Interpretation of Electric Dipole Moments of Complex Systems

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Outline of this talk

- **Part I:** **What are EDMs and why are they interesting in the first place ?**
- Part II: Effective field theory framework
- Part III: Chiral perturbation theory and CP violation
  - EDMs of nucleons, nuclei, and diamagnetic atoms
- Part IV: Semi-leptonic CP violation
  - Paramagnetic atoms and polar molecules

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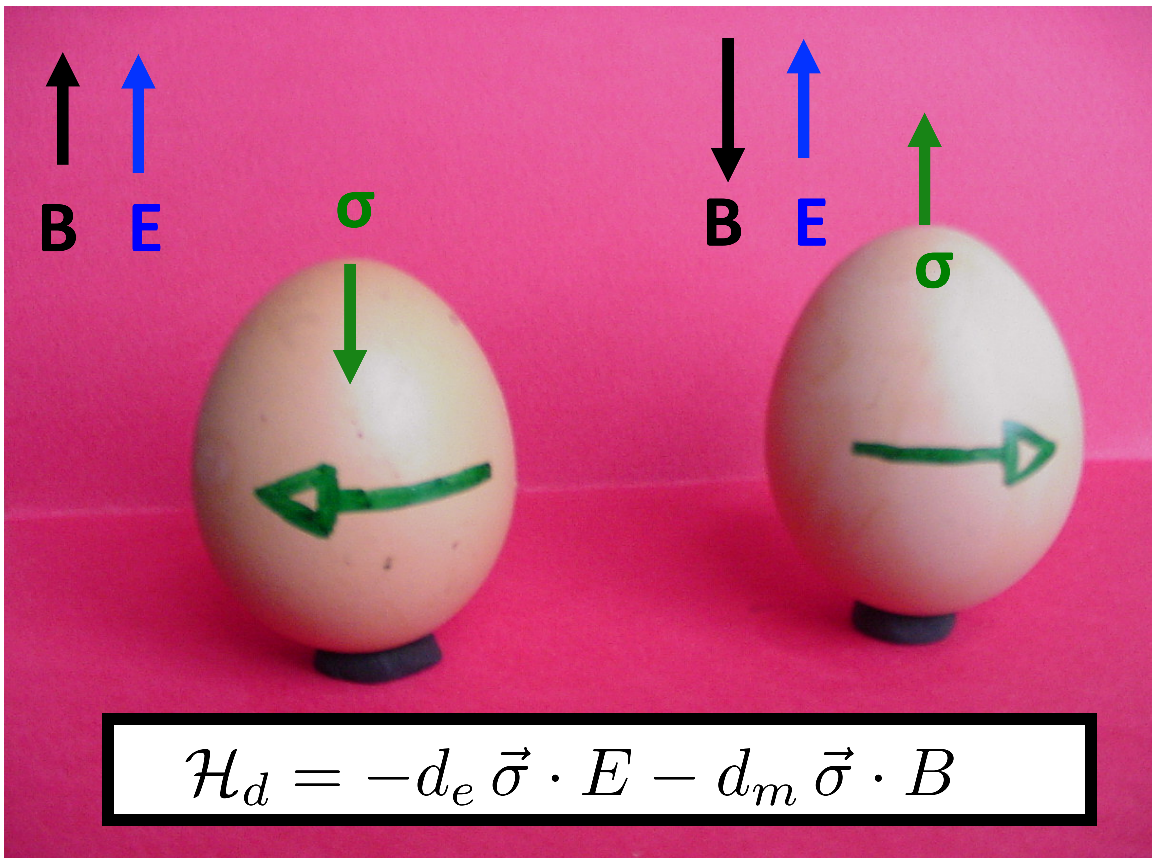
EDMs 101

- Electric and Magnetic Dipole Moment (EDM and MDM)

$$\mathcal{L}_d = -\frac{d_e}{2}\bar{\Psi}\,\sigma^{\mu\nu}\gamma^5\Psi\,F_{\mu\nu} - \frac{d_m}{2}\bar{\Psi}\,\sigma^{\mu\nu}\Psi\,F_{\mu\nu}$$



$$\boxed{\mathcal{H}_d = -d_e\,\vec{\sigma}\cdot E - d_m\,\vec{\sigma}\cdot B}$$

PhD Thesis Hudson

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EDMs 101

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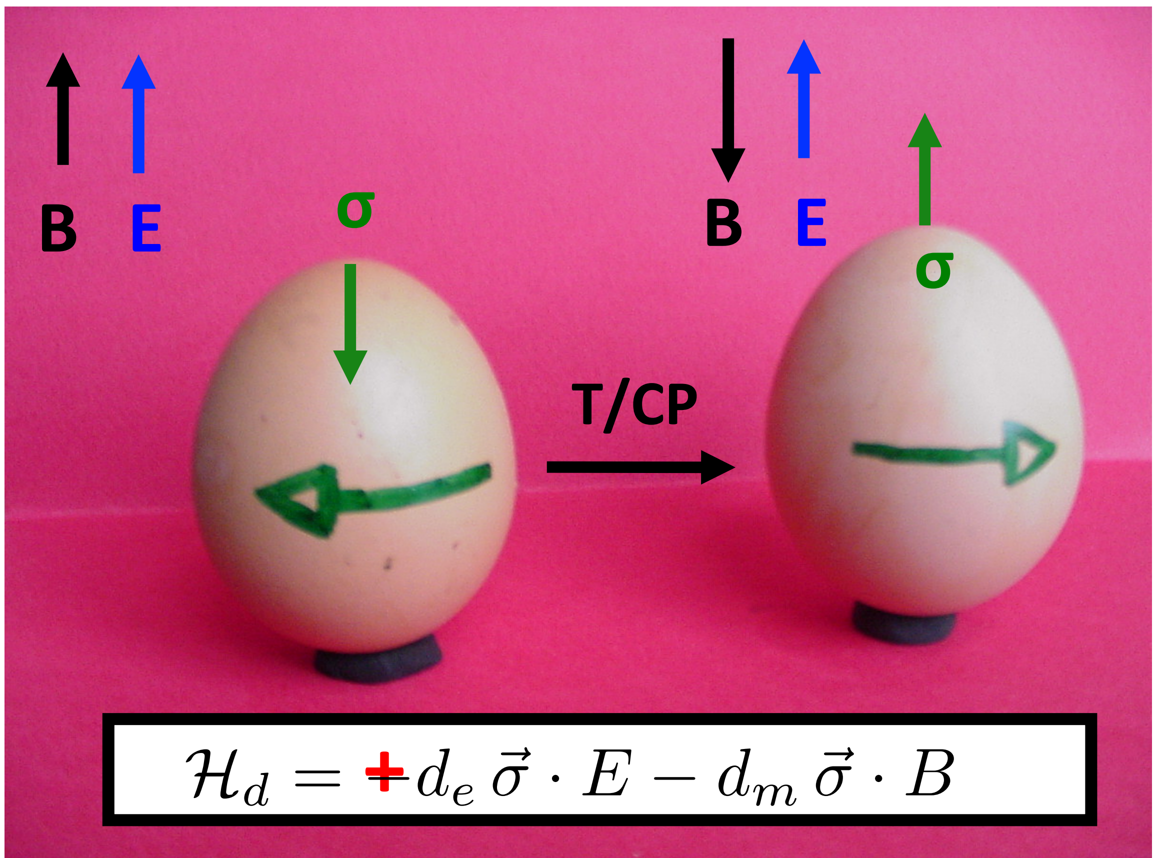

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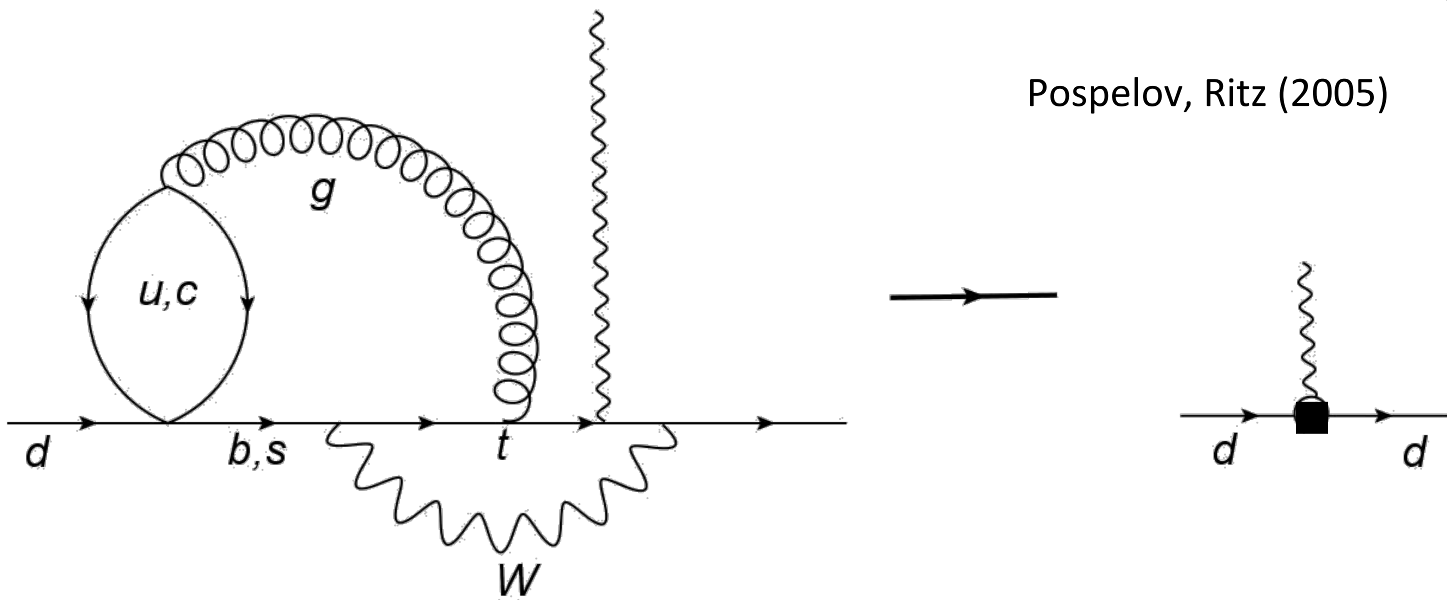
EDMs in the Standard Model

- Electroweak CP-violation very ineffective

Pospelov, Ritz (2005)



- Quark EDMs = 0 at 2-loops , Electron EDM = 0 at 3-loops
- Dominant neutron from four-quark operators

Hoogeveen '90, Khriplovich, Zhitnitsky '82, Czarnecki, Krause '97, Mannel, Uraltsev '12, Seng '14

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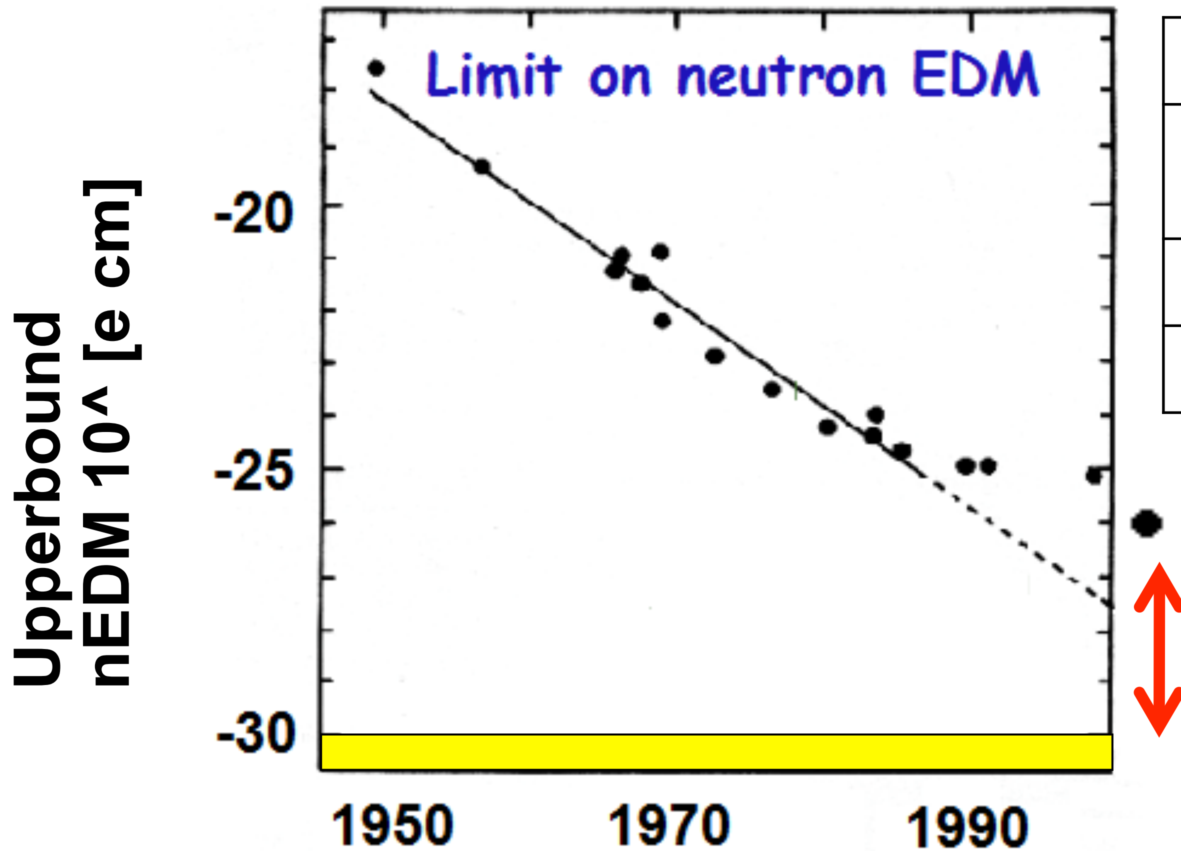
Neutron EDM from CKM



Quarks	$10^{-33,-34}$ e cm
Neutron/ Proton	$10^{-31,-32}$ e cm
^{199}Hg	$10^{-32,-34}$ e cm
Electron	$10^{-37,-38}$ e cm

Baker et al '06

"Here be dragons"

5 to 6 orders **below** upper bound ⟷ **Out of reach!**

With linear extrapolation: CKM neutron EDM in 2075….

I.B. Khriplovich, S.K. Lamoreaux, *CP Violation Without Strangeness*, Springer, 1997

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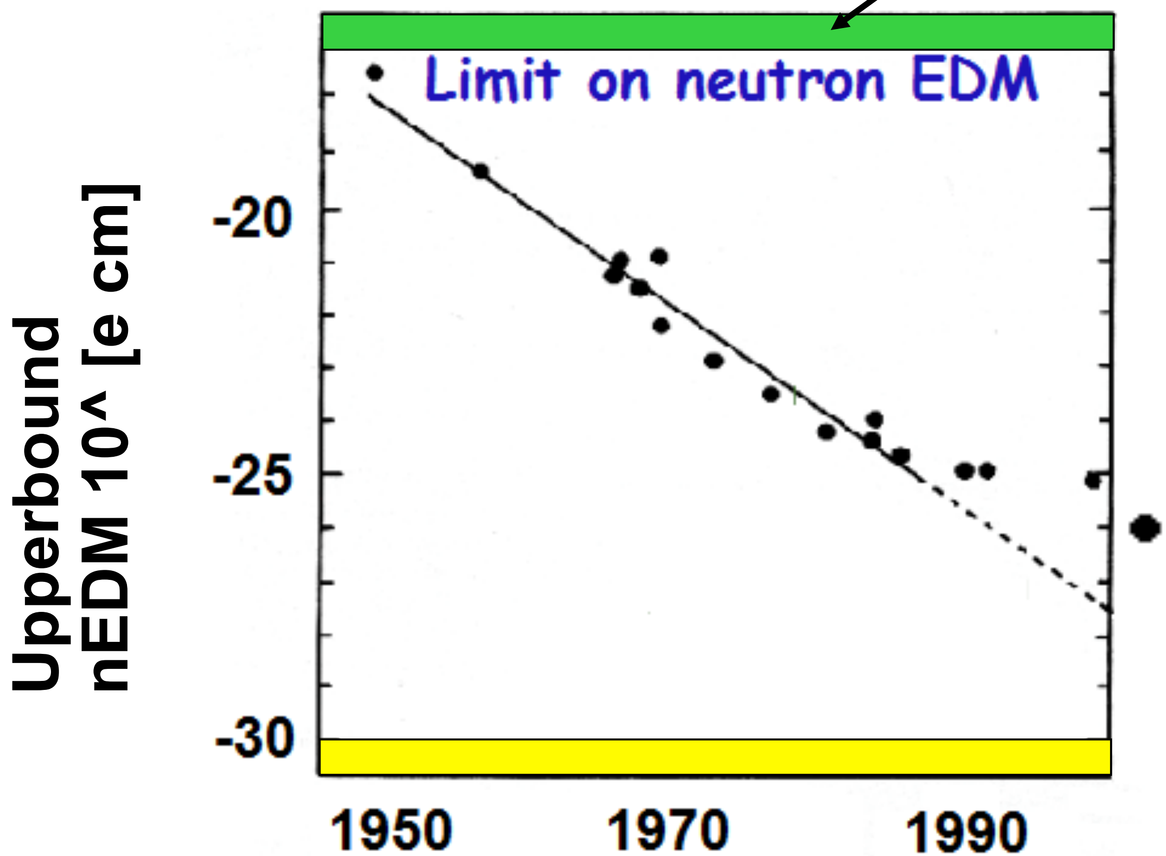
Neutron EDM from theta term

If θ ~ 1



More details on calculation later

$$\theta\,\varepsilon^{\mu\nu\alpha\beta}G_{\mu\nu}G_{\alpha\beta}$$

Crewther et al. (1979)

Sets θ upper bound: **θ < 10^{-10}**

't Hooft '76, '78

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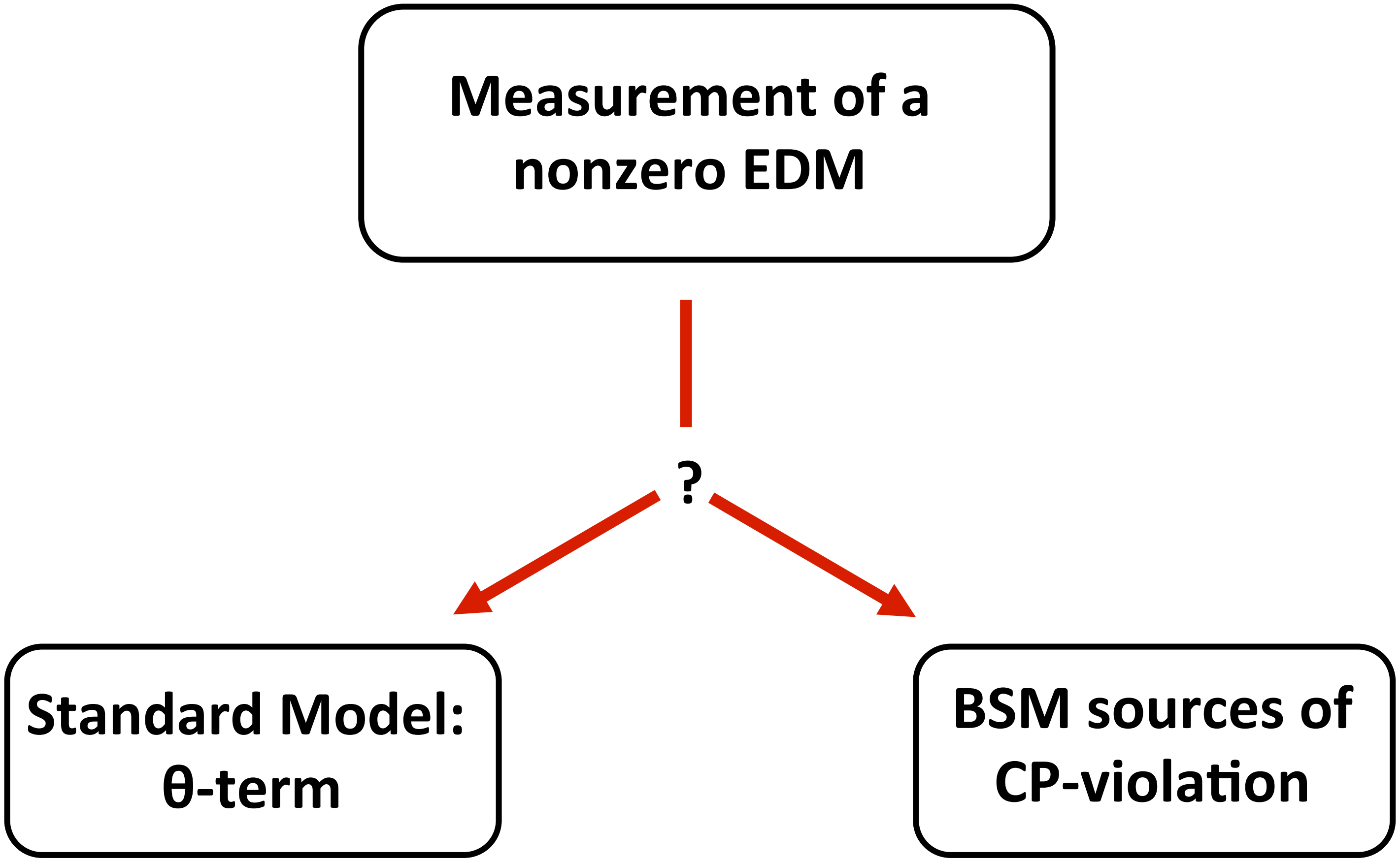
In upcoming experiments:



For the forseeable future: EDMs are ‘background-free’ searches for new physics

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Active experimental field

See next talk by M. Chupp !

System	Group	Limit	C.L.	Value	Year
^{205}Tl	Berkeley	1.6×10^{-27}	90%	$6.9(7.4) \times 10^{-28}$	2002
YbF	Imperial	10.5×10^{-28}	90	$-2.4(5.7)(1.5) \times 10^{-28}$	2011
$Eu_{0.5}Ba_{0.5}TiO_3$	Yale	6.05×10^{-25}	90	$-1.07(3.06)(1.74) \times 10^{-25}$	2012
PbO	Yale	1.7×10^{-26}	90	$-4.4(9.5)(1.8) \times 10^{-27}$	2013
ThO	ACME	8.7×10^{-29}	90	$-2.1(3.7)(2.5) \times 10^{-29}$	2014
n	Sussex-RAL-ILL	2.9×10^{-26}	90	$0.2(1.5)(0.7) \times 10^{-26}$	2006
^{129}Xe	UMich	6.6×10^{-27}	95	$0.7(3.3)(0.1) \times 10^{-27}$	2001
^{199}Hg	UWash	3.1×10^{-29}	95	$0.49(1.29)(0.76) \times 10^{-29}$	2009
muon	E821 BNL g−2	1.8×10^{-19}	95	$0.0(0.2)(0.9) \times 10^{-19}$	2009

e

Current EDM null results → **probe few TeV scale** or $\phi_{CP} \leq O(10^{-2,-3})$

(model dependent!)

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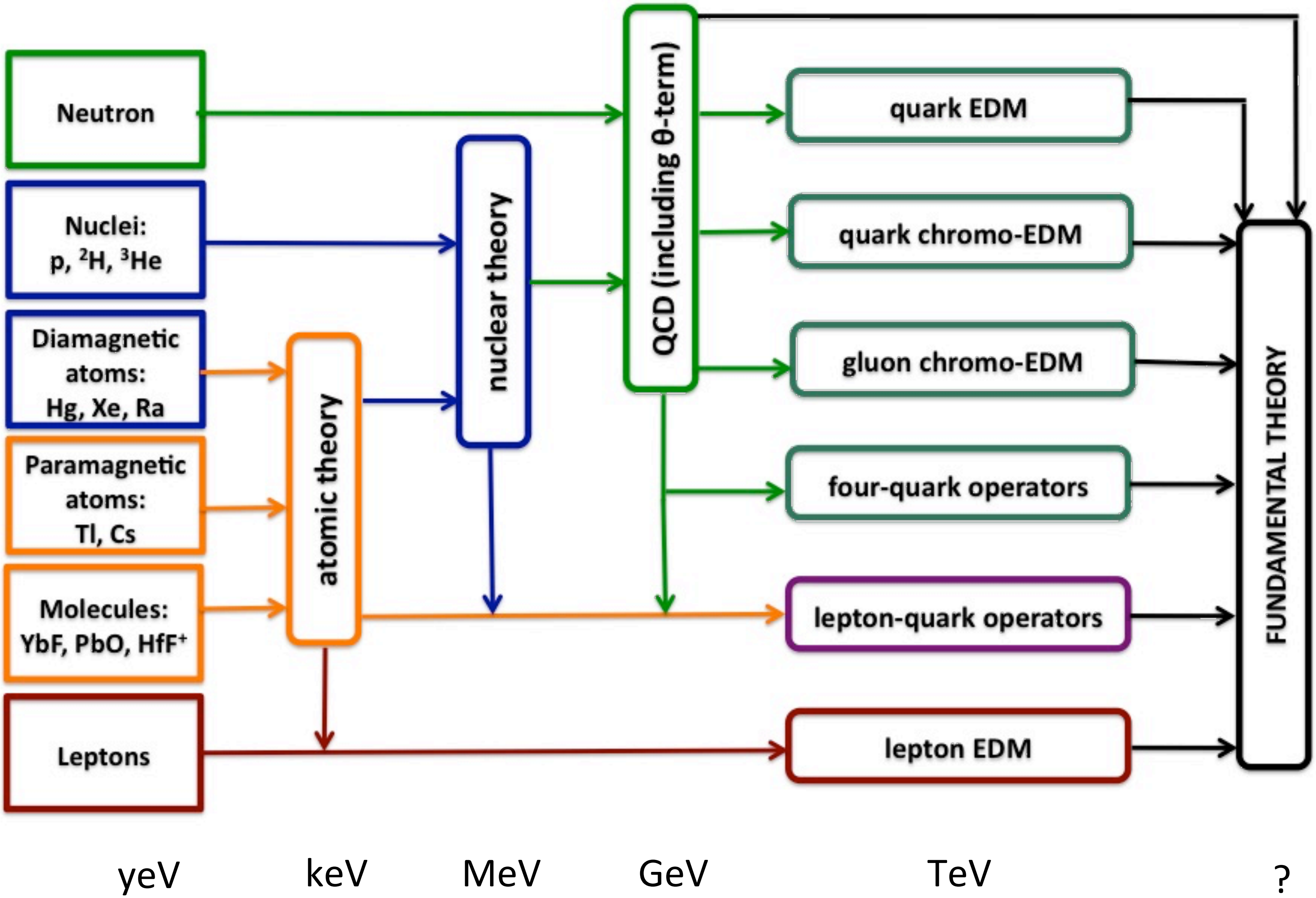
The EDM landscape



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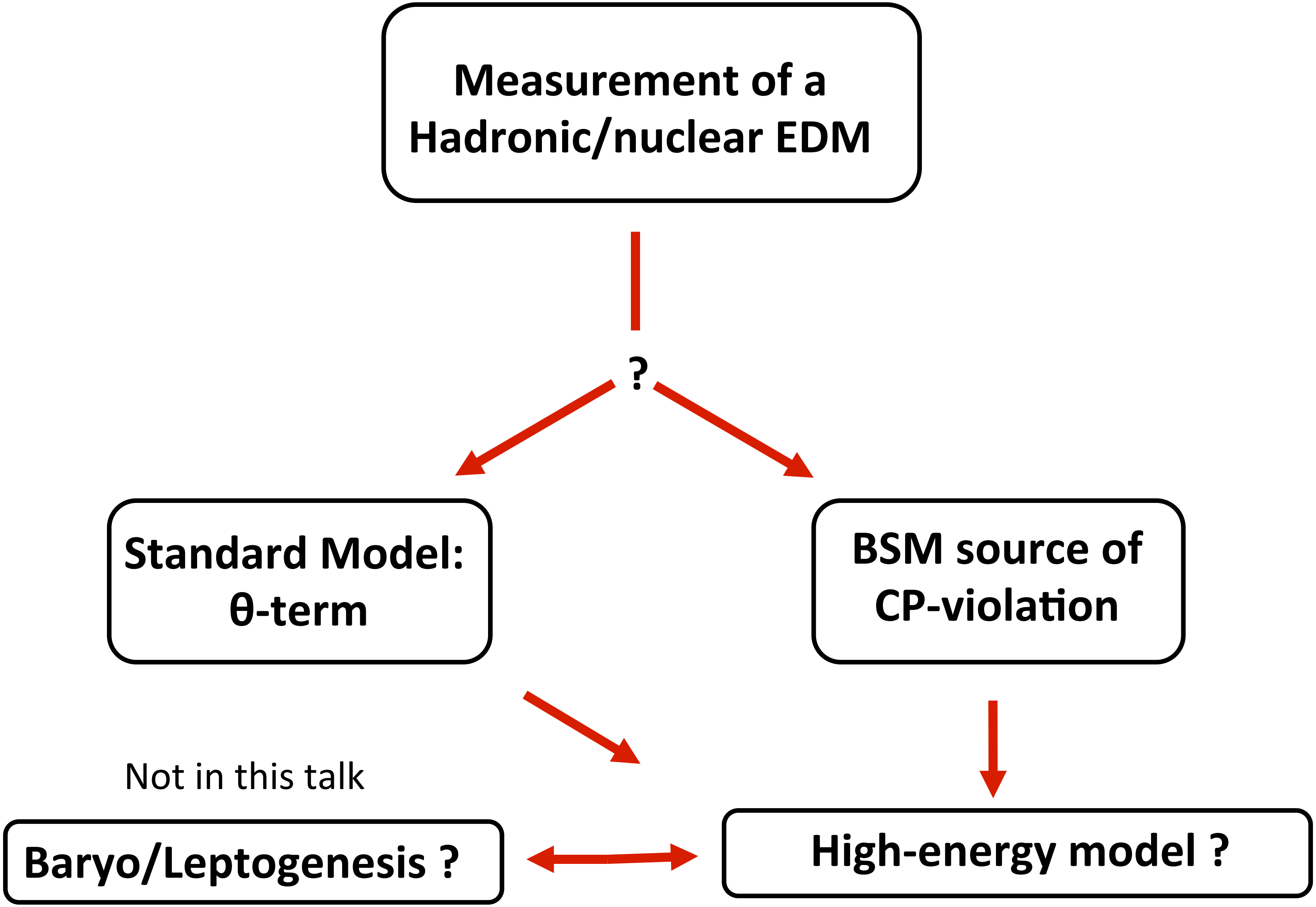
Unraveling the source



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Separation of scales

Energy

BSM physics

?

M_{CP}

? TeV

Integrate out heavy degrees of freedom

L_{EFF}

Renormalization-group evolution

$M_{EW} \sim v \sim M_{Z,W,H,t}$

100 GeV

Integrate out heavy SM degrees of freedom

L'_{EFF}

Renormalization-group evolution

$\Lambda_\chi \sim 2\pi F_\pi \sim M_N$

1 GeV

Nonperturbative QCD regimes

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Separation of scales

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Energy

BSM physics ?

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Integrate out heavy degrees of freedom

$M_{EW} \sim v \sim M_{Z,W,H,t}$ 100 GeV

L_{EFF} Renormalization-group evolution

Integrate out heavy SM degrees of freedom

L'_{EFF} Renormalization-group evolution

$\Lambda_\chi \sim 2\pi F_\pi \sim M_N$ 1 GeV

Nonperturbative QCD regimes

Nonperturbative methods: Lattice + chiral EFT

$F_\pi \sim m_\pi$ 100 MeV

Chiral EFT
Hadronic and nuclear EDMs

$\alpha_{\mathrm{em}} m_e$ 1 keV

Atomic/Molecular observables
Schiff theorem

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Step 1: SM as an EFT

- Assume any BSM physics lives at scales >> M_{EW}
- Match to full set of CP-odd operators (model independent **)

1) Degrees of freedom: Full SM field content

2) Symmetries: Lorentz, SU(3)xSU(2)xU(1)

$$L_{new} = \cancel{\frac{1}{M_{CP}} L_5} + \frac{1}{M_{CP}^2} L_6 + \cdots$$

dim-5 generates neutrino masses/mixing, neglected here

** **Big assumption**: no new light fields
Does not cover for instance light axion DM, Graham et al '13

Buchmuller & Wyler '86
Gradzkowski et al '10

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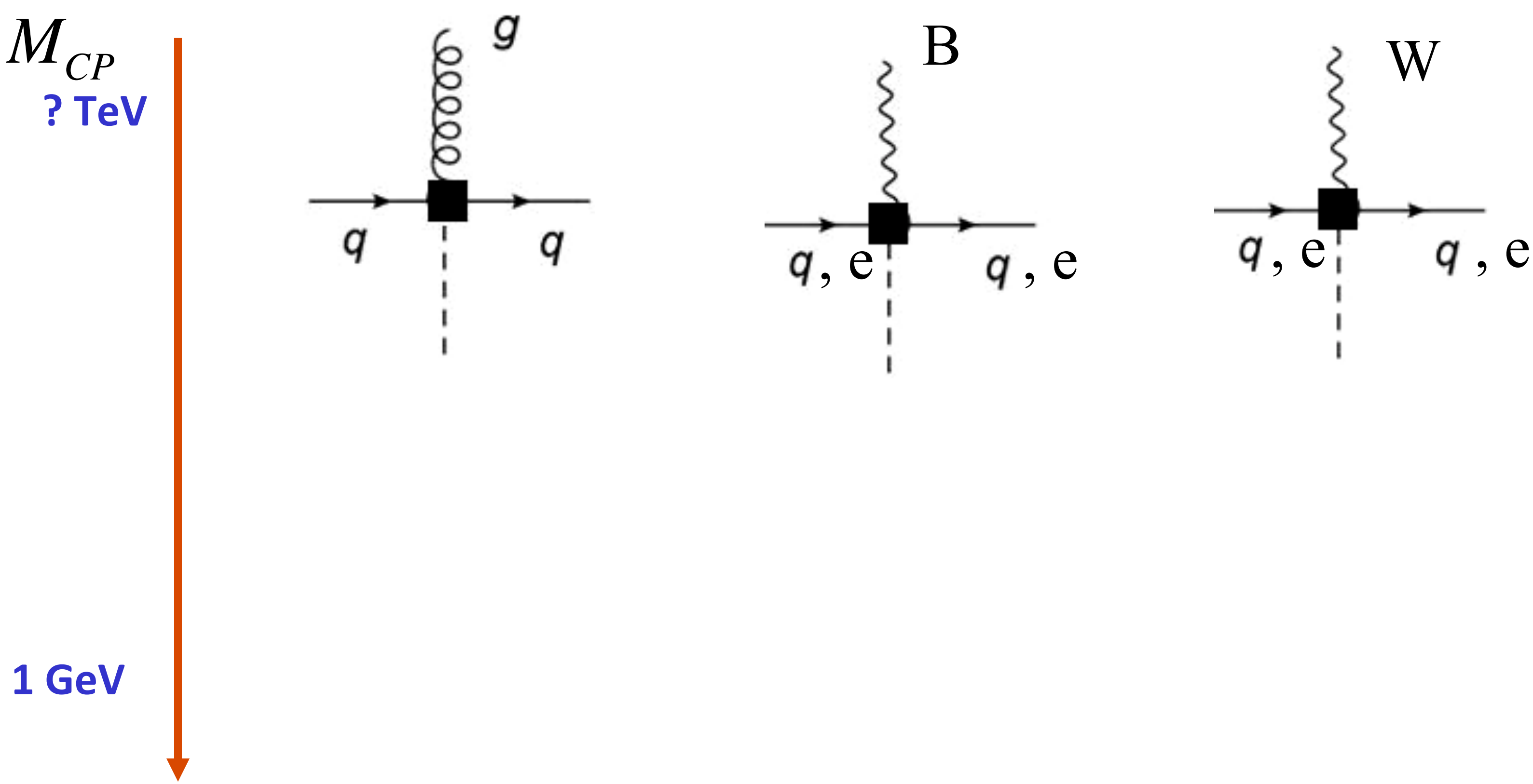
Dipole operators

Requires Higgs: $$\Gamma_X \bar{\Psi}_L \sigma^{\mu\nu} \Psi_R X_{\mu\nu} \varphi + h.c.$$

X=W,B,G quarks
X=W,B leptons

In most models: $$\Gamma_X \propto \frac{m_\Psi}{v\, M_{CP}^2}$$

EDMs typically scale with mass !



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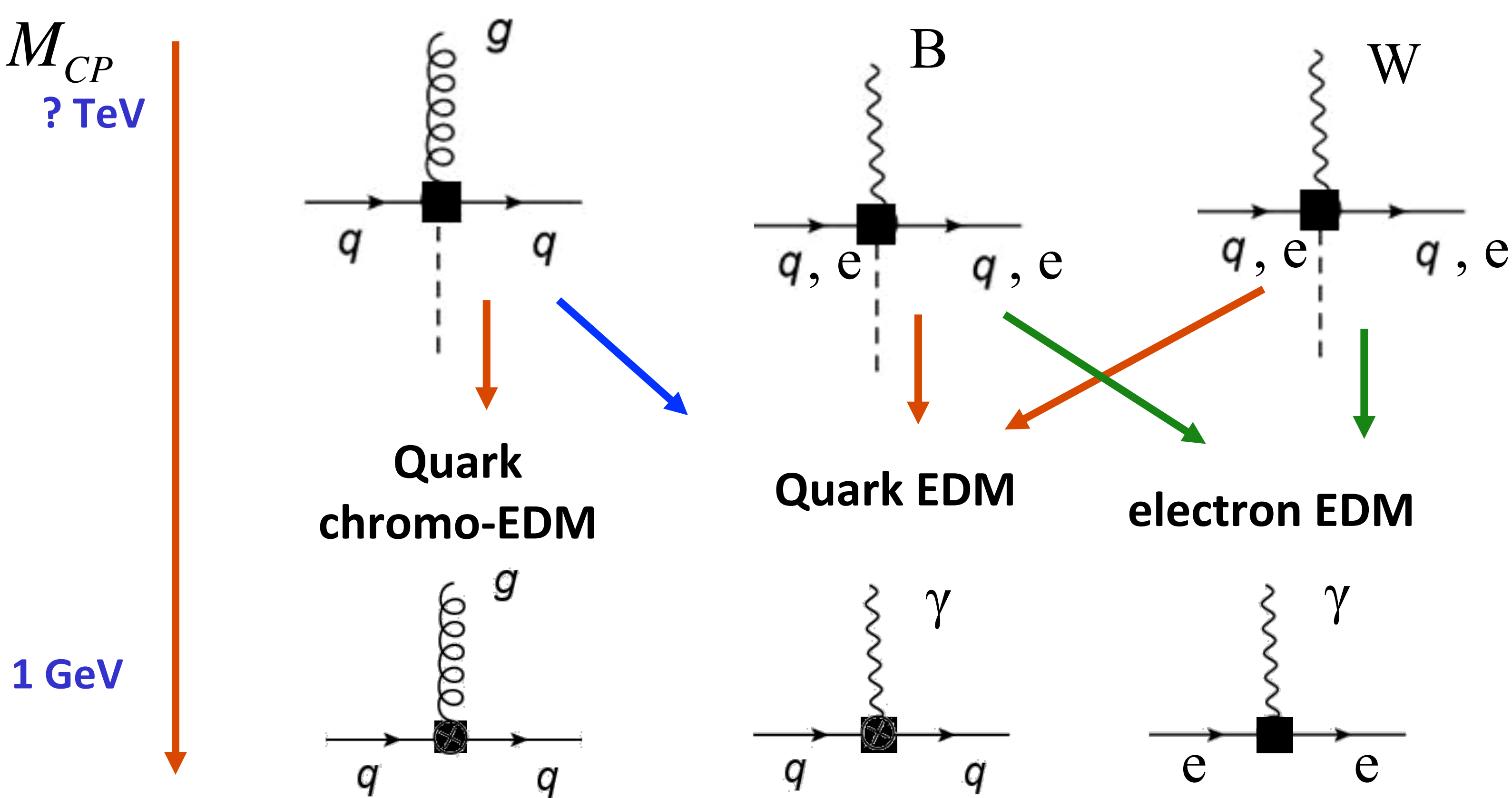

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Gluon chromo-EDM

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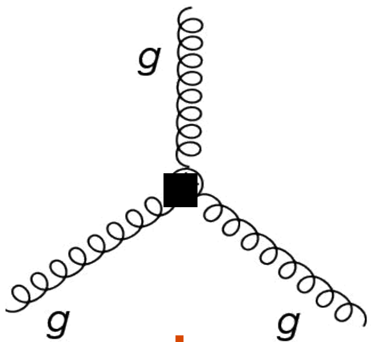
Weinberg operator

Weinberg PRL ’89
Braaten et al PRL ’90

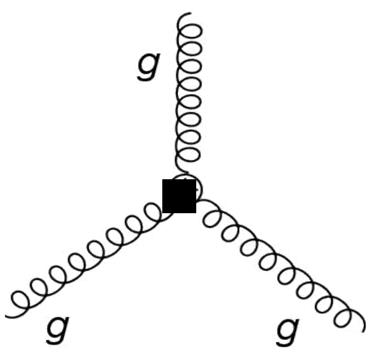
M_{CP}
? TeV



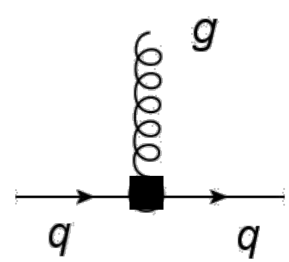
$$d_w\ f^{abc}\varepsilon^{\mu\nu\alpha\beta}\ G^a_{\alpha\beta}G^b_{\mu\lambda}\ G^{c\ \lambda}_{\nu}$$

QCD mixing

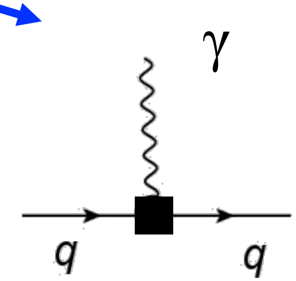
Gluon chromo-EDM



Quark chromo-EDM



Quark EDM



1 GeV

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Four-quark operators

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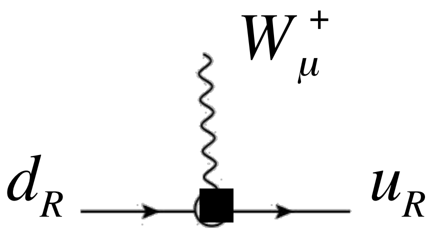
Fermion-Higgs interactions

Energy

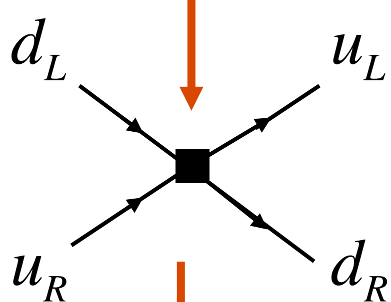
$$\Xi\,\bar{u}_R\gamma^\mu d_R\,(\tilde{\varphi}^\dagger iD_\mu\varphi) + \text{h.c.} \longrightarrow \Xi v^2 g\,(\bar{u}_R\gamma^\mu d_R\,W_\mu^\pm + \text{h.c.})$$

M_{CP}



A right-handed quark-W coupling

$< M_W$



$$L = i\Xi(\bar{u}_R\gamma_\mu d_R)(\bar{u}_L\gamma_\mu d_L) + \text{h.c.}$$

QCD RGE induces another operator

Λ_χ

Ng & Tulin '12
JdV et al '12
An et al '10

Two four-quarks terms (FQLR operators)

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Anomalous gauge/higgs couplings

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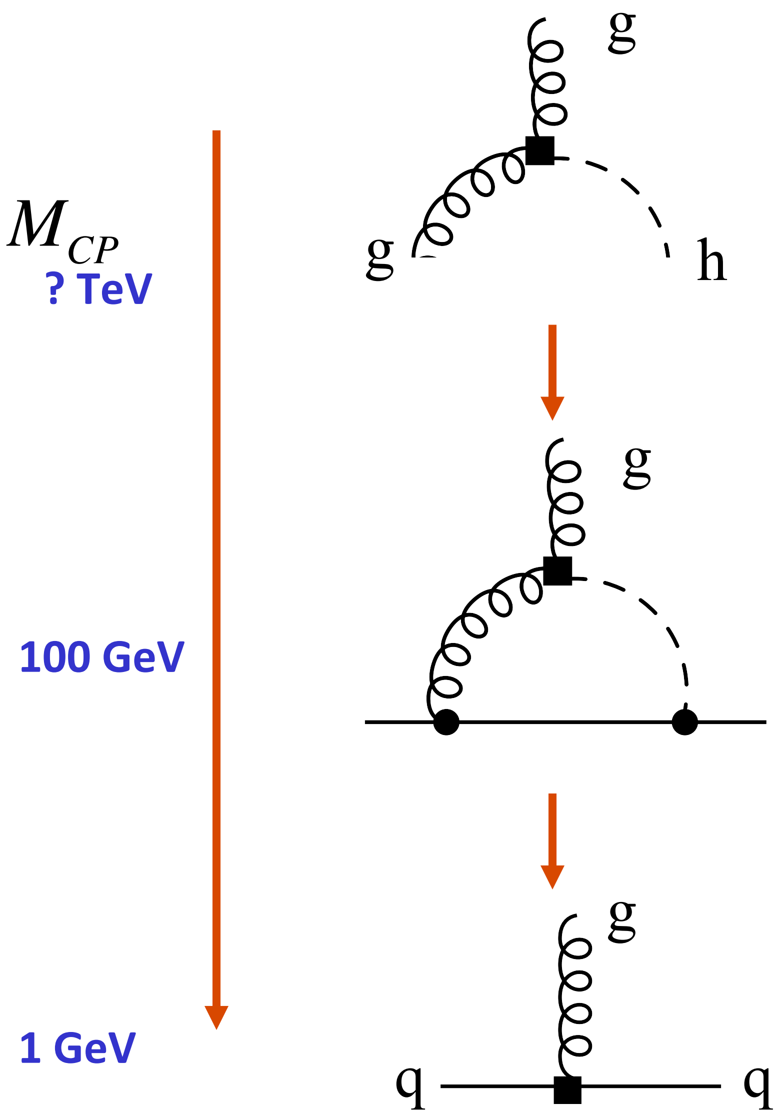
Mckeen et al '12
Manohar et al '13
Chang et al '13
Fan et al '13
Dekens, JdV ' 13



Search at the same time at LHC.

One example: $$\frac{g_s^2}{M_{CP}^2} H^2 G\tilde{G}$$

a) Gluon fusion at LHC

b) Induces quark CEDM → neutron EDM

$M_{CP} > 11\, TeV$ * **(ATLAS/CMS)**

$M_{CP} > 20\, TeV$ * **(neutron EDM**)**

* Loop suppression reduces scales
** depends on hadronic matrix element

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When the dust settles….

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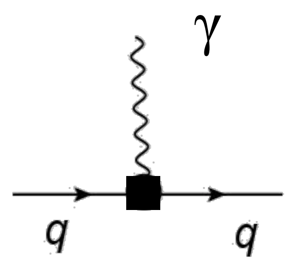
Hadronic interactions

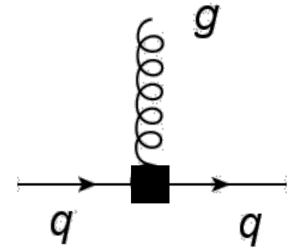
~ 1 GeV

QCD (θ-term) +



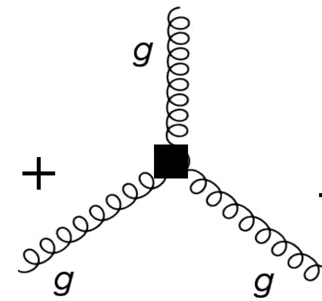
Quark EDM

+



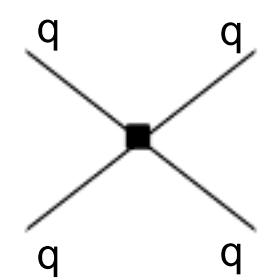
Quark chromo-EDM

+



Gluon chromo-EDM

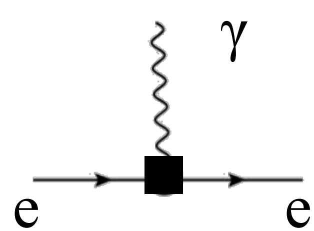
+



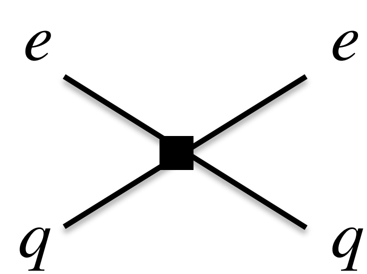
4*4quark operators

(9 coupling constants + strangeness)

(semi-)leptonic interactions



Electron EDM



(4 coupling constants)

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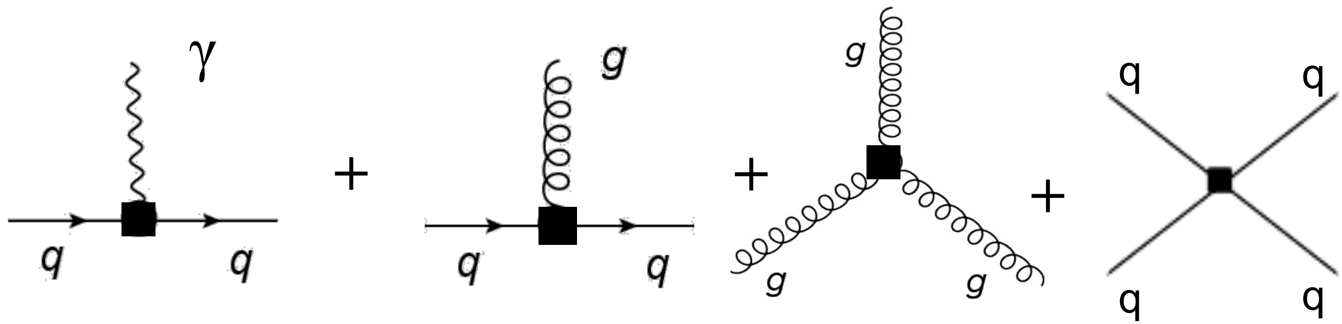
Crossing the barrier

Few GeV

QCD (θ-term) +



Quark EDM

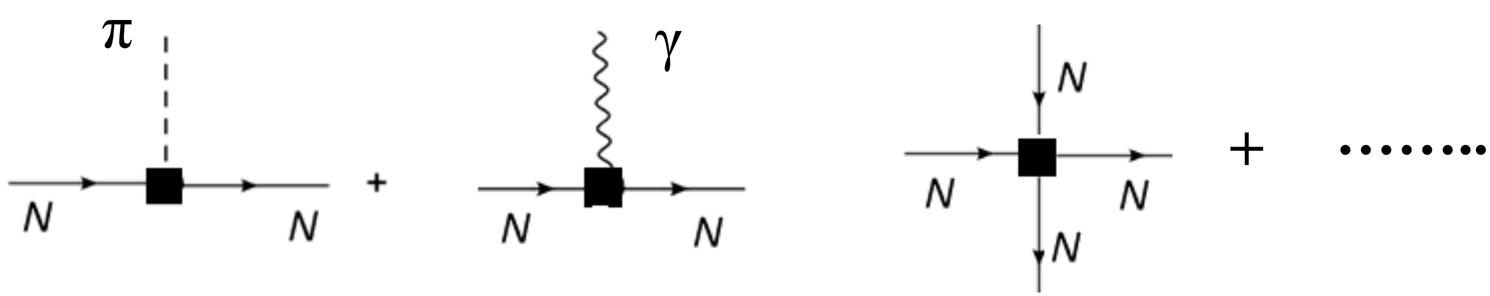
Quark chromo-EDM

Gluon chromo-EDM

3*4quark operators

Chiral Perturbation Theory

100 MeV



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The next EFT

- Use the symmetries of QCD to obtain **chiral Lagrangian**

$$L_{QCD} \rightarrow L_{chiPT} = L_{\pi\pi} + L_{\pi N} + L_{NN} + \cdots$$

- Quark masses = 0 → QCD has $SU(2)_L x SU(2)_R$ symmetry
  - Spontaneously broken to SU(2)-isospin
  - Pions are Goldstone bosons
  - Explicit breaking (quark mass) → pion mass

- ChPT gives systematic expansion in $Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi$ $\quad \Lambda_\chi \cong 1\, GeV$
  - **Form of interactions fixed by symmetries**
  - Each interactions comes with an unknown constant (LEC)
  - Successful nucleon-nucleon potential (chiral EFT)

Weinberg, Gasser, Leutwyler, Meißner, van Kolck, Epelbaum, ……

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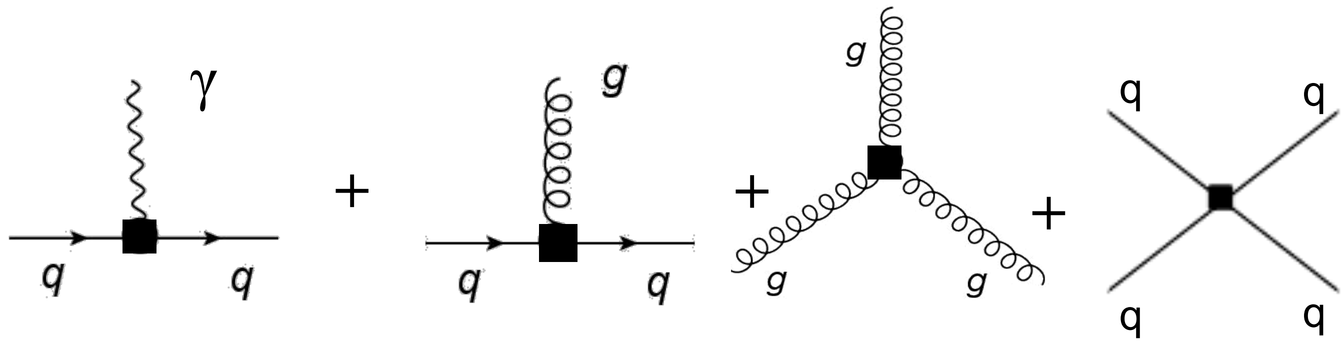
ChiPT with CP violation

QCD
(θ-term) +



- They all break CP….
- But **transform differently** under chiral and isospin symmetry

Different CP-odd chiral Lagrangians

Different hierarchy of EDMs

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CP violation at nuclear level

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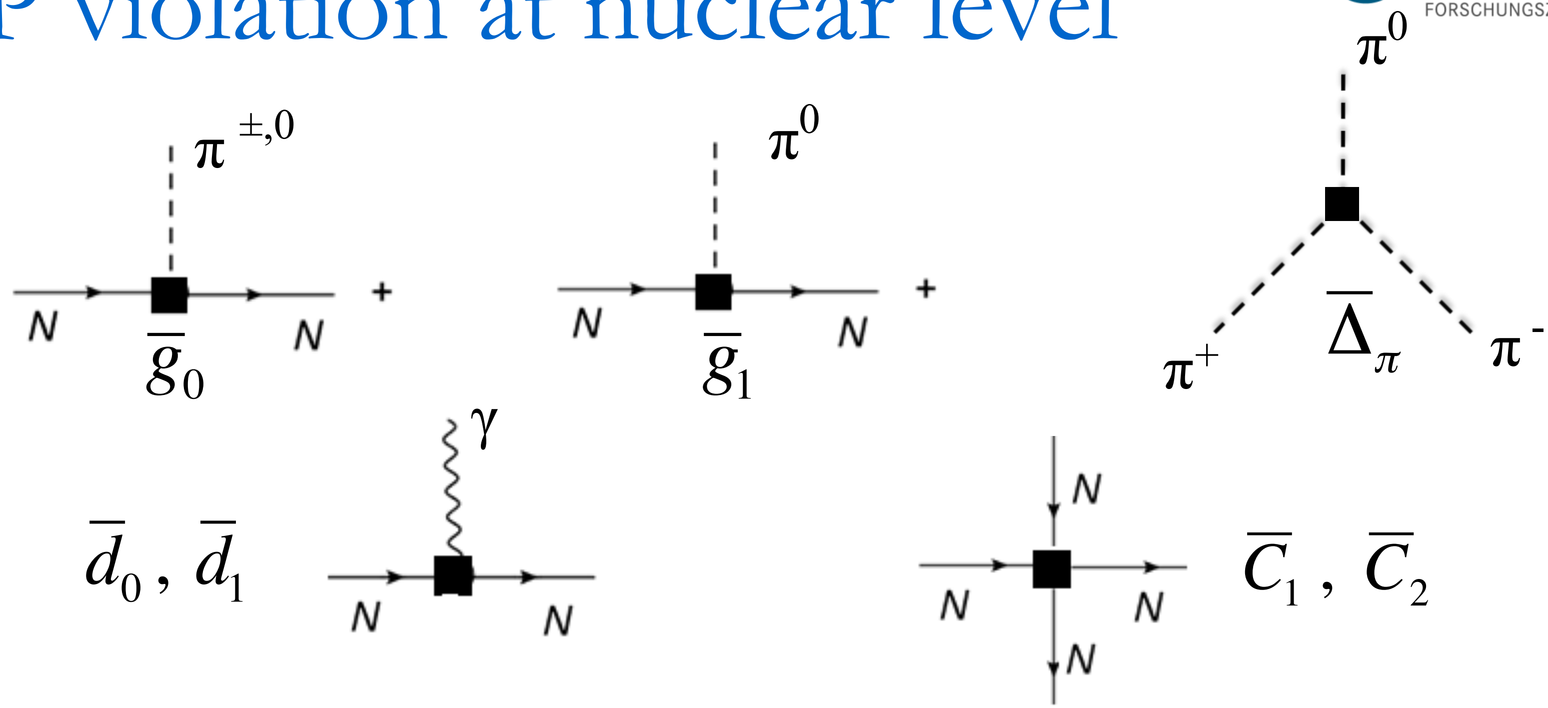

- 2 pion-nucleon
- 1 pion-pion-pion

- 2 nucleon-nucleon
- 2 nucleon-photon (EDM)

- Up to **NLO** **seven** interactions for **all CP-odd** dim4-6 sources
- Different models (SUSY, left-right, multi-Higgs) → **different hierarchies**

Mereghetti et al ’10, JdV et al ’12, Bsaisou et al ‘14

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An example of the hierarchy

- Example: CP-odd **pion-nucleon** interactions
- Traditionally expected to **dominate** nuclear EDMs

$$L = \bar{g}_0 \bar{N}(\vec{\pi}\cdot\vec{\tau})N + \bar{g}_1 \bar{N}\pi_3 N$$

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An example of the hierarchy

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$$L = \bar{g}_0 \bar{N}(\vec{\pi}\cdot\vec{\tau})N + \bar{g}_1 \bar{N}\pi_3 N$$

❖ θ-term $L = im^{*}\theta\,\bar{q}i\gamma^{5}q$ transforms **as quark mass**

$$\varepsilon = \frac{m_u + m_d}{m_u - m_d} = -0.35(10)$$

$$\bar{g}_0 = \frac{(m_n - m_p)^{strong}}{4F_\pi \varepsilon}\bar{\theta} = -0.018(7)\bar{\theta}$$

$$\bar{g}_1 = \frac{8c_1(\delta m_\pi^2)^{strong}}{F_\pi}\frac{1-\varepsilon^2}{2\varepsilon}\bar{\theta} = 0.003(2)\,\bar{\theta}$$

$$\frac{\bar{g}_1}{\bar{g}_0} = -(0.2 \pm 0.1)$$

- Input from lattice QCD (m_n-m_p) and pion-nucleon scattering (c_1)
- g0 > g1 due to **isospin conservation** of theta term

Crewther et al’ 79, Lebedev et al ’04, Mereghetti et al ‘10, Bsaisou et al ’12 ‘14

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$$L = \bar{g}_0 \bar{N}(\vec{\pi}\cdot\vec{\tau})N + \bar{g}_1 \bar{N}\pi_3 N$$

❖ four-quark operators (left-right symmetric models)

Mohapatra, Senjanovic, Pati

$$L = i\Xi(\bar{u}_R\gamma_\mu d_R)(\bar{u}_L\gamma_\mu d_L) + \text{h.c.}$$

- $\bar{g}_0$, $\bar{g}_1$ both poorly known
- **ChPT gives ratio :**

$$\frac{\bar{g}_1}{\bar{g}_0} = \frac{8c_1 m_\pi^2}{(m_n - m_p)^{strong}} = -(68 \pm 25)$$

θ-term

$$\frac{\bar{g}_1}{\bar{g}_0} = -(0.2 \pm 0.1)$$

Seng et al' 14
Maiezza, Nemevsek '14

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An example of the hierarchy

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- Example: CP-odd **pion-nucleon** interactions
- Traditionally expected to **dominate** nuclear EDMs

$$L = \bar{g}_0 \bar{N}(\vec{\pi}\cdot\vec{\tau})N + \bar{g}_1 \bar{N}\pi_3 N$$

❖ Quark chromo-EDM: (MSSM, 2HDM, ….)

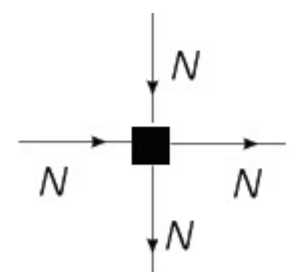
$$|\bar{g}_0| \approx |\bar{g}_1|$$

Relatively **large** uncertainty in LECs
e.g. from QCD sum rules

Pospelov, Ritz '02 '05
Hisano et al ' 12 '13

❖ Weinberg operator, LECs suppressed due to **chiral symmetry** .
Leading contributions from CP-odd NN interactions.

$$L = \bar{C}\ (\bar{N}\vec{\sigma}N)\cdot\ \vec{\partial}(\bar{N}N)$$



JdV et al '11

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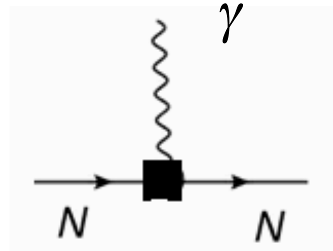
The Nucleon EDM

Nucleon EDM



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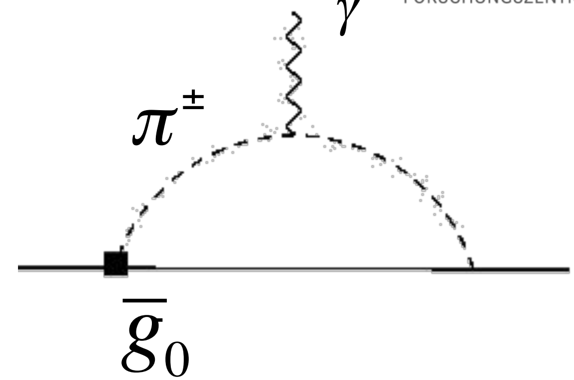

$$d_n = \bar{d}_0 - \bar{d}_1 - \frac{e g_A \bar{g}_0}{4\pi^2 F_\pi}\left(\ln\frac{m_\pi^2}{M_N^2} - \frac{\pi}{2}\frac{m_\pi}{M_N}\right)$$

$$d_p = \bar{d}_0 + \bar{d}_1 + \frac{e g_A}{4\pi^2 F_\pi}\left[\bar{g}_0\left(\ln\frac{m_\pi^2}{M_N^2} - 2\pi\frac{m_\pi}{M_N}\right) - \bar{g}_1\frac{\pi}{2}\frac{m_\pi}{M_N}\right]$$

- absorb UV divergences in $\bar{d}_0\,,\ \bar{d}_1$

Crewther et al., ’79, Pich, Rafael, ‘91 Guo et al, ’10 ’12 ’14, Mereghetti et al ‘10 ’11 ‘14

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The Nucleon EDM

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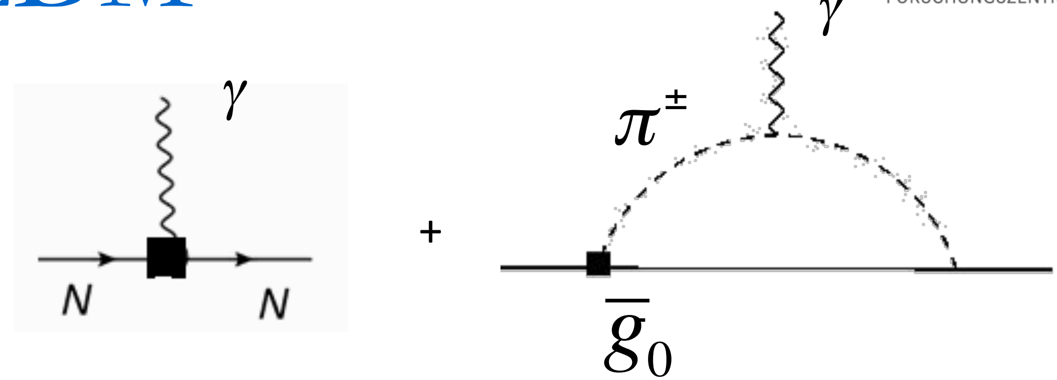
Nucleon EDM



$$d_n = \bar{d}_0 - \bar{d}_1 - \frac{e g_A \bar{g}_0}{4\pi^2 F_\pi}\left(\ln\frac{m_\pi^2}{M_N^2} - \frac{\pi}{2}\frac{m_\pi}{M_N}\right)$$

$$d_p = \bar{d}_0 + \bar{d}_1 + \frac{e g_A}{4\pi^2 F_\pi}\left[\bar{g}_0\left(\ln\frac{m_\pi^2}{M_N^2} - 2\pi\frac{m_\pi}{M_N}\right) - \bar{g}_1\frac{\pi}{2}\frac{m_\pi}{M_N}\right]$$

- absorb UV divergences in $\bar{d}_0, \bar{d}_1$

- 3 (4) LECs at LO (NLO).... Can be fitted by **any** source
- **For all sources,** neutron and proton EDM of **same** order

No hierarchy!

Crewther et al., '79, Pich, Rafael, '91 Guo et al, '10 '12 '14, Mereghetti et al '10 '11 '14

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Lattice QCD to the rescue

Shintani et al ’12 ’13
Guo, Meißner, Akan ‘13 ’14

❖ With QCD lattice input:

$$d_n = (2.7 \pm 1.2) \cdot 10^{-16}\ \bar{\theta}\ e\ cm$$
$$d_p = -(2.1 \pm 1.2) \cdot 10^{-16}\ \bar{\theta}\ e\ cm$$

Other groups:
Horsley et al ’15
Shindler et al ‘14

- ChPT extrapolation to **physical pion mass** and **infinite volume**

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Other groups:
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- ChPT extrapolation to **physical pion mass** and **infinite volume**

- Less known for dimension-six sources (~100% uncertainties)

- **Dedicated Amherst workshop, January ’15 → road map**
  “Hadronic Matrix Elements for Probes for CP-violation”

- Lattice qEDM and qCEDM in progress **(difficult!)**

Bhattacharya et al ’12 ’15

In any case: Need more observables to unravel sources !

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Experiments on charged particles

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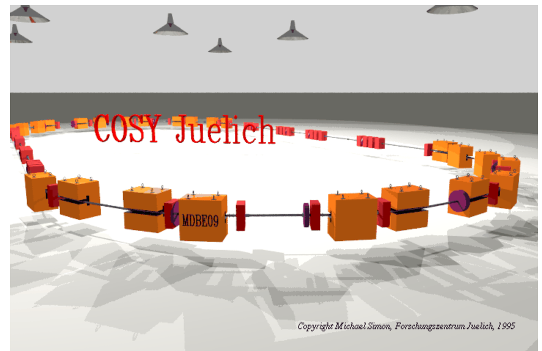
See talk by Yannis Semertzidis

Farley *et al PRL* '04

- New kid on the block: **Charged particle in storage ring**



Bennett *et al* (BNL g-2) PRL '09

- Limit on muon EDM $d_\mu \leq 1.8 \cdot 10^{-19}\ e\ cm$

Anastassopoulos et al '15

- **Proposals to measure EDMs of light nuclei (p, 2H, 3He, ...)**
- Precursor experiment at COSY at Jülich Eversmann et al '15

- High final accuracy (aimed at 10^{-27-29} e cm)

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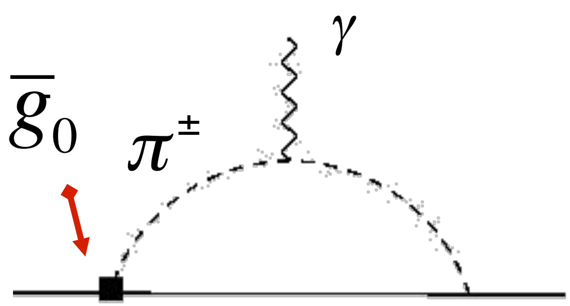
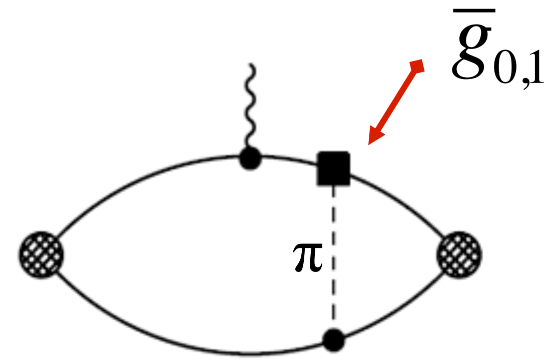
Why light nuclei?





- **Tree-level contributions: no loop suppression**

$$(E - H_{PT})\,|\Psi_A> = 0 \qquad (E - H_{PT})\,|\tilde{\Psi}_A> = V_{\cancel{CP}}\,|\Psi_A>$$

- Input: 1) CP-even potential from **chiral EFT (N2LO)**
  2) **CP-odd** potentials derived for each source

Epelbaum et al '05
Maekawa et al '11

- Numerical solution requires **regulator**, check **cut-off independence**

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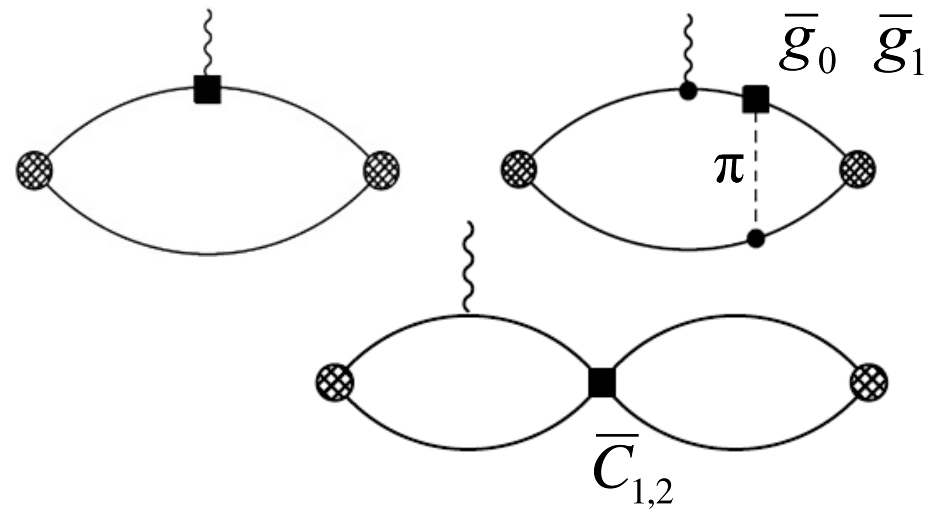
Example: deuteron EDM

Target of storage ring measurement

- Three contributions (NLO)
    1. Sum of nucleon EDMs
    2. CP-odd pion exchange
    3. CP-odd NN interactions



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Example: deuteron EDM

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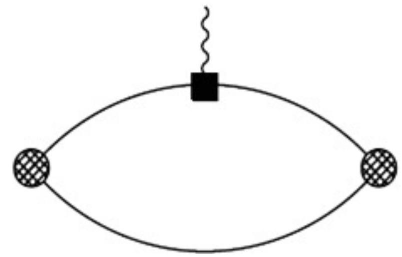
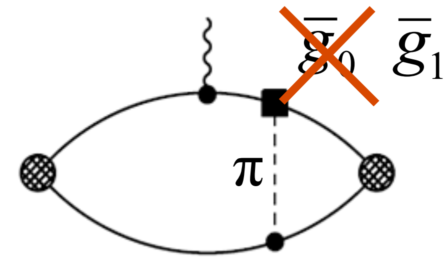
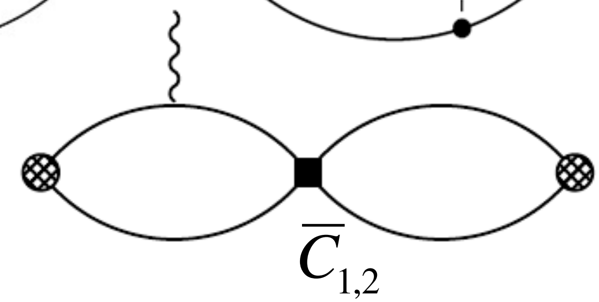


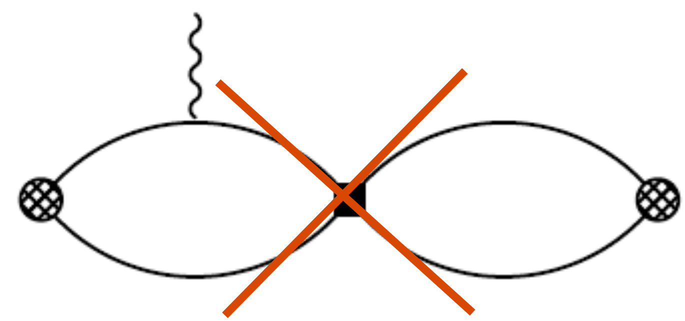




- **Deuteron is a special case due to N=Z**

$$^3S_1 \xrightarrow{\bar{g}_0} {}^1P_1 \xrightarrow{\gamma} {}^3\cancel{S}_1$$

$$^3S_1 \xrightarrow{\bar{g}_1} {}^3P_1 \xrightarrow{\gamma} {}^3S_1$$



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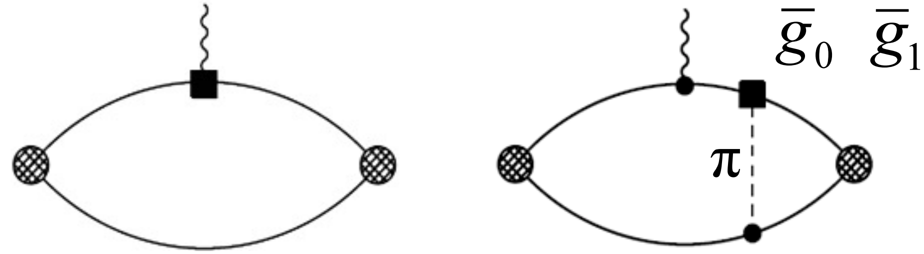
Example: deuteron EDM

- ~~Three~~ Two contributions
    1. Sum of nucleon EDMs
    2. CP-odd pion exchange



$$d_D = d_n + d_p + \left[(0.18 \pm 0.02)\,\bar{g}_1 + (0.0028 \pm 0.0003)\,\bar{g}_0\right] e\ fm$$

Theoretical accuracy is very good
(chiral corrections + cut-off dependence)

Strong isospin filter

Errors from Dekens et al JHEP `14, Bsaisou et al JHEP `14

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Example: deuteron EDM

Filtering the sources

	Theta	Four-quark left-right	Quark chromo-EDM	Quark EDM	Weinberg Operator
$\dfrac{d_D - d_n - d_p}{d_n}$	0.5 ± 0.2	$\cong 7 - 20$	$\cong 5 - 10$	$= 0^*$	$= 0^*$

- Ratio suffers from **hadronic uncertainties (need lattice)**
- Nevertheless: EDM ratio hint towards **underlying source**!

* For quark EDM + Weinberg : $d_D \cong (d_n + d_p)$

Lebedev et al ’04, JdV et al ’11, Bsaisou et al ’12,’14

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Similar for 3He (and 3H)

$$d_{3He} = 0.9\, d_n - 0.05\, d_p + \left[(0.14 \pm 0.03)\, \bar{g}_1 + (0.10 \pm 0.03)\, \bar{g}_0\right] e\ fm$$

- **No isospin filter**, **complementary** to deuteron
- Good nuclear accuracy (25%)
- With deuteron → give g0/g1 ratio

Stetcu et al, ’08, JdV et al, ’11 ‘14, Song et al, ’13, Yamanaka ‘15

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Similar for 3He (and 3H)

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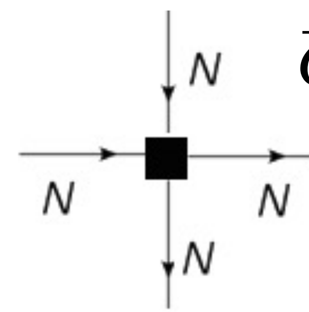
- **No isospin filter**, **complementary** to deuteron
- Good nuclear accuracy (25%)

But…

- Dependence on CP-odd NN operators
- N2LO for most sources (~10%)
- **But LO for Weinberg operator** *(SUSY, 2HDM)*



$\bar{C}_{1,2}$

Contact NN term described by 'heavy meson' exchange

$$\frac{m^2 \bar{C}}{4\pi\, r}\, e^{-m\, r} \rightarrow \bar{C}\ \delta^{(3)}(\vec{r})$$

Stetcu et al, '08, JdV et al, '11 '14, Song et al, '13, Yamanaka '15

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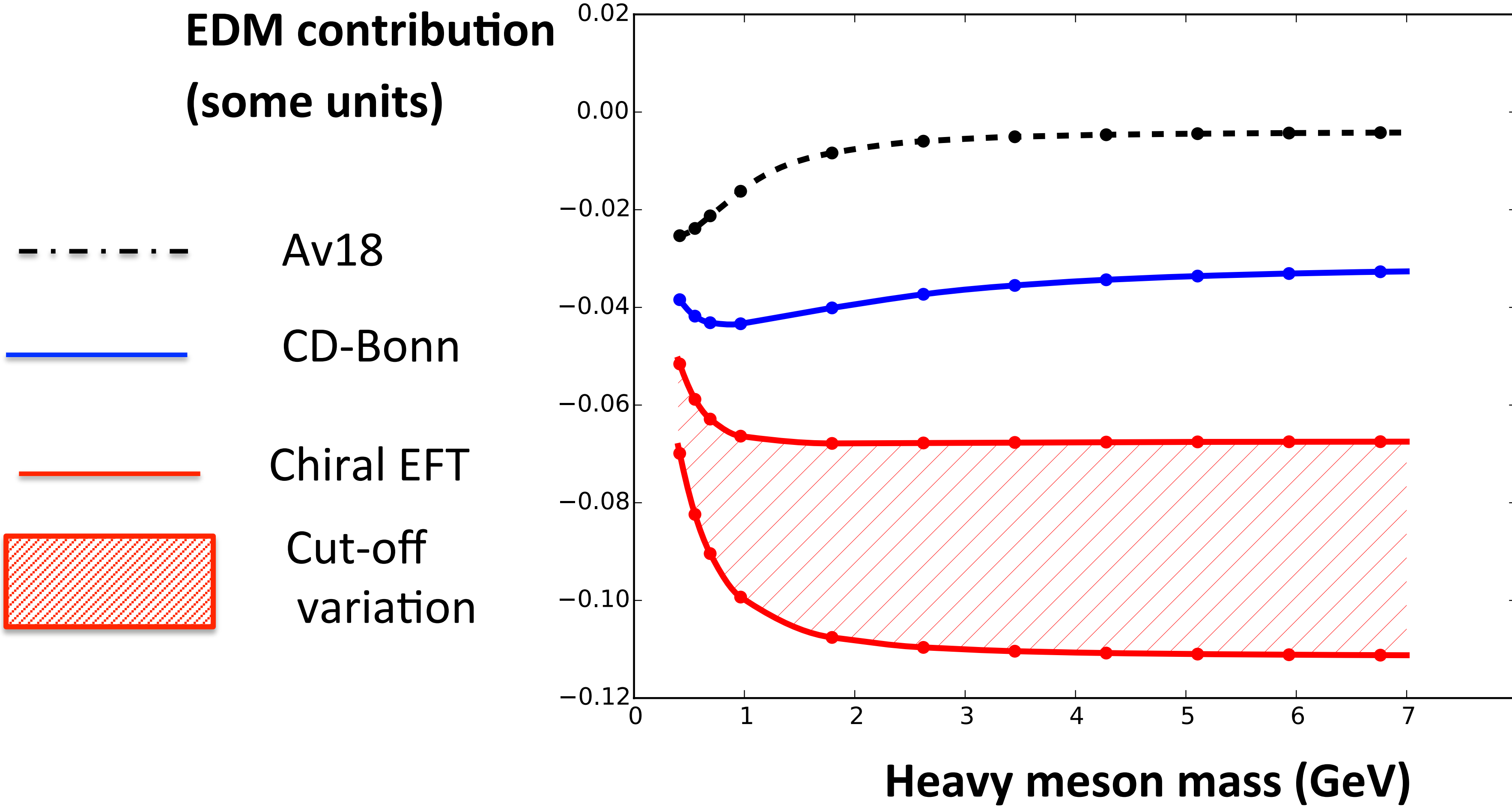
Not so clear….

Plot from Bsaisou et al JHEP '14



- Convergence….. but **not** to the same value……
- Av18 very repulsive at short distances (not best estimate)
- Large nuclear uncertainty (for **Weinberg operator)**

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Onwards to heavy systems

Griffiths et al, '09

Strongest bound on atomic EDM: $$d_{^{199}Hg} < 3.1 \cdot 10^{-29}\ e\,cm$$

New measurements expected: Hg, Ra , Xe, ….

Schiff Theorem: EDM of nucleus is screened by electron cloud if:

1. Point particles
2. Non-relativistic kinematics
3. Electrostatic forces

Schiff, '63

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Schiff, '63

Screening incomplete: nuclear finite size (Schiff moment **S**)

Typical suppression: $\dfrac{d_{Atom}}{d_{nucleus}} \propto 10 Z^2 \left(\dfrac{R_N}{R_A}\right)^2 \approx 10^{-3}$

- **Atomic** part well under control

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

Dzuba et al, '02, '09

$$d_{^{225}Ra} = (7.2 \pm 1.5) \cdot 10^{-4}\ S_{Ra}\ e\ fm^2$$

Sing et al, '15

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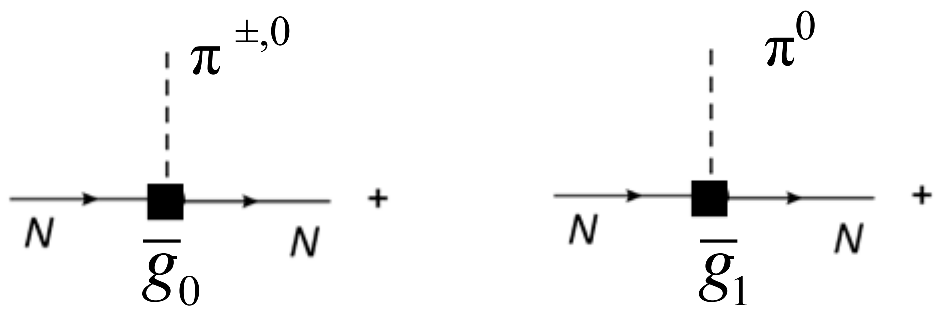
Calculating Schiff Moments

Task: Calculate Schiff Moments of Hg, Ra, Xe, …



- **Typically only one-pion exchange** (sometimes nucleon EDMs)

Dmitriev, Sen'kov '03

- **Very complicated** many-body calculation
- Cannot solve Schrodinger equation directly
- Use nuclear model and mean-field theory (Skyrme interactions)

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Assessment of uncertainties

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$$S = g(a_0\bar{g}_0 + a_1\bar{g}_1)\, e\ fm^3 \qquad g = 13.5$$

	a_0 range (best)		a_1 range (best)	
^{199}Hg	0.03±0.025	(0.01)	0.030±0.060	(±0.02)
^{225}Ra	-3.5±2.5	(-1.5)	14±10	(6)
^{129}Xe	-0.03±0.025	(-0.008)	-0.03±0.025	(-0.009)

- Based on calculations from various groups

Flambaum, de Jesus, Engel, Dobaczewski, Dmitriev, Sen'kov,…..

- Hg & Xe: spread ~>100% (unclear why, difficult 'soft' nuclei)
- **Ra enhanced (~100x) due to octopole deformation and theory better under control.**

table from review: Engel et al, '13

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Comparison of sensitivities

Now include **Schiff screening**: $d = g(b_0\bar{g}_0 + b_1\bar{g}_1)\, e\ fm$

	b_0(best values)	b_1(best values)
^{199}Hg	3×10^{-6}	6×10^{-6}
^{225}Ra	-1×10^{-3}	4×10^{-3}
^{129}Xe	-2×10^{-7}	-2×10^{-7}
^{2}H (ion)	2×10^{-4}	1×10^{-2}
^{3}He (ion)	1×10^{-2}	7×10^{-3}

- Radium almost **overcomes** Schiff screening
- 2H or 3He EDM @ $10^{-24,25}$ competitive with Hg bound
- **But: large nuclear uncertainty and missing CP-odd interactions**

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Outline of this talk

- Part I: What are EDMs and why are they interesting in the first place ?
- Part II: Effective field theory framework
- Part III: Hadronic and nuclear CP-violation
  - Chiral Perturbation Theory
  - EDMs of nucleons, nuclei, and diamagnetic atoms
- **Part IV: Semi-leptonic CP violation**
  - Paramagnetic atoms and polar molecules

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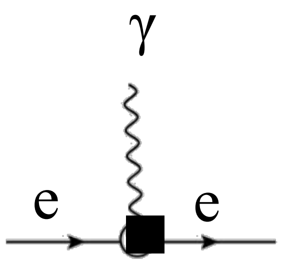
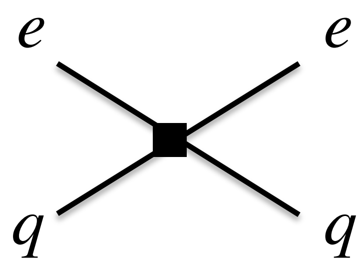
Probing the leptonic interactions

(semi-)leptonic interactions (4 operators)

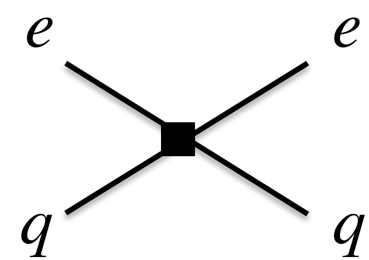
~ 1 GeV



Electron EDM



$C_S(\bar{e}\, i\gamma^5 e\, \bar{q}q)$



$C_P \quad C_T$

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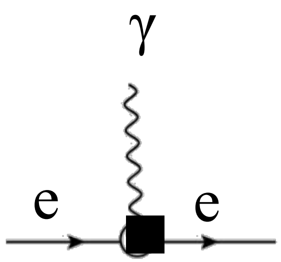
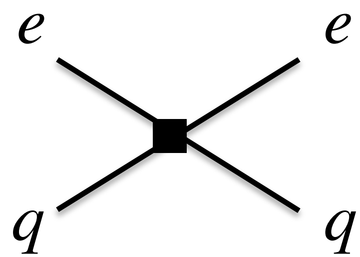


Electron EDM



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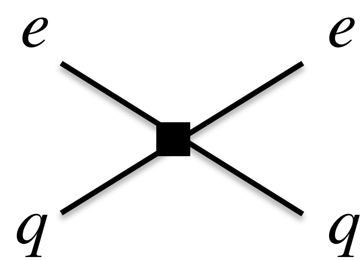
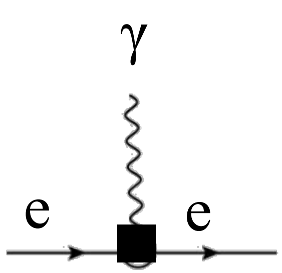


$C_P \quad C_T$

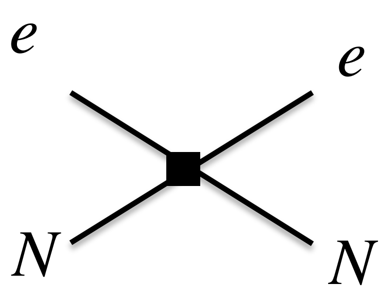
Suppressed (best bounds from Hg EDM**)**

Focus on these

0.1 GeV



Electron EDM



$C_S(\bar{e}\, i\gamma^5 e\, \bar{N}N)$

hadronic matrix elements relatively **well known**

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Probing the leptonic interactions

Regan et al '02

Bound on Tl EDM $d_{^{205}Tl} < 9 \cdot 10^{-25}\ e\ cm$

What about screening? Schiff theorem violated by **relativity**

Sandars '65

$$d_A(d_e) = K_A d_e \qquad K_A \propto Z^3 \alpha_{em}^2$$

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Strong enhancement!

$$K_{Tl} = -(570 \pm 20) \longrightarrow d_e < 1.6 \cdot 10^{-27}\ e\ cm$$

Additional dependence on electron-nucleon interactions

$$d_{Tl} = -(570 \pm 20) d_e - (7.0 \pm 2.0) \cdot 10^{-18}\ C_S\ e\ cm$$

Liu,Kelly ‘92, Dzuba, Flambaum ‘09, Porsev et al ‘12

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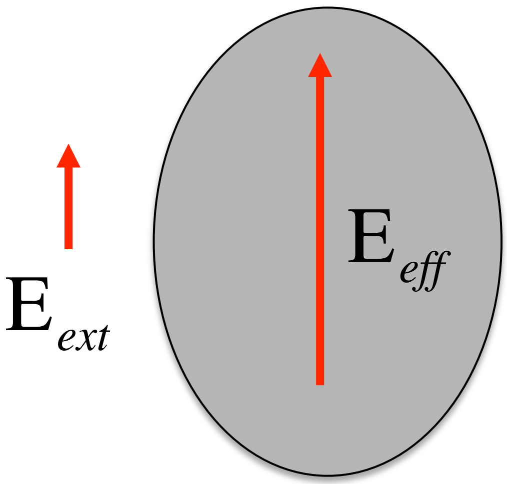
Polar molecules

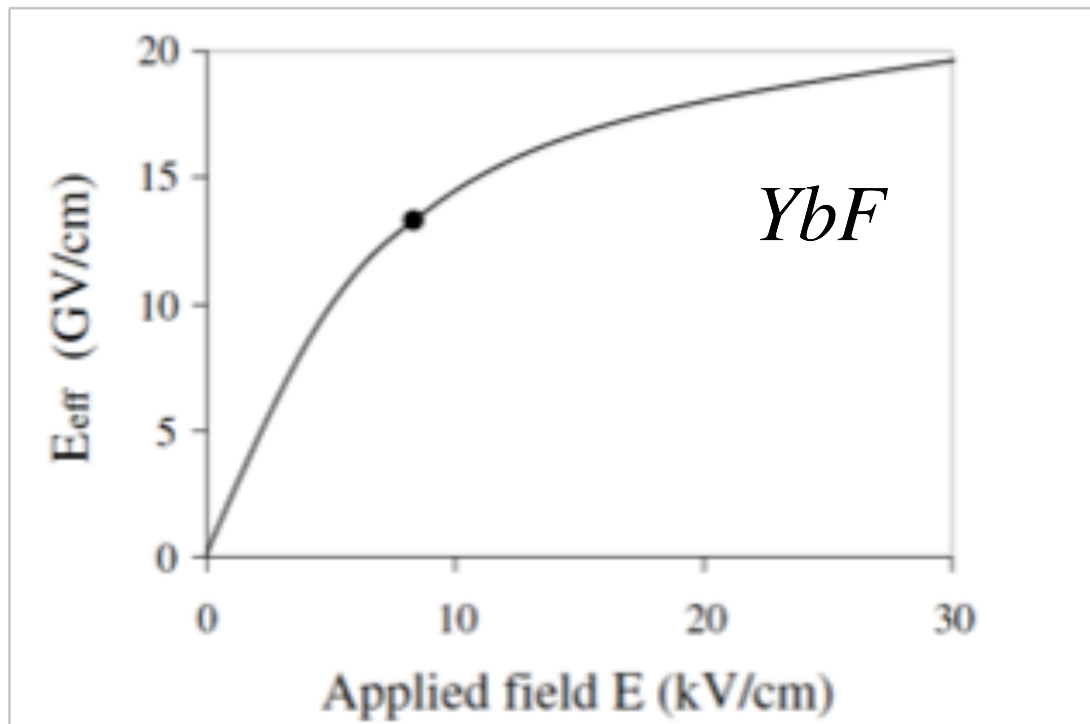
Polar molecules: Convert small external to huge internal field



$$\Delta E \sim E_{eff}(E_{ext})d_e$$

Sandars '75
Sushkov, Flambaum '78

Nonlinear function of external field



Plot from Hudson et al PRL '02

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Polar molecules

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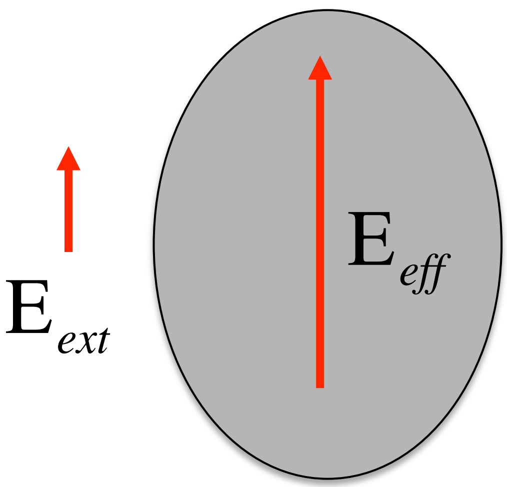
Polar molecules: Convert small external to huge internal field

Kozlov et al ‘94 ‘97, Quiney et al ‘98, Mayer, Bohn ‘08



$$\Delta E_{YbF} = (15 \pm 2) \cdot GeV \left(\frac{d_e}{e\ cm} \right) + O(C_S)$$

$$\Delta E_{ThO} = (80 \pm 10) \cdot GeV \left(\frac{d_e}{e\ cm} \right) + O(C_S)$$

Meyer, Bohn ‘08, Skipnikov et al ’13, Fleig, Nayak ‘14,

Assuming no cancellation with $O(C_S)$: $d_e < 8.7 \cdot 10^{-29}\ e\ cm$

Or no cancellation with eEDM : $C_S < 5.9 \cdot 10^{-9}$

Baron et al ’13

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Finding the source.

- **Find a signal: what is responsible? eEDM or Cs ?**
- Need at least two measurements

$$\Delta E = \alpha\, d_e + \beta\, C_S$$

Dzuba et al '11
M. Jung '13
Chupp, Ramsey-Musolf '15

	Th	YbF	ThO
β/α	1.15	0.85	1.25

$\cdot 10^{-20}\, e\, cm$

- Unfortunately: **Probing roughly same combination**

- Experiments on Fr, Rb could help in this case
- Same for diamagnetic systems (Hg, Ra, …)

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Cancellations ?

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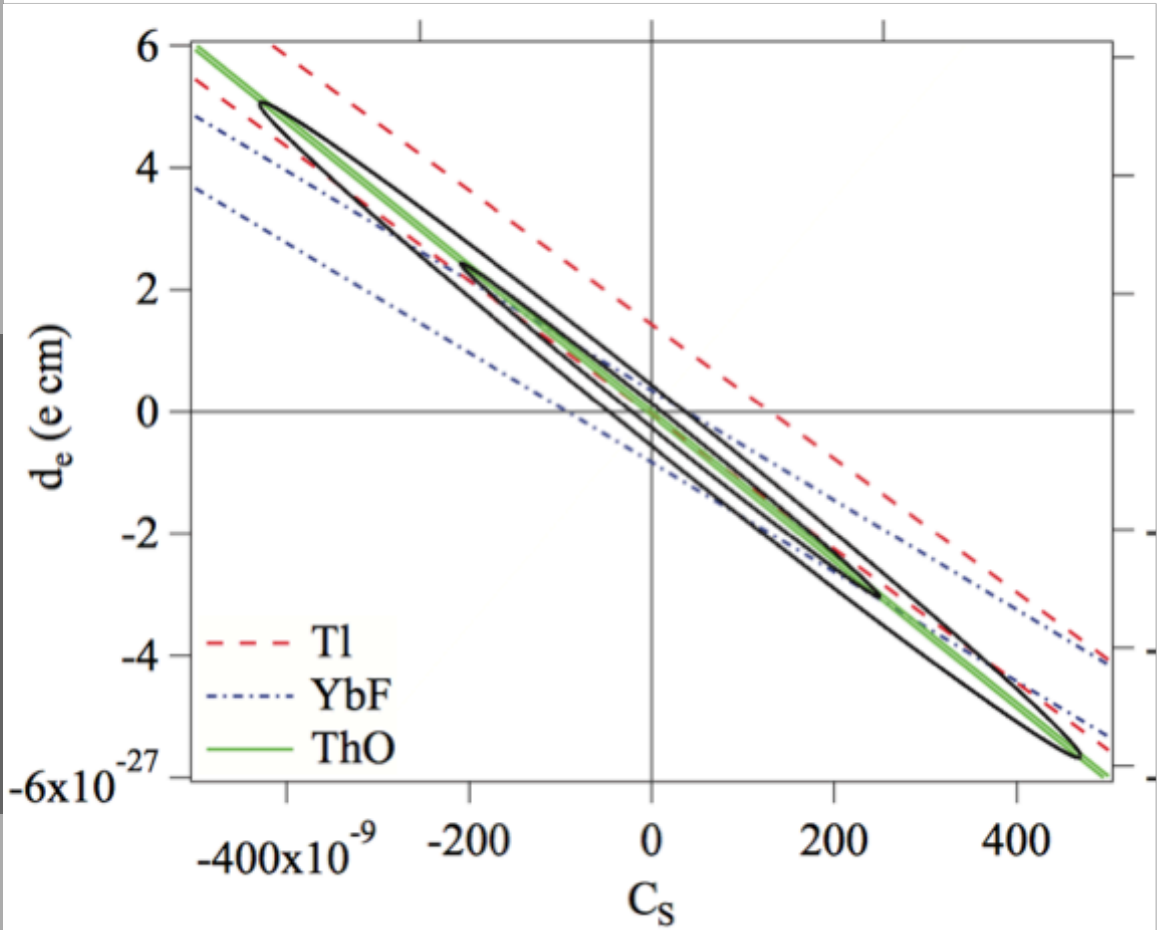

Single source

$$d_e < 8.7 \cdot 10^{-29}\ e\,cm$$
$$C_S < 5.9 \cdot 10^{-9}$$

Allow for cancellations

$$d_e < 5.4 \cdot 10^{-27}\ e\,cm$$
$$C_S < 4.5 \cdot 10^{-7}$$

- Many models have one dominant source (e.g. eEDM in mLRSM)
- But good to keep in mind. Who knows…
- Experiments on Fr, Rb + diamagnetic would help

Plots and numbers from Chupp, Ramsey-Musolf PRC '15

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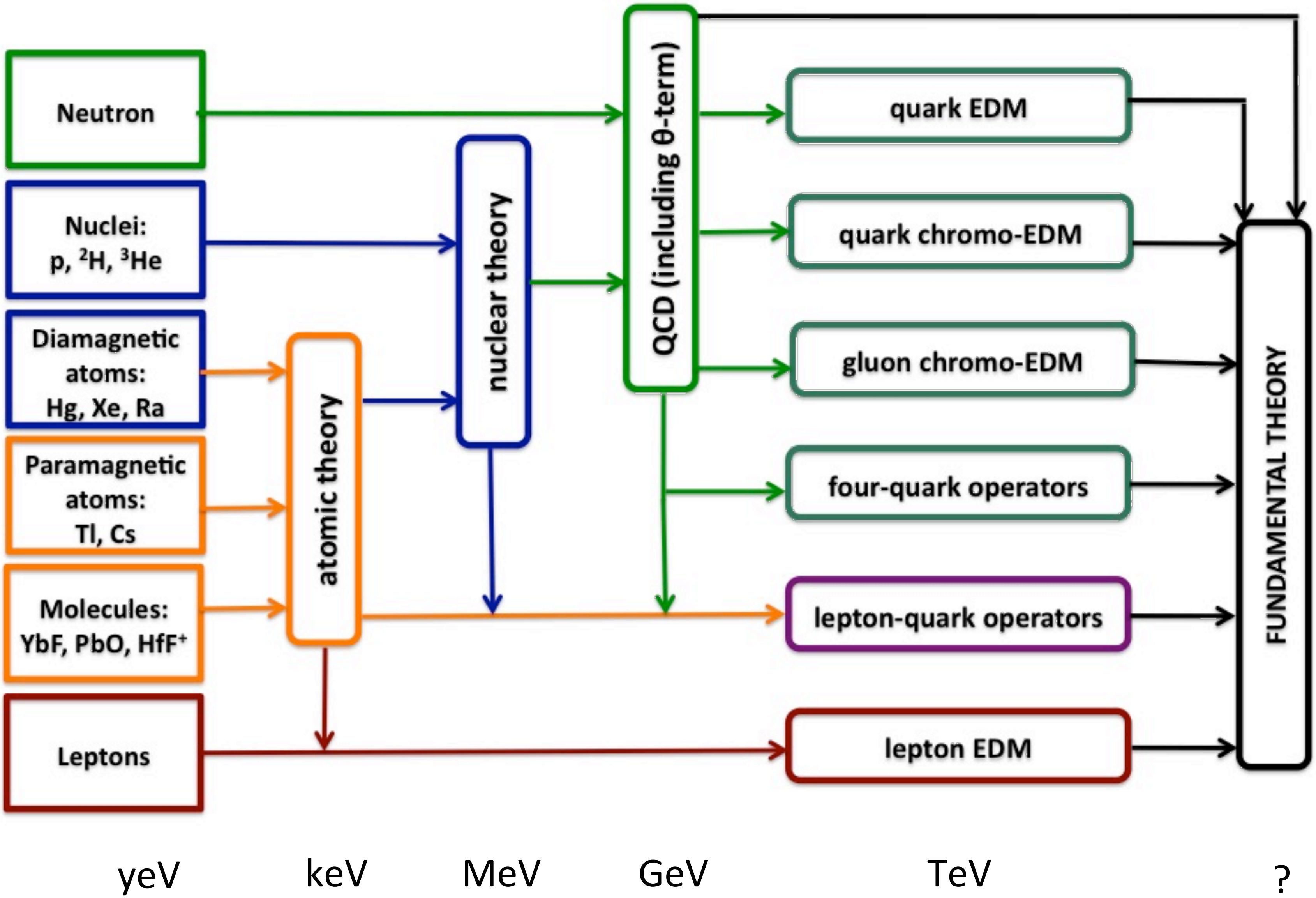
The EDM landscape



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Conclusion/Summary

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- ✓ EDMs are great probes of new CP-odd physics
- ✓ Probe **similar and higher energy scales** as LHC

EFT approach

- ✓ Framework exists for CP-violation (EDMs) from 1st principles
- ✓ Keep track of **symmetries** from multi-Tev to atomic scales
- ✓ Specific models can be matched to EFT framework (not discussed here)

The chiral filter

- ✓ Chiral symmetry determines form of hadronic interactions
- ✓ **Different models → different dim6 → different EDM hierarchy**

Uncertainties

- ✓ Nucleon + light nuclei dominated by hadronic uncertainties (+ short-range)
- ✓ Heavy diamagnetic atoms suffer from additional **nuclear uncertainties**
- ✓ Atomic/Molecular theory in much better shape

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Backup

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Dipoles combined

Numerical solution of the three dipole operators (same for strange quarks)

$$\mathcal{O}(\alpha_s^2)$$

$$C_q(1\,\mathrm{GeV}) = 0.39\,C_q(1\,\mathrm{TeV}) + 0.37\,\tilde{C}_q(1\,\mathrm{TeV}) - 0.072\,C_W(1\,\mathrm{TeV})$$

$$\tilde{C}_q(1\,\mathrm{GeV}) = \quad + 0.88\,\tilde{C}_q(1\,\mathrm{TeV}) - 0.29\,C_W(1\,\mathrm{TeV})$$

$$C_W(1\,\mathrm{GeV}) = \quad + 0.33\,C_W(1\,\mathrm{TeV})$$

1) Diagonal terms are all suppressed

2) Suppressions are moderate

3) Mixing is important, e.g. if qCEDM at low energy then also qEDM (unless cancellations….)

* 2-loop running in Degrassi et al, JHEP '05 , O(10%) corrections to LO running

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Bounds and scales

Use the neutron* EDM bound (**big uncertainty for some operators: that's why we are here !**)

Dekens, JdV JHEP '13

Dimensionless couplings

	$M_{\not T} = 1\,\mathrm{TeV}$	$M_{\not T} = 10\,\mathrm{TeV}$
$(M_{\not T}^2)d_{u,\,d}\,(M_{\not T})$	$\leq \{1.8,\, 1.8\} \cdot 10^{-3}$	$\leq \{2.1,\, 2.1\} \cdot 10^{-1}$
$(M_{\not T}^2)\tilde{d}_{u,\,d}\,(M_{\not T})$	$\leq \{1.9,\, 0.91\} \cdot 10^{-3}$	$\leq \{1.7,\, 0.94\} \cdot 10^{-1}$
$(M_{\not T}^2)d_W\,(M_{\not T})$	$\leq 5.6 \cdot 10^{-5}$	$\leq 7.0 \cdot 10^{-3}$
$(M_{\not T}^2)\mathrm{Im}\,\Sigma_1\,(M_{\not T})$	$\leq 3.2 \cdot 10^{-5}$	$\leq 2.3 \cdot 10^{-3}$
$(M_{\not T}^2)\mathrm{Im}\,\Sigma_8\,(M_{\not T})$	$\leq 3.3 \cdot 10^{-4}$	$\leq 2.4 \cdot 10^{-2}$
$(M_{\not T}^2)\mathrm{Im}\,\Xi_1\,(M_{\not T})$	$\leq 1.7 \cdot 10^{-4}$	$\leq 1.7 \cdot 10^{-2}$
$(M_{\not T}^2)\mathrm{Im}\,Y'^{u,\,d}\,(M_{\not T})$	$\leq \{8.9,\, 8.9\} \cdot 10^{-5}$	$\leq \{7.9,\, 7.9\} \cdot 10^{-3}$
$(M_{\not T}^2)\theta'\,(M_{\not T})$	$\leq 2.4 \cdot 10^{-3}$	$\leq 1.5 \cdot 10^{-1}$

* Hg EDM bound gives stronger limits for some operators (e.g. quark CEDM) but also suffers from larger theoretical uncertainty

Engel et al, PNPP '13

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Bounds and scales

Use the neutron EDM bound (**big uncertainty for some operators: that's why we are here !**)

Dekens, JdV JHEP '13

Dimensionless couplings

	$M_{\not T} = 1\,\mathrm{TeV}$	$M_{\not T} = 10\,\mathrm{TeV}$
$(M_{\not T}^2) d_{u,\,d}\,(M_{\not T})$	$\leq \{1.8,\ 1.8\} \cdot 10^{-3}$	$\leq \{2.1,\ 2.1\} \cdot 10^{-1}$
$(M_{\not T}^2) \tilde{d}_{u,\,d}\,(M_{\not T})$	$\leq \{1.9,\ 0.91\} \cdot 10^{-3}$	$\leq \{1.7,\ 0.94\} \cdot 10^{-1}$
$(M_{\not T}^2) d_W\,(M_{\not T})$	$\leq 5.6 \cdot 10^{-5}$	$\leq 7.0 \cdot 10^{-3}$
$(M_{\not T}^2) \mathrm{Im}\,\Sigma_1\,(M_{\not T})$	$\leq 3.2 \cdot 10^{-5}$	$\leq 2.3 \cdot 10^{-3}$
$(M_{\not T}^2) \mathrm{Im}\,\Sigma_8\,(M_{\not T})$	$\leq 3.3 \cdot 10^{-4}$	$\leq 2.4 \cdot 10^{-2}$
$(M_{\not T}^2) \mathrm{Im}\,\Xi_1\,(M_{\not T})$	$\leq 1.7 \cdot 10^{-4}$	$\leq 1.7 \cdot 10^{-2}$
$(M_{\not T}^2) \mathrm{Im}\,Y'^{u,\,d}\,(M_{\not T})$	$\leq \{8.9,\ 8.9\} \cdot 10^{-5}$	$\leq \{7.9,\ 7.9\} \cdot 10^{-3}$
$(M_{\not T}^2) \theta'\,(M_{\not T})$	$\leq 2.4 \cdot 10^{-3}$	$\leq 1.5 \cdot 10^{-1}$

So 1 TeV seems 'unnatural' but note loop factors. For instance:

$$M_{CP}^2 \tilde{d}_q \sim \frac{\alpha_s}{4\pi} \sin\phi_{CP} \sim 10^{-2} \sin\phi_{CP} \longrightarrow \sin\phi_{CP} \leq 10^{-1}$$

The interpretation is model dependent

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Bounds and scales

Use the neutron EDM bound (**big uncertainty for some operators: that's why we are here !**)

Dekens, JdV JHEP '13

'electroweak suppressed operators'

Dimensionless couplings

	$M_{\not T} = 1\,\mathrm{TeV}$	$M_{\not T} = 10\,\mathrm{TeV}$
$(M_{\not T}^2) C_B\,(M_{\not T})$	$\leq 8.1 \cdot 10^{-2}$	≤ 4.6
$(M_{\not T}^2) C_W\,(M_{\not T})$	$\leq 1.9 \cdot 10^{-2}$	≤ 1.1
$(M_{\not T}^2) C_{WB}\,(M_{\not T})$	$\leq 1.3 \cdot 10^{-2}$	≤ 0.74
$(M_{\not T}^2) C_{dW}\,(M_{\not T})$	≤ 0.11	≤ 11
$(M_{\not T}^2) C_{W u,\,d}\,(M_{\not T})$	$\leq \{1.0,\, 0.84\} \cdot 10^{-2}$	$\leq \{0.53,\, 0.45\}$
$(M_{\not T}^2) C_{Z u,\,d}\,(M_{\not T})$	$\leq \{5.3,\, 2.8\} \cdot 10^{-2}$	$\leq \{2.7,\, 1.4\}$

First 4 operators better bound by eEDM

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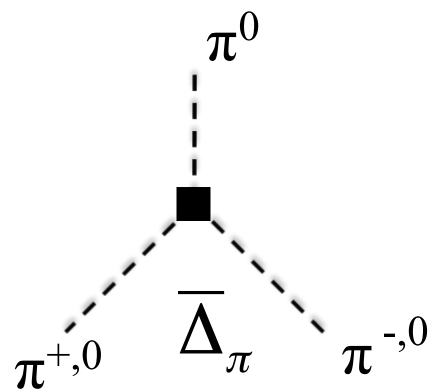
Three-body force



Bsaisou et al '14

- Gives rise to 3-body force in A>2 nuclei.
- But much smaller than power counting suggests in 3He/3H EDMs
- Does renormalize g1, 50% for theta term

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