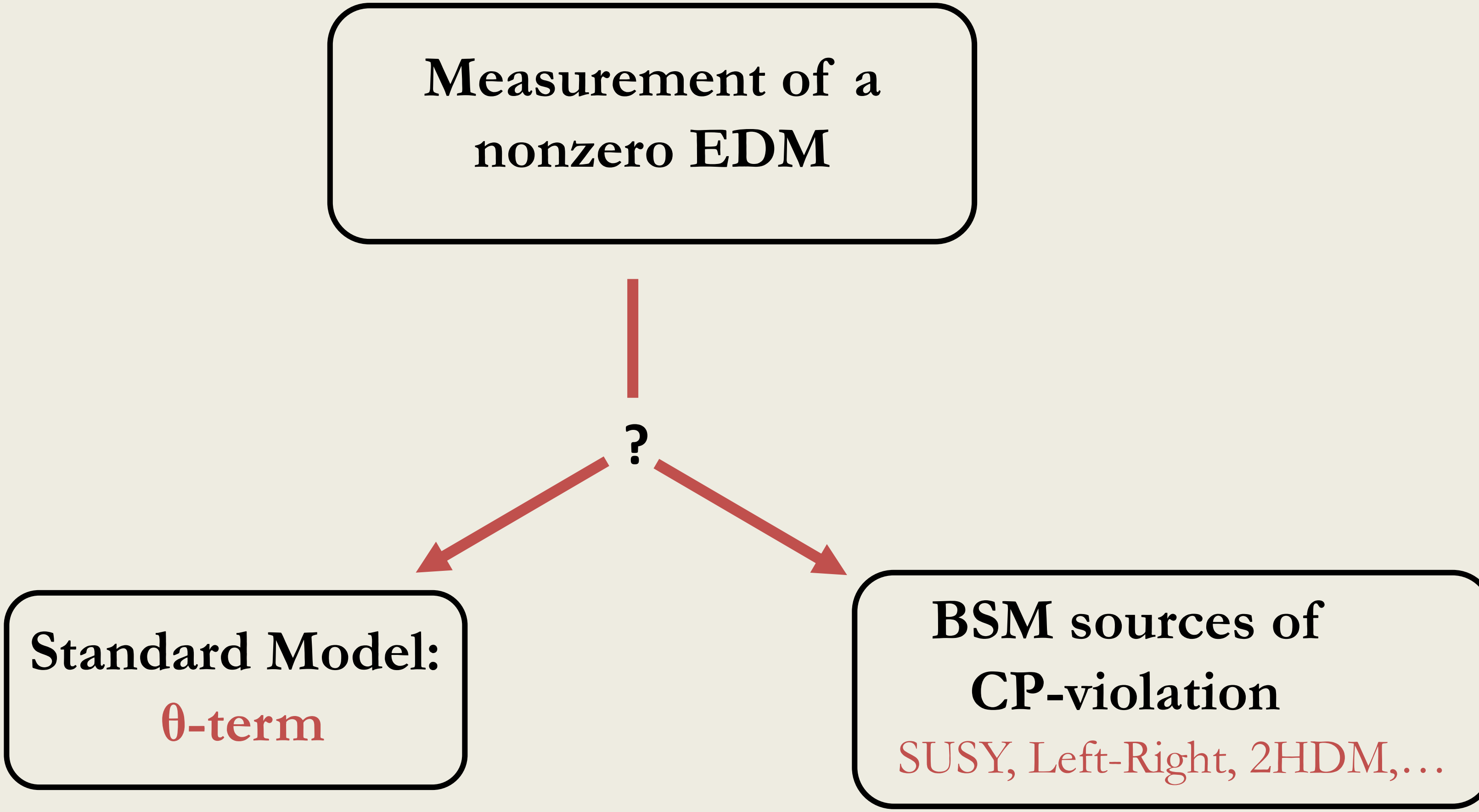
CP-odd moments in (chiral) effective field theory

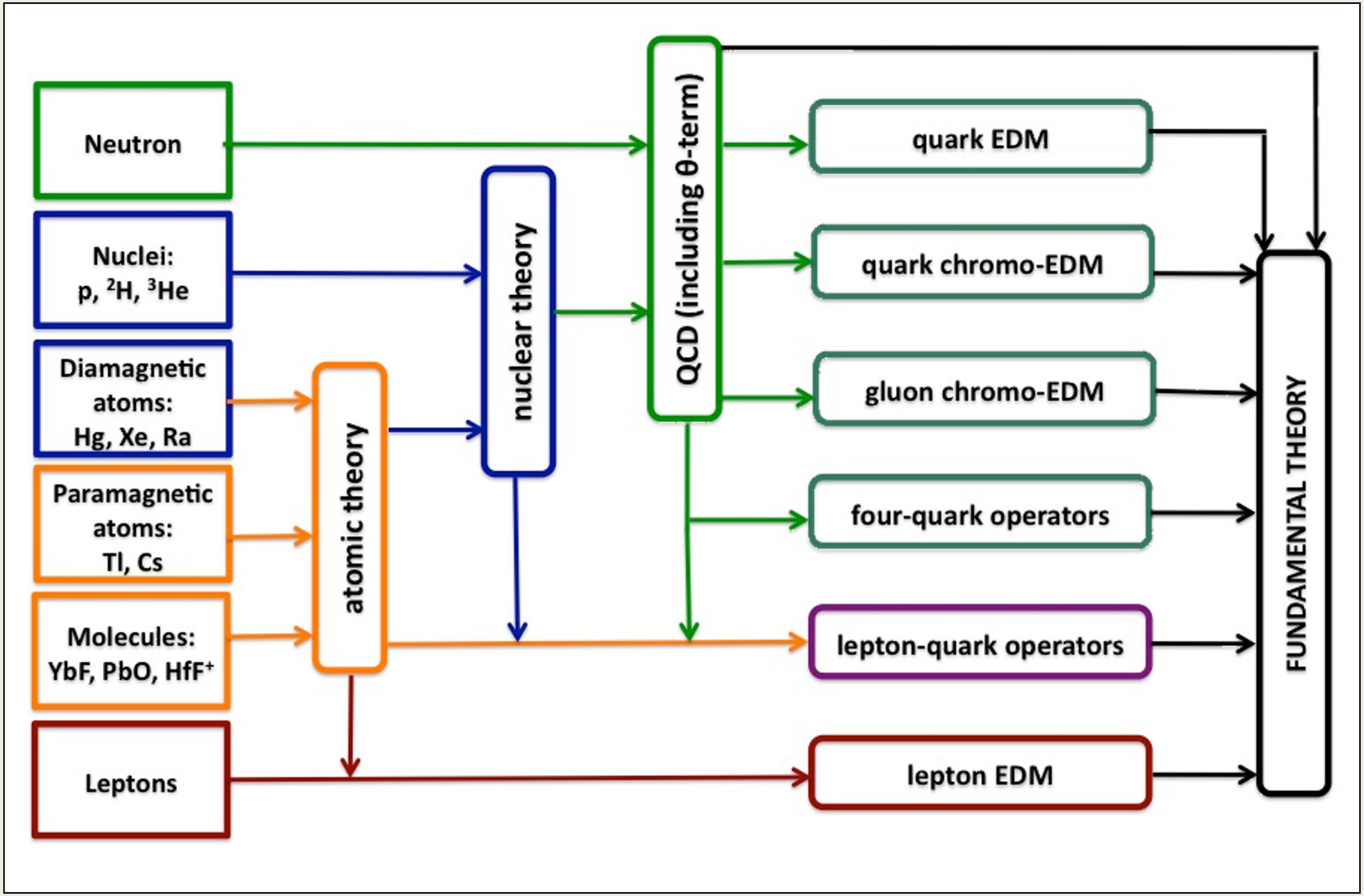
Jordy de Vries

University of Amsterdam, Nikhef



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

The EDM metromap



CP-odd effective interactions

- EFTs are very appropriate for low-energy measurements

1) Degrees of freedom: Full SM field content
2) Symmetries: Lorentz, **SU(3)xSU(2)xU(1)**

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

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

- Effects at low energy (E) suppressed by powers of (E/Λ)

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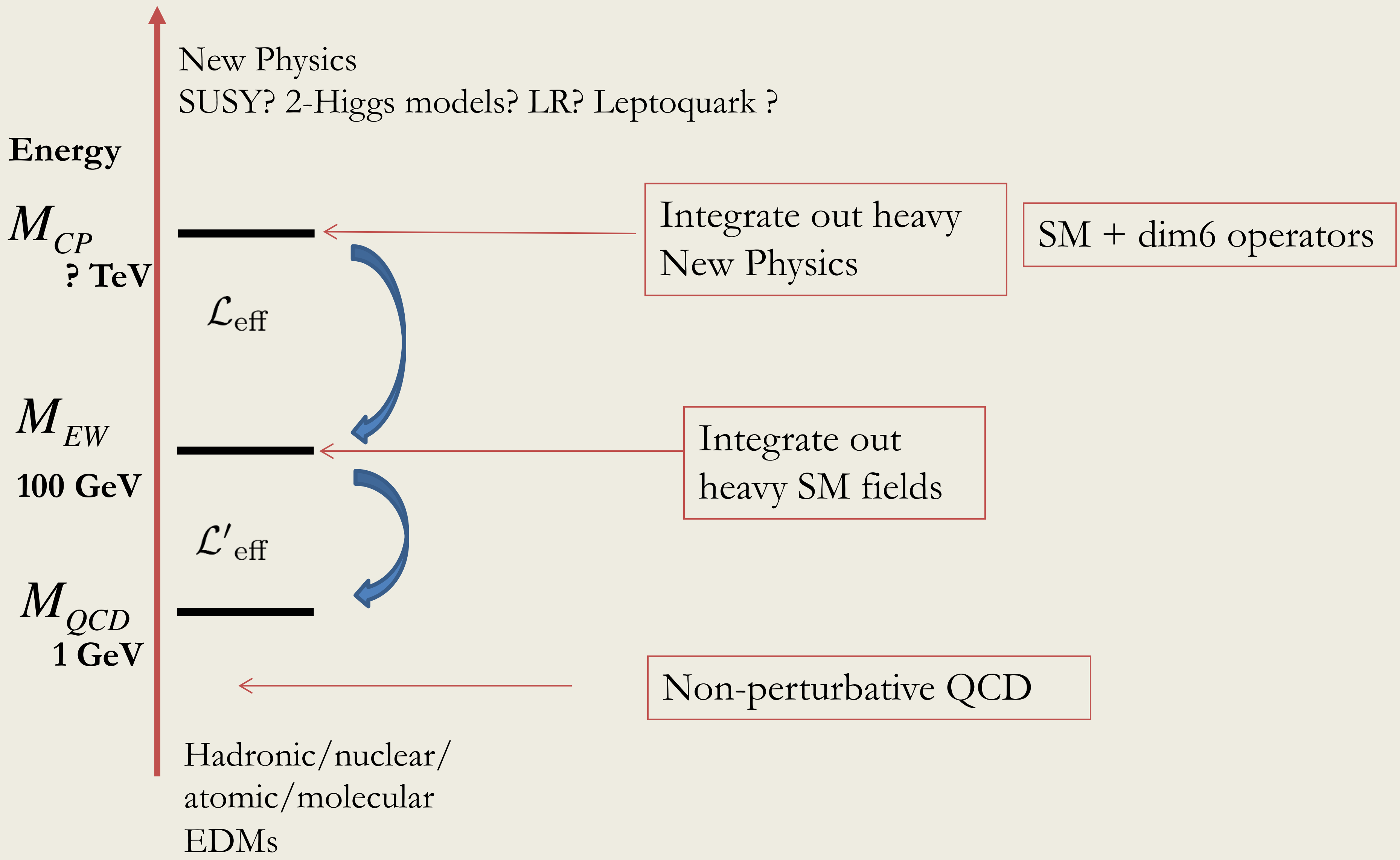
Dekens & JdV, '13
Cirigliano et al' 15,'16'17

- Focus on **CP-odd operators at dimension-six**
- Run down → Integrate out H,W,Z,t → Run down → Obtain low-energy form of CP-odd interactions

- **Can be easily matched to specific BSM models**

Running through the scales

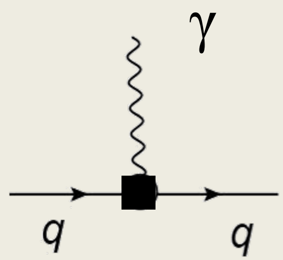
See Vincenzo's talk



When the dust settles…..

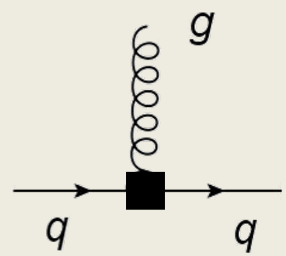
Few GeV

QCD (θ-term) +



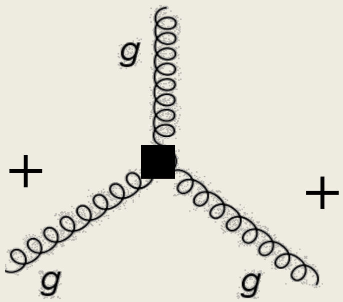
Quark EDM

+



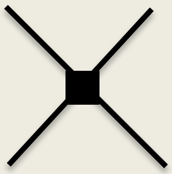
Quark chromo-EDM

+



Gluon chromo-EDM

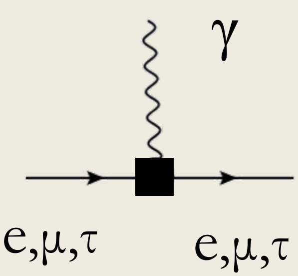
+

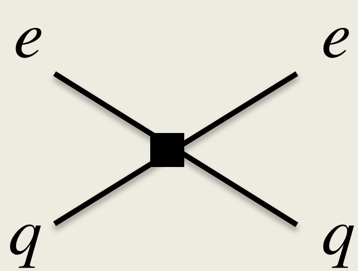


4quark operators

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

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





Intermediate summary I

- Parametrized BSM CP violation in terms of **dim6** operators
- Several operators at low energy: theta, (C)EDMs, Weinberg, Four-fermion
- **Important:** different BSM models -> different EFT operators

1. Standard Model: only **theta** for now (CKM too small)

Intermediate summary I

- Parametrized BSM CP violation in terms of **dim6** operators
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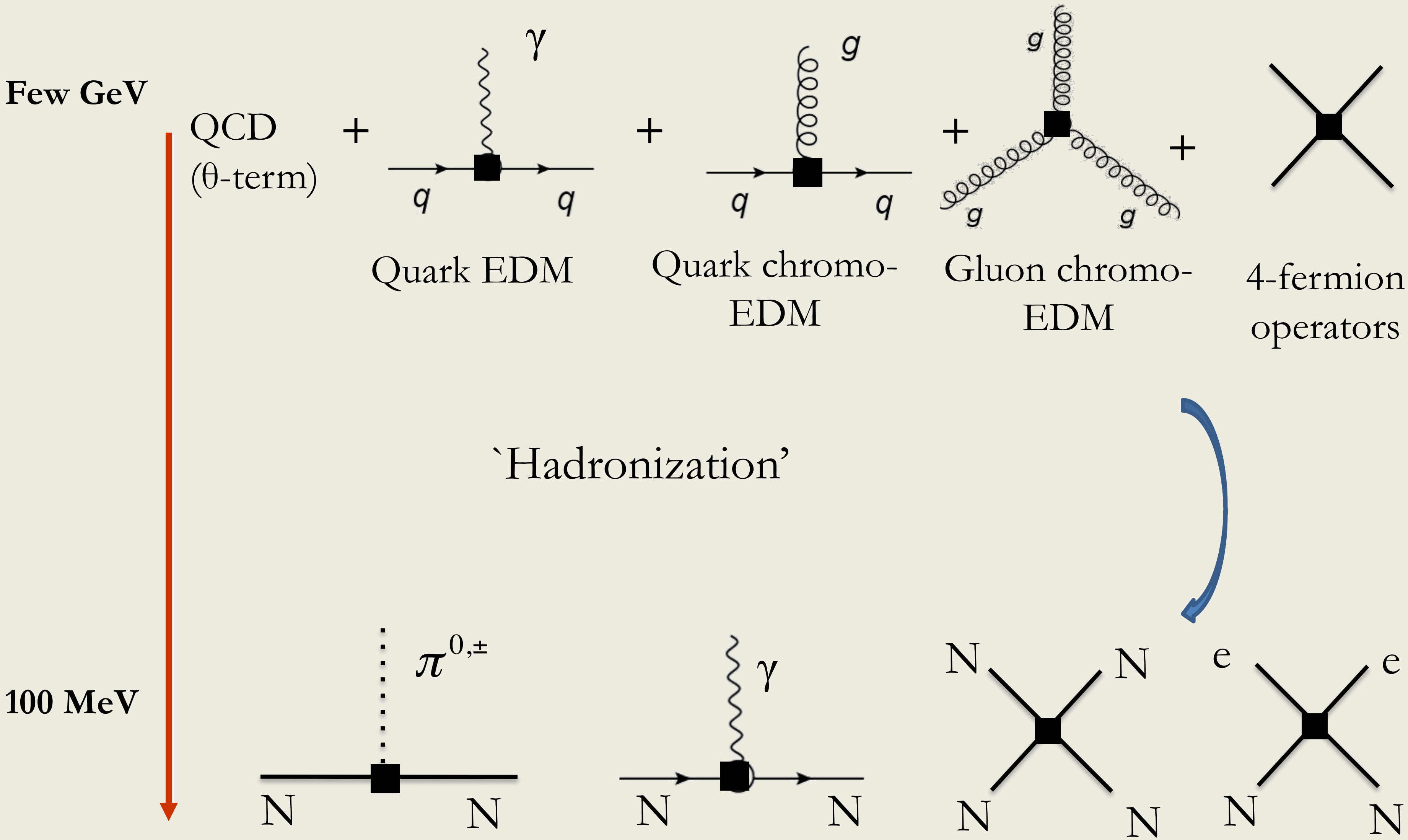
- **Important:** different BSM models -> different EFT operators

1. Standard Model: only **theta** for now (CKM too small)
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: **Four-quark LR operators**, small (C)EDMs

5 Leptoquarks: Semi-leptonic four-fermion and four-quark (tree-level)

Mohapatra et al '75 Giudice et al '06 Dekens et al '14 '18 Pich & Jung '14 Fuyuto et al '18, Cesarotti et al '18

When the dust settles…..



CP violation in chiral EFT

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

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

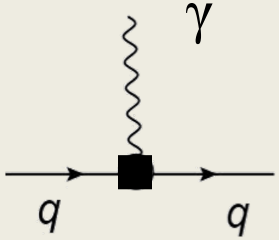
- Quark masses = 0 → SU(2)$_L$xSU(2)$_R$ symmetry
  - Spontaneously broken to SU(2)-isospin (pions = Goldstone)

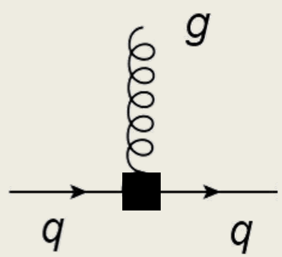
- ChPT has systematic expansion in $Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi$ $\Lambda_\chi \cong 1\,GeV$
  - **Form of interactions fixed by symmetries**
  - Each interactions comes with an unknown constant (LEC)

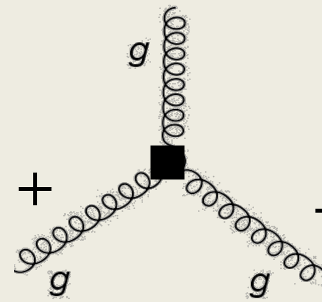
- **Extended to include CP violation** Mereghetti et al' 10, JdV et al '12, Bsaisou et al '14

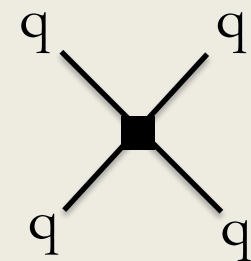
Weinberg, Gasser, Leutwyler, and many many others

ChiPT with CP violation

QCD (θ-term) + 

+ 

+ 

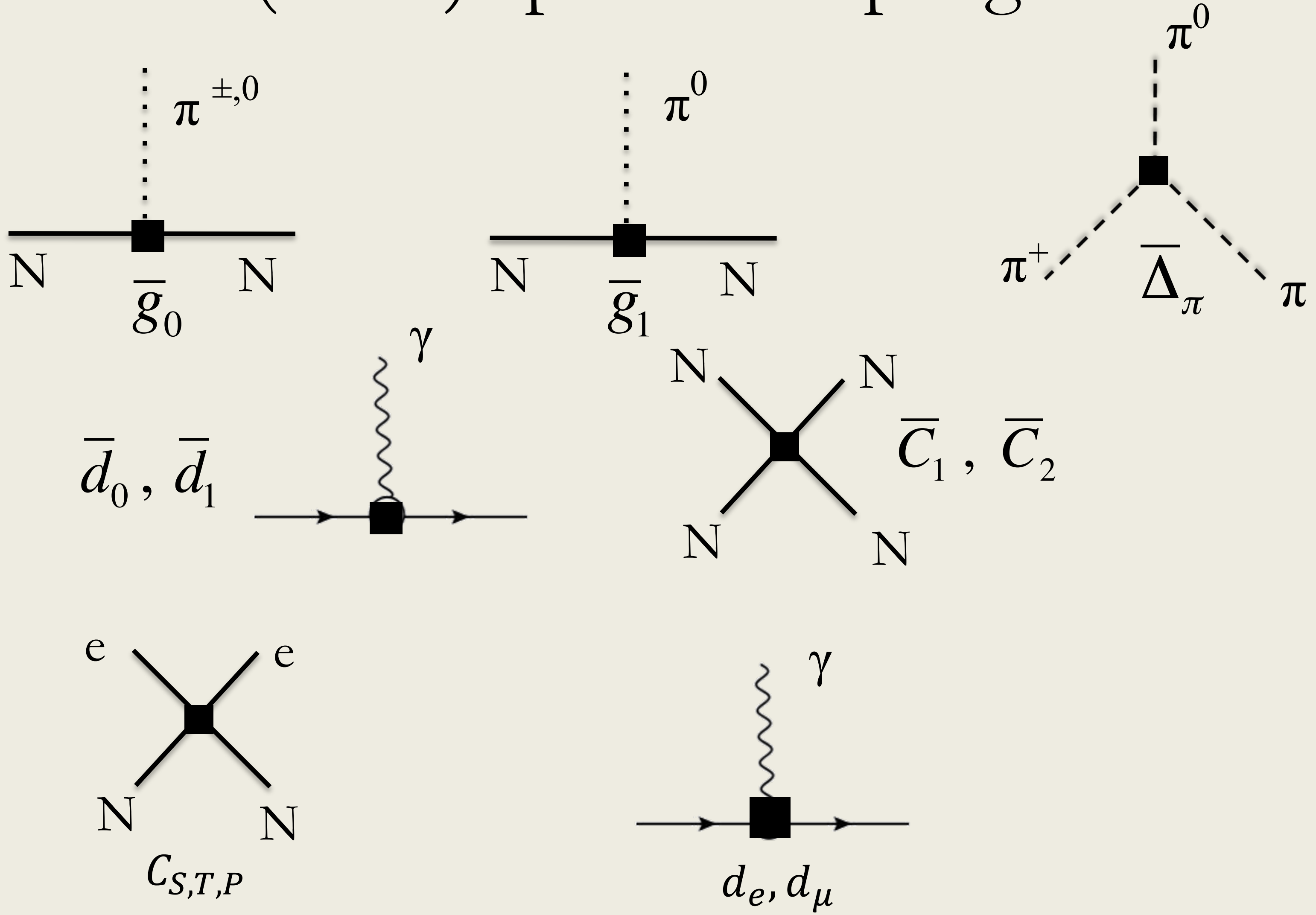
+ 

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

Different CP-odd chiral Lagrangians

Different hierarchy of CP-odd moments

Hadronic + (semi-)leptonic couplings

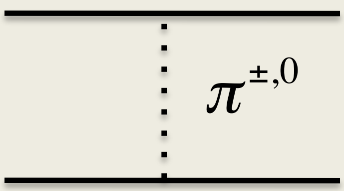


- Two more for Magnetic Quadrupole Moments (nucleon-pion-photon)
- Semi-leptonic also relevant for hadronic CP-odd sources (*Flambaum et al '19*)

Hierarchy of CPV nuclear forces

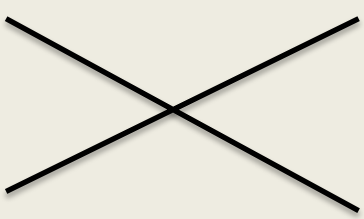
CP-even

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



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

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



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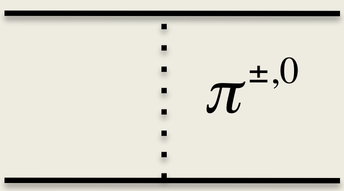

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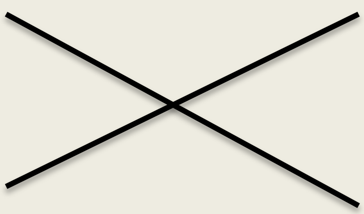
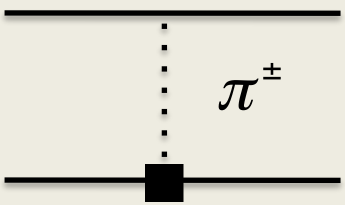


$$\sim Q^0$$

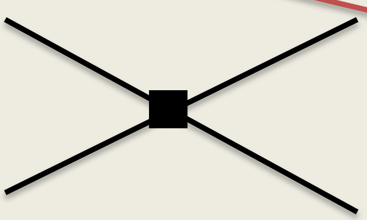
CP-odd

$$\bar{g}_0\bar{N}(\vec{\tau}\cdot\vec{\pi})N$$



$$\sim \frac{(g_A Q)\bar{g}_0}{Q^2} \sim Q^{-1}$$

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



$$\sim Q^1$$

Maekawa et al '11

- In general: short-range CPV appear at next-to-next-to-leading order
- **Unless symmetries forbid pion-nucleon interactions !**

The benchmark: QCD theta term

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

Crewther et al' 79
Baluni '79

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

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

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

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$$\downarrow$$

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

Strong proton-neutron mass splitting

Theta and chiral perturbation theory

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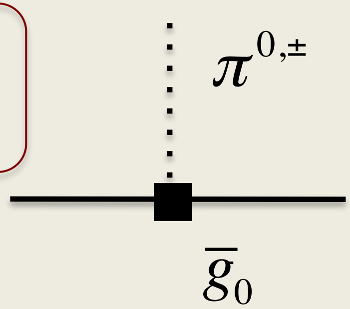

CP-odd pion-nucleon vertex

Theta and chiral perturbation theory

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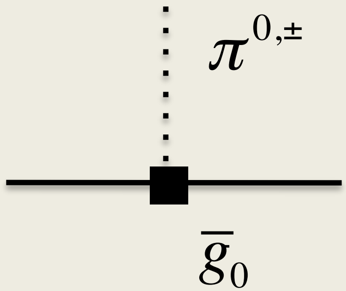
Linked via $SU_A(2)$ rotation

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



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

Use **lattice** for mass splitting

Walker-Loud '14, Borsanyi '14

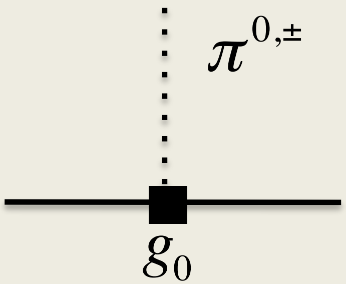
$$g_0 = \delta m_N \frac{1-\varepsilon^2}{2\varepsilon}\bar{\theta} = (15.5 \pm 2.5)\cdot 10^{-3}\,\bar{\theta}$$

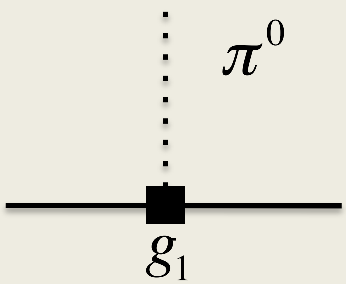
JdV et al '15

Back to pion-nucleon couplings

- 2 CP-odd structures

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





- Four-quark left-right operator breaks isospin !

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

- ChPT gives ratio of couplings

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

Back to pion-nucleon couplings

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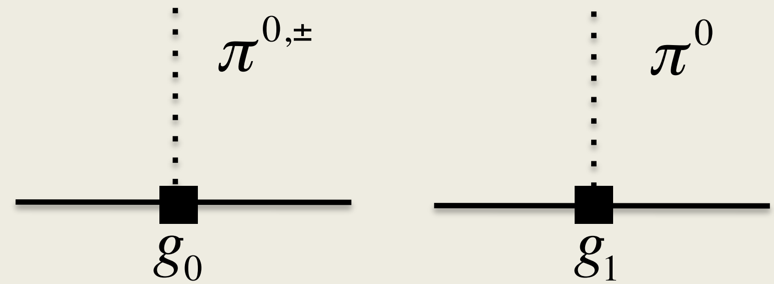

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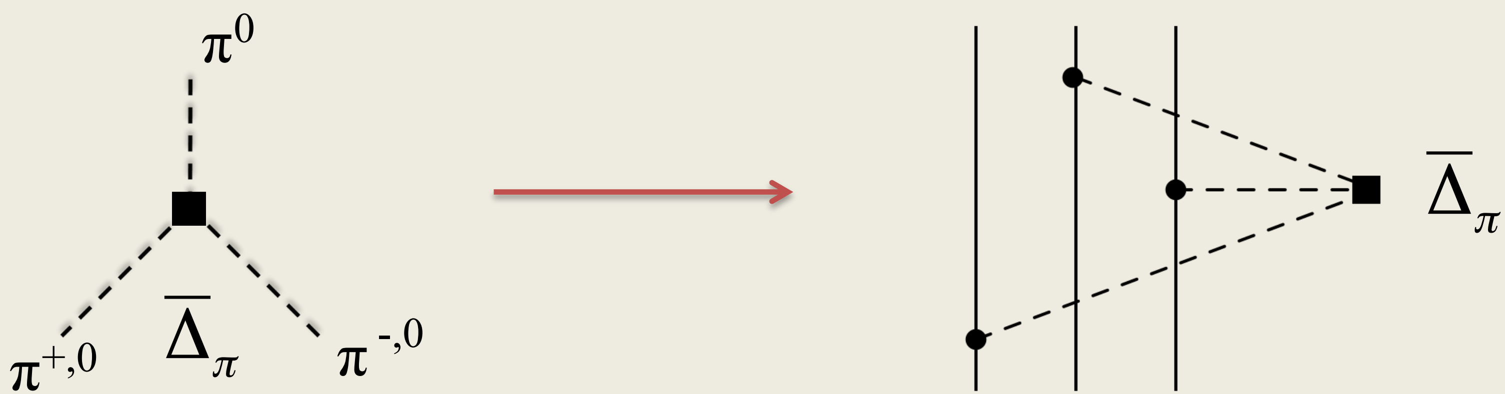
- Unique CPV pion-pion-pion interaction

JdV et al ’12, Viviani et al ‘19

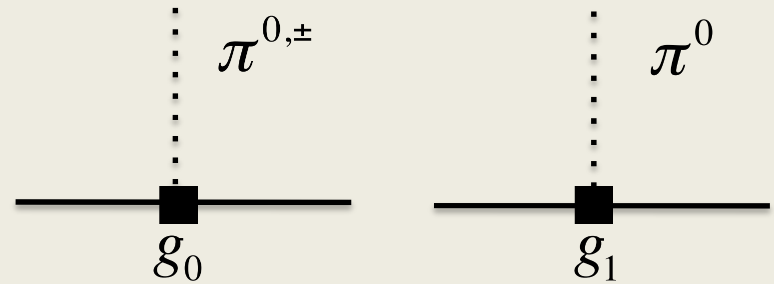


enters at NLO

Back to pion-nucleon couplings

- 2 CP-odd structures

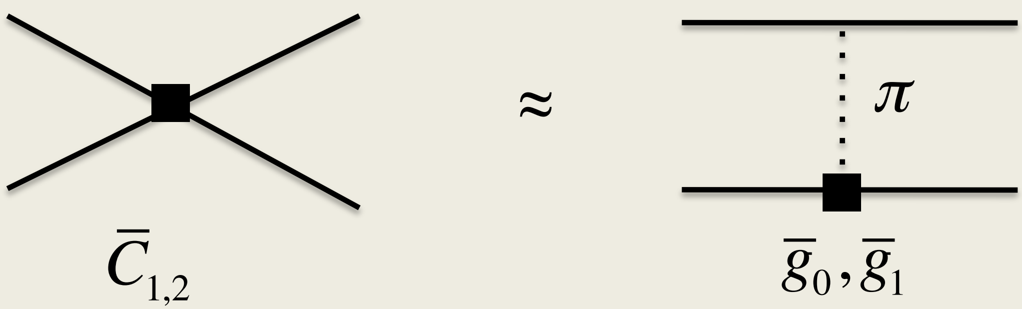
$$L = g_0\ \bar{N}\pi\cdot\tau N + g_1\ \bar{N}\pi^0 N$$



- Finally: CPV operators that are chiral invariant: e.g. Weinberg operator

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

- CPV pion-nucleon operators forbidden at LO → m_π^2 / Λ_χ^2

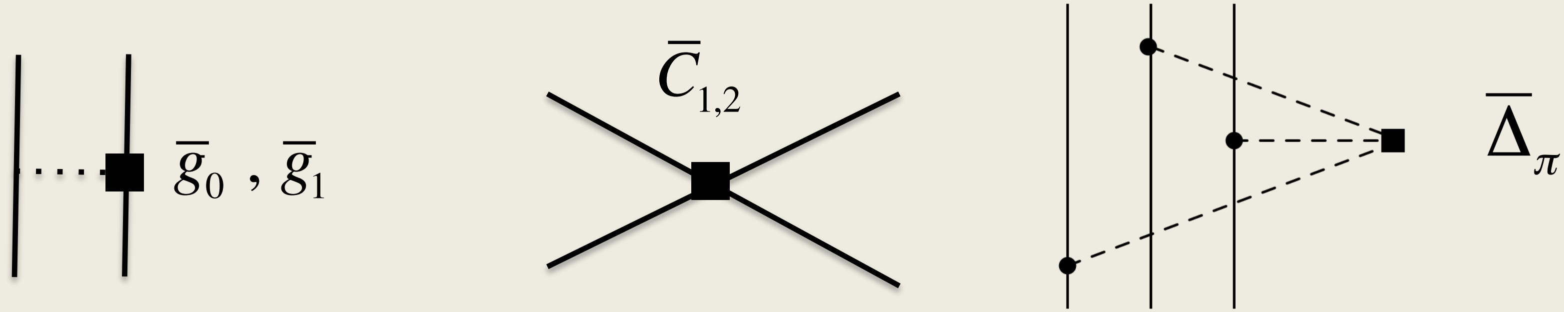


- Short-range are important but **only for 2 out of 5 S-P transitions**

$$^3S_1 \leftrightarrow {}^1P_1 \qquad {}^1S_0 \leftrightarrow {}^3P_0\ \ (np = nn = pp)$$

The CPV NN +NNN potential

For all dim4 + dim6 sources, NN + NNN CPV potential is subset of

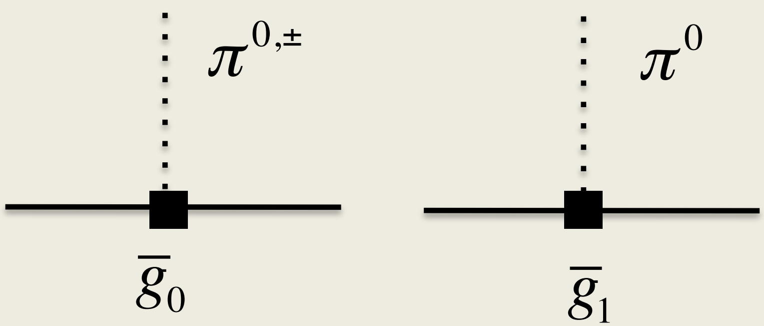


- **Different models of new physics 'pick' different couplings**

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

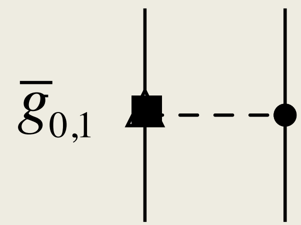
We cannot measure the CPV force directly

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

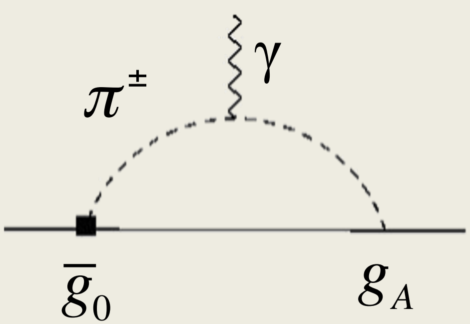


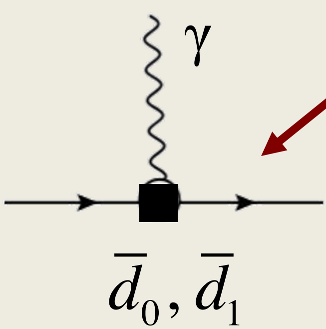
Tree

CP-odd nuclear force

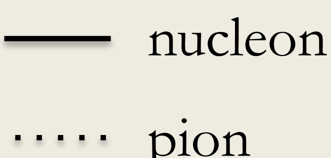


1-Loop
Neutron EDM



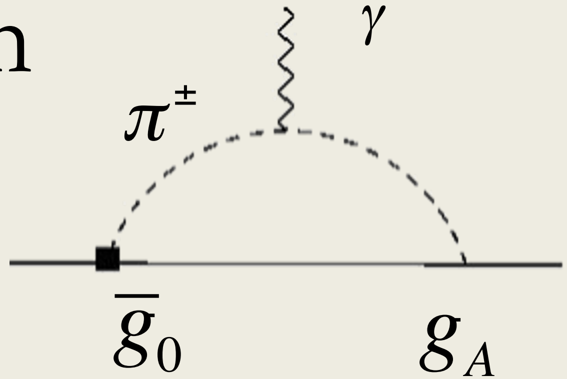


2 new low-energy constants ☹



The strong CP problem

Nucleon EDM



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

Crewther '79 Borasoy '02
Guo et al, '10 '12 '14,
JdV et al '10 '11

$$\mu = m_N$$

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

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

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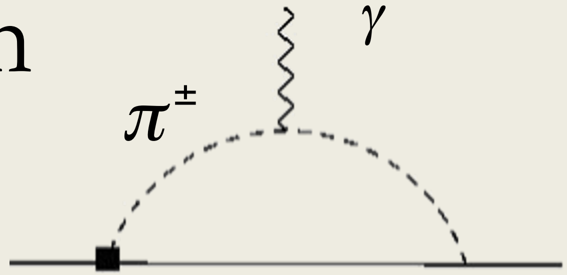

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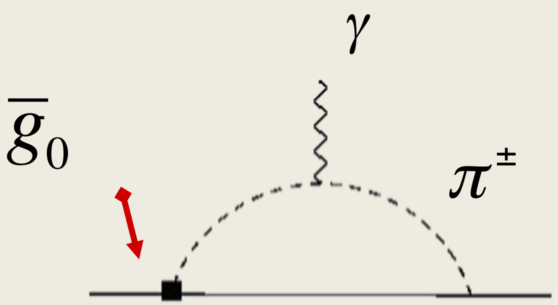
A proper assessment requires a non-perturbative calculation !

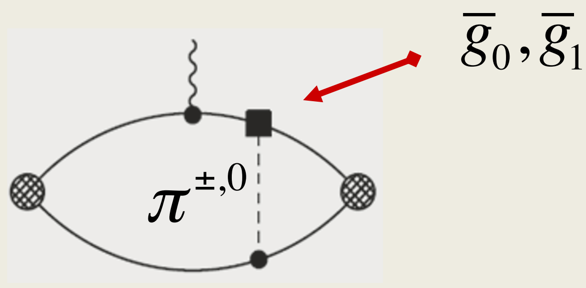
Lattice QCD (Shindler et al '19) $d_n = -(1.52 \pm 0.7)\cdot 10^{-16}\, e\,\bar{\theta}$ cm

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

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

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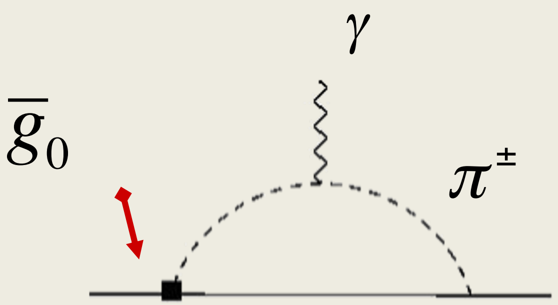

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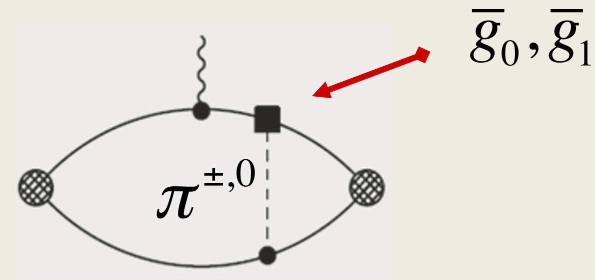


Nuclear EDM

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

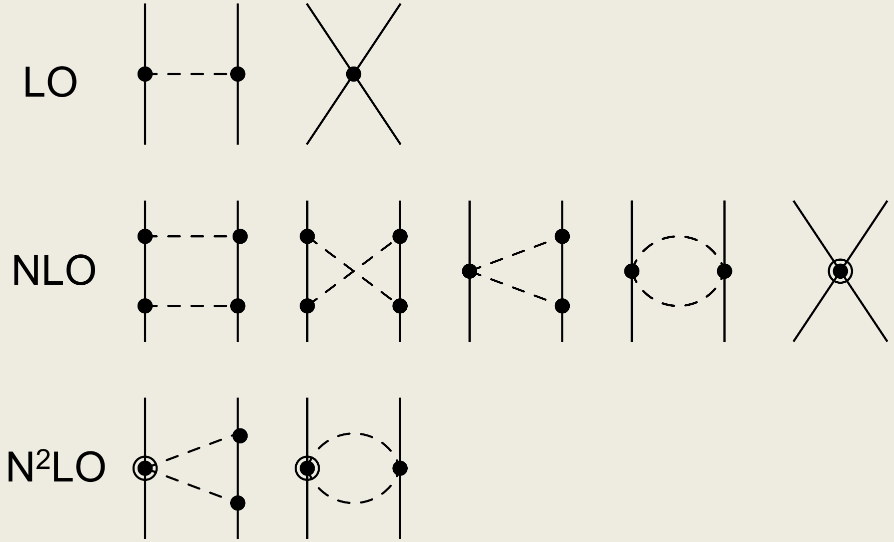
$$d_A = \langle \Psi_A \| \vec{J}_{\cancel{CP}} \| \Psi_A \rangle \; + \; 2 \langle \Psi_A \| \vec{J}_{CP} \| \tilde{\Psi}_A \rangle$$

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

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

Getting the wave functions

- Idea: obtain the nucleon-nucleon potential in chiral expansion

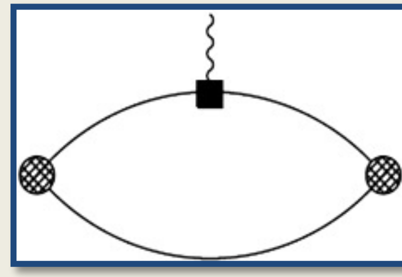


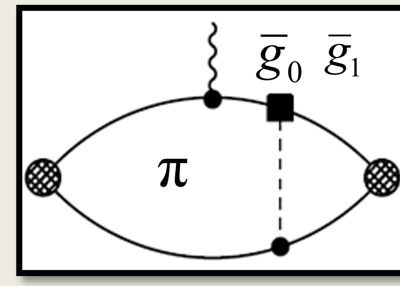
Weinberg
Van Kolck et al,
Epelbaum et al,
Machleidt et al,
And many more…

- Potential nowadays known up to N^4LO → LECs fitted to pi-N and NN data
- Calculate wave functions by solving Schrodinger equation

EDM of the deuteron

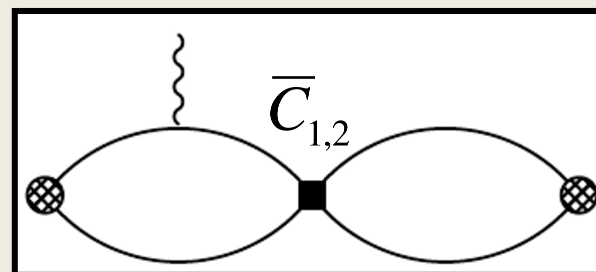
- Example: the simplest nucleus ^2H
- Target of storage ring measurement and interesting theoretical laboratory





- Three contributions (NLO)

  1. Sum of nucleon EDMs
  2. CP-odd pion exchange
  3. CP-odd NN interactions
  4. No three-body force obviously



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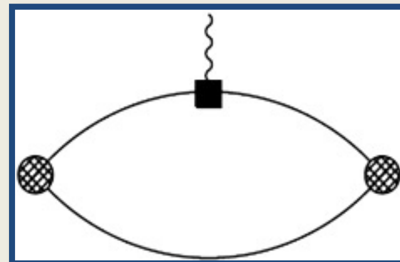

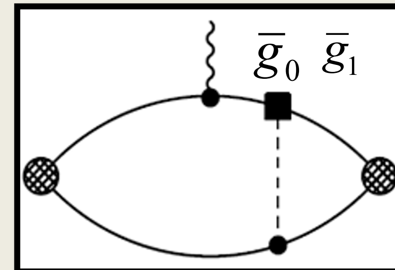

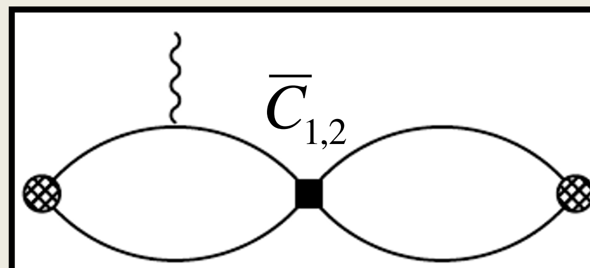

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  1. Sum of nucleon EDMs
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- **Deuteron is a special case**

$$^3S_1 \xrightarrow{\bar{g}_0,\bar{C}_{1,2}} {}^1P_1 \xrightarrow{\gamma} \cancel{{}^3S_1}$$

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

The chiral filter

Khriplovich/Korkin '00
Bsaisou et al '14

Chiral filter

- Deuteron EDM results

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

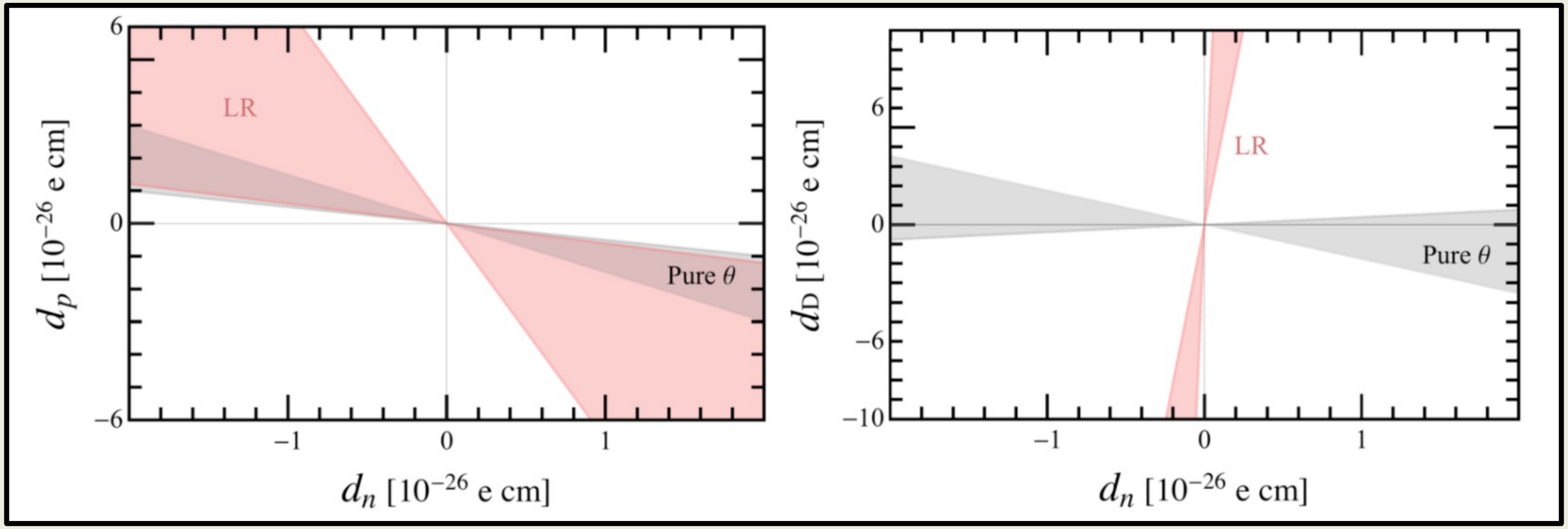
- Error estimate from cut-off variations + higher-order terms

`	**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**!

Unraveling sources with 2 EDMs

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



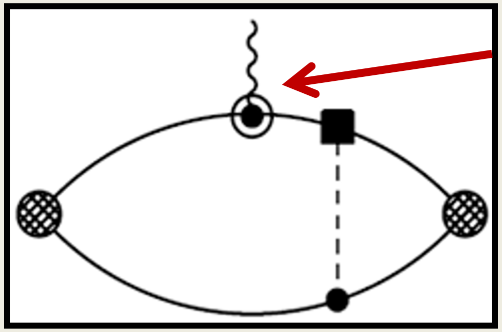
- **Nuclear EDMs complementary to nucleon EDMs**
- Deuteron is just a placeholder: other nuclear systems are similar
- **If we can control nuclear matrix elements !**

The magnetic quadrupole moment

- A spin 1 particle has **a Magnetic Quadrupole Moment**

$$H = \frac{\overline{\mathrm{M}}_d}{4} \varepsilon^{*i} \varepsilon^j \nabla^i B^j$$

- There is is **no** one-body contribution



nucleon magnetic moment

Sensitive to **both** $\bar{g}_0$ and $\bar{g}_1$ exchange

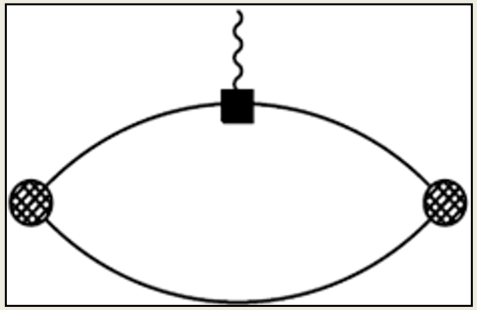
For chromo-EDM $$\frac{\overline{\mathrm{M}}_d}{d_d} m_d = 1.6\,(\mu_p - \mu_n) + 2.2 \frac{\bar{g}_0}{\bar{g}_1} (\mu_p + \mu_n)$$

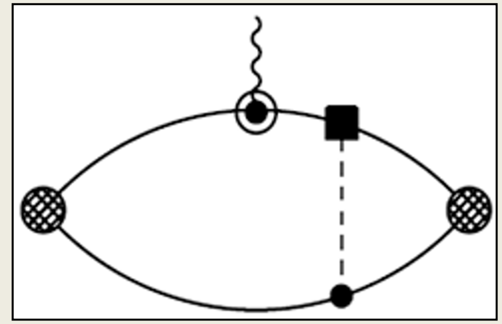
The magnetic quadrupole moment

deuteron EDM

deuteron MQM

For theta:





Liu et al, PLB '12

$$\frac{\bar{\mathrm{M}}_d}{d_d} m_d = 0.22(\mu_p + \mu_n)\left|\frac{\bar{g}_0}{F_\pi d_0}\right| e\ fm \ \propto 20(\mu_p + \mu_n)$$

- Higher moments like **MQMs can provide additional input**
- Deuteron MQM is **not** a realistic target

- But nuclear MQMs important in atoms and molecules

Flambaum et al 17 '18

EDMs of the tri-nucleon system

Stetcu et al ‘08
JdV et al ’11
Song et al ‘13
Bsaisou et al ’14
Froese et al ’21

- Let’s look at a bit bigger system
- More contributions than deuteron:
  1. Nucleon EDMs
  2. Both g_0 and g_1 pion exchange

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

comparable

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

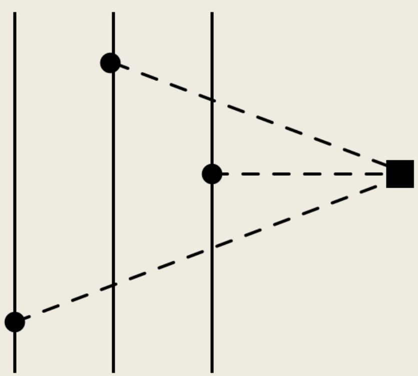
Other light nuclei up to ^{19}F in NCSM (see talk by Petr Navratil)

EDMs of the tri-nucleon system

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

- 3He can be put in a ring as well (3H too but radioactive…)
- More contributions than deuteron:
  1. Nucleon EDMs
  2. Both g_0 and g_1 pion exchange

$$d_{3He} = 0.9\, d_n - 0.05\, d_p + \left[(0.14 \pm 0.04)\, \bar{g}_1 + (0.10 \pm 0.03)\, \bar{g}_0\right] e\ fm + \ldots.$$
$$-(0.2\ \pm 0.02)\Delta\ e\ fm$$



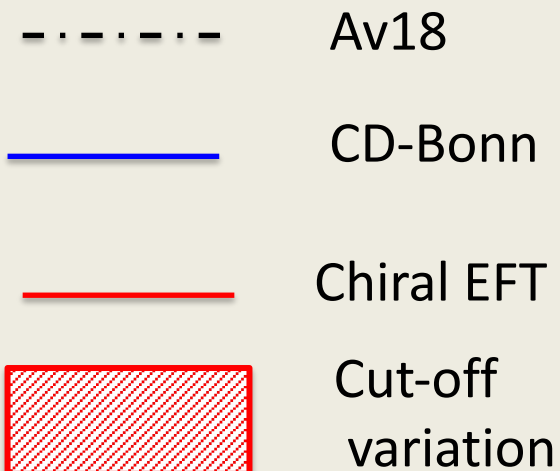
JdV et al '12

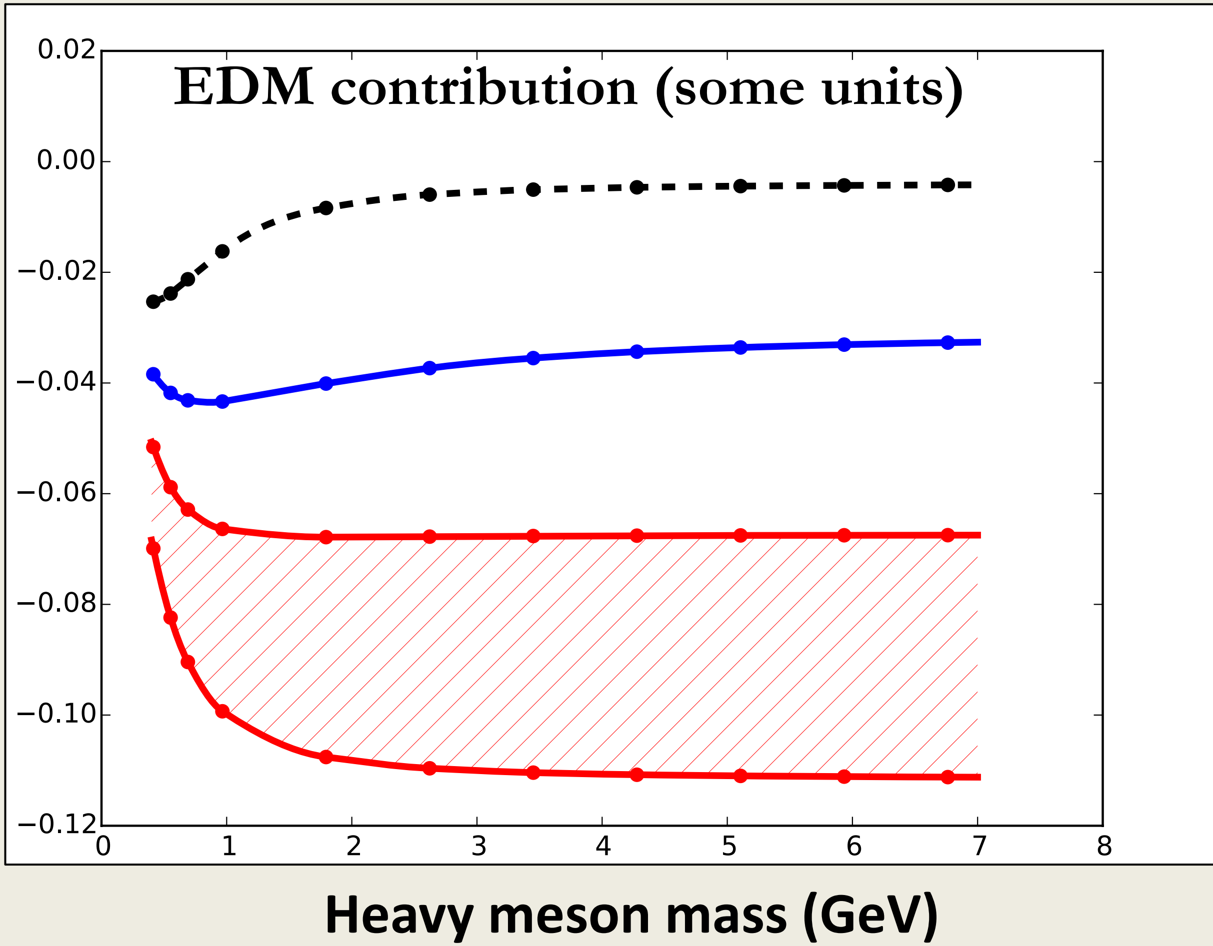
- Found to give small contributions (smaller than expectations) Bsaisou et al '14
- Viviani + Gnech '19 reinvestigated this and found a larger contribution (30% for mLRSM)
- **No calculations include this for heavier nuclei**

Cut-off dependence

Plot from Bsaisou et al JHEP ‘14

$$\frac{m_1^2 \overline{C}_1}{4\pi\, r}\, e^{-m_1 r} \rightarrow \overline{C}_1\, \delta^{(3)}(\vec{r})$$





- Quite a large spread ….
- Leading CP-odd force in certain models (e.g. through Weinberg operator)
- **How to understand this?**

Cut-off dependence

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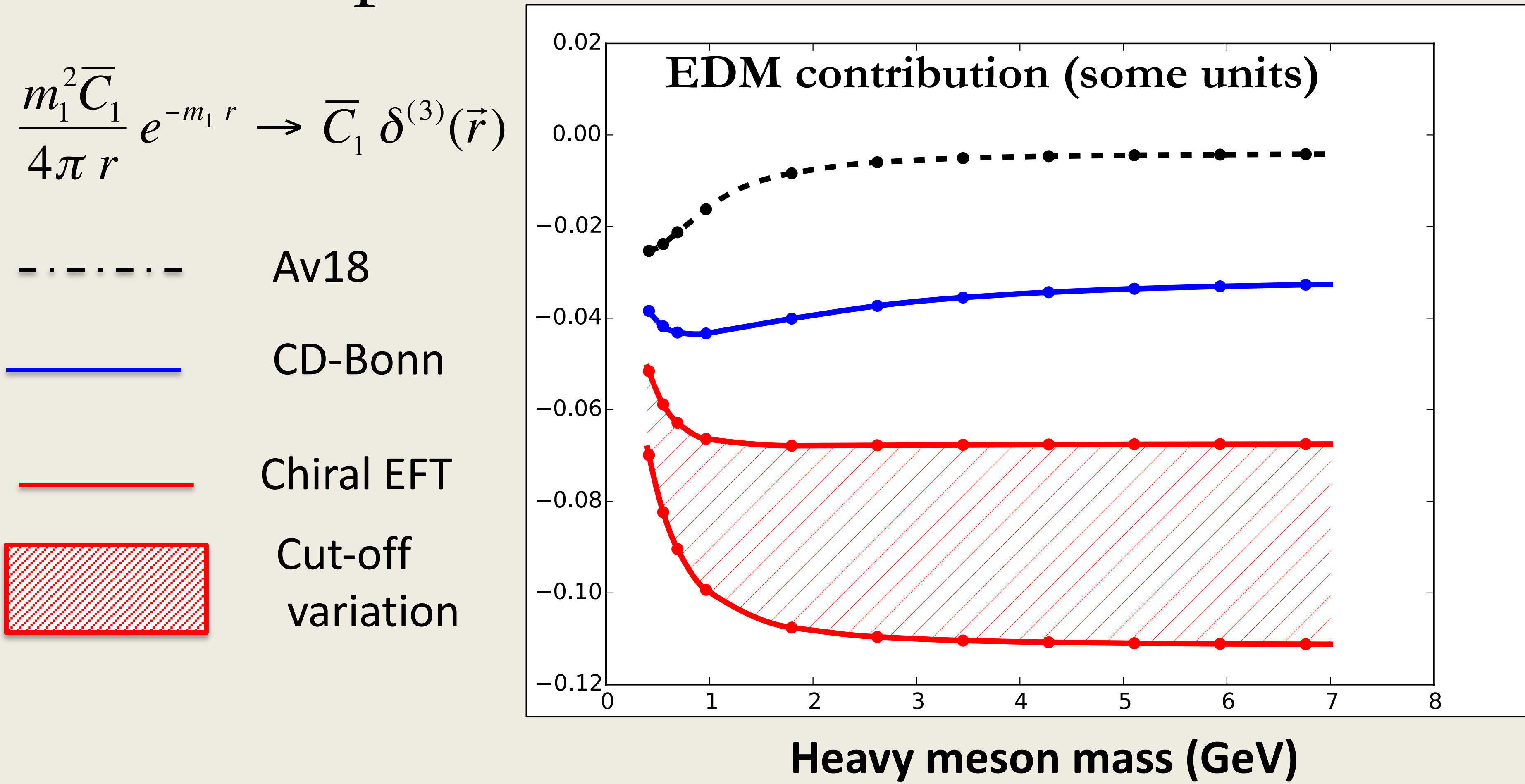

- For a given regulator Λ : fit $\overline{C}_1(\Lambda)$ to data. Requires nonzero EDMs…
- **Better: calculate S ←→ P transitions on lattice → fit** $\overline{C}_1(\Lambda)$

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

See talk by Victor Flambaum

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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
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:

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

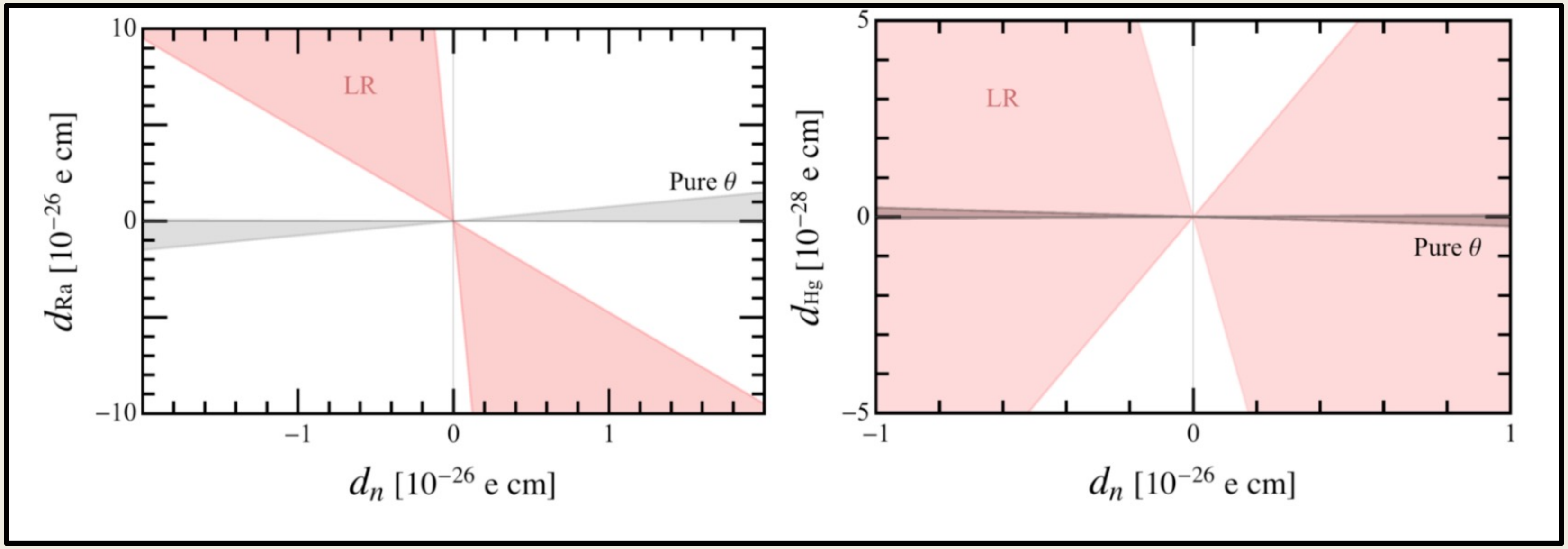
	a_0 range	a_1 range
^{199}Hg	0.3±0.4	0.45±0.7
^{225}Ra	2.5±7.5	65±40

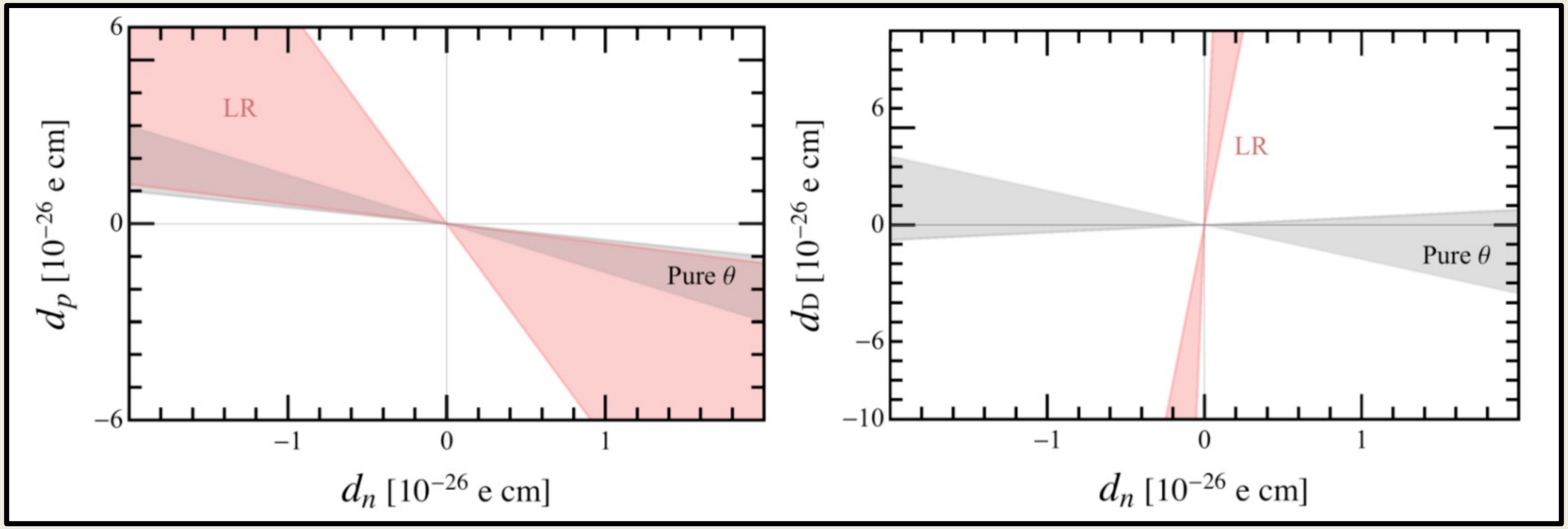
Flambaum, de Jesus, Engel, Dobaczewski,….

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

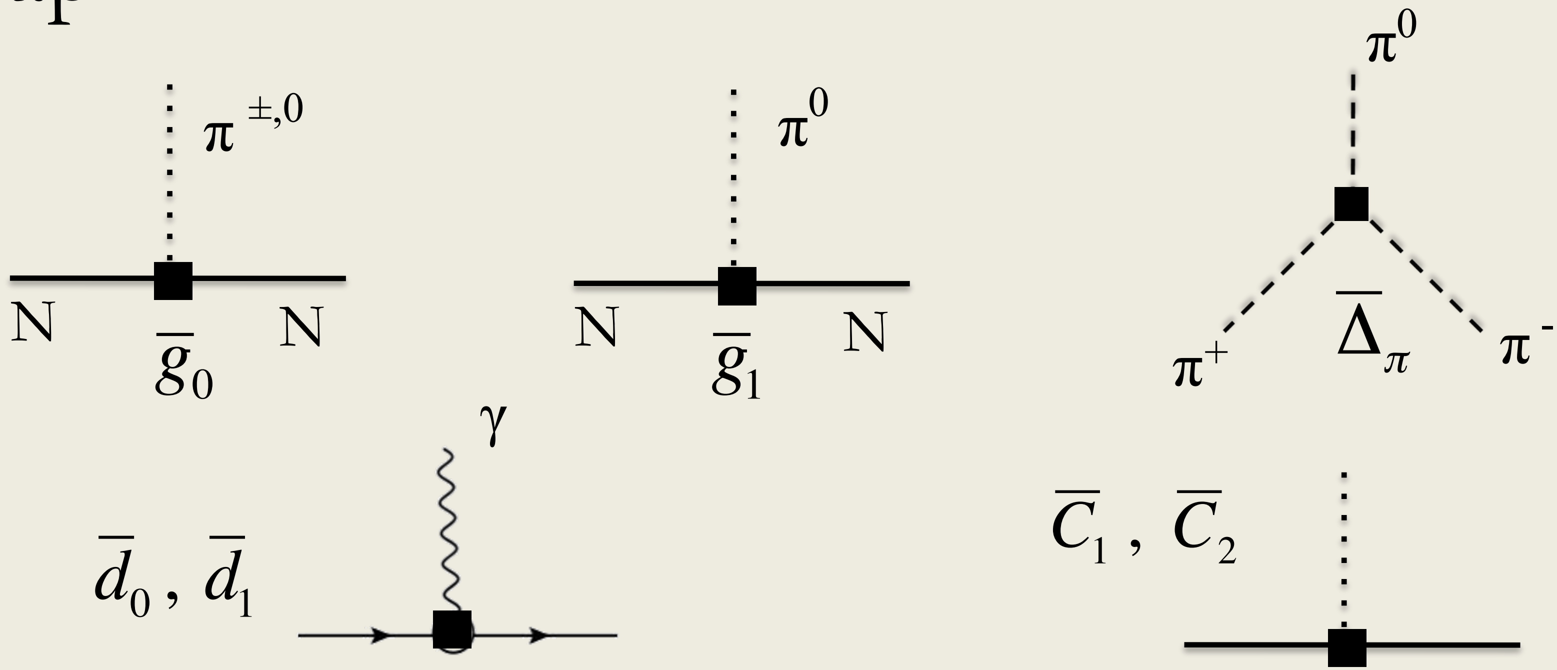
table from review: Engel, Ramsey-Musolf, van Kolck, ’13 + updates e.g. Engel et al PRL ‘18

EDM ratios: theta term versus left-right symmetric model





Recap

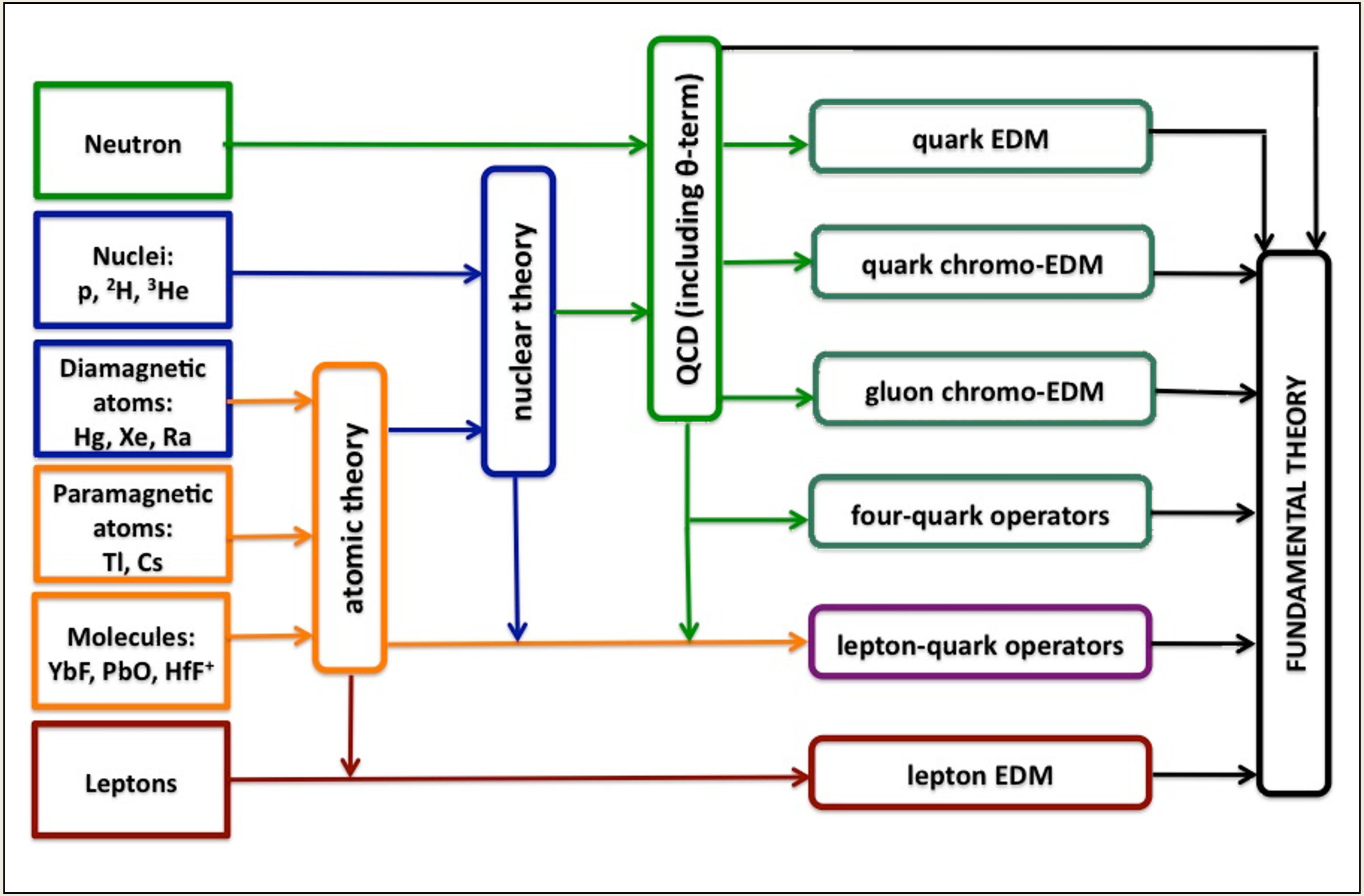


- 2 pion-nucleon (no g_2 !)
- 1 pion-pion-pion

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

- **Each hadronic/nuclear CPV observables probes a linear combination**
- **Compare EDMs and MQMs in a single framework**
- Link to particle physics exists

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

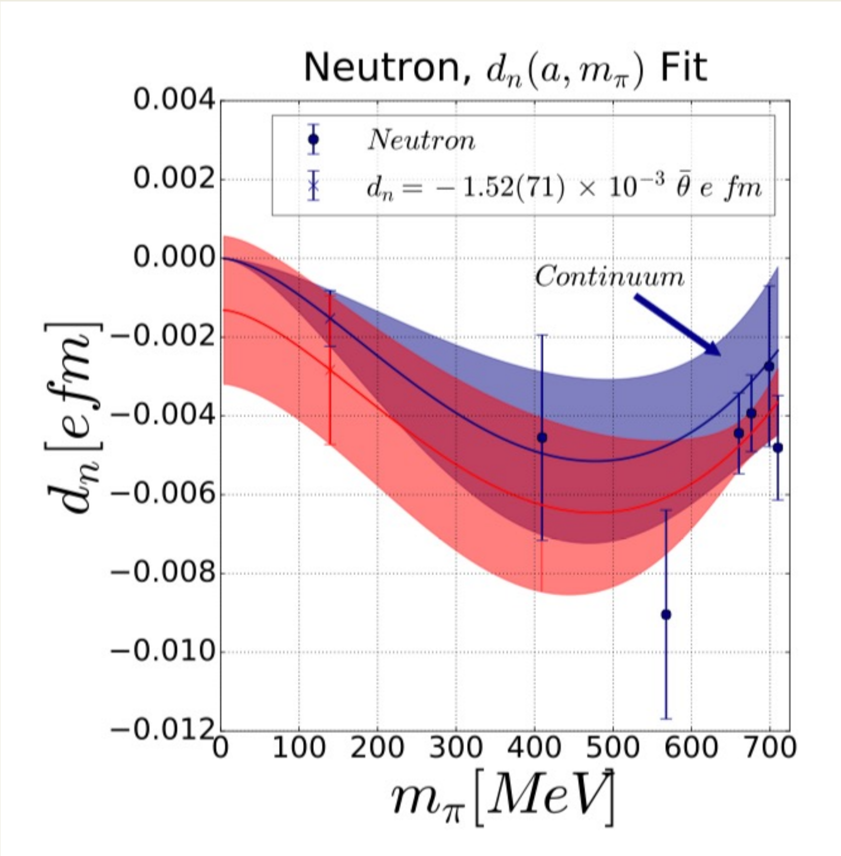
- ✓ **Need theory improvement to fully exploit the experimental program**

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

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