An Effective Approach to Hadronic Electric Dipole Moments

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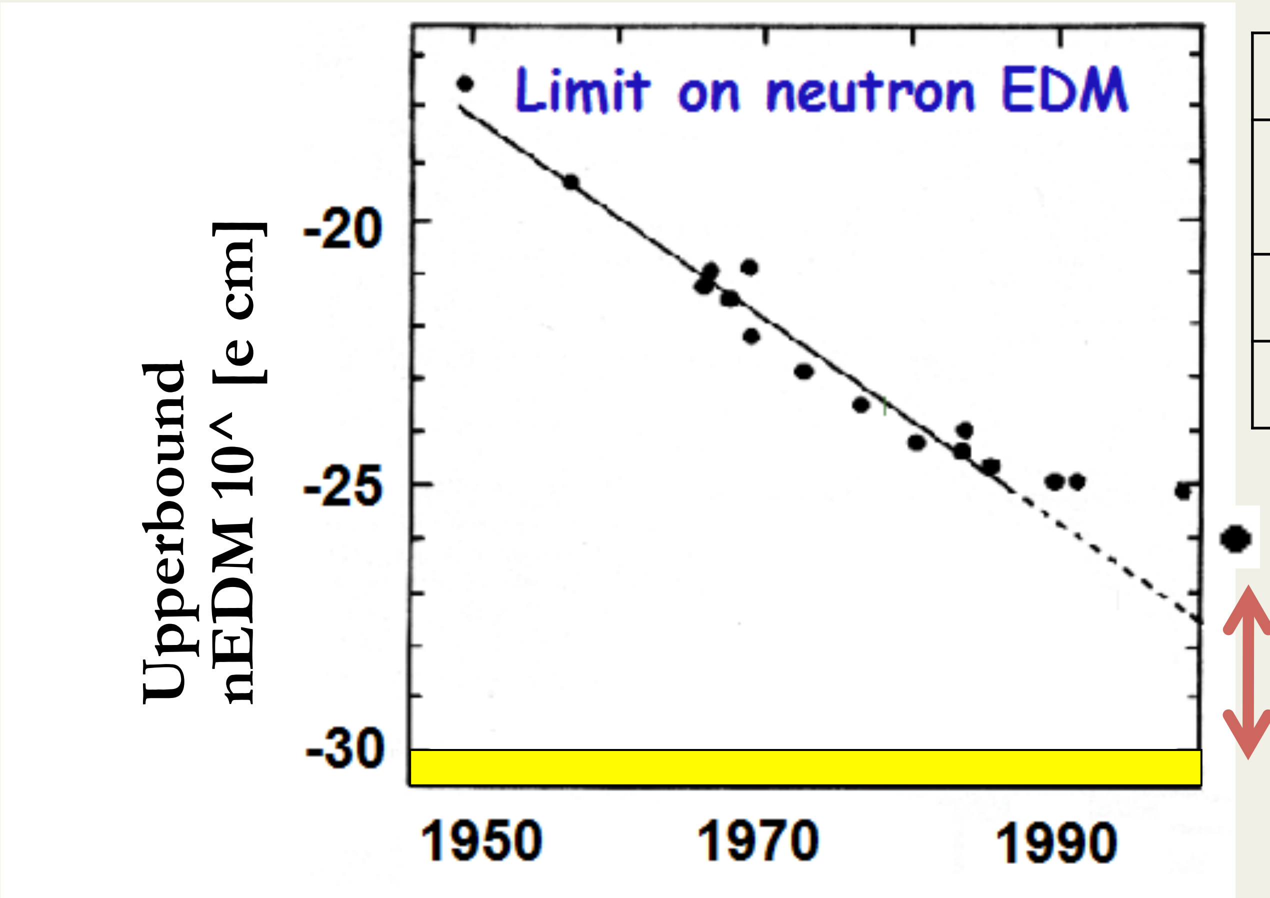
Outline

- Part I: The Standard Model EFT and EDMs
- Part II: Chiral considerations
- Part III: EDMs of nucleons and nuclei

Standard Model suppression



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 '15

"Here be dragons"

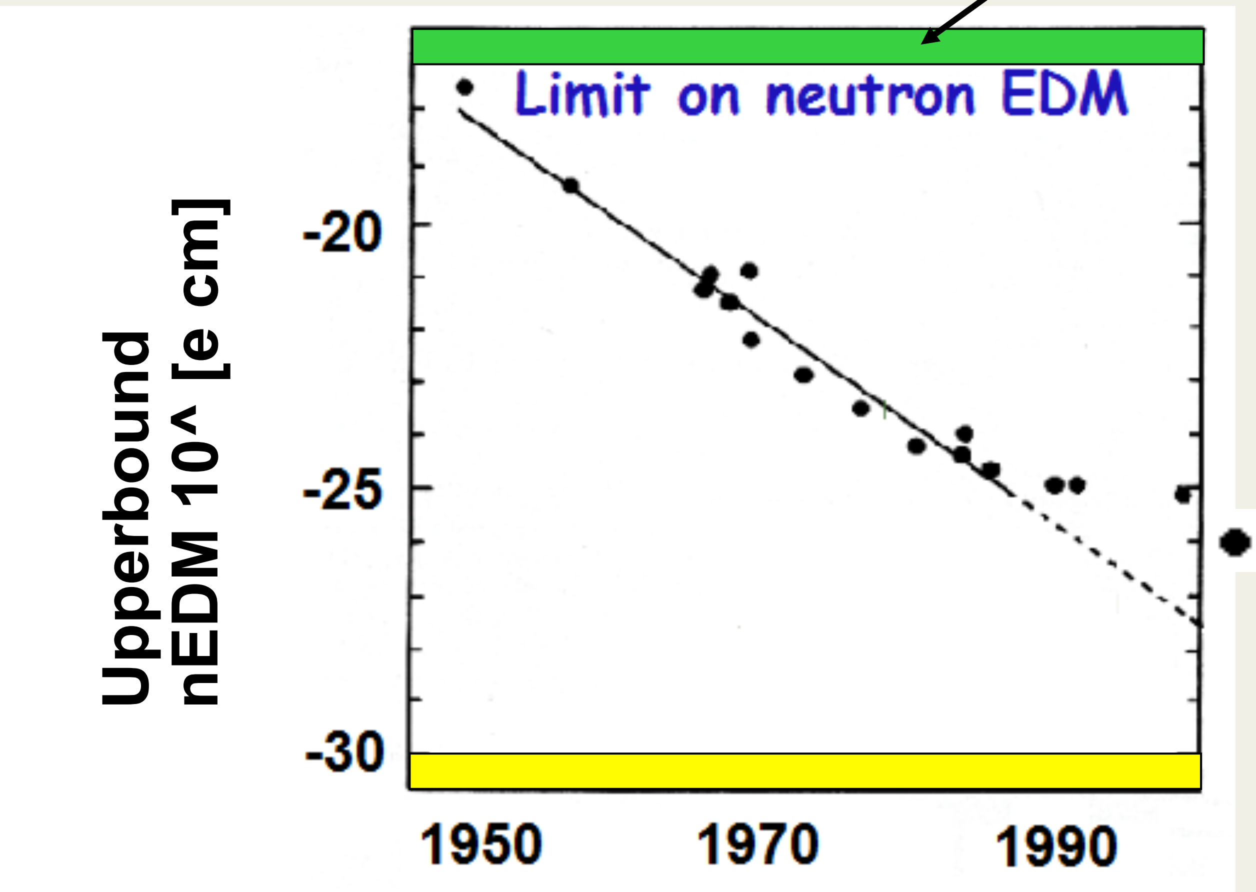
5 to 6 orders **below** upper bound ⟷ **Out of reach!**

With linear extrapolation: CKM neutron EDM in 2075….

Note: actual size of SM nEDM is unclear (factor >10 uncertainty)

The strong CP problem

If θ ~ 1



More details on calculation later

Sets θ upper bound: $\theta < 10^{-10}$

Is there a reason for this suppression? Axions?
Is $\theta = 0$ exact, or merely very small?

Measurement of a nonzero EDM

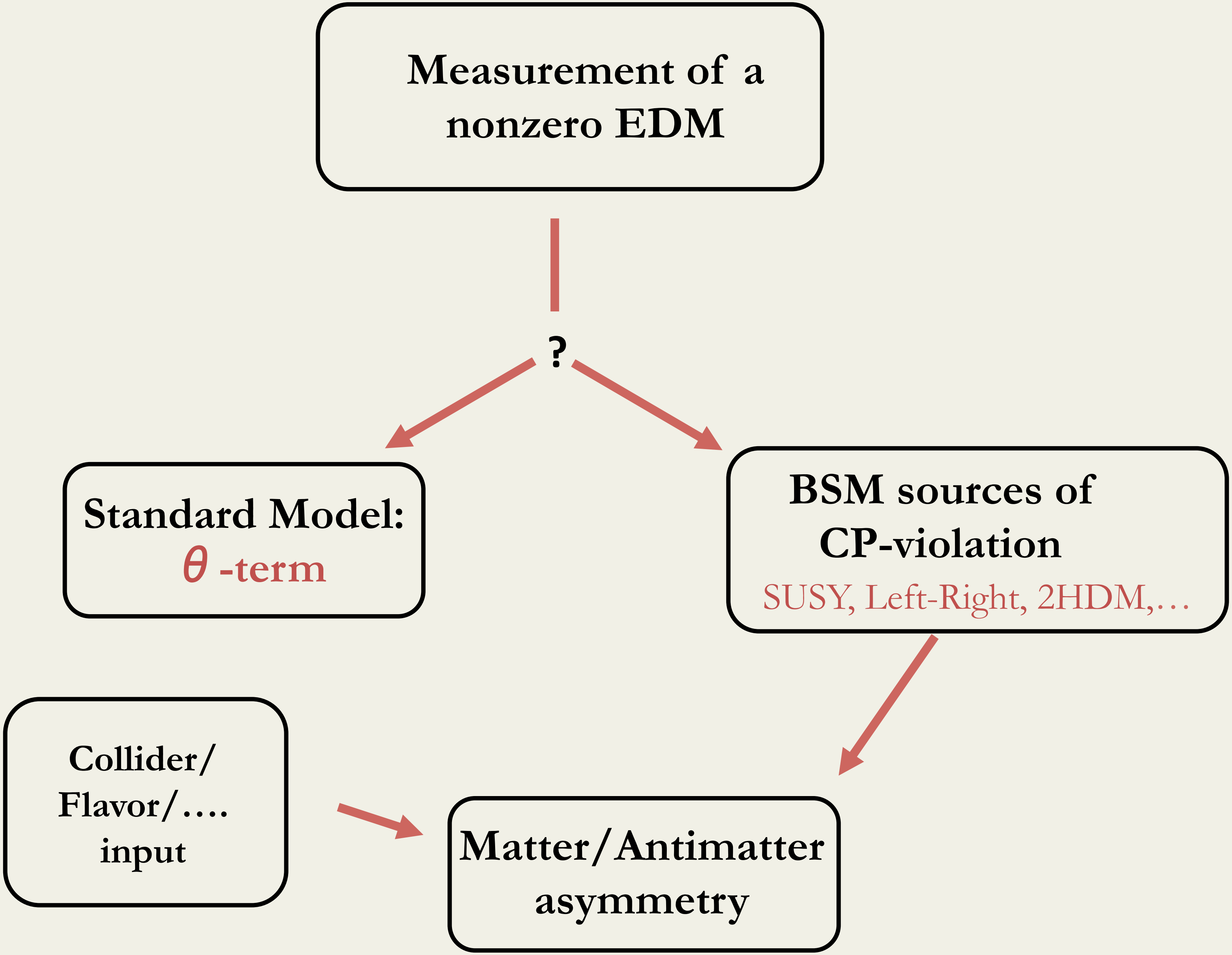
?

Standard Model:
θ -term

BSM sources of CP-violation
SUSY, Left-Right, 2HDM,…

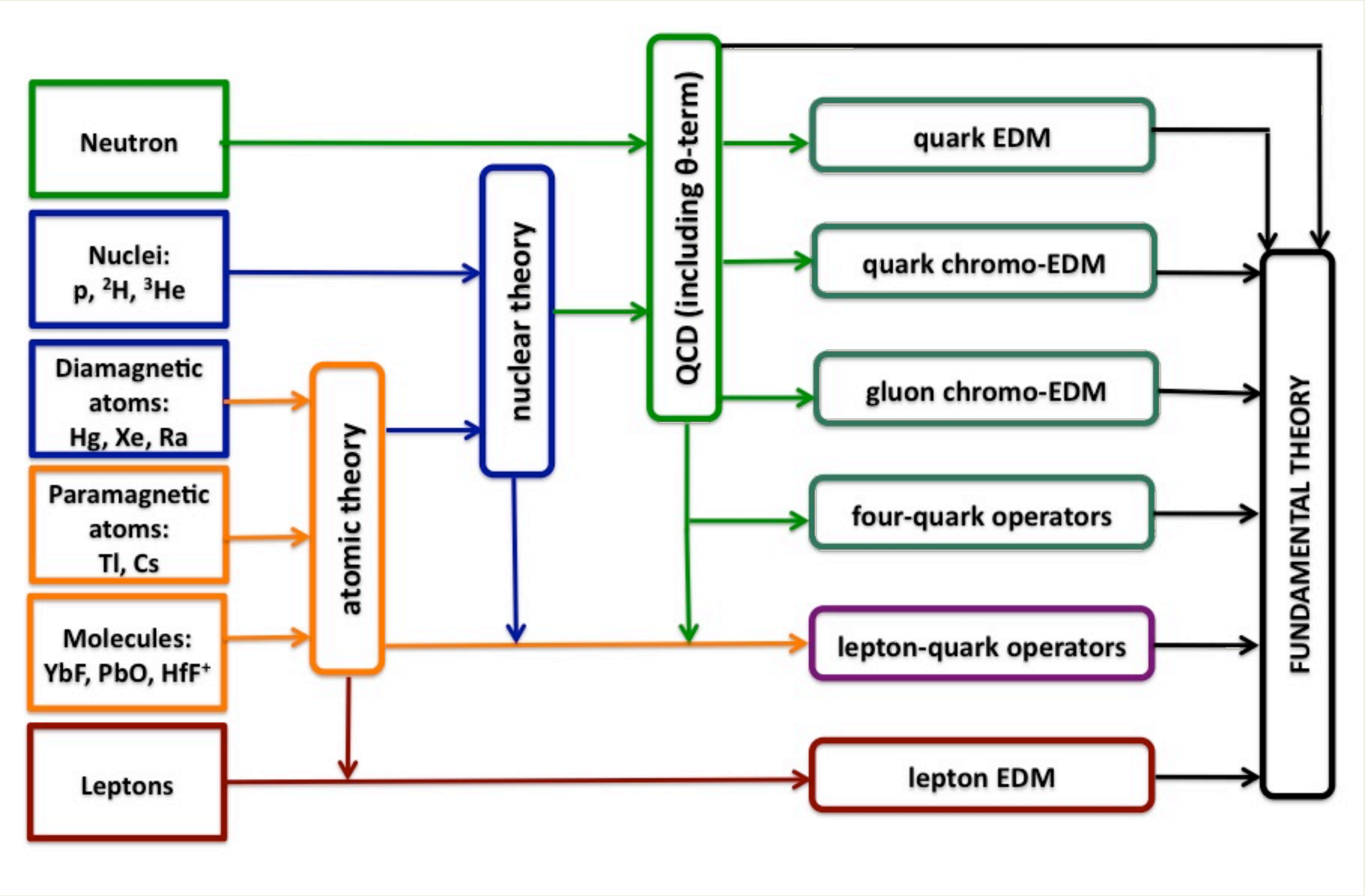
Forseeable future: EDMs are **'background-free'** searches for new physics

Can we **pinpoint** the microscopic source of CPV from EDM measurements alone ?



Measurement of a nonzero EDM
?
Standard Model:
θ -term
BSM sources of CP-violation
SUSY, Left-Right, 2HDM,…
Collider/ Flavor/…. input
Matter/Antimatter asymmetry

The EDM metromap



EFT for new physics

Energy

M_{CP}

? TeV

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

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

$F_\pi \sim m_\pi$

$\alpha_{\text{em}} m_e$

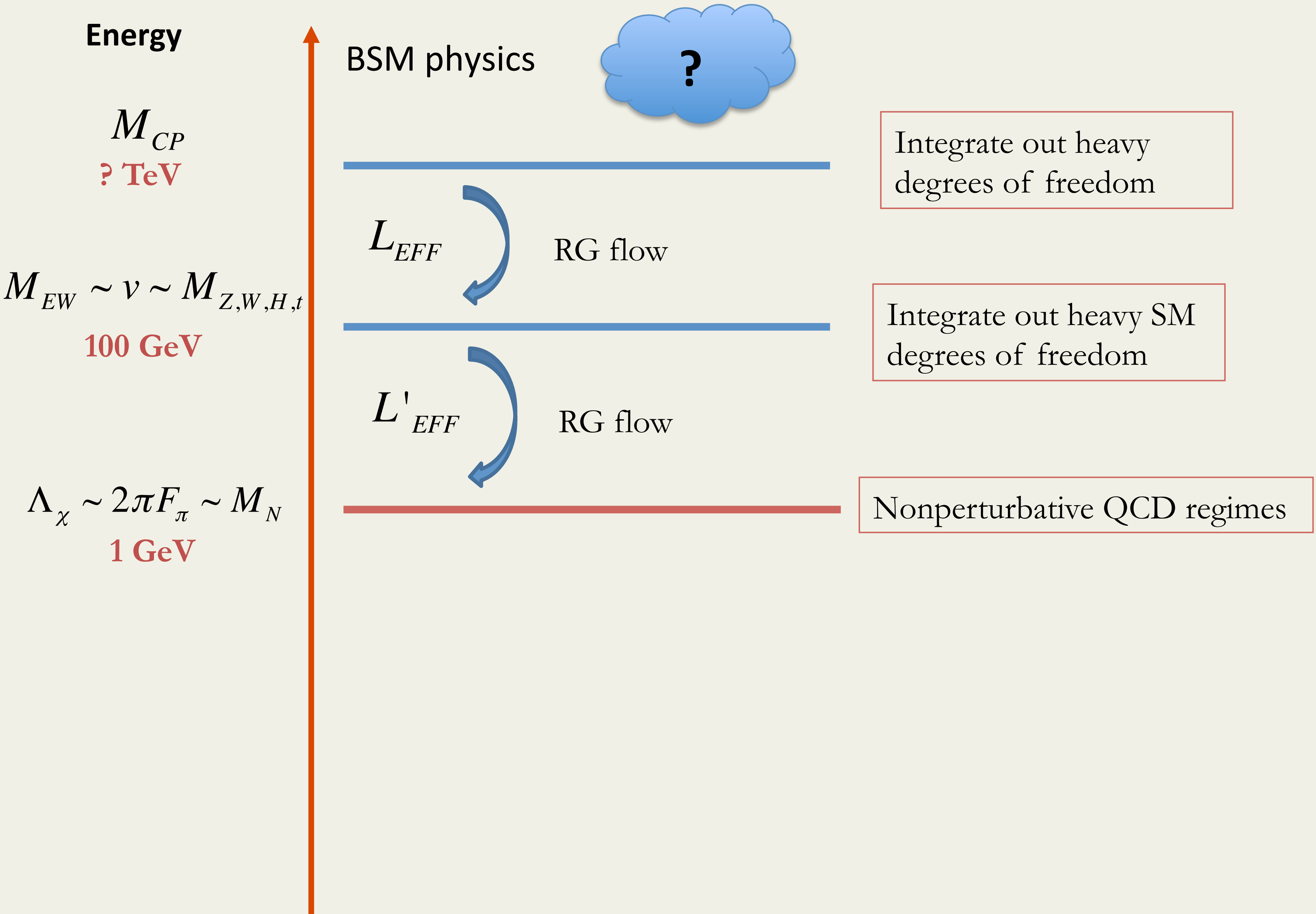
Probing models of CP violation via EDMs, involves a large hierarchy in scales

$$M_{CP} > v >> m_N > m_\pi >> m_e$$

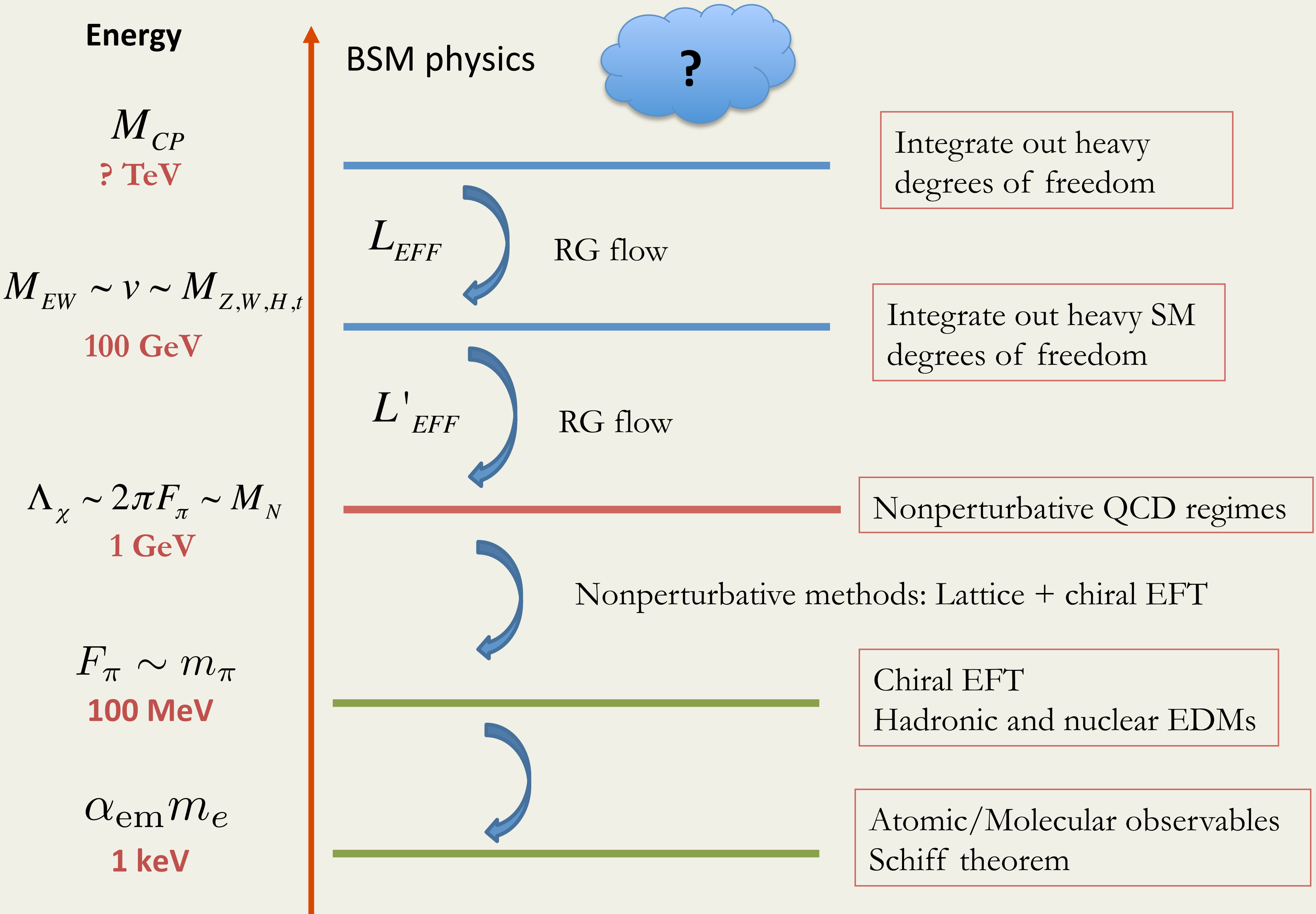
All scales involve new dynamics or even new degrees of freedom (QCD phase transition)

Strategy: Use a cascade of effective field theories to go from one scale to the next

Separation of scales



Separation of scales



Separation of scales

Energy

BSM physics ?

Model dependent

Integrate out heavy degrees of freedom

M_{CP}
? TeV

L_{EFF} RG flow

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

L'_{EFF} RG flow

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

Can be done once and for all!

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

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

Step 1: SM as an EFT

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

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

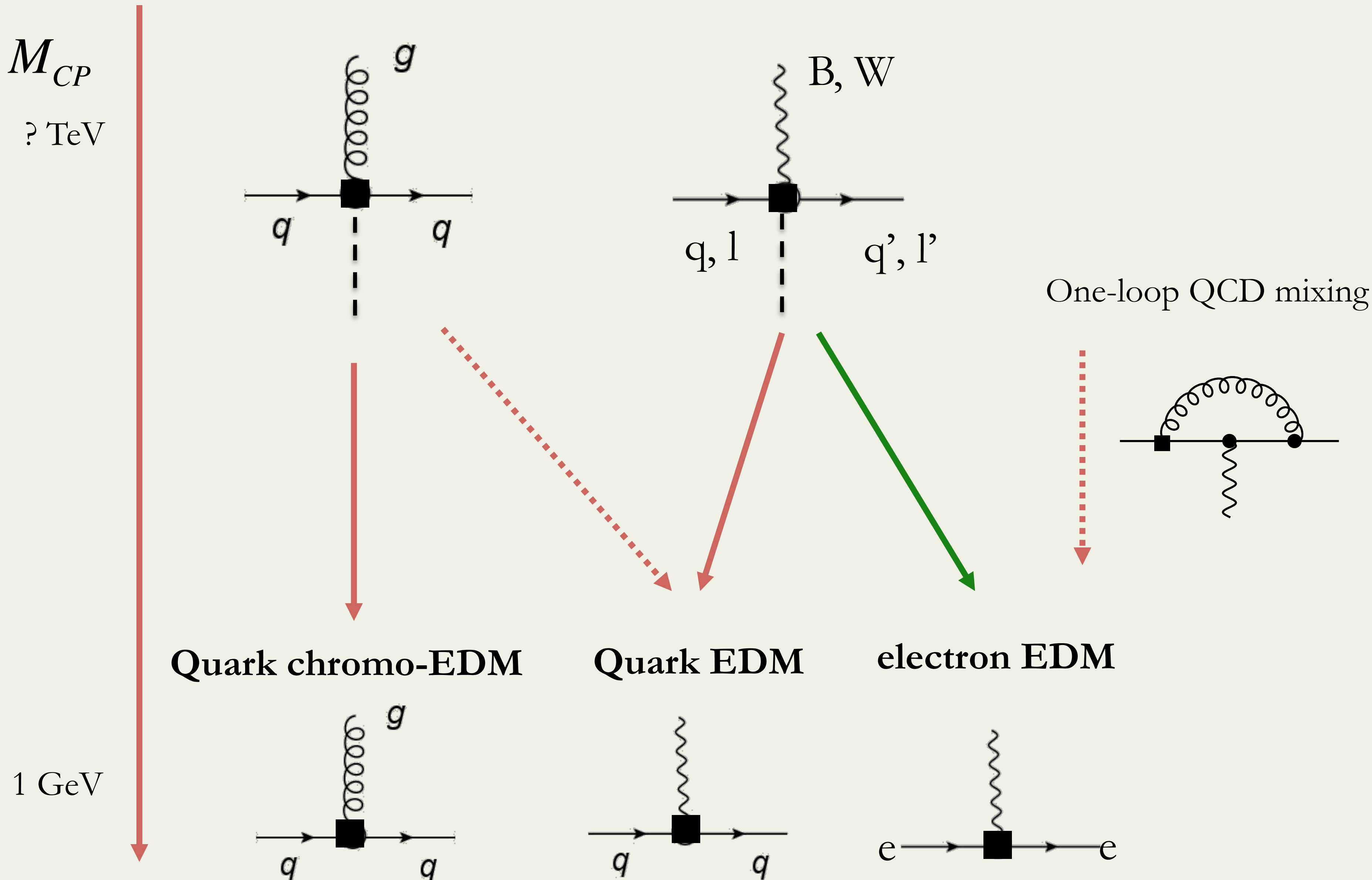
dim-5 generates neutrino masses/mixing, neglected here

3) Few operators generate EDMs directly… But SM loops…
4) Discuss only a subset. More general set : W. Dekens et al '13 '16

* **Assumption**: no new light fields

Buchmuller & Wyler '86
Gradzkowski et al '10
Many others

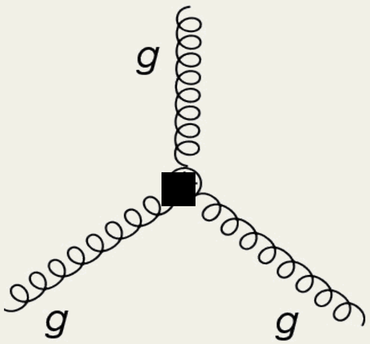
Fermion dipole operators



Gluon chromo-EDM

Weinberg PRL '89
Braaten et al PRL '90

Weinberg operator

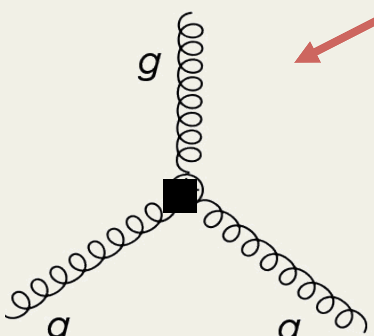


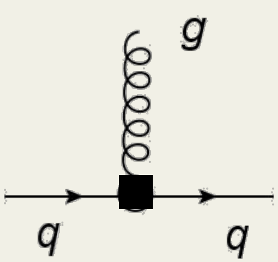
M_{CP}
? TeV

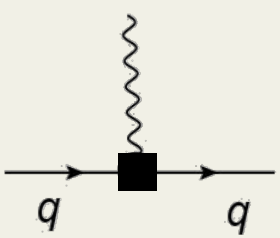
$$d_w \, f^{abc} \varepsilon^{\mu\nu\alpha\beta} \, G^a_{\alpha\beta} G^b_{\mu\lambda} \, G^{c\,\lambda}_{\nu}$$

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

1 GeV







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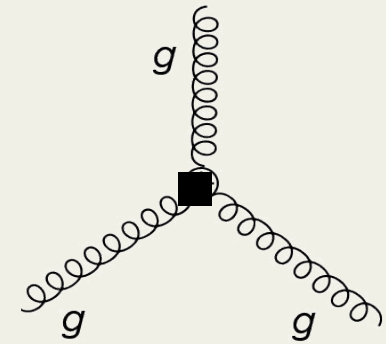
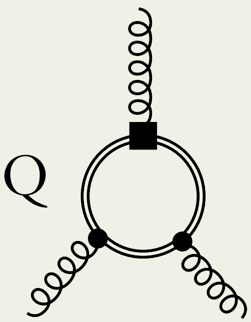


M_{CP}
? TeV

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

m_Q

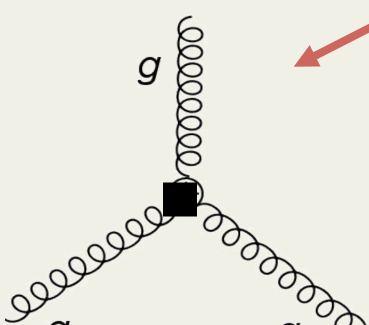
Q

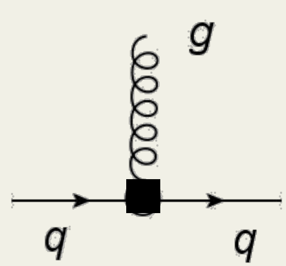


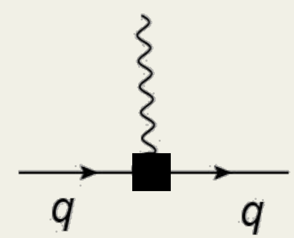
Threshold contributions
from heavy CEDMs

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

1 GeV







Dipole mixing

Numerical solution of the three dipole operators

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

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

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

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

1) **Diagonal terms are all suppressed**

2) Suppressions are moderate

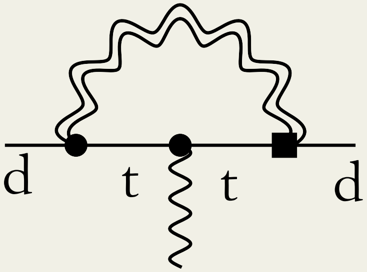
3) Mixing is important, e.g. if qCEDM at low energy then also qEDM (unless cancellations….)

* 2-loop running in Degrassi et al, JHEP ’05 , few % corrections to LO running

Top electromagnetic dipoles

- What if the BSM physics couples mainly to third generation ?
- Example: top EDM

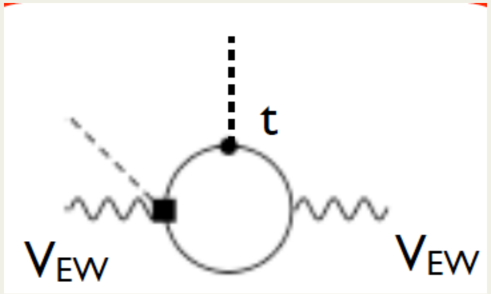
Concero-Cid et al '08



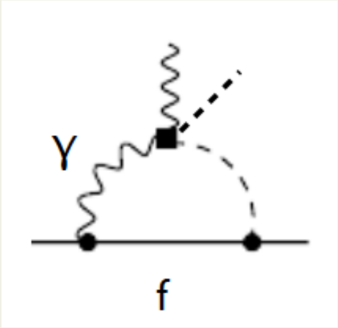
- 1-loop suppressed by $|V_{td}|^2 \sim 10^{-5}$
- Two-loop path to electron EDM

Cirigliano et al '16

Mckeen et al '12



$$\longrightarrow H^2 F\tilde{F} \longrightarrow$$



- Much more stringent constraints ! Far better than LHC.

Talk by Vincenzo Cirigliano

Four-quark operators

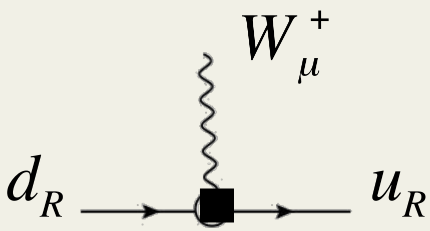
Ng & Tulin '12
Mereghetti et al '12

Fermion-Higgs interactions **(appears in left-right models)**

Energy

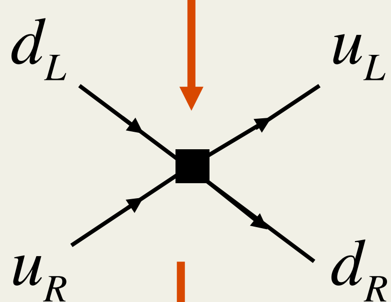
$$\Xi\,\bar{u}_R\gamma^\mu d_R\,(\tilde{\varphi}^\dagger iD_\mu\varphi) + \text{h.c.} \longrightarrow \Xi v^2 g\,(\bar{u}_R\gamma^\mu d_R\,W^\pm_\mu + \text{h.c.})$$

M_{CP}



A right-handed quark-W coupling

$< M_W$



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

Λ_χ

QCD RGE induces another operator

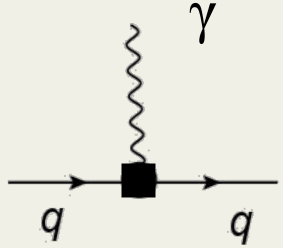
Two four-quarks terms (FQLR operators)

Ng & Tulin '12
Mereghetti et al '12
Maiezza et al'14

Many more… But when the dust settles…..

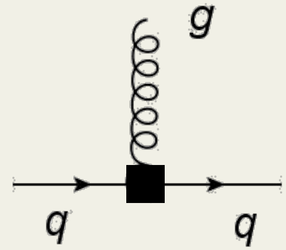
Few GeV

QCD (θ -term) +



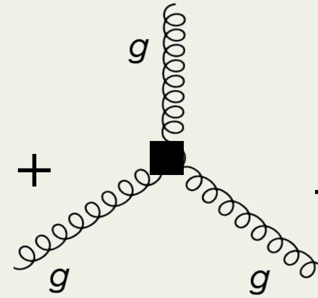
Quark EDM

+



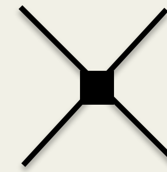
Quark C-EDM

+



Gluon C-EDM

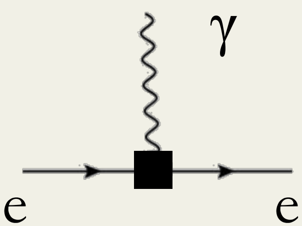
+



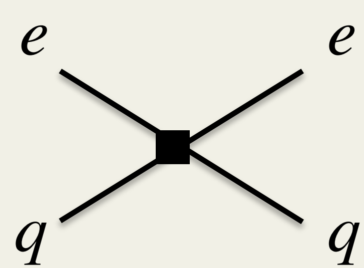
FQ

Without SU(2) invariance it would be > 20 operators

(semi-)leptonic interactions



Electron EDM



$$\sim \frac{1}{M_{CP}^2}\frac{m_e^2}{m_h^2}$$

Intermediate summary I

- Parametrized BSM CP violation in terms of **dim6** operators
- Evolved them to lower energies to ~ 1 GeV
- Several operators left: theta, (C)EDMs, Weinberg, Four-fermion
- **Important:** different BSM models -> different EFT operators

Intermediate summary I

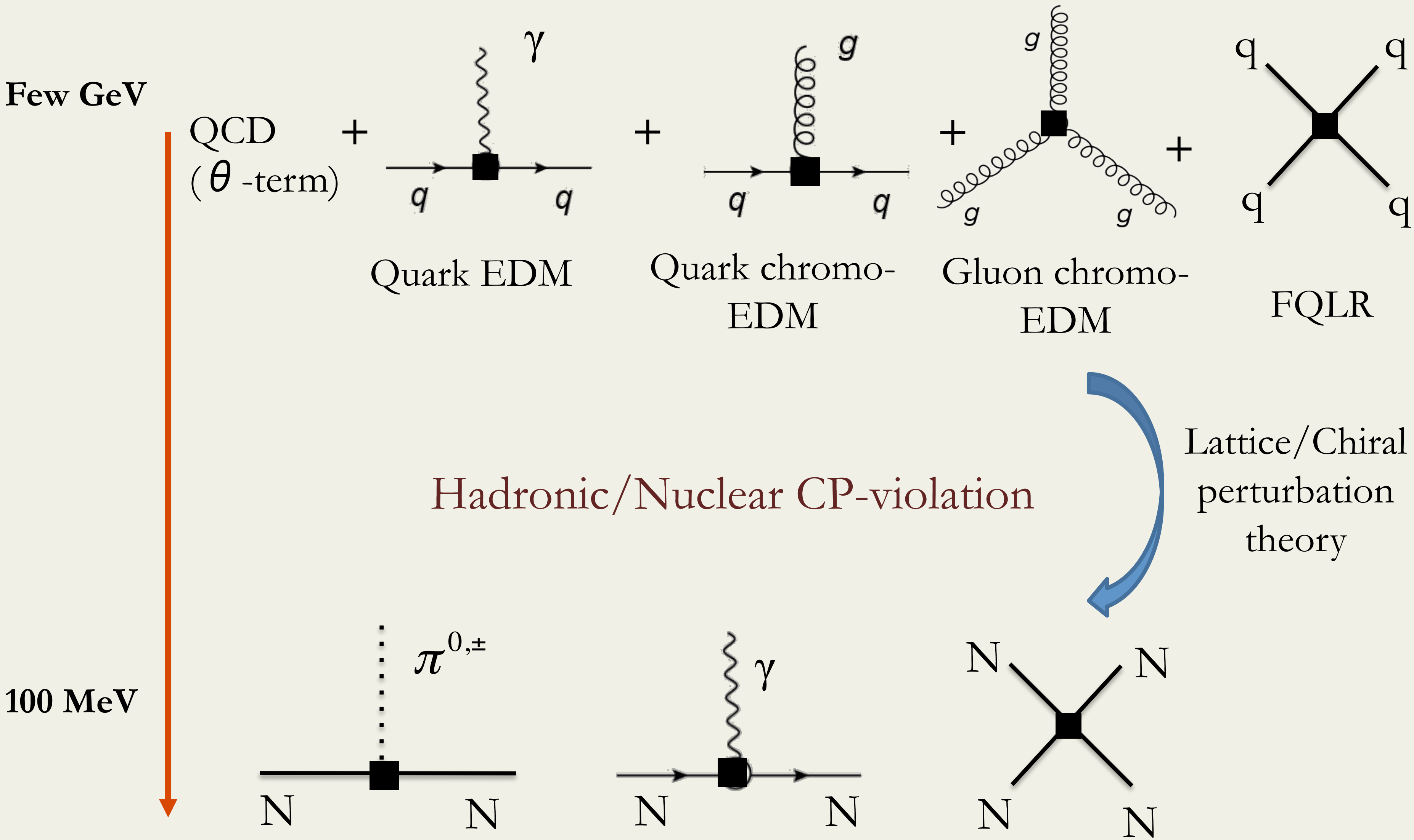
Mohapatra et al '75
Giudice et al '06
Dekens et al '14
Pich & Jung '14

- Parametrized BSM CP violation in terms of **dim6** operators
- Evolved them to lower energies to ~ 1 GeV
- Several operators left: theta, (C)EDMs, Weinberg, Four-fermion
- **Important:** different BSM models -> different EFT operators

1. Standard Model: only **theta** has a chance to be measured
2. 2-Higgs doublet model: **quark+electron EDM, CEDMs, Weinberg** (exact hierarchy depends on detail of models)
3. Split SUSY: only **electron + quark EDMs** (ratio fixed)
4. Left-right symmetric models: **FQLR operators**, way smaller (C)EDMs
5. Leptoquarks: Semi-leptonic four-fermion and four-quark (tree-level)

- **Main question: can we unravel these scenarios with EDMs ?**
- Can EDMs compete with high-energy experiments ?

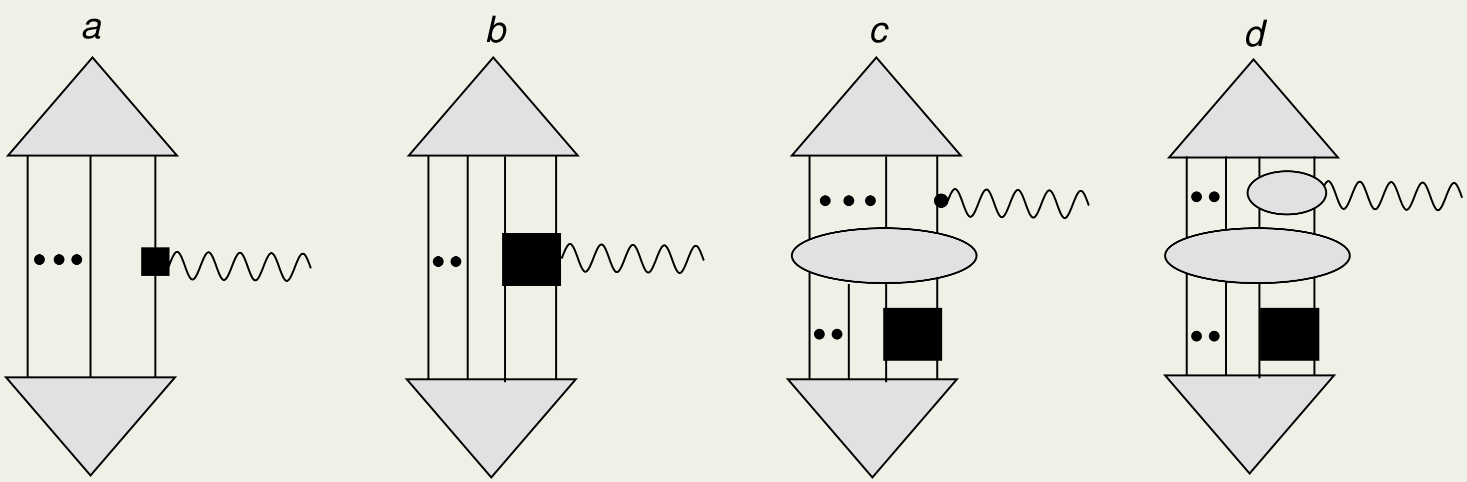
Onwards to hadronic CPV



CPV in hadrons and nuclei

- Goal is to calculate CPV properties of **hadrons** and **nuclei**
  - Electric dipole moments
  - Higher moments (Schiff moments/magnetic quadrupole…)

- Wishlist
  - **Link** to underlying theory (QCD + CPV operators)
  - **Power counting**
  - **General** (several observables in one framework)



  - Require nucleon quantities and CPV nuclear forces/currents

An ultrashort intro to 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 → SU(2)$_L$xSU(2)$_R$ symmetry
  - Spontaneously broken to SU(2)-isospin (pions = Goldstone)
  - Explicit breaking (quark mass) → pion mass

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

- **Extended to include CP violation**

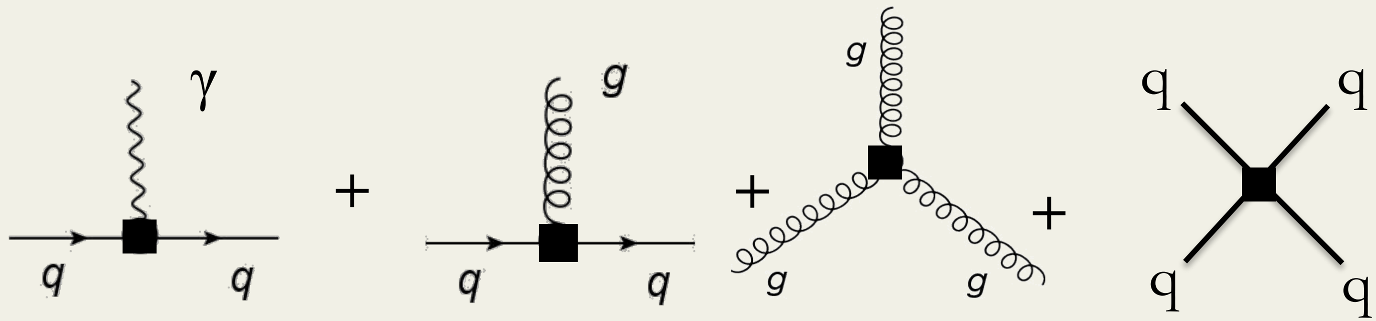
Mereghetti et al' 10, JdV et al '12, Bsaisou et al '14

Review: Meißner/JdV '15

Weinberg, Gasser, Leutwyler, and many many others

ChiPT with CP violation

QCD +
(θ -term)



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

$\downarrow$

Different CP-odd chiral Lagrangians

$\downarrow$

Different hierarchy of EDMs

Theta and chiral perturbation theory

After axial U(1) and SU(2) rotations, **complex CP-odd quark mass**:

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

Crewther et al' 79

Baluni '79

Theta and chiral perturbation theory

After axial U(1) and SU(2) rotations, **complex CP-odd quark mass:**

Crewther et al' 79

Baluni '79

$$\mathcal{L}_{\mathrm{QCD}} = \mathcal{L}_{\mathrm{kin}} - \boxed{\bar{m}\bar{q}q} - \varepsilon\bar{m}\,\bar{q}\tau^3 q \;\; + m_\star\,\bar{\theta}\,\bar{q}i\gamma^5 q$$

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

$$\mathcal{L}'_\chi = \mathcal{L}_\chi - \boxed{\frac{m_\pi^2}{2}\pi^2} - \delta m_N\,\bar{N}\tau^3 N \quad + \bar{g}_0\,\bar{N}\tau\cdot\pi N$$

Pion mass

Theta and chiral perturbation theory

After axial U(1) and SU(2) rotations, **complex CP-odd quark mass:**

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Baluni '79

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

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

$$\mathcal{L}'_\chi = \mathcal{L}_\chi - \frac{m_\pi^2}{2}\pi^2 - \boxed{\delta m_N\,\bar{N}\tau^3 N} + \bar{g}_0\,\bar{N}\tau\cdot\pi N$$

Strong proton-neutron mass splitting

Theta and chiral perturbation theory

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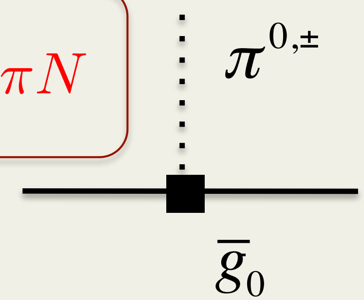
Crewther et al' 79

Baluni '79

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

$$\mathcal{L}'_\chi = \mathcal{L}_\chi - \frac{m_\pi^2}{2}\pi^2 - \delta m_N\,\bar{N}\tau^3 N \;\boxed{+\bar{g}_0\,\bar{N}\tau\cdot\pi N}$$



CP-odd pion-nucleon interaction

Theta and chiral perturbation theory

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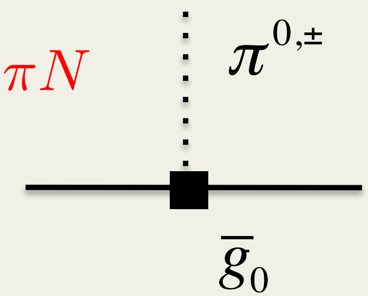
Crewther et al' 79

Baluni '79

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

Linked via SU$_A$(2) rotation

$$\mathcal{L}'_\chi = \mathcal{L}_\chi - \frac{m_\pi^2}{2}\pi^2 - \delta m_N\,\bar{N}\tau^3 N \;\; +\bar{g}_0\,\bar{N}\tau\cdot\pi N$$



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

Use **lattice** for mass splitting

$$g_0 = \delta m_N \frac{1-\varepsilon^2}{2\varepsilon}\bar{\theta} = (15.5 \pm 2.5)\cdot 10^{-3}\,\bar{\theta}$$

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

Trust issues

- The relations are no longer unique if we use SU(3) chPT

$$g_0 = \delta m_N \frac{m_*}{\bar{m}\varepsilon}\bar{\theta} \qquad\qquad g_0 = (m_\Xi - m_\Sigma)\frac{2m_*}{(m_s - \bar{m})}\bar{\theta}$$

- Numerically: LO relations differ by **more than 100%** (sometimes sign...)

$$g_0 = (15.5 \pm 2.5)\cdot 10^{-3}\,\bar{\theta}$$

Can this be trusted ??

Trust issues

- The relations are no longer unique if we use SU(3) chPT

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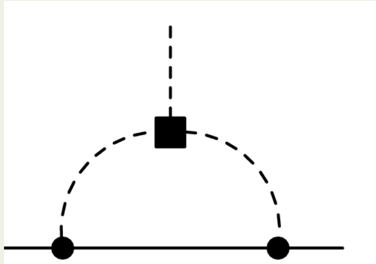
- Numerically: LO relations differ by **more than 100%** (sometimes sign...)

$$g_0 = (15.5 \pm 2.5)\cdot 10^{-3}\,\bar{\theta}$$

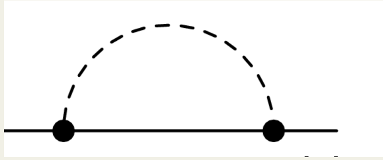
Can this be trusted ??

- Investigate higher-order corrections to left- right-sides of relations

g_0 @ NLO

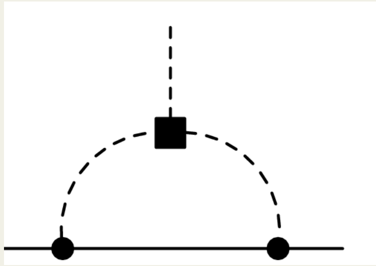


Mass terms @ NLO



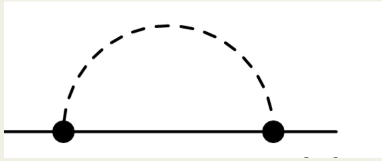
Protected relations

g_0 @ NLO



$$g_0 = \delta m_N \frac{m_*}{\bar{m}\varepsilon}\bar{\theta}$$

Mass terms @ NLO



$$g_0 = (m_\Xi - m_\Sigma)\frac{2m_*}{(m_s - \bar{m})}\bar{\theta}$$

- Relation 1: All corrections obey the relation
- Relation 2: Explicit violation already at NLO

$$\frac{g_0}{(m_\Xi - m_\Sigma)} = \left[1 + \frac{(D^2 - 6DF - 3F^2)}{6(4\pi f_\pi)^2}\frac{(m_K - m_\pi)^2(m_K + m_\pi)}{(m_\Xi - m_\Sigma)}\right]\frac{2m_*}{(m_s - \bar{m})}\bar{\theta}$$

$$\approx [1 - 0.7]\frac{2m_*}{(m_s - \bar{m})}\bar{\theta}$$

JdV, Mereghetti, Walker-Loud '15

Wrap-up

- Identify **protected relations** (including N2LO) for various couplings

	Values obtained here ($\times 10^{-3}\,\bar\theta$)
$\bar g_0/(2F_\pi)$	15.5 ± 2.5
$\bar g_{0\eta}/(2F_\eta)$	115 ± 37
$\bar g_{0N\Sigma K}/(2F_K)$	-36 ± 11
$\bar g_{0N\Lambda K}/(2F_K)$	-44 ± 13

JdV et al '15

- Values recommended for **lattice extrapolations** of neutron EDM

- Used to estimate **short-range CPV NN** forces
- Similar couplings appear in axion phenomenology   Stadnik et al '14

- Isospin-violating coupling g_1 has **no** protected relation.

$$g_1 = -(3 \pm 2) \cdot 10^{-3}\,\bar\theta$$

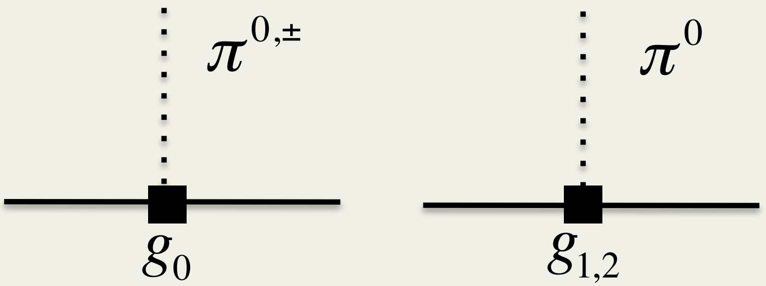
Partially based on resonance saturation

Bsaisou et al '12

Back to pion-nucleon couplings

- 2 relevant CP-odd structures

$$L = g_0\, \bar{N}\pi\cdot\boldsymbol{\tau}N + g_1\, \bar{N}\pi^0 N$$



- θ **-**term conserves isospin! So g_1 is **suppressed**.

Pospelov et al '01,'04
Mereghetti et al '10, '12,
Bsaisou et al '12

$$g_0 = (15.5 \pm 2.5)\cdot 10^{-3}\ \bar{\theta}$$

$$g_1 = -(3 \pm 2)\cdot 10^{-3}\ \bar{\theta}$$

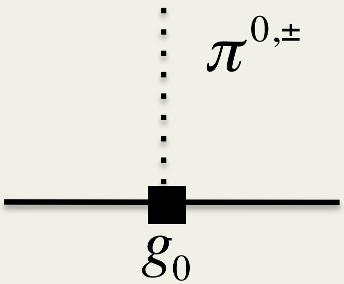
$$\frac{\bar{g}_1}{\bar{g}_0} = -(0.2 \pm 0.1)$$

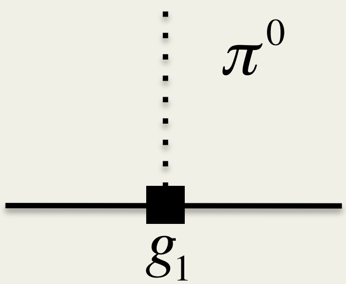
- Large uncertainty for g_1 due to pion mass splitting and unknown LEC
- g_0 relation **protected** from higher-order SU(2) and SU(3) corrections

Back to pion-nucleon couplings

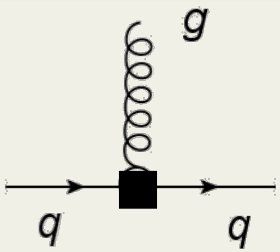
- Dominant CPV force from:

$$L = g_0\, \bar{N}\pi\cdot\boldsymbol{\tau}N + g_1\, \bar{N}\pi^0 N$$





- **Dimension-six qCEDMs have isospin-odd component** !



- ChPT gives no direct info about size. Both $g_{0,1}$ are LO

- QCD sum rules to the rescue

Pospelov '02

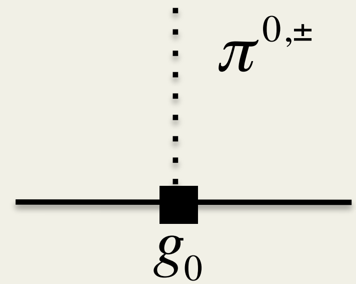
$$\bar{g}_0 = (5 \pm 10)(\tilde{d}_u + \tilde{d}_d)\,\mathrm{fm}^{-1} \qquad \bar{g}_1 = (20^{+20}_{-10})(\tilde{d}_u - \tilde{d}_d)\,\mathrm{fm}^{-1}$$

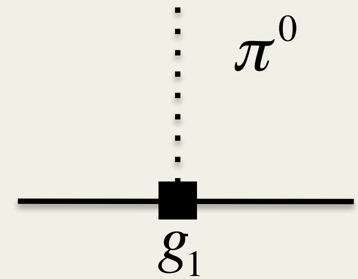
- Large uncertainties. But generally: $|\bar{g}_1| \geq |\bar{g}_0|$

Back to pion-nucleon couplings

- 2 CP-odd structures

$$L = g_0\, \bar{N}\pi\cdot\tau N + g_1\, \bar{N}\pi^0 N$$





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

Pospelov -Ritz '05
Hisano et al '12

$$\tilde{d}_q\, \bar{q}\sigma^{\mu\nu}\gamma^5 q\, G_{\mu\nu} \quad \xleftrightarrow[\mathrm{SU_A(2)}]{} \quad \tilde{c}_q\, \bar{q}\sigma^{\mu\nu}\tau^3 q\, G_{\mu\nu}$$

$$\bar{g}_0 \;=\; \tilde{d}_0\left(\frac{d}{d\tilde{c}_3} + r\frac{d}{d(\bar{m}\varepsilon)}\right)\delta m_N + \delta m_{N,\mathrm{QCD}}\frac{1-\varepsilon^2}{2\varepsilon}\left(\bar{\theta} - \bar{\theta}_{\mathrm{ind}}\right)\;,$$

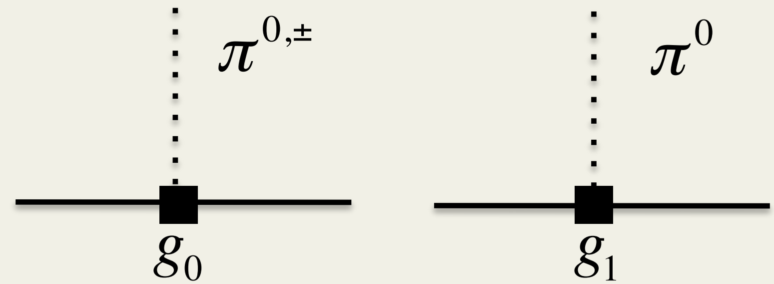
$$\bar{g}_1 \;=\; -2\tilde{d}_3\left(\frac{d}{d\tilde{c}_0} - r\frac{d}{d\bar{m}}\right)\Delta m_N + 4\frac{\phi}{\sqrt{3}}\left[\tilde{d}_s\left(\frac{d}{d\tilde{c}_s} - r\frac{d}{dm_s}\right)\right]\Delta m_N$$

- Relations protected up to N2LO — JdV, Mereghetti, Seng, Walker-loud 'in prep
- Promising way to get g_0 , g_1 from lattice

Back to pion-nucleon couplings

- 2 CP-odd structures

$$L = g_0\, \bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N + g_1\, \bar{N}\pi^0 N$$



Mohapatra, Senjanovic, Pati '75

Maiezza et al ' 14

- Four-quark left-right operator breaks isospin !

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

- Absolute sizes of $g_{0,1}$ are not given by ChPT. No sum rules either….
- ChPT gives ratio of couplings

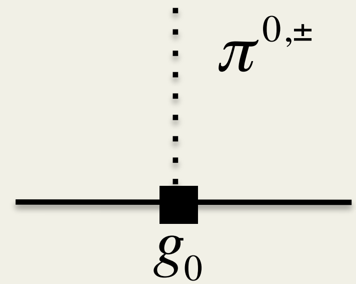
$$\frac{\bar{g}_1}{\bar{g}_0} = \frac{8c_1 m_\pi^2}{(m_n - m_p)^{strong}} = -(68 \pm 25)$$

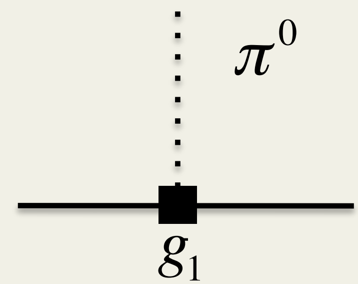
JdV et al '12
Bsaisou et al '14

Back to pion-nucleon couplings

- 2 CP-odd structures

$$L = g_0\, \bar{N}\pi \cdot \tau N + g_1\, \bar{N}\pi^0 N$$





Key idea

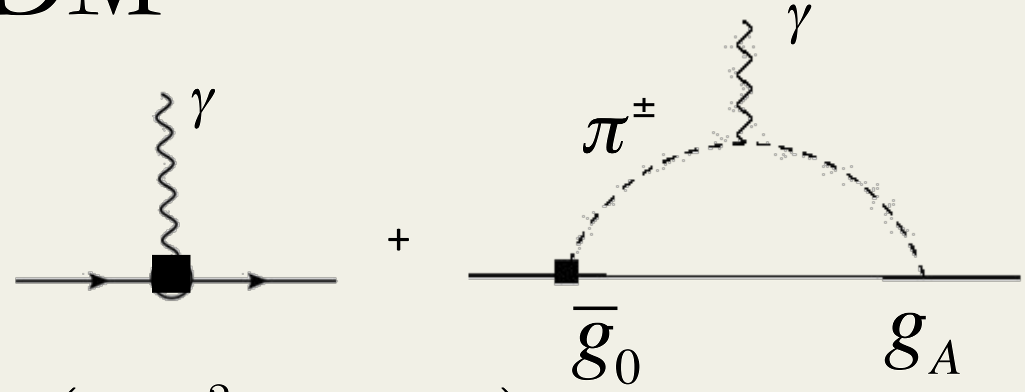
- The theta-term and dim-6 operators have different chiral properties
- **Different models -> Different g0/g1 ratios**

	Theta	2HDM	mLRSM	
	Theta term	**Quark CEDMs**	**FQLR**	**Quark EDM and Weinberg**
$\dfrac{\bar{g}_1}{\bar{g}_0}$	-0.2	≈ 1	$+50$	**Both couplings are suppressed !**

- **But how to experimentally probe these ratios ?**

The Nucleon EDM

Nucleon EDM



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

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

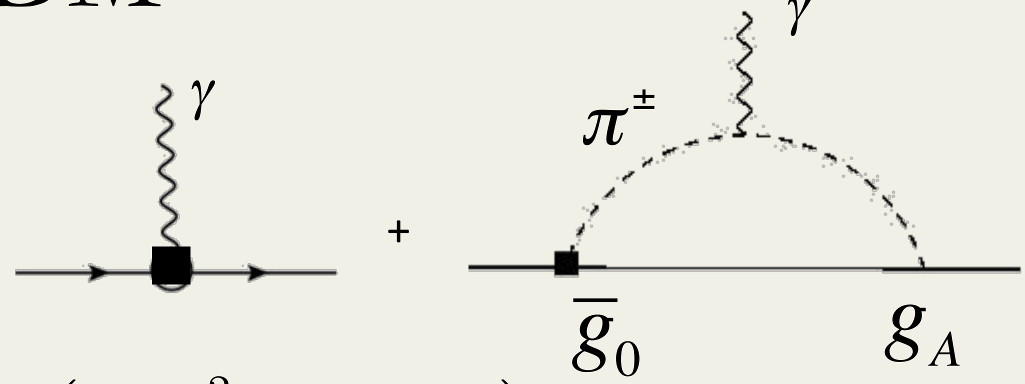
- absorbed UV divergences in $\bar{d}_0$, $\bar{d}_1$
- LO counterterms…. No ChPT prediction for size.

- **For all CPV sources,** neutron and proton EDM of **same** order
- More can be said with lattice and/or model calculations

Crewther et al., ’79, Pich, Rafael, ’91, Borasoy ‘00 Guo et al, ’10 ’12 ’14, Mereghetti et al ‘10 ’11 ‘14

The Nucleon EDM

Nucleon EDM



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

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

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

- Experimental constraint: ⟶ $\bar{\theta} < 10^{-10}$
- Lattice + **ChPT** $d_n = -(3.9 \pm 1.0)\cdot 10^{-16}\,\bar{\theta}\,e\,\mathrm{cm}$ Guo et al '14 '15

O' Connell /Savage '06

See also: Shindler et al '15, Shintani et al '15, Alexandrou et al '15

Extracting g_0

- ChPT makes a 'robust' prediction $\bar{g}_0 = -(15.5 \pm 2.5) \cdot 10^{-3}\,\bar{\theta}$
- Lattice Test

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

EDM

Radius (Schiff moment)

- Schiff moments are **ChPT predictions**

$$S_n = -S_p = -\frac{e g_A \bar{g}_0}{48\pi^2 F_\pi}\frac{1}{m_\pi^2}\left(1 - \frac{5\pi}{4}\frac{m_\pi}{m_N}\right)$$

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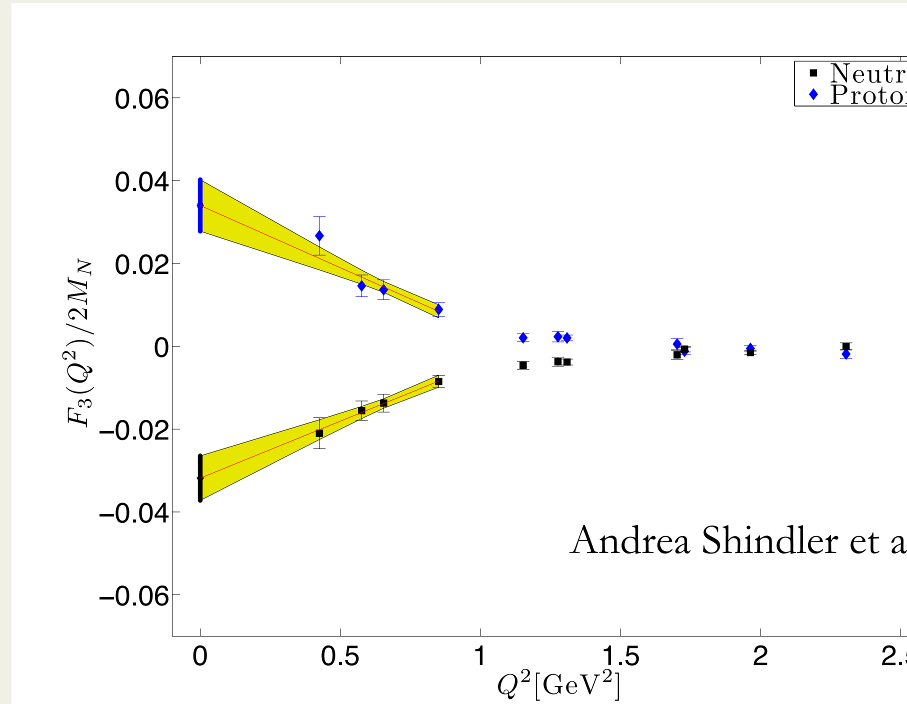


- Signs of slopes agree
- Magnitudes larger then ChPT (larger g0 by factor 5)
- However, quenched + large pion masses + large Q^2 …..

- Similar pattern in Shintani et al, PRD '16. Need higher precison.

And dim-6 sources ?

- Quark EDM accurately determined recently !

Bhattacharya et al '15 '16

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

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

QCD sum rules: nucleon EDMs ~ 50-75% uncertainty

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

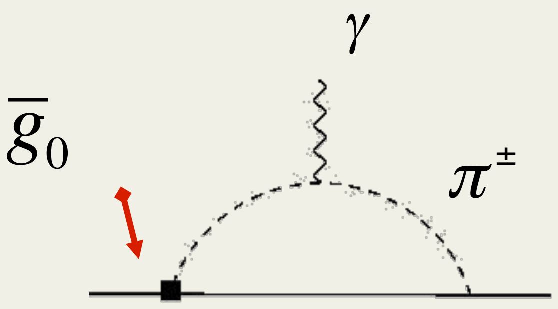
- Weinberg (and four-quark) only **estimates**

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

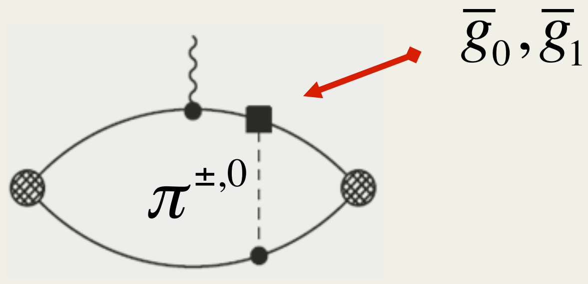
Weinberg '89
Demir et al '03

- **Ratio of |proton/neutron EDM|~O(1) for all sources**
- **Need more input to unravel the models**

Probe these ratios with nuclear EDMs



Nucleon EDM



Nuclear EDM

- Tree-level: **no loop** suppression
- Orthogonal to nucleon EDMs, sensitive to different CPV structures

$$d_A = \langle \Psi_A \parallel \vec{J}_{CP} \parallel \Psi_A \rangle + 2 \langle \Psi_A \parallel \vec{J}_{CP} \parallel \tilde{\Psi}_A \rangle$$

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

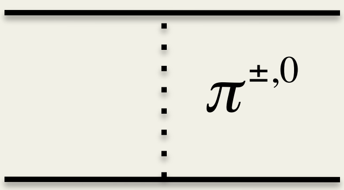
- CP-even forces + currents from chiral EFT
- **Need to describe the CPV nuclear force !**

A quick look at the P- and T-odd potential

- How do we know that pion exchange **(long-range)** dominates?

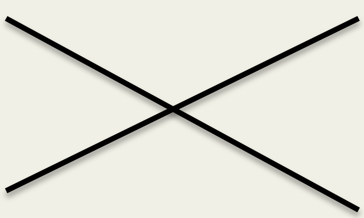
CP-even

$$\frac{g_A}{2F_\pi}\bar{N}(\vec{\sigma}\cdot\vec{D}\pi^a)\boldsymbol{\tau}^a N$$



$$\sim \frac{(g_A Q)^2}{Q^2} \sim Q^0$$

$$\bar{N}N\,\bar{N}N$$



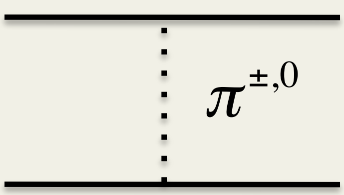
$$\sim Q^0$$

A quick look at the P- and T-odd potential

- How do we know that pion exchange **(long-range)** dominates?
- If CPV + **chiral breaking** then **nonderivative pi-N** couplings

CP-even

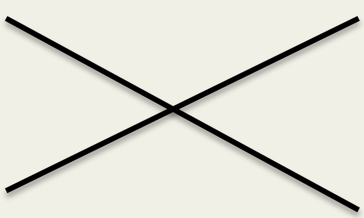
$$\frac{g_A}{2F_\pi}\bar{N}(\vec{\sigma}\cdot\vec{D}\pi^a)\tau^a N$$



$\pi^{\pm,0}$

$$\sim \frac{(g_A Q)^2}{Q^2} \sim Q^0$$

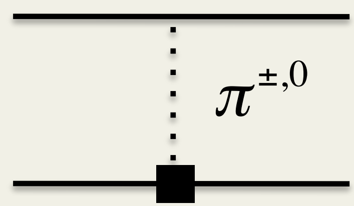
$$\bar{N}N\,\bar{N}N$$



$$\sim Q^0$$

CP-odd

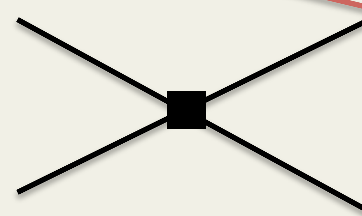
$$g_0\,\bar{N}\pi\cdot\tau N + g_1\,\bar{N}\pi^0 N$$



$\pi^{\pm,0}$

$$\sim \frac{(g_A Q)g_{0,1}}{Q^2} \sim Q^{-1}$$

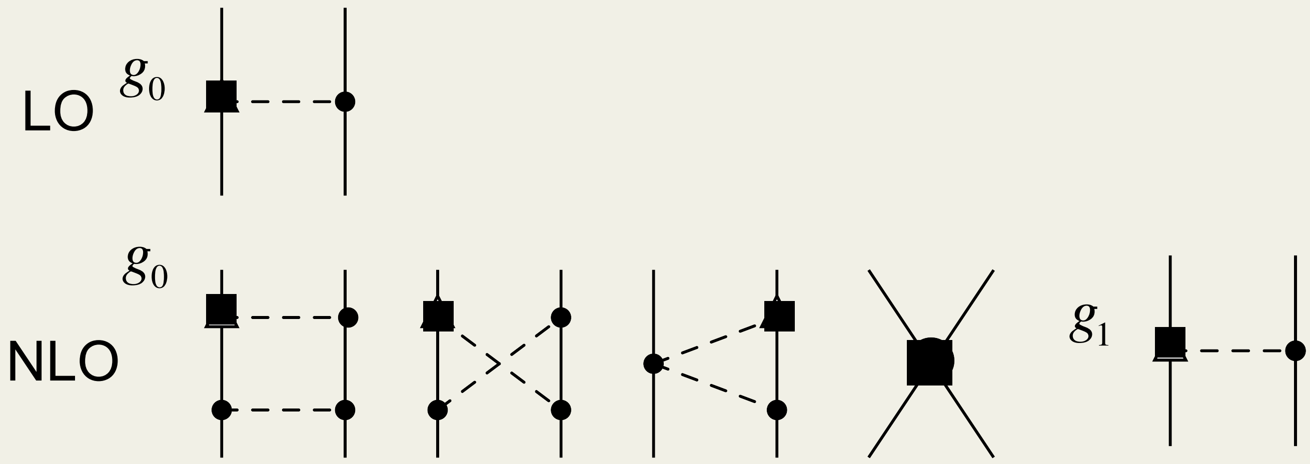
$$\bar{N}N\,\partial^i(\bar{N}\sigma^i N)$$



$$\sim Q^1$$

A quick look at the P- and T-odd potential

- Apply this to the theta term



- LO only g_0 pion exchange, NLO two-pion-exchange + g_1

- short-range estimated by resonance saturation (eta, kaon couplings)
- 10% contributions in 3He EDM

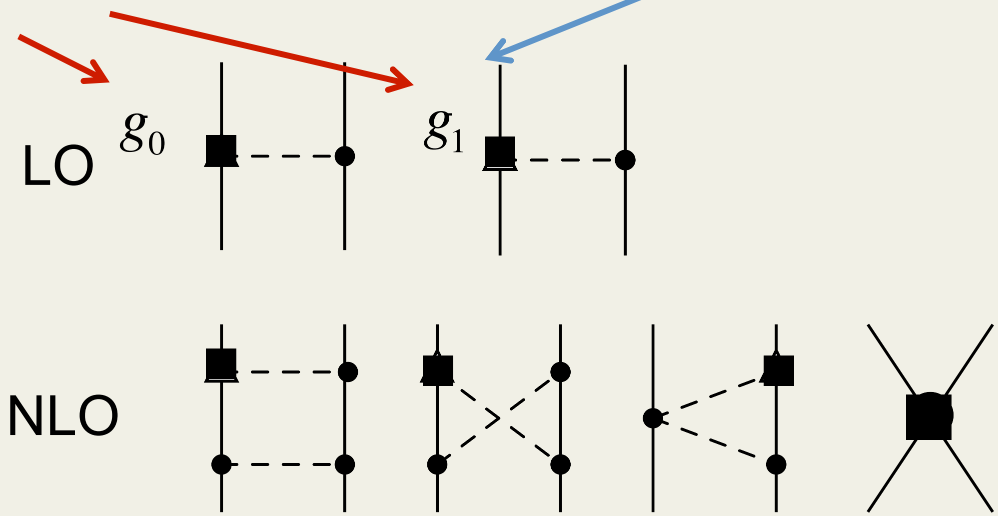
JdV et al '11 Bsaisou et al '14

A quick look at the P- and T-odd potential

JdV et al ‘11

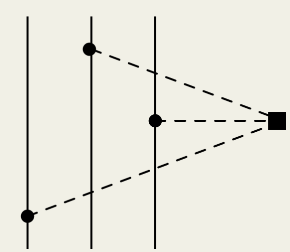
- Quark CEDMs

FQLR



- Both pion exchange at leading order (but LECs not well known yet)
- Short-range expected to be small (good!)
- TPE g_1 diagrams vanish, g_0 work in same channel as OPE

- For FQLR only: three-nucleon force at NLO
- Found to be **small** in 3He



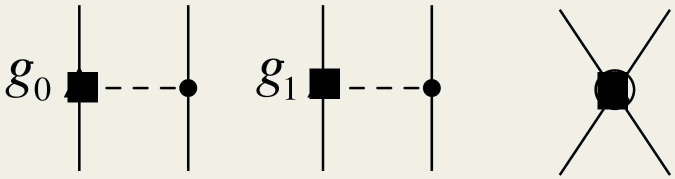
A quick look at the P- and T-odd potential

- Weinberg operator + chiral-invariant FQ operators

JdV et al '11

LO

NLO



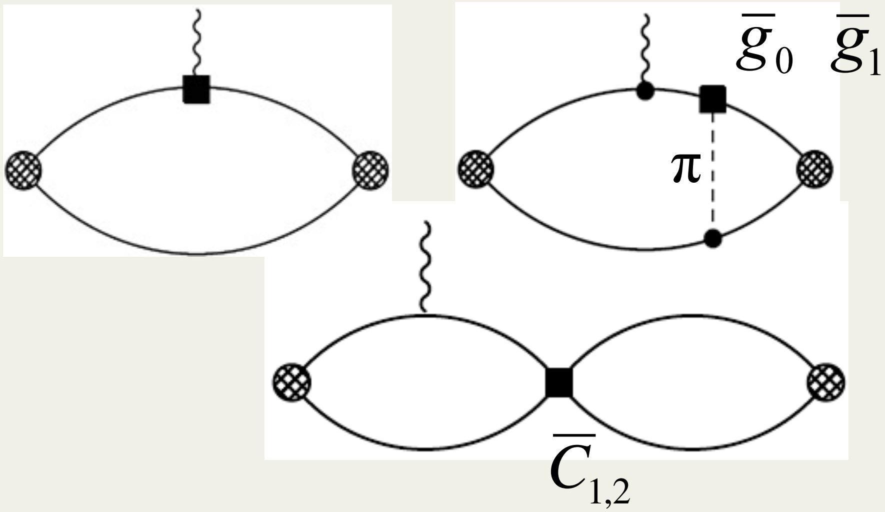
- Pion-exchange suppressed because of **chiral symmetry**

- Short-range NN terms **not suppressed** compared to OPE !
- **Large uncertainties** in both LECs and nuclear matrix elements

EDM of the deuteron

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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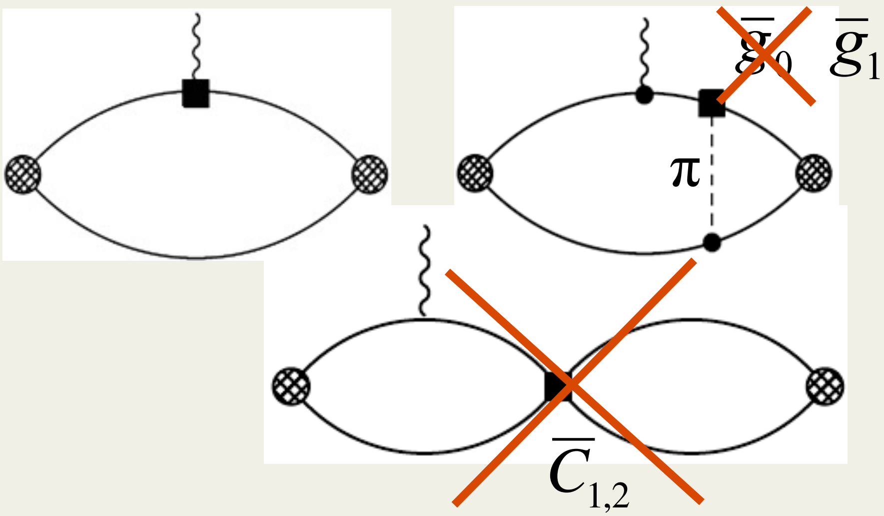


- **Deuteron is a special case due to N=Z**

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

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

The chiral filter

Liu/Timmermans '04
JdV et al '11
Bsaisou et al '14

Chiral filter

- Deuteron EDM results

$$d_D = 0.9(d_n + d_p) + \left[(0.18 \pm 0.02)\,\bar{g}_1 + (0.0028 \pm 0.0003)\,\bar{g}_0\right] e\ fm$$

- Error estimate from cut-off variations + higher-order terms

`	Theta term	Quark CEDMs	Four-quark operator	Quark EDM and Weinberg
$\left\lvert \frac{d_D - d_n - d_p}{d_n} \right\rvert$	0.5 ± 0.2	5 ± 3	20 ± 10	$\cong 0$

- Ratio suffers from hadronic (not nuclear!) uncertainties **(need lattice)**
- EDM ratio hint towards **underlying CP-odd operator**!

The chiral filter

Stetcu et al '08
JdV et al '11
Song et al '13
Bsaisou et al '14

- Deuteron EDM results

$$d_D = 0.9(d_n + d_p) + \left[(0.18 \pm 0.02)\,\bar{g}_1 + (0.0028 \pm 0.0003)\,\bar{g}_0\right] e\ fm$$

$$d_{3He} = 0.9\, d_n - 0.05\, d_p + \left[(0.14 \pm 0.04)\,\bar{g}_1 + (0.10 \pm 0.03)\,\bar{g}_0\right] e\ fm + \ldots.$$

`	**Theta term**	**Quark CEDMs**	**Four-quark operator**	**Quark EDM and Weinberg**
$\left\lvert \frac{d_D - d_n - d_p}{d_n} \right\rvert$	0.5 ± 0.2	5 ± 3	20 ± 10	$\cong 0$

- Ratio suffers from hadronic (not nuclear!) uncertainties **(need lattice)**
- EDM ratio hint towards **underlying CP-odd operator**!
- 3He is complementary but also short-range corrections….
- Extended to 6Li, 13C, 19F? (**nuclear cluster model**)

Yamanaka et al '15, '16

Uuugh….

Plot from Bsaisou et al JHEP '14

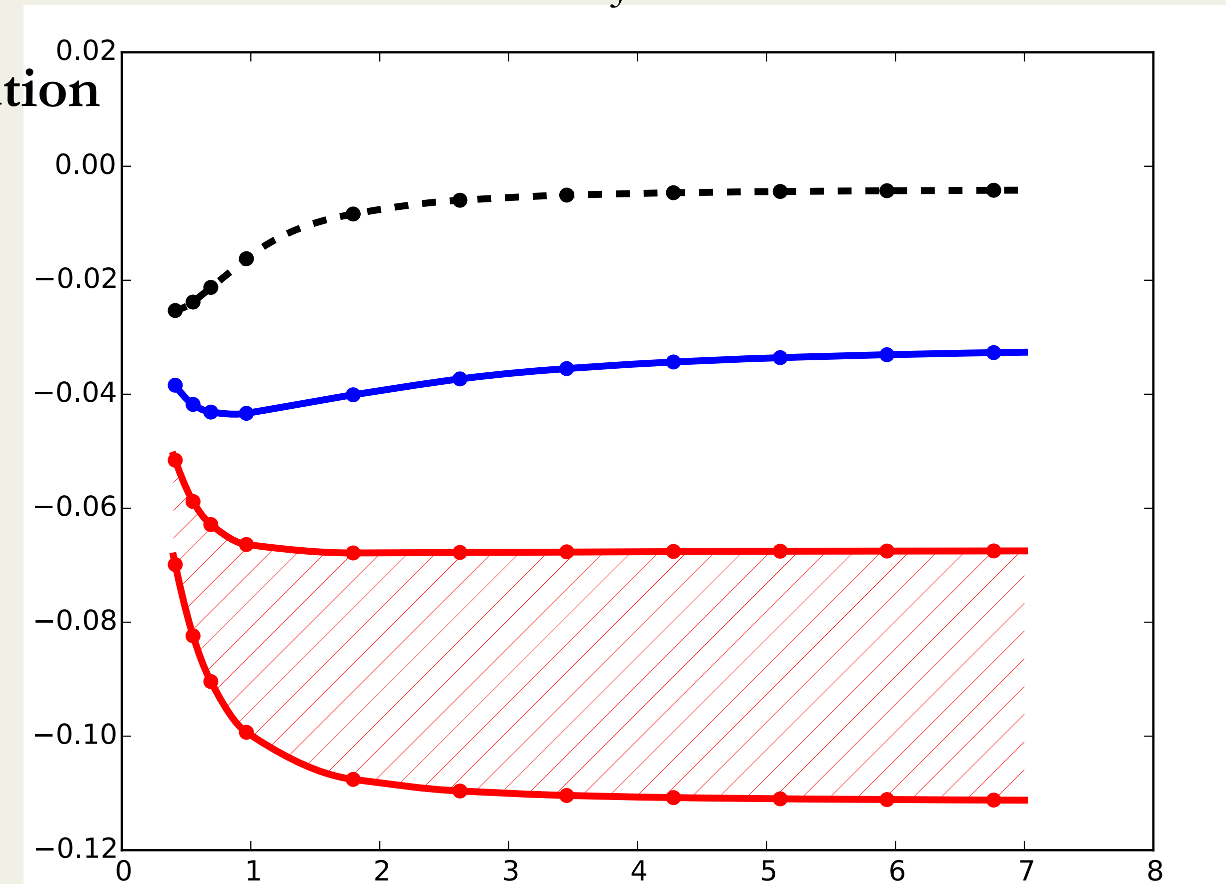
EDM contribution (some units)

Av18

CD-Bonn

Chiral EFT

Cut-off variation



Heavy meson mass (GeV)

- Quite a large spread ….
- Av18 very repulsive at short distances
- Only 10-30% for theta/qCEDM (but unknown for Weinberg)

Unraveling models

Dekens et al '14

Theta term: quantitative predictions

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

$$d_D - d_n - d_p = -(0.89 \pm 0.3) \cdot 10^{-16} \theta \, e \, cm$$

$$d_{3He} - 0.9 d_n = (1.0 \pm 0.4) \cdot 10^{-16} \theta \, e \, cm$$

Left-right symmetry

$$\left| \frac{d_{2H}}{d_{n,p}} \right| = 20 \pm 10$$

$$d_{3He} = (0.8 \pm 0.1) d_D$$

Identifying **Aligned 2HDM** more difficult. Need lattice input.

$$|d_{3He}| \sim |d_D| \sim 5 \, |d_{n,p}|$$

Complementary info from electron EDM (assuming similar phases)

Theta: $\frac{d_e}{d_n} = 0$ **mLRSM:** $\frac{d_e}{d_n} \sim 10^{-4}$ **2HDM:** $\frac{d_e}{d_n} \sim 10^{-2}$

Onwards to heavy systems

Graner et al, '16

Strongest bound on atomic EDM: $d_{^{199}Hg} < 8.7 \cdot 10^{-30}\ e\,cm$

New measurements expected: Ra , Xe, ….

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

1. Non-relativistic kinematics
2. Point particles

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

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

Dzuba et al, '02, '09

Sing et al, '15

EFT and many-body problems

- Need to calculate Schiff Moment (or MQM) of Hg, Ra, Xe….
- **Issue:** no power counting…. Do pions dominate ?
- Say we assume so:

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

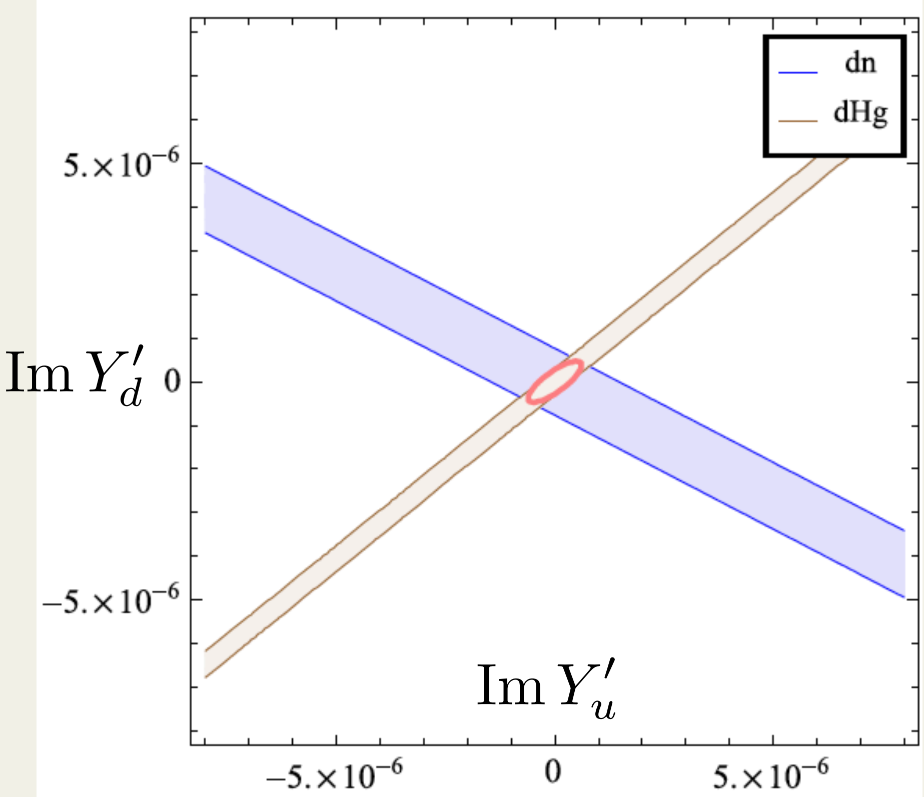
	a_0 range (best)	**a_1 range (best)**
^{199}Hg	0.03±0.025 (0.01)	0.030±0.060 (±0.02)
^{225}Ra	-3.5±2.5 (-1.5)	14±10 (6)
^{129}Xe	-0.03±0.025 (-0.008)	-0.03±0.025 (-0.009)

Flambaum, de Jesus, Engel, Dobaczewski,,….

- Uncertainties would make interpretation more difficult
- **Great challenge: connect chiral-EFT approach to heavier nuclei**

table from review: Engel et al, '13

Role of uncertainties

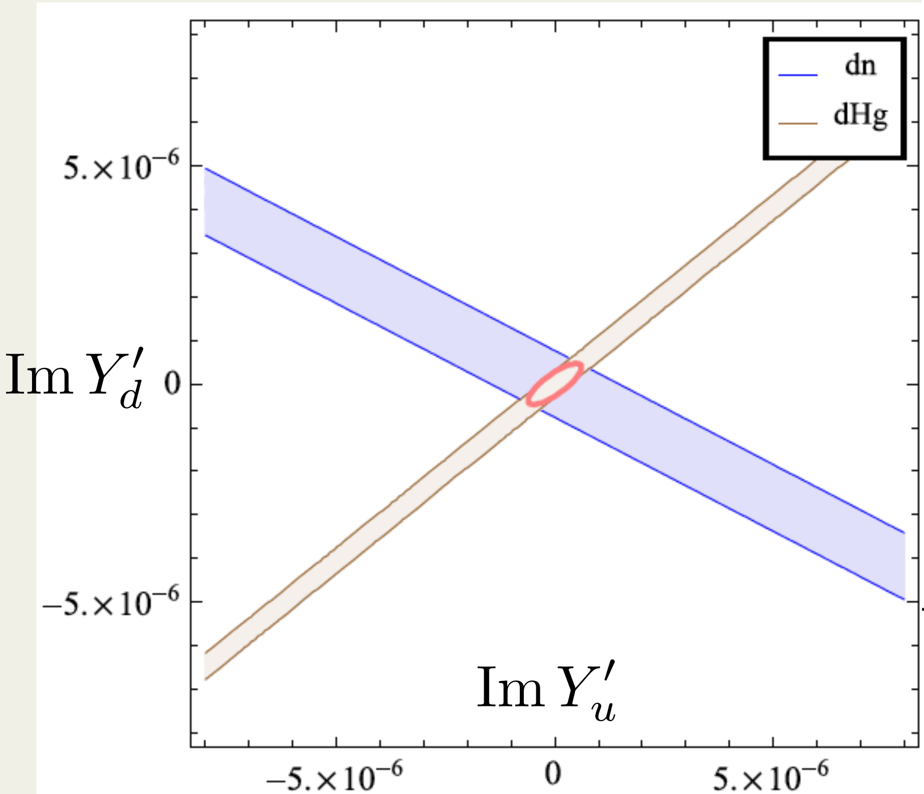


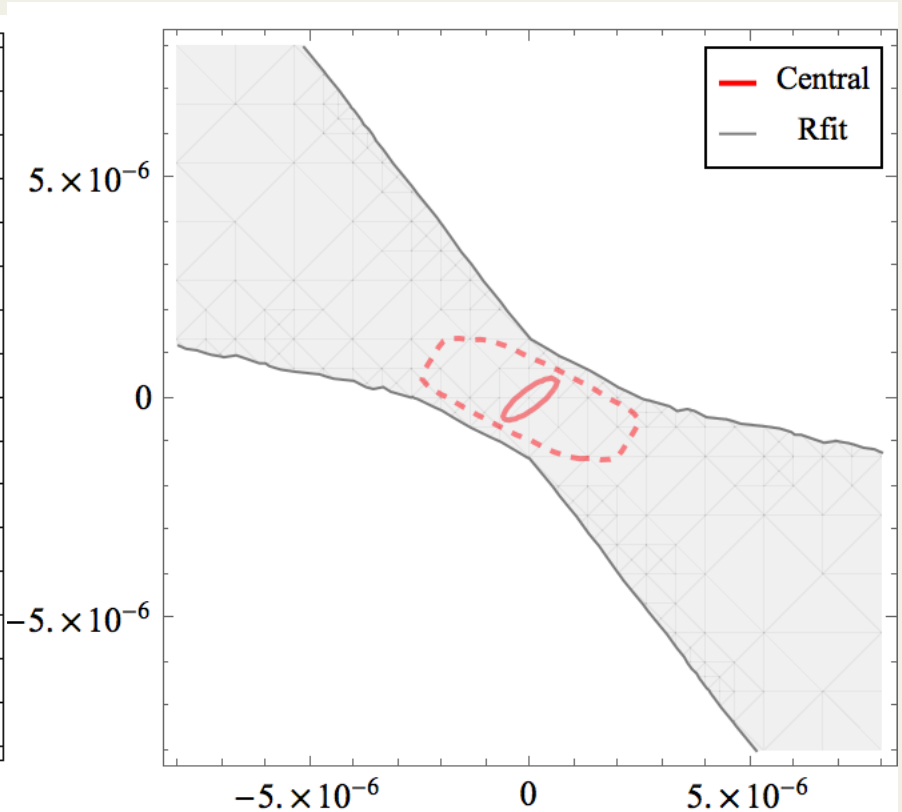
- The Higgs Yukawa couplings to quarks can be complex (2HDM, SUSY, …)
- Central values matrix elements

$$v^2 \mathrm{Im}\, Y'_{u,d} < 10^{-6}$$

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

Role of uncertainties





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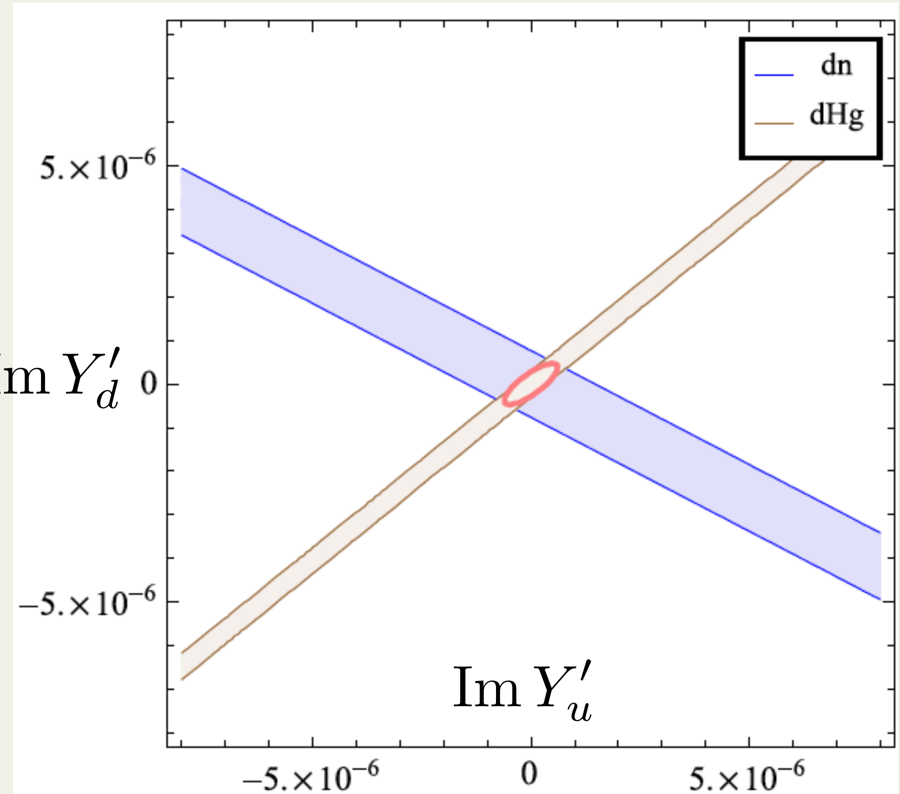
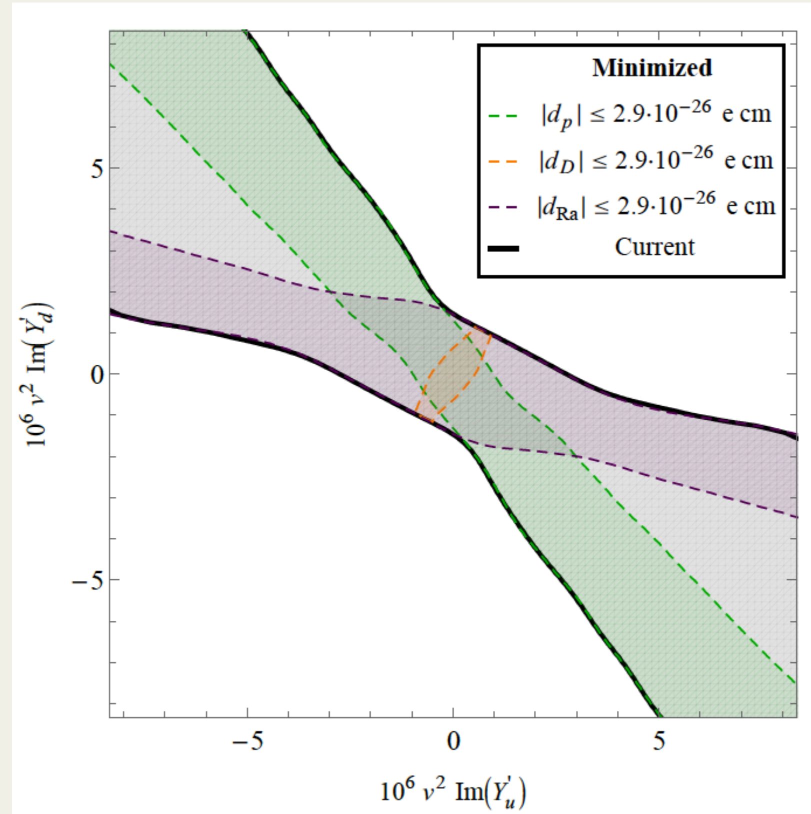
- Central values matrix elements
- Once uncertainties are included. **Free direction appears !**
- Modest hadronic+nuclear theory improvements (50%) would help a lot

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

Role of uncertainties





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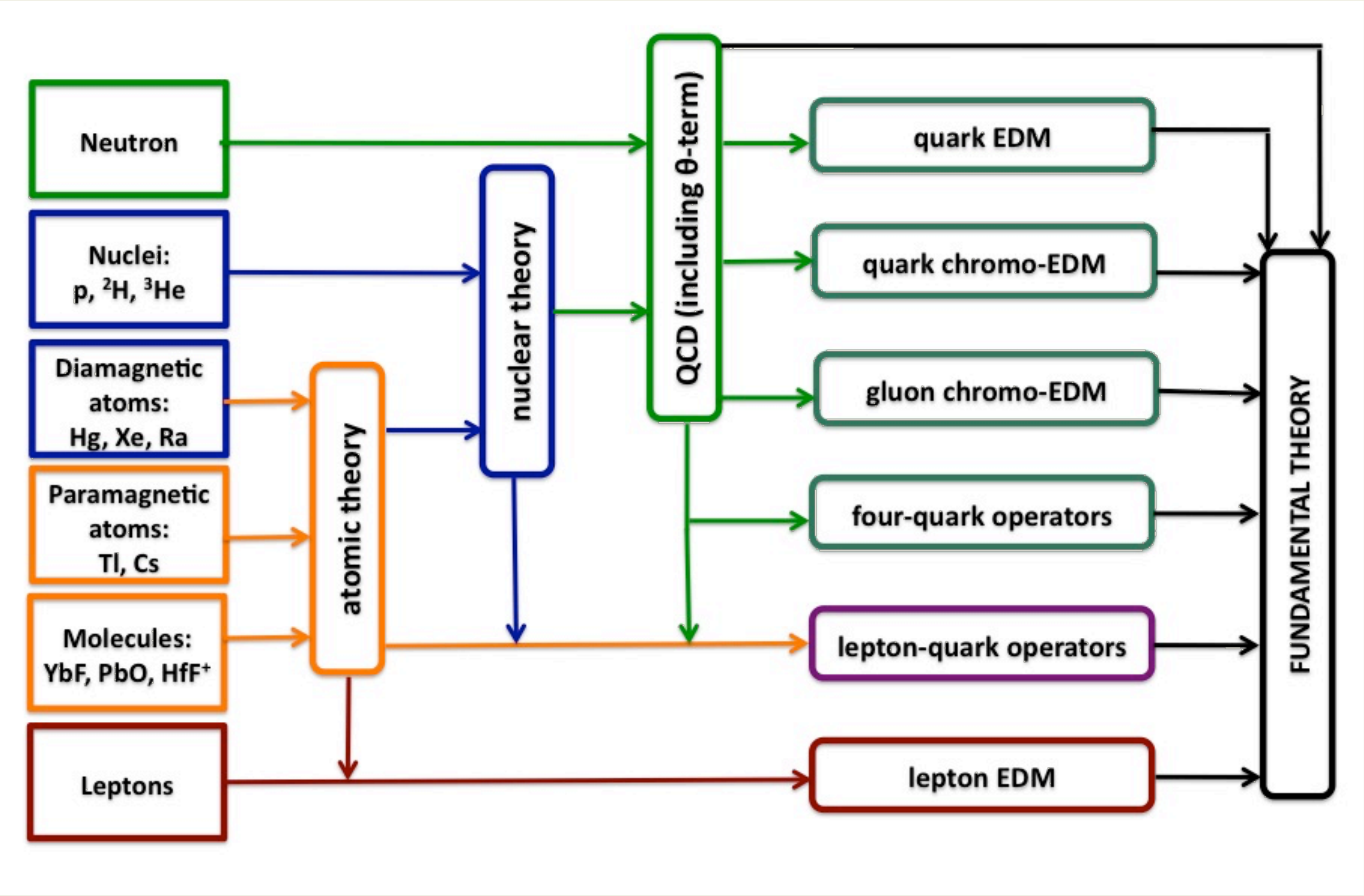
- Once uncertainties are included. **Free direction appears !**
- Modest hadronic+nuclear theory improvements (50%) would help a lot
- Or new experiments !

Plots from Chien, Cirigliano, Dekens, JdV, Mereghetti, ‘15

The EDM metromap



Conclusion/Summary/Outlook

EDMs

- ✓ Very powerful search for BSM physics (probe the highest scales)
- ✓ Heroic experimental effort and great outlook
- ✓ Theory needed to interpret measurements and constraints

EFT framework

- ✓ Framework exists for CP-violation (EDMs) from 1st principles
- ✓ Keep track of **symmetries** (gauge/CP/chiral) from multi-Tev to atomic scales

The chiral filter

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

- ✓ **Need theory improvement to fully exploit the experimental program**