Electric dipole moments of light nuclei

Emanuele Mereghetti

April 16th, 2019

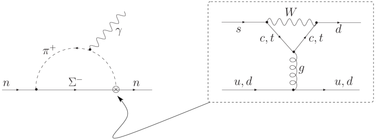
Atomic Nuclei as laboratories for BSM physics

Los Alamos
NATIONAL LABORATORY
EST. 1943

A permanent Electric Dipole Moment (EDM)

- signal of T and P violation (CP)
- insensitive to CP violation in the SM
- BSM CP violation needed for baryogenesis

neutron

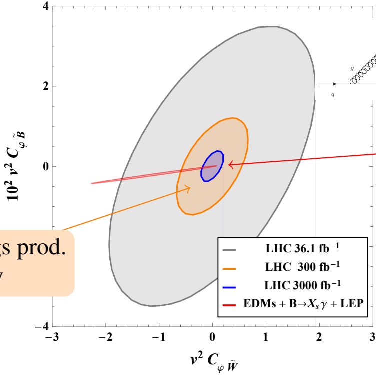


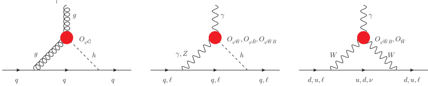
current bound
$|d_n| < 3.0 \cdot 10^{-13}\ e$ fm
J. M. Pendlebury *et al.*, ‘15

SM
$d_n \sim 10^{-19}\ e$ fm
M. Pospelov and A. Ritz, ‘05

- large window & strong motivations for new physics!

The reach of EDM experiments





one-loop running to eEDM

tree level Higgs prod. & decay

F. Bernlochner, *et al*, '18

V. Cirigliano, *et al*, '19

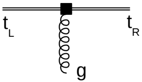
Non standard Higgs couplings: $\varphi^\dagger \varphi X_{\mu\nu} \tilde{X}^{\mu\nu}$ ($X^{\mu\nu} = F^{\mu\nu}, W^{\mu\nu}, G^{\mu\nu}$)

- electron EDM much more constraining than LHC

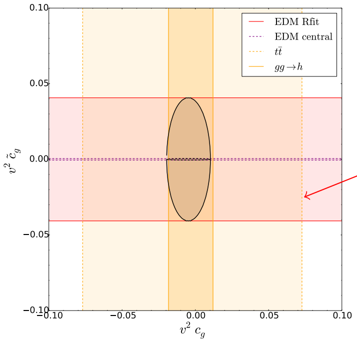
$\Lambda \sim 100$ TeV

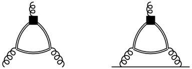
- not affected by large theory uncertainties

…and the issue of theory uncertainties



$$\frac{m_t}{\Lambda^2}\bar{t}_L \sigma^{\mu\nu} t_R G_{\mu\nu}$$



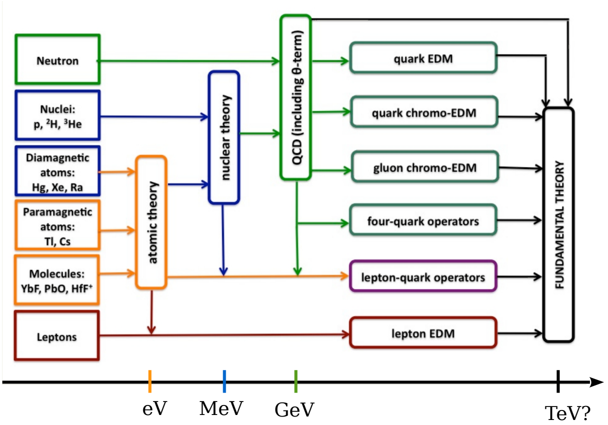


one/two-loop running to gCEDM, qCEDM

Non standard top couplings: top chromo-EDM

- runs onto gluon-CEDM and light-quark CEDM $\Longrightarrow$ nEDM
- nucleon ME have $\sim 100\%$ uncertainties

  bounds weakers by factor of 10, commensurable with LHC

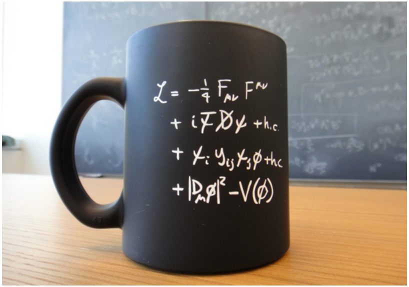


(stolen from Jordy de Vries)

what do we learn from EDM measurements?
how do we control uncertainties from nuclear & hadronic physics?

Outline

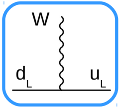
The Standard Model as an Effective Field Theory



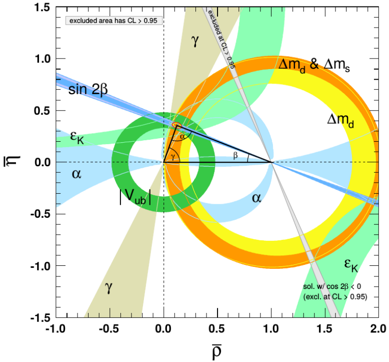
Write down all possible operators with

- SM fields
- local $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariance
- dimension ≤ 4

The Standard Model as an EFT



$\bar{u}_L^i V_{ij} \gamma^\mu d_L^j \, W_\mu$



Two sources of CPV:

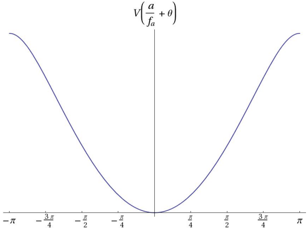
- phase of the CKM matrix (if ≥ 3 gen. of u and d quarks)
- explains all observed CPV ✓
- not enough for baryogenesis ×

M. B. Gavela *et al*, '93; M. B. Gavela *et al*, '94

- unobservable EDMs ×

C. Y. Seng, '14

The Standard Model as an EFT



- QCD $\bar{\theta}$ term:

$$\mathcal{L}_{\bar{\theta}} = \theta \frac{g_s^2}{64\pi^2} \varepsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta} \Longrightarrow \frac{m_u m_d}{m_u + m_d} \sin\bar{\theta}\, r^{-1}(\bar{\theta})\, \bar{q} i \gamma^5 q$$

- $\bar{\theta}$ is a parameter of the strong interaction

$$d_n \sim 2 \cdot 10^{-3}\, \bar{\theta}\, e\, \text{fm}$$

$\bar{\theta} \lesssim 10^{-10}$
strong CP problem! axions ...

The Standard Model as an EFT

- why stop at dim=4?

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_{i,5}}{\Lambda}\mathcal{O}_{5\,i} + \sum \frac{c_{i,6}}{\Lambda^2}\mathcal{O}_{6\,i} \qquad + \sum \frac{c_{i,7}}{\Lambda^3}\mathcal{O}_{7\,i} + \dots$$

$$\Lambda \gg v = 246\,\mathrm{GeV}$$

- $\mathcal{O}$ have the same symmetries as the SM

  gauge symmetry!

  but not accidental (almost) symmetries as *CP*

The Standard Model as an EFT

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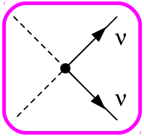
- **one** dimension 5 operator S. Weinberg, '79

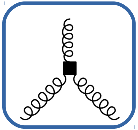


$$\tfrac{1}{\Lambda}\varepsilon_{ij}\varepsilon_{mn}L_i^T C L_m\, H_j H_n \to \tfrac{v^2}{\Lambda}\nu_L^T C \nu_L$$

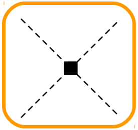
neutrino masses and mixings

$\Lambda \sim 10^{14}$ GeV

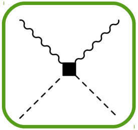
The Standard Model as an EFT



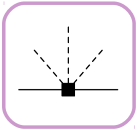
three/four bosons



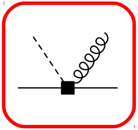
h self-coupling



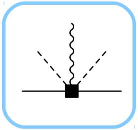
scalar-gauge



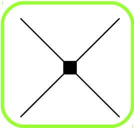
Yukawa



dipole



vector/axial currents



four-fermion

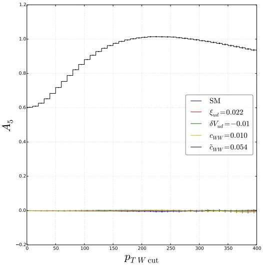
- 2499 dimension 6 ($\propto v^2/\Lambda^2$), 1149 CPV

  Buchmuller & Wyler ‘86, Weinberg ‘89, de Rujula *et al.* ‘91, Grzadkowski *et al.* ‘10 . . .

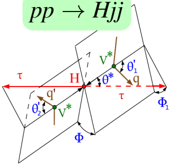
- CP symmetry is not a generic feature of BSM models. . .

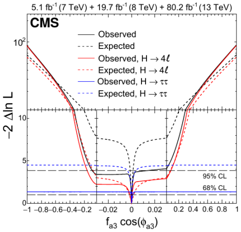
CPV at colliders

$pp \to HW(l\nu)$



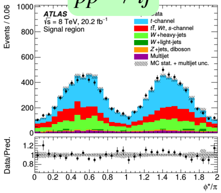
$pp \to Hjj$

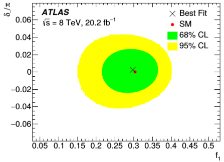




CMS, 1903.06973

$pp \to tj$





ATLAS, 1707.05393

- CPV dim. 6 operators affect a variety of distributions
- . . . but don’t spoil low-energy probes!

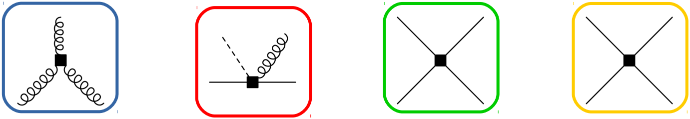
Low-energy EFT for T violation

Low-energy EFT for T violation

- integrate out W, Z, t, ...
- one dim-4 operator: QCD $\bar{\theta}$ term

$$\mathcal{L}_{\not{T}\,4} = m_* \bar{\theta} \bar{q} i \gamma_5 q$$

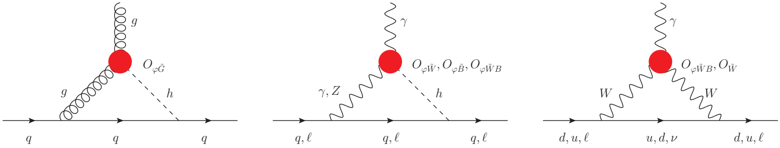
- 9 (+ 10 w. strangeness) dim-6 hadronic operators:



gluon CEDM	quark (C)EDM	LL RR 4-quark	LR LR 4-quark
$C_{\tilde{G}}$	$c_{g,\gamma}^{(u,d,s)}$	$\Xi_{ud,us,ds}^{(1,8)}$	$\Sigma_{ud,us}^{(1,8)}$, $\Sigma_{us,S}^{(1,8)}$

- electron, muon EDMs + 3 (+1) scalar and tensor semileptonic operators

Low-energy EFTs for T violation

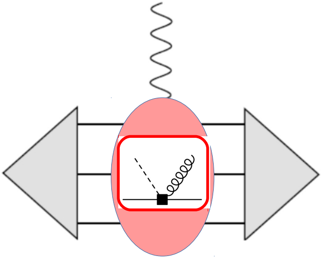


- matching is perturbative
- resum large logs of m_W/Λ_χ, e.g.

$$\frac{d}{d\log\mu}\tilde{c}_\gamma^{(e)} = \frac{\alpha_{\rm em}}{4\pi}\frac{4}{\sin^2\theta_w}C_{\varphi\tilde{W}}$$

- loop suppression (often) not enough to eliminate the constraint
- correlations between different low energy observables

  e.g. eEDM and CP asymmetry in $b \to s\gamma$



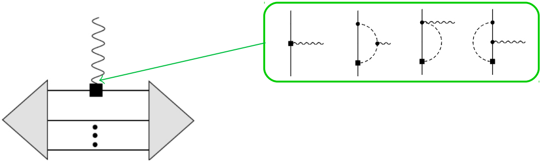
- nucleon and nuclear EDMs as a function of quark/gluon operators?

EFT in terms of pions, nucleons and photons!

- at LO in chiral EFT, for all quark-level ops.

$$\mathcal{L}_{\not T} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S^\mu v^\nu N F_{\mu\nu} - \frac{\bar{g}_0}{2F_\pi}\bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N - \frac{\bar{g}_1}{2F_\pi}\pi_3\bar{N}N$$
$$+\bar{C}_1\bar{N}N\,\partial_\mu\left(\bar{N}S^\mu N\right) + \bar{C}_2\bar{N}\boldsymbol{\tau}N\,\partial_\mu\left(\bar{N}S^\mu\boldsymbol{\tau}N\right)$$

Hadronic EFTs



$$\mathcal{L}_{\not T} \quad = \quad -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S^\mu v^\nu N F_{\mu\nu} - \frac{\bar{g}_0}{2F_\pi}\bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N - \frac{\bar{g}_1}{2F_\pi}\pi_3\bar{N}N + \dots$$

- operators in $\mathcal{L}_{\not T}$ & scaling of couplings dictated by chiral symmetry

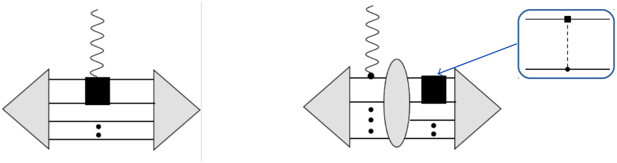
$\bar{d}_0$, $\bar{d}_1$ neutron & proton EDM,
one-body contribs. to A $\geq$ 2 nuclei

$\bar{g}_0$, $\bar{g}_1$ pion loop to nucleon & proton EDMs, leading OPE $\not T$ potential

$\bar{C}_1$, $\bar{C}_2$ short-range $\not T$ potential

relative size of the coupling
depends on chiral/isospin properties of $\not T$ source

Hadronic EFTs



$$\mathcal{L}_{\not{T}} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S^\mu v^\nu N F_{\mu\nu} - \frac{\bar{g}_0}{2F_\pi}\bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N - \frac{\bar{g}_1}{2F_\pi}\pi_3\bar{N}N + \dots$$

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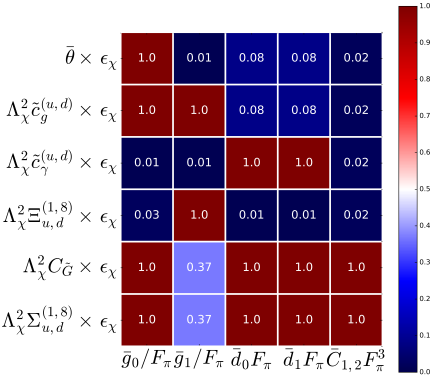


$\Lambda_\chi \sim 1$ GeV

$\epsilon_\chi \sim \frac{m_\pi}{\Lambda_\chi} \sim 0.15$

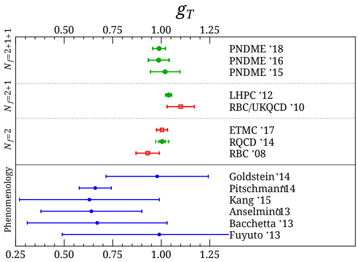
WARNING
naive dim. analysis!

- chiral breaking operators generate large $\bar g_0$
- chiral & isospin breaking large $\bar g_1$
- can we be more precise?

Hierarchies observable in experiment

From quarks to nucleons

From quarks to nucleons: quark bilinears.



	g_T^u	g_T^d	g_T^s
Connected	0.790(27)	−0.198(10)	
Disconnected	−0.0064(33)	−0.0064(33)	−0.0027(16)
PNDME'18	0.784(28)(10)	−0.204(11)(10)	−0.0027(16)
ETMC'17 [15]	0.782(21)	−0.219(17)	−0.00319(72)
PNDME'15 [5]	0.774(66)	−0.233(28)	0.008(9)

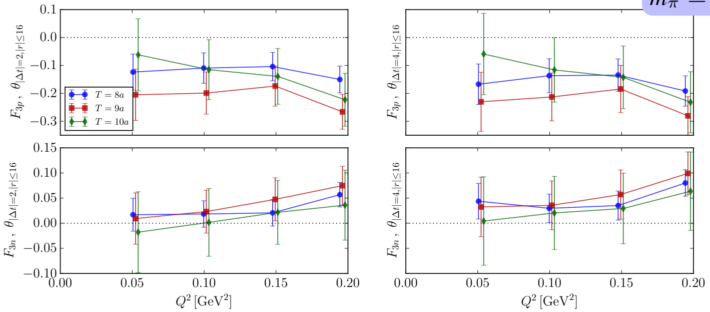
R. Gupta *et al*, PNDME coll., '18

$$\mathcal{L}_{\rm qEDM} = m_q \tilde{c}_q\, \bar{q}\sigma_{\mu\nu} q\, \varepsilon^{\alpha\beta\mu\nu} F_{\mu\nu} \quad \Longrightarrow \quad d_N \propto \langle N|\bar{q}\sigma^{\mu\nu} q|N\rangle$$

- single nucleon charges well determined by LQCD
- $\sim 5\%$ uncertainty on u, d
- first signal for s

Nucleon EDM from the $\bar{\theta}$ term

$m_\pi = 139$ MeV



S. Syritsyn, T. Izubuchi, H. Ohki, '19

- lot of effort from LQCD … but inconclusive results
- no signal at physical pion mass
- signal at heavier masses
  … maybe a bit too heavy to trust χ-extrapolation

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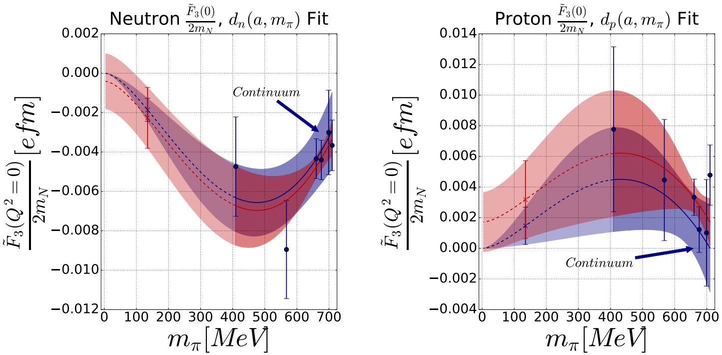

J. Dragos, T. Luu, A. Shindler, J. de Vries, A. Yousif, '19

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Nucleon EDM from dim. 6 hadronic operators

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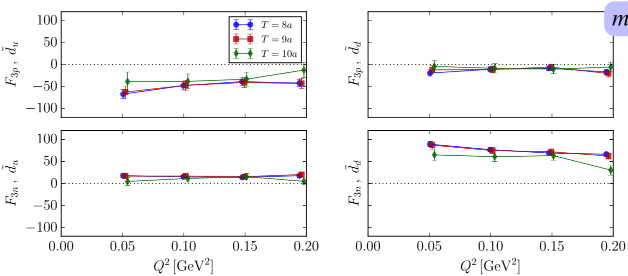
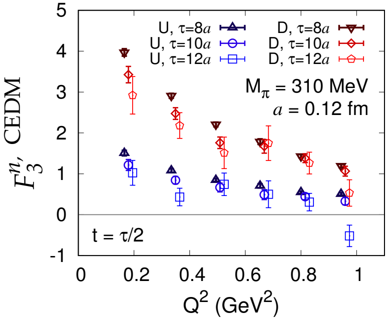


S. Syritsyn, T. Izubuchi, H. Ohki, '19

- qCEDM more promising
- still preliminary
  e.g no renormalization

$$[\bar{q}i\sigma^{\mu\nu}\gamma^5\tau^3 qG_{\mu\nu}] = \frac{1}{a^2}\bar{q}i\gamma^5\tau^3 q + \log a\,\bar{q}i\sigma^{\mu\nu}\gamma^5\tau^3 qG_{\mu\nu} + \ldots$$

Nucleon EDM from dim. 6 hadronic operators



$m_\pi = 310$ MeV

B. Yoon, T. Bhattacharya, R. Gupta

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$$[\bar{q} i \sigma^{\mu\nu} \gamma^5 \tau^3 q G_{\mu\nu}] = \frac{1}{a^2} \bar{q} i \gamma^5 \tau^3 q + \log a \, \bar{q} i \sigma^{\mu\nu} \gamma^5 \tau^3 q G_{\mu\nu} + \ldots$$

- chiral-breaking $\not{T}$ operators belong to chiral multiplets

$$\mathcal{L} = \mathbf{C} \cdot \begin{pmatrix} \mathcal{O}_{\not{T}} \\ \mathcal{O}_{T} \end{pmatrix} \qquad \begin{pmatrix} \mathcal{O}_{\not{T}} \\ \mathcal{O}_{T} \end{pmatrix} \xrightarrow{SU_A(2)} \begin{pmatrix} \alpha\mathcal{O}_{T} \\ \alpha\mathcal{O}_{\not{T}} \end{pmatrix}$$

- CP-even $\Longrightarrow$ hadron masses and mass splittings
- CP-odd $\Longrightarrow$ pion-nucleon couplings

related by χ symmetry!

Pion nucleon couplings

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- CP-even $\Longrightarrow$ hadron masses and mass splittings
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related by χ symmetry!

- e.g. $\bar{\theta}$ term

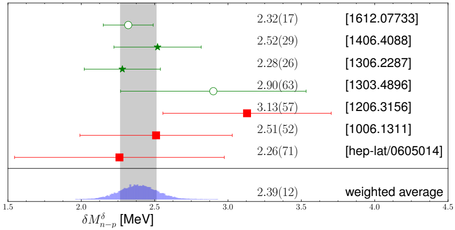
$$\mathcal{L}_4 = r^{-1}(\bar{\theta}) \left(\bar{m}\varepsilon\, \bar{q}\tau_3 q + m_* \sin\bar{\theta}\, \bar{q} i\gamma_5 q \right)$$

$$2\bar{m} = m_u + m_d$$
$$\bar{m}\varepsilon = m_d - m_u$$

- one spurion enough to construct iso- and T-breaking couplings

$$\frac{\text{T violation}}{\text{isospin breaking}} = \frac{1-\varepsilon^2}{2\varepsilon} \sin\bar{\theta} \equiv \rho_{\bar{\theta}}$$

Pion-nucleon couplings. $\bar{\theta}$ term.



- χ-symmetry relates π-N couplings to spectral properties
- LQCD calculations of $m_n - m_p$ determines $\bar{g}_0$

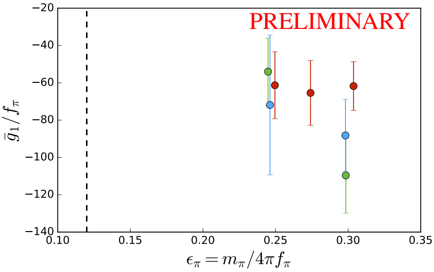
$$\frac{\bar{g}_0}{2F_\pi}(\bar{\theta}) = \frac{(m_n - m_p)|_{\rm str}}{2F_\pi}\,\frac{1-\varepsilon^2}{2\varepsilon}\,\bar{\theta} = (15.5 \pm 2.0 \pm 1.6)\cdot 10^{-3}\bar{\theta}$$

LQCD $\quad$ N^2LO χPT

- precise prediction of chiral log in $d_n(\bar{\theta})$

$$d_n(\bar{\theta}) = \bar{d}_n(\mu) + e\,\frac{g_A \bar{g}_0}{(4\pi F_\pi)^2}\log\frac{\mu^2}{m_\pi^2} \sim 1.99\cdot 10^{-3}\,\bar{\theta}\; e\,\mathrm{fm}$$

Pion-nucleon couplings. qCEDM



thanks to D. Brantley, CalLat coll.

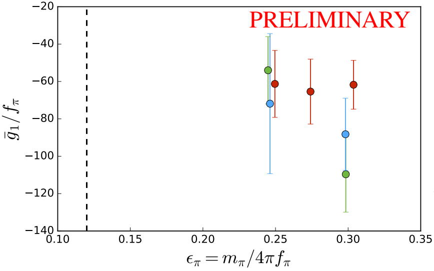
- π-N couplings poorly determined

$$\frac{\bar{g}_0}{2F_\pi} = (5 \pm 10)(m_u \tilde{c}_g^{(u)} + m_d \tilde{c}_g^{(d)})\ \mathrm{fm}^{-1}$$

$$\frac{\bar{g}_1}{2F_\pi} = (20^{+40}_{-10})(m_u \tilde{c}_g^{(u)} - m_d \tilde{c}_g^{(d)})\ \mathrm{fm}^{-1}.$$

QCD sum rules, M. Pospelov and A. Ritz, ‘05

Pion-nucleon couplings. qCEDM



thanks to D. Brantley, CalLat coll.

- can use similar relations to spectrum

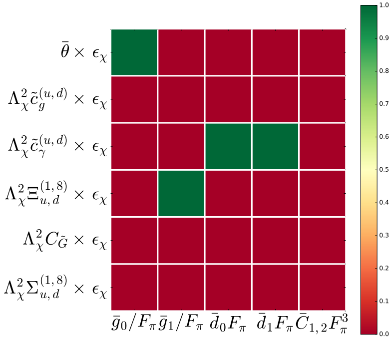
$$\bar{g}_0 = (m_u \tilde{c}_g^{(u)} + m_d \tilde{c}_g^{(d)}) \left(\frac{d}{d\tilde{c}_3} - r \frac{d}{d\bar{m}\varepsilon} \right) (m_n - m_p)$$

$$\bar{g}_1 = (m_u \tilde{c}_g^{(u)} - m_d \tilde{c}_g^{(d)}) \left(\frac{d}{d\tilde{c}_0} + r \frac{d}{d\bar{m}} \right) (m_n + m_p)$$

$\tilde{c}_{0,3}$: iso-scalar (-vector) chromo-magnetic operators

- results coming soon!

From quarks to nucleons: summary



- only a few couplings are known with satisfactory accuracy
- sustained LQCD for nucleon EDMs
- & π-N couplings
- *NN* couplings are even harder...

From nucleons to nuclei

Why light ions?

JEDI @ COSY (Julich)

1. “orthogonal” to the nucleon EDM
   - sensitive to different combinations of $\not{T}$ couplings
2. theoreticaly clean
   - no Schiff screening, *ab initio* calculations
3. experimentally feasibile

Staged approach

Stage 1

precursor experiment

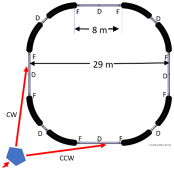
at COSY (FZ Jülich)

- magnetic storage ring

now

Stage 2

prototype ring

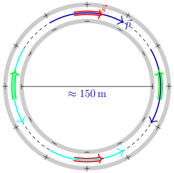


- electrostatic storage ring
- simultaneous ↻ and ↺ beams

5 years

Stage 3

dedicated storage ring



- magic momentum

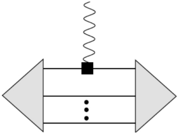
(701 MeV/c)

10 years

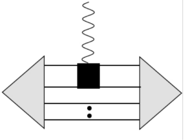
$\sigma_{EDM}/(e \cdot \mathrm{cm})$

10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21} 10^{-22} 10^{-23} 10^{-24} 10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29}

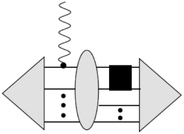
From nucleons to nuclei



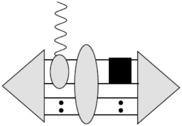
One-body $\not{T}$ current



Two-body $\not{T}$ current

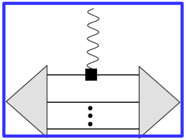


NN $\not{T}$ potential



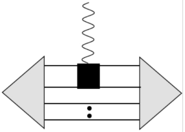
NN $\not{T}$ potential
& two-body $\not{T}$ currents

From nucleons to nuclei

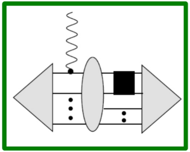


One-body $\not{T}$ current

$d_A \sim d_n, d_p$



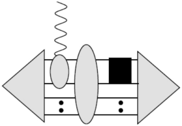
Two-body $\not{T}$ current



NN $\not{T}$ potential

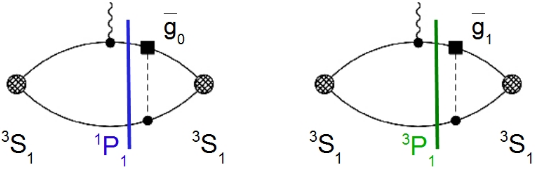
for χ-breaking source

$d_A \sim \frac{\Lambda_\chi^2}{F_\pi^2} d_{n,p}$



NN $\not{T}$ potential
& two-body T currents

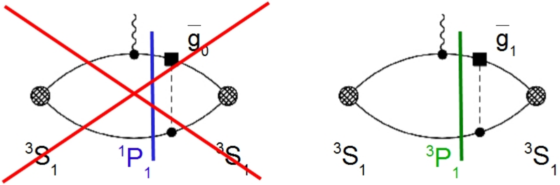
Deuteron EDM



Deuteron is "isospin filter"

- isoscalar interactions cause mixing with $^1P_1$ intermediate state

  need spin-flip to overlap back with deuteron
- isoscalar ($\bar{g}_0$, $\bar{C}_{1,2}$) TV corrections to wavefunction vanish at LO,
- but $\bar{g}_1$ gives large contribs.



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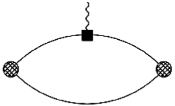
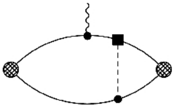
Deuteron EDM. Perturbative Pions

One-body



$\not{T}$ corrections to wavefunction



- only sensitive to isoscalar nucleon EDM

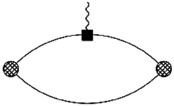
$$d_d = d_n + d_p$$

- sensitive to **isobreaking** $\bar{g}_1$

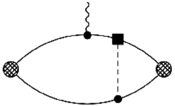
$$d_d = -\frac{2}{3} e \frac{g_A \bar{g}_1}{m_\pi^2} \frac{m_N m_\pi}{4\pi F_\pi^2} \frac{1+\xi}{(1+2\xi)^2}, \qquad \xi = \frac{\gamma}{m_\pi}$$

Deuteron EDM. Perturbative Pions

One-body



$\not{T}$ corrections to wavefunction



- only sensitive to isoscalar nucleon EDM

$$d_d = d_n + d_p$$

- sensitive to **isobreaking** $\bar{g}_1$

$$d_d = -0.22 \frac{\bar{g}_1}{F_\pi^2}$$

- good agreement with ptb. pion power counting $Q/M_{NN} \sim 1/3$

Deuteron EDM

	Potential (references)	d_n	d_p	$\bar{g}_0/F_\pi$	$\bar{g}_1/F_\pi$	$\bar{C}_1 F_\pi^3$	$\bar{C}_2 F_\pi^3$
	Perturbative pion (141, 129)	1	1	—	−0.23	—	—
d_d	Av18 (125, 130, 131, 86, 132)	0.91	0.91	—	−0.19	—	—
	N^2LO (131, 86)	0.94	0.94	—	−0.18	—	—

from EM and U.van Kolck, ‘15

- several calculations with non-perturbative iteration of OPE potential
- using pheno & chiral T-conserving potentials

C. P. Liu and R. Timmermans, ‘05; J. de Vries *et al*, ‘11;
J. Bsaisou *et al*, ‘13, J. Bsaisou *et al*, ‘15;
N. Yamanaka and E. Hiyama, ‘15

- one-body & $\not{T}$ OPE contribution not affected by different potentials
- results agree well with ptb. pion estimates

EDM of ^{3}He and ^{3}H

	Potential (references)	d_n	d_p	$\bar{g}_0/F_\pi$	$\bar{g}_1/F_\pi$	$\bar{C}_1 F_\pi^3$	$\bar{C}_2 F_\pi^3$
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	N^2LO (131, 86)	0.94	0.94	—	−0.18	—	—
	Av18 (126, 130, 132)	−0.05	0.90	0.08	−0.14	0.01	−0.02
d_t	Av18+UIX (128, 86)	−0.05	0.90	0.07	−0.14	0.002	−0.005
	N^2LO (86)	−0.03	0.92	0.11	−0.14	0.05	−0.10
	Av18 (126, 130, 132)	0.88	−0.05	−0.08	−0.14	−0.01	0.02
d_h	Av18+UIX (128, 86)	0.88	−0.05	−0.07	−0.14	−0.002	0.005
	N^2LO (86)	0.90	−0.03	−0.11	−0.14	−0.05	0.11

- one-body not affected by different potentials

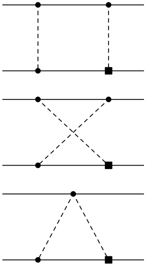
$$d_h = 0.9 d_n \qquad d_t = 0.9 d_p$$

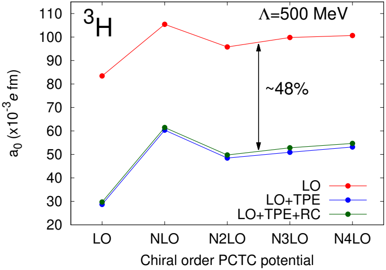
- OPE agrees well with ptb. pion counting

$$< 10\% \text{ error on } \bar{g}_1$$
$$\sim 30\% \text{ error on } \bar{g}_0$$

- short-range $\bar{C}_{1,2}$ much harder to estimate

EDM of ^{3}He and ^{3}H





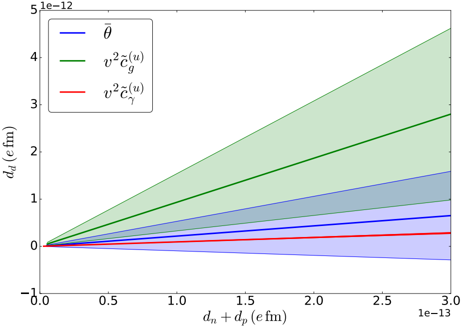
thanks to A. Gnech and M. Viviani

- NLO corrections to the $\bar{g}_0$-induced $\not{T}$ potential are large
- issues with $\not{T}$ three-body forces?

don't affect d_d!

Disentangling $\not{T}$ mechanisms

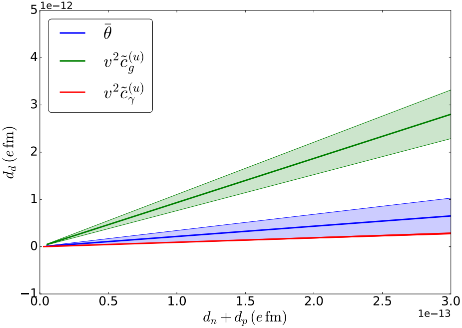
Disentangling low-energy couplings



- $d_d \gg d_n + d_p$ isospin-breaking sources
  $d_d \sim d_n + d_p$ QCD $\bar{\theta}$ term
  $d_d = d_n + d_p$ qEDM

  . . . but swamped by current theory uncertainties
- $\mathcal{O}(20\%)$ uncertainties sufficient to discriminate!

Disentangling low-energy couplings



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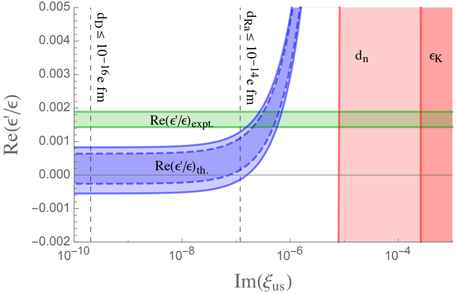
Disentangling $\not{T}$ sources



$$(\epsilon'/\epsilon)_{\rm expt} = (16.6 \pm 2.3) \cdot 10^{-4}$$

$$(\epsilon'/\epsilon)_{\rm LQCD} = (1.4 \pm 6.9) \cdot 10^{-4}$$

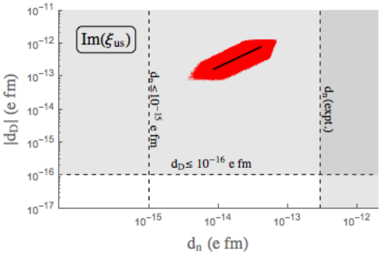
- LQCD/experiment discrepancy in ϵ'/ϵ could be explained with tiny right-handed currents

$$\mathcal{L} = \frac{g}{\sqrt{2}} \left(\xi_{ud}\, \bar{u}_R \gamma^\mu d_R + \xi_{us}\, \bar{u}_R \gamma^\mu s_R\right) W_\mu + \text{h.c.}$$

- in this scenario: d_n, d_d and $d_{\rm Ra}$ in the next generation of experiments
- and correlated!

falsify with better hadronic and nuclear input

Disentangling $\not{T}$ sources



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- in this scenario: d_n, d_d and d_{Ra} in the next generation of experiments
- and correlated!

falsify with better hadronic and nuclear input

Conclusion

Exciting times for EDMs

- several experiments running or coming online
- increase sensitivity to CP violation by one-two orders of magnitude

To take full advantage of EDM experiments:

1. first principle calculations of d_n, d_p

   ongoing LQCD effort

2. robust estimates of π-N coupings $\bar{g}_0$, $\bar{g}_1$

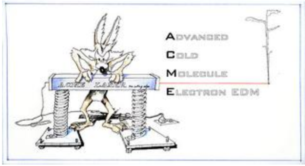
   LQCD + χEFT

3. some more work in few (and many)-body nuclear theory

- electron EDM
  (via ThO energy levels)

$$|d_e| \leq 8.7 \cdot 10^{-16}\, e\,\mathrm{fm}$$

ACME collaboration, ‘14.



- neutron EDM

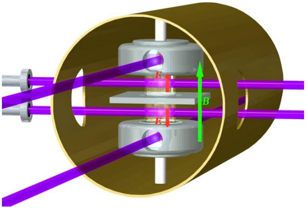
$$|d_n| \leq 3.0 \cdot 10^{-13}\, e\,\mathrm{fm}$$

J. M. Pendlebury *et al*, ‘15

- Hg EDM

$$|d_{^{199}\mathrm{Hg}}| \leq 6.2 \cdot 10^{-17}\, e\,\mathrm{fm}$$

B. Graner *et al*, ‘16.



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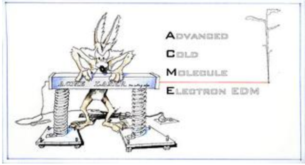

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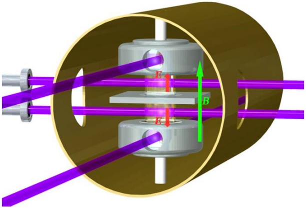
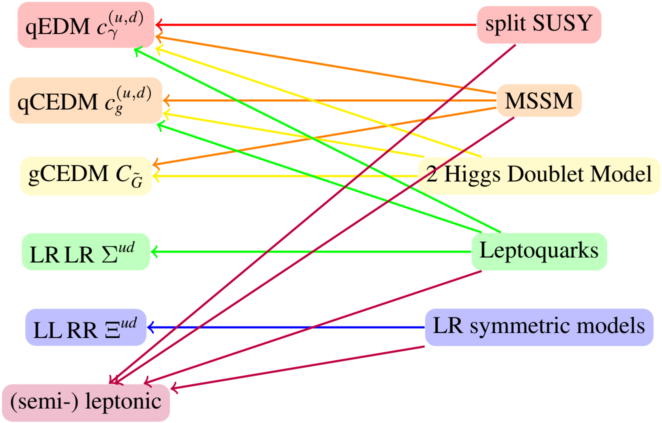


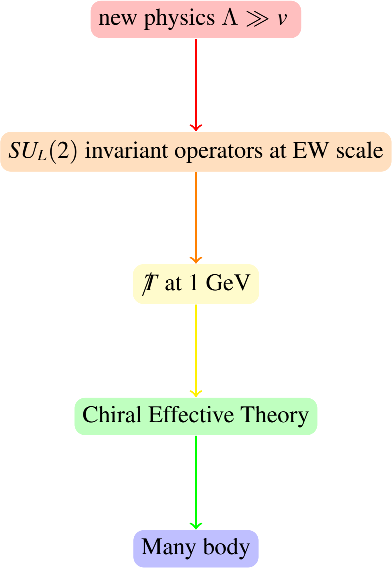
Connection to models

- new physics models induce one, a subset or all these operators



M. Pospelov and A. Ritz, ‘05; W. Dekens *et al*, ‘14;
J. Engel, M. Ramsey-Musolf and U. van Kolck, ‘13;
T. E. Chupp, P. Fierlinger, M. Ramsey-Musolf and J. T. Singh, ‘17;

Effective Field Theories



- model independent link
  to collider phenomenology
- minimal set of low-energy $\not{T}$ operators
- connection with flavor/low energy probes
- from quarks to hadrons
  non-perturbative matching (LQCD)
- EDMs of nucleons & light nuclei

Storage Ring EDM experiments

JEDI @ COSY (Julich)

- measure spin precession relative to $\boldsymbol{\beta}$ ($\eta \propto d$)

$$\boldsymbol{\omega}_a = \frac{e}{m}\left[a\mathbf{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\boldsymbol{\beta} \times \mathbf{E}\right] \qquad \boxed{\boldsymbol{\omega}_e = \frac{\eta e}{m}\left[\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B}\right]}, \quad a = \frac{g-2}{2}$$

Storage Ring EDM experiments

JEDI @ COSY (Julich)

$10^{-16} e$ fm by 2020?

srEDM

- measure spin precession relative to $\boldsymbol{\beta}$ ($\eta \propto d$)

$$\xcancel{\boldsymbol{\omega}_a = \frac{e}{m}\left[a\mathbf{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\boldsymbol{\beta}\times\mathbf{E}\right]} \qquad \boxed{\boldsymbol{\omega}_e = \frac{\eta e}{m}\left[\mathbf{E} + \boldsymbol{\beta}\times\mathbf{B}\right]}, \qquad a = \frac{g-2}{2}$$

$a > 0$: all electric ring

$\boldsymbol{\omega}_a$ vanishes for "magic momentum"
e.g. proton $\mathbf{p} = 0.7$ GeV, $E = 1.171$ GeV

$a < 0$: electric & magnetic ring

need both B & E to cancel $\boldsymbol{\omega}_a$
case of deuteron, ^{3}He