Direct and indirect constraints on CP-violation in the Higgs sector

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Mostly based on: Arxiv:1510:00725

With: V. Cirigliano, Y-T. Chien, W. Dekens, E. Mereghetti
(Los Alamos National Laboratory)

Outline of this talk

- Part I: The search for CP violation with EDMs.

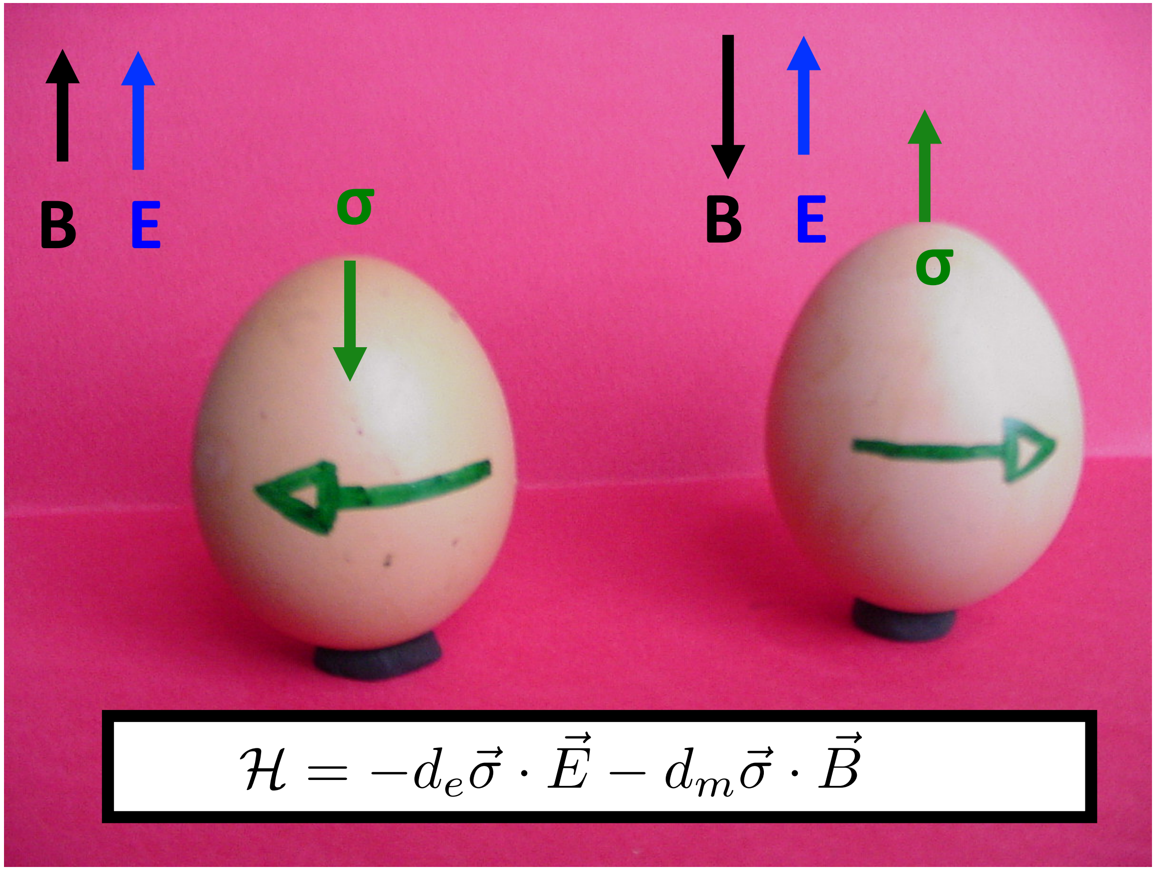
- Part II: The EFT framework and its connection to low energy
  - EDMs of hadrons, nuclei, atoms, and molecules

- Part III: EDM/LHC Constraints on CPV Higgs couplings

EDMs 101

- Electric and Magnetic Dipole Moment (EDM and MDM)

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



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

PhD Thesis Hudson

EDMs 101

- Electric and Magnetic Dipole Moment (EDM and MDM)

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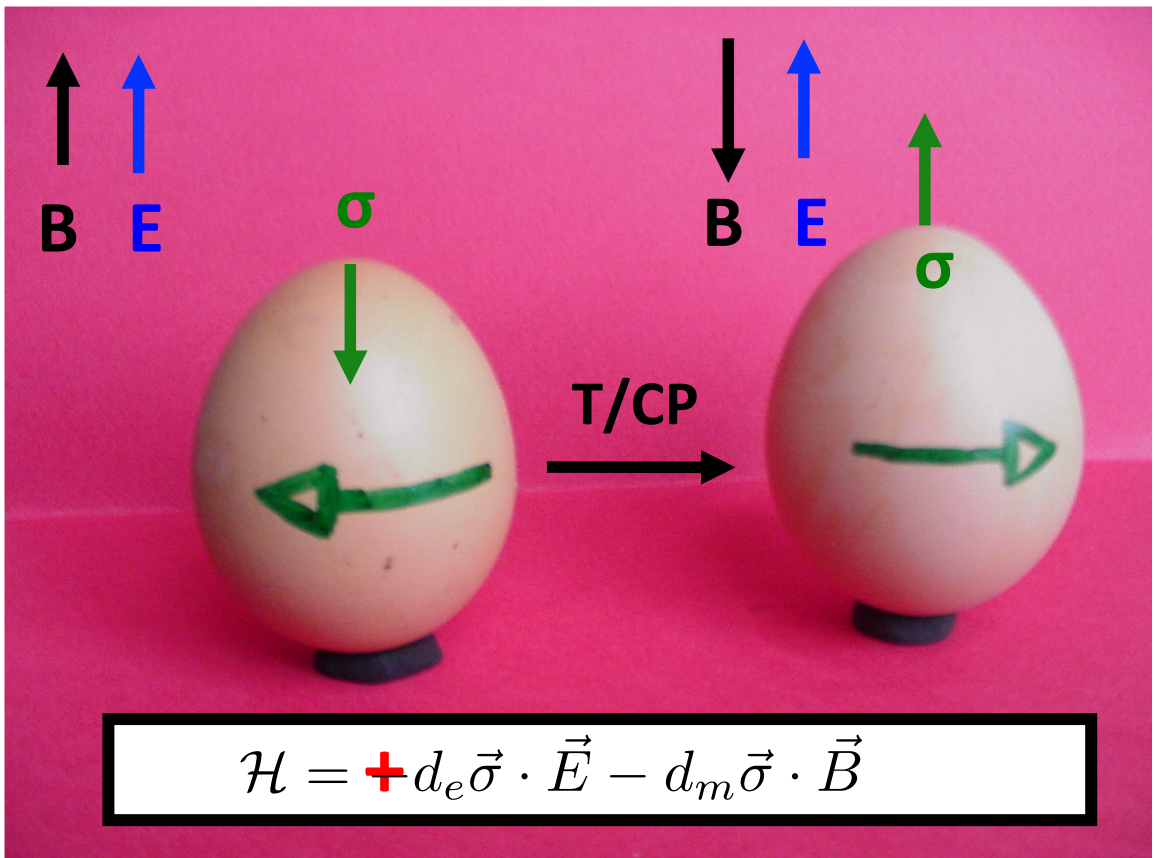
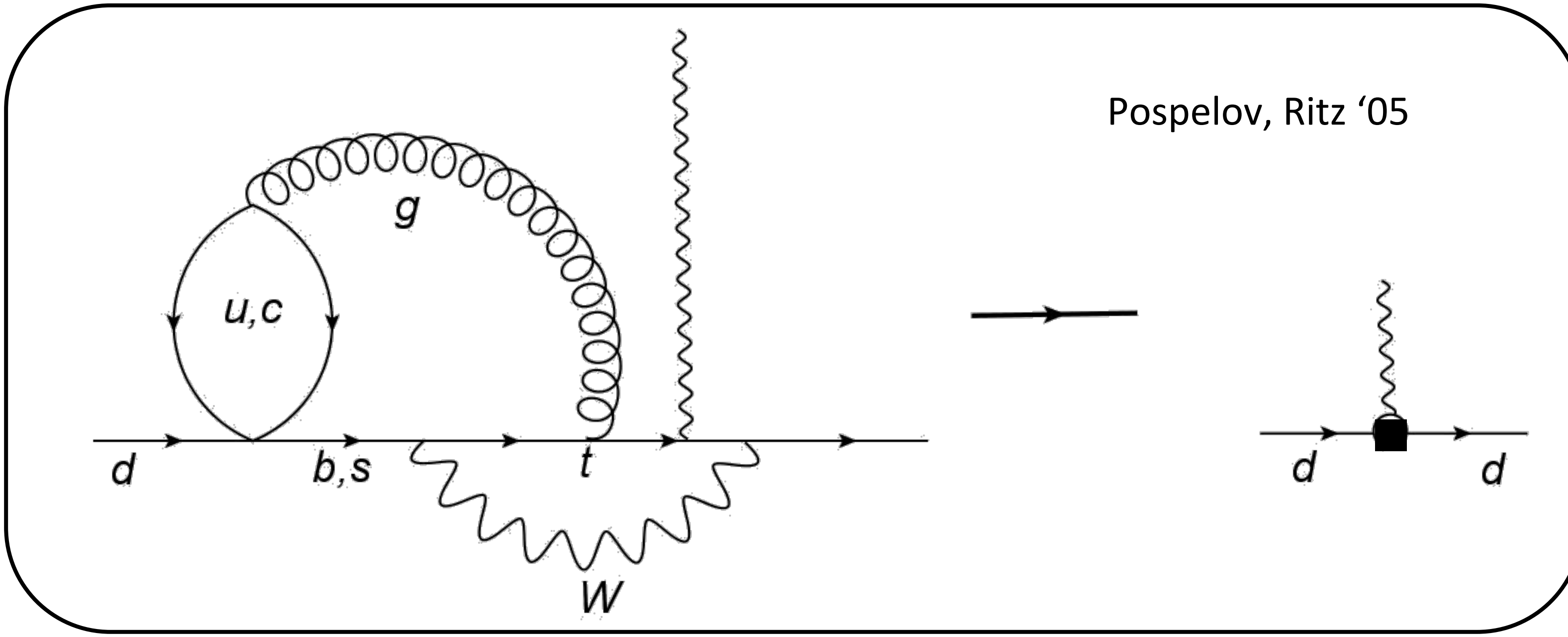


PhD Thesis Hudson

EDMs in the Standard Model

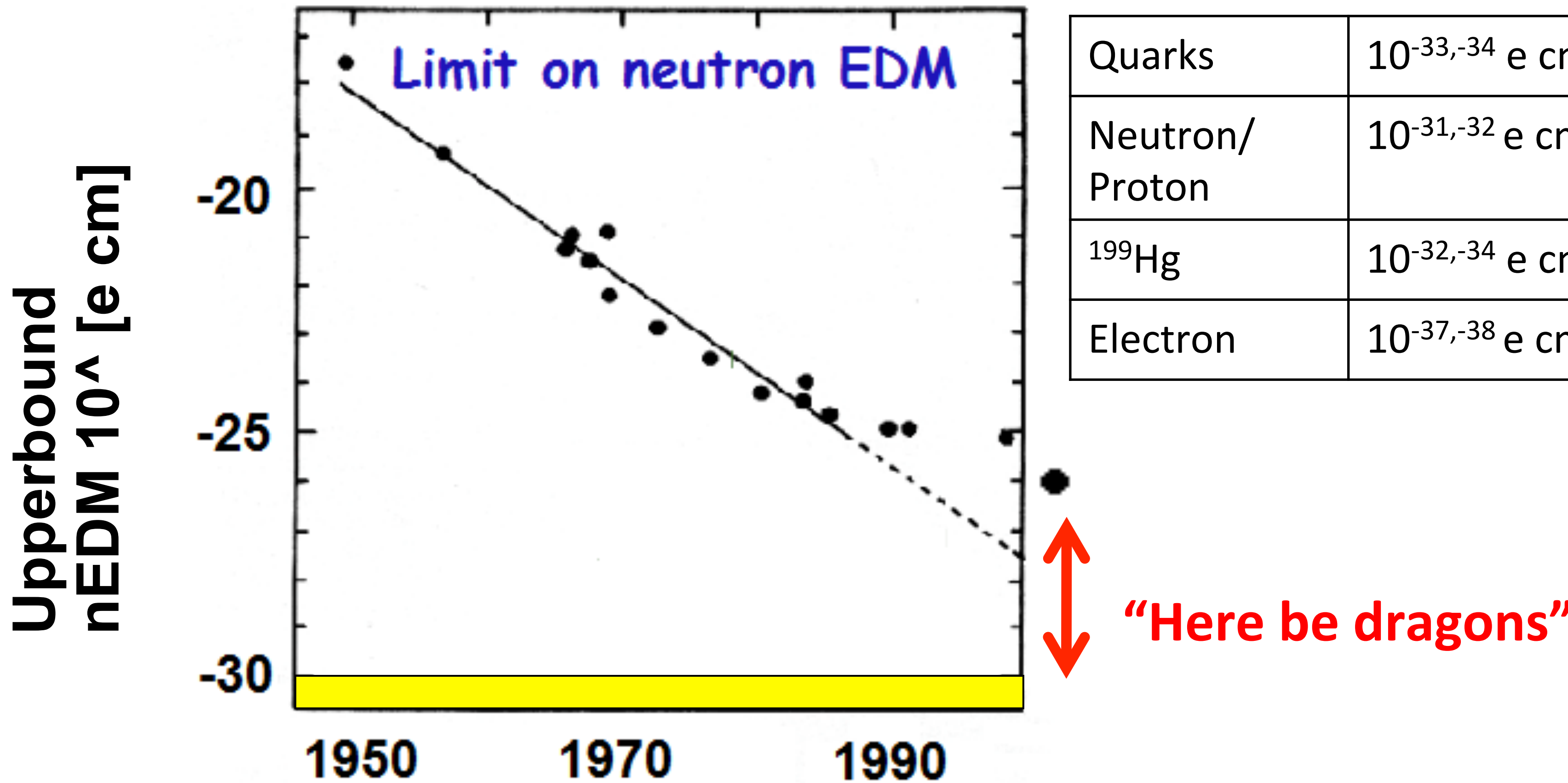
- Electroweak CP-violation very ineffective



- 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

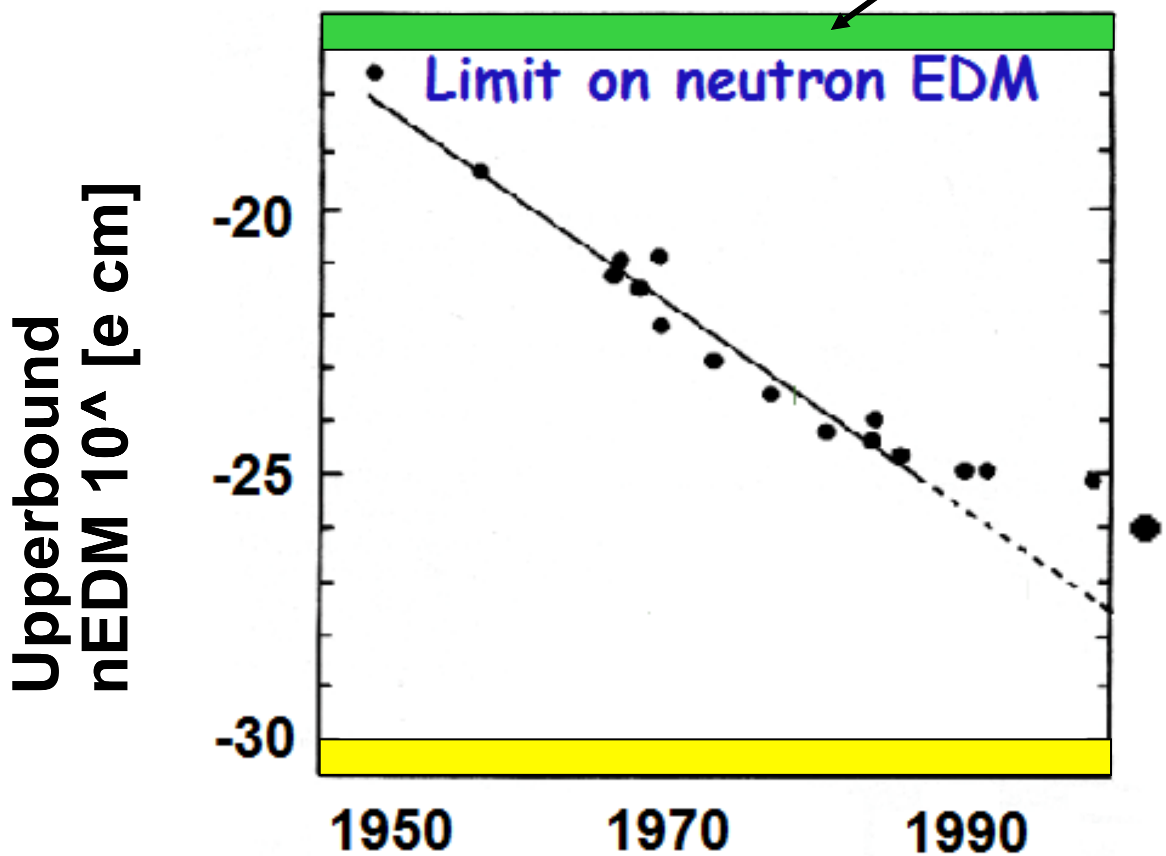
5 to 6 orders **below** upper bound ⟷ **Out of reach!**

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

If θ ~ 1



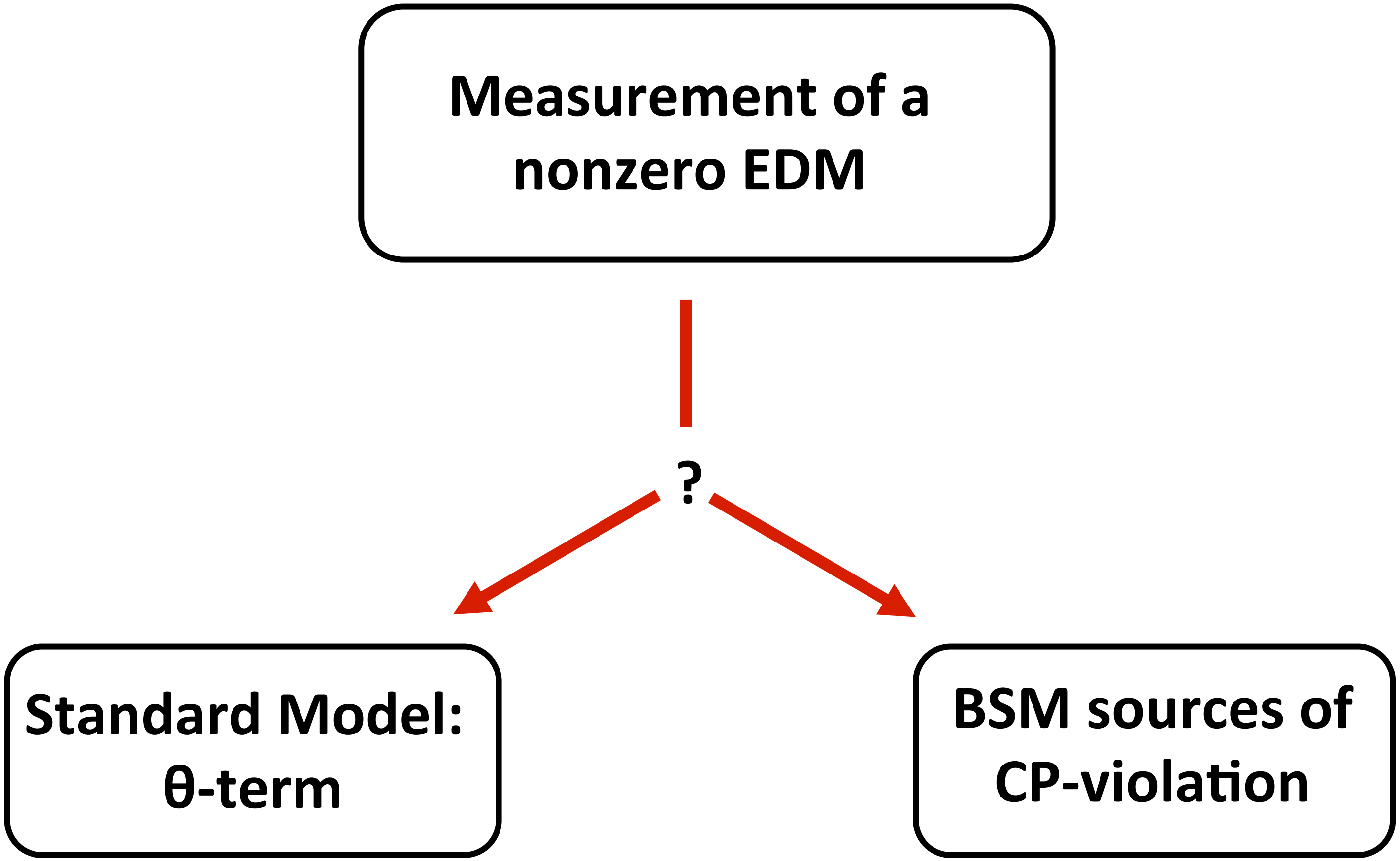
More details on calculation later

'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:



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

Active experimental field

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 (bracket spanning rows ^{205}Tl, YbF, $Eu_{0.5}Ba_{0.5}TiO_3$, PbO, ThO)

$$d_e \leq 10^{-28} e\, cm \simeq 10^{-14}\, e\, \mathrm{GeV}^{-1} \qquad d_e \sim \left(\frac{\alpha_{em}}{\pi}\right)^n \frac{m_e}{\Lambda^2} \sin\phi$$

If phase = O(1): Λ > 10 TeV (n=1), Λ > 0.5 TeV (n=2)

(Model dependent!)

Active experimental field

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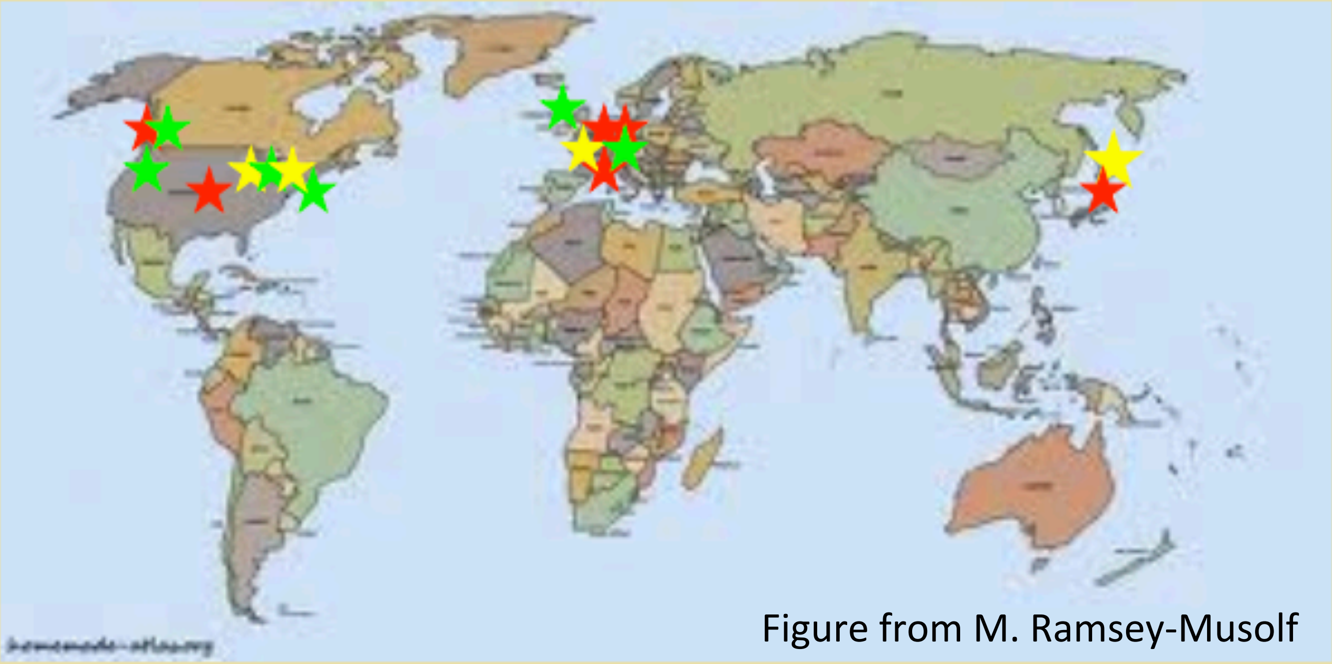

★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

$$d_e \leq 10^{-28} e\, cm \simeq 10^{-14}\, e\, \mathrm{GeV}^{-1} \qquad d_e \sim \left(\frac{\alpha_{em}}{\pi}\right)^n \frac{m_e}{\Lambda^2} \sin\phi$$

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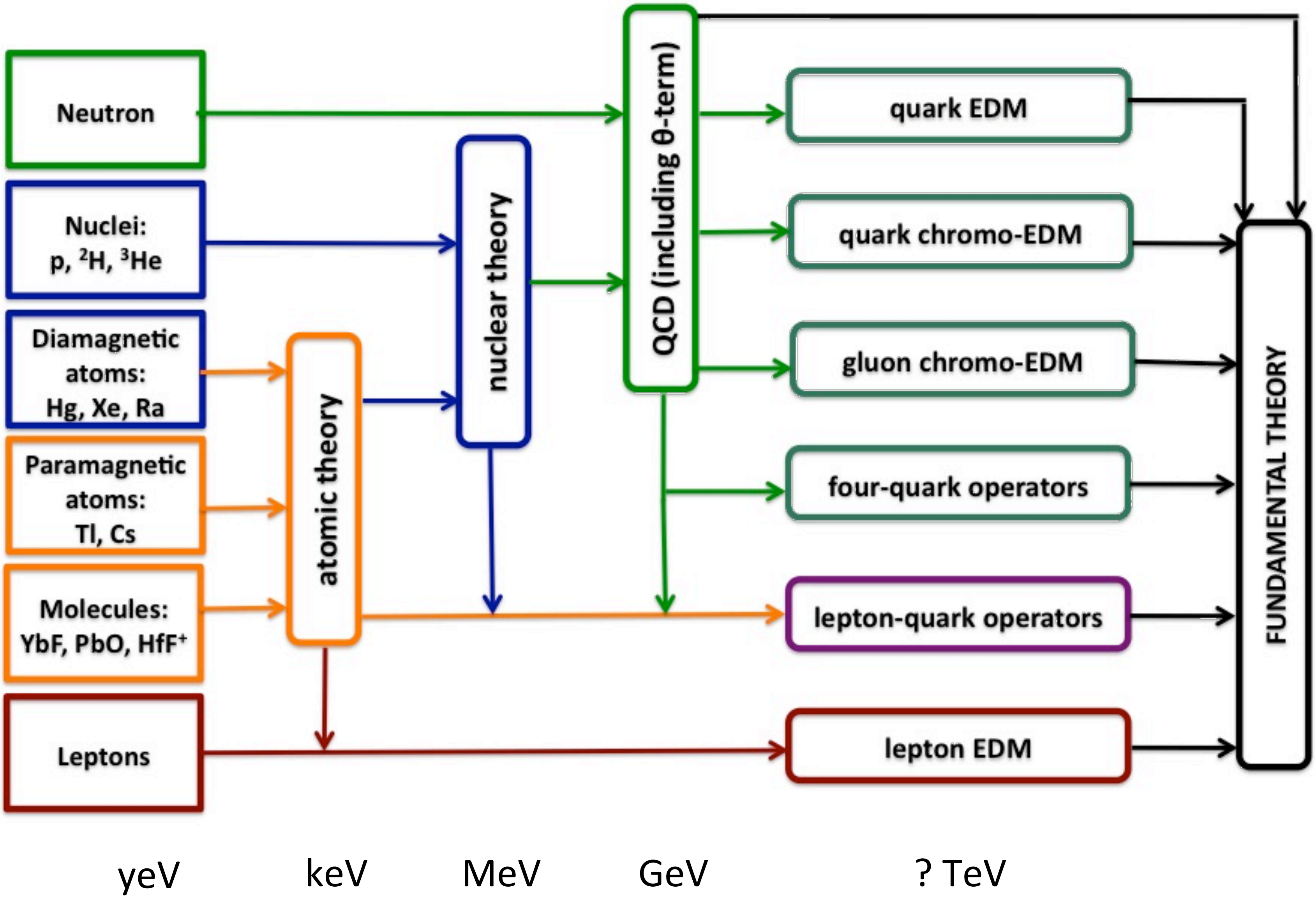
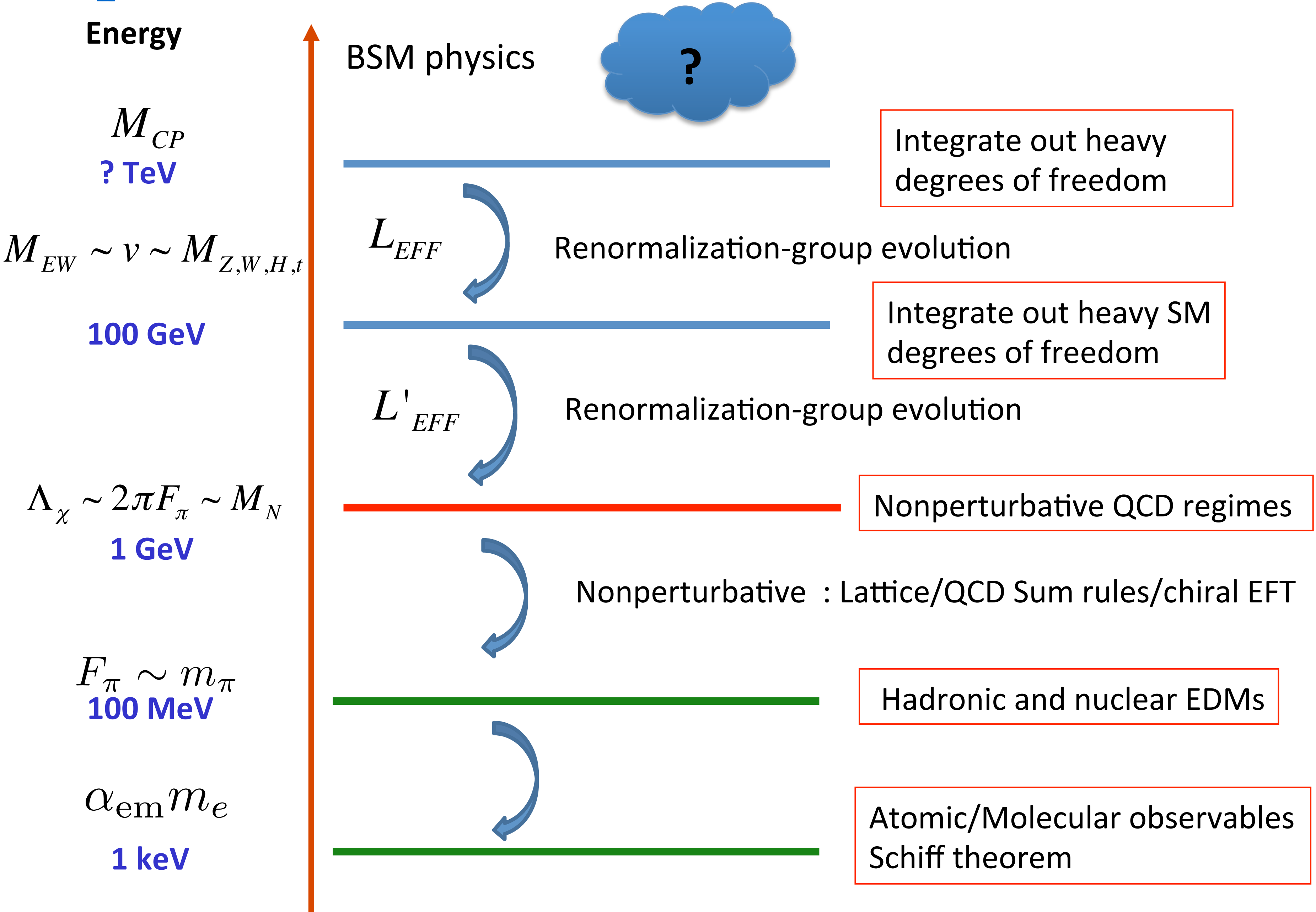
The EDM landscape



Separation of scales



Step 1: SM as an EFT

- Assume any BSM physics lives at scales >> $M_{\rm EW}$
- 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)**

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

dim-5 generates neutrino masses/mixing, neglected here

* **Big assumption**: no new light fields

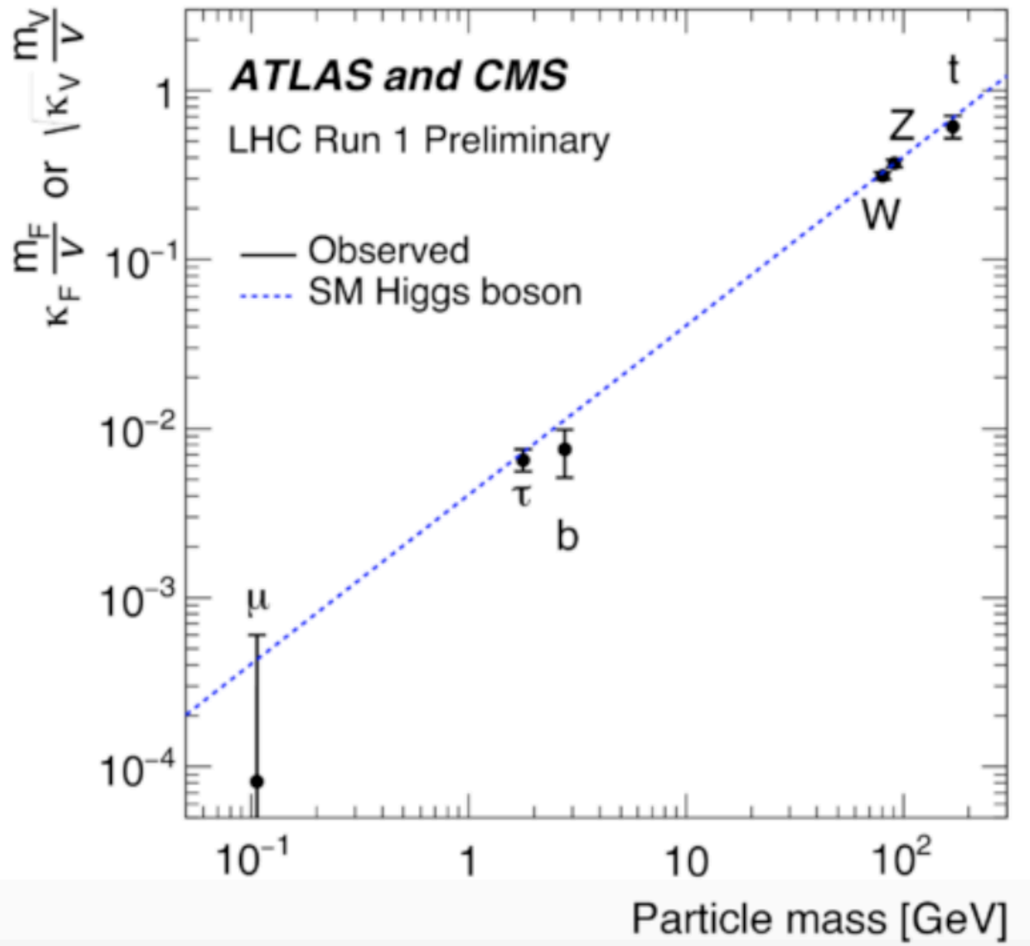
Buchmuller & Wyler '86
Gradzkowski et al '10

One must focus

- Focus on CPV quark-Higgs and gluon-Higgs terms
- Still room for SM deviations

- Typical CP-violation in 2HDMs (and similar models)
- Popular for baryogenesis (e.g. **Im yt > 0.1**)

- **Ilustrates EDM/LHC complementarity + caveats**



Some earlier studies: Kamenik et al '12, Brod et al '13

Flavor-changing Yukawa's:
Harnik et al '12 & Blankenburg et al '12

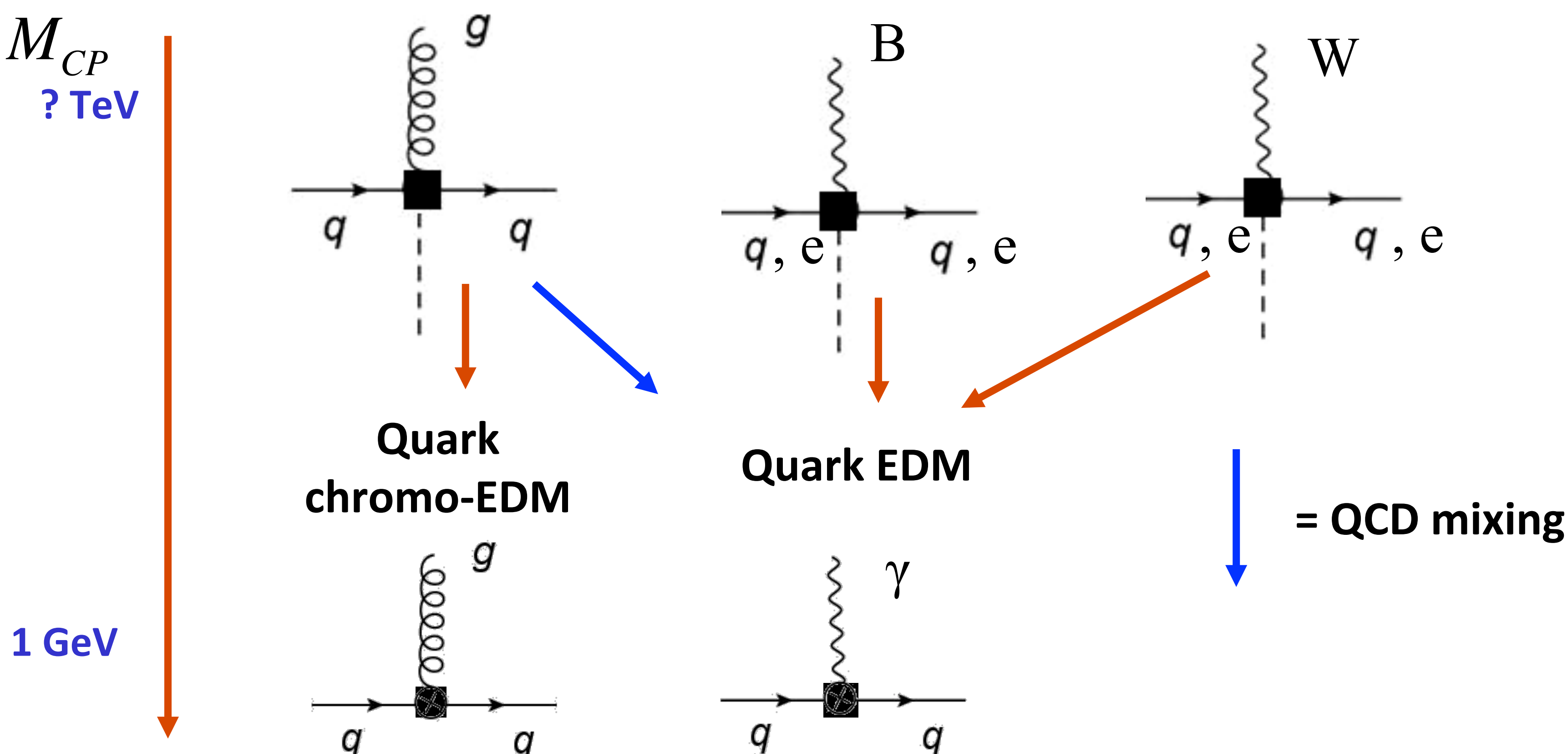
Dipole operators

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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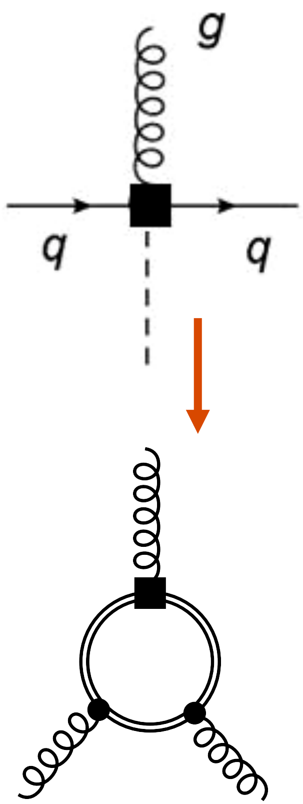
M_{CP}

? TeV



Integrate out heavy quarks

Weinberg operator

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

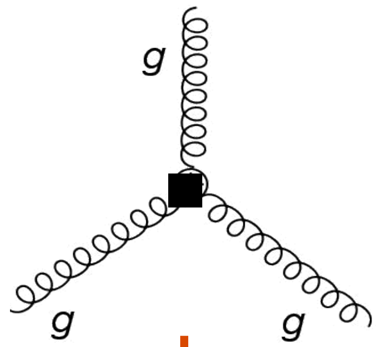
mt, mb

Gluon chromo-EDM

Weinberg operator

Weinberg PRL ’89
Braaten et al PRL ’90

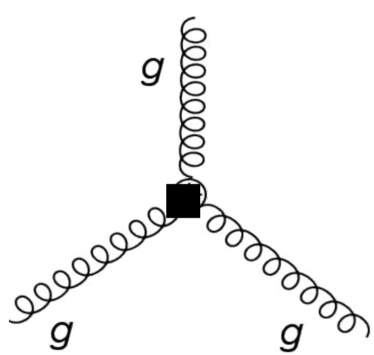
m_t



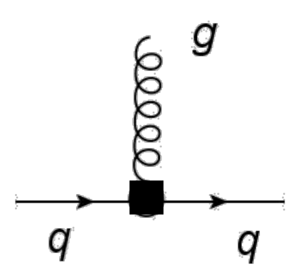
$$d_w \, f^{abc} \varepsilon^{\mu\nu\alpha\beta} \, G^a_{\alpha\beta} G^b_{\mu\lambda} \, G^{c\,\lambda}_{\nu}$$

QCD mixing

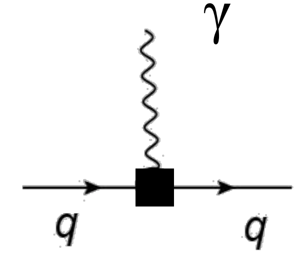
Gluon chromo-EDM



Quark chromo-EDM



Quark EDM



1 GeV

Gluon chromo-EDM

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Gauge-Higgs operators (focus on gluonic term)

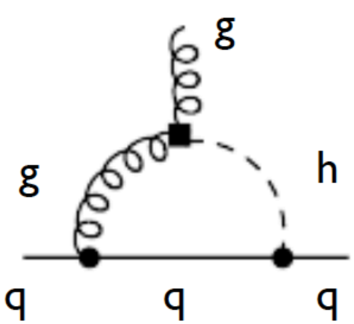
M_{CP}

? TeV

$$\theta' \, G_{\mu\nu}\tilde{G}^{\mu\nu}(\varphi^\dagger\varphi)$$

Absorb v^2 term in SM ***(Strong CP problem)***

$< M_W$



Solution of the RG equations

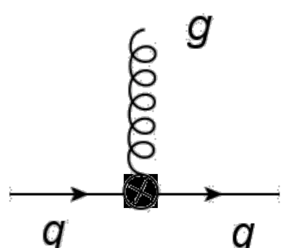
$$\frac{d_q}{m_q}(1\,\mathrm{GeV}) = 1.4 \cdot 10^{-4} Q_q \, \theta'(1\,\mathrm{TeV})$$

$$\frac{\tilde{d}_q}{m_q}(1\,\mathrm{GeV}) = 1.7 \cdot 10^{-4} \, \theta'(1\,\mathrm{TeV})$$

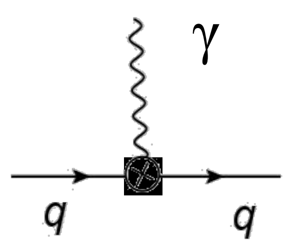
$$d_W(1\,\mathrm{GeV}) = -7.3 \cdot 10^{-6} \, \theta'(1\,\mathrm{TeV})$$

1 GeV

Quark chromo-EDM



Quark EDM



Dim-6 Yukawa interactions

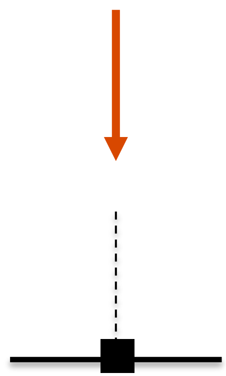
$$\varphi^T = (0 \;\; h+v)/\sqrt{2}$$

$$-\sqrt{2}(\varphi^\dagger\varphi)\,(\bar{q}_L Y'_u u_R \tilde{\varphi} + \bar{q}_L Y'_u d_R \varphi) + \text{h.c.}$$

? TeV

M_{CP}

Absorb (1 + h/v) term in SM mass + Yukawa term



CP-odd Yukawa $\quad v^2 \sum_q \text{Im}\, Y'_q \,\bar{q} i\gamma^5 q\, h + \mathcal{O}(h^2)$

Dim-6 Yukawa interactions

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? TeV

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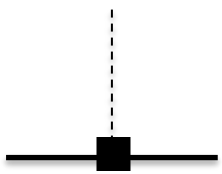
Absorb (1 + h/v) term in SM mass + Yukawa term

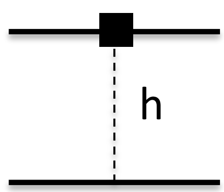


CP-odd Yukawa $\quad v^2 \sum_q \mathrm{Im}\, Y_q' \, \bar{q} i \gamma^5 q \, h + \mathcal{O}(h^2)$

Barr & Zee '90

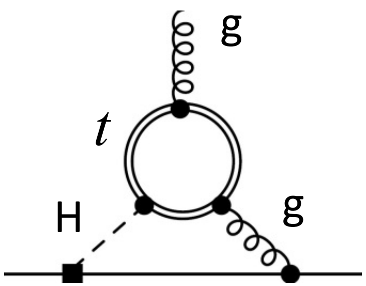
Chang et al '92

Light quarks (u,d,s)



$< M_W$

$<<$



$$C_{FQ} \sim \frac{v^2}{m_h^2} y_q \,\mathrm{Im} Y_q'$$

$$\tilde{C}_q(m_t) \sim \frac{\alpha_s(m_t)}{32\pi^3} \frac{v}{m_q} \mathrm{Im}\, Y_q' \simeq \mathrm{Im}\, Y_q'$$

Dim-6 Yukawa interactions

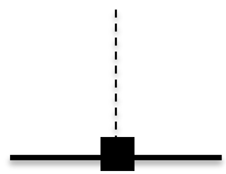
$$\varphi^T = (0 \;\; h+v)/\sqrt{2}$$

$$-\sqrt{2}(\varphi^\dagger\varphi)\left(\bar{q}_L Y_u' u_R \tilde{\varphi} + \bar{q}_L Y_u' d_R \varphi\right) + \text{h.c.}$$

? TeV

M_{CP}

Absorb (1 + h/v) term in SM mass + Yukawa term



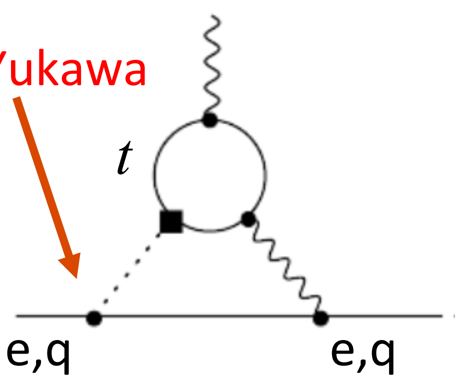
CP-odd Yukawa $\quad v^2 \sum_q \operatorname{Im} Y_q' \, \bar{q} i \gamma^5 q \, h + \mathcal{O}(h^2)$

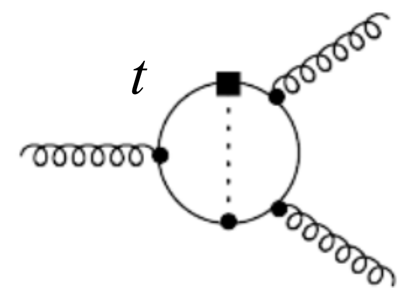
Heavy quarks (t,b,c)

Zupan et al '13

$< M_W$

SM Yukawa





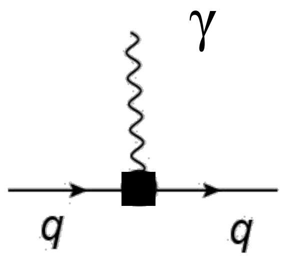
Electron EDM and quark (C)EDMs.

Weinberg operator

When the dust settles….

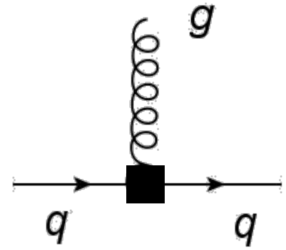
Hadronic interactions

QCD (θ-term) +



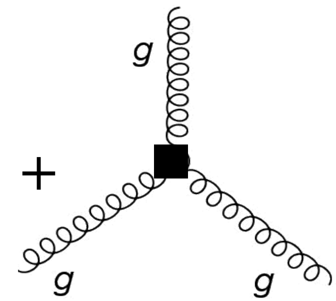
Quark EDM

+



Quark chromo-EDM

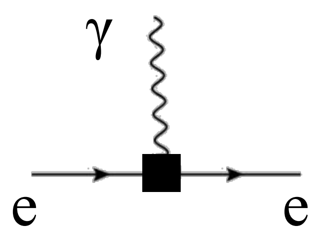
+



Gluon chromo-EDM

~ 1 GeV

leptonic interactions

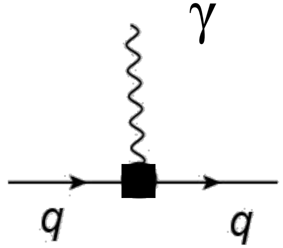


Electron EDM

Crossing the barrier

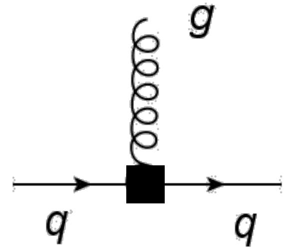
Few GeV

QCD
(θ-term) +



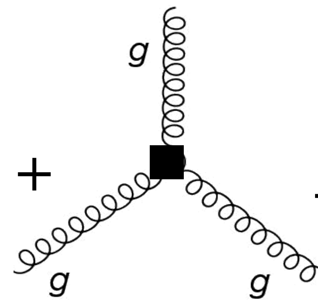
Quark EDM

+



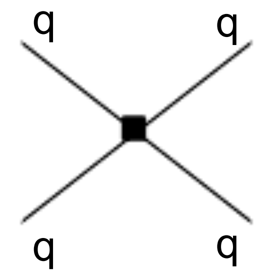
Quark
chromo-EDM

+



Gluon
chromo-EDM

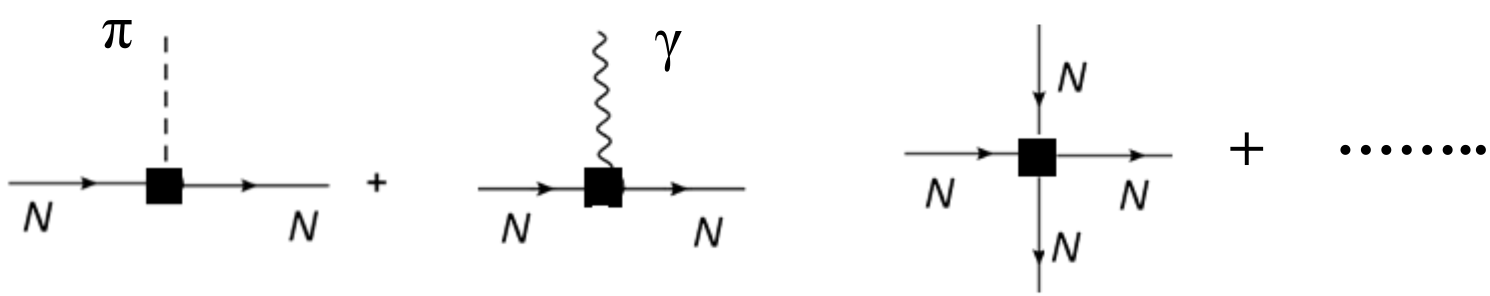
+



4quark
operators

Hadronic/Nuclear/Atomic 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

The strong CP problem

$$\mathcal{L} = -e^{i\rho}\bar{q}_L M q_R - \theta\frac{\alpha_s}{16\pi}G\tilde{G} + \text{h.c.}$$

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

$$\bar{\theta} = \theta + 2\rho$$

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

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

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

The strong CP problem

JÜLICH FORSCHUNGSZENTRUM

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Crewther et al' 79

Baluni '79

$$\bar{\theta} = \theta + 2\rho$$

Linked via $SU_A(2)$ rotation

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

Isospin breaking related to strong CP violation

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

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

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

The strong CP problem

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

Explicit ChPT construction shows a relation between:

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

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

The strong CP problem

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

Explicit ChPT construction shows a relation between:

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

Nucleon mass splitting (strong part, no QED part!) ⟷ **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

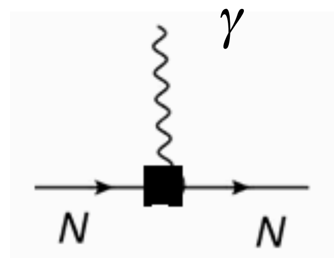
  Walker-Loud '14, Borsanyi '14, Aoki (FLAG) '13,

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

  JdV, Mereghetti, Walker-Loud '15

The strong CP problem

Nucleon EDM



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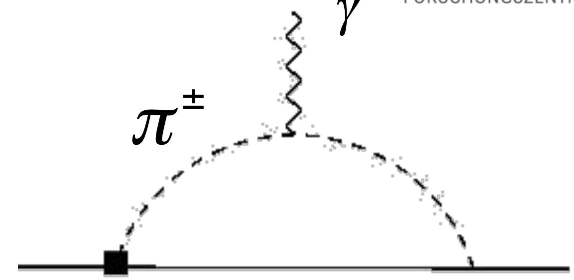

CP-even pion-nucleon coupling

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

- Loop is divergent…. Need a counter-term
- Loop is **enhanced** by chiral logarithm (long-rang physics)

$$\bar{g}_0 \;= -(15.5 \pm 2.5)\cdot 10^{-3}\,\bar{\theta} \quad \longrightarrow \quad d_n \simeq -2.5\cdot 10^{-16}\,\bar{\theta}\, e\,\mathrm{cm}$$

- Experimental constraint: $\longrightarrow$ $\bar{\theta} < 10^{-10}$

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

The strong CP problem

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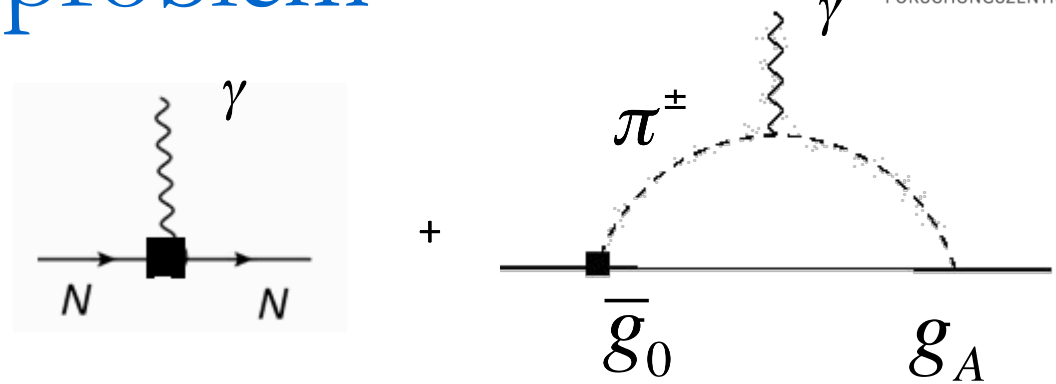
Nucleon EDM



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- Experimental constraint: $\longrightarrow$ $\bar{\theta} < 10^{-10}$

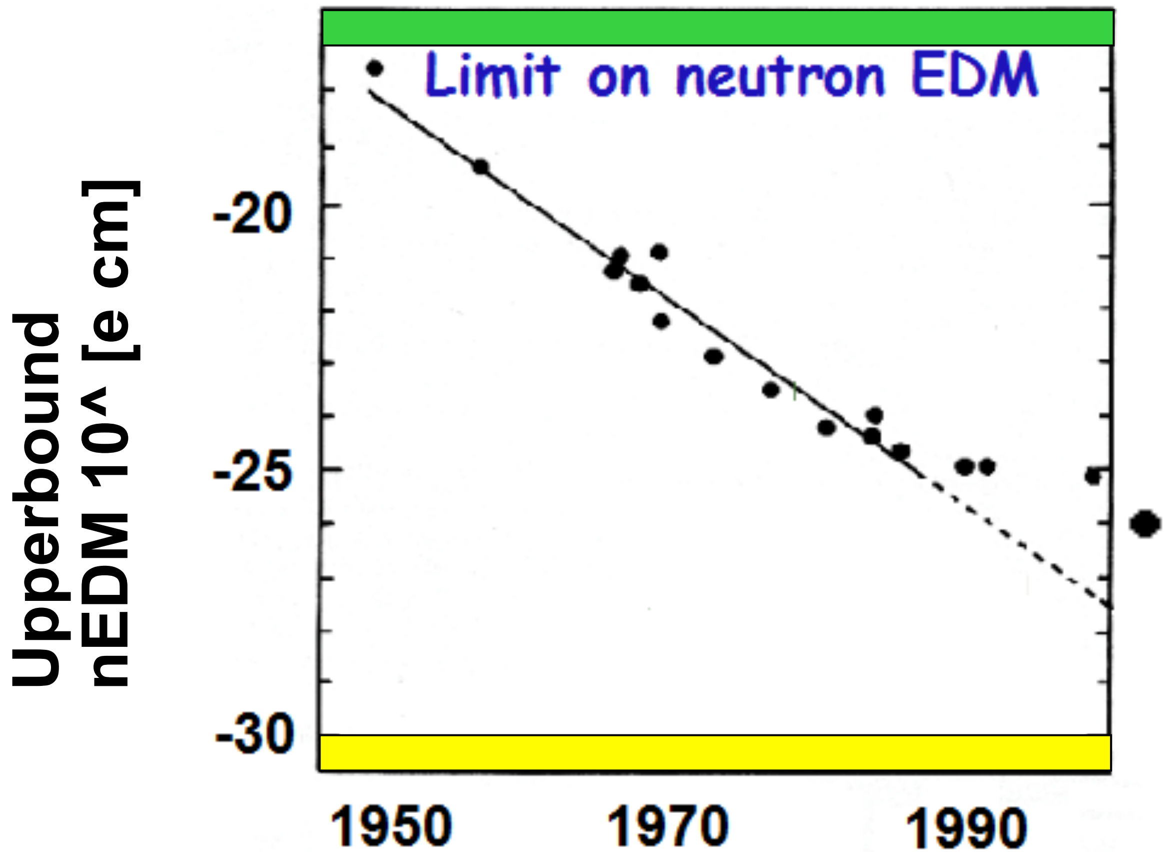
- Lattice + ChPT

$$d_n = -(2.7 \pm 1.2)\cdot 10^{-16}\,\bar{\theta}\,e$$ Shintani et al '12

$$d_n = -(3.9 \pm 1.0)\cdot 10^{-16}\,\bar{\theta}\,e$$ Guo et al '15

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

Strong CP problem



- Set one quark mass to zero. Disfavored by lattice QCD.
- Assume P or CP exact at high energies (e.g. left-right models)
- **Peccei-Quinn mechanism -> axions (we assumed this)**

Left with the dim6 sources

❖ Quark EDM accurately determined recently !

T. Bhattacharya et al '15

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

- ChPT extrapolation to **physical pion mass**

Left with the dim6 sources

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T. Bhattacharya et al ‘15

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

  - ChPT extrapolation to **physical pion mass**

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

ChiPT/QCD sum rules: pion-nucleon couplings and nucleon EDMs
50-75% uncertainty

Pospelov, Ritz ‘02 ’05
JdV et al ‘10 ‘13
Hisano et al ’ 12 ‘13

- Weinberg **estimate for nEDM**

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

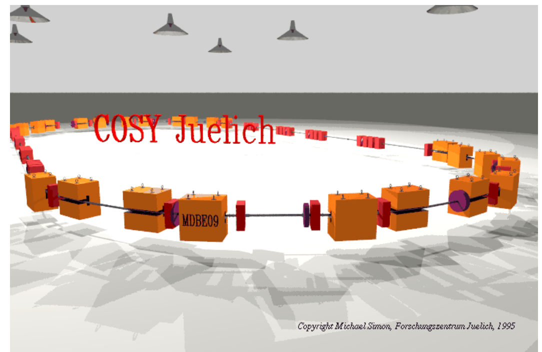
Demir et al ’03

pion-nucleon couplings **suppressed** (chiral symmetry)

Storage rings experiments

Farley *et al PRL* '04

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



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

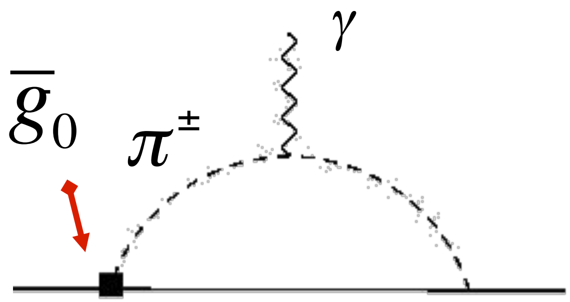
- Limit on muon EDM $d_\mu \leq 1.8 \cdot 10^{-19}\ e\ cm \quad (95\%\ \ C.L.)$

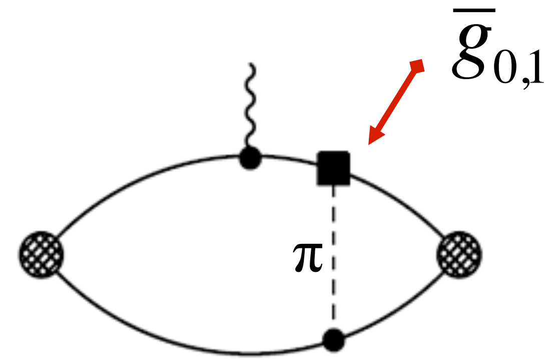
COSY @ Jülich
Brookhaven/Fermilab

- **Proposals to measure EDMs of proton, deuteron, 3He at level** $\sim 10^{-29}\ e\ cm$

- Other light nuclei?

Why light nuclei?





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

$$d_A = \langle \Psi_A \| \vec{J}_{\not{CP}} \| \Psi_A \rangle + 2 \langle \Psi_A \| \vec{J}_{CP} \| \tilde{\Psi}_A \rangle$$

$$(E - H_{PT}) | \Psi_A \rangle = 0 \qquad (E - H_{PT}) | \tilde{\Psi}_A \rangle = V_{\not{CP}} | \Psi_A \rangle$$

Input

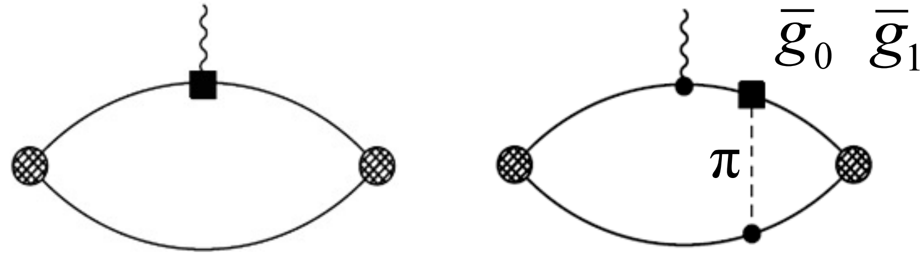
1. CP-even and -odd potential from **chiral EFT**
2. Solve Schrodinger equations numerically

Epelbaum et al '05
Maekawa et al '11

Example: deuteron EDM

Target of storage ring measurement

- Two contributions (NLO)
  1. Sum of nucleon EDMs
  2. CP-odd pion exchange



Errors from Bsaisou et al JHEP `14

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

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

Strong isospin filter

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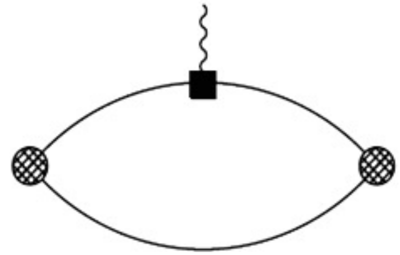

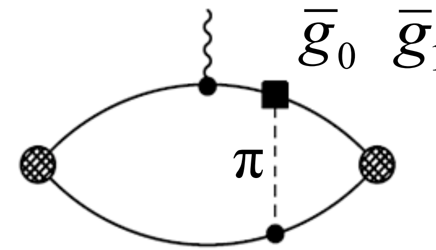

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Strong isospin filter

- Tree-level pion exchange can dominate the nuclear EDM
- dD ~ |6 dn| for qCEDMs, dD~dn+dp for qEDM/Weinberg
- Differentiate between various BSM models (2HDM, MLRSM)

JdV, Bernreuther et al '14

Diamagnetic EDMs

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

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

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

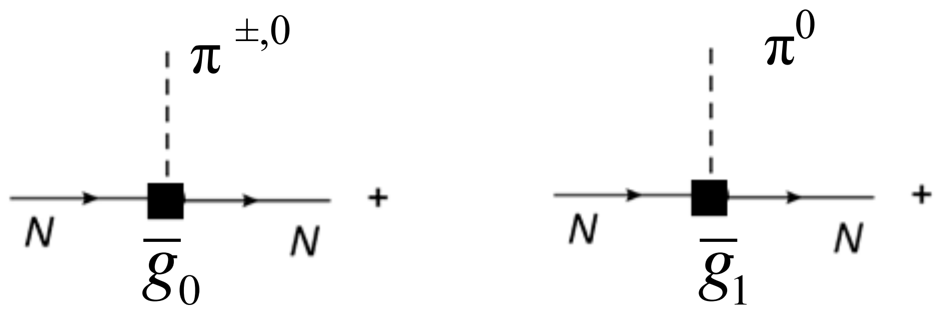
$$d_{^{225}Ra} = (7.2 \pm 1.5) \cdot 10^{-4}\ S_{Ra}\ e\ fm^2$$

Dzuba et al, '02, '09

Sing et al, '15

Calculating Schiff Moments

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



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

- **Typically only one-pion exchange** (sometimes nucleon EDMs)
- **Very complicated** many-body calculation

Dmitriev, Sen'kov '03

- Use nuclear model and mean-field theory

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

- **Large** uncertainties. Even unknown sign !

Probing the electron EDM

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

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

Strong enhancement!

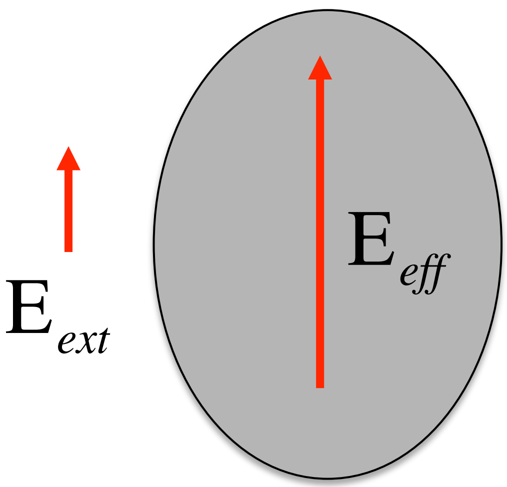
$$K_{Tl} = -(570 \pm 20) \longrightarrow d_e < 1.6 \cdot 10^{-27}\ e\ cm$$

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

Polar molecules

Polar molecules: Convert small external to huge internal field

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



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

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

Meyer, Bohn '08, Skipnikov et al '13, Fleig, Nayak '14,

The most recent constraint is then: $d_e < 8.7 \cdot 10^{-29}\ e\ cm$

One order improvement expected next 5 years...

Baron et al '13

Strategy for setting limits

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Study impact of uncertainties in the hadronic/nuclear EDMs

1. **Central:** use central value matrix elements (most common method)

2. **RFit** ("Range-Fit"): vary matrix elements in their allowed ranges; minimized chi-squared (=most conservative bounds)

Strategy copied from CKMfitter group '04

Chien, Cirigliano, Dekens, JdV, Mereghetti, '15

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3. **RFit+:** Rfit with improved theory (50% uncertainties everywhere)

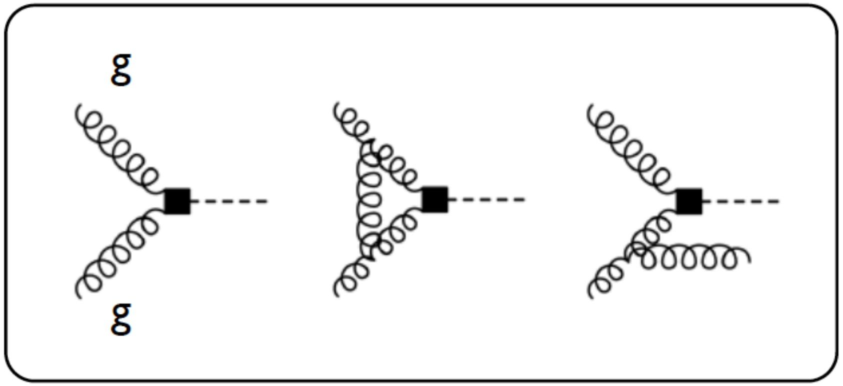
Realistic (but challenging) target for Lattice-QCD + nuclear structure

- **Dedicated Amherst workshop, January '15 → road map**
  "Hadronic Matrix Elements for Probes for CP-violation"

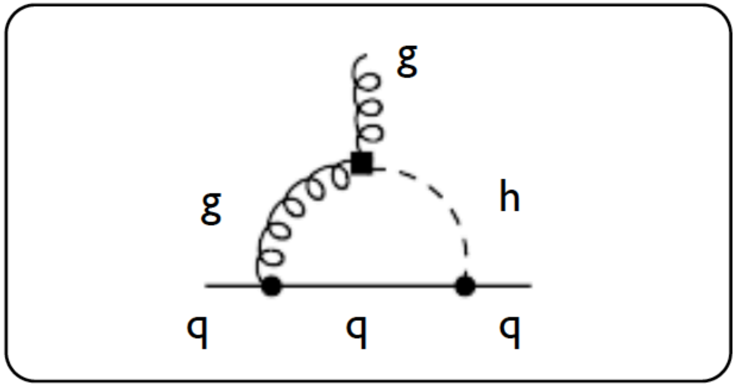
Chien, Cirigliano, Dekens, JdV, Mereghetti, '15

Anomalous gluon-higgs coupling

LHC: Higgs production via gluon fusion



Low Energy: quark (C)EDM + Weinberg



$$\mu = \frac{\sigma_{\rm GGF}^{SM} + \sigma_{\rm GGF}^{\theta'}}{\sigma_{\rm GGF}^{SM}}$$

$$= 1 + (2.28 \pm 0.1)(v^2\theta')^2$$

- Cross section known to N2LO
- Error from scale variation + PDFs

Harlander, Kilgore '02, '03
Anastasiou, Melnikov '02 '03

$$\frac{d_q}{m_q}(1\,\mathrm{GeV}) = 1.4 \cdot 10^{-4} Q_q\,\theta'(1\,\mathrm{TeV})$$

$$\frac{\tilde{d}_q}{m_q}(1\,\mathrm{GeV}) = 1.7 \cdot 10^{-4}\,\theta'(1\,\mathrm{TeV})$$

$$d_W(1\,\mathrm{GeV}) = -7.3 \cdot 10^{-6}\,\theta'(1\,\mathrm{TeV})$$

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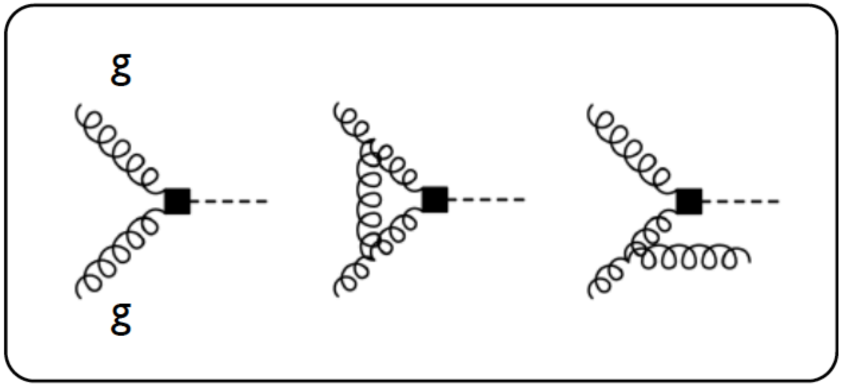

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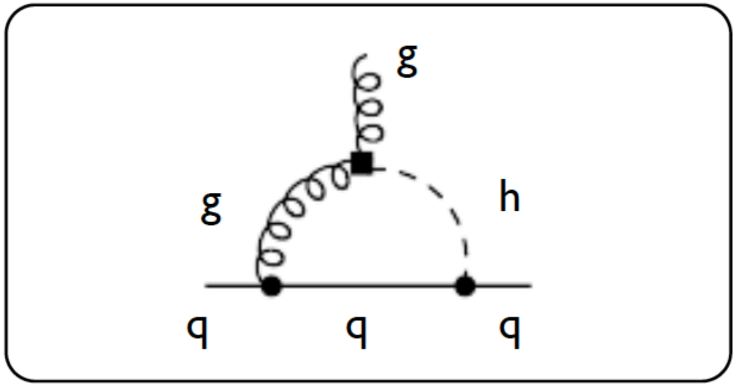


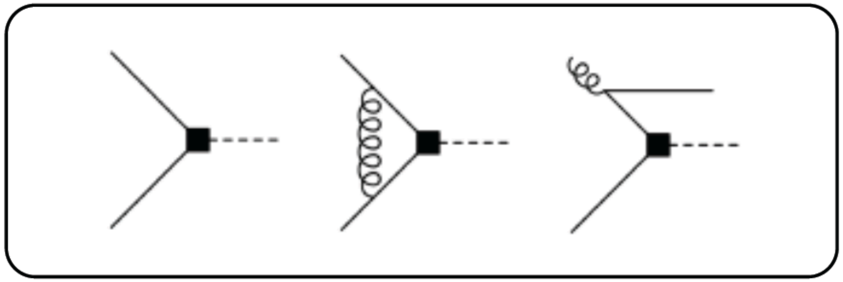
Current experiments

$v^2\theta'$	d_n	d_{Hg}	d_n, d_{Hg} (comb)	LHC (CMS)
Central	0.06	0.04	0.04	0.27
RFit	0.23	x	0.23	0.27
RFit+			0.05	0.27

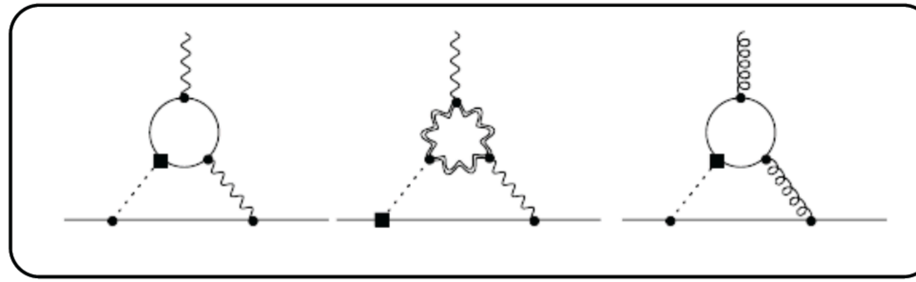
Bounds on couplings at the scale $\mu = M_{BSM} = 1\,\text{TeV}$

Yukawa's u, d, s, c, b

LHC: Higgs production



Low Energy: quark (C)EDM, Weinberg, *and* d_e

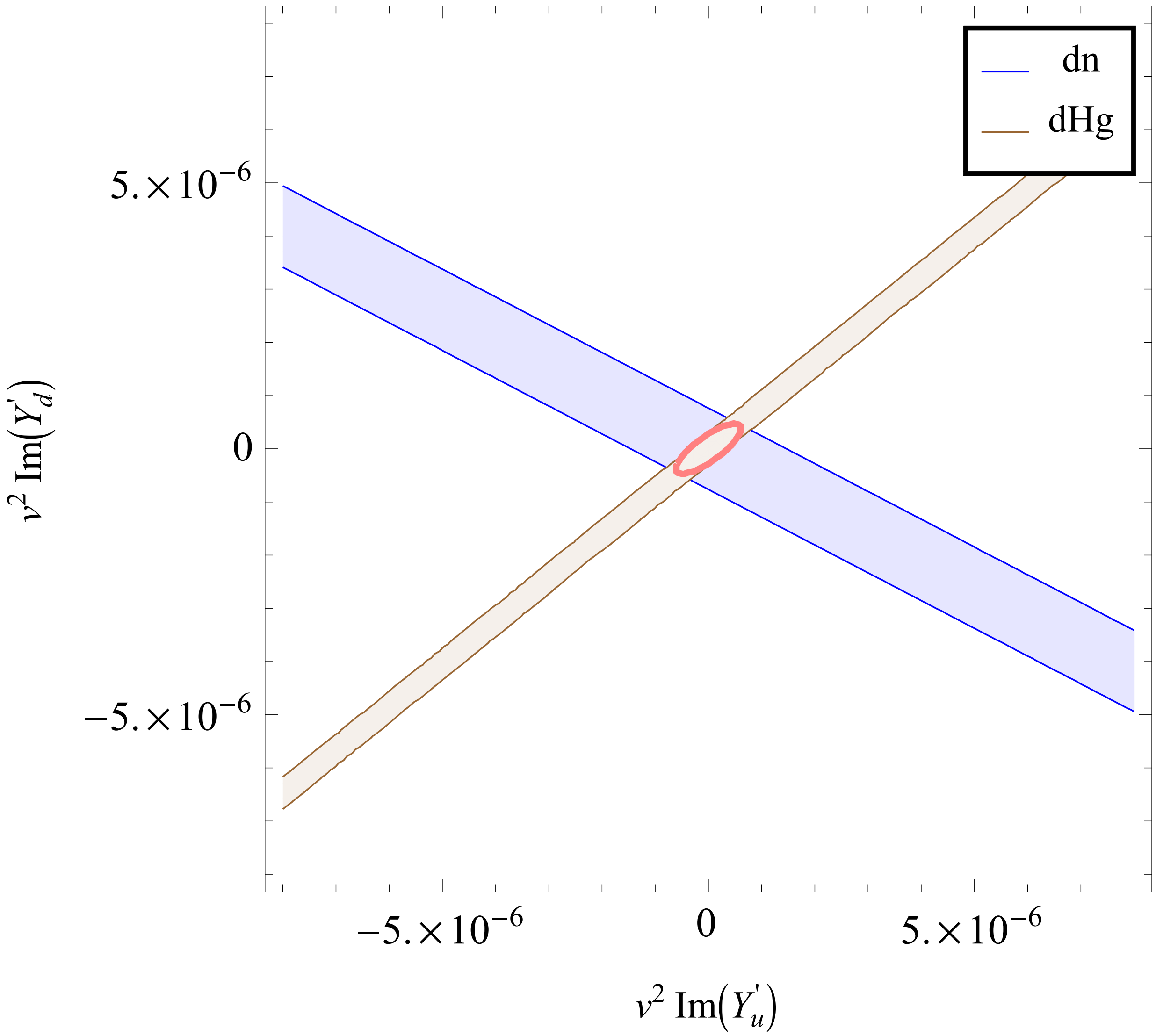


	$v^2 \mathrm{Im}\, Y'_u$	$v^2 \mathrm{Im}\, Y'_d$	$v^2 \mathrm{Im}\, Y'_s$	$v^2 \mathrm{Im}\, Y'_c$	$v^2 \mathrm{Im}\, Y'_b$
Central	$3.9 \cdot 10^{-7}$	$3.0 \cdot 10^{-7}$	$4.3 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	$8.4 \cdot 10^{-3}$
Rfit	$2.8 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$	0.42	$6.5 \cdot 10^{-3}$	0.041
LHC	$6.0 \cdot 10^{-3}$	$7.0 \cdot 10^{-3}$	0.020	0.016	0.036

- u- and d-quark out of reach, but for s, c, b LHC is better or comparable
- With improved theory EDMs could beat LHC Higgs production

- **CAVEAT: Only bounds from Higgs production.**
- Should study: Higgs decays and CP-odd correlations

Constraining CPV Yukawa's



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

Constraining CPV Yukawa's

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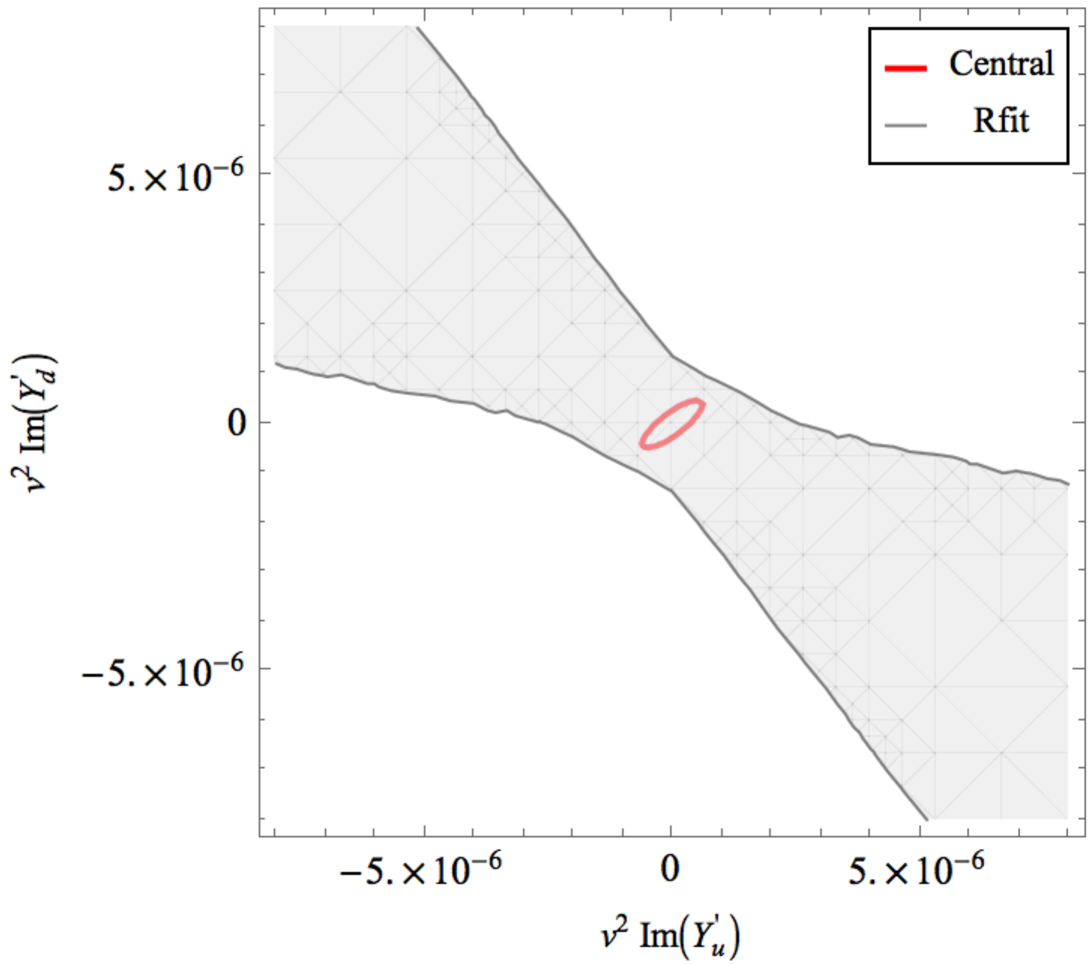
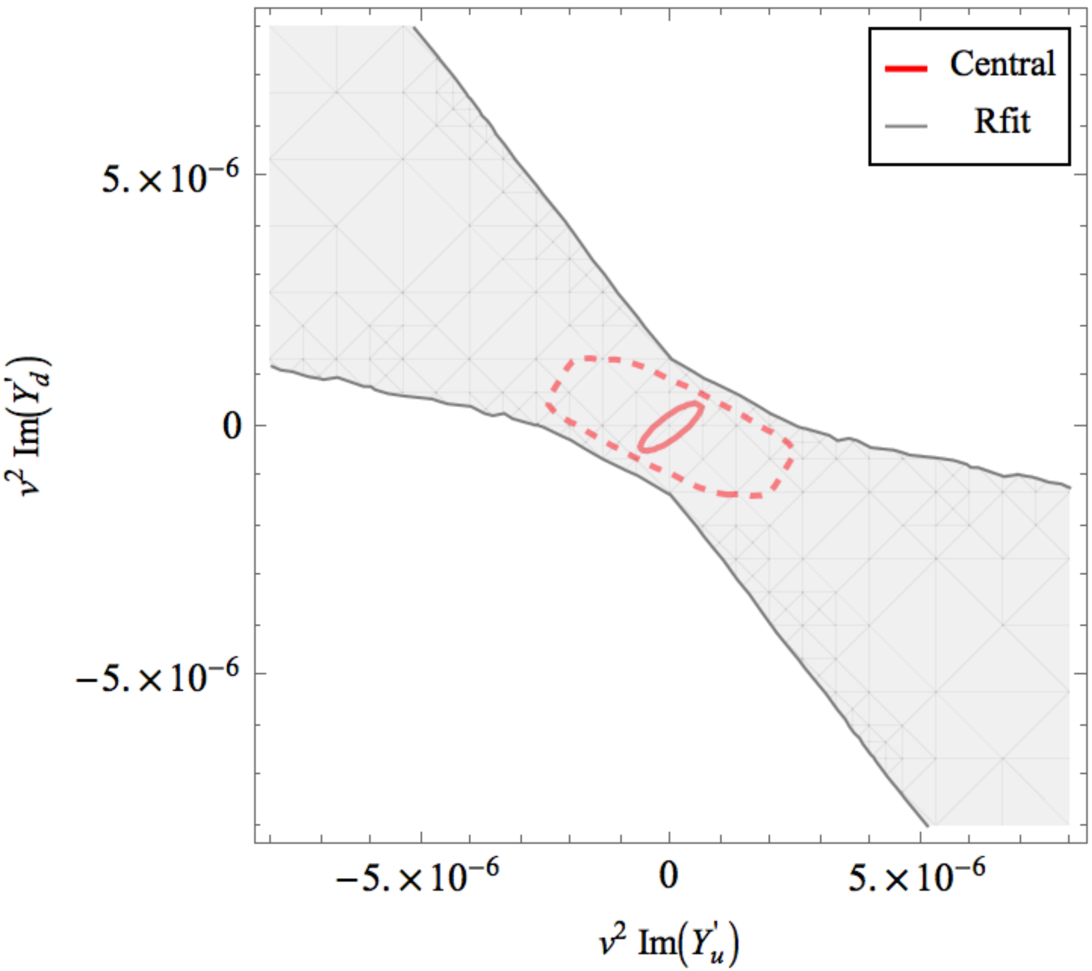


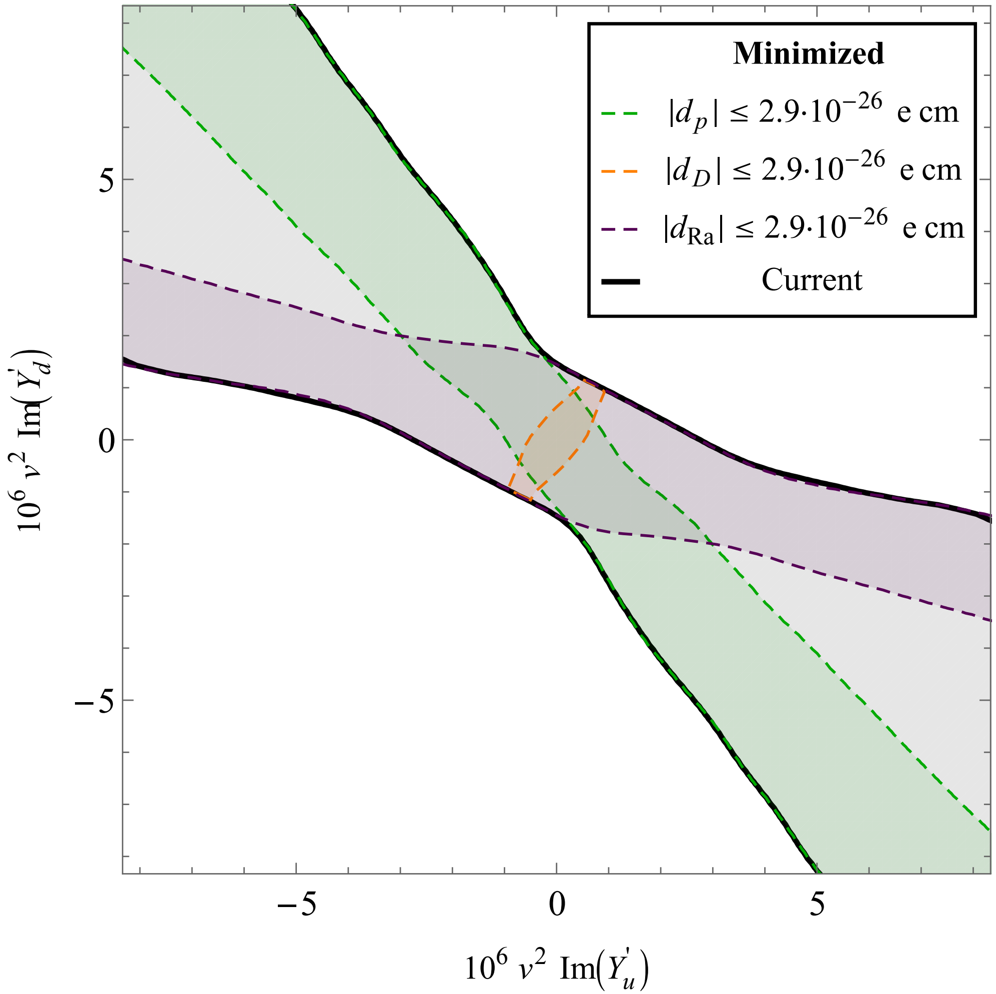
Due to nuclear/hadronic uncertainties **a free direction** emerges

Improved matrix elements



50% matrix elements: almost maximum reach

Additional probes

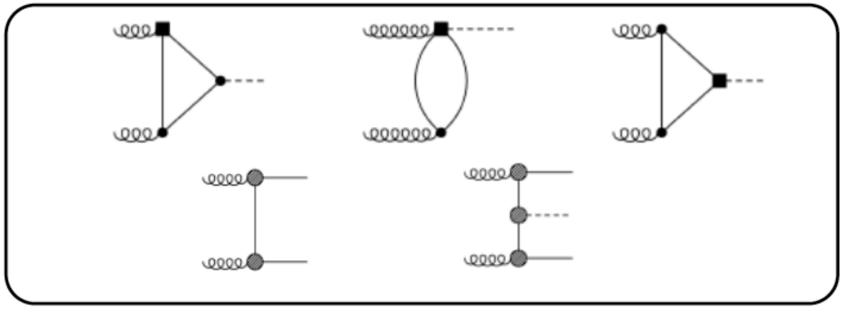


Deuteron EDM **very** complementary !

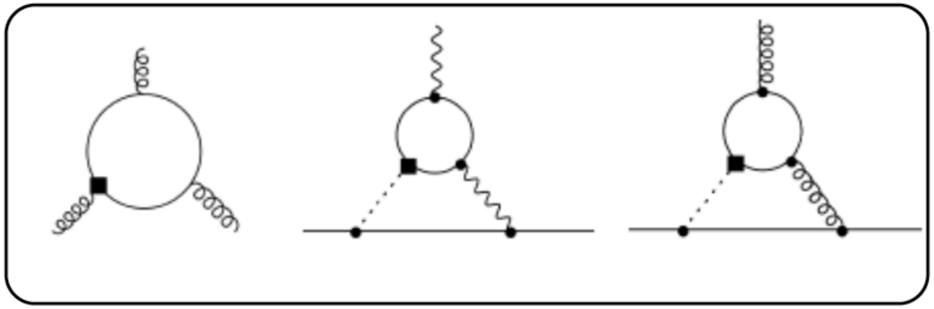
Radium as well, but uncertainties are larger

Top quark Yukawa and CEDM

LHC: pp → h (via ggF), $t\bar{t}$, $t\bar{t}h$



Low Energy: quark (C)EDM, Weinberg, *and* d_e



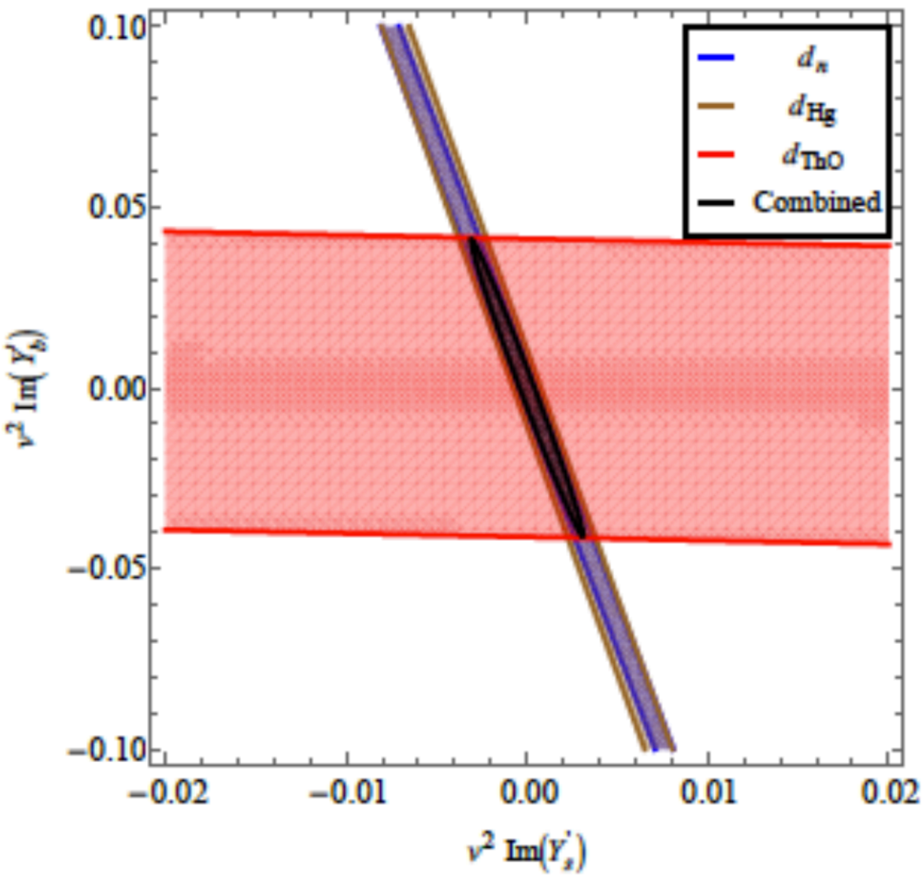
$v^2 \mathrm{Im}\, Y_t'$	d_n	d_{Hg}	d_e	$[d_n,\, d_{Hg},\, d_e]$(comb)	LHC
Central	0.047	0.036	$7.8 \cdot 10^{-3}$	$7.8 \cdot 10^{-3}$	0.15
Rfit	0.11	> 1	$7.8 \cdot 10^{-3}$	$7.8 \cdot 10^{-3}$	0.15

- Richer collider phenomenology (ggFusion, ttbar, ttbar h)
- Strong constraint on Im Yt from eEDM (~ **SM electron Yukawa**!)
- Little uncertainty on EDM constraint

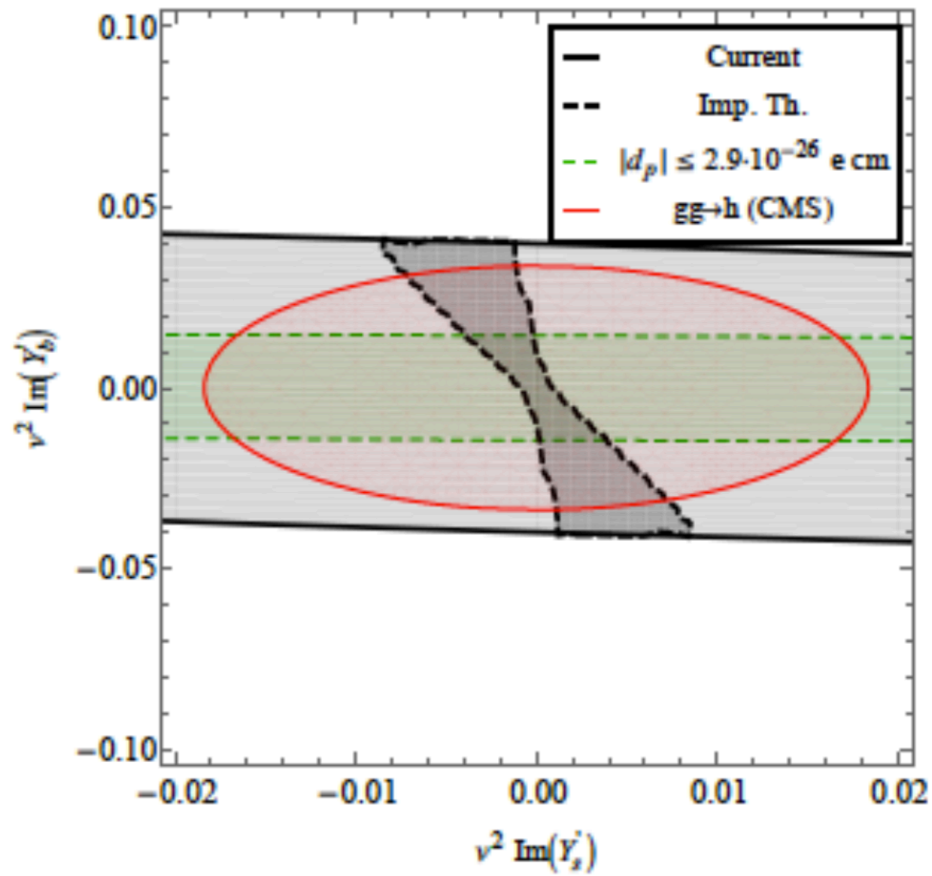
LHC-EDM complementarity

- Two coupling analysis (bottom and strange Yukawa)

Central



RFit

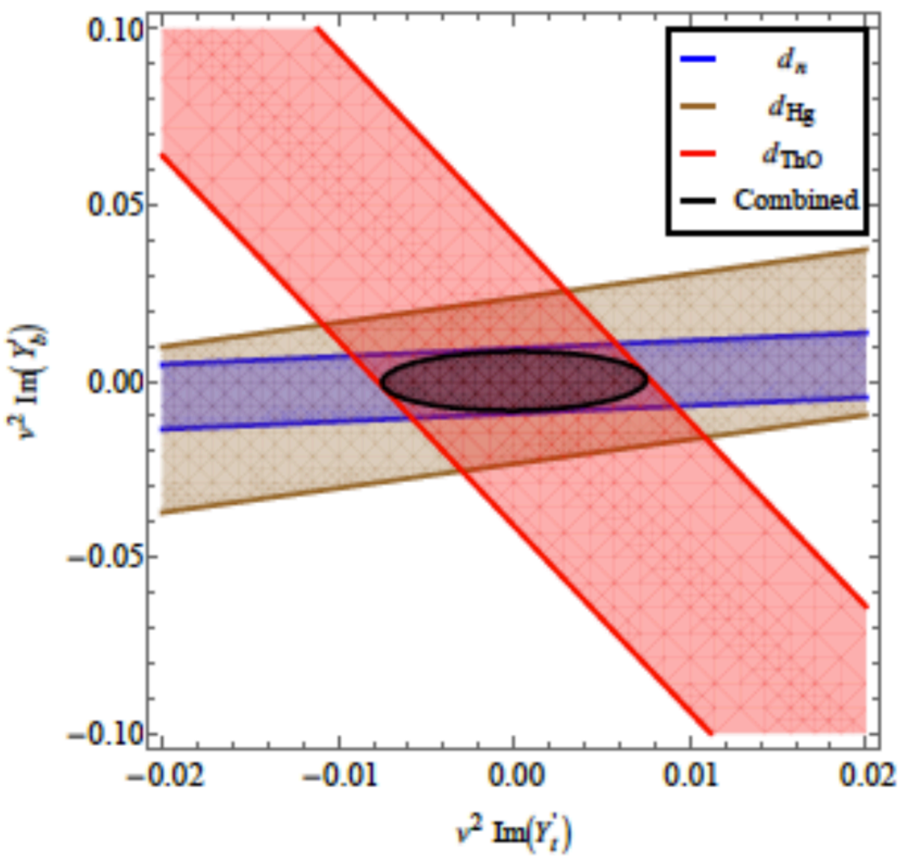


LHC or improved theory removes free direction

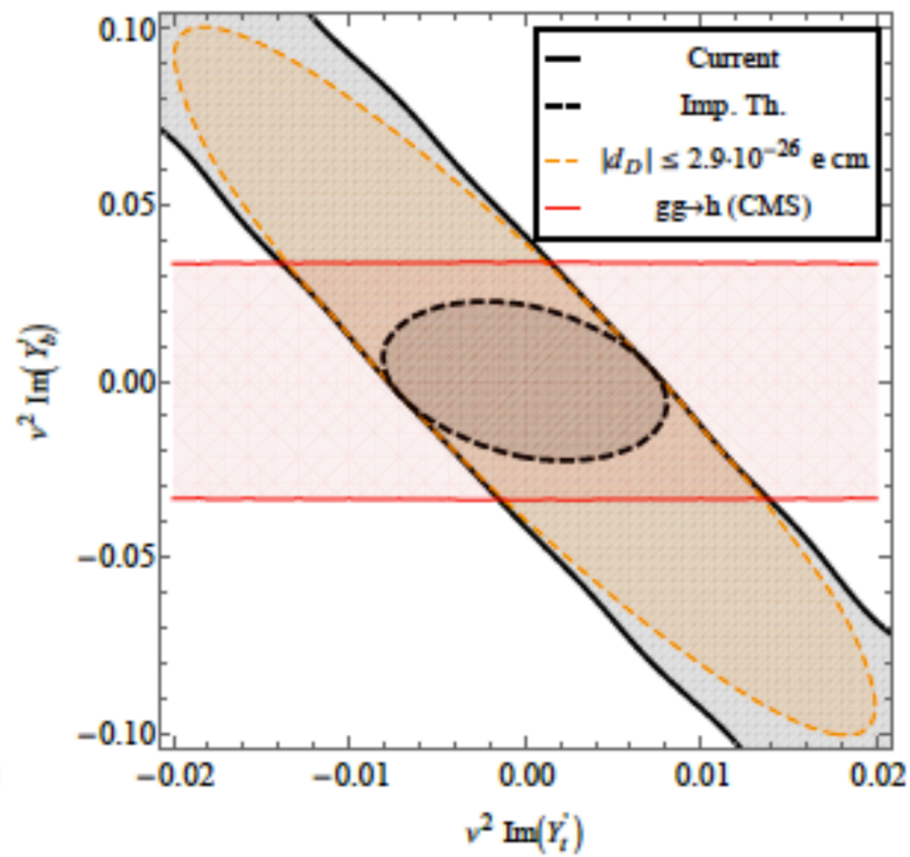
LHC-EDM complementarity

- Two coupling analysis (bottom and top Yukawa)

Central



RFit



LHC or improved theory removes free direction

Summary table

	$v^2 \mathrm{Im}\, Y'_u$	$v^2 \mathrm{Im}\, Y'_d$	$v^2 \mathrm{Im}\, Y'_c$	$v^2 \mathrm{Im}\, Y'_s$	$v^2 \mathrm{Im}\, Y'_t$	$v^2 \mathrm{Im}\, Y'_b$	$v^2 \theta'$
EDMs	$2.8 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$	$6.3 \cdot 10^{-3}$	0.42	$7.8 \cdot 10^{-3}$	0.041	0.23
LHC Run 1	0.06	0.07	0.02	0.015	0.15	0.038	0.27

- Pseudoscalar Yukawa's in units of SM Yukawa's

$$\mathcal{L} = \frac{m_q}{v}\, \tilde{\kappa}_q\, \bar{q} i \gamma_5 q\, h$$

$\tilde{\kappa}_u$	$\tilde{\kappa}_d$	$\tilde{\kappa}_s$	$\tilde{\kappa}_c$	$\tilde{\kappa}_b$	$\tilde{\kappa}_t$
0.45	0.11	58	2.3	3.6	0.01

- Impressive constraints on up, down, and top !
- Can improve a lot with theory + experimental improvements

Conclusion/Summary

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EFT approach

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

CP-violating quark- and gluon-Higgs interactions

- ✓ EDMs and LHC Higgs production are complementary
- ✓ EDMs have a **potential** edge but suffer from hadronic/nuclear uncertainties
- ✓ Set a **target** for lattice/nuclear structure to improve matrix elements

Outlook

- ✓ Study CP-odd effects at colliders (e.g. Bernreuther et al, Tattersall et al)
- ✓ Include Higgs decay and differential distributions
- ✓ Extend analysis to Higgs-EW gauge bosons (in preparation)
- ✓ Compare linear v non-linear EFT realization

Backup

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

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

Dekens, JdV JHEP '13

Dimensionless couplings

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

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

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

	$M_T = 1\,\mathrm{TeV}$	$M_T = 10\,\mathrm{TeV}$
$(M_T^2)C_B\,(M_T)$	$\leq 8.1 \cdot 10^{-2}$	≤ 4.6
$(M_T^2)C_W\,(M_T)$	$\leq 1.9 \cdot 10^{-2}$	≤ 1.1
$(M_T^2)C_{WB}\,(M_T)$	$\leq 1.3 \cdot 10^{-2}$	≤ 0.74
$(M_T^2)C_{dW}\,(M_T)$	≤ 0.11	≤ 11
$(M_T^2)C_{W\,u,\,d}\,(M_T)$	$\leq \{1.0,\, 0.84\} \cdot 10^{-2}$	$\leq \{0.53,\, 0.45\}$
$(M_T^2)C_{Z\,u,\,d}\,(M_T)$	$\leq \{5.3,\, 2.8\} \cdot 10^{-2}$	$\leq \{2.7,\, 1.4\}$

First 4 operators better bound by eEDM

Lattice QCD to the rescue

JÜLICH FORSCHUNGSZENTRUM

❖ With QCD lattice input:

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

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

Shintani et al '12 '13

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

Guo et al '15

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

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

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

- Popular problem: see also

Shindler et al '15
Alexandrou et al '15

Still not really clear though….

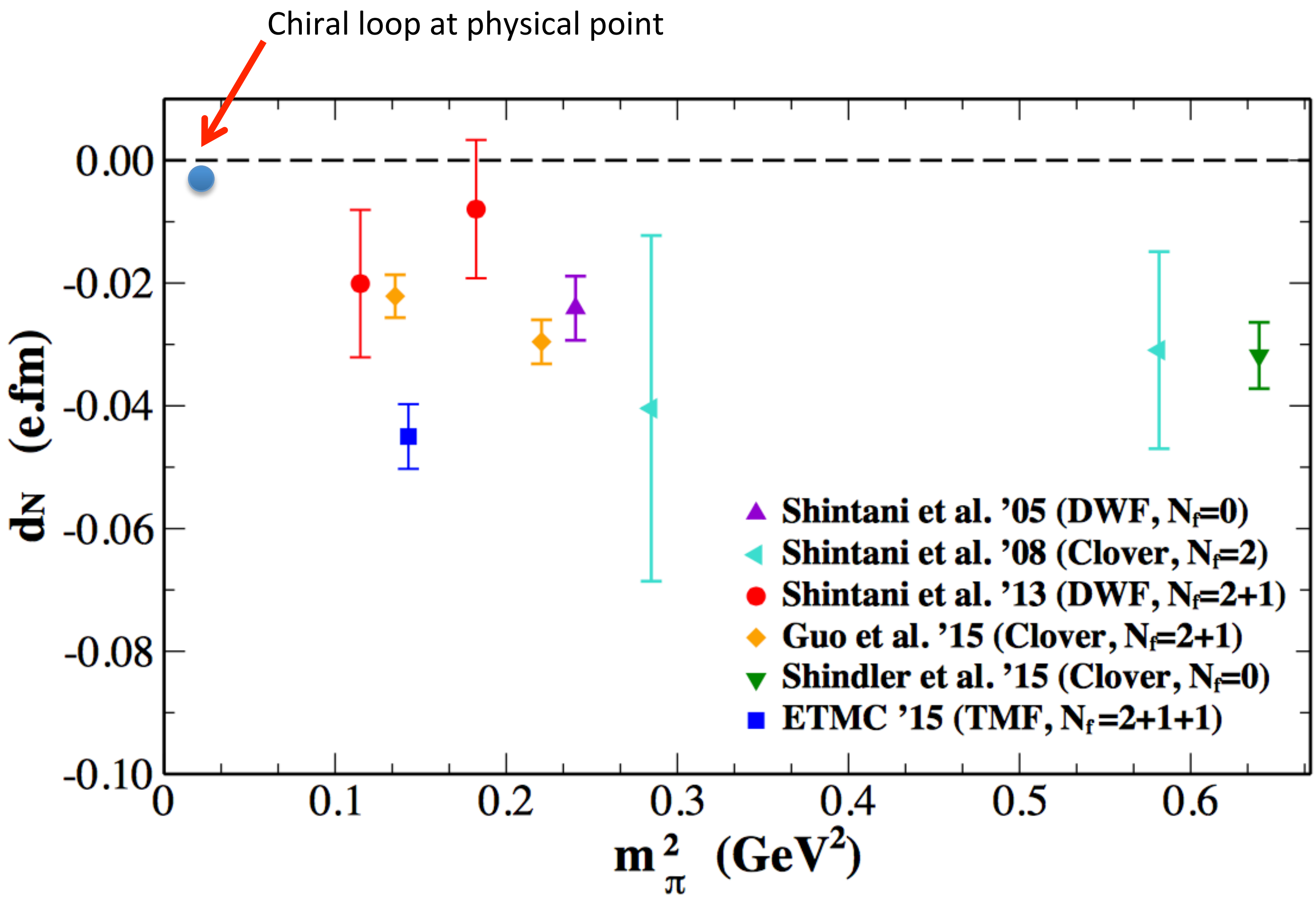
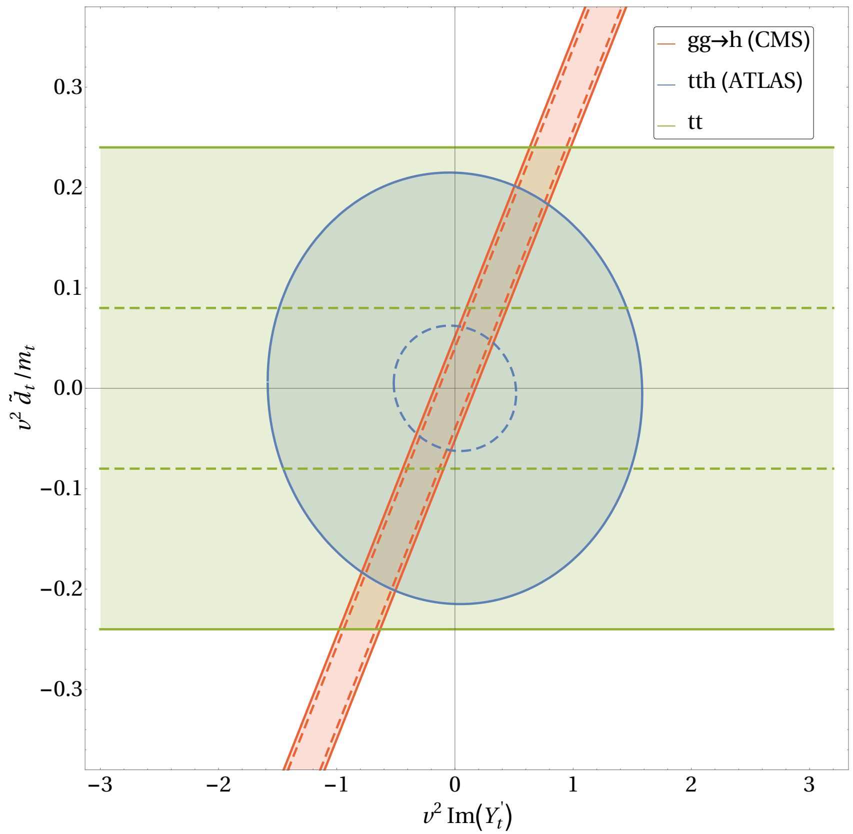
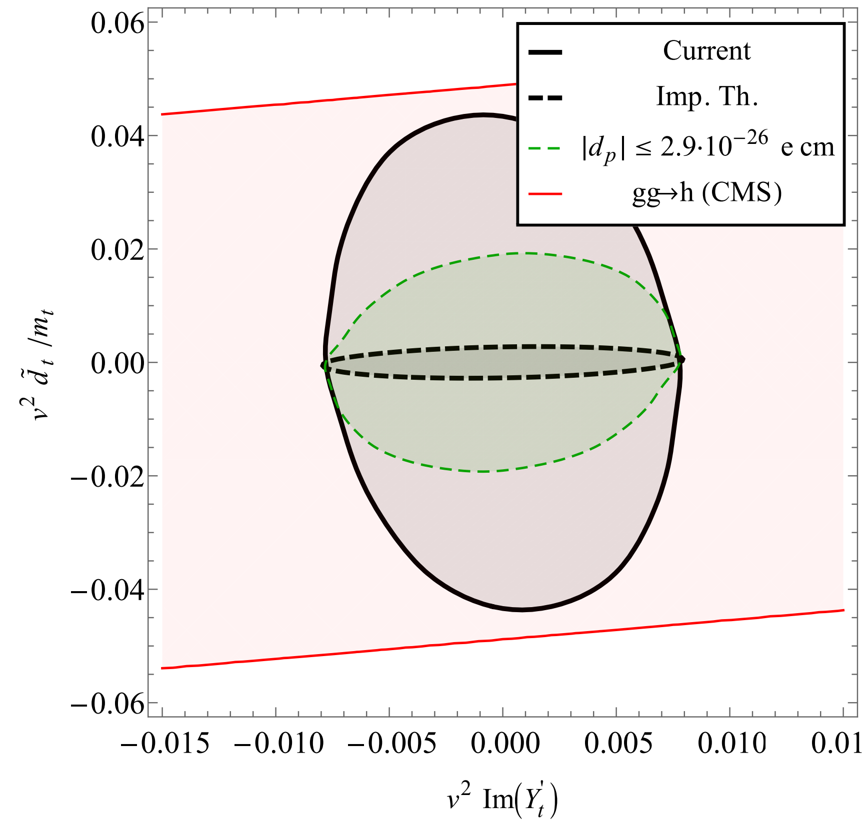


Fig from M. Constantinou '15


gg→h (CMS)
tth (ATLAS)
tt
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−3
−2
−1
0
1
2
3
$v^2 \tilde{d}_t / m_t$
$v^2 \, \mathrm{Im}(Y_t')$


Current
Imp. Th.
$|d_p| \leq 2.9 \cdot 10^{-26}$ e cm
gg→h (CMS)
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
−0.015
−0.010
−0.005
0.000
0.005
0.010
0.015
$v^2 \tilde{d}_t / m_t$
$v^2 \, \mathrm{Im}(Y_t')$