T-violation in nucleons and nuclei: an effective field theory approach

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Main purpose of this talk

1. How to describe T-violating hadronic interactions in a systematic fashion ? What interactions to include for ‘leading order’ calculations ?

2. Using these interactions to calculate T-odd nuclear observables (EDMs, Schiff moments, Magnetic quadrupole, neutron spin rotation, analyzing powers …). **I will focus on PVTV not on PCTV (but happy to discuss)**

3. Focus on simple observables that capture main ideas (analogue of program of hadronic PV) → extension to complicated observables in heavy nuclei is far from trivial.

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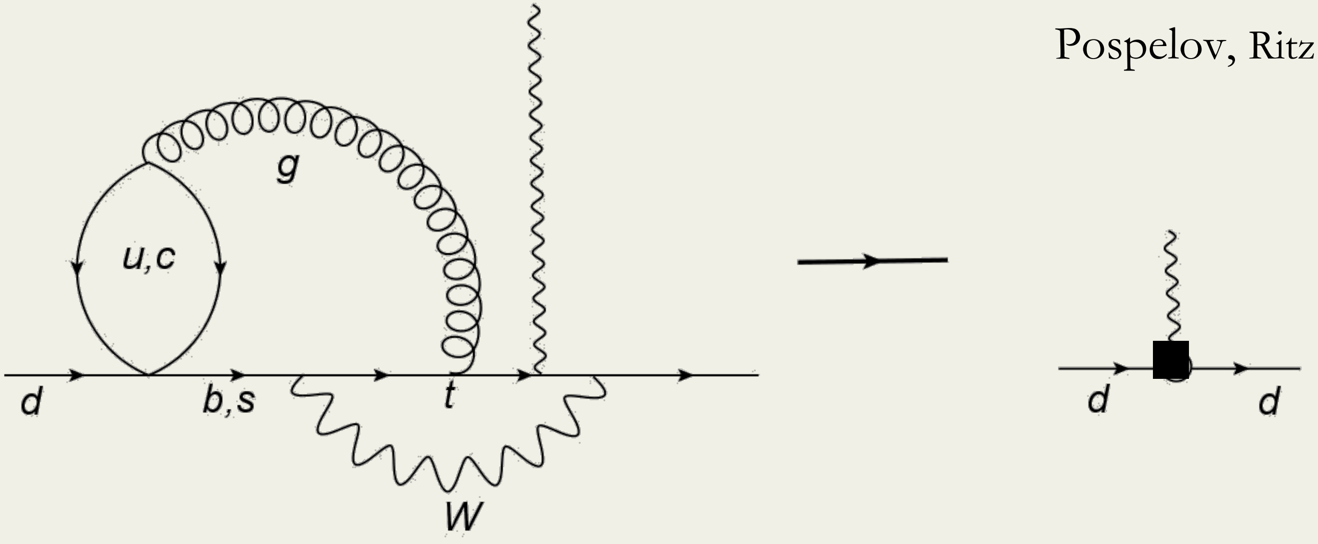
4. **Very important:** measurable T-violating signals require BSM physics (or nonzero theta term). Need some sort of link between hadronic T-violation and particle physics to be able to do 1) and then 2) and 3).

5. Will **not** discuss in detail specific BSM models or implications or baryogenesis motivations → talks by Kaori and Michael on Saturday.

EDMs in the SM

- CP is broken in the CM via the Kobayashi-Maskawa mechanism
- CP-odd phase in the **off-diagonal** CKM matrix
- Manifests in flavor-diagonal (our goal) **at 3 loops (electron 4 loops)**

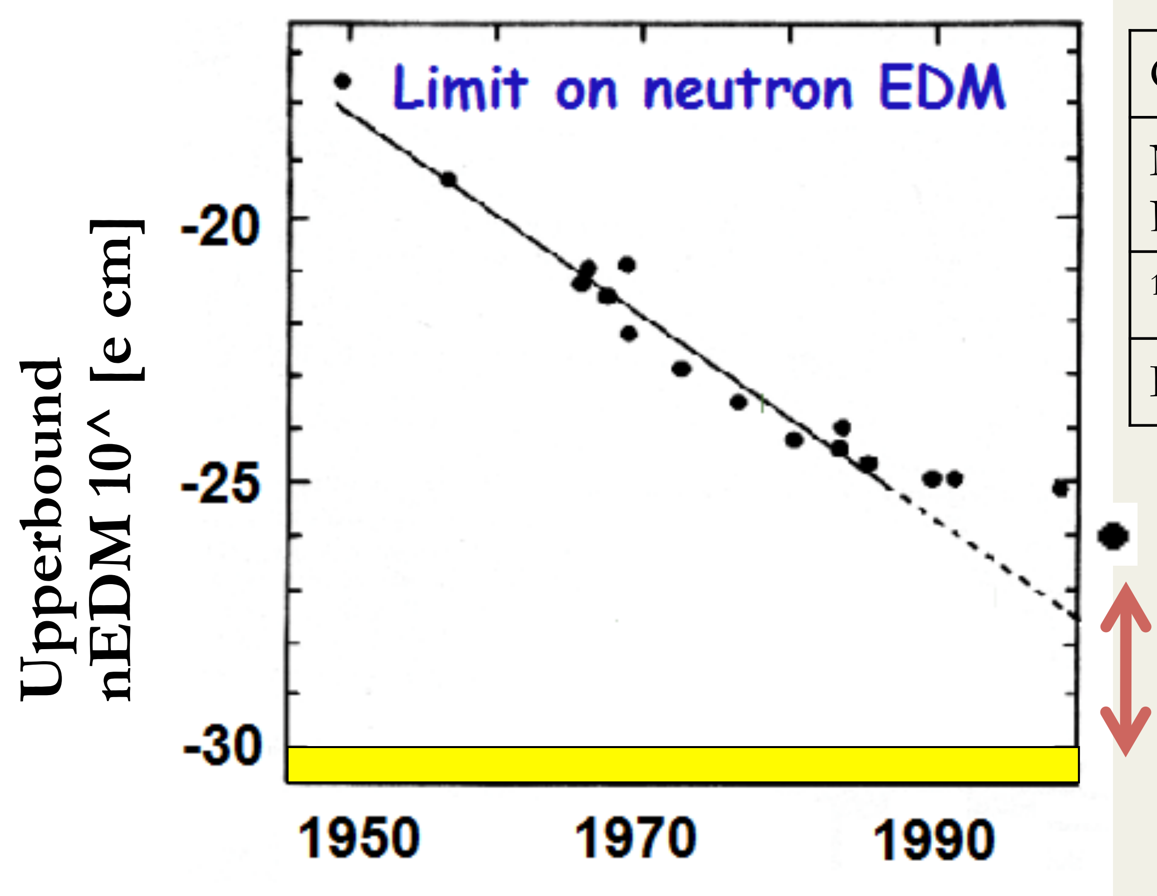


Pospelov, Ritz ‘05

- **Very very suppressed SM electroweak contributions to EDMs**

Hoogeveen ’90, Khriplovich, Zhitnitsky ‘82, Czarnecki, Krause ’97, Uraltsev ‘13, Seng ‘14

Standard Model suppression



Baker et al '06 '15

“Here be dragons”

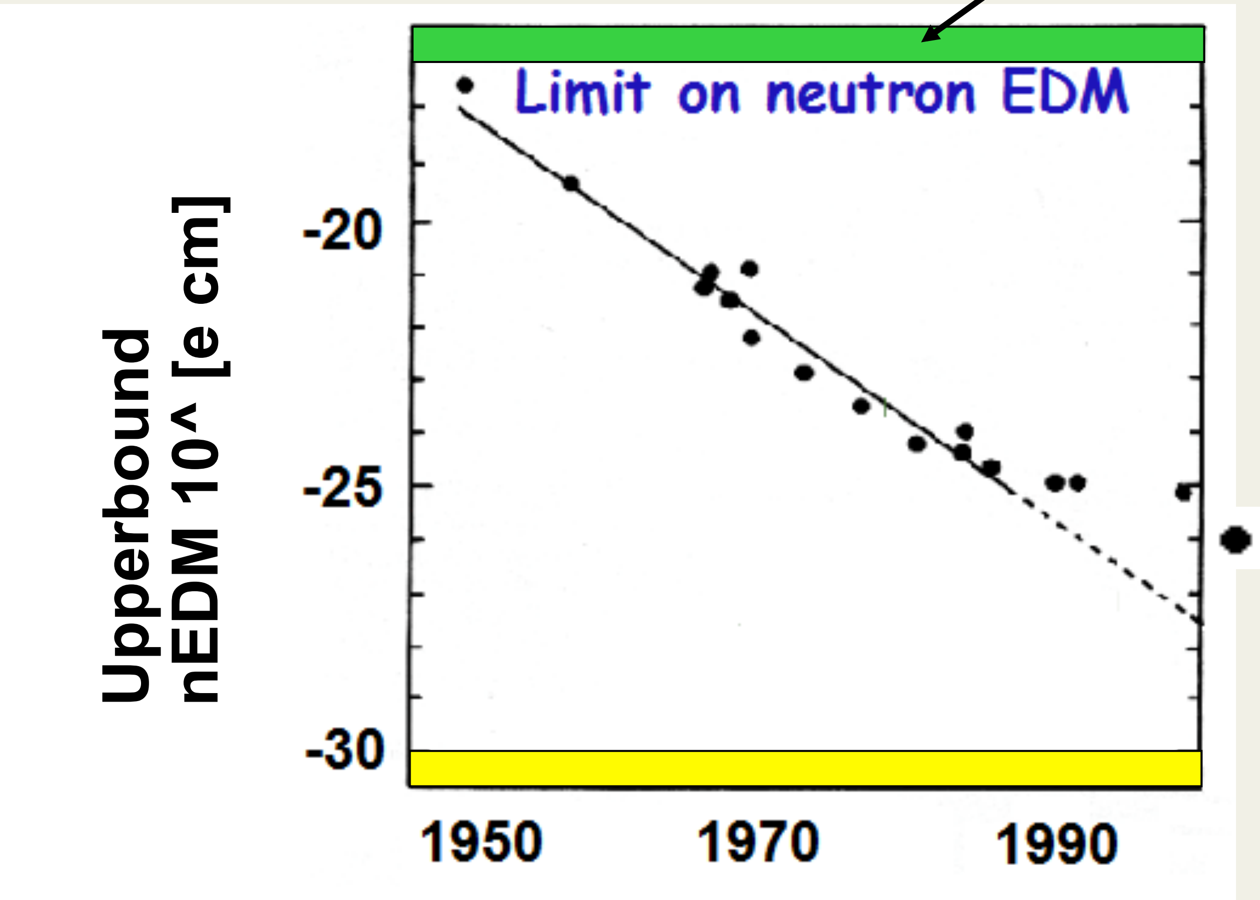
Quarks	$10^{-33,-34}$ e cm
Neutron/ Proton	$10^{-31,-32}$ e cm
^{199}Hg	$10^{-32,-34}$ e cm
Electron	$10^{-37,-38}$ e cm

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

With linear extrapolation: CKM neutron EDM in 2075….

The strong CP problem

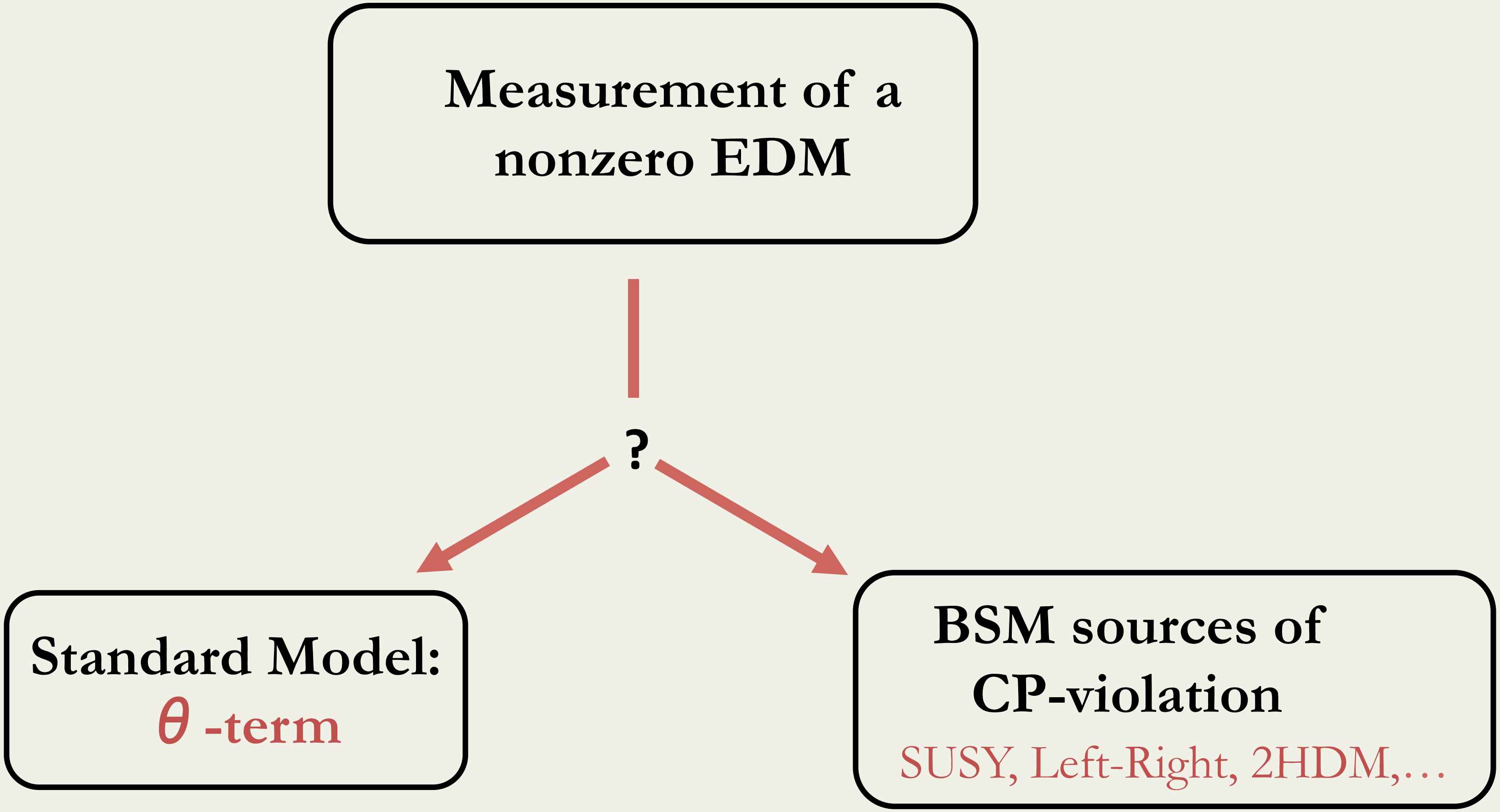
If $\theta \sim 1$



More details on calculation later

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

Reason for this suppression? Axions? Nelson-Barr ?
All solutions have problems…. Dine/Draper '15



Measurement of a nonzero EDM

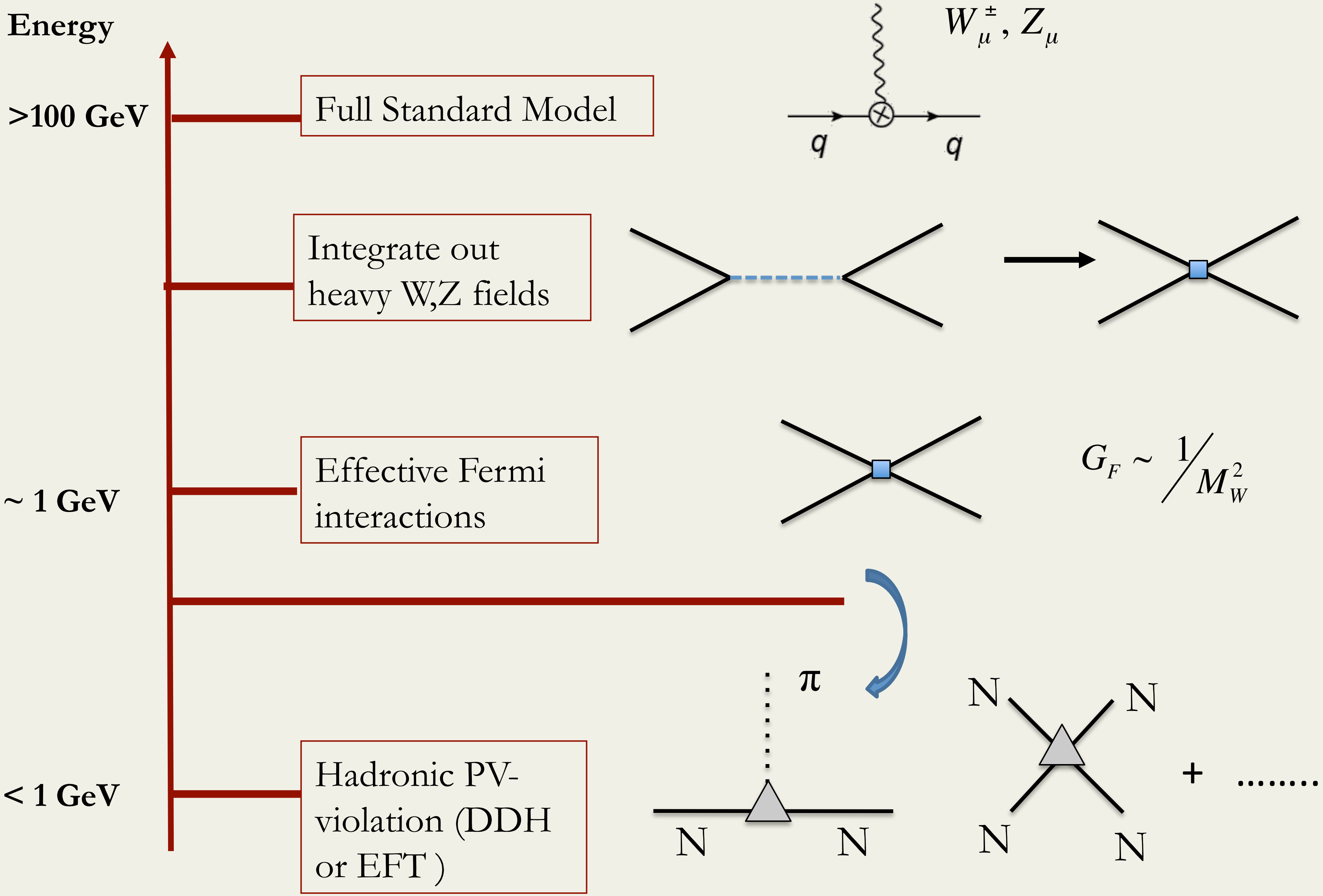
?

Standard Model:
θ -term

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

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

Comparing to hadronic parity violation



Energy

>100 GeV

Full Standard Model

Integrate out heavy W,Z fields

~ 1 GeV

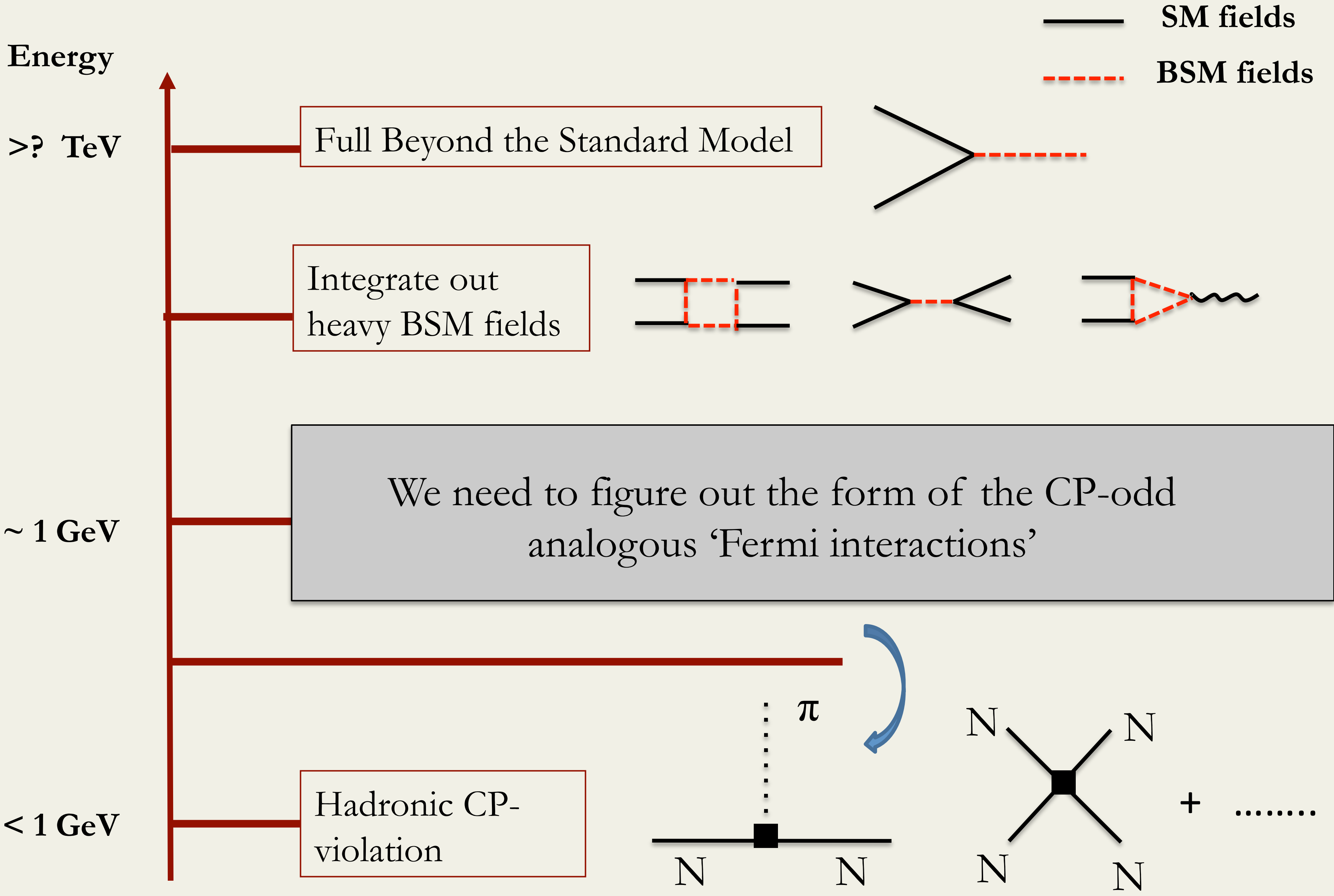
Effective Fermi interactions

$$G_F \sim {}^{1}\!/_{M_W^2}$$

< 1 GeV

Hadronic PV-violation (DDH or EFT)

Comparing to hadronic parity violation



Full Beyond the Standard Model

Integrate out heavy BSM fields

We need to figure out the form of the CP-odd analogous 'Fermi interactions'

Hadronic CP-violation

The form of the CP-odd 'Fermi' interactions

- To stay **model independent:** add all EFT operators (infinite…)

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

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

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

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

- Focus on **all CP-odd operators at dimension-six**
- Run down → Integrate out H,W,Z,t → Run down → integrate out b,c → Obtain form of the 'CP-odd' Fermi interactions

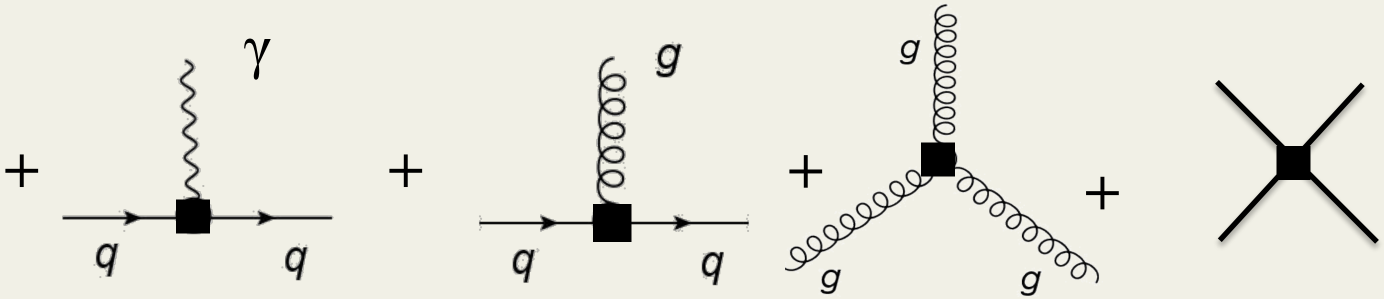
- Can be easily matched to specific BSM models
- CPV unlikely to arise from light BSM fields but loopholes exist!

Le Dall, Pospelov, Ritz '15

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

I am mostly neglecting (semi-)leptonic CPV for this talk

Intermediate summary I

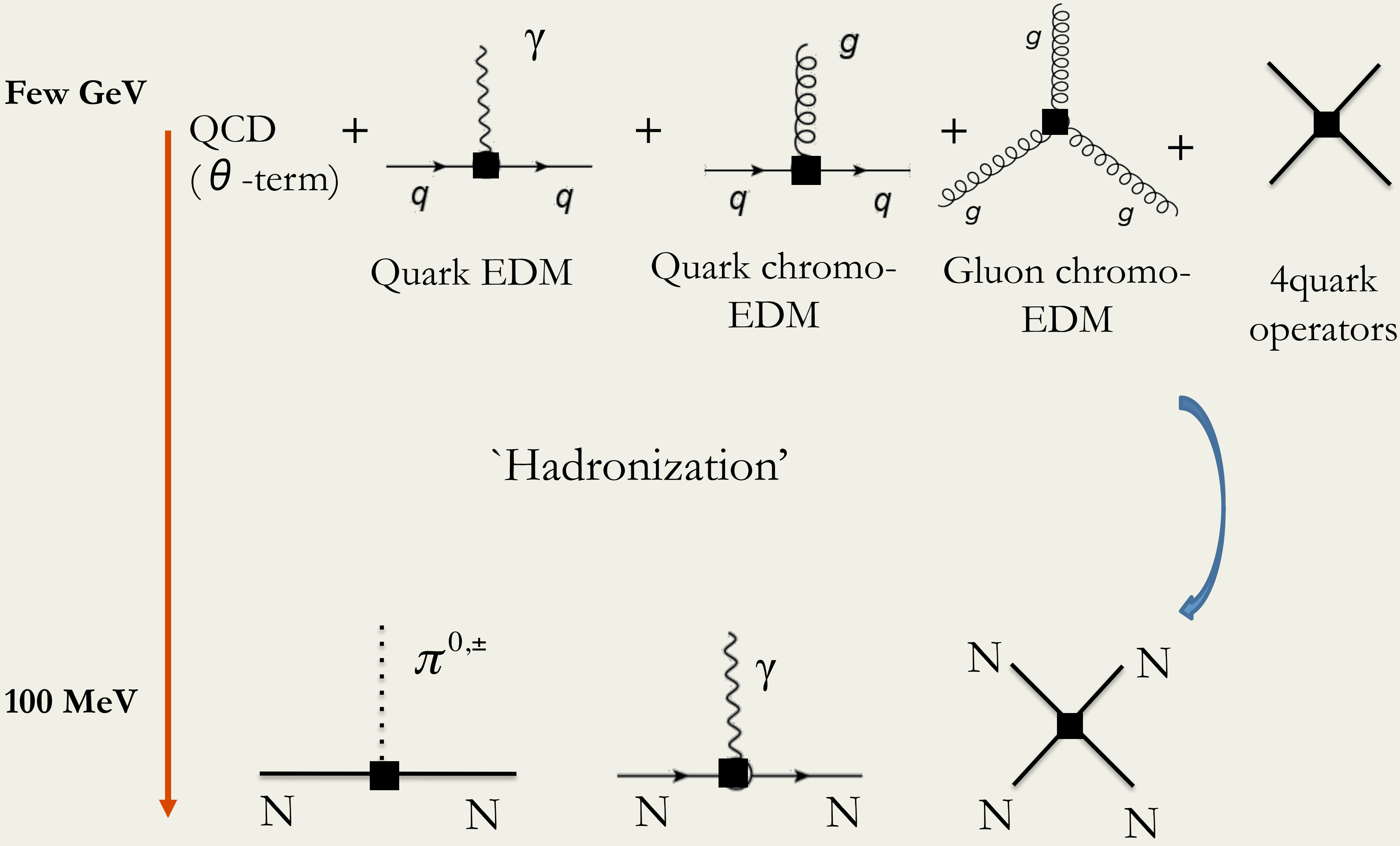
- Parametrized BSM CP violation in terms of **dim6** operators
- Several operators at low energy: theta, (C)EDMs, Weinberg, Four-fermion
- **Important:** different BSM models -> different EFT operators

1. Standard Model: only **theta** 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: **Four-quark LR operators**, small (C)EDMs
5. Leptoquarks: Semi-leptonic four-fermion and four-quark (tree-level)

- But we neglect these 'high-energy details' in this talk and focus on the EFT operators around 1 GeV

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

When the dust settles…..



Few GeV

QCD (θ -term) + Quark EDM + Quark chromo-EDM + Gluon chromo-EDM + 4quark operators

`Hadronization’

100 MeV

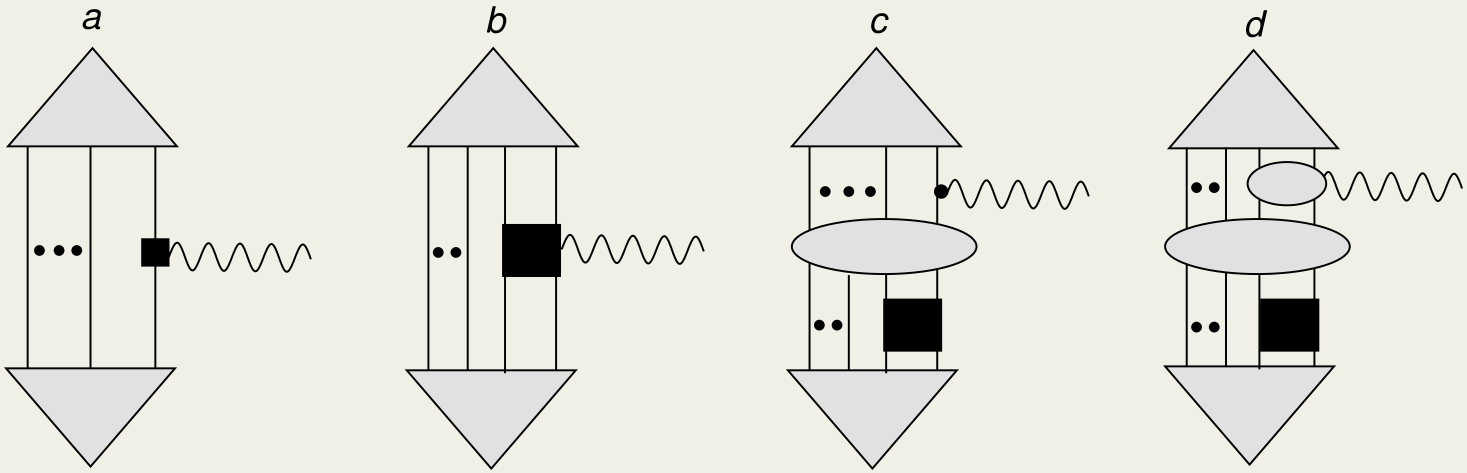
CPV in hadrons and nuclei

Goal is to calculate CPV properties of **hadrons** and **nuclei**

- Electric dipole + higher moments (Schiff, magnetic quadrupole…)
- CP-odd scattering observables

Wishlist

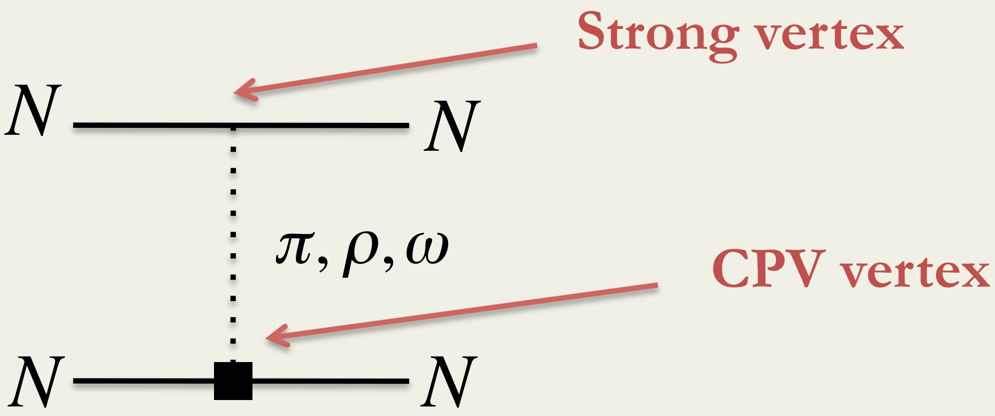
- **Link** to underlying theory (QCD + CPV operators)
- **Power counting of nuclear forces and currents**
- **General** (several observables in one framework)



General CP-violating NN force

Herczeg '66, 87
Gudkov et al '93

- Parametrize the CPV nuclear force with one-meson exchange
- CP-odd analogue of the PV DDH model with O(10) CPV couplings



Gudkov et al '11 '13

- Or in EFT with just contact terms: five $S \leftrightarrow P$ transitions

$$^3S_1 \leftrightarrow {}^1P_1 \qquad {}^3S_1 \leftrightarrow {}^3P_1 \qquad {}^1S_0 \leftrightarrow {}^3P_0$$

$$np \qquad np \qquad np, nn, pp$$

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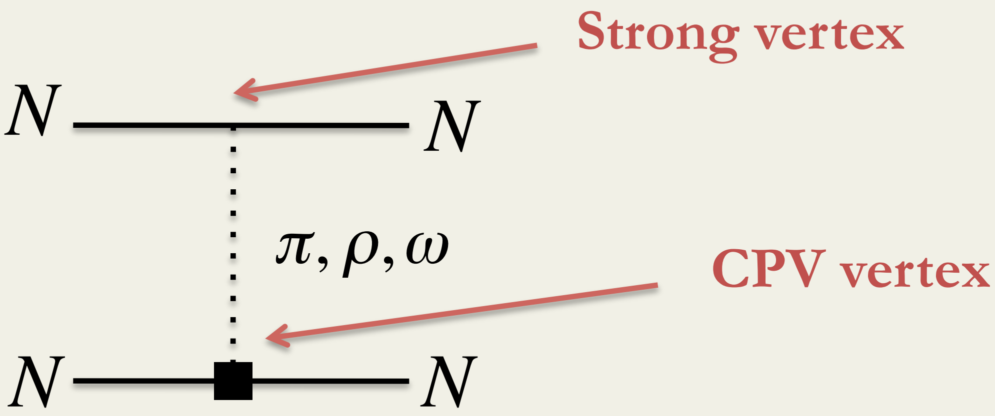

Gudkov et al ’11 ‘13

- Or in EFT with just contact terms: five $S \leftrightarrow P$ transitions

Here we use chiral EFT: startpoint QCD + CPV dim-6 operators

1. Systematic derivation of CPV potential + CPV 3-body forces
2. Direct connection between forces and currents (for EDMs!)
3. Link to lattice QCD

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

- ChPT has systematic expansion in $Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi$ $\quad \Lambda_\chi \cong 1\,GeV$

Weinberg, Gasser, Leutwyler, and many many others

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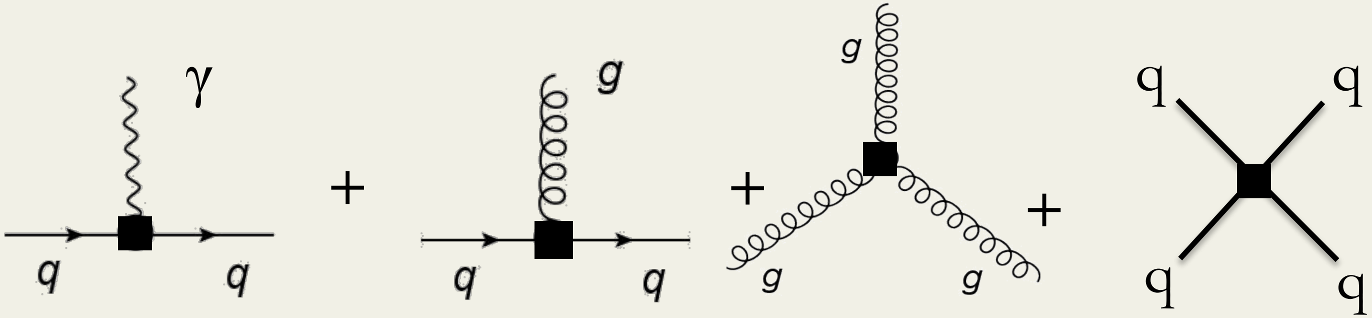
- ChPT has systematic expansion in $Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi$ $\Lambda_\chi \cong 1\,GeV$
  - **Form of interactions fixed by symmetries**
  - Each interactions comes with an unknown constant (LEC)
  - Can be used to derive a nucleon-nucleon potential (chiral EFT)

- **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

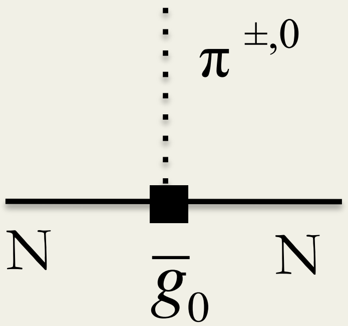
↓

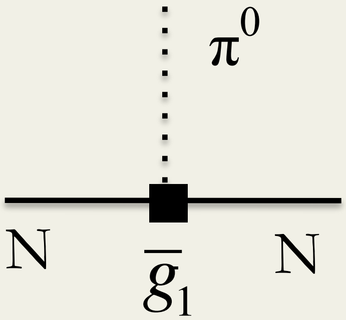
Different CP-odd chiral Lagrangians

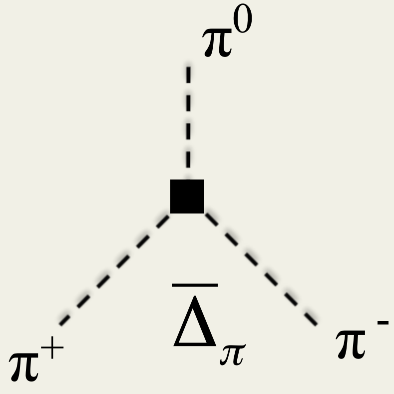
↓

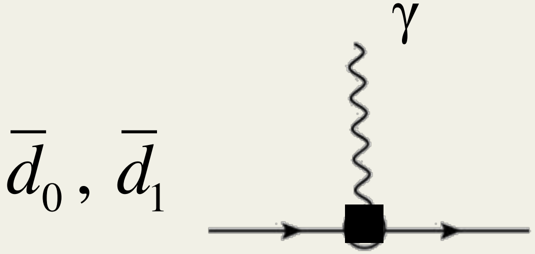
Different hierarchy of CP-odd moments and scattering observables

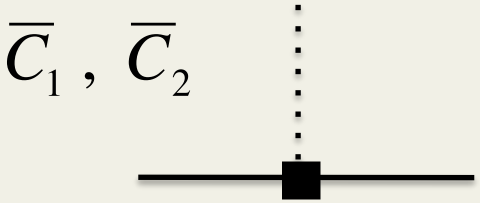
The magnificent seven











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

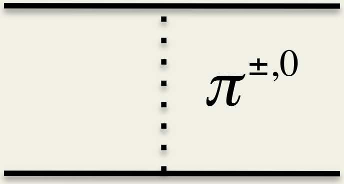
- Up to **NLO,** **seven** interactions for **all CP-odd** dim4-6 sources
- **Each hadronic/nuclear CPV observables probes a linear combination**
- More terms if leptons are included !

Mereghetti et al ’10, JdV et al ’12, Bsaisou et al ’14, Chupp/Ramsey-Musolf ‘13

Hierarchy of CPV nuclear forces

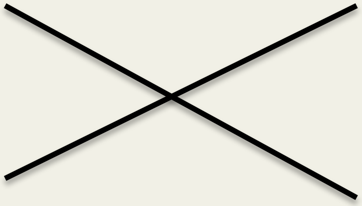
CP-even

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



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

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



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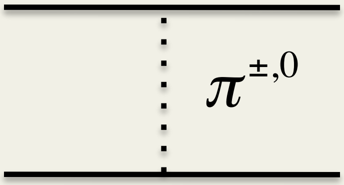

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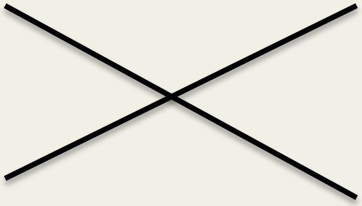
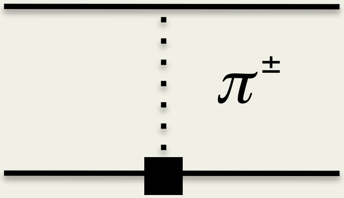


$$\sim Q^0$$

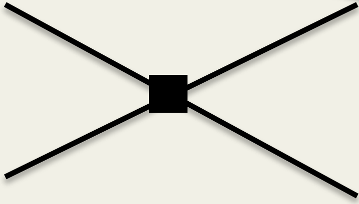
CP-odd

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



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

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



$$\sim Q^1$$

Maekawa et al ‘11

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

An explicit example: the theta term

U(1) and SU(2) rotations + vacuum alignments: **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

Easy to include in ChPT $\chi = 2B(\bar{m} + \varepsilon\bar{m}\tau^3) \rightarrow 2B(\bar{m} + \varepsilon\bar{m}\tau^3 + im_*\bar{\theta})$

Theta and chiral perturbation theory

U(1) and SU(2) rotations + vacuum alignments: **CP-odd quark mass:**

Crewther et al' 79

Baluni '79

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

$$\Big\downarrow$$

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

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

Strong proton-neutron mass splitting

Theta and chiral perturbation theory

U(1) and SU(2) rotations + vacuum alignments: **CP-odd quark mass:**

Crewther et al' 79

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$$\varepsilon = \frac{m_u - m_d}{m_u + m_d} \qquad\qquad \Big\downarrow \qquad\qquad m_\star = \frac{m_u m_d}{m_u + m_d}$$

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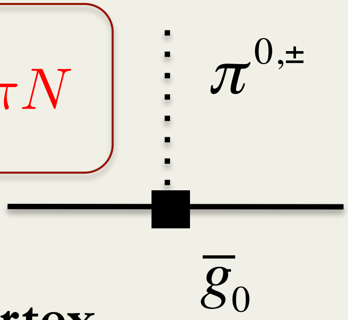
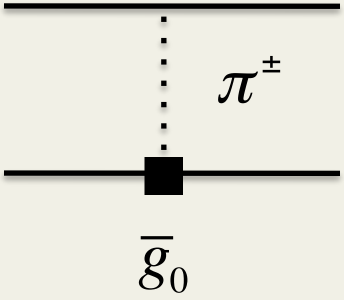


CP-odd pion-nucleon vertex



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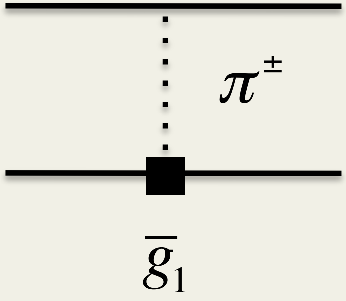
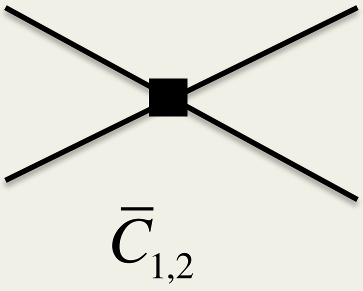




Theta and chiral perturbation theory

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

Crewther et al' 79

Baluni '79

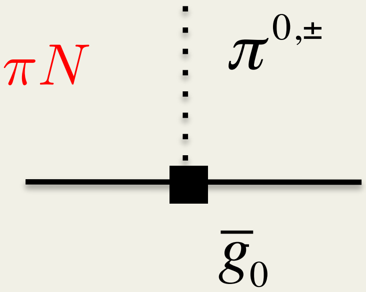
$$\mathcal{L}_{\text{QCD}} = \mathcal{L}_{\text{kin}} - \bar{m}\bar{q}q - \varepsilon\bar{m}\,\bar{q}\tau^3 q \;\; + m_\star\,\bar{\theta}\,\bar{q}i\gamma^5 q$$

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

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

Linked via SU$_{\text{A}}$(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

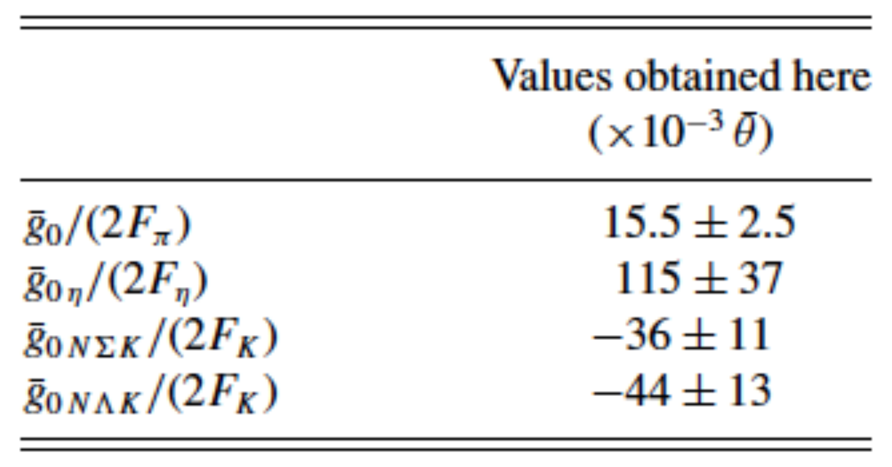
Walker-Loud '14, Borsanyi '14, Aoki (FLAG) '13

Use **lattice** for mass splitting

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

Wrap-up

- Identify protected relations 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

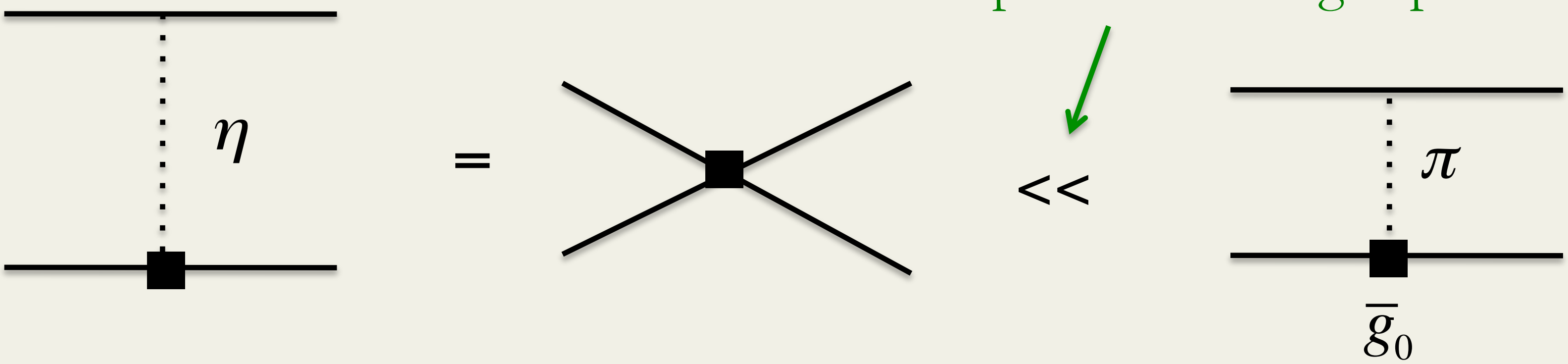
JdV et al ‘15

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

Small due to isospin symmetry

- Used to estimate **short-range CPV NN** forces from theta term

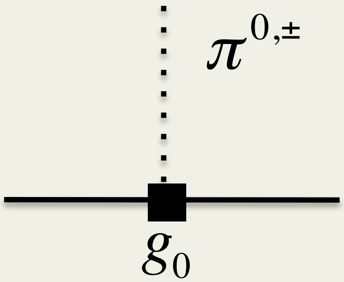
Confirms power counting expectation !

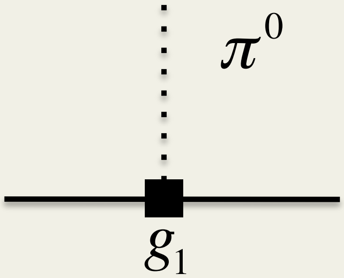


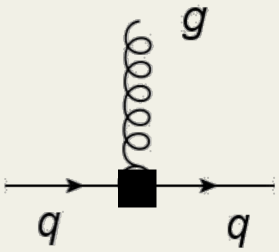
Back to pion-nucleon couplings

- Dominant CPV force from:

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







- **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

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

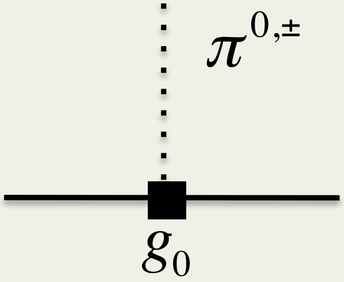
- Large uncertainties. But generally: $|\bar{g}_1| \geq |\bar{g}_0|$

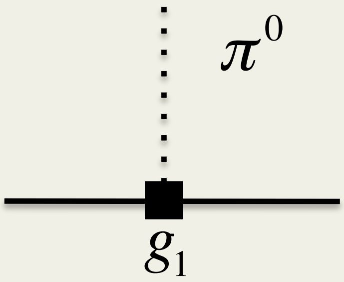
- Lattice in progress (CALLAT)

Back to pion-nucleon couplings

- 2 CP-odd structures

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





- Four-quark left-right operator breaks isospin !

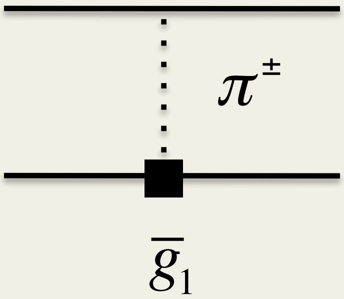
Mohapatra, Senjanovic, Pati '75

Maiezza et al ' 14

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

- ChPT gives ratio of couplings

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



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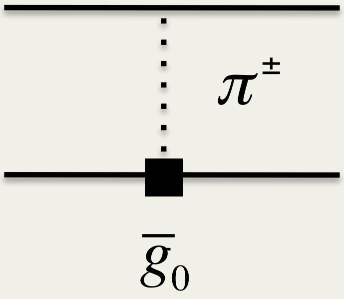
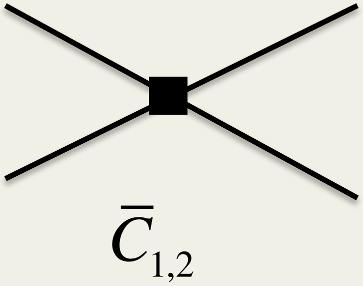
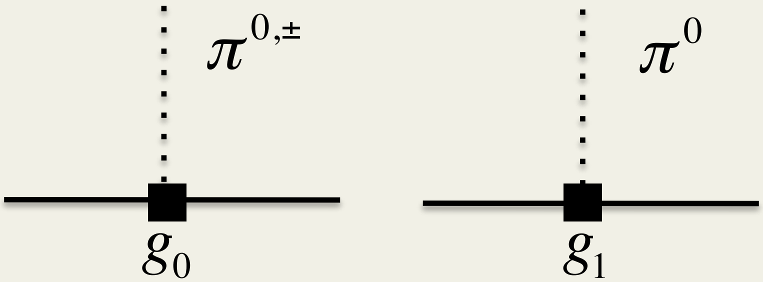




Back to pion-nucleon couplings

- 2 CP-odd structures

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



- Four-quark left-right operator breaks isospin !

Mohapatra, Senjanovic, Pati '75

Maiezza et al ' 14

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

- Due to current-current form: more complicated chiral Lagrangian
- Unique CPV pion-pion-pion interaction

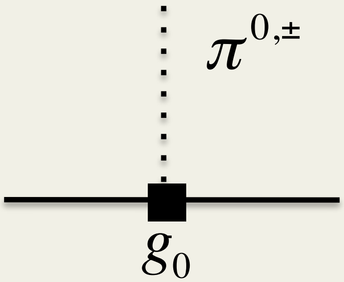
JdV et al '12

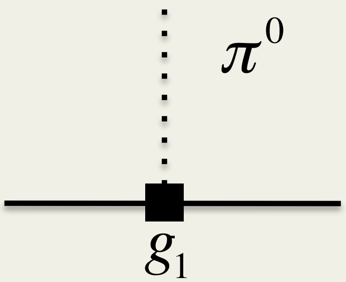
enters at NLO

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

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

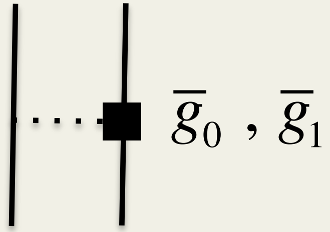
- CPV pion-nucleon operators forbidden at LO → m_π^2 / Λ_χ^2

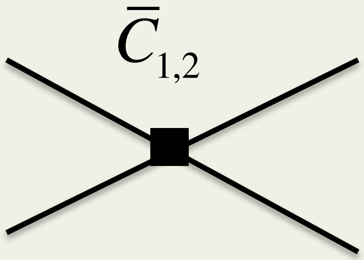
- Short-range are important but **only for 2 out of 5 S-P transitions**

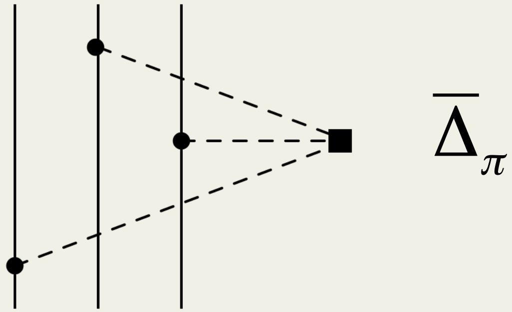
$${}^3S_1 \leftrightarrow {}^1P_1 \qquad {}^1S_0 \leftrightarrow {}^3P_0\ \ (np = nn = pp)$$

The CPV NN +NNN potential

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







- Long-range (pions): $\bar{g}_0$ $\quad {}^3S_1 \leftrightarrow {}^1P_1 + {}^1S_0 \leftrightarrow {}^3P_0 \quad np = nn = pp$

  $\bar{g}_1$ $\quad {}^3S_1 \leftrightarrow {}^3P_1 + {}^1S_0 \leftrightarrow {}^3P_0 \quad nn = -pp$

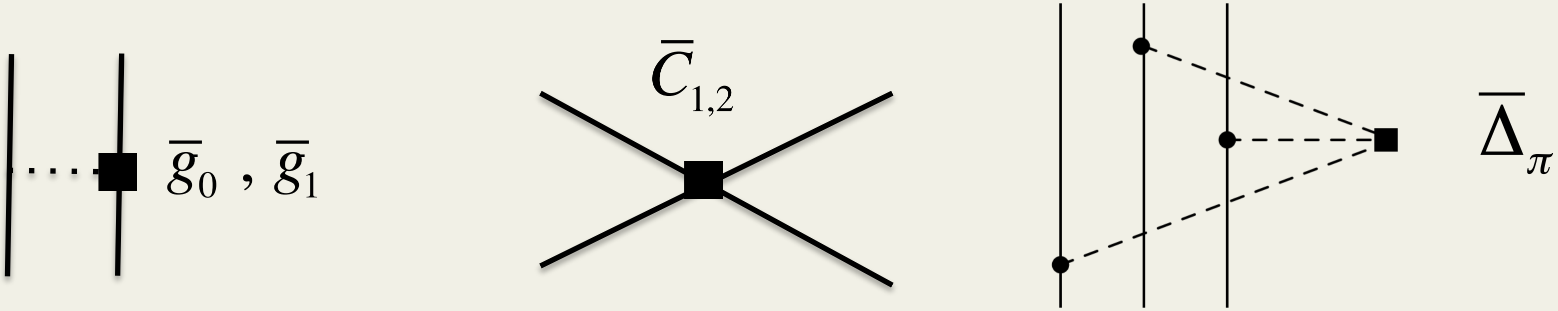
- Short range $\bar{C}_{1,2}$ $\quad {}^3S_1 \leftrightarrow {}^1P_1 \ \& \ {}^1S_0 \leftrightarrow {}^3P_0 \quad np = nn = pp$

- Quite different (simpler) from general boson-exchange model:

  3 long-range + 5 short-range transitions and no 3-body

The CPV NN +NNN potential

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



These 5 interactions can form the starting point for CP-violating scattering and transmission experiments.

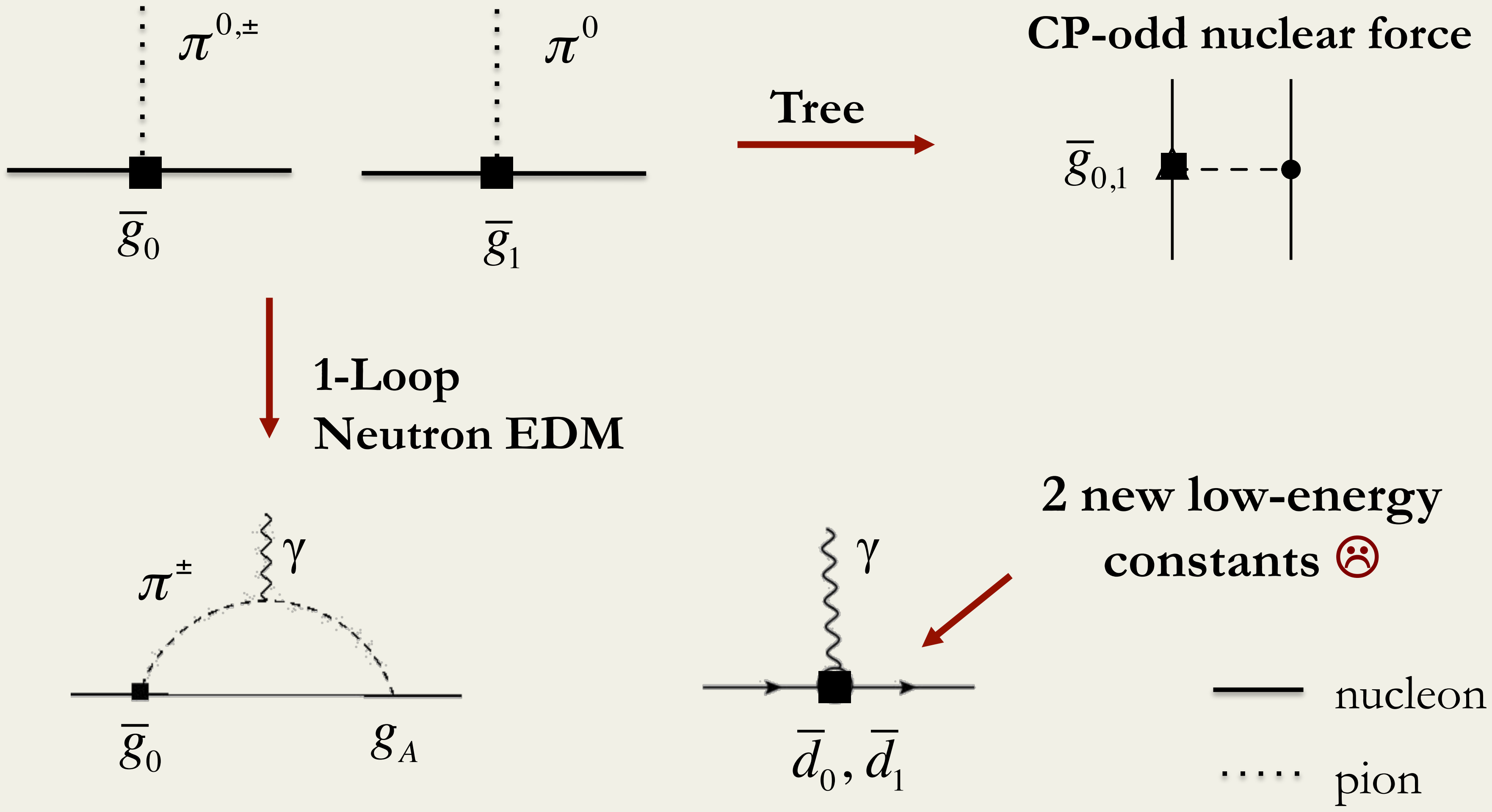
They can be linked to CPV at quark level and to BSM models.

Existing/future calculations for CPV reactions can be matched to this framework and then compared to EDMs.

For EDMs we also need currents!

The problem of the nucleon EDMs

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



Tree

CP-odd nuclear force

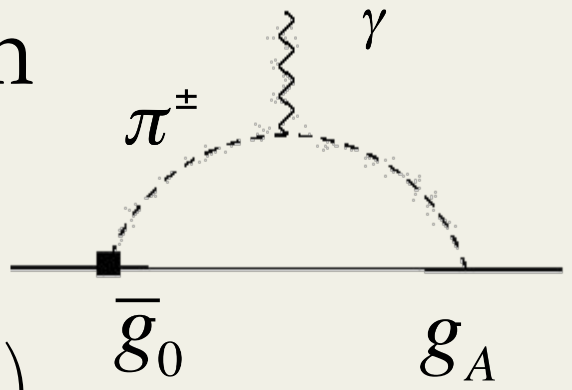
1-Loop
Neutron EDM

2 new low-energy constants ☹

— nucleon

..... pion

The strong CP problem



Nucleon EDM

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

$$d_p = \bar{d}_0(\mu) + \bar{d}_1(\mu) + \frac{e g_A \bar{g}_0}{4\pi^2 F_\pi}\left(\ln\frac{m_\pi^2}{\mu^2} - 2\pi\frac{m_\pi}{m_N}\right) - \frac{e g_A \bar{g}_1}{8\pi F_\pi}\frac{m_\pi}{m_N}$$

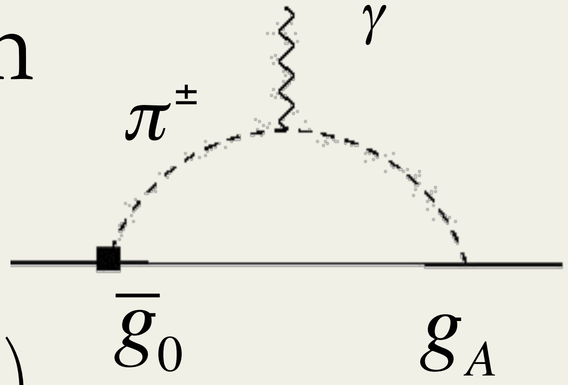
Crewther ‘79 Borasoy ’02
Guo et al, ’10 ’12 ’14,
JdV et al ‘10 ’11 ‘14

- Loop **enhanced** by chiral logarithm (long-range physics)
- But depends on renormalization-scale μ

- Counter terms absorb μ: no direct link between EDMs and CPV potential **at the hadronic level** (but there is one at the quark level)

The strong CP problem

Nucleon EDM



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

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

$$d_p = \bar{d}_0(\mu) + \bar{d}_1(\mu) + \frac{e g_A \bar{g}_0}{4\pi^2 F_\pi}\left(\ln\frac{m_\pi^2}{\mu^2} - 2\pi\frac{m_\pi}{m_N}\right) - \frac{e g_A \bar{g}_1}{8\pi F_\pi}\frac{m_\pi}{m_N}$$

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

$$\mu = m_N$$

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

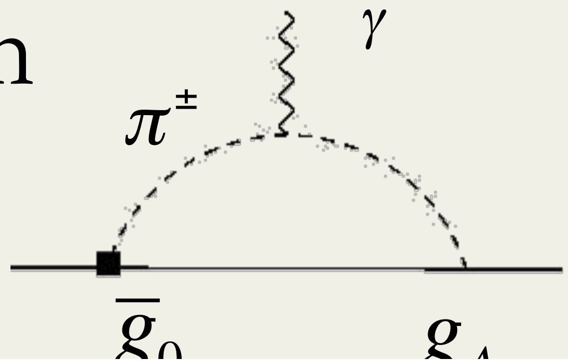
Guo et al '15

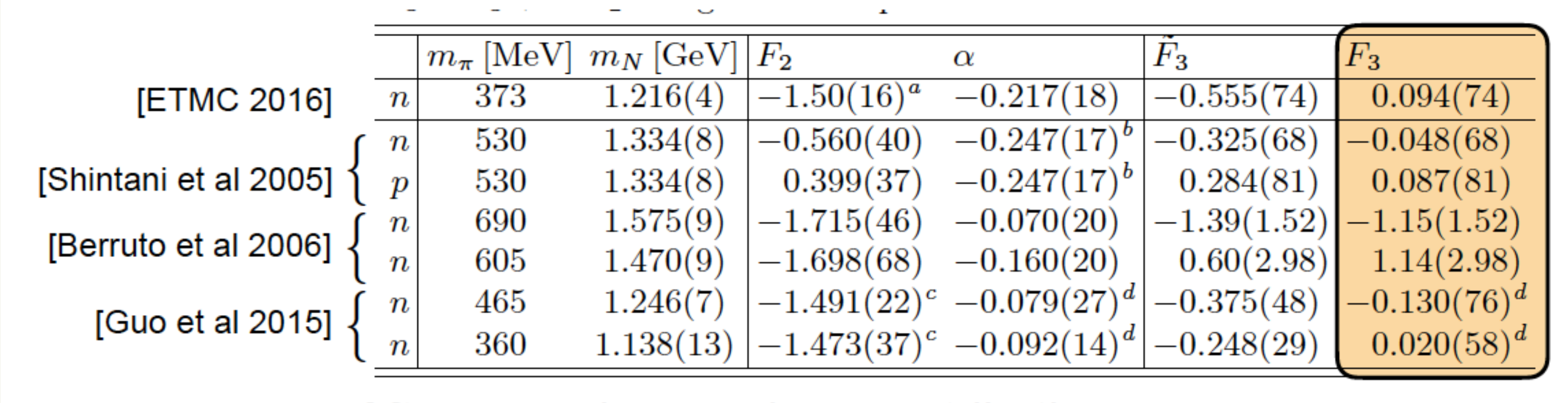
- Lattice + **ChPT** $d_n = -(3.9 \pm 1.0)\cdot 10^{-16}\,\bar{\theta}\, e\,\mathrm{cm}$
- **But: BNL group criticizes the lattice extraction** Abramczyk et al '17

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

The strong CP problem

Nucleon EDM



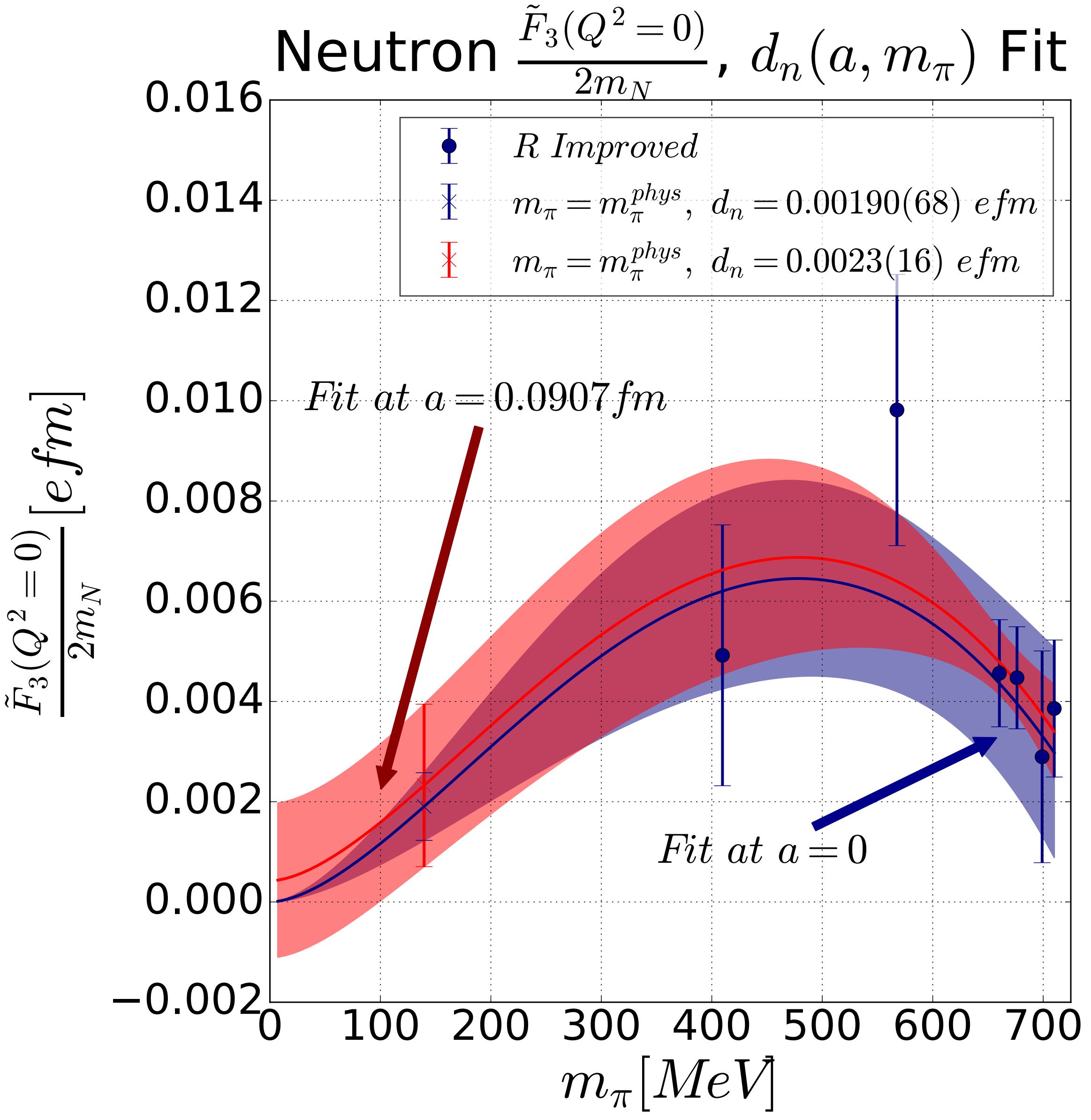


		m_π [MeV]	m_N [GeV]	F_2	α	$\tilde{F}_3$	F_3
[ETMC 2016]	n	373	1.216(4)	−1.50(16)[a]	−0.217(18)	−0.555(74)	0.094(74)
[Shintani et al 2005]	n	530	1.334(8)	−0.560(40)	−0.247(17)[b]	−0.325(68)	−0.048(68)
	p	530	1.334(8)	0.399(37)	−0.247(17)[b]	0.284(81)	0.087(81)
[Berruto et al 2006]	n	690	1.575(9)	−1.715(46)	−0.070(20)	−1.39(1.52)	−1.15(1.52)
	n	605	1.470(9)	−1.698(68)	−0.160(20)	0.60(2.98)	1.14(2.98)
[Guo et al 2015]	n	465	1.246(7)	−1.491(22)[c]	−0.079(27)[d]	−0.375(48)	−0.130(76)[d]
	n	360	1.138(13)	−1.473(37)[c]	−0.092(14)[d]	−0.248(29)	0.020(58)[d]

Abramczyk et al ‘17

- **Lattice results contaminated by spurious signal**
- Corrected EDM signal consistent with zero within errors

- No sign for strong CP problem on the lattice yet



Preliminiary: A. Shindler, T. Luu, J. Dragos, A. Yousif, JdV

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

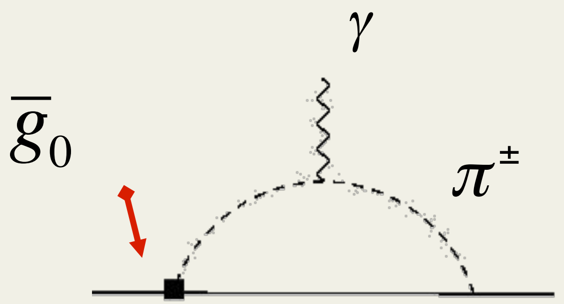
- Weinberg (and four-quark) only **estimates**

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

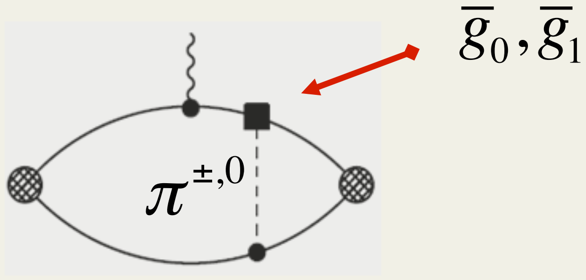
Weinberg ‘89
Demir et al ’03
JdV et al ‘10

- **Not easy to unravel source from nucleon EDMs**

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

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

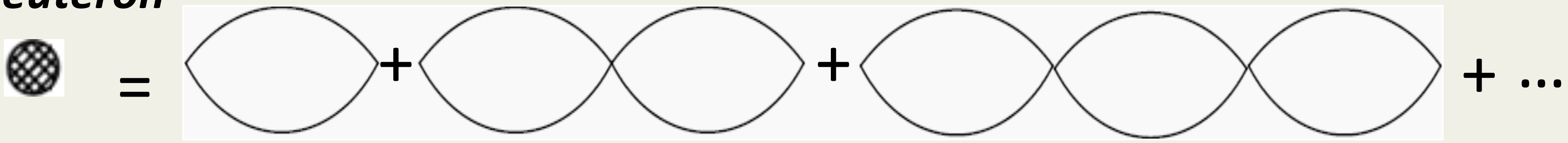
$$(E - H_{PT}) \,|\Psi_A > = 0 \qquad\qquad (E - H_{PT}) \,|\tilde{\Psi}_A > = V_{\cancel{CP}} \,|\Psi_A >$$

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

EDM of the deuteron

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

Deuteron



- Use a perturbative pion approach (Kaplan, Savage, Wise (1996))
- **S-wave NN** interactions are **resummed and generate deuteron**

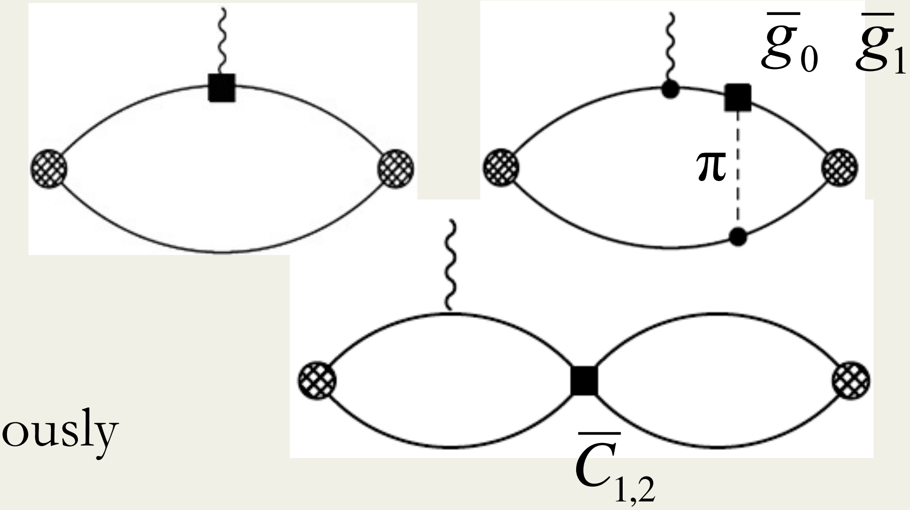
- Pion exchange treated in perturbation theory (for now)
- Fails for denser nuclei/higher momenta but useful to get some insight

Expansion parameter:

$$m_\pi\left(\frac{g_A^2 m_N}{4\pi F_\pi^2}\right) \equiv \frac{m_\pi}{M_{NN}} \approx 0.4$$

EDM of the deuteron

Target of storage ring measurement



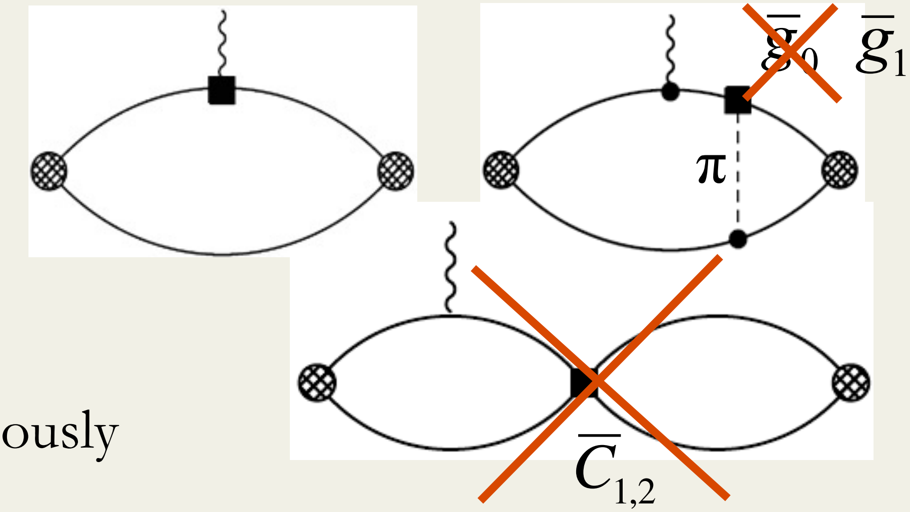
- Three contributions (NLO)
  1. Sum of nucleon EDMs
  2. CP-odd pion exchange
  3. CP-odd NN interactions
  4. No three-body force obviously
- **Deuteron is a special case due to N=Z**

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

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

EDM of the deuteron

Target of storage ring measurement



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JdV et al PRL '11

$$F_D(\vec{q}^{\,2}) = (d_n + d_p)\left(1 - \frac{1}{3}\left(\frac{\vec{q}}{4\gamma}\right)^2 + \cdots\right) \qquad \gamma = \sqrt{m_N E_b} \approx 45\ MeV$$

$$F_D(\vec{q}^{\,2}) = \bar{g}_1 \frac{2e\,g_A}{3m_\pi M_{NN}} \frac{1+\gamma/m_\pi}{(1+2\gamma/m_\pi)^2}\left(1 - 0.48\left(\frac{\vec{q}}{4\gamma}\right)^2 + \cdots\right)$$

- Get the full form factor: extract EDM and Schiff Moment

Deuteron as a chiral filter

- Deuteron EDM results $d_D = (d_n + d_p) + 0.23\,\bar{g}_1 e\ fm$

- Do the nucleon EDMs or the CPV NN force dominate ?
- **Depends on the source of CP violation !**

JdV et al PRL 11

`	**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 uncertainties **(need lattice)**
- **EFT approach connects different measurements**

Deuteron as a chiral filter

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- Ratio suffers from hadronic uncertainties **(need lattice)**
- **Using a realistic NN potential and solving Schrodinger equation:**

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

Liu+Timmermans PRC ’04
Bsaisou et al ‘15

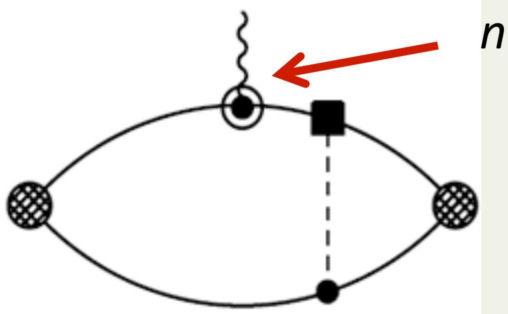
- Analytic approach works up to 20% (for ^{2}H)

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

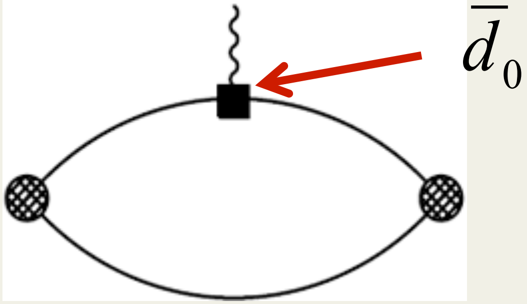
Sensitive to **both** $\bar{g}_0$ and $\bar{g}_1$ exchange

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

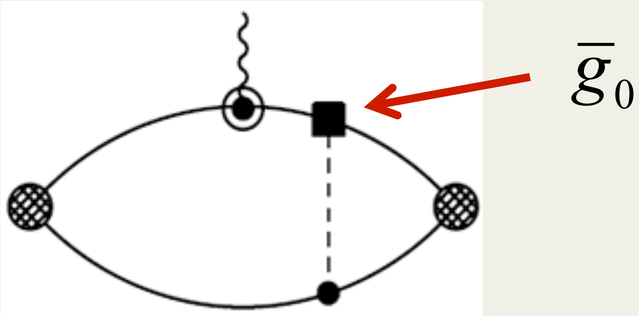
The magnetic quadrupole moment

For theta:

deuteron EDM



deuteron MQM



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 can be 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

- 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

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

comparable

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

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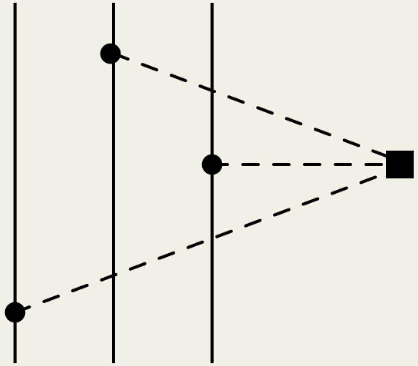


- Found to give small contributions (smaller than expectations) Bsaisou et al ‘14
- Unclear why, related to 3He structure?

- Viviani + Gnech reinvestigated this and found a larger and significant contribution! (talk at CD ’18)
- No calculations include this for heavier nuclei

Cut-off dependence

Plot from Bsaisou et al JHEP '14

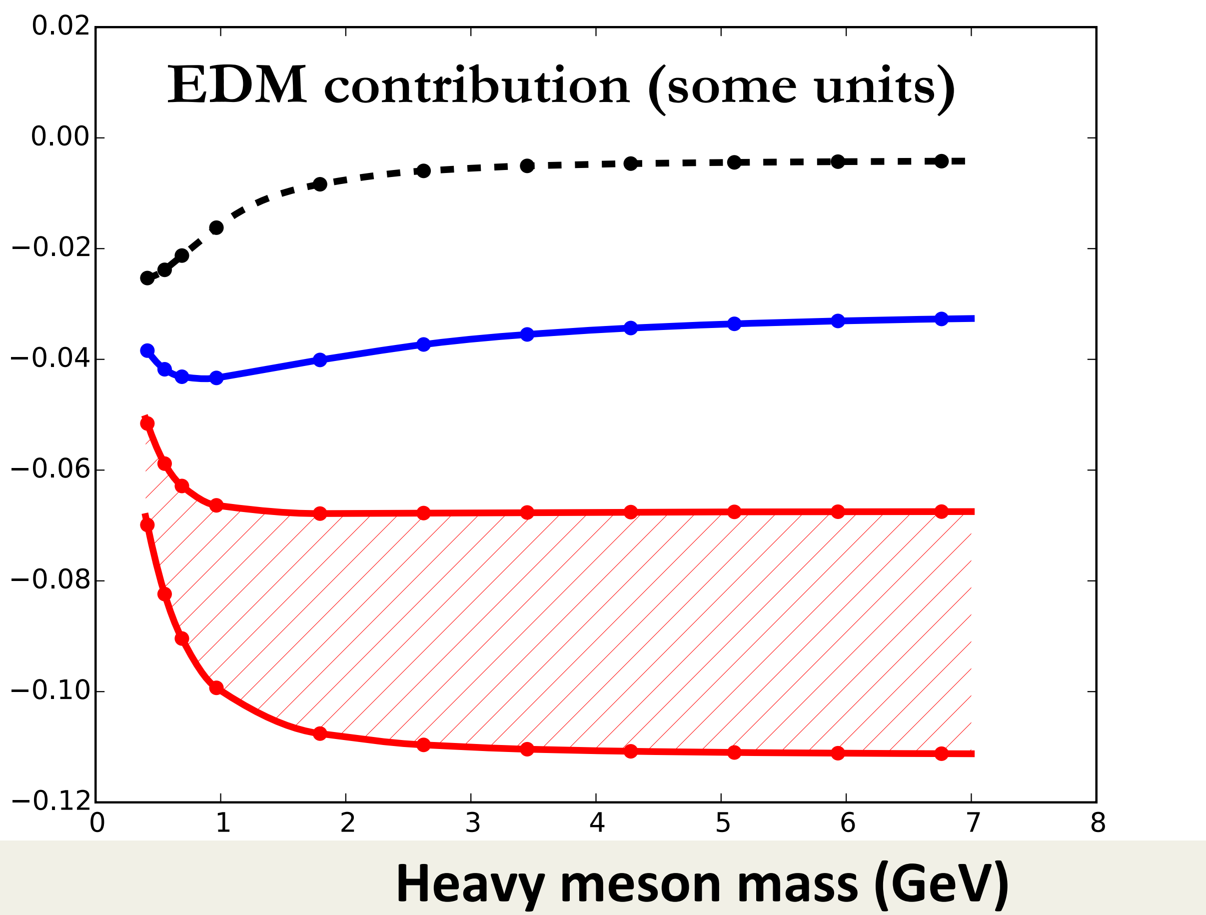
$$\frac{m_1^2 \overline{C}_1}{4\pi\, r}\, e^{-m_1\, r} \rightarrow \overline{C}_1\, \delta^{(3)}(\vec{r})$$

- - - Av18

— CD-Bonn

— Chiral EFT

▨ Cut-off variation



- Quite a large spread ….
- Only 10-20% for most CPV sources but leading for Weinberg operator
- **How to understand this?**

Cut-off dependence

Plot from Bsaisou et al JHEP ‘14

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

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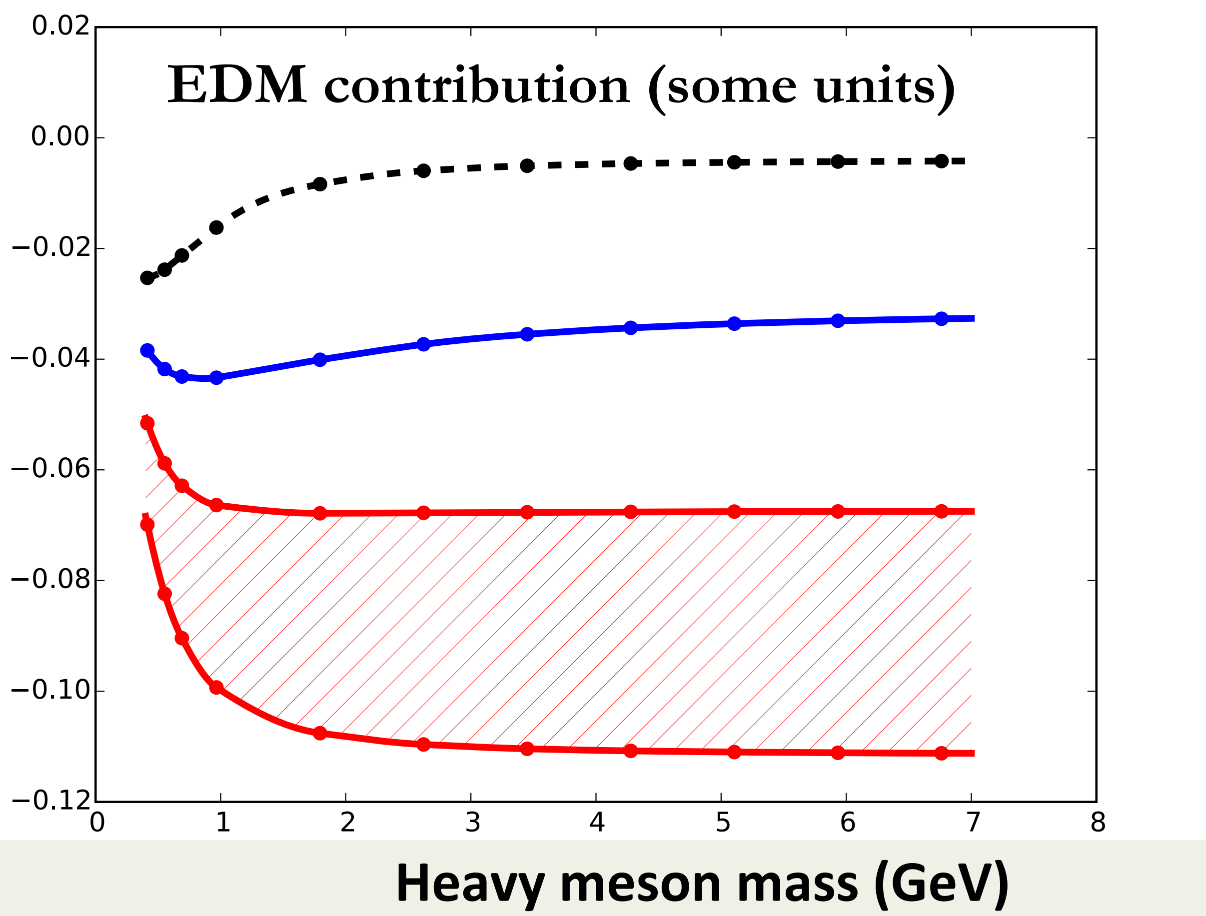

- Spread for different wave functions → different short-range NN force
- No consistent renormalization of CP-even + CP-odd force
- For a given regulator Λ : fit $\overline{C}_1(\Lambda)$ to data . Requires nonzero EDMs…
- **Better: calculate S ←→ P transitions on lattice → fit** $\overline{C}_1(\Lambda)$

Towards denser systems….

Yamanaka et al ’15 ’16 ‘17 ‘18

- Yamanaka and collaborators started a program for larger EDMs
- Focus only one pion-exchange + nucleon EDMs
- So far: ^{6}Li, ^{7}Li, ^{9}Be, ^{11}B, ^{13}C and ^{19}F is in progress

- ^{6}Li described as α + n + p
- Use phenomenological α-N and α−α interaction
- Use ‘folding’ to describe CPV nucleon-α interaction

$$V_{\alpha-N}(\mathbf{r}) = \int d^3\mathbf{r}'\, V_{\not P \not T}(\mathbf{r}-\mathbf{r}')\rho_\alpha(\mathbf{r}'),$$

Nucleon density in α

$$\rho_\alpha(r) = \frac{4}{b^3\pi^{3/2}}e^{-r^2/b^2}$$

Towards denser systems….

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- Focus only one pion-exchange + nucleon EDMs
- So far: ^{6}Li, ^{7}Li, ^{9}Be, ^{11}B, ^{13}C and ^{19}F is in progress

- ^{6}Li described as α + n + p
- Use phenomenological α-N and α−α interaction
- Use ‘folding’ to describe CPV nucleon-α interaction

Nucleon density in α

$$V_{\alpha-N}(\mathbf{r}) = \int d^3\mathbf{r}'\, V_{\not{P}\not{T}}(\mathbf{r}-\mathbf{r}')\rho_\alpha(\mathbf{r}'),$$

$$\rho_\alpha(r) = \frac{4}{b^3\pi^{3/2}} e^{-r^2/b^2}$$

$$d_{6Li} = 0.86(d_n + d_p) + 0.28\, \bar{g}_1\ e\ fm$$

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

- Accuracy: I don’t know…..
- **Main point: no light nuclei with significant enhancements over ^{2}H**

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

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Schiff, ‘63

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

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

- **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

Onwards to heavy systems

Graner et al, ‘16

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New measurements expected: Ra , Xe, ….

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Schiff, ‘63

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

$$S \equiv \left\langle \Psi_0 \middle| \hat{S}_0 \middle| \Psi_0 \right\rangle \cong \sum_{i \neq 0} \frac{\left\langle \Psi_0 \middle| \hat{S}_0 \middle| \Psi_i \right\rangle \left\langle \Psi_i \middle| V_{\cancel{PT}} \middle| \Psi_0 \right\rangle}{E_0 - E_i}$$

CPV potential

Schiff operator $S_0 \sim \sum_i \left(r_i^3 - \frac{5}{3} r_{ch}^2 r_i \right) Y_0^1$

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:

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

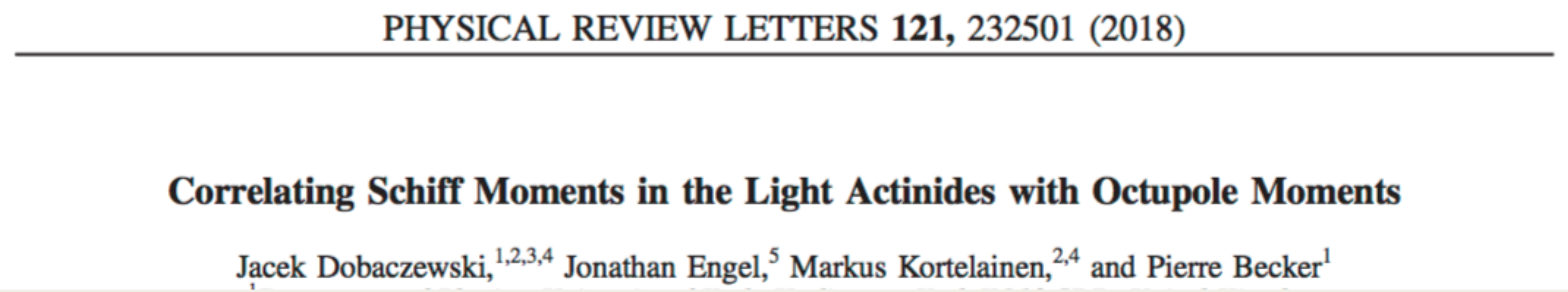
	a_0 range (best)	**a_1 range (best)**
^{199}Hg	0.03±0.025 (0.01)	0.030±0.060 (±0.02)
^{225}Ra	-3.5±3.5 (-1.5)	14±12 (6)
^{129}Xe	-0.03±0.025 (-0.008)	-0.03±0.025 (-0.009)

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

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

table from review: Engel et al, '13

Recent progress



PHYSICAL REVIEW LETTERS **121**, 232501 (2018)

Correlating Schiff Moments in the Light Actinides with Octupole Moments

Jacek Dobaczewski,[1,2,3,4] Jonathan Engel,[5] Markus Kortelainen,[2,4] and Pierre Becker[1]

- In nuclei like ^{225}Ra there is a low-lying state with opposite parity

$$S \cong -2\frac{\langle \Psi_0 | \hat{S}_0 | \bar{\Psi}_0 \rangle \langle \bar{\Psi}_0 | V_{\cancel{PT}} | \Psi_0 \rangle}{\Delta E}$$

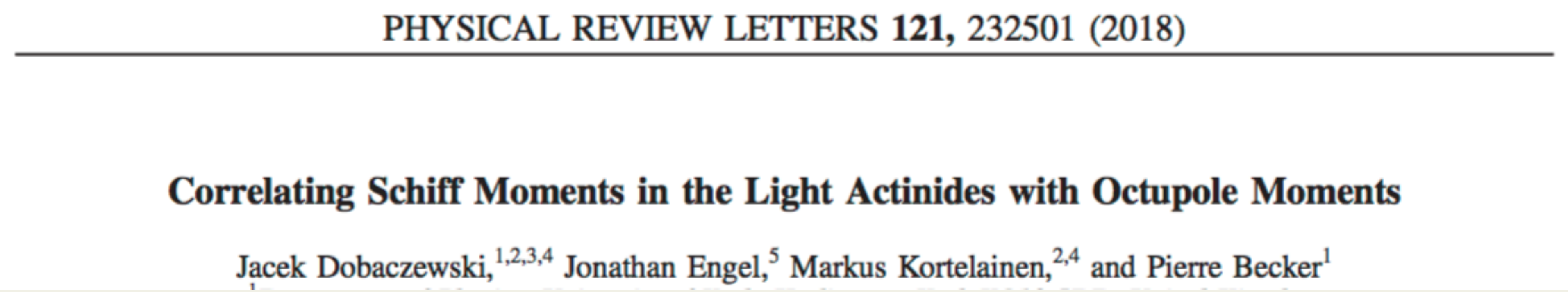
- Schiff operator closely related to the **octupole charge operator**

$$\hat{Q}_0^3 \sim e\sum_i \left(r_i^3\right) Y_0^3 \qquad \longrightarrow \qquad \left\langle \hat{Q}_0^3 \right\rangle = (940 \pm 30)e\ fm^3$$

Gaffney et al, Nature ‘13

Note: measurement is for ^{224}Ra

Recent progress



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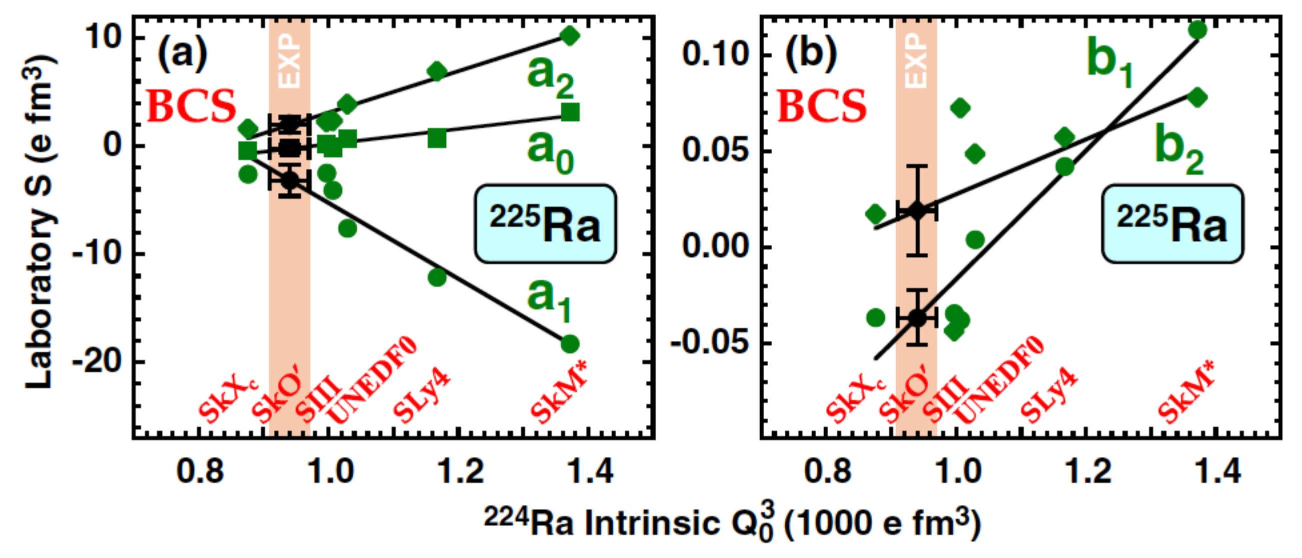
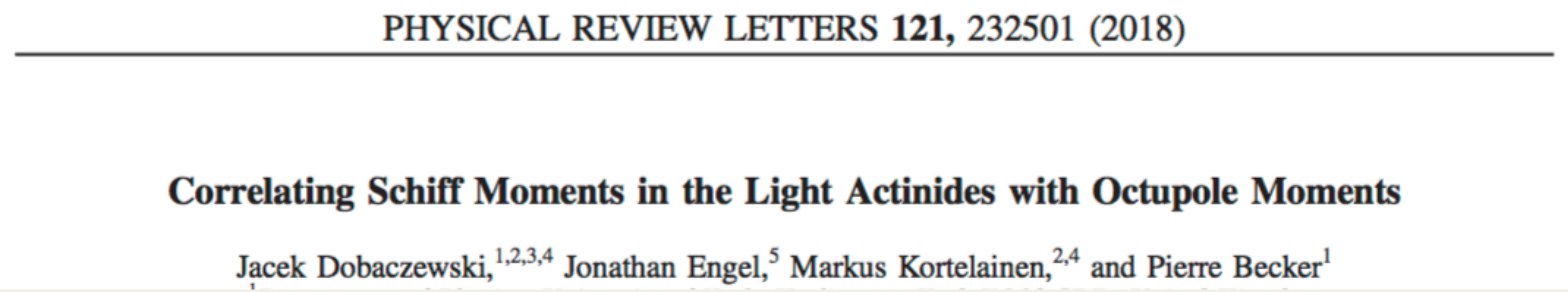
- CPV potential from EFT $$S = g(a_0\bar{g}_0 + a_1\bar{g}_1) + b_1\bar{C}_1 + b_2\bar{C}_2$$
- Observe relation between a_i , b_i and octupole moment



Recent progress



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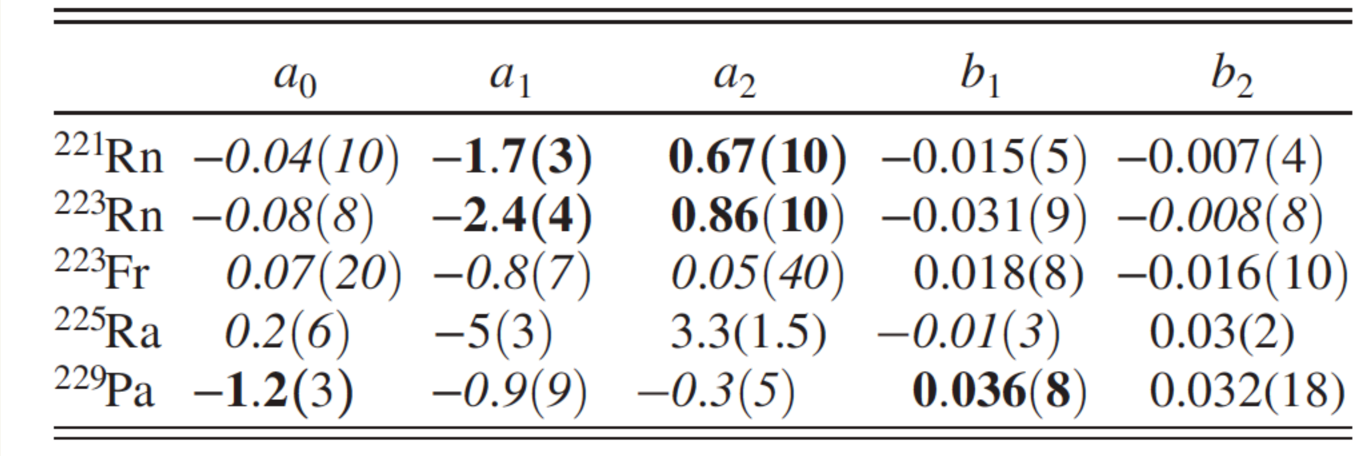
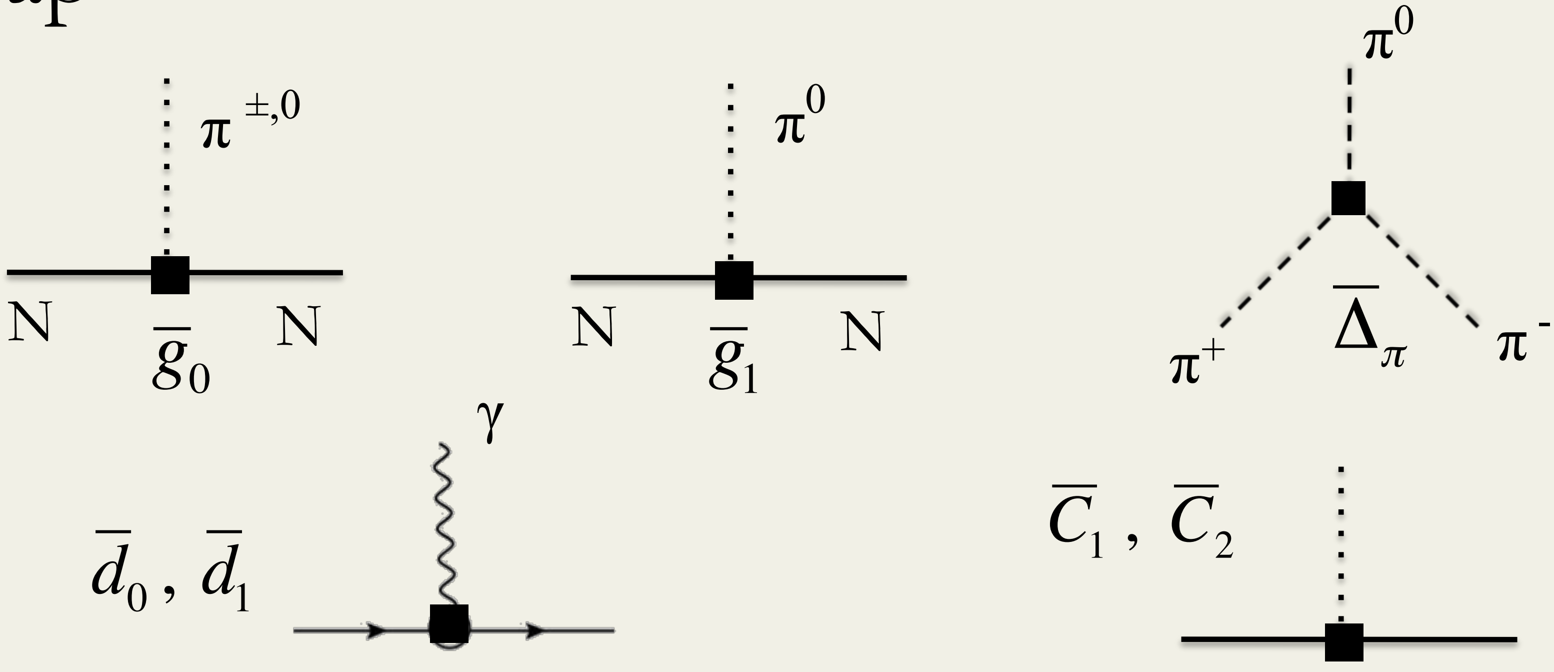
- CPV potential from EFT $S = g(a_0\bar{g}_0 + a_1\bar{g}_1) + b_1\bar{C}_1 + b_2\bar{C}_2$
- Significant improvement for matrix elements !



	a_0	a_1	a_2	b_1	b_2
^{221}Rn	*−0.04(10)*	**−1.7(3)**	**0.67(10)**	−0.015(5)	−0.007(4)
^{223}Rn	*−0.08(8)*	**−2.4(4)**	**0.86(10)**	−0.031(9)	*−0.008(8)*
^{223}Fr	*0.07(20)*	*−0.8(7)*	*0.05(40)*	0.018(8)	−0.016(10)
^{225}Ra	*0.2(6)*	−5(3)	3.3(1.5)	*−0.01(3)*	0.03(2)
^{229}Pa	**−1.2(3)**	*−0.9(9)*	*−0.3(5)*	**0.036(8)**	0.032(18)

Recap

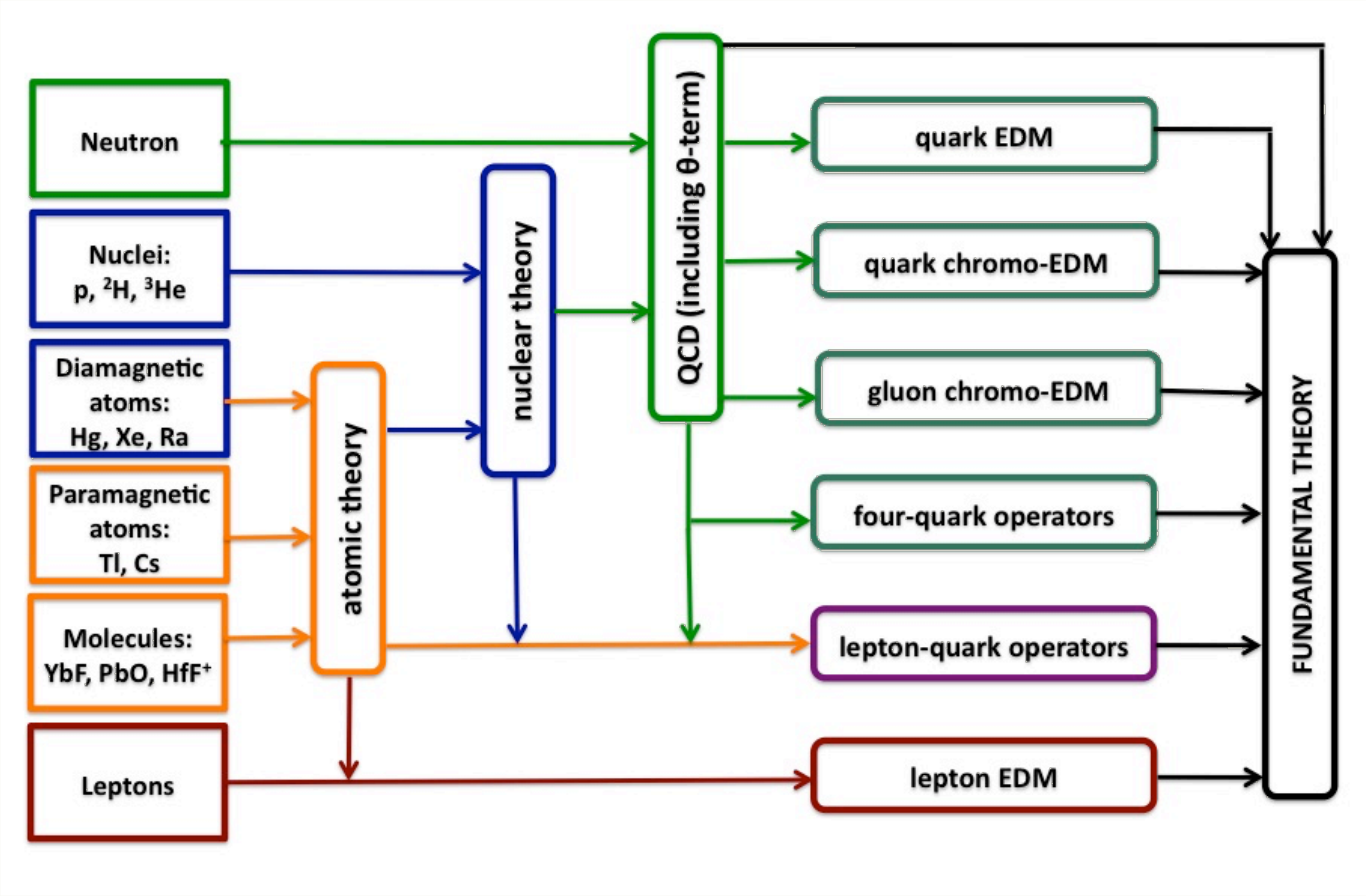


- 2 pion-nucleon (no g_2 !)
- 1 pion-pion-pion

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

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

The EDM metromap

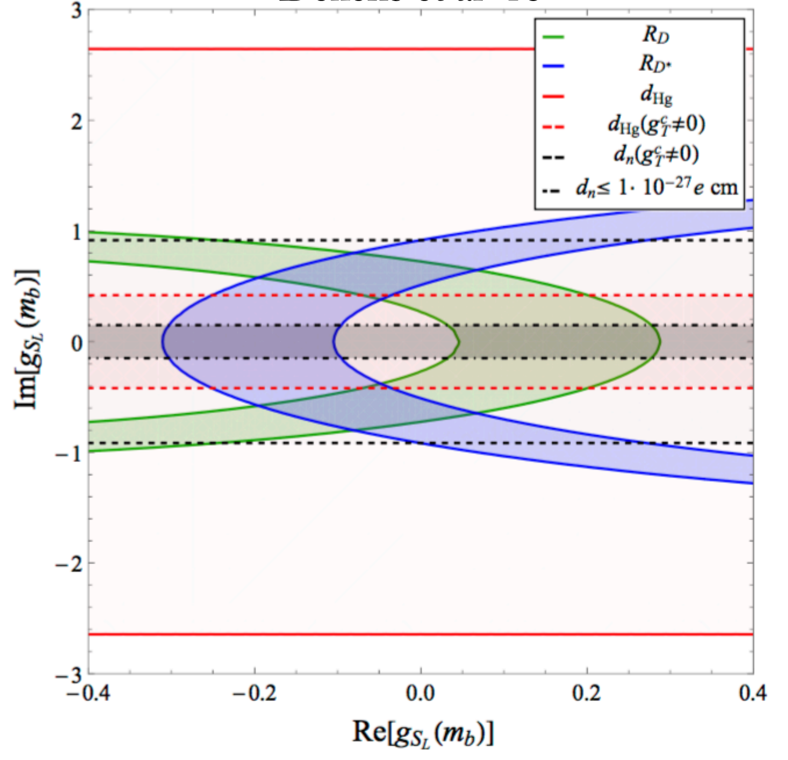


EDMs are important for particle physics

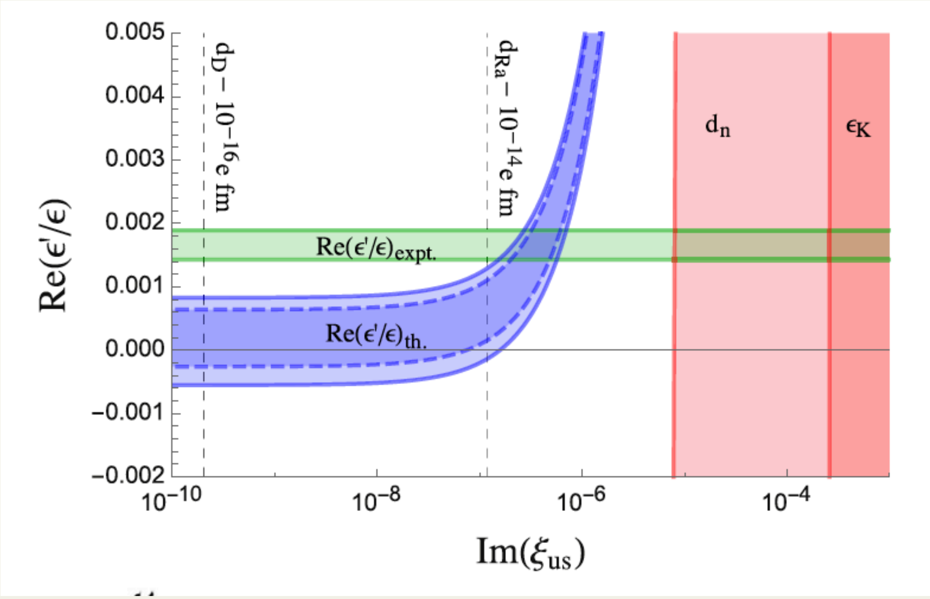
- Connected to open questions like matter/antimatter asymmetry (see Michaels talk) and existence of axions (Kaori's talk)
- Strong limits on specific BSM scenarios
- Strong limits on CP-violation in top-Higgs sector
- Testing explanations of B- and K-anomalies

Brod et al '13
Cirigliano et al '15'16
Fuyuto et al '17

Dekens et al '18



Cirigliano et al '16



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**