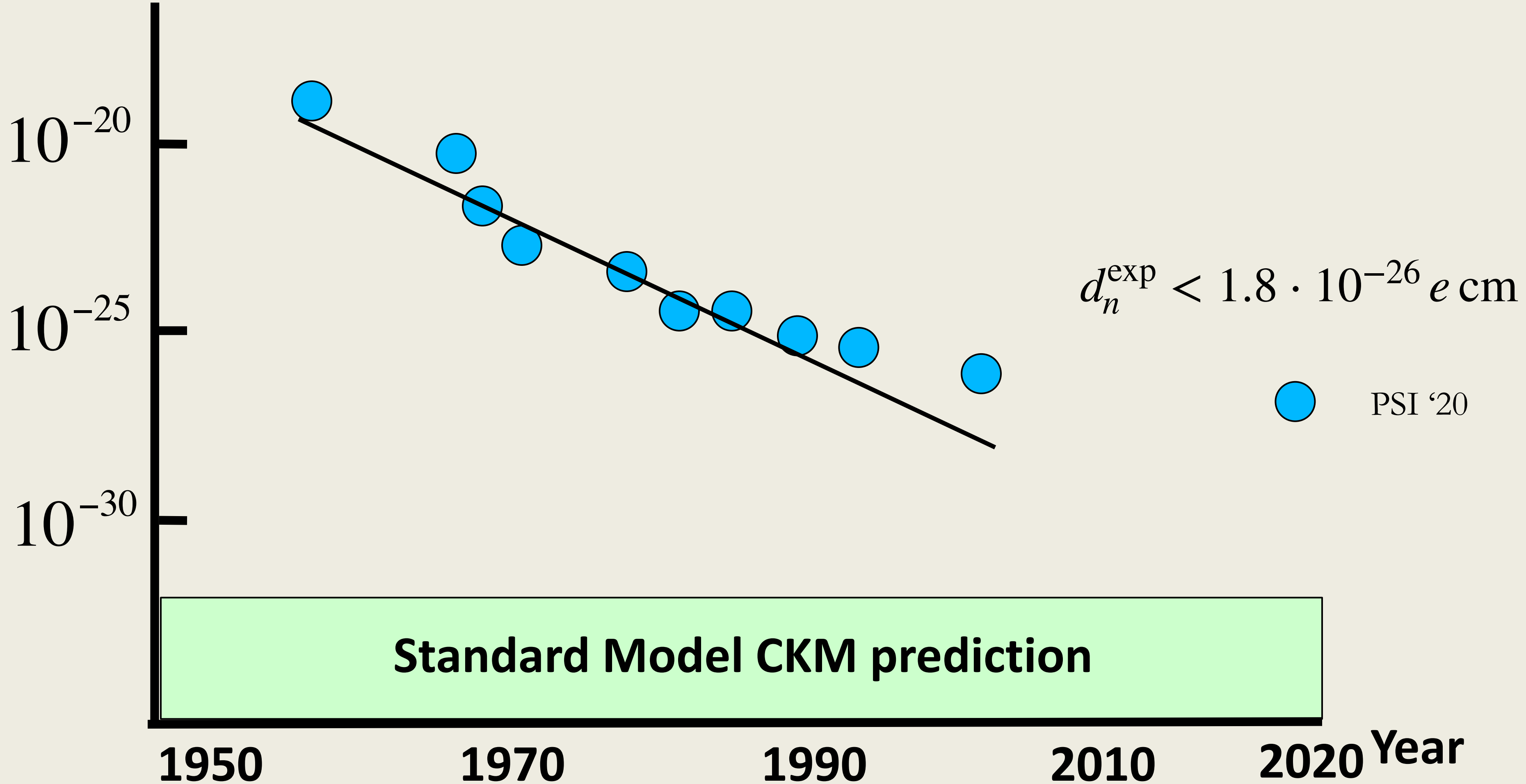
How to compute electric dipole moments

Jordy de Vries

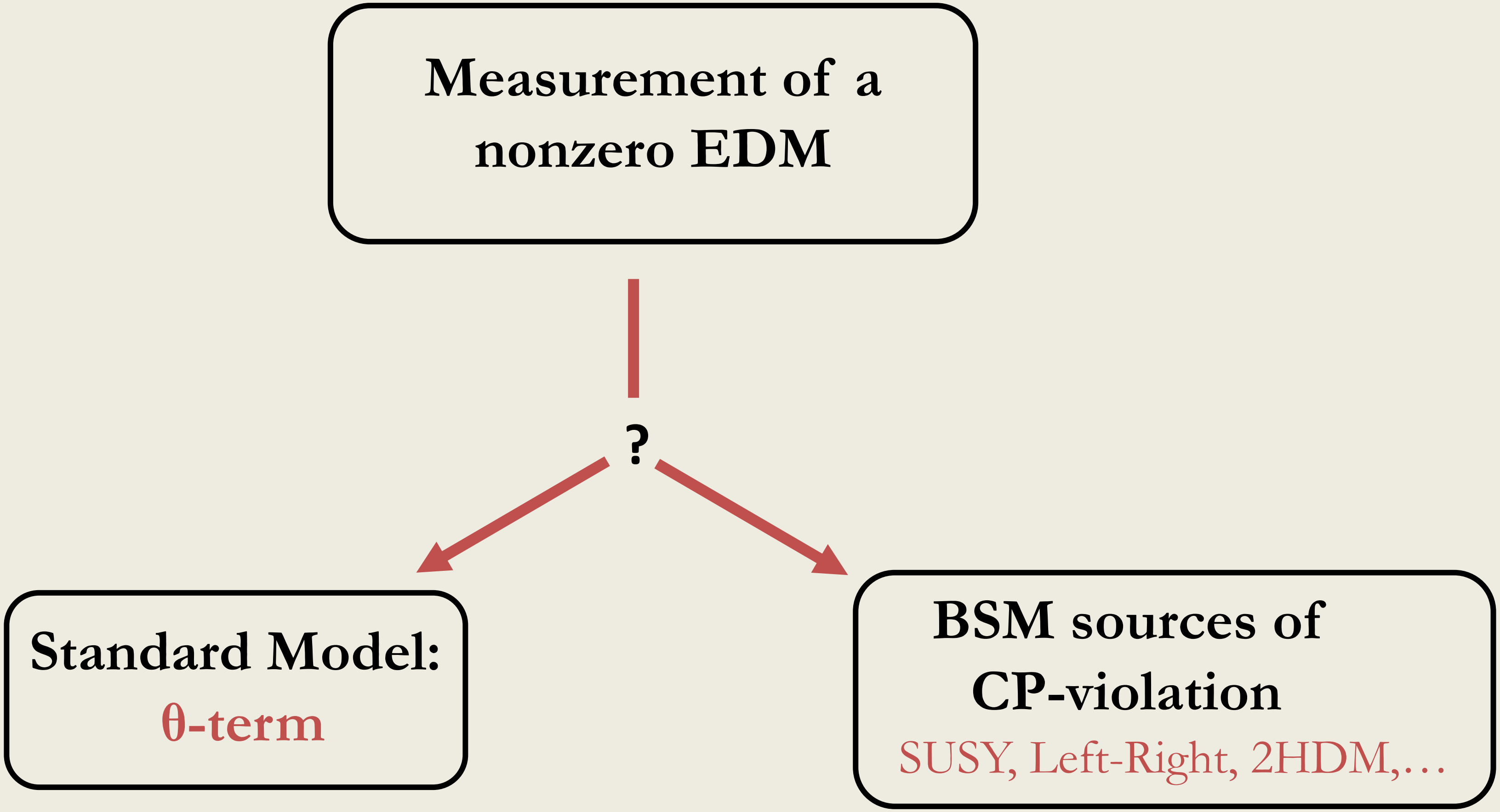
University of Amsterdam, Nikhef

Electric dipole moments and the CKM matrix

Limit on **neutron** EDM in e cm



More progress on electron EDM in recent times (factor 100 in 10 years)



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

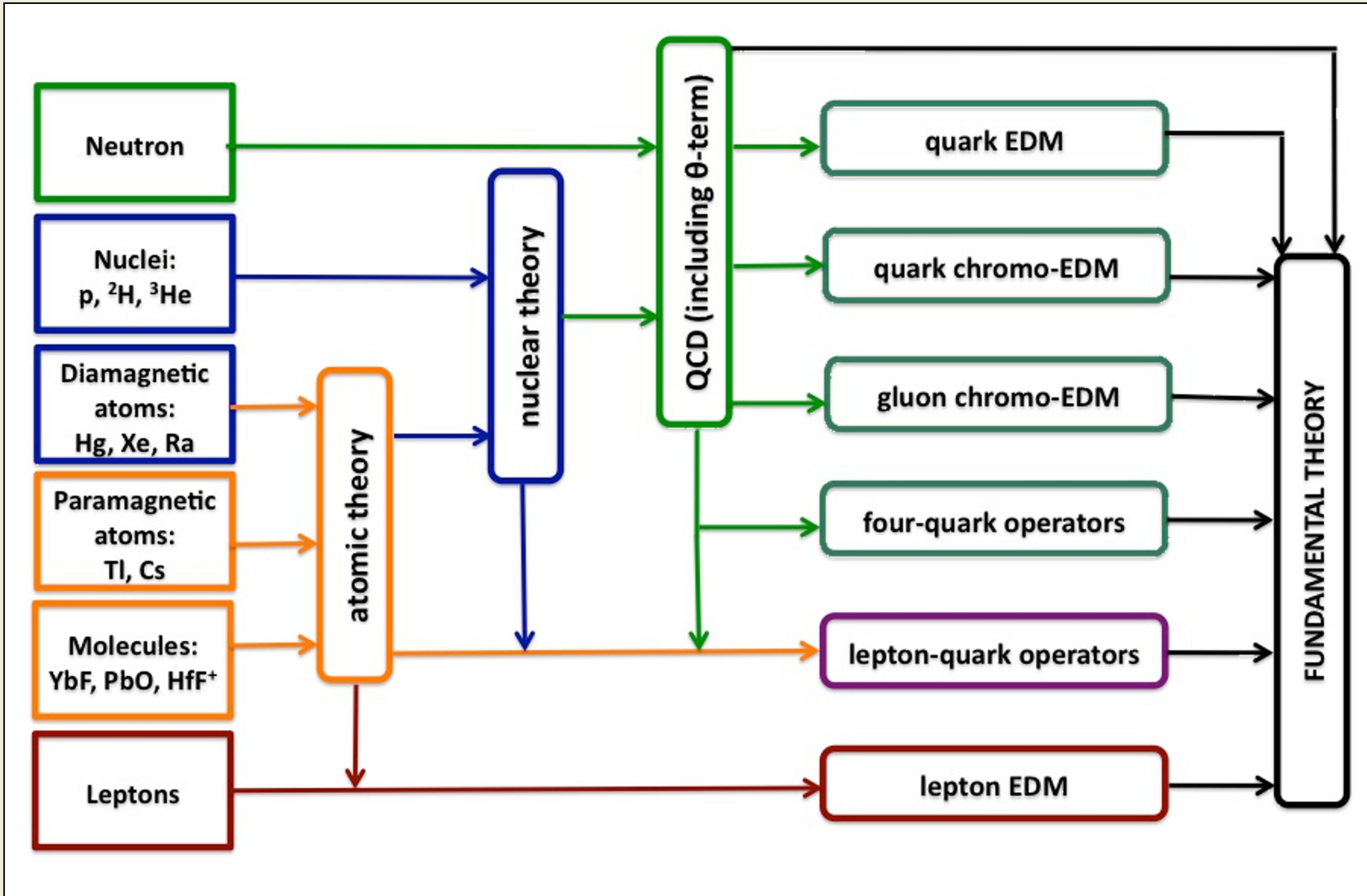
Very active experimental field

e

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
ThO	ACME	1.1×10^{-29}	90	$4.3(3.1)(2.6) \times 10^{-30}$	2018
HfF^{+}	Boulder	1.3×10^{-28}	90	$0.9(7.7)(1.7) \times 10^{-29}$	2017
n	PSI	1.8×10^{-26}	90	$0.0(1.1)(0.2) \times 10^{-26}$	2020
^{129}Xe	UMich	4.8×10^{-27}	95	$0.26(2.3)(0.7) \times 10^{-27}$	2019
^{199}Hg	UWash	7.4×10^{-30}	95	$-2.2(2.8)(1.5) \times 10^{-30}$	2016
^{225}Ra	Argonne	1.4×10^{-23}	95	$4(6.0)(0.2) \times 10^{-24}$	2016
muon	E821 BNL g−2	1.8×10^{-19}	95	$0.0(0.2)(0.9) \times 10^{-19}$	2009

- Why do experiments on so many different systems?
- How to compare different EDM and other experiments (beta decay)
- How to compare EDM experiments to other probes of CPV ?

The EDM metromap



Preliminaries

1. To separate theta from 'whatever' we need a 'whatever' description
   - Consider specific (class of) Beyond-the-SM models:
     - *Supersymetric models (MSSM, cMSSM, pMSSM, …)*
     - *Multi-Higgs or composite Higgs models*
     - *Left-right symmetric models*
     - ……….

   - EDMs are low-energy experiments → insensitive to many UV details
   - Suggests an EFT approach can be useful

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

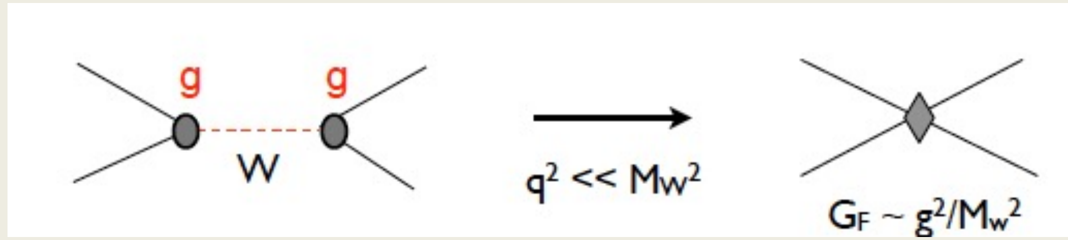
2. We require **(semi-)-precise** predictions for EDMs to separate sources
   - Not always easy since EDM experiments involve horrible objects

Describing the unknown

Buchmuller & Wyler '86
Gradzkowski et al '10

- Assume BSM physics exists but is heavy → **Integrate them out**

Fermi's theory:

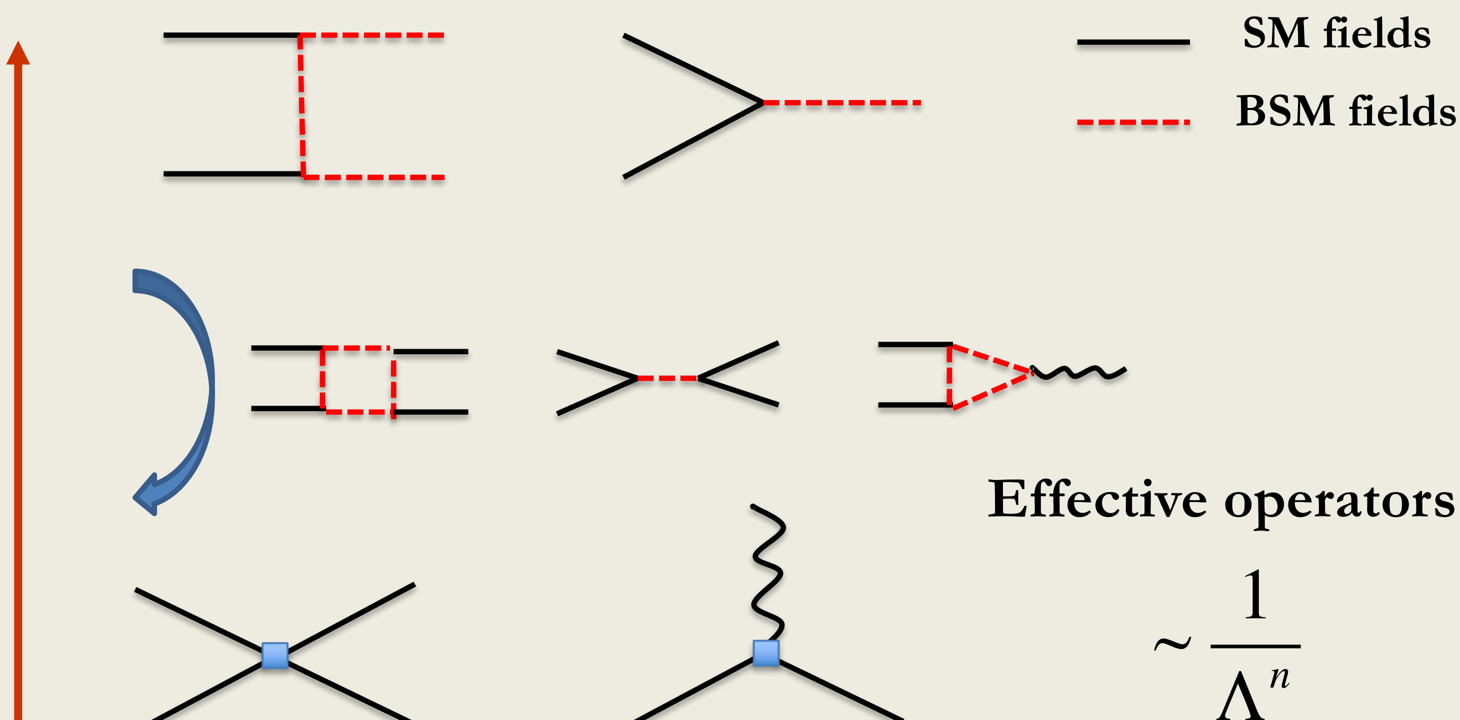


- We don't need 'high-energy details', the W boson, at low energies !

Energy

Λ

$E_{\rm exp} << \Lambda$



Effective operators

$$\sim \frac{1}{\Lambda^n}$$

Describing the unknown

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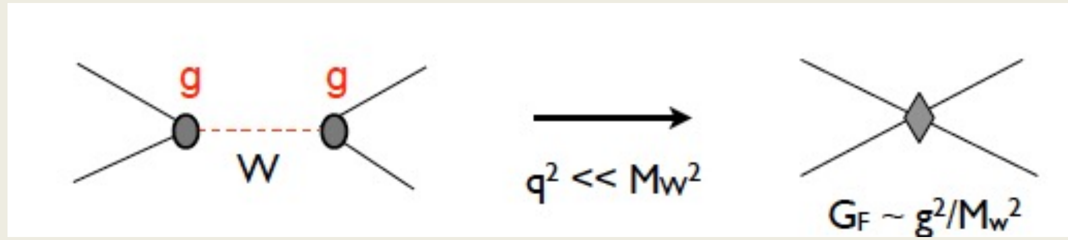
Fermi's theory:



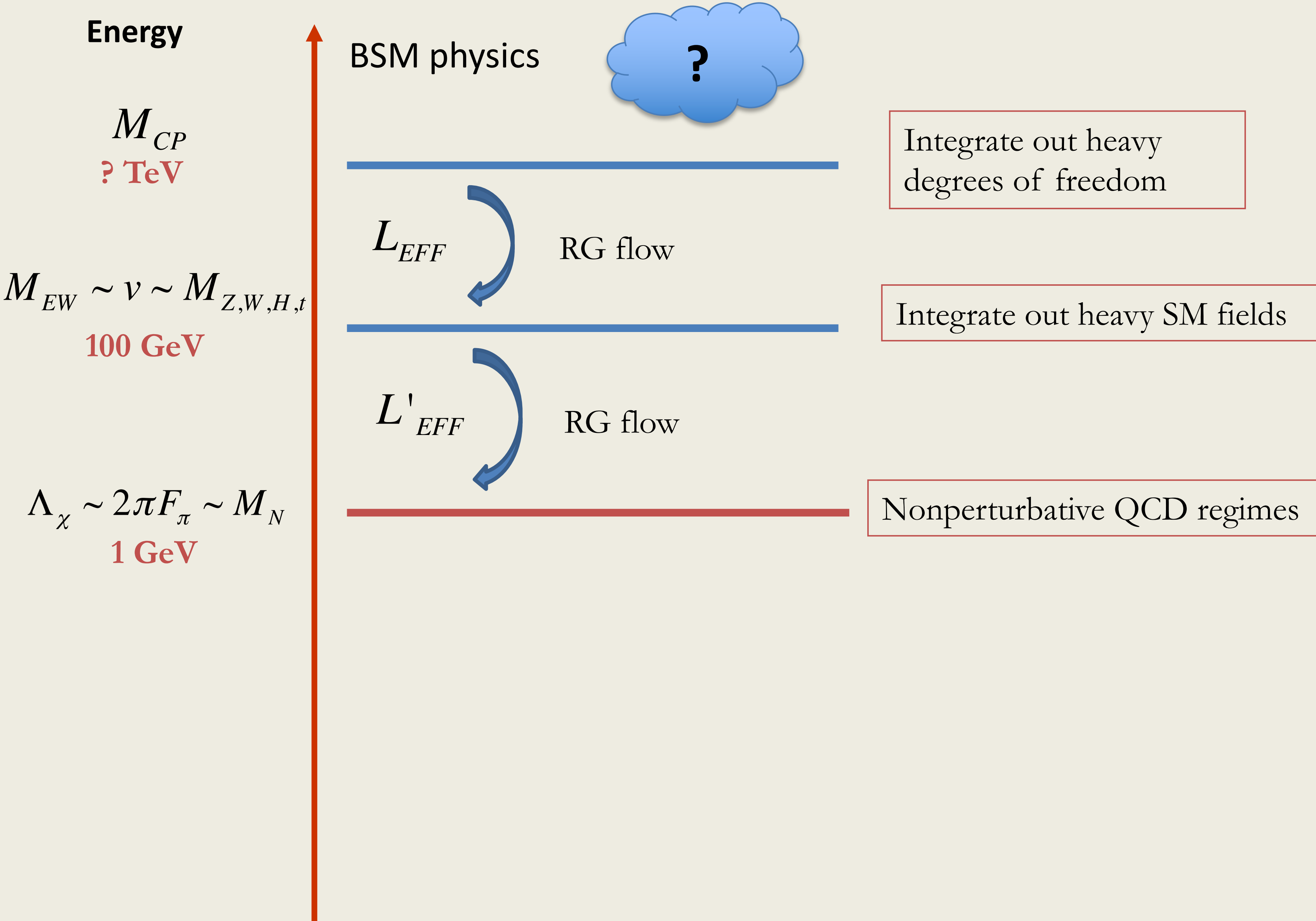
- We don't need 'high-energy details', the W boson, at low energies !

- The SM might **just** be the dim-4 part of an effective field theory

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

- Lorentz- and gauge-invariant operators from all SM fields
- For a given BSM model, we can calculate $L_{5,6,7....}$ Explicitly
- EFT approximation good at scales << Λ

Separation of scales



Separation of scales

Energy

BSM physics

?

M_{CP}
? TeV

Integrate out heavy degrees of freedom

L_{EFF}

RG flow

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

Integrate out heavy SM fields

L'_{EFF}

RG flow

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

Nonperturbative QCD regimes

Nonperturbative methods: **Lattice QCD + chiral EFT**

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

Chiral EFT
Hadronic and nuclear EDMs

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

Atomic/Molecular observables
Schiff theorem

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

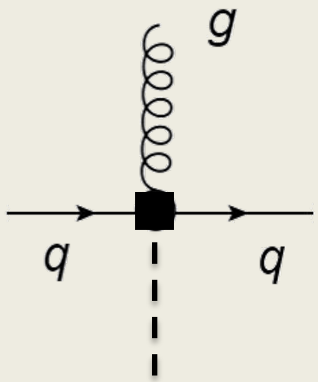
Fermion dipole operators

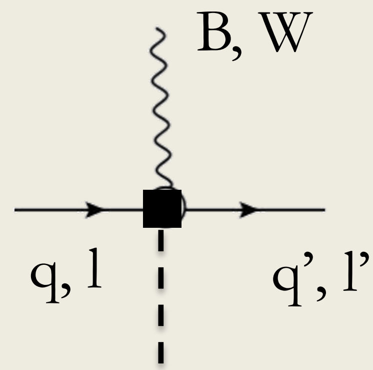
M_{CP}

? TeV

Electric and magnetic dipoles: **canonical dimension five**

Chirality flip → $SU_L(2)$ gauge symmetry requires Higgs

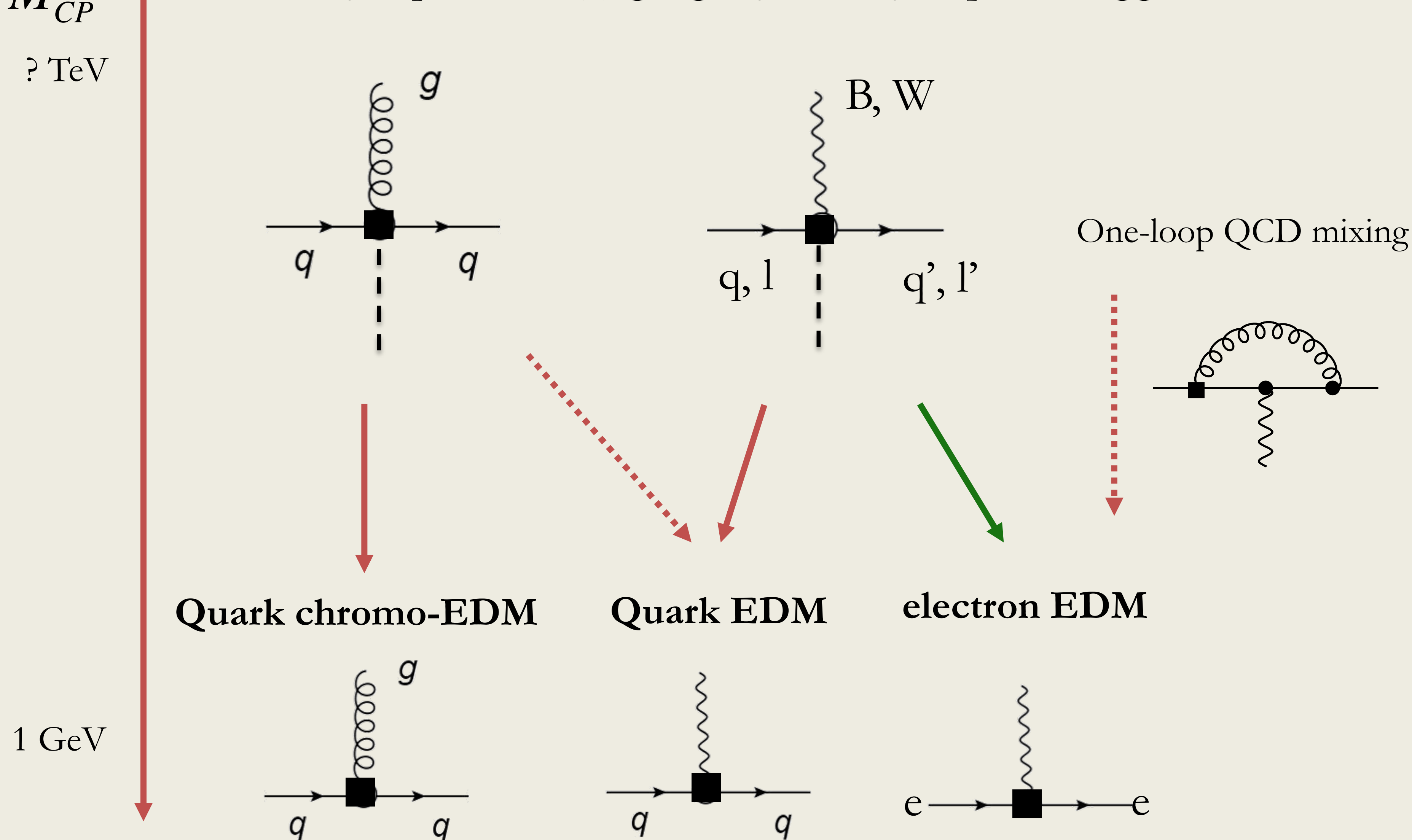




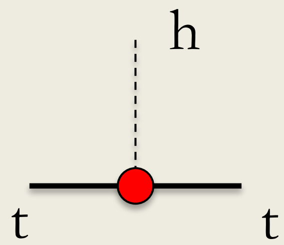
1 GeV

Fermion dipole operators

Electric and magnetic dipoles: **canonical dimension five**
Chirality flip → $SU_L(2)$ gauge symmetry requires Higgs



Yukawa couplings of heavy quarks



$$C_Y \, y_t \bar{t}_L t_R \tilde{\varphi} \, (\varphi^\dagger \varphi) + h.c.$$

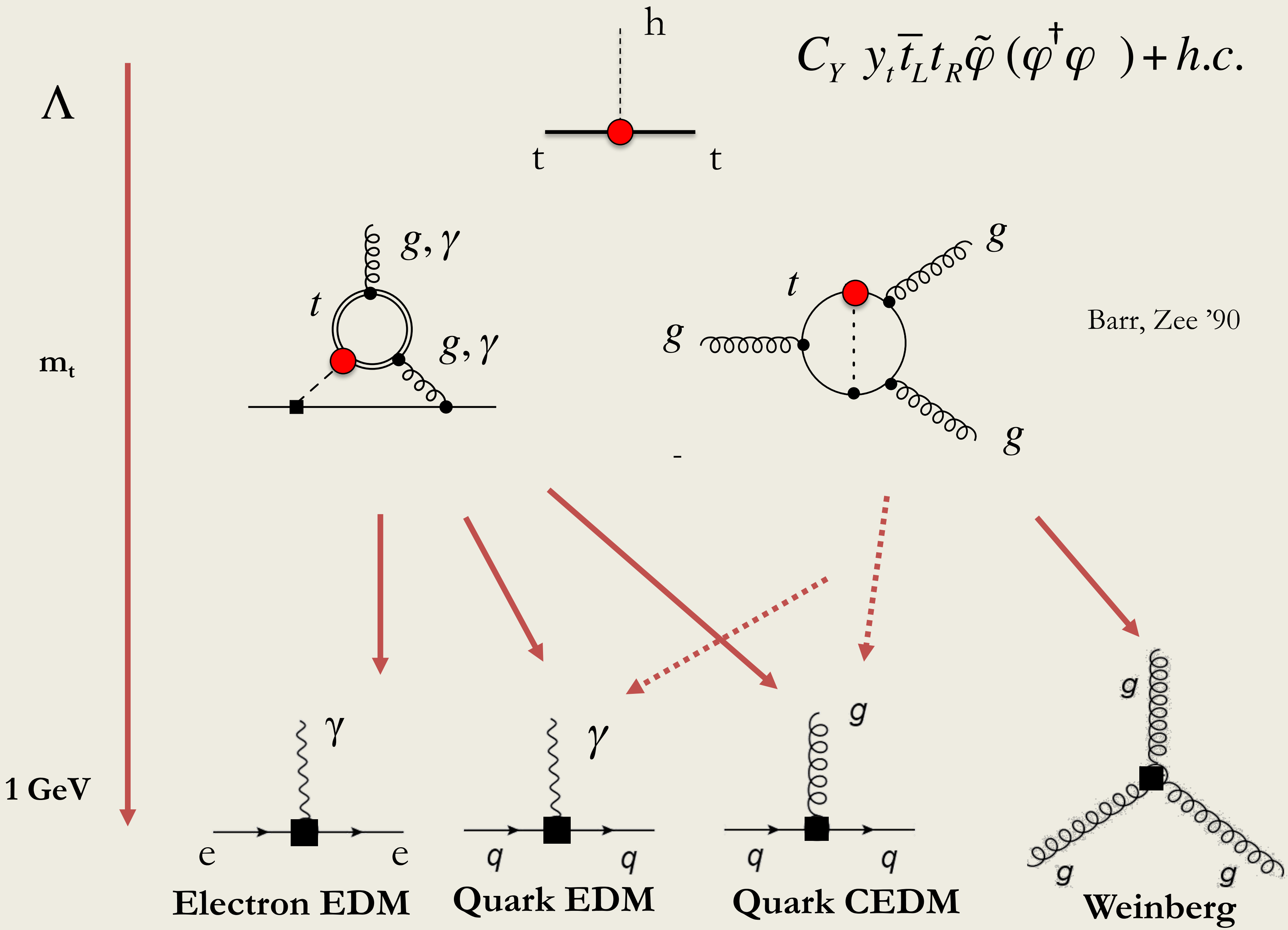
Λ

m_t

1 GeV

Yukawa couplings of heavy quarks

$$C_Y\; y_t \bar{t}_L t_R \tilde{\varphi}\,(\varphi^\dagger \varphi\;\;) + h.c.$$

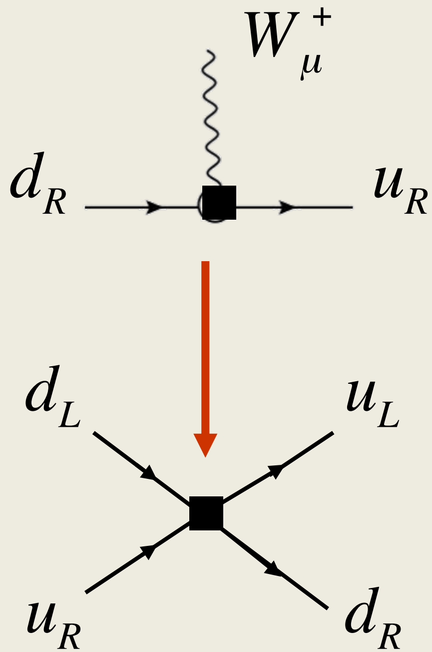


Four-quark operators

Energy

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

M_{CP}



A right-handed quark-W coupling

Ng & Tulin '12
jdV et al '12

$< M_W$

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

Λ_χ

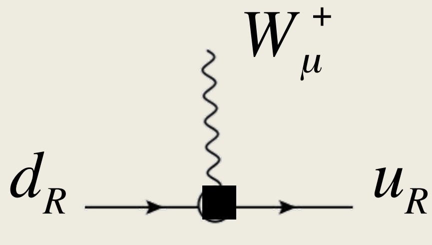
CP-violating four-quark operators

Four-quark operators

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

Energy

M_{CP}



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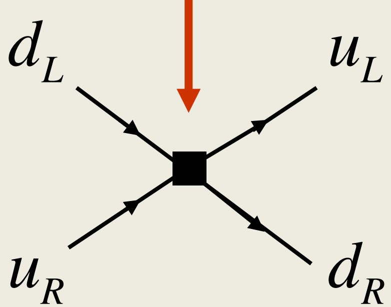
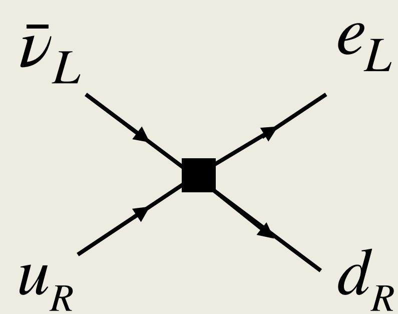




EDMs

T-violation in beta-decay (D-coefficient)

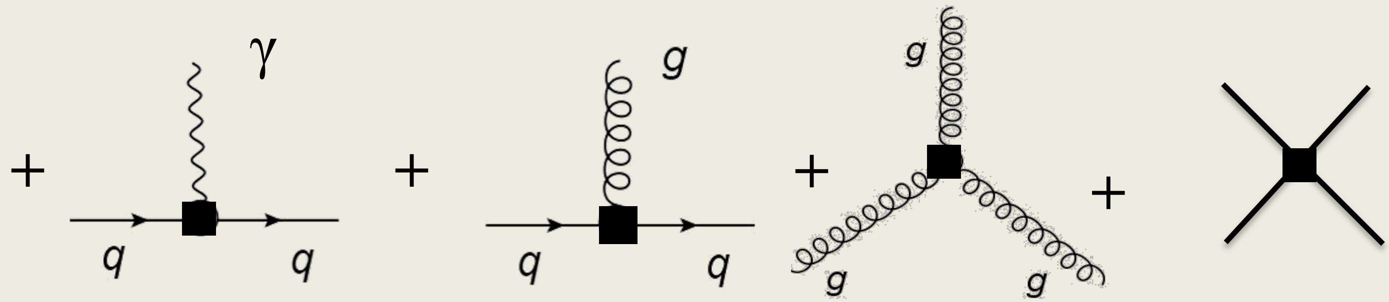
Λ_χ

Connection between \`little d and big D' at dim-6
(note LQ provide dim-8 contributions not captured here)

When the dust settles…..

Few GeV

QCD
(θ-term)



Quark EDM

Quark chromo-EDM

Gluon chromo-EDM

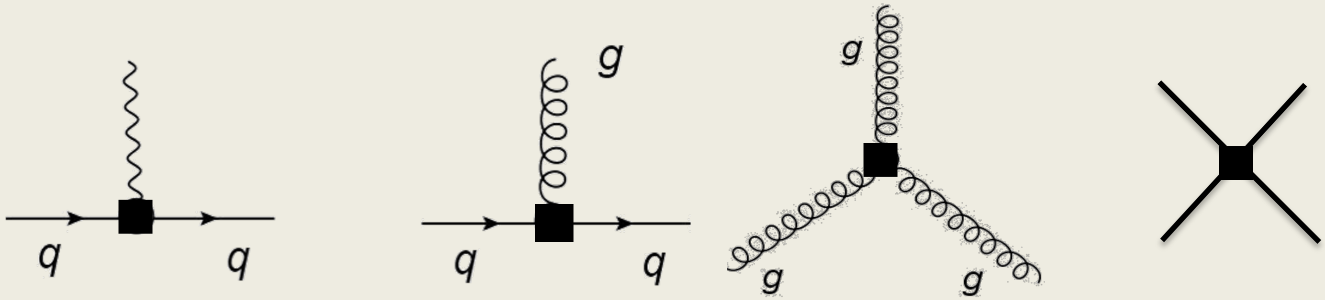
4quark operators

Different beyond-the-SM models predict different **dominant** operator(s)

EFT p.o.v: just look at these low-energy structures

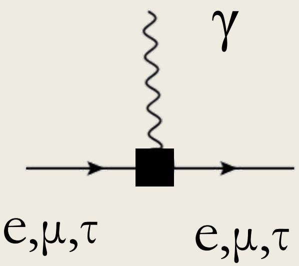
Traditional division of labor

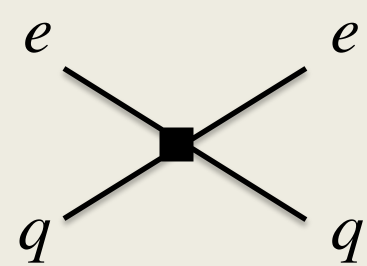
QCD
(θ-term)



'Diamagnetic' EDMs. No electron spin and nonzero nuclear spin.

- Examples: neutron, deuteron, atoms such as ^{199}Hg, ^{225}Ra





'Paramagnetic' EDMs. Nonzero electron spin and zero nuclear spin.

- Examples: ^{205}Tl,   Molecules such as HfF, ThO, BaF

Paramagnetic systems

e

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- Why these complicated systems ? Cannot use free electrons….
- **Why not simply use Hydrogen ?**

Paramagnetic systems

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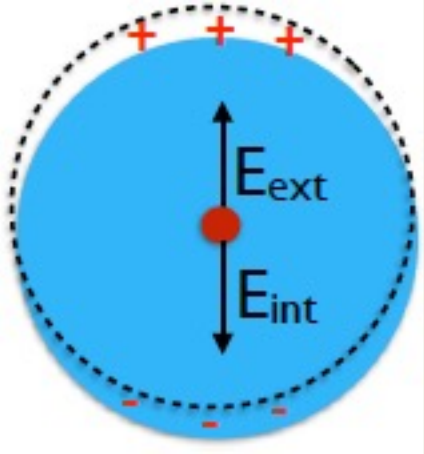
- Why these complicated systems ? Cannot use free electrons….
- **Why not simply use Hydrogen ?**

Schiff Theorem: EDMs of charged constituents are screened in a neutral atom Schiff, '63

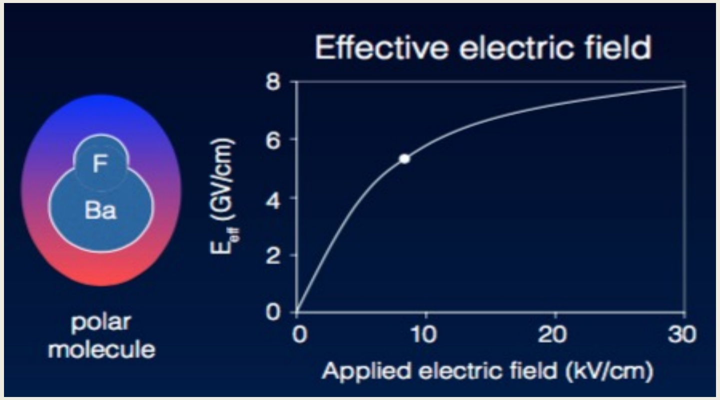


- Assumption : **non-relativistic constituents**
- **Invalid in heavy atoms/molecules**

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

Sandars '65

Probing the leptonic interactions

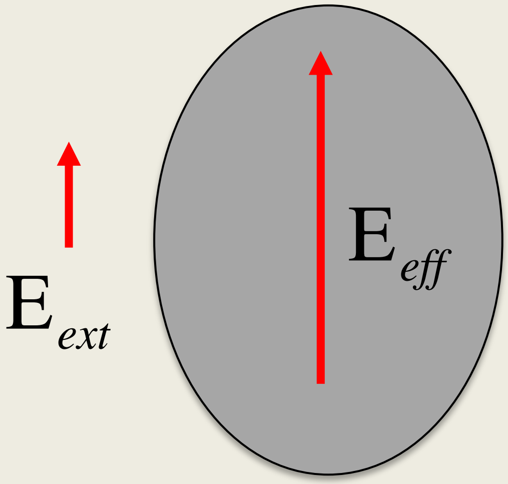


Polar molecules:

Convert small external to **huge** internal E field

$$\mathrm{E}_{eff} \propto 10^{6} E_{ext}$$

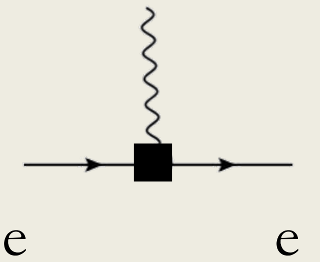
Requires high-accuracy electronic structure computations



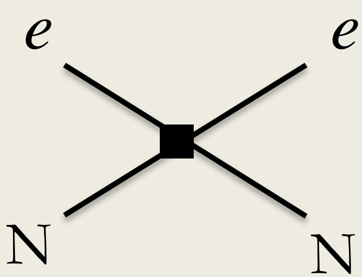
$$\Delta E_{ThO} = (80 \pm 10) \cdot GeV \left(\frac{d_e}{e\ cm} \right)$$

$$d_e < 1.4 \cdot 10^{-29}\ e\ cm$$ Andreev et al '18

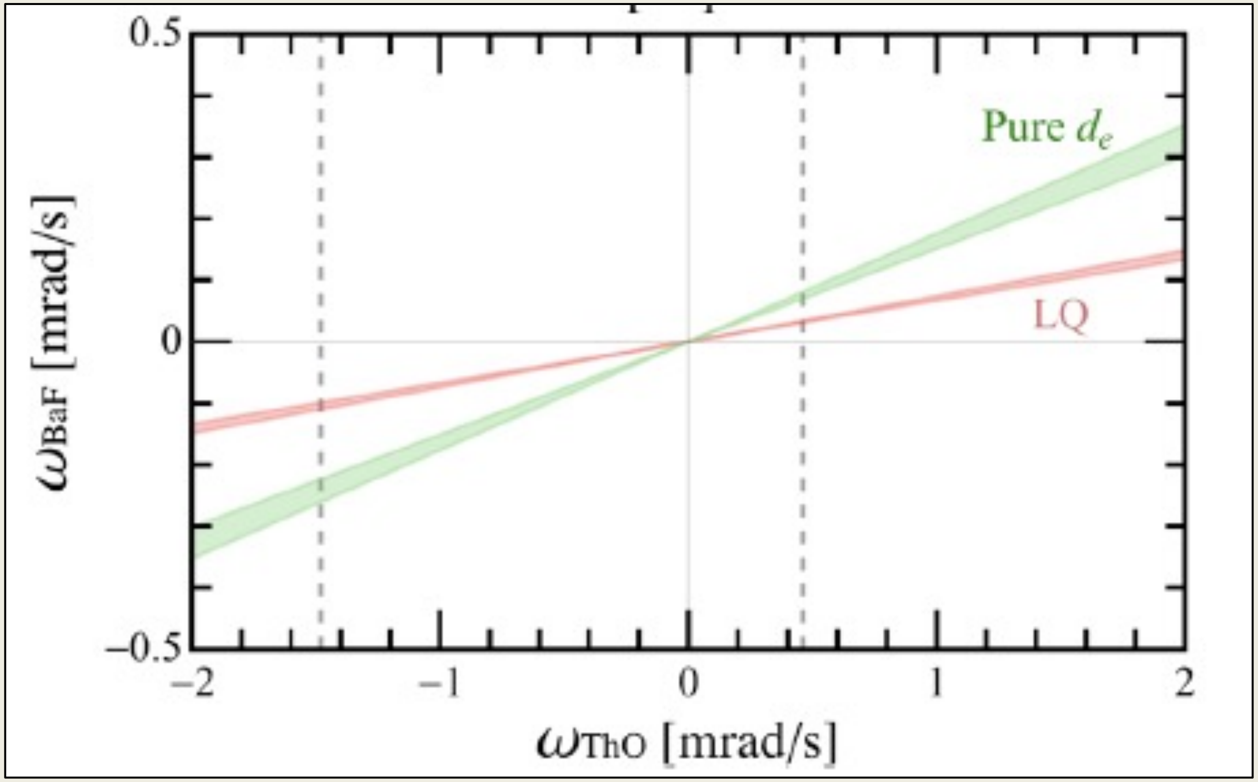
Complementary measurements



Electron EDM



Electron-Nucleus interactions

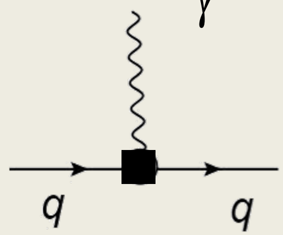


Onwards to hadronic CPV

Few GeV

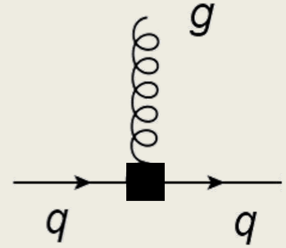
QCD
(θ-term)

+



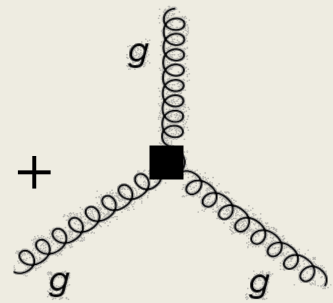
Quark EDM

+

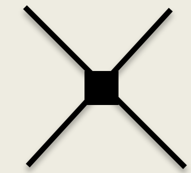


Quark chromo-
EDM

+



Weinberg
operator



Four-quark
operators

Hadronic/Nuclear CP-violation

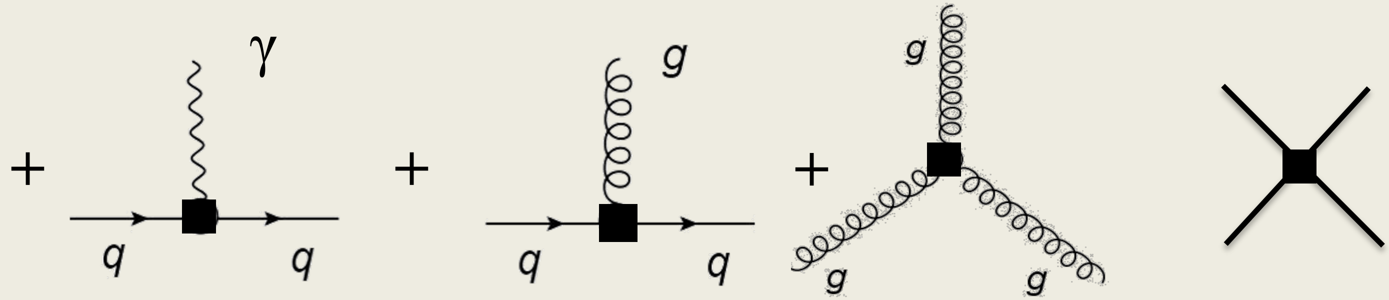
Theoretically more difficult

Goal: **Electric dipole moments of nucleons,
nuclei, and diamagnetic systems**

Onwards to hadronic CPV

Few GeV

QCD
(θ-term)



Quark EDM

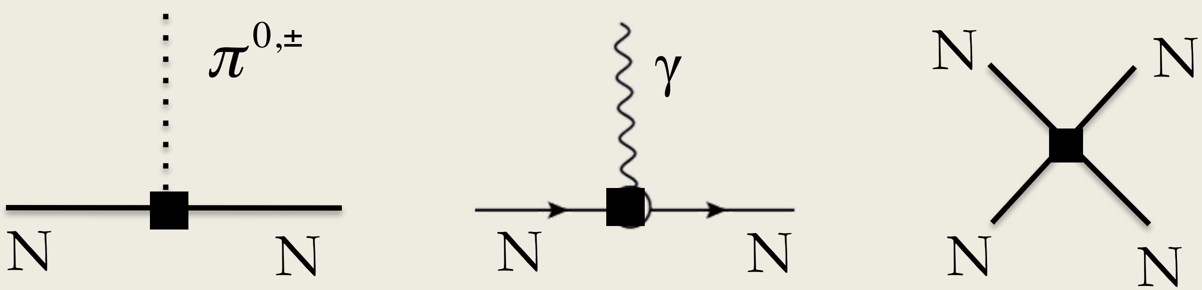
Quark chromo-EDM

Weinberg operator

Four-quark operators

Intermediate step

Lattice/Chiral perturbation theory



Goal: Electric dipole moments of nucleons, nuclei, and diamagnetic atoms

CP violation in chiral EFT

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

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

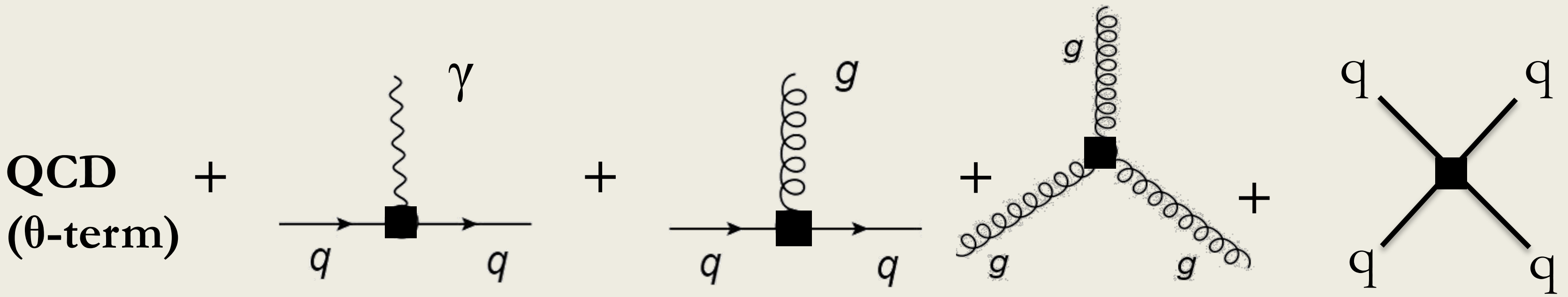
- Quark masses = 0 → SU(2)$_L$xSU(2)$_R$ symmetry
  - Spontaneously broken to SU(2)-isospin (pions = Goldstone)

- ChPT has 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)

- **Extended to include CP violation** Mereghetti et al' 10, JdV et al '12, Bsaisou et al '14

Weinberg, Gasser, Leutwyler, and many many others

ChiPT with CP violation



- They all break CP….

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

$\downarrow$

Different CP-odd chiral Lagrangians

$\downarrow$

Different hierarchy of CP-odd moments

The benchmark: QCD theta term

- Let's see what interactions occur from the theta term

Crewther et al' 79
Baluni '79

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

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

The benchmark: QCD theta term

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

$$\downarrow$$

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

Strong proton-neutron mass splitting

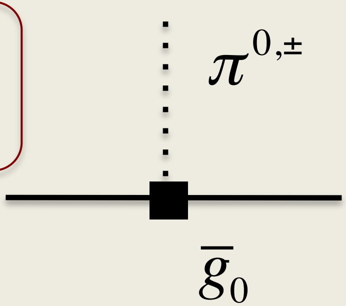
Theta and chiral perturbation theory

- Let's see what interactions occur from the theta term

Crewther et al' 79
Baluni '79

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

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



CP-odd pion-nucleon vertex

Theta and chiral perturbation theory

- Let's see what interactions occur from the theta term

Crewther et al' 79
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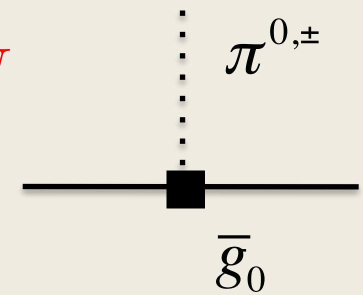
$$\mathcal{L}_{\rm QCD} = \mathcal{L}_{\rm kin} - \bar{m}\bar{q}q - \varepsilon\bar{m}\,\bar{q}\tau^3 q \;\; {\color{red} +m_\star\,\bar{\theta}\,\bar{q}i\gamma^5 q}$$

Linked via $\mathbf{SU_A(2)}$ rotation

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



Nucleon mass splitting ⟷ **CP-odd pion-nucleon interaction**

(strong part, no EM!)

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

JdV et al '15

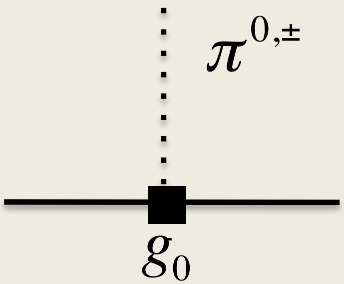
Use **lattice** for mass splitting

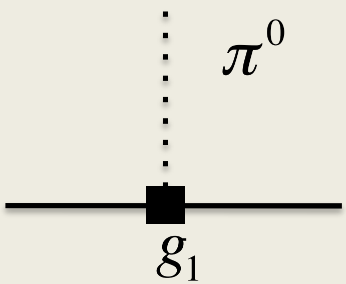
Walker-Loud '14, Borsanyi '14

Back to pion-nucleon couplings

- 2 relevant CP-odd structures

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





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

Pospelov et al ’01,’04
Mereghetti et al ‘10, ’12,
Bsaisou et al ‘12

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

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

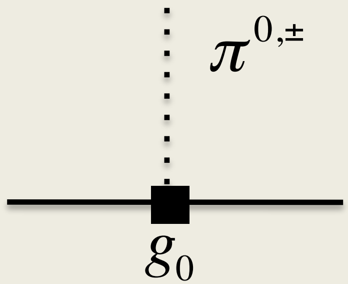
$$\frac{\bar{g}_1}{\bar{g}_0} = -\,(0.2 \pm 0.1)$$

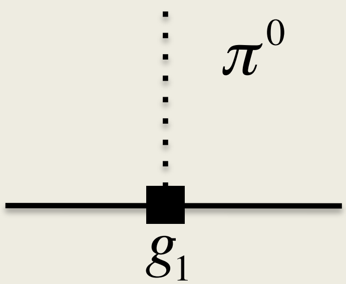
- Large uncertainty for g_1 due to pion mass splitting and unknown LEC

Back to pion-nucleon couplings

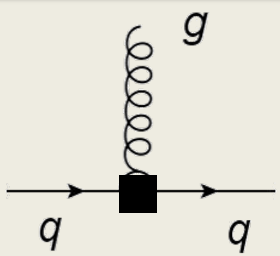
- Dominant CPV force from:

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





- **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

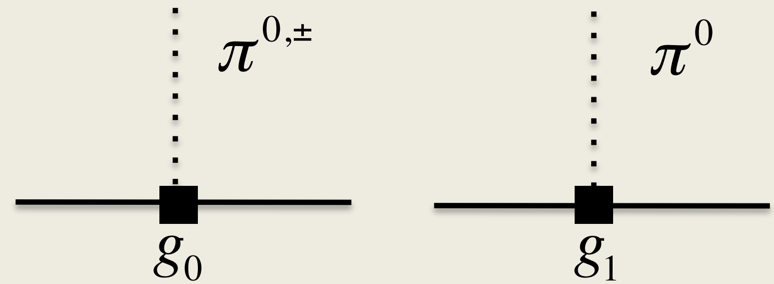
$$\bar{g}_0 = (5 \pm 10)(\tilde{d}_u + \tilde{d}_d)\ \mathrm{fm}^{-1} \qquad \bar{g}_1 = (20^{+20}_{-10})(\tilde{d}_u - \tilde{d}_d)\ \mathrm{fm}^{-1}$$

- Large uncertainties. But generally: $|\bar{g}_1| \geq |\bar{g}_0|$
- Calculations with lattice QCD in progress

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

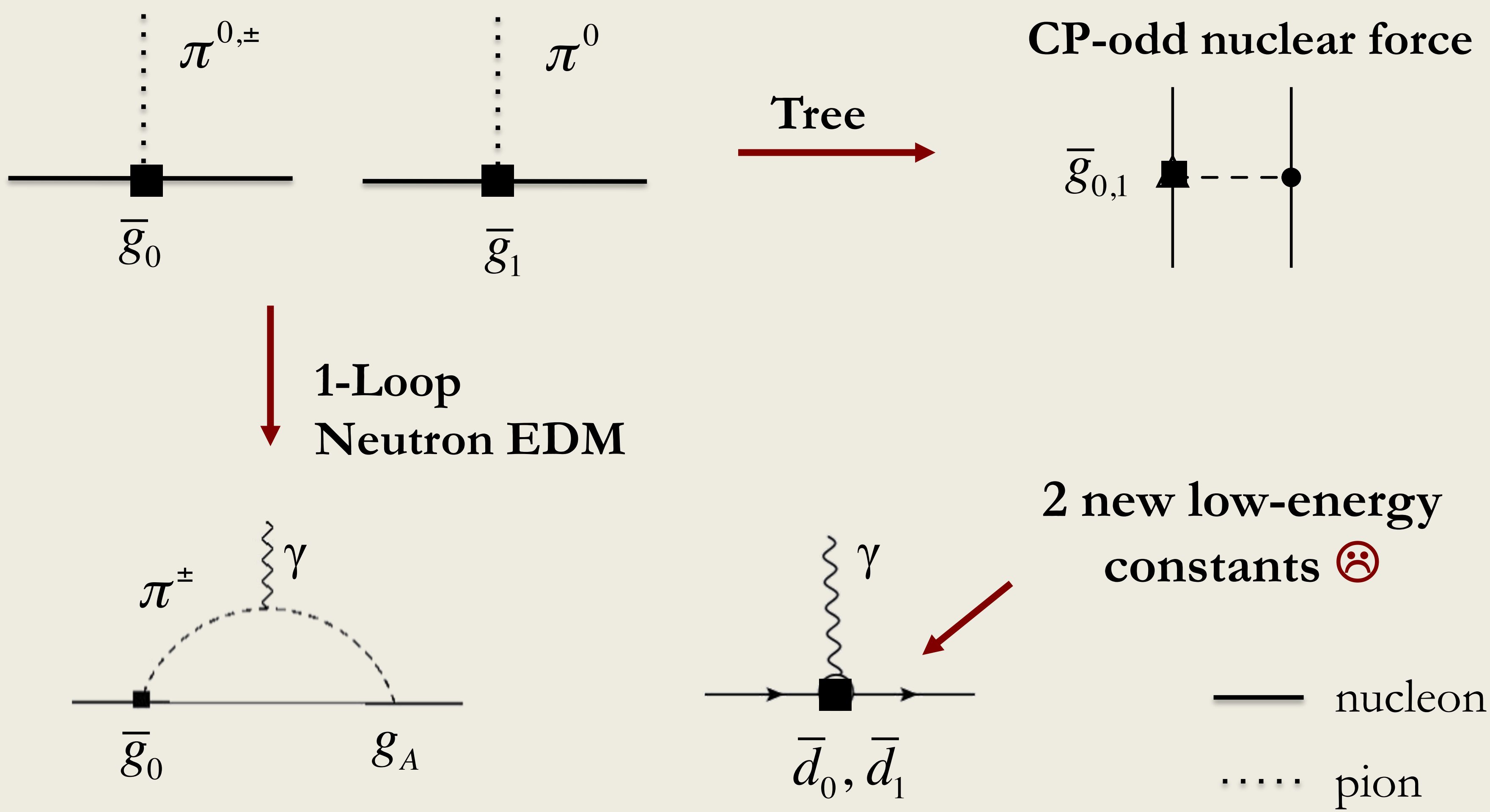
- The theta-term and dim-6 operators have different chiral properties
- **Different models -> Different g_0/g_1 ratios**

	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 !

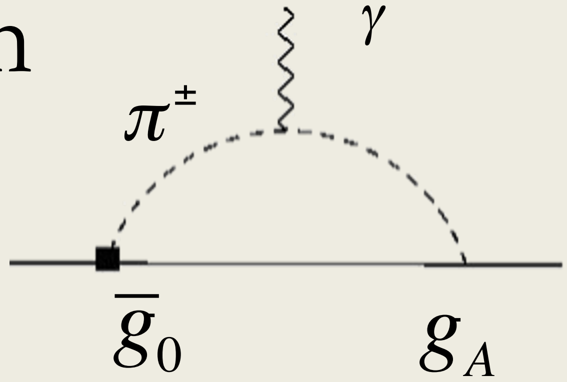
- **How to measure these ratios?**

We cannot measure the CPV force directly

- Lowest-order interactions: **CPV pion-nucleon couplings (2x)**



The strong CP problem



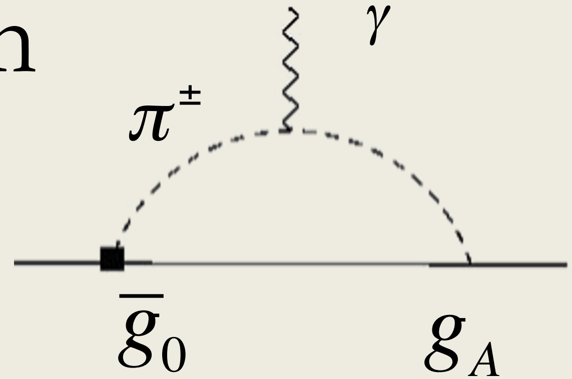
Neutron EDM

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

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

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

The strong CP problem



Neutron EDM

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

A proper assessment requires a non-perturbative calculation !

Lattice QCD (Shindler et al '19) $\quad d_n = -(1.52 \pm 0.7) \cdot 10^{-16}\, e\,\bar{\theta}\ \mathrm{cm}$

Not confirmed by other groups (e.g. LANL '21)

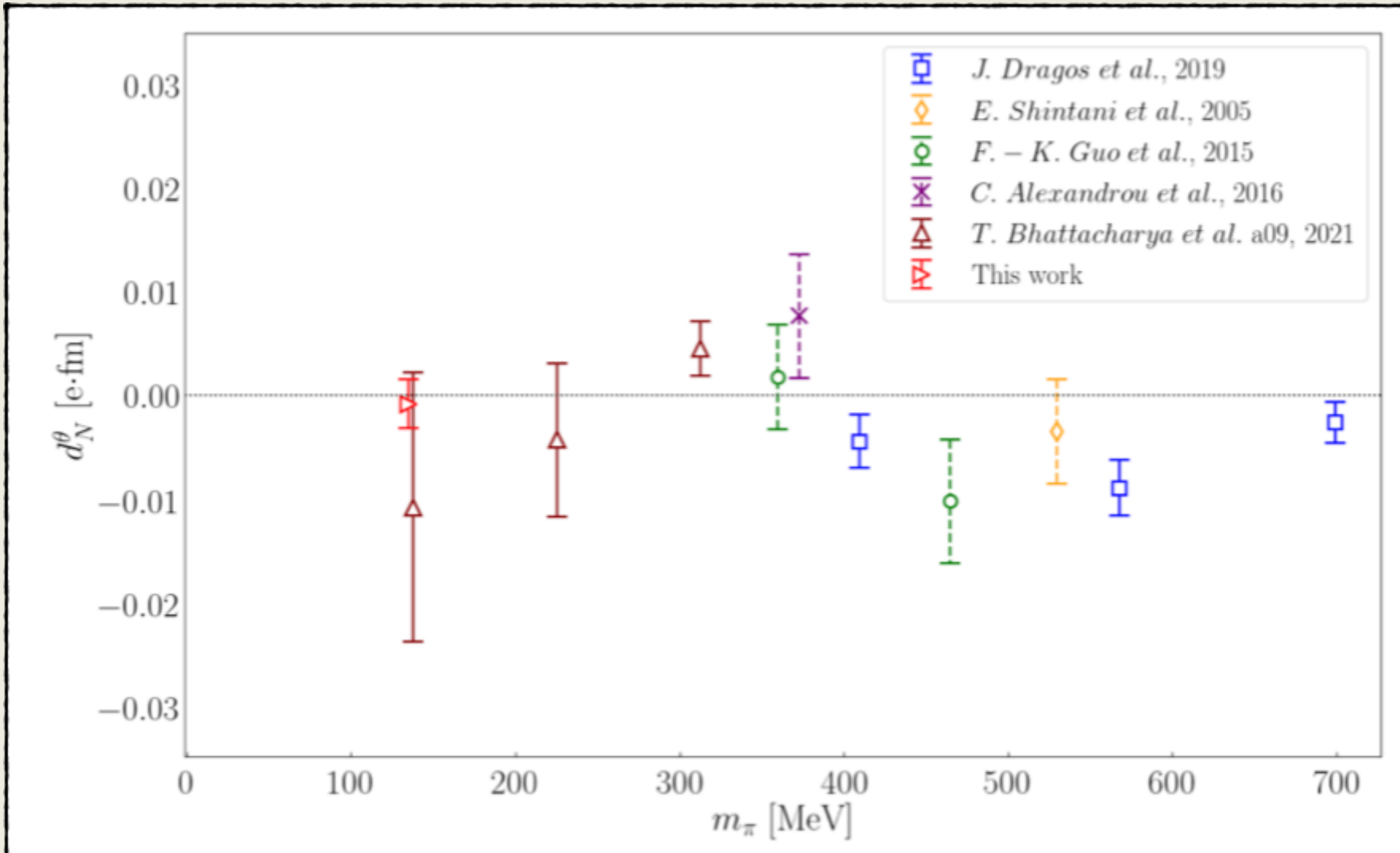


Figure from Alexandrou et al '21

And dim-6 sources ?

- Quark EDM accurately determined

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**

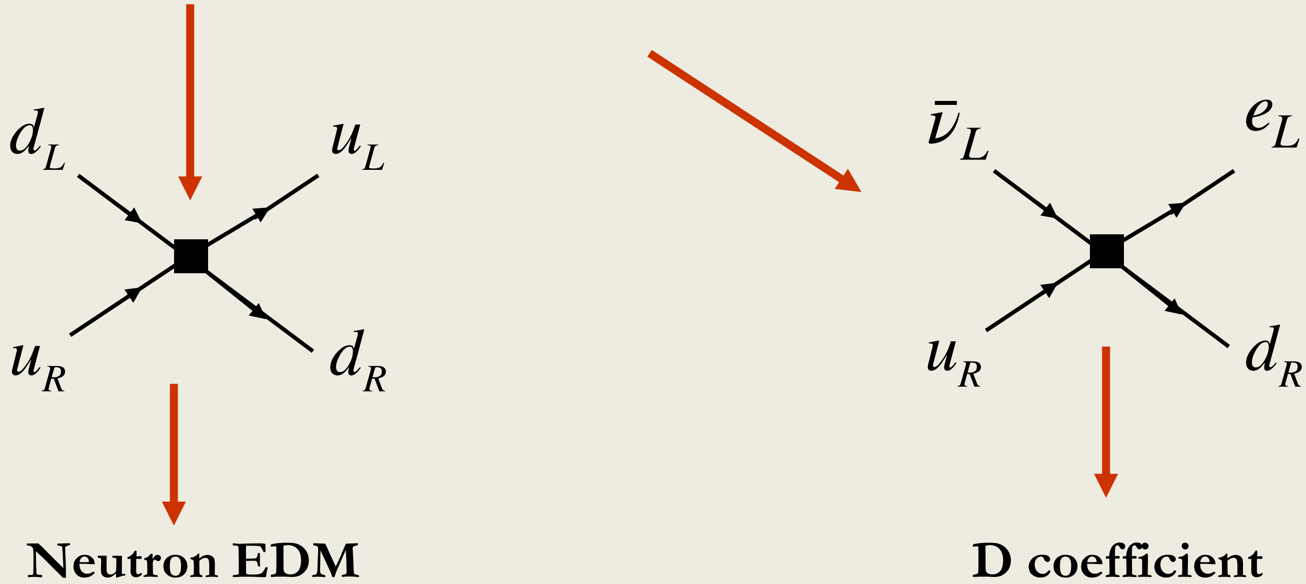
$$d_n \sim d_p \sim \pm(50 \pm 40) MeV\ ed_W$$

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

- **Uncertainties dilute EDM constraining/discriminating power**
- **Also more difficult to compare beta decay to EDMs**

Little d versus D

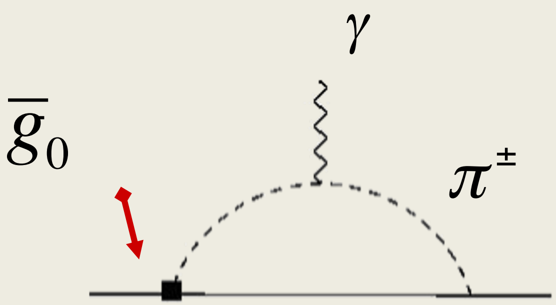
$$\Xi\, \bar{u}_R \gamma^\mu d_R \,(\tilde{\varphi}^\dagger i D_\mu \varphi) + \text{h.c.}$$



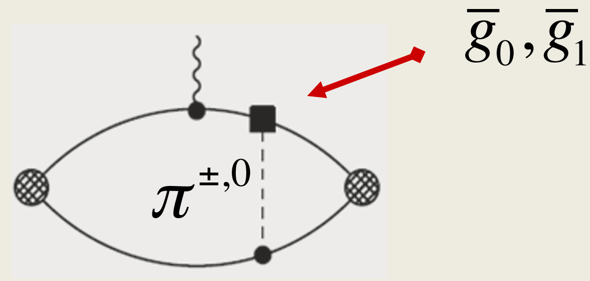
- Ng and Tulin (2012) argued EDM constraints impy D < 10^{-7}
- **But neutron EDM computation performed was invalid**
- Seng et al (2014) found D < 10^{-5} to 10^{-6} with sizeable uncertainty

- **Global fits EDMs and D are complementary: crucial to unravel source**

The CPV NN force and nuclear EDMs



Nucleon EDM



Nuclear EDM

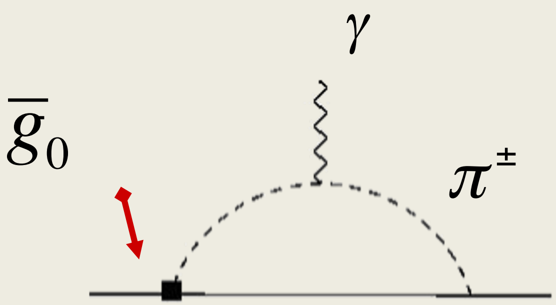
- Tree-level: **no loop** suppression
- Orthogonal to nucleon EDMs, sensitive to different CPV structures

Recent review: arXiv:2001.09050

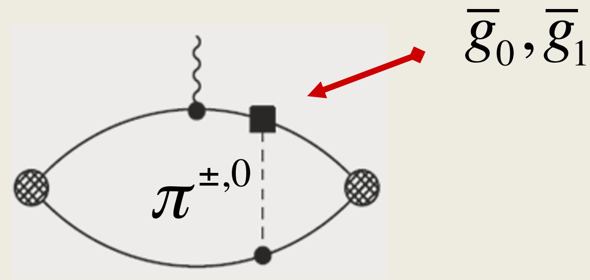
Parity- and Time-Reversal-Violating Nuclear Forces

Jordy de Vries[1,2], Evgeny Epelbaum[3], Luca Girlanda[4,5], Alex Gnech[6], Emanuele Mereghetti[7] and Michele Viviani[8*]

The CPV NN force and nuclear EDMs



Nucleon EDM



Nuclear EDM

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

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

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

- Solve Schrodinger eq. with CP-even NN potential
- **Perturb with CPV nuclear force we derived before**

The chiral filter

Khriplovich/Korkin '00
Bsaisou et al '14

- Deuteron EDM results

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

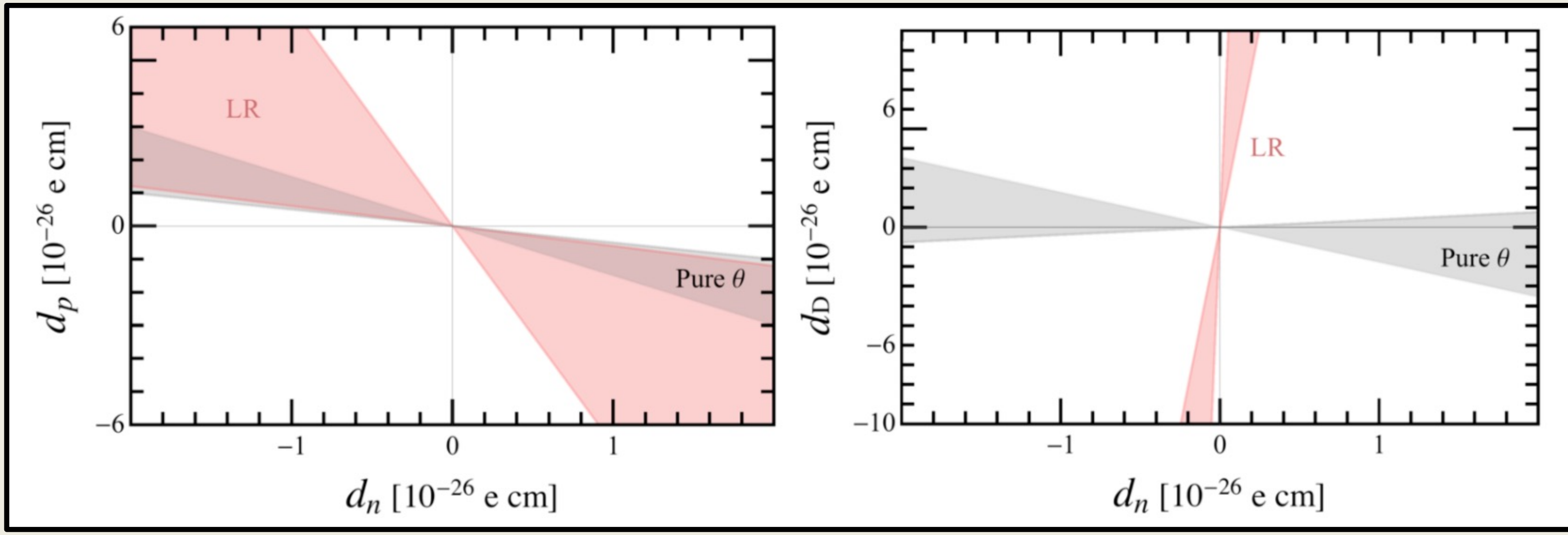
- Error estimate from cut-off variations + higher-order terms

`	**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**!

Unraveling sources with 2 EDMs

- Compare EDM ratios for theta term and left-right symmetric model



- **Nuclear EDMs complementary to nucleon EDMs**
- Deuteron is just a placeholder: other nuclear systems are similar
- **If we can control nuclear matrix elements !**

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
3. Electrostatic interactions

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

Jung, Fleig '18

EFT and many-body problems

- Need to calculate Schiff Moment (or MQM) of Hg, Ra, Xe….
- **Issue:** does chiral power counting hold ? Do pions dominate ?
- Say we assume so:

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

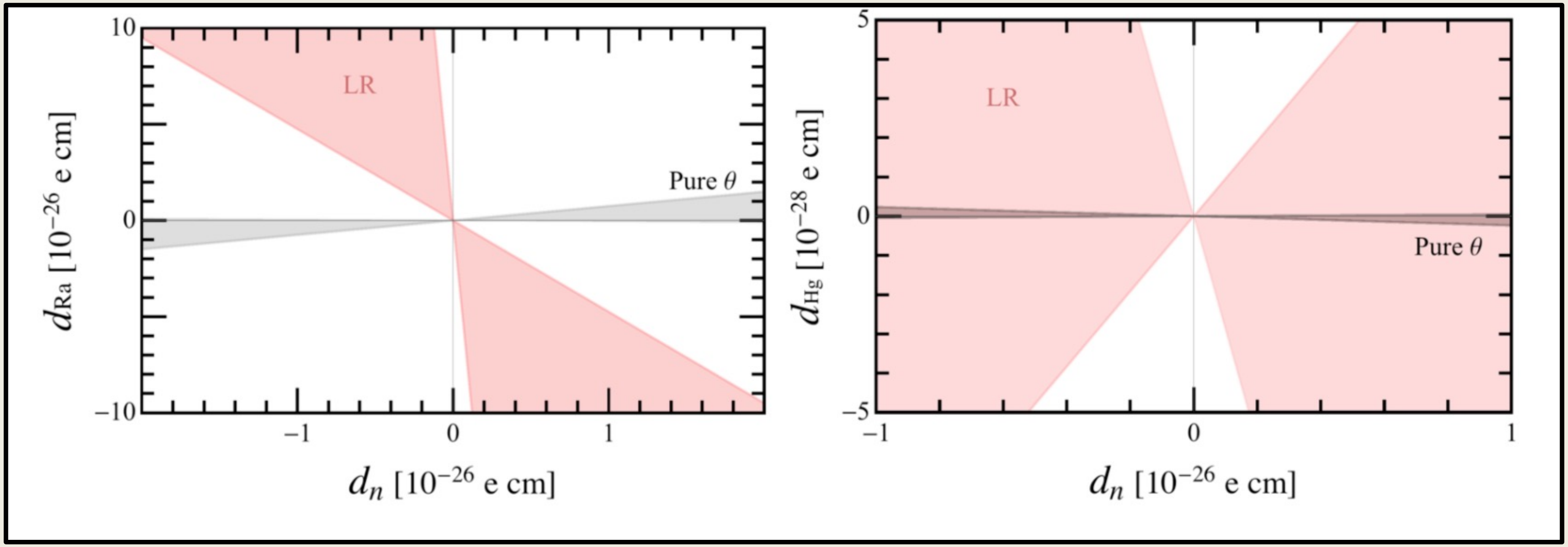
	a_0 range	a_1 range
^{199}Hg	0.3±0.4	0.45±0.7
^{225}Ra	2.5±7.5	65±40

Flambaum, de Jesus, Engel, Dobaczewski,….

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

table from review: Engel, Ramsey-Musolf, van Kolck, ’13 + updates e.g. Engel et al PRL ‘18

Reduced discriminatory power

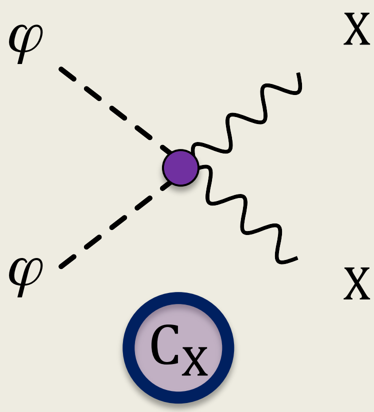


Goal for theory: matrix elements with 25-50% uncertainty

An explicit example: CPV in Higgs sector

- CP violation typically ignored in fits of Higgs, top, EW global fits
- 4 gauge-Higgs operators exist (B, W, BW, G)

$\varphi^{+}\varphi\, X\tilde{X}$



After EW symmetry breaking

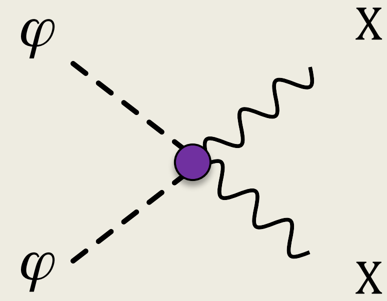
- **h-gluon-gluon**
- **h-gamma-gamma**
- **h-gamma-Z**
- **W-W-gamma**
- **h-Z-Z (not independent)**

- Evades flavor constraints (MFV automatic). Scale can be relatively low
- Motivated by universal theories (BSM couples to SM bosons/fermions through SM currents)

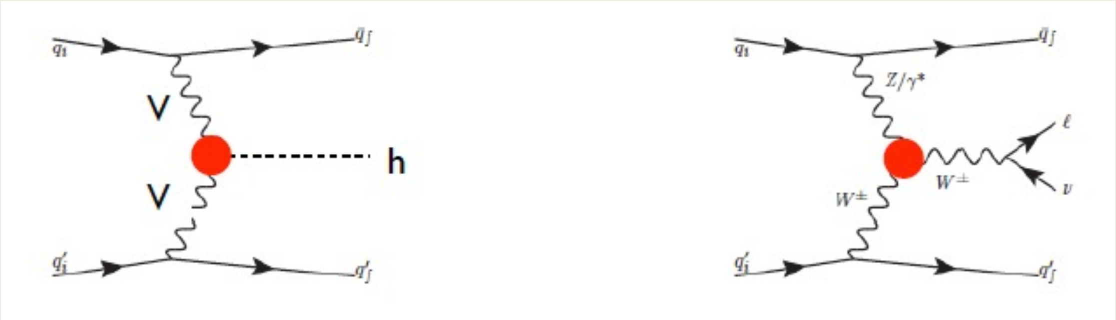
Peskin, Takeuchi '90
Barbieri et al '04
Ferreira et al '17

Collider and low-energy probes

$\varphi^+\varphi\, X\tilde{X}$



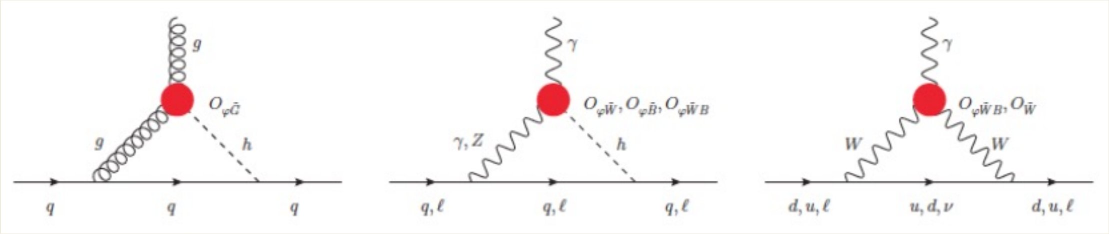
- Induce CPV angular distribution in pp → h/V + 2 jets



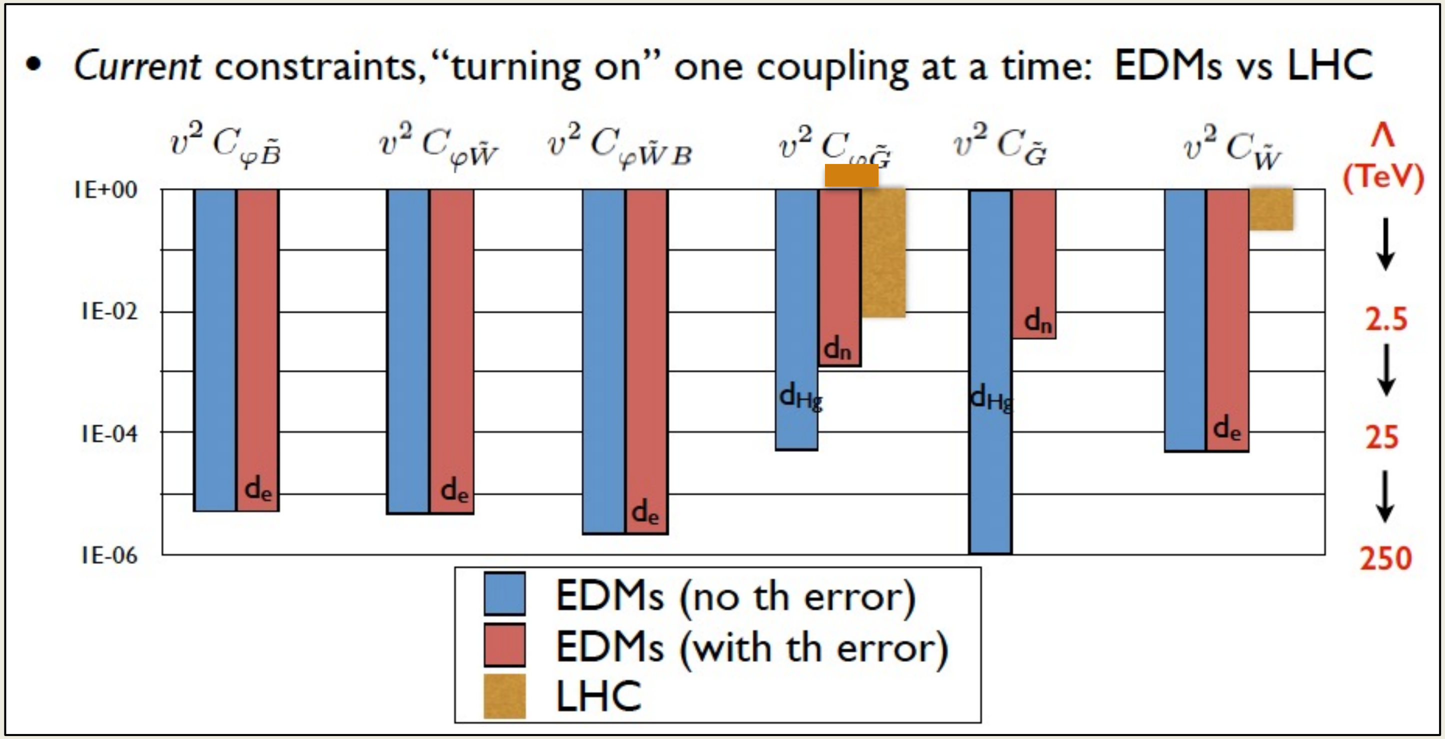
e.g. ATLAS 2006.15458 $0.23 < \tilde{C}_{HWB}/\Lambda^2 < 2.34\ (TeV^{-2})$

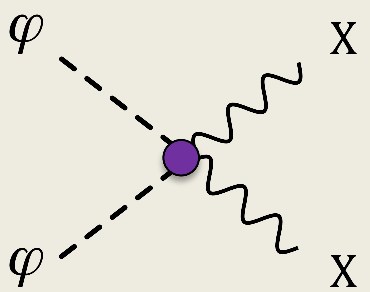
Bernlochner et al '19 $-0.19 < \tilde{C}_{HGG}/\Lambda^2 < 0.03\ (TeV^{-2})$

- Same couplings induce contributions to EDMs at loop level
- Also induce CPV in B → s gamma transitions



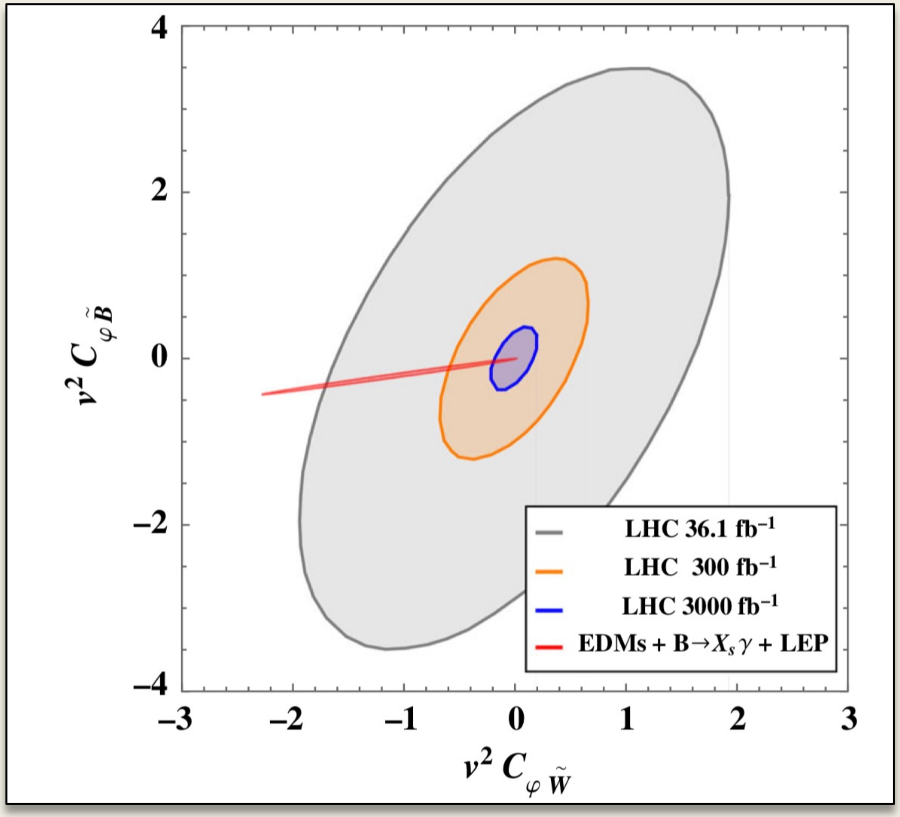
Low-energy constraints are stringent





- EDM constraints are very stringent for single couplings
- **But EDMs only probe several direction in parameter space**

CP violation in ‘universal theories’

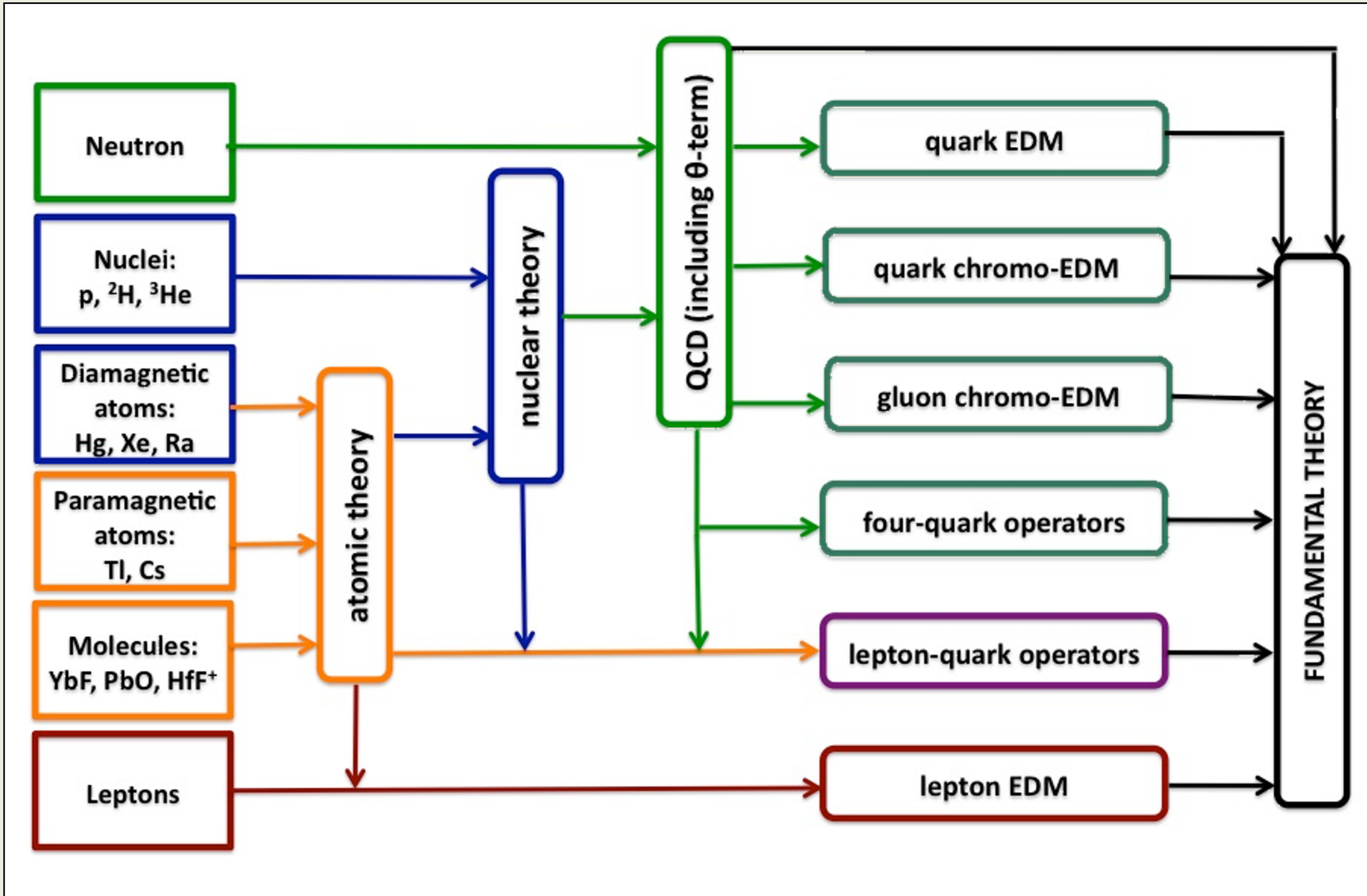


Cirigliano et al PRL ‘19

HL-LHC projections from Bernlochner et al ‘18

- Low-energy limits avoided in global fits (free directions)
- **Future of BSM searches: inclusive low- and high-energy probes**
- **CP violation in Beta-decay would provide another orthogonal direction**

The EDM metromap



Conclusion/Summary/Outlook

EDMs

- ✓ Very powerful search for BSM physics (probe high scales)
- ✓ Heroic experimental effort and **great outlook**

EFT framework

- ✓ Framework exists for CP-violation (EDMs) from 1st principles
- ✓ Keep track of **symmetries** (gauge/CP/chiral) from multi-Tev to molecular scales
- ✓ Close connection between EDMs and D coefficients

EDMs in era of the LHC

- ✓ EDMs play important role in global searches for BSM physics
- ✓ Complementary to many high-energy searches

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

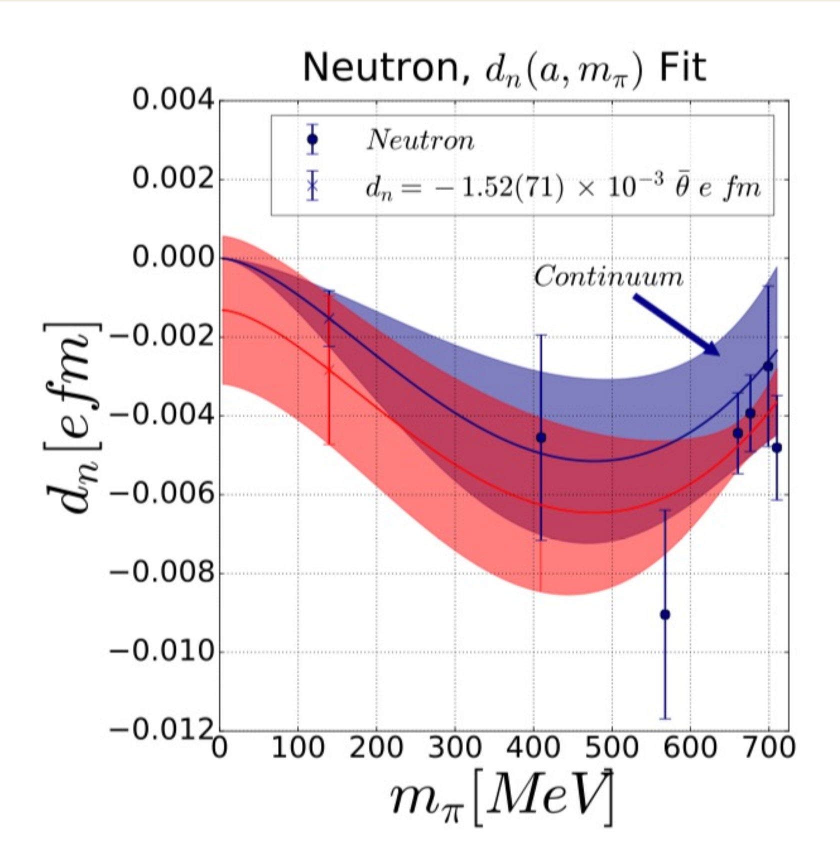
An attempt

Dragos, JdV, Shindler, Luu, Yousif '19

- Calculation with `Gradient Flow' at 3 pions masses and 3 lattice spacings
- Improved signal-to-noise by restricted sum of topological charge
- Pion masses are large ... nevertheless try a chiral fit …

$$d_{n,p} = C_1 m_\pi^2 + C_2\, m_\pi^2 \log m_\pi^2 + C_3 a^2$$

	$C_1\ [\bar\theta\, e\ \mathrm{fm}^3]$	$C_2\ [\bar\theta\, e\ \mathrm{fm}^3]$	$C_3\ \left[\frac{\bar\theta\, e\ \mathrm{fm}}{\mathrm{fm}^2}\right]$
proton	$-3.6(5.3)\times 10^{-4}$	$-6.8(6.6)\times 10^{-4}$	0.20(31)
neutron	$3.1(3.2)\times 10^{-4}$	$8.8(4.4)\times 10^{-4}$	$-0.16(23)$



- C_2 is related to g_0

$$\bar g_0 = -\frac{8\pi^2 f_\pi}{g_A}\frac{C_2\, m_\pi^2}{e} = -12.8(6.2)\cdot 10^{-3}\bar\theta$$

- Agrees with prediction from ChPT

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

- EDMs nonzero only a 2 sigma

$$d_n = -(1.52 \pm 0.7)\cdot 10^{-3}\ e\,\bar\theta\ \mathrm{fm}$$