole moment of the deuteron from the QCD θ-term,* Eur. Phys. J. A **49** (2013) 31 [arXiv:1209.6306 [hep-ph]].

Jump slides

EW Baryogenesis: Standard Model

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

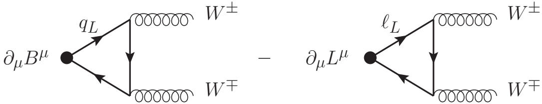


$\propto N_c \cdot (Q_u + Q_d) + (0 - 1) = 1 - 1 = 0$

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

EW Baryogenesis: Standard Model

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



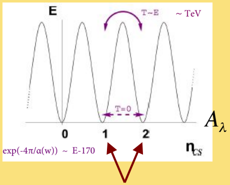
$\propto N_c \cdot 1/3 - 1 = 1 - 1 = 0$

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



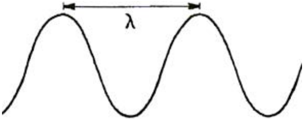
Different vacua: $\Delta(B+L) = \Delta N_{CS}$

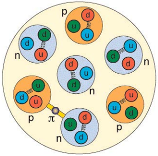
Sphaleron Transitions

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))

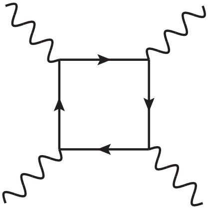
Power-law expand the amplitudes in *energy(momentum) / scale.*

- 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

back

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: $F_{\mu\nu}F^{\mu\nu} \propto \vec{E}^2 - \vec{B}^2$ & $F_{\mu\nu}\tilde{F}^{\mu\nu} \propto \vec{E}\cdot\vec{B}$

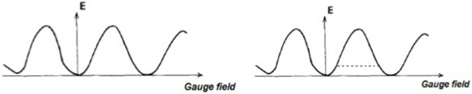
$$\mathcal{L}_{\text{eff}} = \frac{1}{2}\left(\vec{E}^2 - \vec{B}^2\right) + \frac{e^4}{16\pi^2 m_e^4}\left[a\left(\vec{E}^2 - \vec{B}^2\right)^2 + b\left(\vec{E}\cdot\vec{B}\right)^2\right] + \ldots$$

- 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.

back

θ vacua in strong interaction physics

The topologically non-trivial vacuum structure of QCD



induces winding number n and strong gauge transformation (instanton)

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

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

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

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

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 absorbed into the effective Lagrangian

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

◂ back

θ term

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

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

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

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

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 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: frustrating search for a (light) axion !

back

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

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

- Axions in our galaxy *spatially* constant over a scale of $\lesssim 500\,\mathrm{km}\,(f_a/M_{\rm GUT})$:
  ↪ Ansatz: $a(t,\vec{x}) \approx a(t) = a_0 \cos(m_a t)$ in the lab.

- Equating $\frac{1}{2}m_a^2 a_0^2 \sim \rho_{\rm local\,DM} \approx 0.2\,\mathrm{GeV/cm^3}$ gives an axion amplitude of

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

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

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

Non-relativistic reduction of

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

back1 back2

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

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

The symmetries of QCD

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

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

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

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

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

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

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

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

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

Hidden Symmetry and Goldstone Bosons

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

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

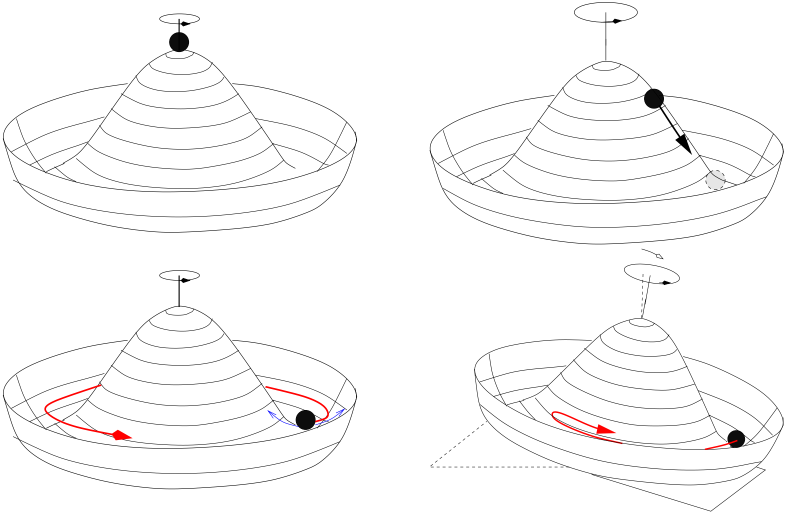
$$H\, e^{-iQ_A^a}|0\rangle = e^{-iQ_A^a} H|0\rangle = 0 \quad \text{is a massless state!}$$

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

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

back

Illustration: spontaneous symmetry breaking (SSB)



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Decoupling theorem of Goldstone bosons

Goldstone bosons do not interact at zero energy/momentum

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

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

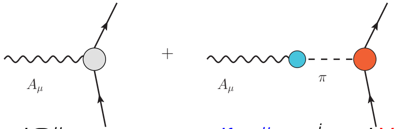
   A_b^μ axial current

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

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

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

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



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

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

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

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

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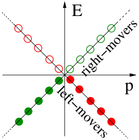

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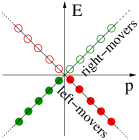

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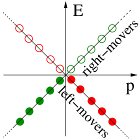

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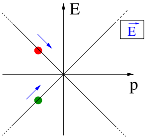

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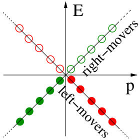

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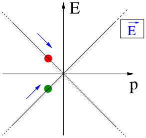

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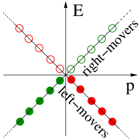

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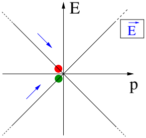

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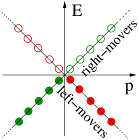

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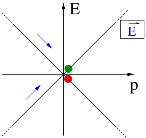

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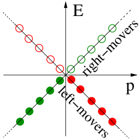

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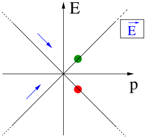

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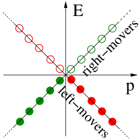

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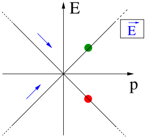

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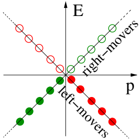

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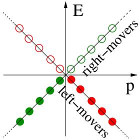

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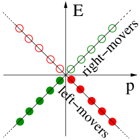

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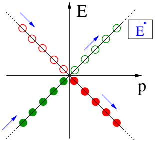

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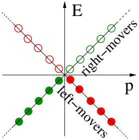

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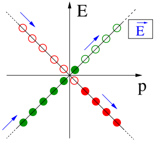

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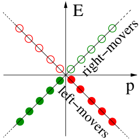

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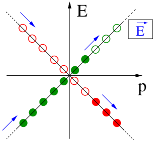

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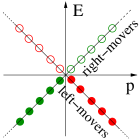

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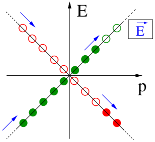

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