EDMs and (chiral) effective field theory

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Outline of this talk

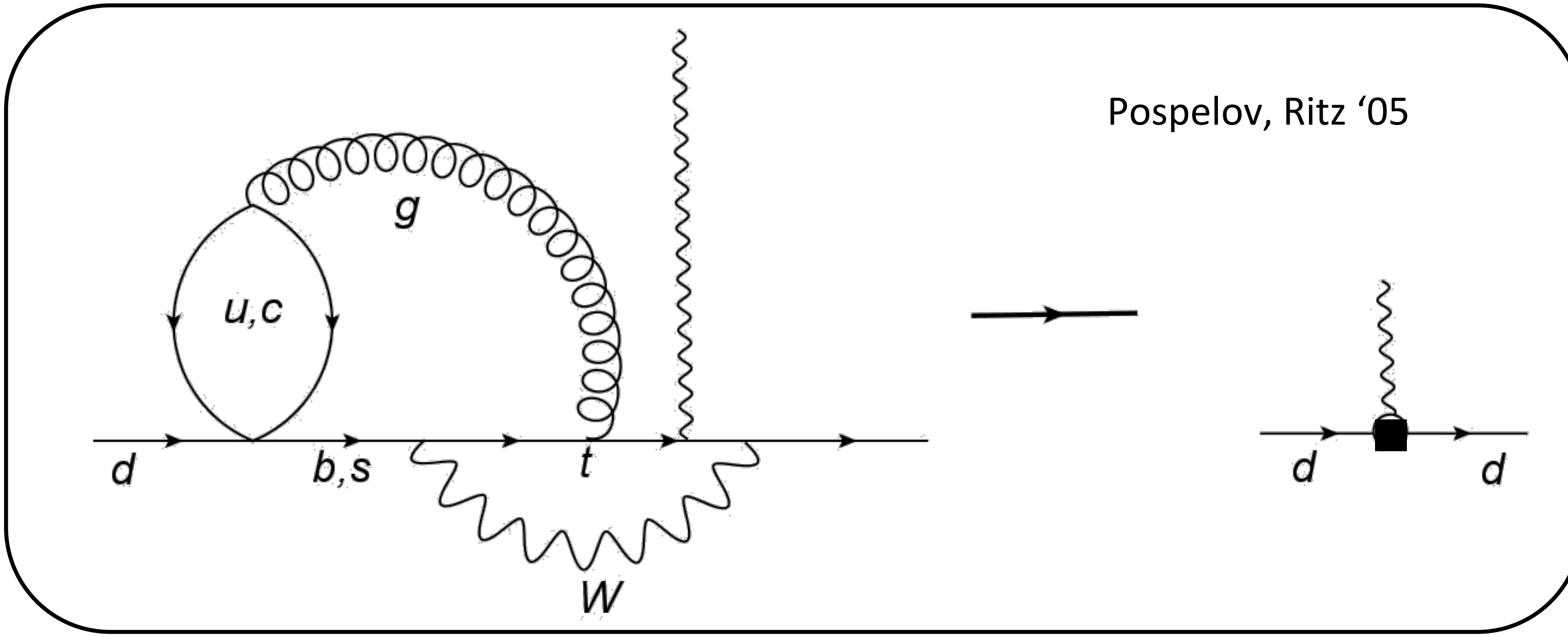
- Part I: EDMs 101 and the EFT framework (very brief)

- Part II: CP violation and chiral symmetry:
  EDMs of hadrons and nuclei

- Part III: Role of hadronic uncertainties on CPV Higgs couplings

EDMs in the Standard Model

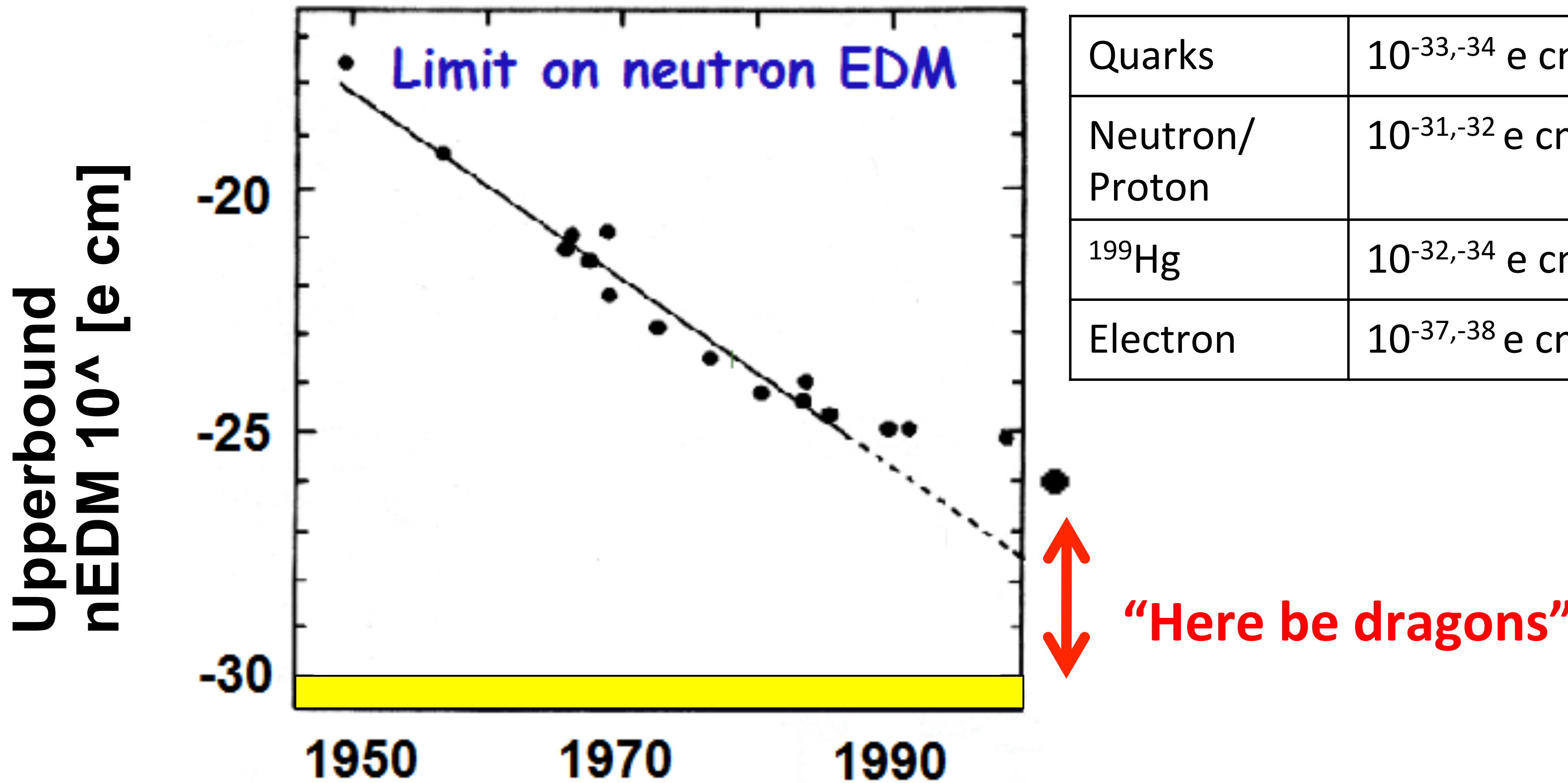
- Electroweak CP-violation very ineffective



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

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

Neutron EDM from CKM



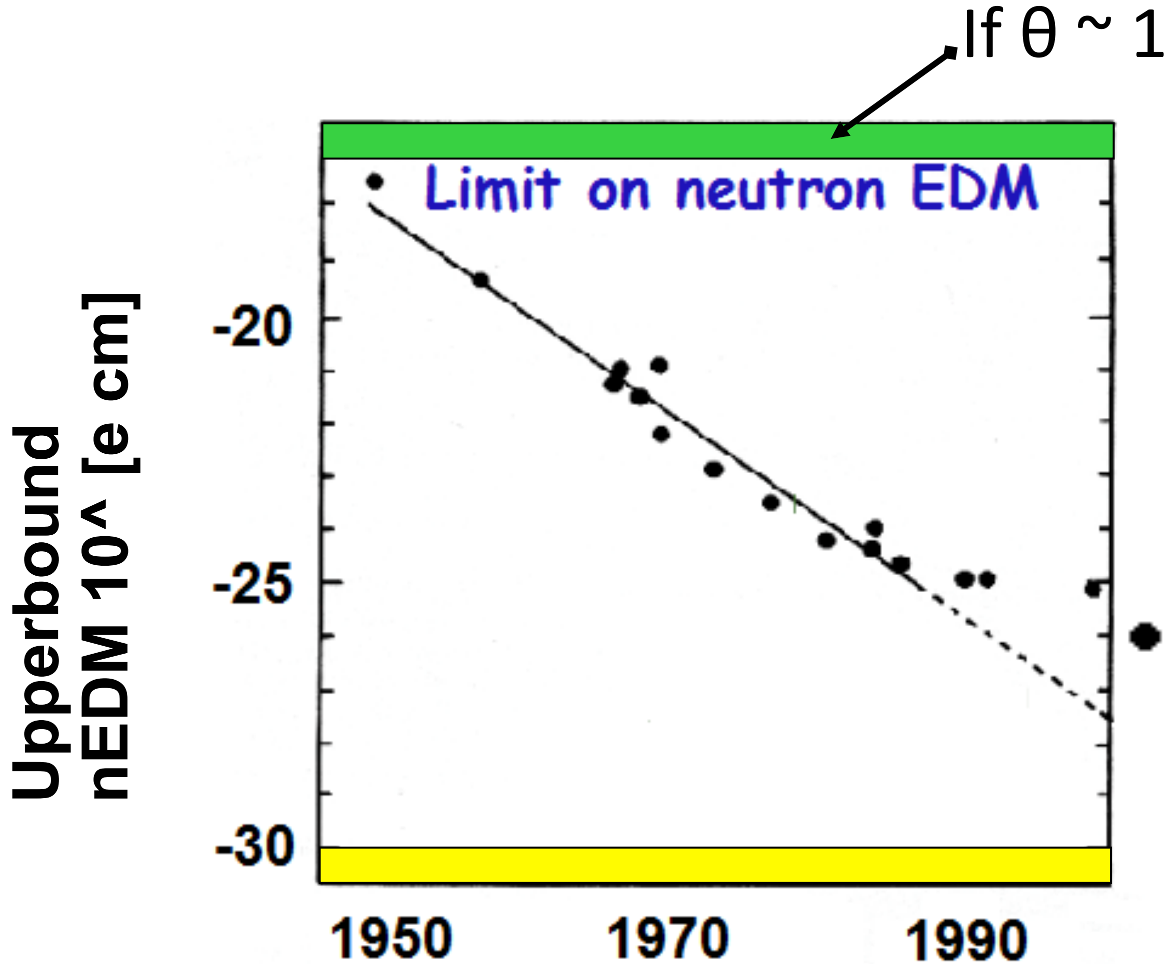
Quarks	$10^{-33,-34}$ e cm
Neutron/ Proton	$10^{-31,-32}$ e cm
^{199}Hg	$10^{-32,-34}$ e cm
Electron	$10^{-37,-38}$ e cm

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

Neutron EDM from theta term



More details on calculation later

't Hooft '76, '78   Crewther et al. '79

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

Sets θ upper bound: **θ < 10^{-10}**

In upcoming experiments:

Measurement of a nonzero EDM

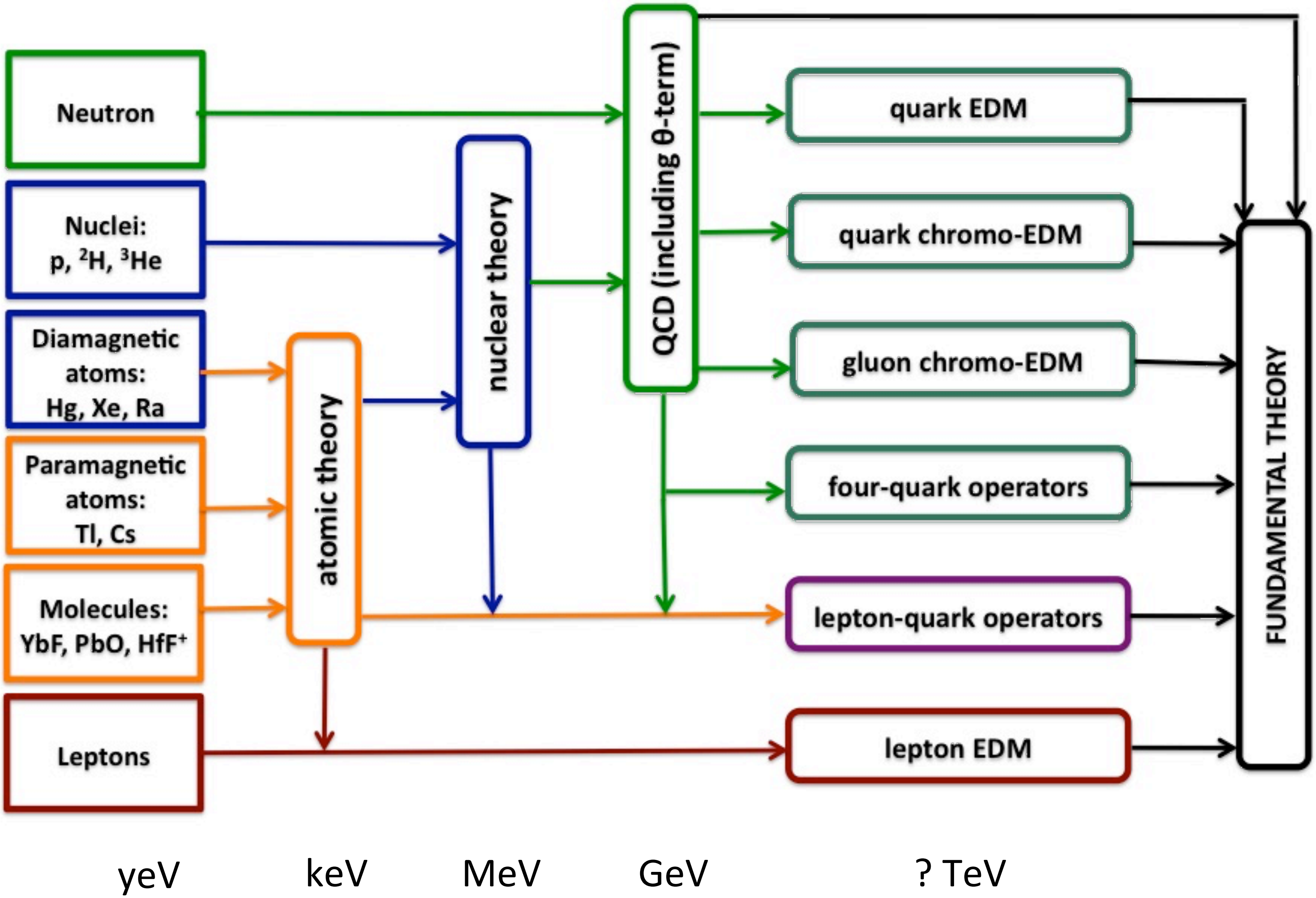
?

Standard Model: θ-term

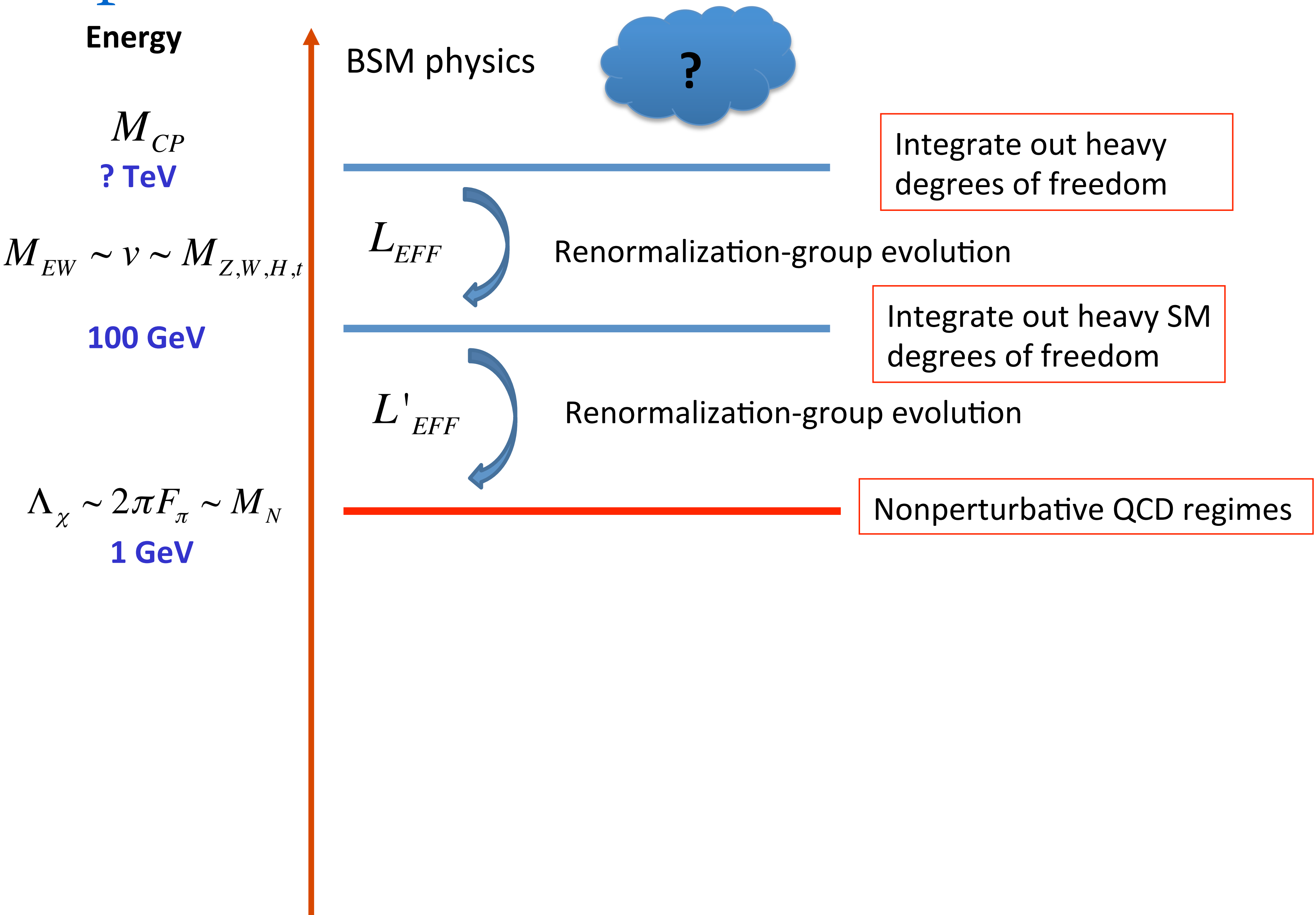
BSM sources of CP-violation

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

The EDM landscape



Separation of scales



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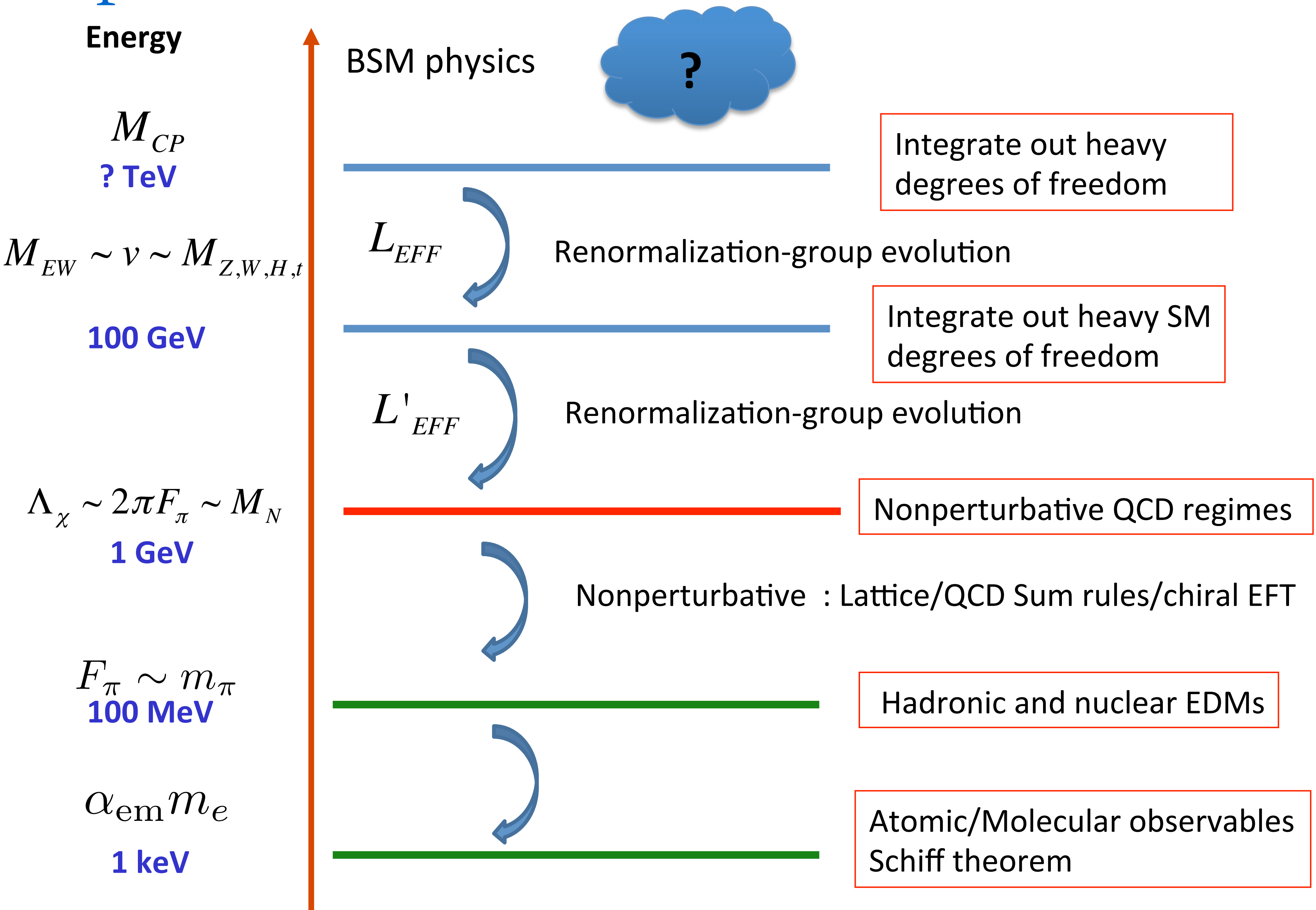


Step 1: SM as an EFT

- 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 new light particles, talk by M. Pospelov.

Buchmuller & Wyler '86
Gradzkowski et al '10

Dipole operators

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

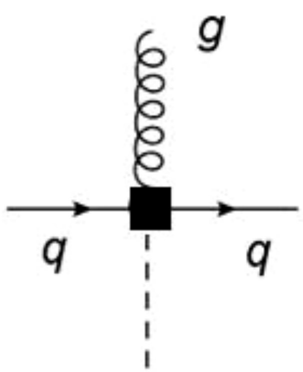
X=W,B,G quarks
X=W,B leptons

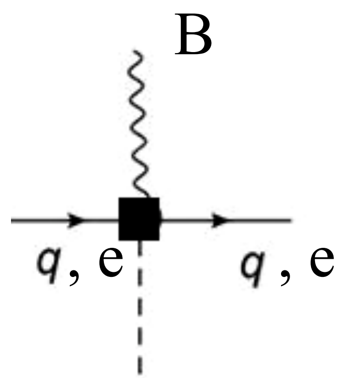
In most models: $\Gamma_X \propto \dfrac{m_\Psi}{v\, M_{CP}^2}$

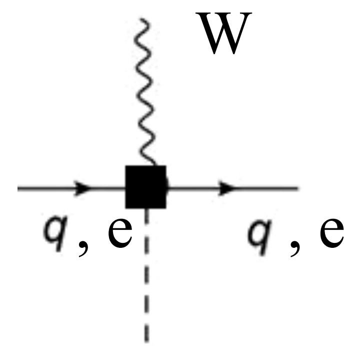
EDMs typically scale with mass !

M_{CP}

? TeV







1 GeV

Dipole operators

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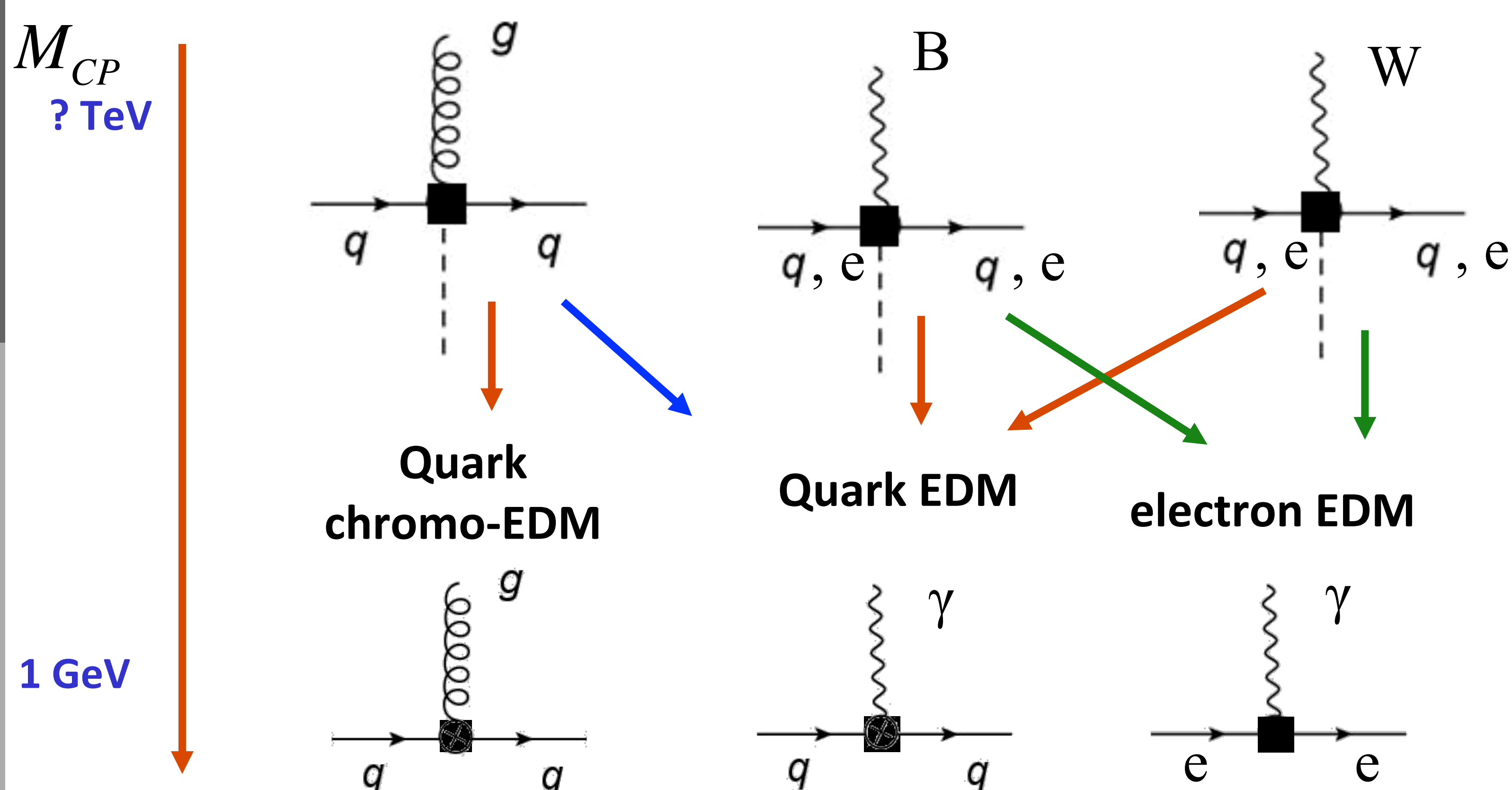

Gluon chromo-EDM

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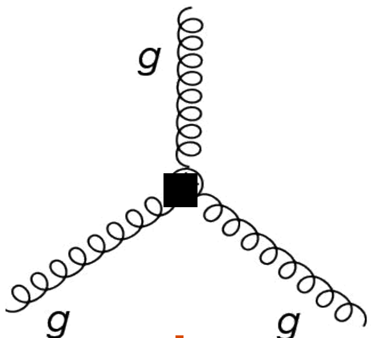
Weinberg operator

Weinberg PRL ’89
Braaten et al PRL ’90

M_{CP}
? TeV



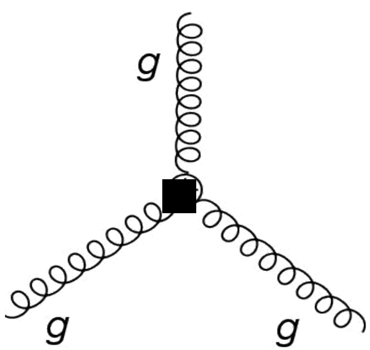
$$d_w \; f^{abc} \varepsilon^{\mu\nu\alpha\beta} \; G^a_{\alpha\beta} G^b_{\mu\lambda} \; G^{c\,\lambda}_{\nu}$$

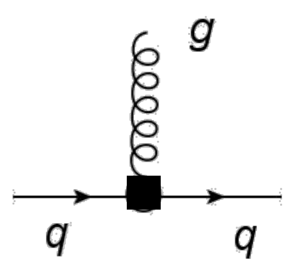
QCD mixing

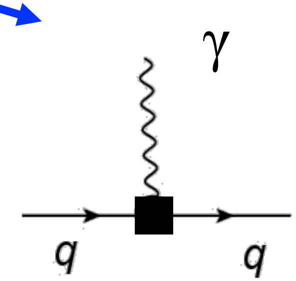
Gluon chromo-EDM

Quark chromo-EDM

Quark EDM







1 GeV

Four-quark operators

Fermion-Higgs interactions

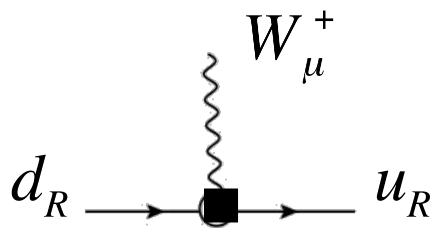
Energy

M_{CP}

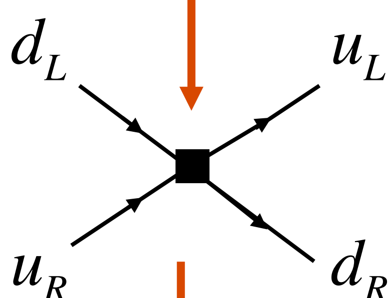
$< M_W$

Λ_χ

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



A right-handed quark-W coupling



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

QCD RGE induces another operator

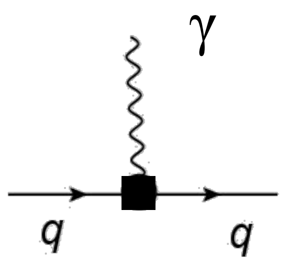
Two four-quarks terms (FQLR operators)

Ng & Tulin ’12
JdV et al ’12
An et al ‘10

When the dust settles….

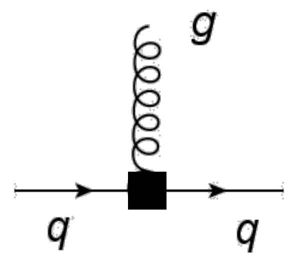
Hadronic interactions

QCD (θ-term) +



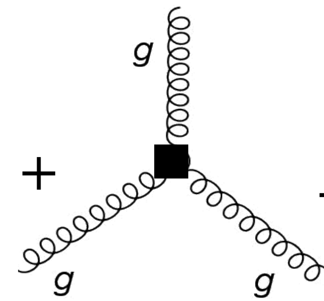
Quark EDM

+



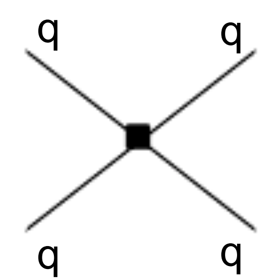
Quark chromo-EDM

+



Gluon chromo-EDM

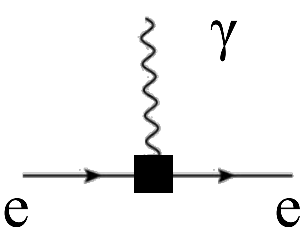
+



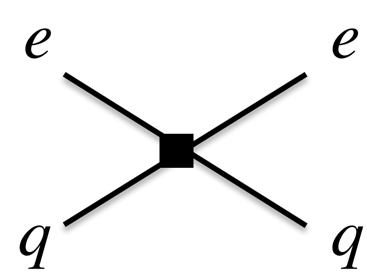
FQLR operators

~ 1 GeV

(semi-)leptonic interactions



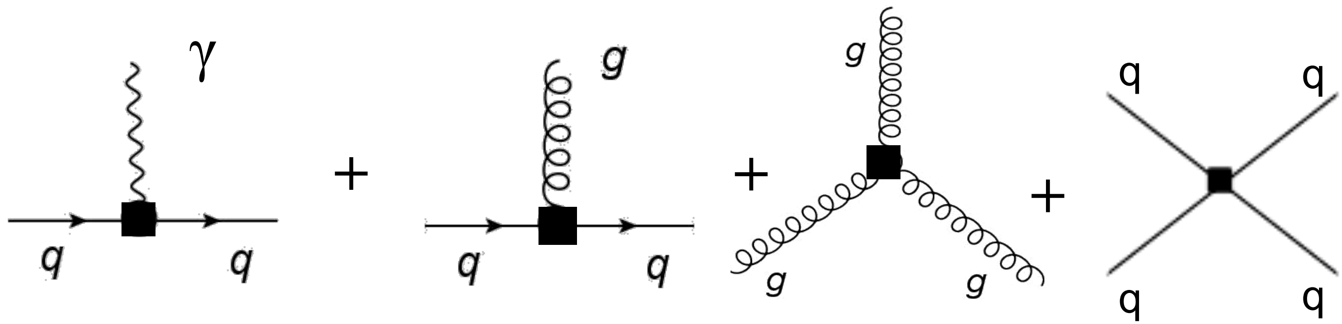
Electron EDM



Crossing the barrier

Few GeV

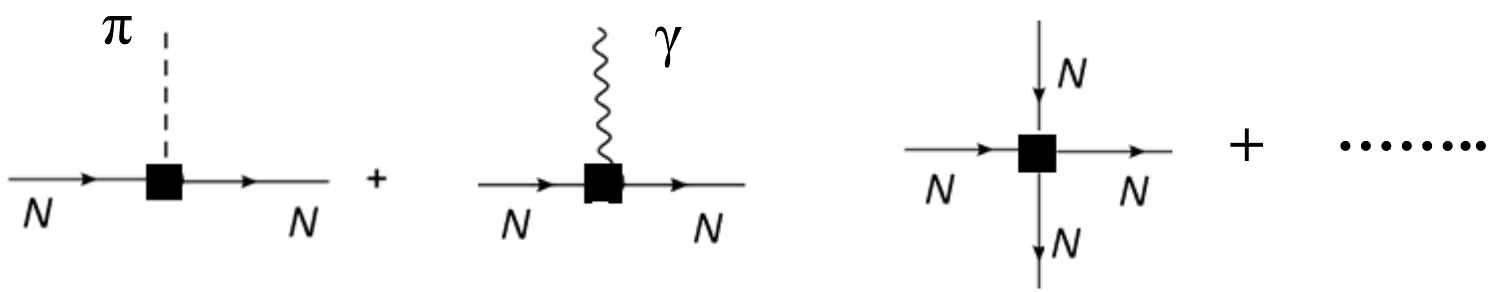
QCD (θ-term) +



Quark EDM | **Quark chromo-EDM** | **Gluon chromo-EDM** | **4quark operators**

Hadronic/Nuclear CP-violation

100 MeV



Chiral EFT

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

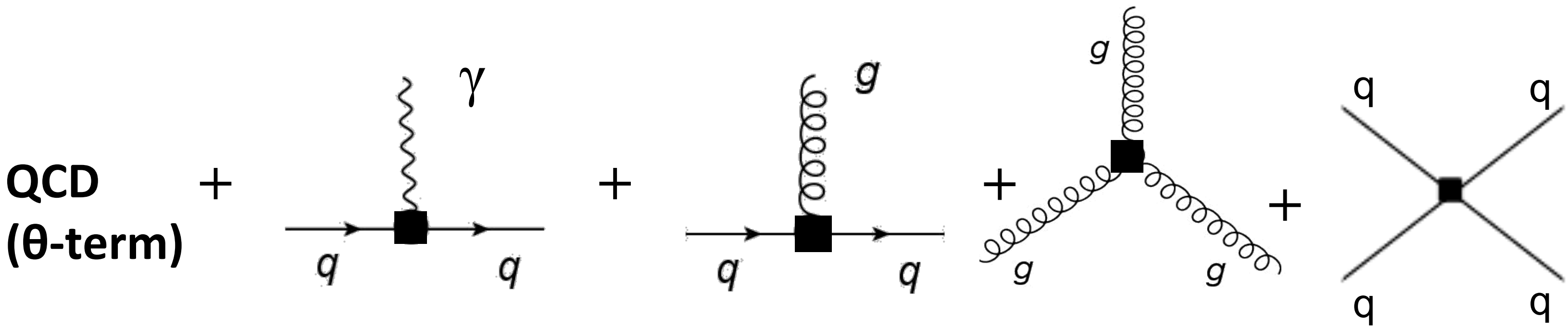
$$L_{QCD} \rightarrow L_{chiPT} = L_{\pi\pi} + L_{\pi N} + L_{NN} + \cdots$$

- 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, and many many others

ChiPT with CP violation



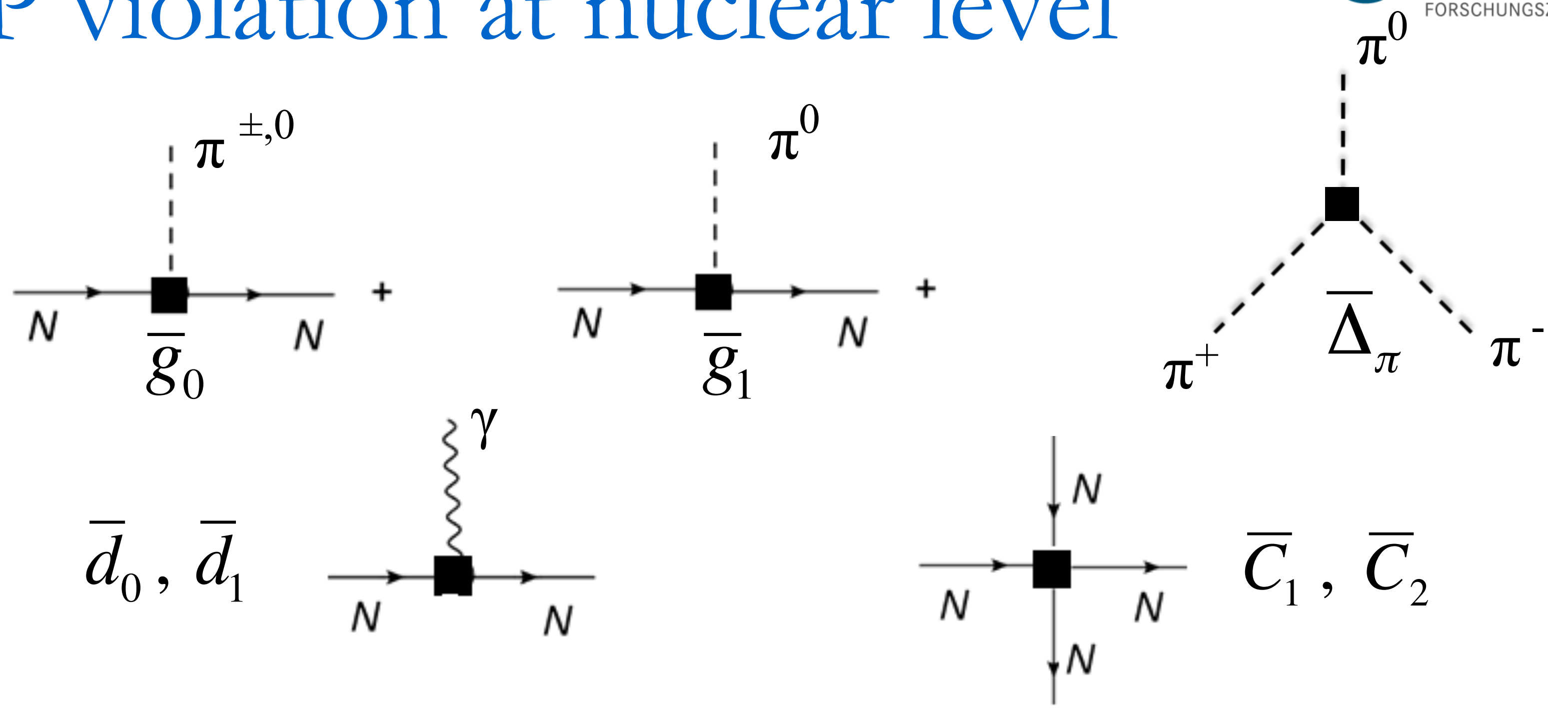
- They all break CP....

- But transform **differently** under chiral/isospin symmetry

Different CP-odd chiral Lagrangians

Different hierarchy of EDMs

CP violation at nuclear level



- 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
- ChPT gives the form/hierarchy of interactions, **but not the LECs**

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

The QCD theta term

After axial U(1) and SU(2) rotations, two-flavored mass part of QCD:

$$\mathcal{L} = -\bar{m}\,\bar{q}q - \varepsilon\bar{m}\,\bar{q}\tau^3 q + m_\star\bar{\theta}\,\bar{q}i\gamma^5 q$$

Crewther et al' 79

Baluni '79

$$\bar{m} = \frac{m_u + m_d}{2}$$

$$\varepsilon = \frac{m_u - m_d}{m_u + m_d}$$

$$m_\star = \frac{m_u m_d}{m_u + m_d}$$

The QCD theta term

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$$\mathcal{L} = -\bar{m}\,\bar{q}q - \underbrace{\varepsilon\bar{m}\,\bar{q}\tau^3 q + m_\star\bar{\theta}\,\bar{q}i\gamma^5 q}_{\text{Linked via } SU_A(2) \text{ rotation}}$$

Crewther et al' 79

Baluni '79

$$\bar{m} = \frac{m_u + m_d}{2}$$

$$\varepsilon = \frac{m_u - m_d}{m_u + m_d}$$

$$m_\star = \frac{m_u m_d}{m_u + m_d}$$

Isospin breaking related to strong CP violation

$$\rho_\theta = -\frac{m_\star\bar{\theta}}{\varepsilon\bar{m}} \simeq -\frac{1-\varepsilon^2}{2\varepsilon}\bar{\theta}$$

The QCD theta term

$$\mathcal{L} = -\varepsilon \bar{m}\, \bar{q}\tau^3 q + m_\star \bar{\theta}\, \bar{q} i\gamma^5 q$$

Explicit construction shows a relation between:

Crewther et al' 79

$$\mathcal{L} = \frac{\delta m_N}{2} \bar{N}\tau^3 N + \bar{g}_0 \bar{N}\pi \cdot \tau N \qquad N = (p\ n)$$

Nucleon mass splitting (strong part, no EM!) ⟷ **CP-odd pion-nucleon interaction**

The QCD theta term

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Nucleon mass splitting (strong part, no EM!) ⟷ **CP-odd pion-nucleon interaction**

$$\frac{\bar{g}_0}{f_\pi} = \delta m_N \rho_\theta = -\delta m_N \frac{1-\varepsilon^2}{2\varepsilon}\bar{\theta} = -(15.5 \pm 2.5)\cdot 10^{-3}\,\bar{\theta}$$

- Using **lattice results** for (nucleon, quark) mass differences

  Walker-Loud '14, Borsanyi '14, Aoki (FLAG) '13,

- This and other relations hold up to N2LO in SU(2) and SU(3) ChPT

  JdV, Mereghetti, Walker-Loud '15

Hierarchy of couplings

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- Hierarchy of CP-odd **pion-nucleon** interaction
- Traditionally expected to **dominate** nuclear EDMs

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

❖ θ-term conserves isospin! So g1 is **suppressed**.

$$\bar{g}_0 = \frac{(m_n - m_p)^{strong}}{4F_\pi \varepsilon}\bar{\theta} = -0.015(2)\bar{\theta}$$

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

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

- Large uncertainty for g1 due to pion mass splitting and unknown LEC

Crewther et al' 79, Pospelov et al '01,'04, Mereghetti et al '10, '12

Hierarchy of couplings

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

❖ Quark chromo-EDM: **no easy tricks**....

- Non-perturbative calculation with QCD sum rules:

Pospelov '02

$$\bar{g}_0 = (5 \pm 10)(\tilde{d}_u + \tilde{d}_d)\,\mathrm{fm}^{-1} \qquad \bar{g}_1 = (20^{+20}_{-10})(\tilde{d}_u - \tilde{d}_d)\,\mathrm{fm}^{-1}$$

- Fairly large uncertainties. But generally: $|\bar{g}_1| \geq |\bar{g}_0|$
- Can be used to differentiate from theta term

Hierarchy of couplings

- Hierarchy of CP-odd **pion-nucleon** interaction
- 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: **a not-so-easy trick**

- Quark Chromo-EDM is chiral partner of chromo-MDM

$$\tilde{d}_q\, \bar{q}\sigma^{\mu\nu}\gamma^5 q\, G_{\mu\nu} \longleftrightarrow \tilde{c}_q\, \bar{q}\sigma^{\mu\nu}\tau^3 q\, G_{\mu\nu}$$

$$\bar{g}_0 = \tilde{\delta}m_N \frac{\tilde{d}_q}{\tilde{c}_q}$$

Pospelov -Ritz '05
JdV et al '12

- Need lattice calculation of splitting $\tilde{\delta}m_N$ from chromo-MDM

Walker-Loud, in prep

Hierarchy of couplings

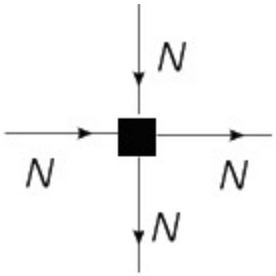
- Hierarchy of CP-odd **pion-nucleon** interaction
- Traditionally expected to **dominate** nuclear EDMs

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

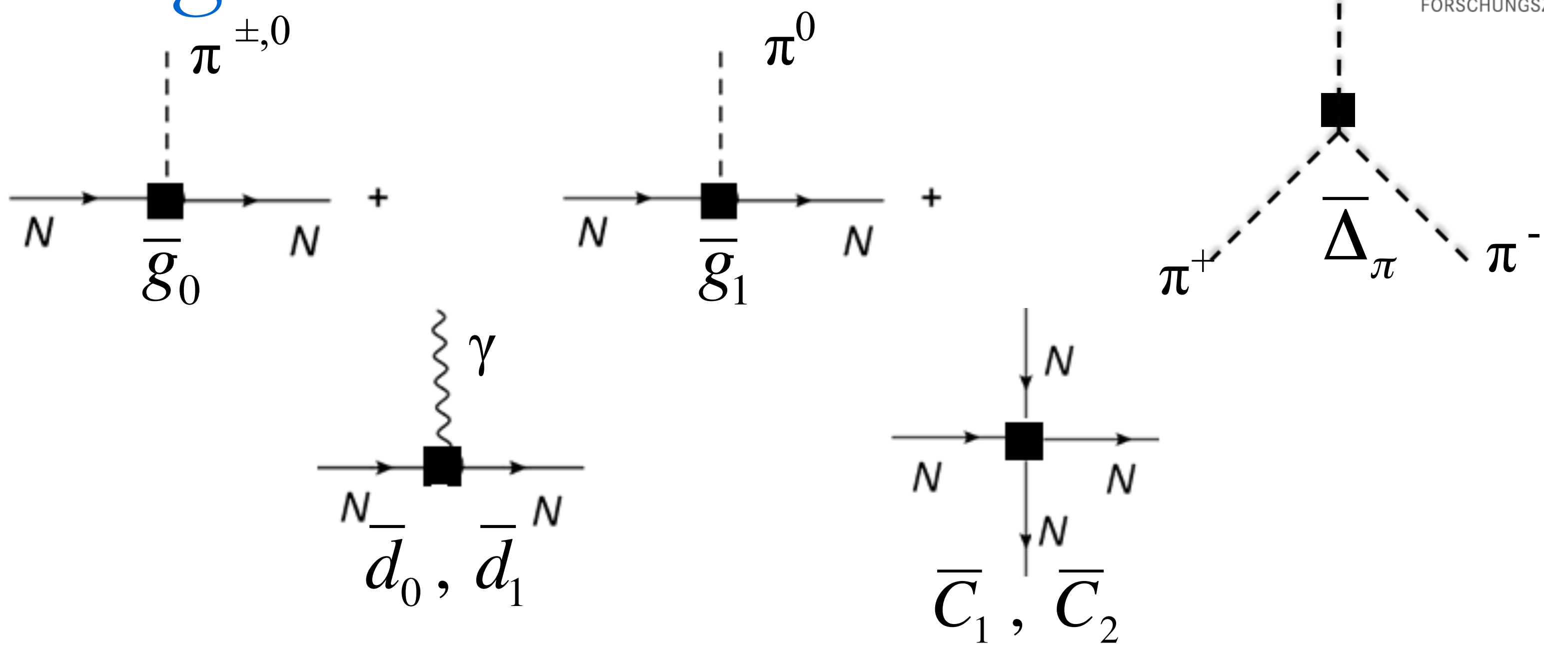
❖ Weinberg operator, LECs suppressed due to **chiral symmetry**.

Leading contributions from CP-odd NN interactions.

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



The magnificent seven



Different sources of CP-violation

↓

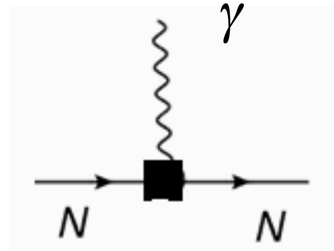
Different hierarchies of hadronic interactions

↓

Can we probe these hierarchies experimentally ?

The Nucleon EDM

Nucleon EDM



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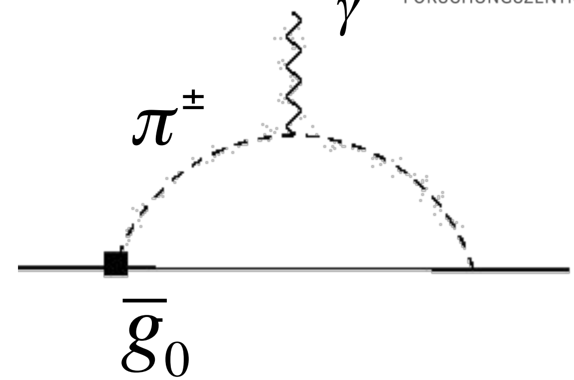


$$d_n = \overline{d}_0 - \overline{d}_1 - \frac{e g_A \overline{g}_0}{4\pi^2 F_\pi}\left(\ln\frac{m_\pi^2}{M_N^2} - \frac{\pi}{2}\frac{m_\pi}{M_N}\right)$$

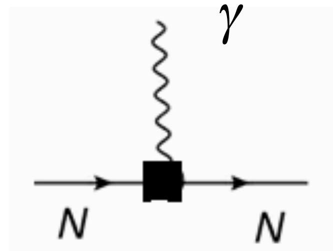
$$d_p = \overline{d}_0 + \overline{d}_1 + \frac{e g_A}{4\pi^2 F_\pi}\left[\overline{g}_0\left(\ln\frac{m_\pi^2}{M_N^2} - 2\pi\frac{m_\pi}{M_N}\right) - \overline{g}_1\frac{\pi}{2}\frac{m_\pi}{M_N}\right]$$

- absorbed UV divergences in $\overline{d}_0\,,\ \overline{d}_1$

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

The Nucleon EDM

Nucleon EDM



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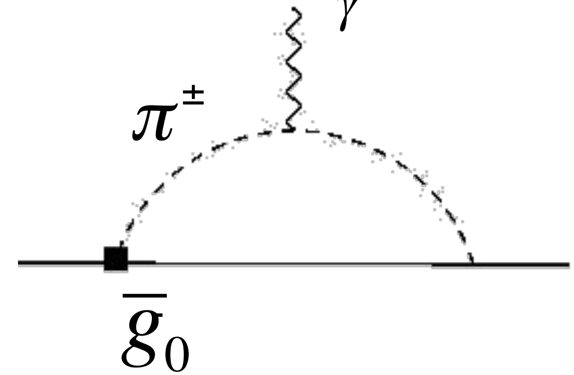

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$$d_p = \overline{d}_0 + \overline{d}_1 + \frac{e g_A}{4\pi^2 F_\pi}\left[\overline{g}_0\left(\ln\frac{m_\pi^2}{M_N^2} - 2\pi\frac{m_\pi}{M_N}\right) - \overline{g}_1\frac{\pi}{2}\frac{m_\pi}{M_N}\right]$$

- absorbed UV divergences in $\overline{d}_0$, $\overline{d}_1$

- 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

Lattice QCD to the rescue

- With QCD lattice input:

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

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

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

See E. Shintani’s talk last week

$$d_n = (3.9 \pm 1.0) \cdot 10^{-16}\ \bar{\theta}\ e\ cm$$

Guo et al ‘15
Talk later today by G. Schierholz

Lattice QCD to the rescue

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See E. Shintani's talk last week

$$d_n = (3.9 \pm 1.0) \cdot 10^{-16}\ \bar{\theta}\ e\ cm$$

Guo et al '15
Talk later today by G. Schierholz

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

O'Connell, Savage '06
Guo, Meißner, Akan '14

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

- **Value of g0 from ChPT is inserted in the extrapolation.**
  Would be nice to confirm this value!

Nucleon Schiff moments

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$$F(Q^2) = d + Q^2 S + Q^4 H + \ldots$$

EDM **Schiff Moment**

- Schiff moments are **counterterm-free** up to N2LO

$$S_n = -S_p = -\frac{e g_A \bar{g}_0}{48\pi^2 F_\pi} \frac{1}{m_\pi^2}$$

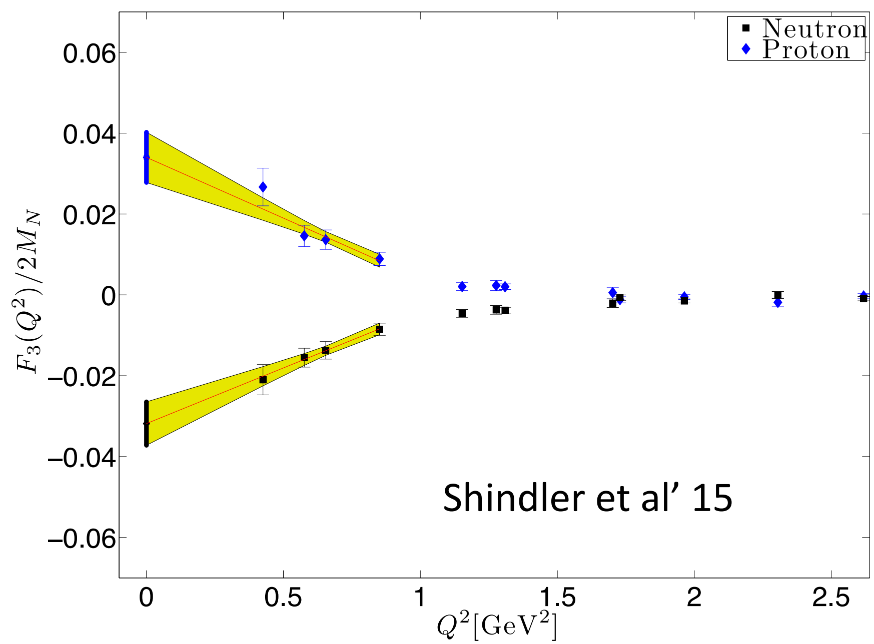
Nucleon Schiff moments

$$F(Q^2) = \underbrace{d}_{\text{EDM}} + Q^2 \underbrace{S}_{\text{Schiff Moment}} + Q^4 H + \ldots$$

- Schiff moments are **counterterm-free** up to N2LO

$$S_n = -S_p = -\frac{e g_A \bar{g}_0}{48\pi^2 F_\pi} \frac{1}{m_\pi^2}$$

- Schiff moment is few times bigger than chPT prediction. (4x or so)
- But, **quenched plus huge pion masses**. So should be seen as proof of principle.



Talk last week by A. Shindler

And dim6 sources ?

❖ Quark EDM accurately determined recently !

$$d_n = -(0.22 \pm 0.03)d_u + (0.74 \pm 0.07)d_d + (0.008 \pm 0.01)d_s$$

❖ Quark CEDM no lattice calculations yet. **But in progress**.

Talk later today by T. Bhattacharya

QCD sum rules: nucleon EDMs ~ 50% uncertainty

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

❖ Weinberg (and four-quark) only **estimates**

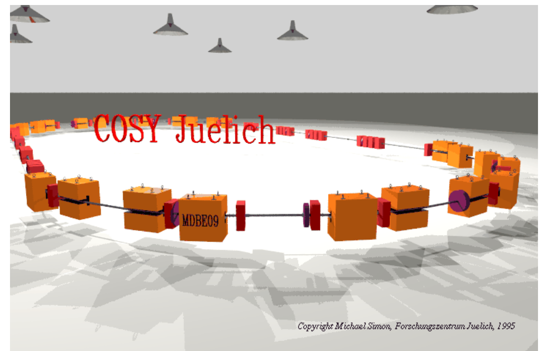
Weinberg '89
Demir et al '03
JdV et al '10

$$d_n = \pm[(50 \pm 40)\,\mathrm{MeV}]\, e\, d_W$$

Experiments on charged particles

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 $$d_\mu \leq 1.8 \cdot 10^{-19}\ e\ cm$$

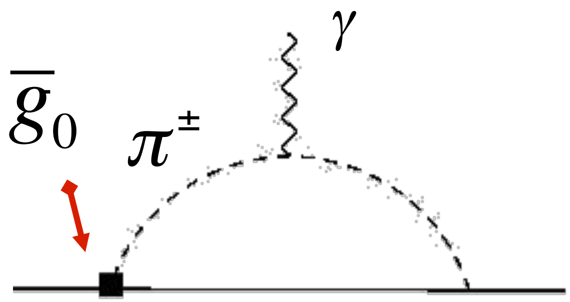
Anastassopoulos et al ‘15

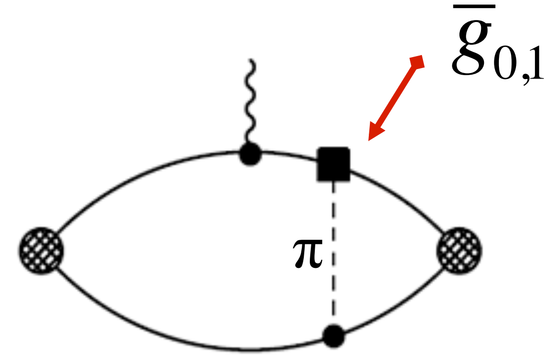
- **Proposals to measure EDMs of light nuclei (p, 2H, 3He, ...)**
- Precursor experiment at COSY at Jülich. **Progress!**

Eversmann et al ‘15

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

Why light nuclei?

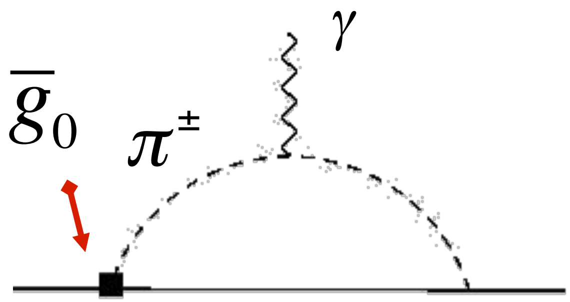


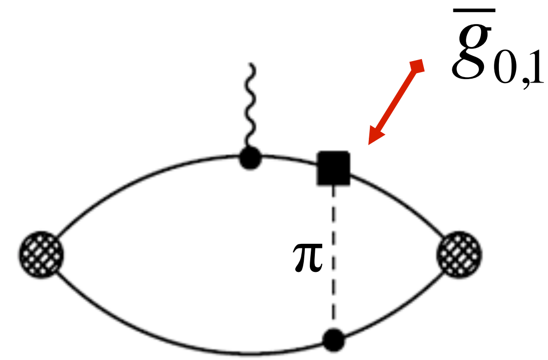


- **Tree-level**: no loop suppression
- Very good **theoretical control** !

$$d_A = <\Psi_A \,||\, \vec{J}_{\cancel{CP}} \,||\, \Psi_A> + \; 2 <\Psi_A \,||\, \vec{J}_{CP} \,||\, \tilde{\Psi}_A>$$

Why light nuclei?





- **Tree-level**: no loop suppression
- Very good **theoretical control** !

$$d_A = <\Psi_A \| \vec{J}_{\cancel{CP}} \| \Psi_A> + \; 2 <\Psi_A \| \vec{J}_{CP} \| \tilde{\Psi}_A>$$

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

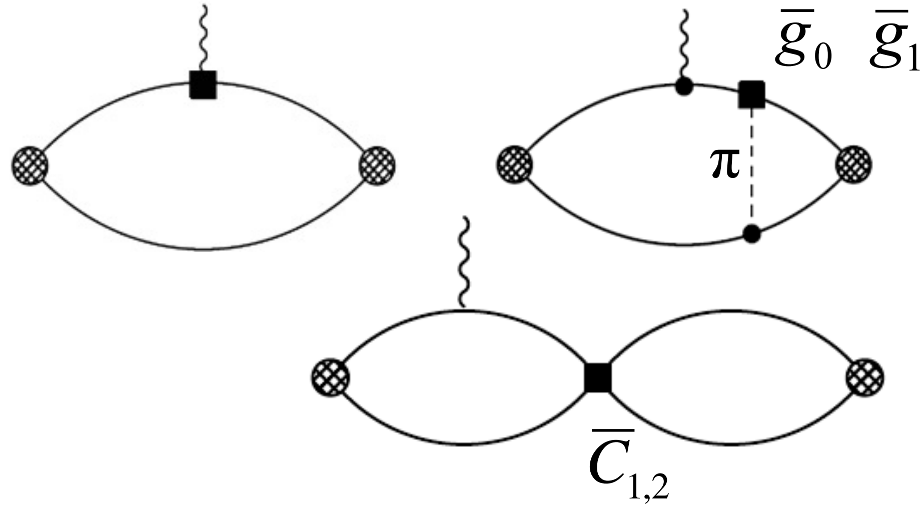
Input

1. CP-even potential from **chiral EFT** — Epelbaum et al ‘05
2. CP-odd potential as well, derived for each source — Maekawa et al ‘11
3. Same for CP-even/odd EM currents

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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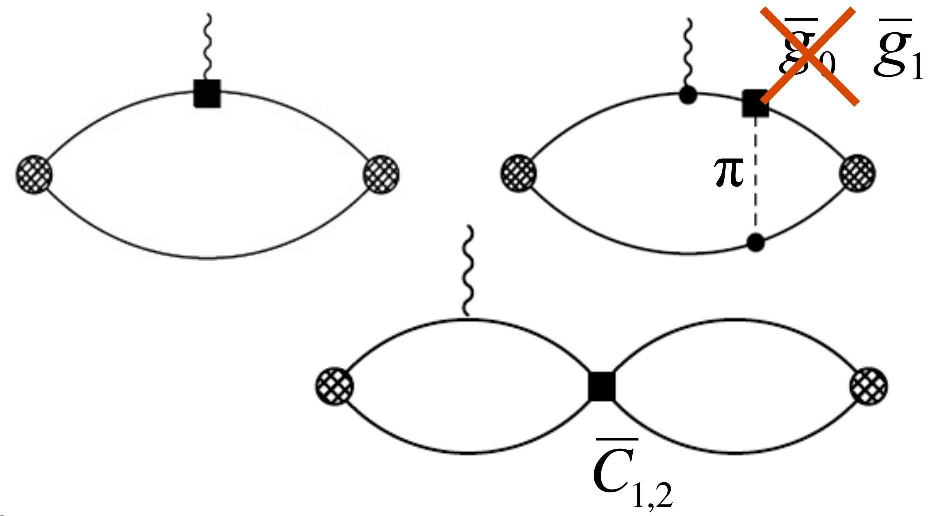
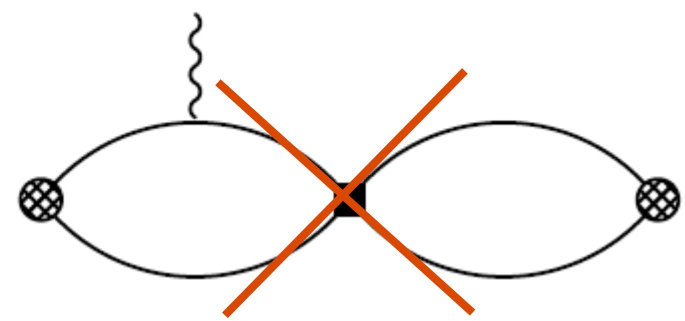


- Three contributions (NLO)
  1. Sum of nucleon EDMs
  2. CP-odd pion exchange
  3. CP-odd NN interactions

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

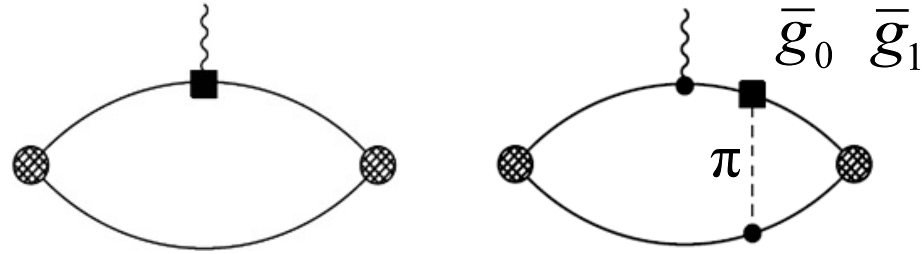
$$ {}^3S_1 \xrightarrow{\bar{g}_0} {}^1P_1 \xrightarrow{\gamma} \cancel{{}^3S_1} $$

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



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 Bsaisou et al JHEP `14

Example: deuteron EDM

Filtering the sources

	Theta	Four-quark left-right	Quark chromo-EDM	Quark EDM	Weinberg Operator
$\left\lvert \frac{d_D - d_n - d_p}{d_n} \right\rvert$	0.5 ± 0.2	$\cong 7 - 20$	$\cong 3 - 10$	$\cong 0$	$\cong 0$

- Ratio suffers from hadronic uncertainties **(need lattice)**
- Nuclear EDMs are **complementary** to nucleon EDMs
- EDM ratio hint towards **underlying source**!

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

Onwards to Hg….

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

- **No isospin filter**, **complementary** to deuteron
- Good nuclear accuracy (30%) but a jump from deuteron (10%)

Stetcu et al '08 '11 Bsaisou et al '12,'14

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- **No isospin filter**, **complementary** to deuteron
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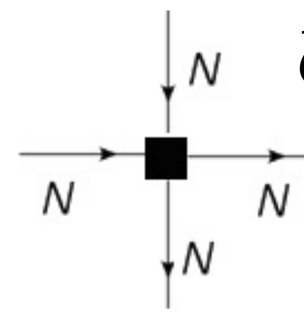
But…

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



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

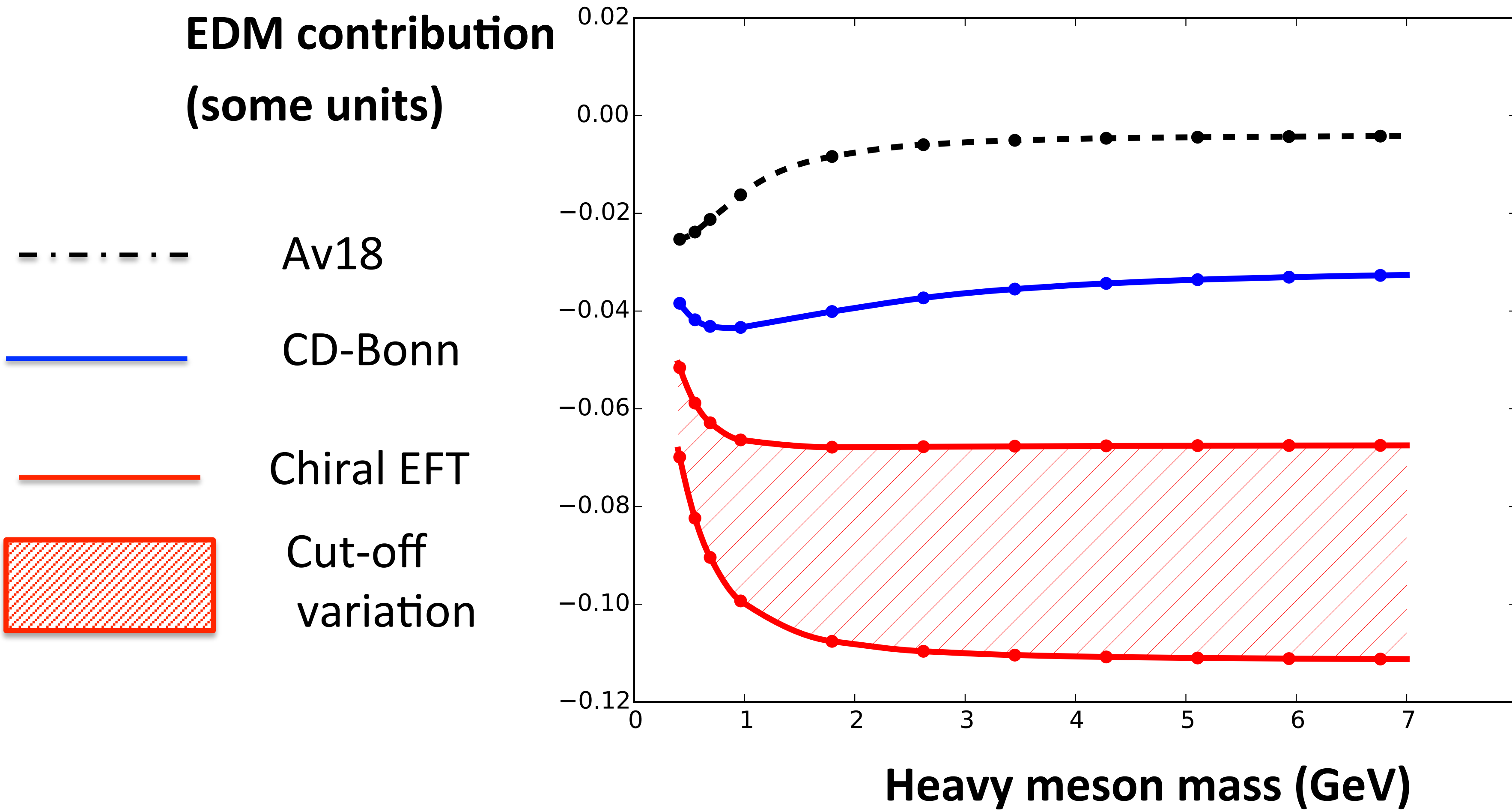
Contact NN term described by ‘heavy meson’ exchange

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

Stetcu et al ‘08 ’11 Bsaisou et al ’12,’14

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)**

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.

Schiff, '63

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Schiff, '63

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

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

- **Atomic** part well under control

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

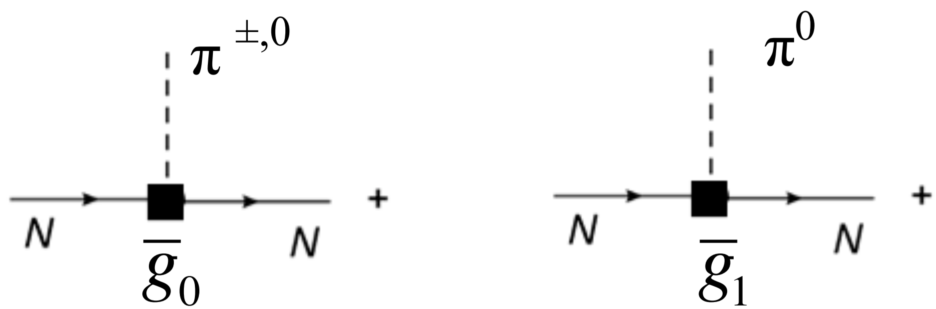
$$d_{^{225}Ra} = (7.2 \pm 1.5) \cdot 10^{-4}\ S_{Ra}\ e\ fm^2$$

Dzuba et al, '02, '09

Sing et al, '15

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)

Calculating Schiff Moments

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

- Based on calculations from various groups

$$S_{\text{Hg}} = [(0.35 \pm 0.3)\bar{g}_0 + (0.35 \pm 0.70)\bar{g}_1]\ e\,\text{fm}^3$$

- Spread > 100%   (unclear why, difficult 'soft' nucleus (J. Engel))

- Nucleon EDMs contribution better under control

$$S_{\text{Hg}} = (1.9 \pm 0.2)d_n + (0.2 \pm 0.02)d_p$$

- **More difficult** to interpret the limits on BSM parameters.

Calculating Schiff Moments

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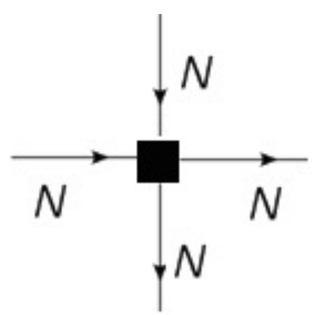
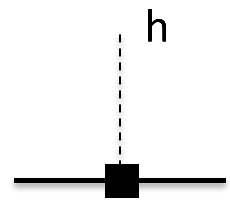


????

CP-violating Higgs couplings

- Briefly focus on a specific application

$$\mathcal{L} = v^2 \sum_q \mathrm{Im}\, Y_q \, \bar{q} i \gamma^5 q$$



Brod et al '13
Cirigliano et al '15

- Highly relevant: Test SM, electroweak baryogenesis, Higgs-portal DM

V. Cirigliano's & E. Mereghetti's talk

CP-violating Higgs couplings

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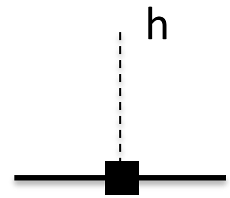
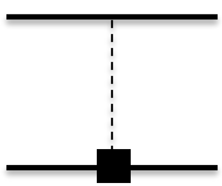


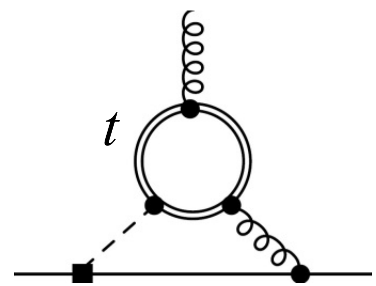
Brod et al '13
Cirigliano et al '15

- Highly relevant: Test SM, electroweak baryogenesis, Higgs-portal DM

V. Cirigliano's & E. Mereghetti's talk

- Look at **up** and **down** CP-odd Yukawa's





Barr, Zee '90

$$C_{FQ} \sim \frac{v^2 Y_q y_q}{m_H^2} \sim y_q Y_q$$

$$y_q \sim 10^{-4}$$

$$\tilde{C}_q(m_t) \sim -\frac{\alpha_s(m_t)}{32\pi^3} \frac{v}{m_q} Y^q \sim Y^q$$

So up and down (C)EDMs at low energy

Bounds on individual couplings

Handle hadronic/nuclear uncertainties with 2 extreme strategies

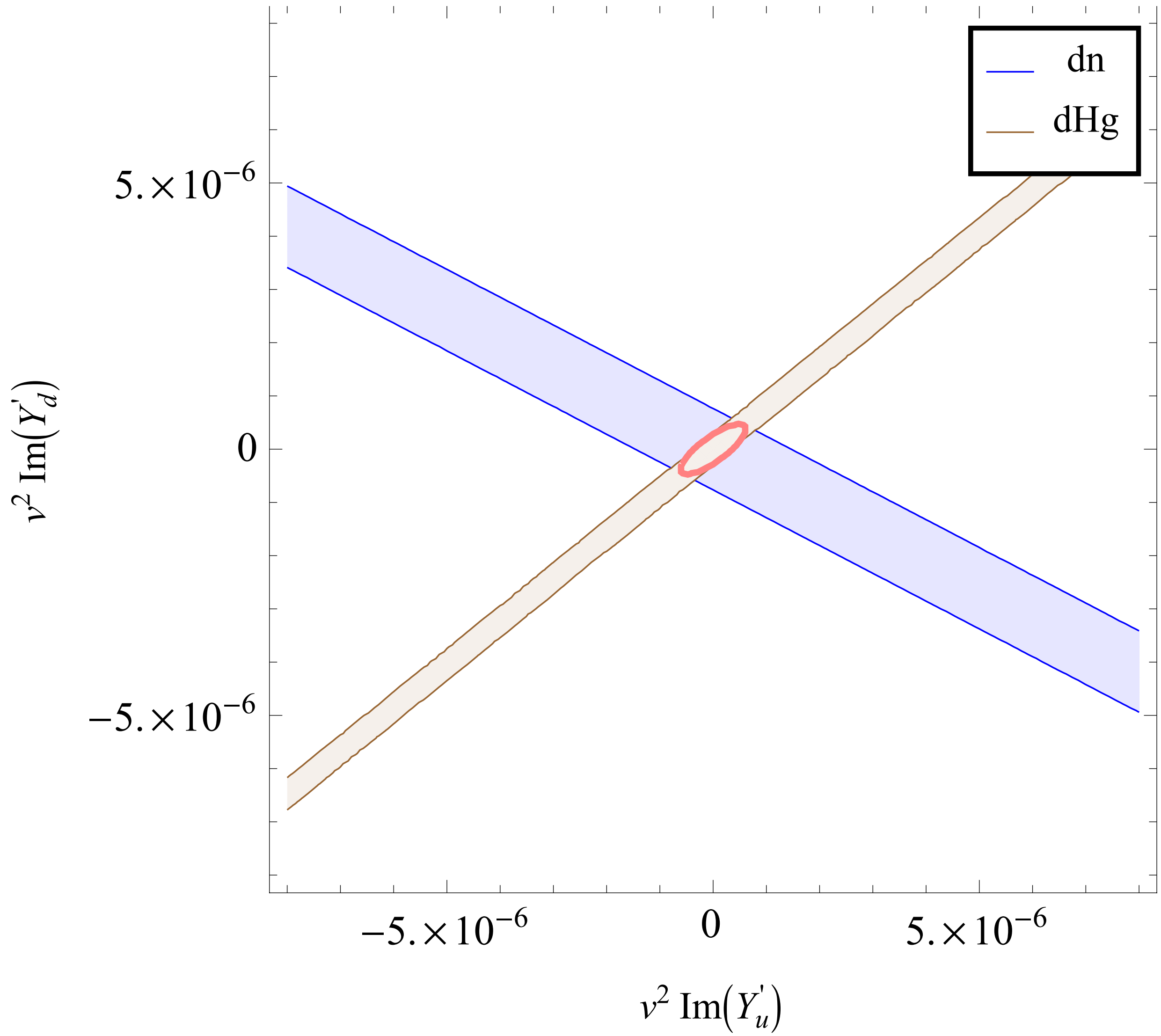
1. Simply use central values everywhere
2. Minimize the chi^2 within the range of matrix elements (Range Fit)

	v^2 Im Y_u (1 TeV)	v^2 Im Y_d (1 TeV)
Central matrix elements	$< 3.9 \times 10^{-7}$	$< 3.0 \times 10^{-7}$
Rfit procedure (most conservative)	$< 2.8 \times 10^{-6}$	$< 1.5 \times 10^{-6}$

Seems reasonably ok… We lose a factor 10 due to QCD uncertainties

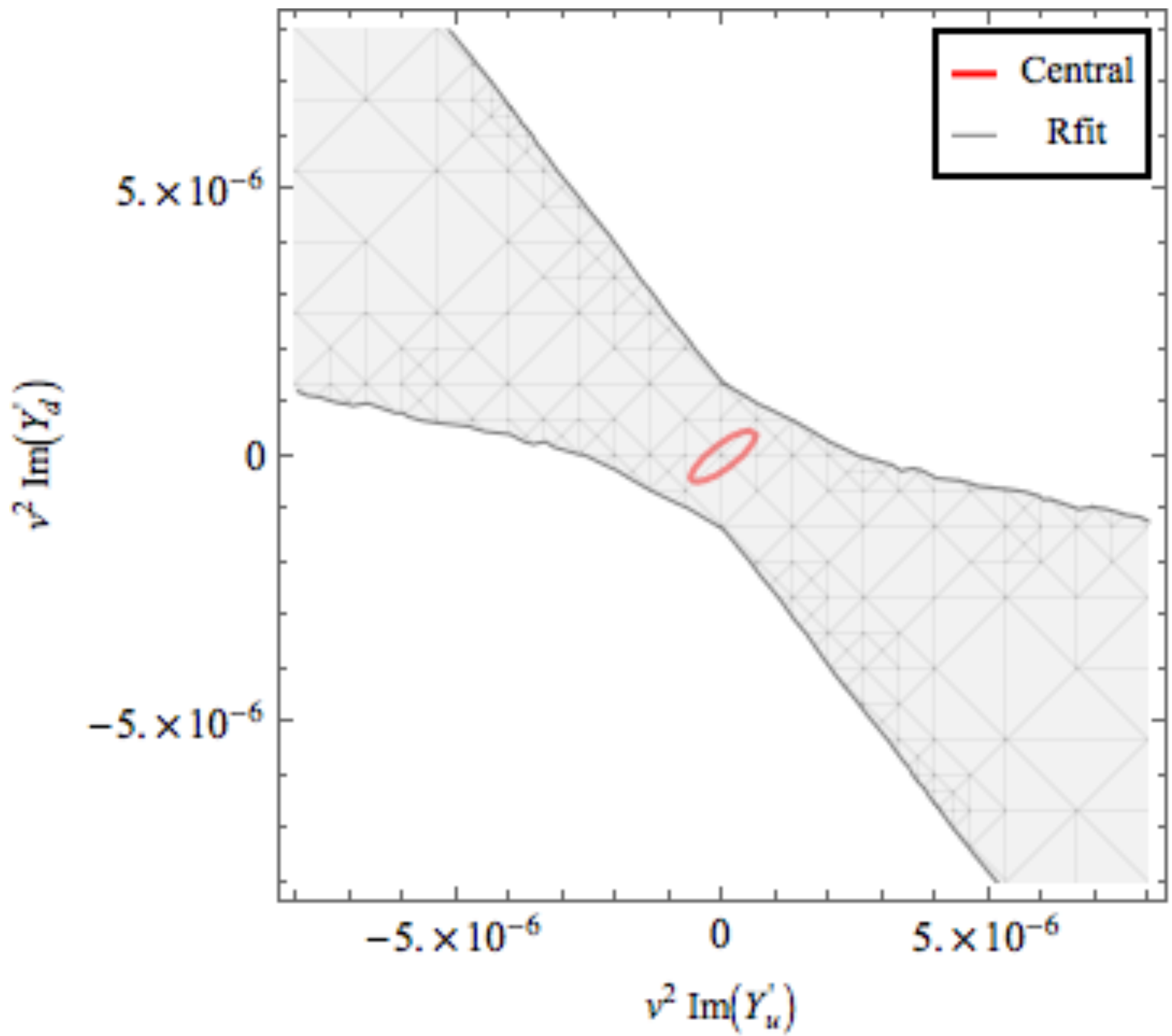
Chien, Cirigliano, Dekens, JdV, Mereghetti, to appear

Constraining CPV Yukawa's



EDMs bound imaginary Yukawa's at **ppm** level

Constraining CPV Yukawa's



Nuclear/Hadronic uncertainties have a big impact....
Perhaps overconservative ?

Constraining CPV Yukawa's

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- In this case uncertainties are dominated by:

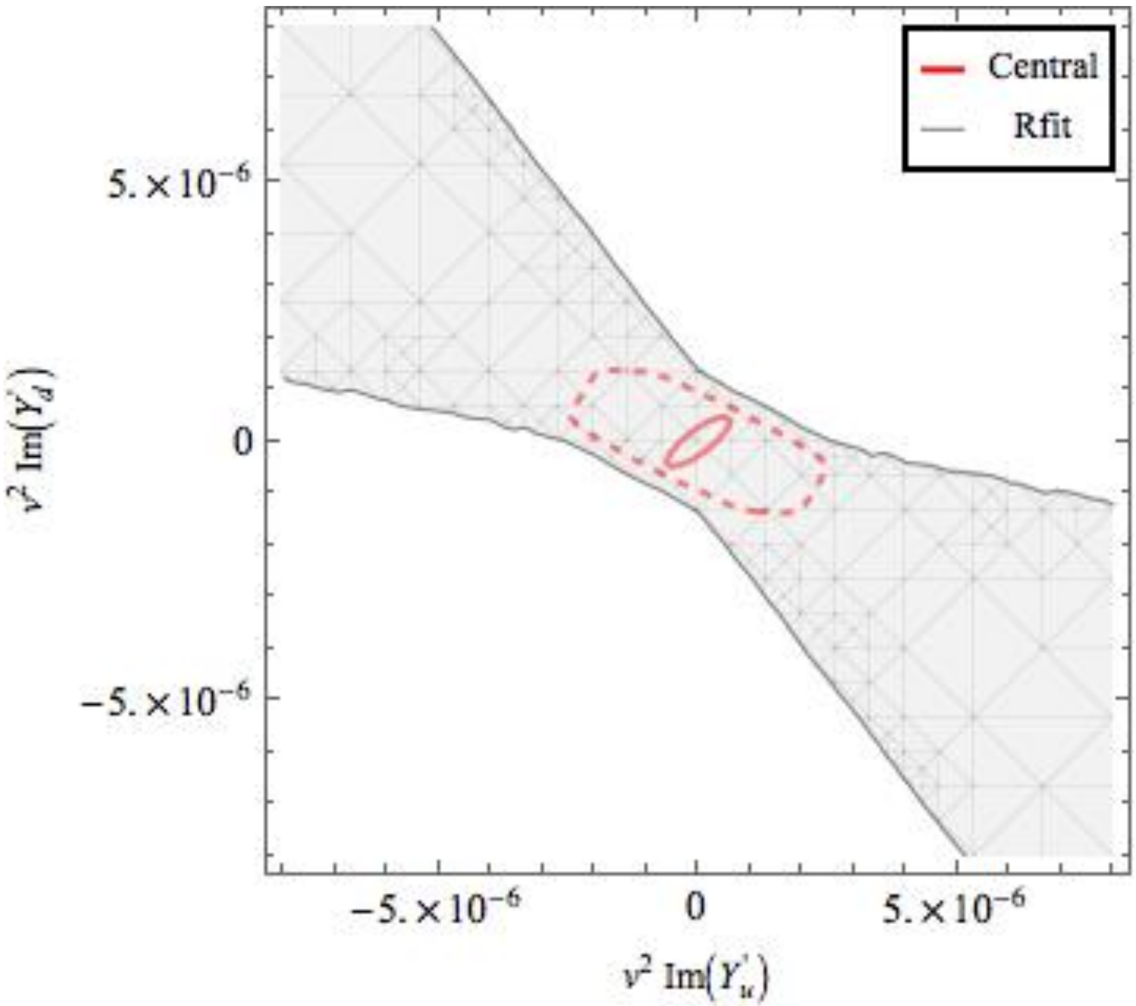
$\bar{g}_{0,1}[\tilde{d}_{u,d}]$ **Hadronic** O(100%) uncertainty

$d_{\mathrm{Hg}}[\bar{g}_{0,1}]$ **Nuclear** O(100%) uncertainty

- As we heard yesterday: André is solving problem 1
- Problem 2 more difficult but nuclear theory is developing rapidly.
- 200 nucleons is a stress though…

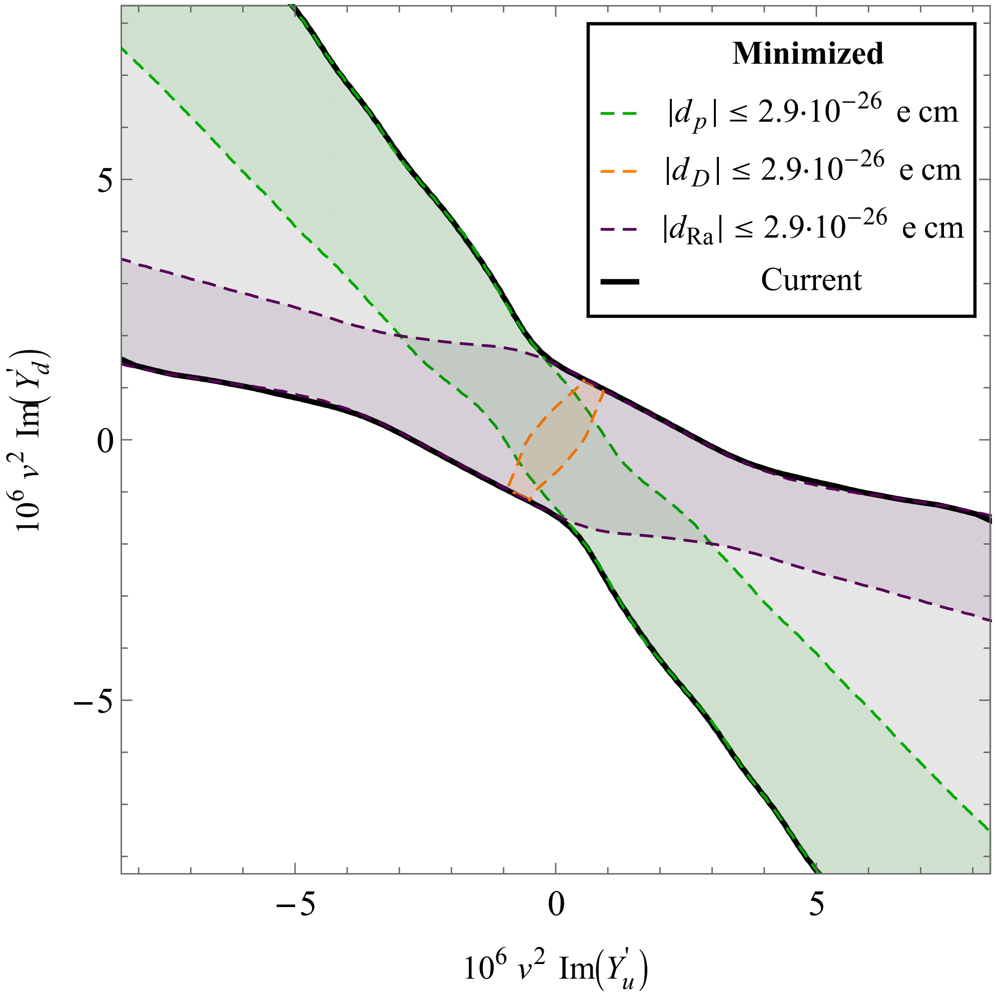
- Say we know these matrix elements with O(50%) uncertainty.

Improved matrix elements



With 50% matrix elements we almost get maximum reach

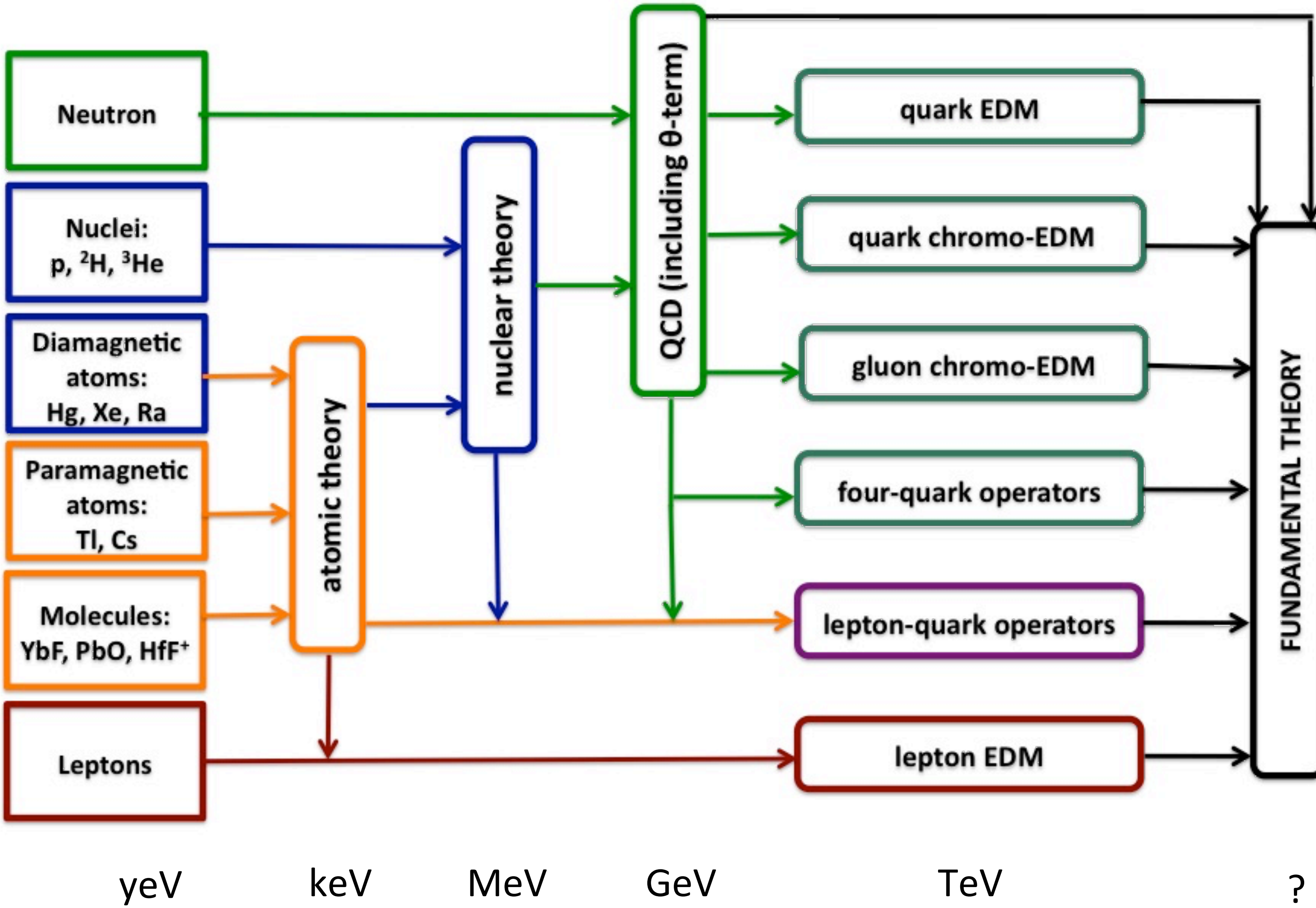
Additional probes



Deuteron is more complementary than proton

Radium very interesting, but uncertainties are larger

The EDM landscape



Conclusion/Summary

- ✓ 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**
- ✓ 50% matrix elements would already help a lot!

Backup

Dipoles combined

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

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

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

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

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

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

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

Bounds and scales

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$(M_{\not T}^2) \theta'\,(M_{\not T})$	$\leq 2.4 \cdot 10^{-3}$	$\leq 1.5 \cdot 10^{-1}$

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

Bounds and scales

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

Dekens, JdV JHEP '13

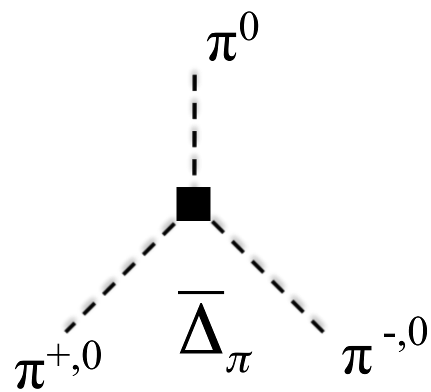
'electroweak suppressed operators'

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
$(M_{\not T}^2)C_{Wu,\,d}\,(M_{\not T})$	$\leq \{1.0,\, 0.84\} \cdot 10^{-2}$	$\leq \{0.53,\, 0.45\}$
$(M_{\not T}^2)C_{Zu,\,d}\,(M_{\not T})$	$\leq \{5.3,\, 2.8\} \cdot 10^{-2}$	$\leq \{2.7,\, 1.4\}$

First 4 operators better bound by eEDM

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