JÜLICH
FORSCHUNGSZENTRUM

# Theory of Electric Dipole Moments of complex systems

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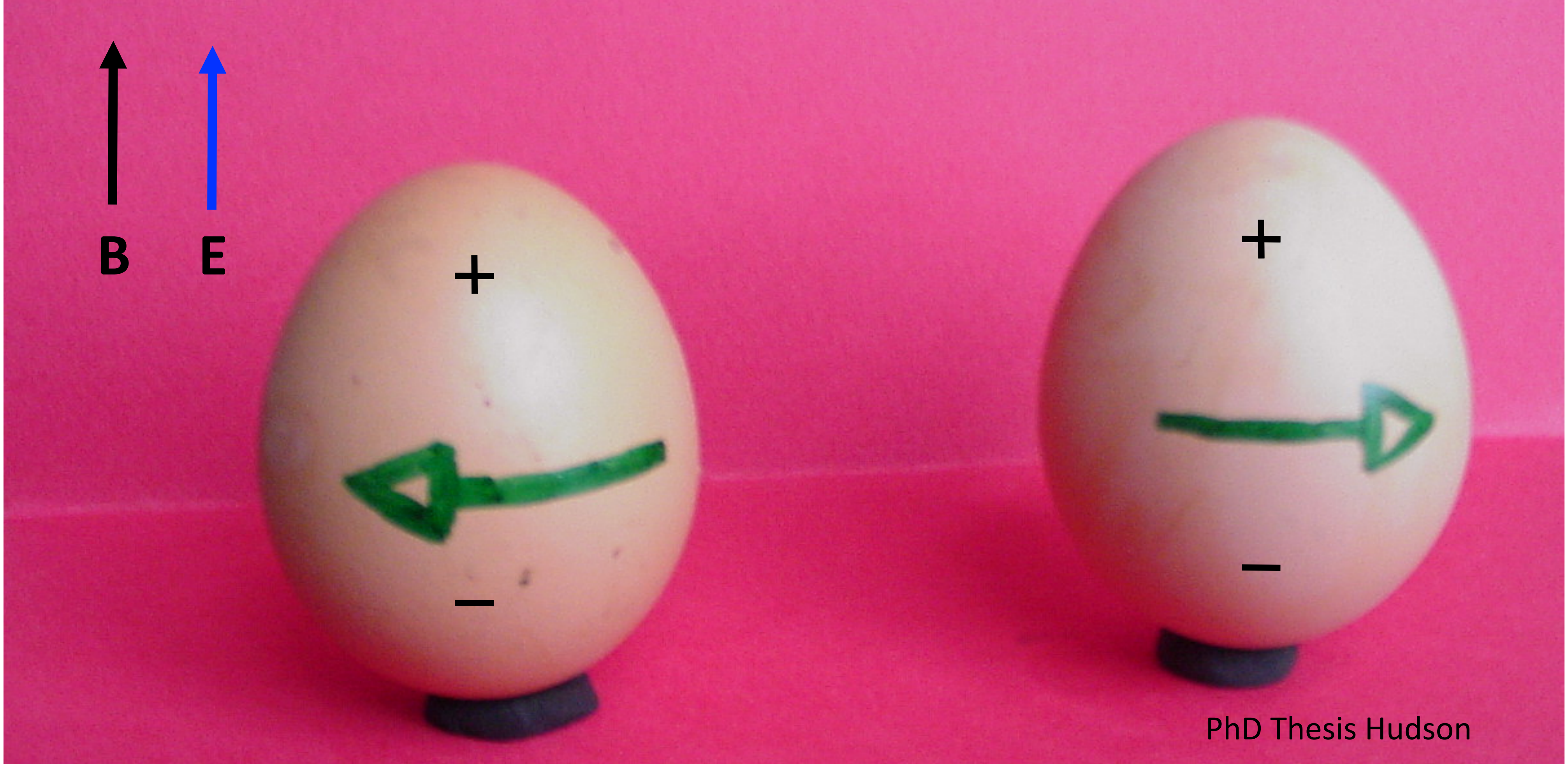
J. Bsaisou, A. Wirzba, Ulf-G. Meißner, C. Hanhart......

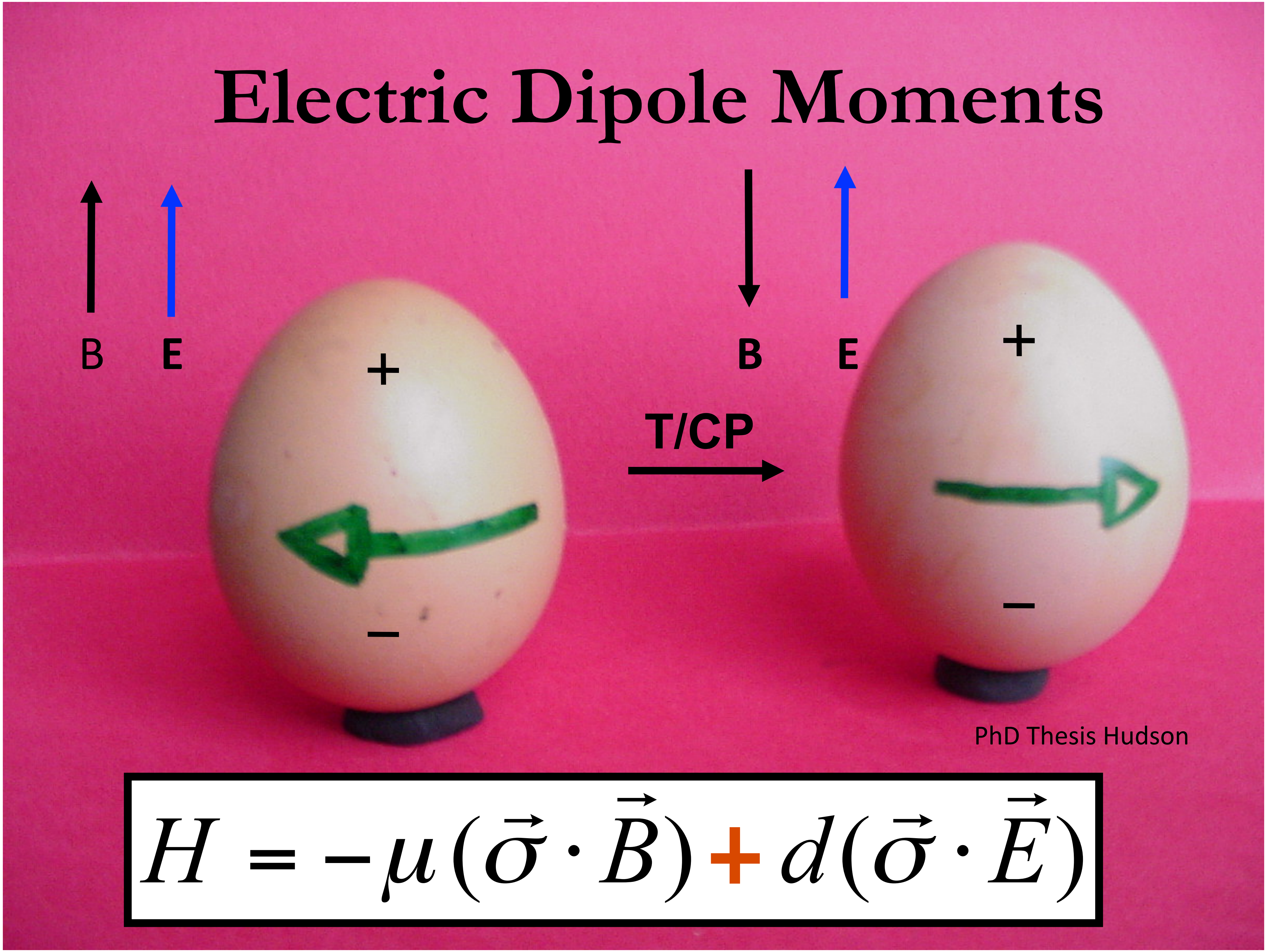
# Outline of this talk

- **Part I: What are EDMs and why are they interesting in the first place ?**
- Part II: Effective field theory framework
- Part III: EDMs of nucleons and nuclei

# Electric Dipole Moments



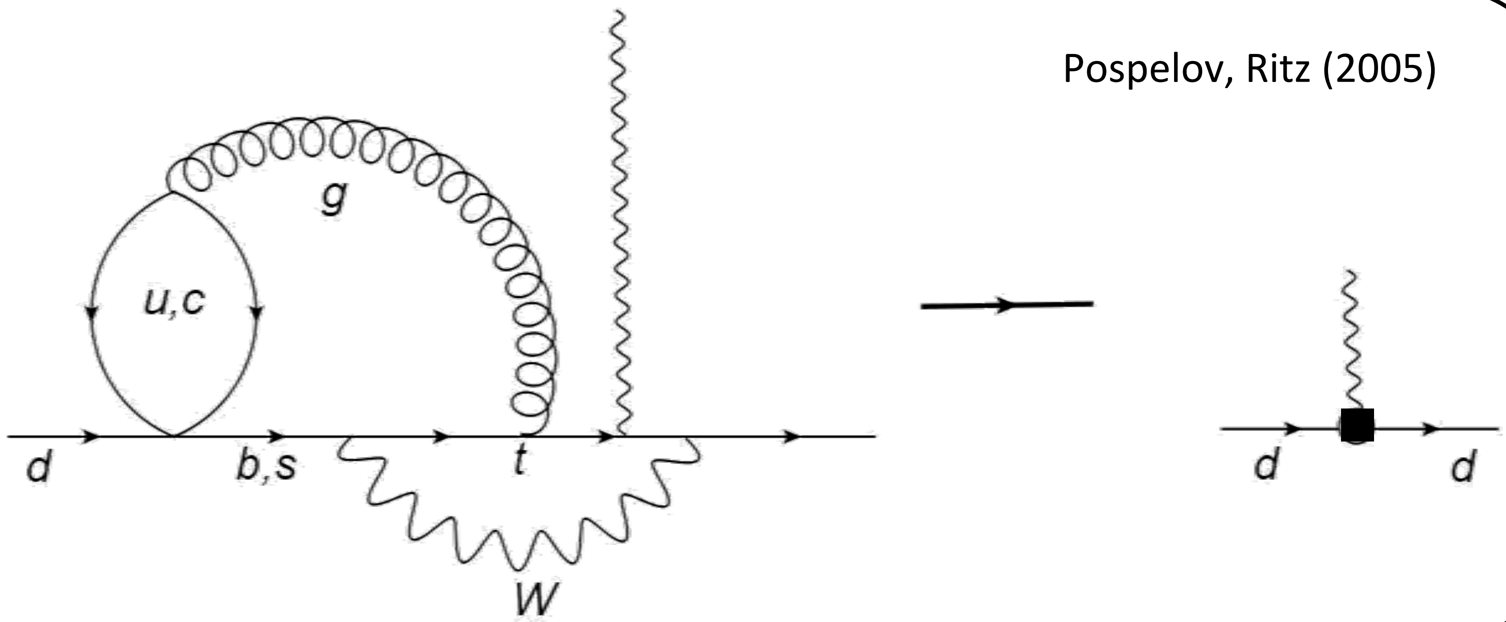

$$H = -\mu(\vec{\sigma}\cdot\vec{B}) - d(\vec{\sigma}\cdot\vec{E})$$


Electric Dipole Moments
B
E
+
−
T/CP
B
E
+
−
PhD Thesis Hudson
$H = -\mu(\vec{\sigma}\cdot\vec{B}) + d(\vec{\sigma}\cdot\vec{E})$

# EDM's in the Standard Model

$$L = \bar{d}\ \overline{\Psi}\sigma^{\mu\nu} i\gamma^5 \Psi F_{\mu\nu}$$

- Electroweak CP-violation
- Nobel prize for predicting **third** generation

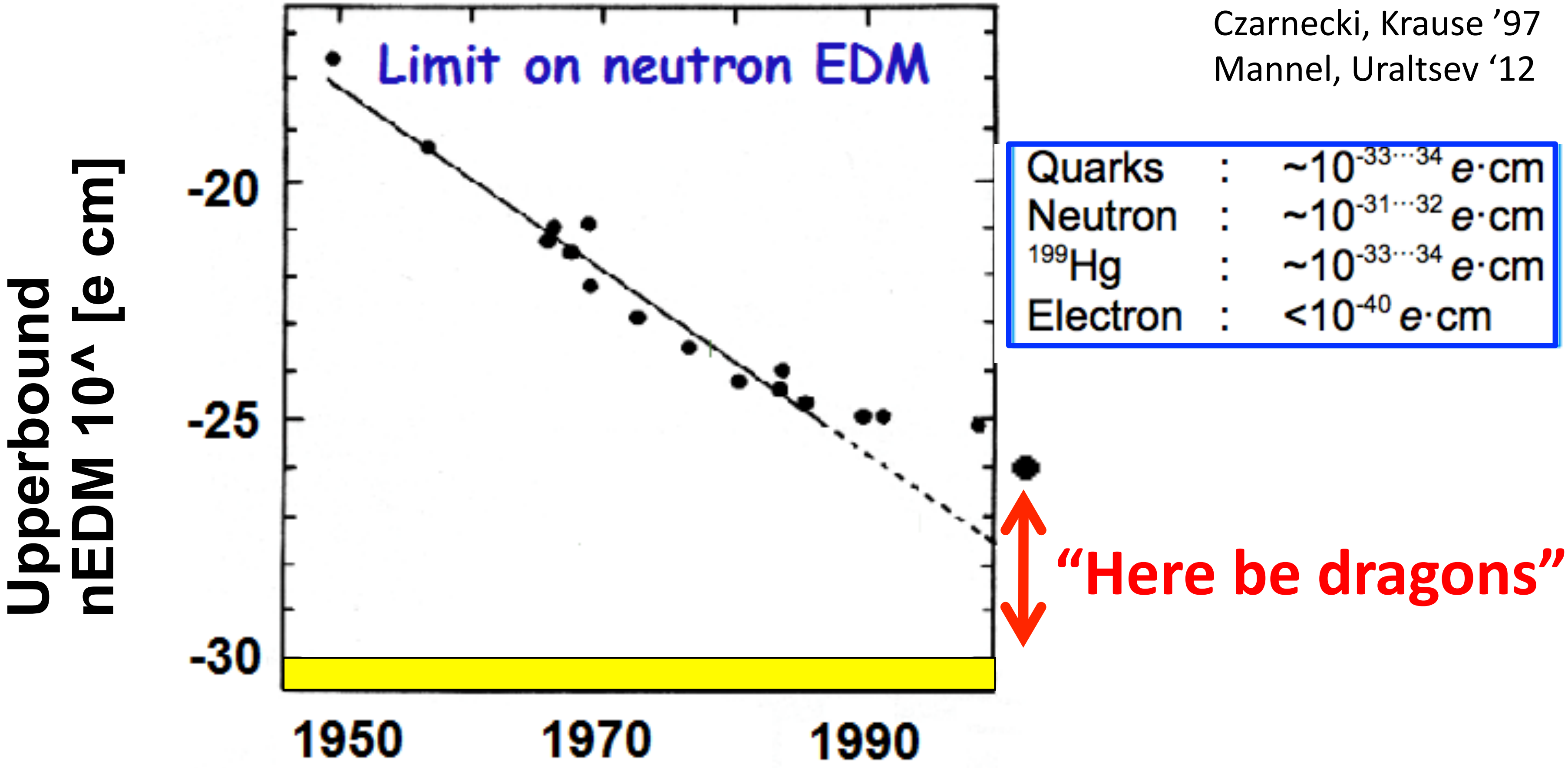



Pospelov, Ritz (2005)

**Highly Suppressed**

# Electroweak CP-violation

Hoogeveen '90
Czarnecki, Krause '97
Mannel, Uraltsev '12



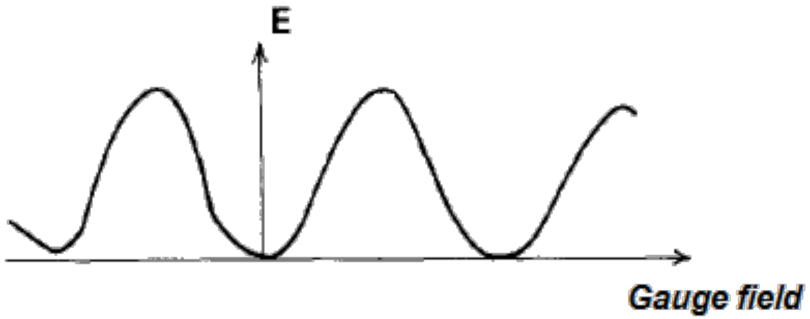

| | | |
|---|---|---|
| Quarks | : | $\sim 10^{-33\cdots 34}$ e·cm |
| Neutron | : | $\sim 10^{-31\cdots 32}$ e·cm |
| $^{199}$Hg | : | $\sim 10^{-33\cdots 34}$ e·cm |
| Electron | : | $< 10^{-40}$ e·cm |

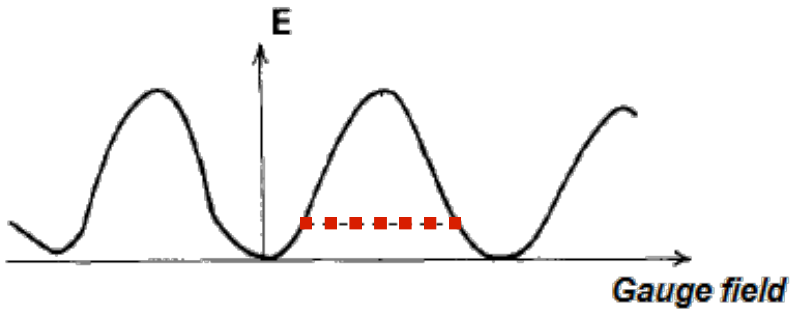
5 to 6 orders **below** upper bound ⟷ **Out of reach!**

I.B. Khriplovich, S.K. Lamoreaux, *CP Violation Without Strangeness*, Springer, 1997

# EDM’s in the Standard Model

- Second source: QCD **theta-term**
- Due to complicated vacuum structure of QCD



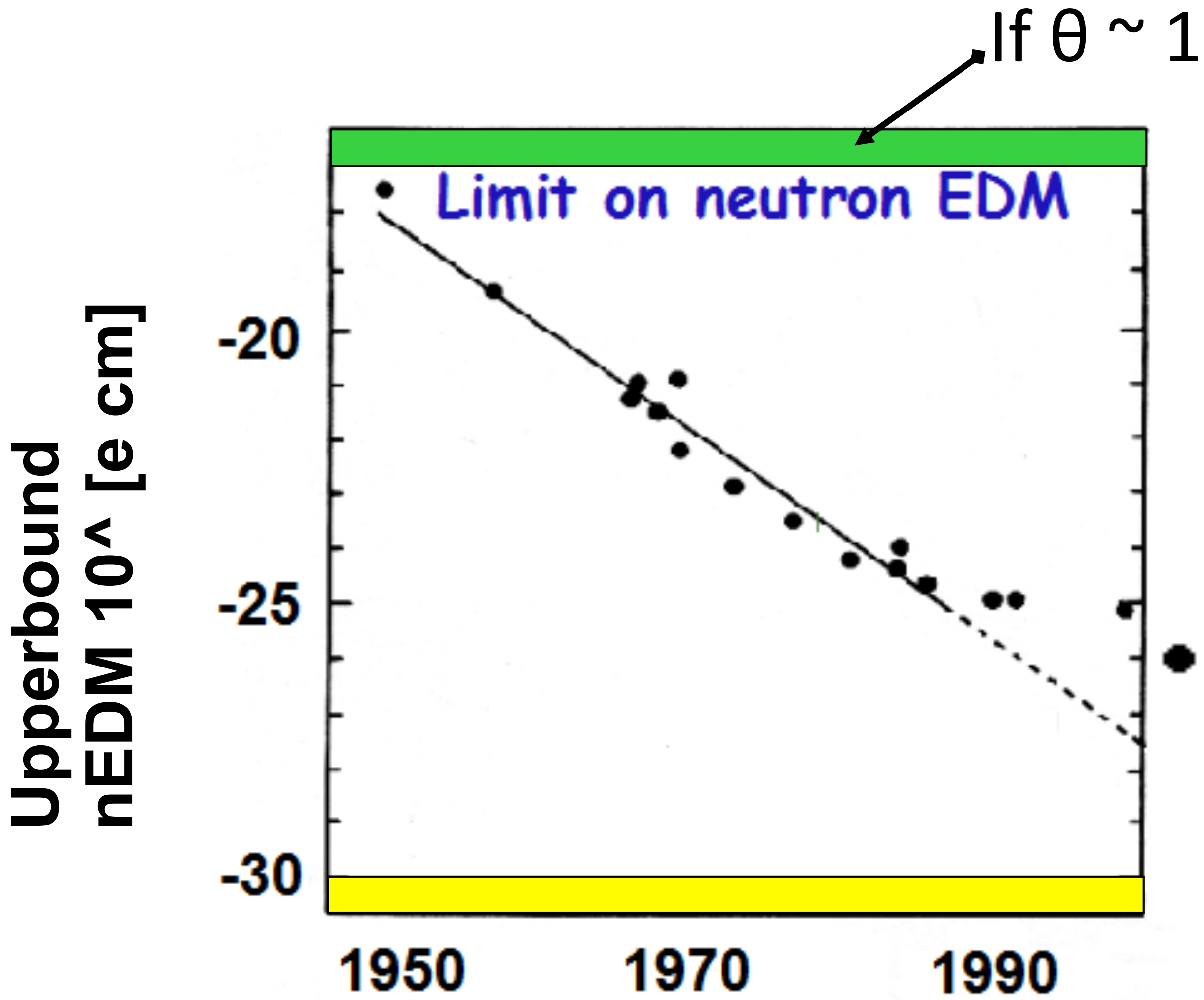




- Causes a ‘new’ CP-violating interaction with **coupling constant** $\theta$

$$\theta\, \varepsilon^{\mu\nu\alpha\beta} G_{\mu\nu} G_{\alpha\beta} \qquad \text{(in QED} \sim \vec{E}\cdot\vec{B}\text{ )}$$

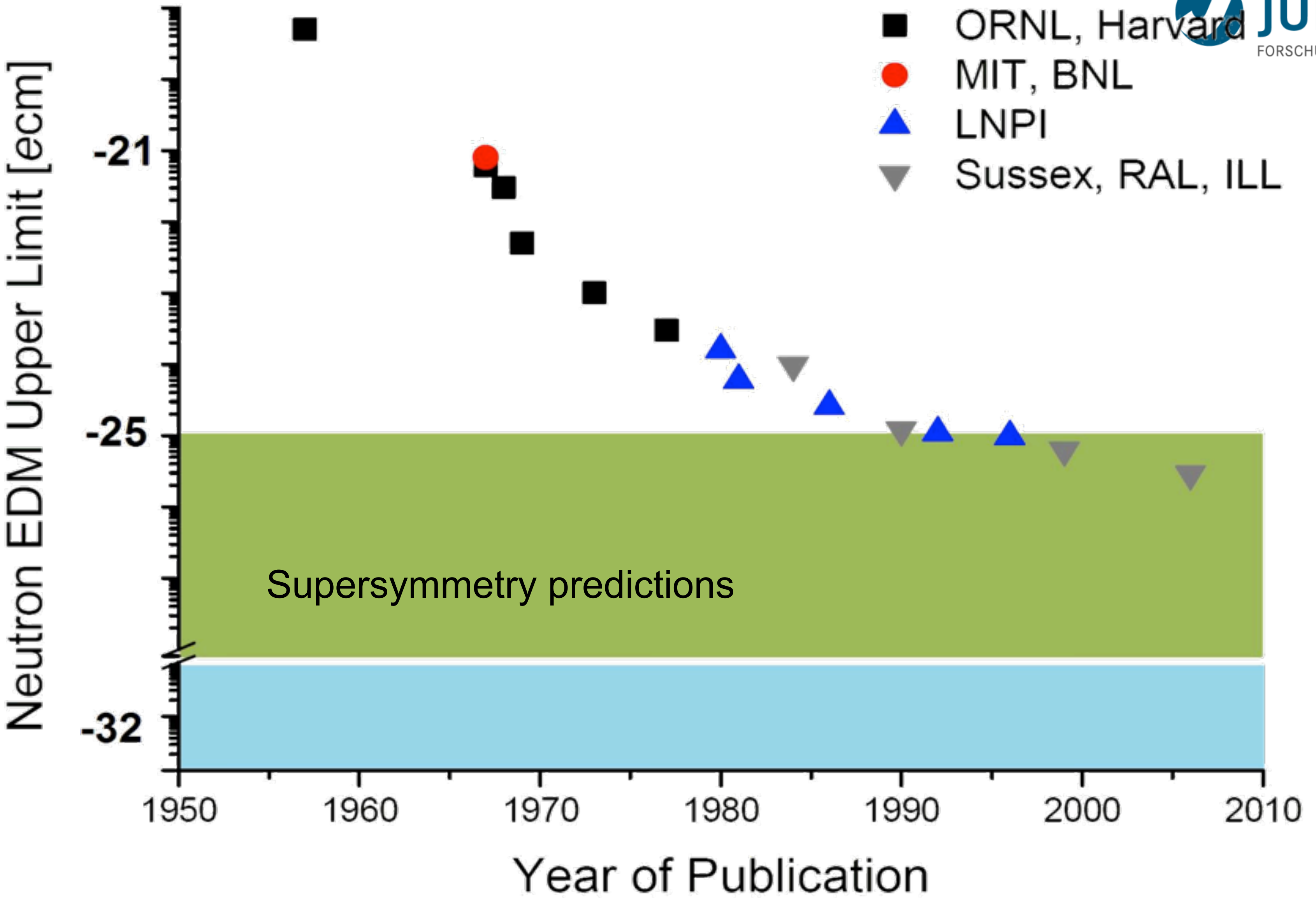
- Size of $\theta$ is **unknown, one of SM parameters**

# Theta Term Predictions




Crewther et al. (1979)

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




**Electric Dipole Moments =**

***"the poor man's high-energy physics"* (S. Lamoreaux)**

# Active experimental field



| | System | Group | Limit | C.L. | Value | Year |
|---|---|---|---|---|---|---|
| | $^{205}$Tl | Berkeley | $1.6 \times 10^{-27}$ | 90% | $6.9(7.4) \times 10^{-28}$ | 2002 |
| | YbF | Imperial | $10.5 \times 10^{-28}$ | 90 | $-2.4(5.7)(1.5) \times 10^{-28}$ | 2011 |
| *e* | $Eu_{0.5}Ba_{0.5}TiO_3$ | Yale | $6.05 \times 10^{-25}$ | 90 | $-1.07(3.06)(1.74) \times 10^{-25}$ | 2012 |
| | PbO | Yale | $1.7 \times 10^{-26}$ | 90 | $-4.4(9.5)(1.8) \times 10^{-27}$ | 2013 |
| | ThO | ACME | $8.7 \times 10^{-29}$ | 90 | $-2.1(3.7)(2.5) \times 10^{-29}$ | 2014 |
| | *n* | Sussex-RAL-ILL | $2.9 \times 10^{-26}$ | 90 | $0.2(1.5)(0.7) \times 10^{-26}$ | 2006 |
| | $^{129}$Xe | UMich | $6.6 \times 10^{-27}$ | 95 | $0.7(3.3)(0.1) \times 10^{-27}$ | 2001 |
| | $^{199}$Hg | UWash | $3.1 \times 10^{-29}$ | 95 | $0.49(1.29)(0.76) \times 10^{-29}$ | 2009 |
| | muon | E821 BNL *g*−2 | $1.8 \times 10^{-19}$ | 95 | $0.0(0.2)(0.9) \times 10^{-19}$ | 2009 |

Current EDM null results → **probe few TeV scale** or $\phi_{CP} \leq O(10^{-2,-3})$

Next generation sensitive to **10 TeV (beyond LHC)** or $\phi_{CP} \leq O(10^{-4,-5})$

# Storage rings experiments

Farley *et al PRL* '04

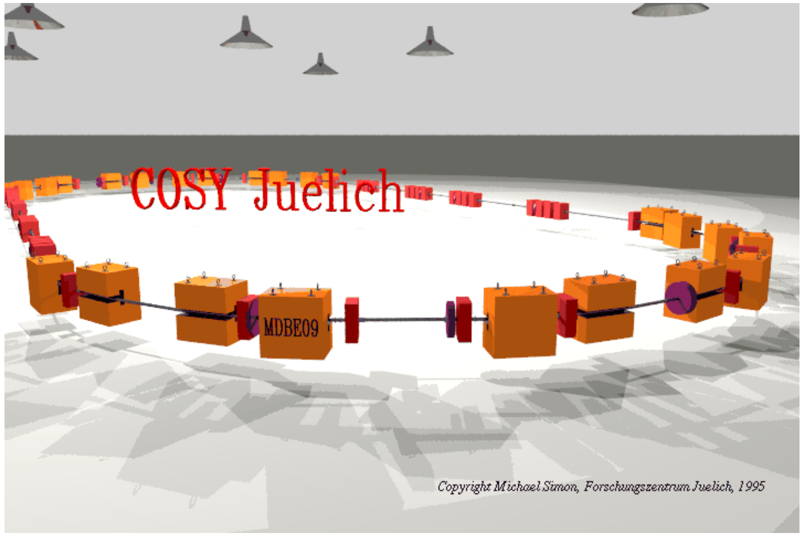
Anomalous magnetic moment

Electric dipole moment

$$\frac{d\vec{S}}{dt} = \vec{S} \times \vec{\Omega} \qquad \vec{\Omega} = \frac{q}{m}\left[a\vec{B} + \left(\frac{1}{v^2} - a\right)\vec{v} \times \vec{E}\right] + 2d\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

Proton at Brookhaven/ Fermilab?

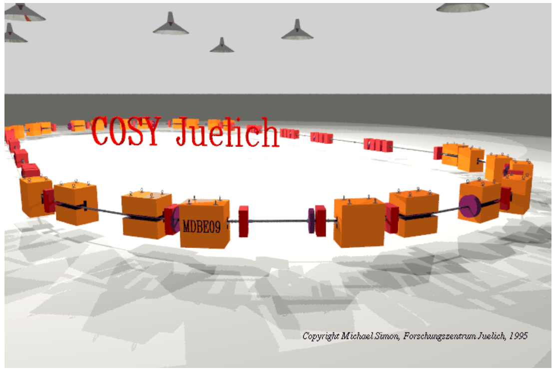
All-purpose ring (proton, deuteron, helion) at COSY?



# Experiments on hadronic EDMs

Farley *et al PRL* '04

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




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

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

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

COSY @ Jülich
Brookhaven/Fermilab

- Other light nuclei?

# Why bother with them ?

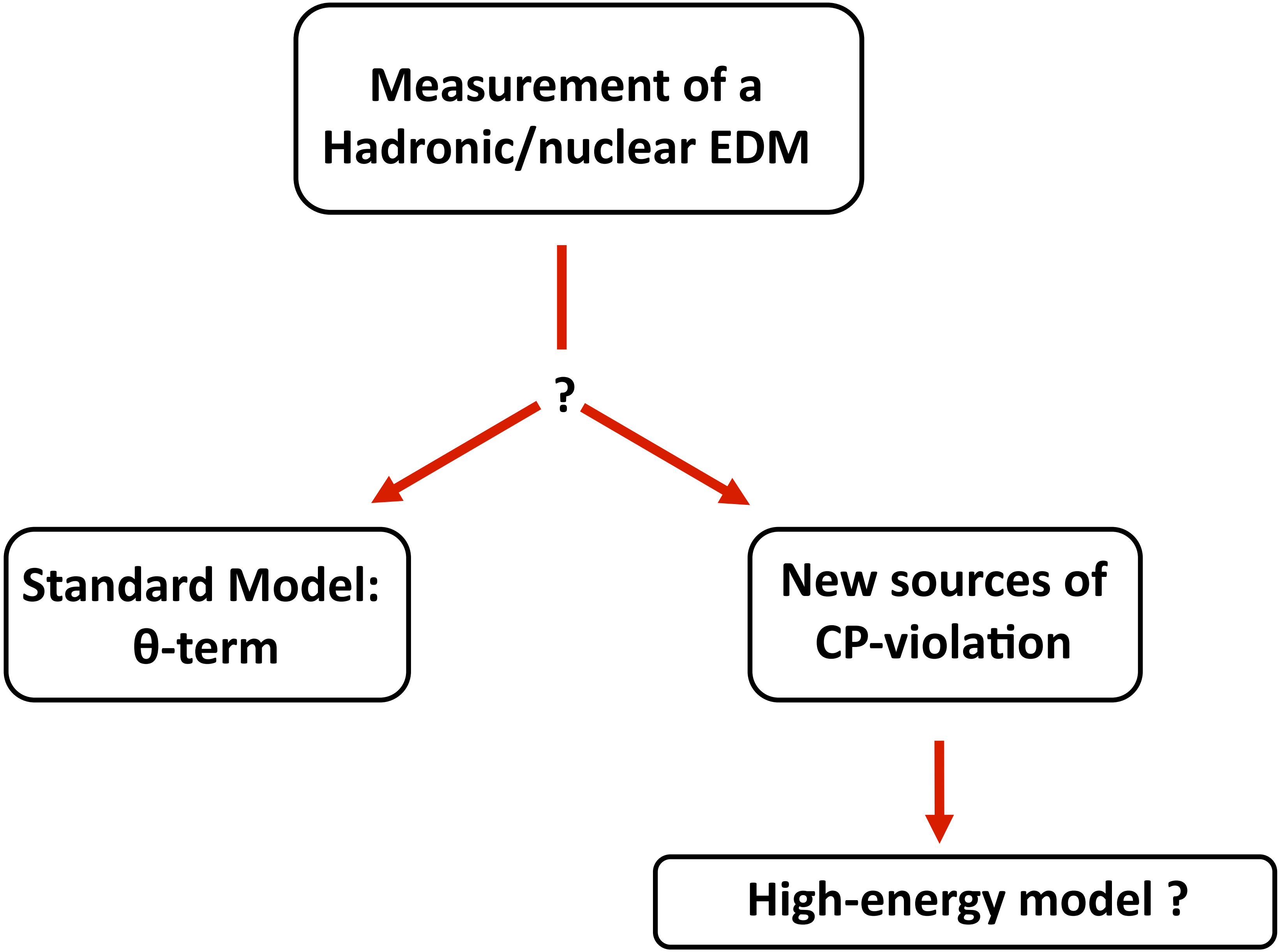
**Why are EDMs interesting to measure?**

**A search for new physics which is** ***'background free'***

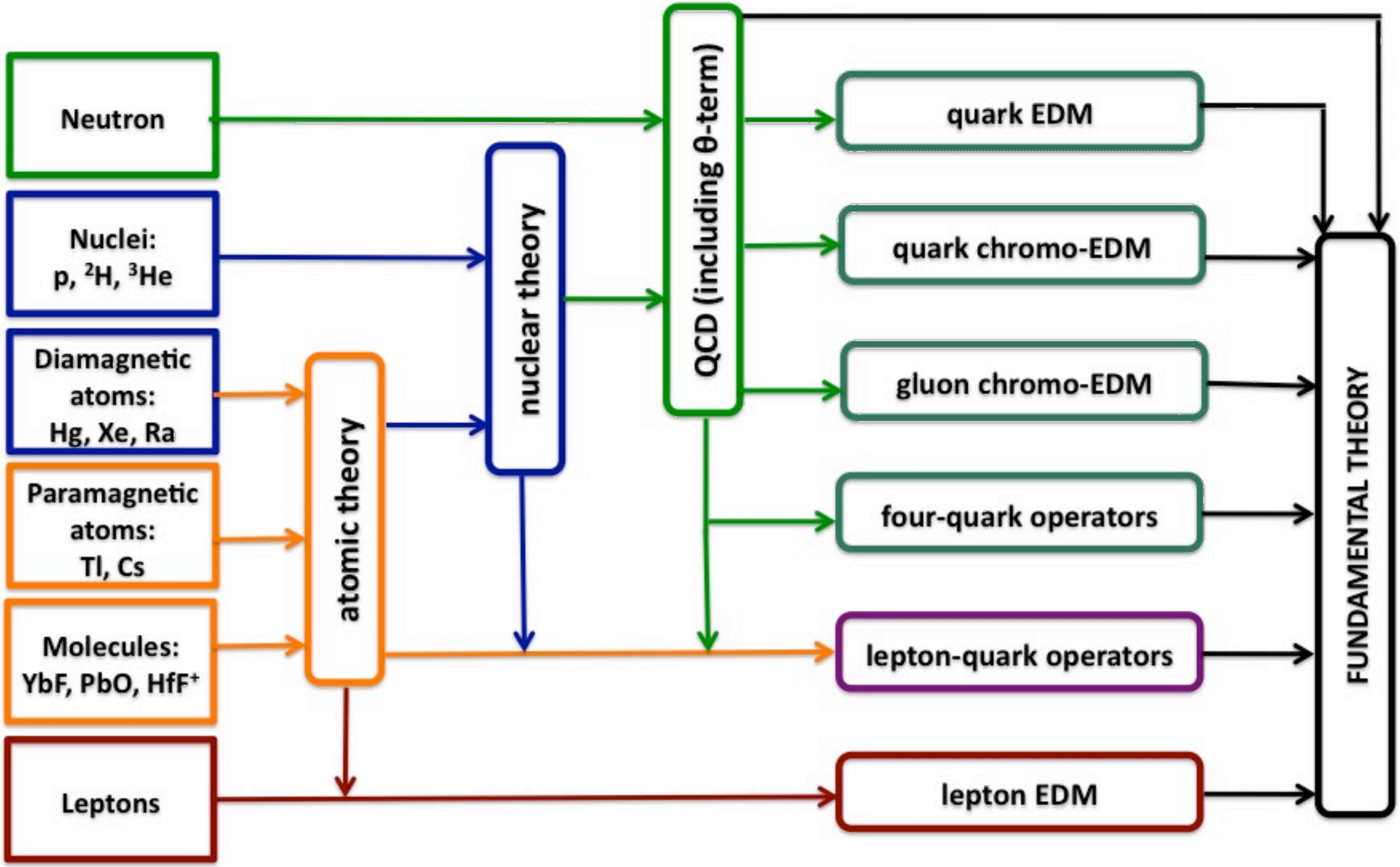
**Many beyond-the-SM models predict large EDMs:** ***Complementary to LHC search***

**Matter/Antimatter asymmetry requires more CPV:** ***EDMs are excellent probes***

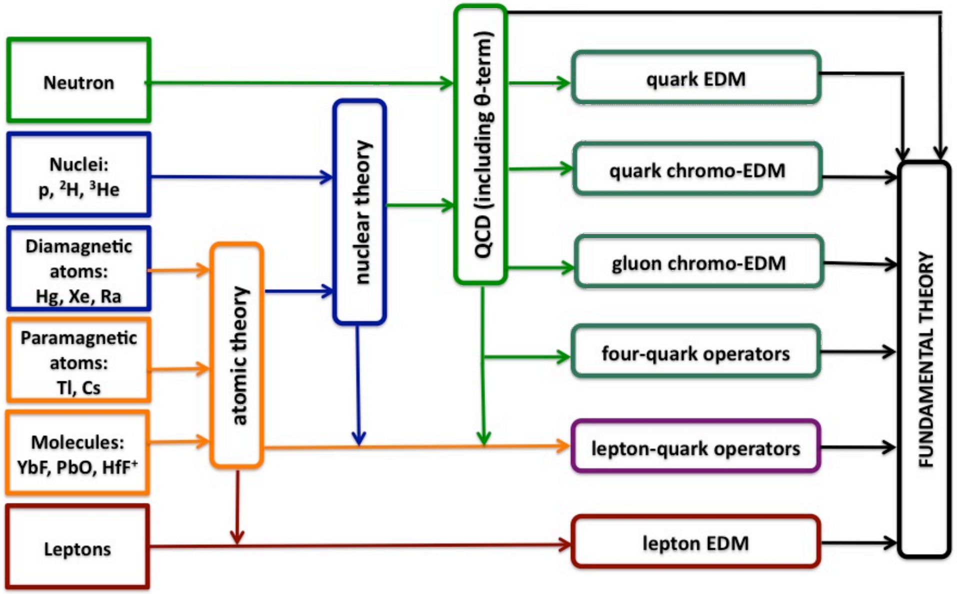
# Not really background free……



# Finding the **Source**



# Footprint ?




Questions :

Do **different** models of CP-violation leave behind a **different** 'EDM-footprint'

Can we **pinpoint** the microscopic source of CP-violation from **EDM measurements**?

# Outline of this talk

- Part I: What are EDMs and why are they interesting in the first place ?

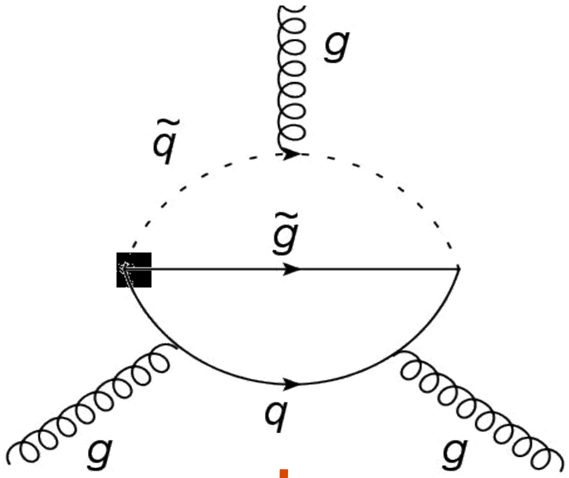
- **Part II: Effective field theory framework**

- Part III: EDMs of nucleons, light nuclei, and heavier systems

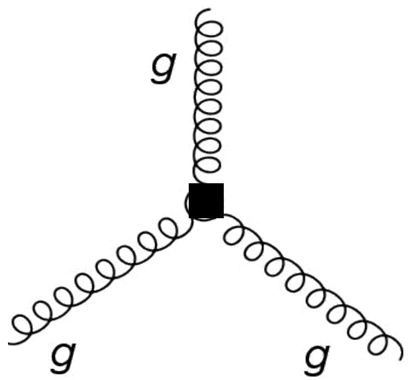
# Separation of scales



1 TeV ? SUSY?




Effectively becomes




$$\propto \frac{1}{M_{CP}^2}$$

100 GeV Standard Model

Energy

# A systematic approach

Buchmuller & Wyler NPB '86
Gradzkowski et al JHEP '10

- Add all possible CP-odd operators with:

  1) Degrees of freedom: Full SM field content

  2) Symmetries: Lorentz, SU(3)xSU(2)xU(1)

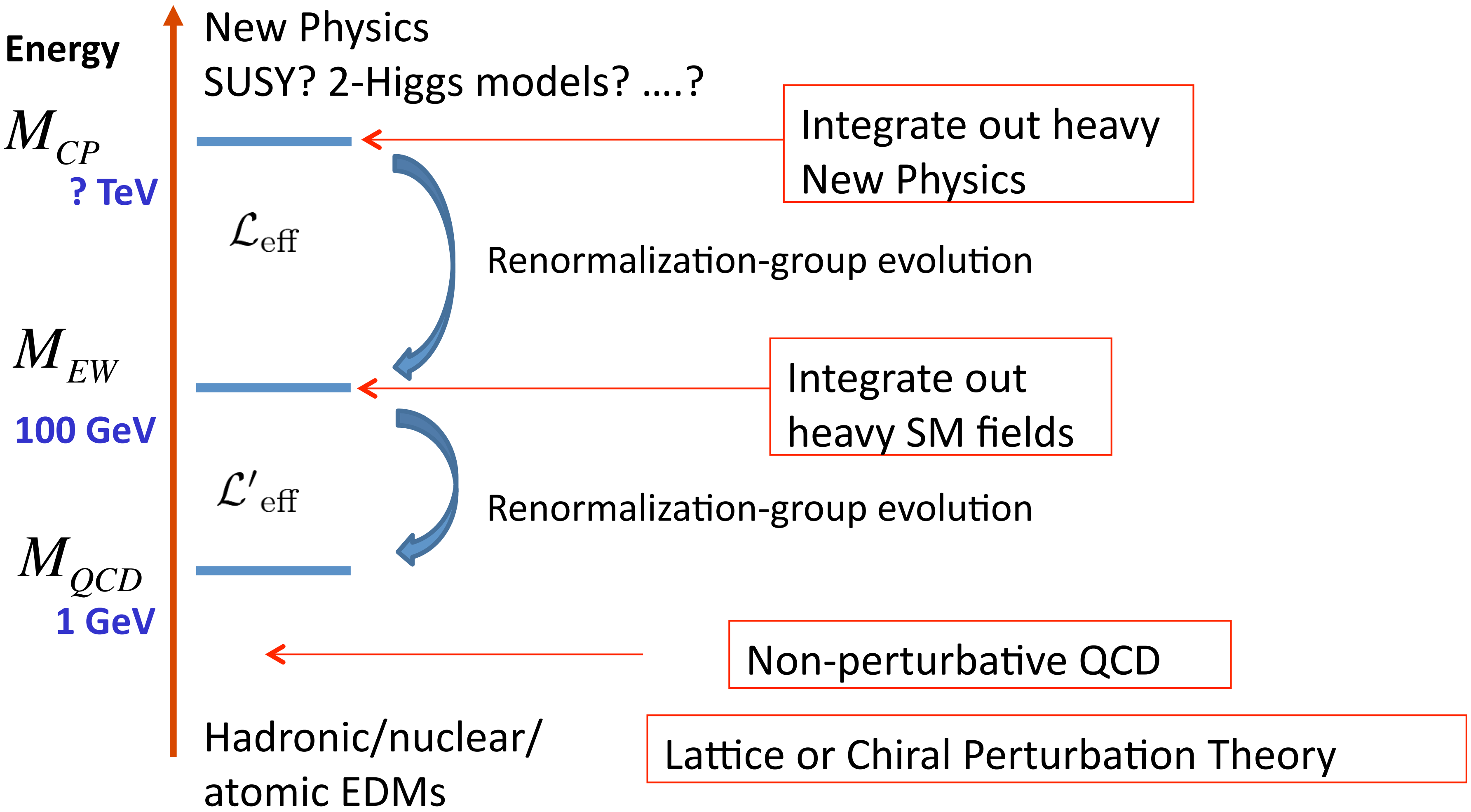
$$L_{new} = \frac{1}{M_{CP}} L_5 + \frac{1}{M_{CP}^2} L_6 + \cdots$$

- Model independent, ***but can be matched to particular models***

Mitglied der Helmholtz-Gemeinschaft

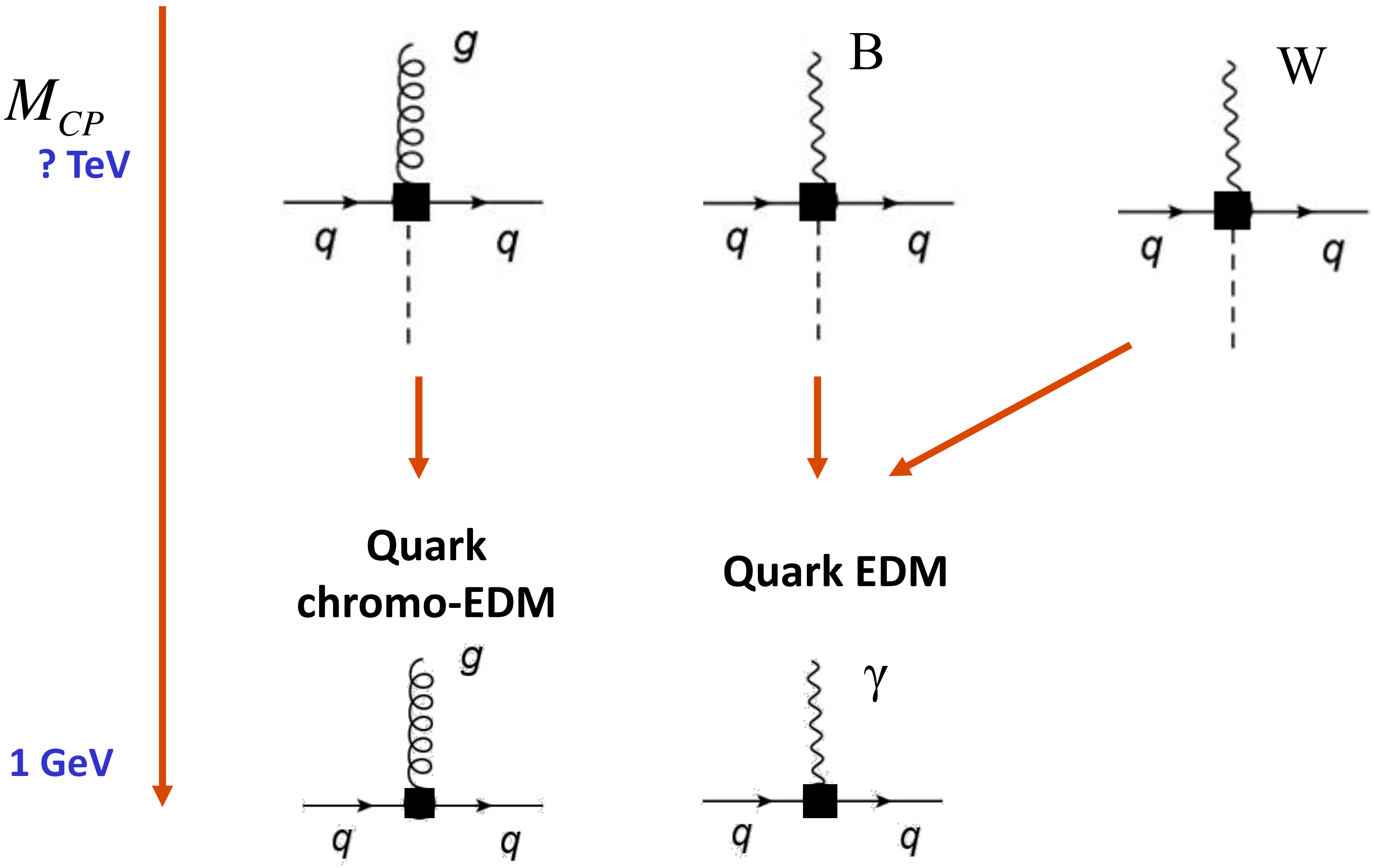
# Separation of scales

Dekens & JdV, JHEP, '13



# Examples of dim6 operators

Quark-Higgs-Gauge couplings



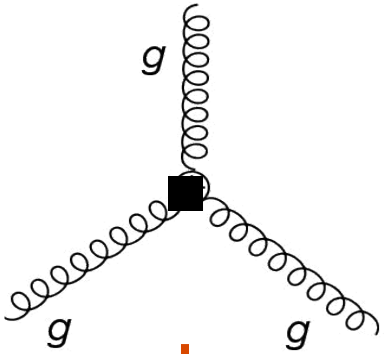
# Examples of dim6 operators

Pure gauge operators

Weinberg PRL '89

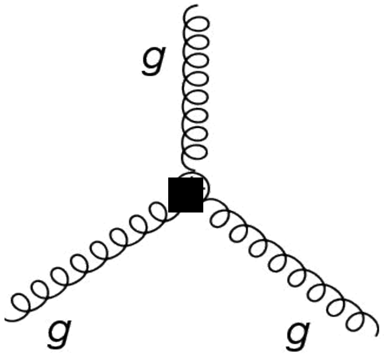
$M_{CP}$

? TeV

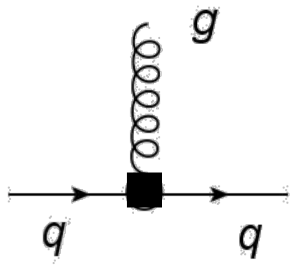



$$d_w \; f^{abc} \varepsilon^{\mu\nu\alpha\beta} \; G^a_{\alpha\beta} G^b_{\mu\lambda} \; G^{c\;\lambda}_{\nu}$$

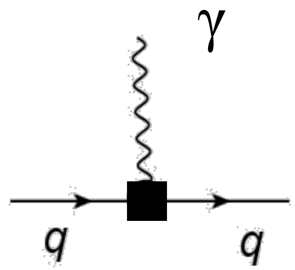
**Gluon chromo-EDM**




**Quark chromo-EDM**




**Quark EDM**




1 GeV

# Complements LHC

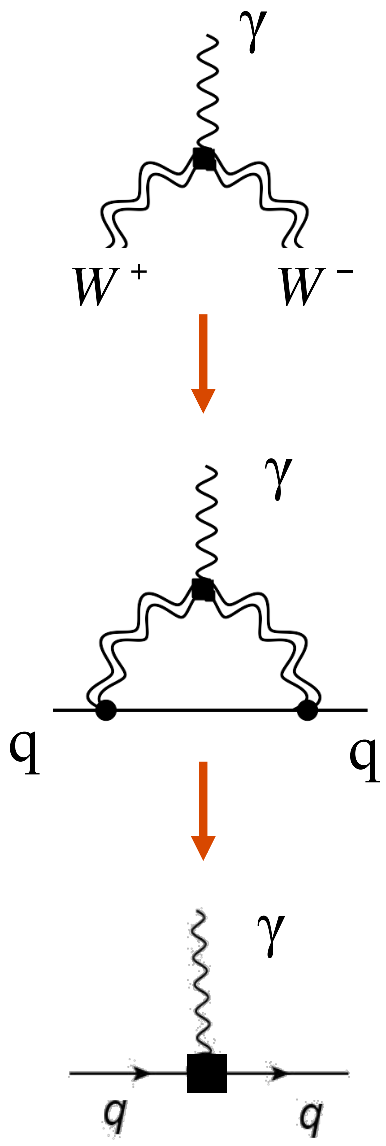
Mckeen et al ‘12
Manohar et al ’13
Fan et al ’13
Dekens et al ‘ 13

$M_{CP}$
**? TeV**

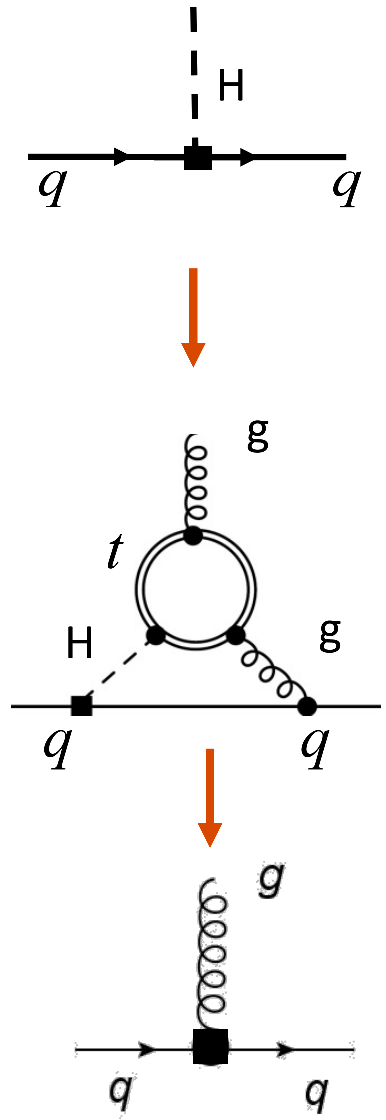
**100 GeV**

**1 GeV**

**Anomalous triple gauge boson vertices**



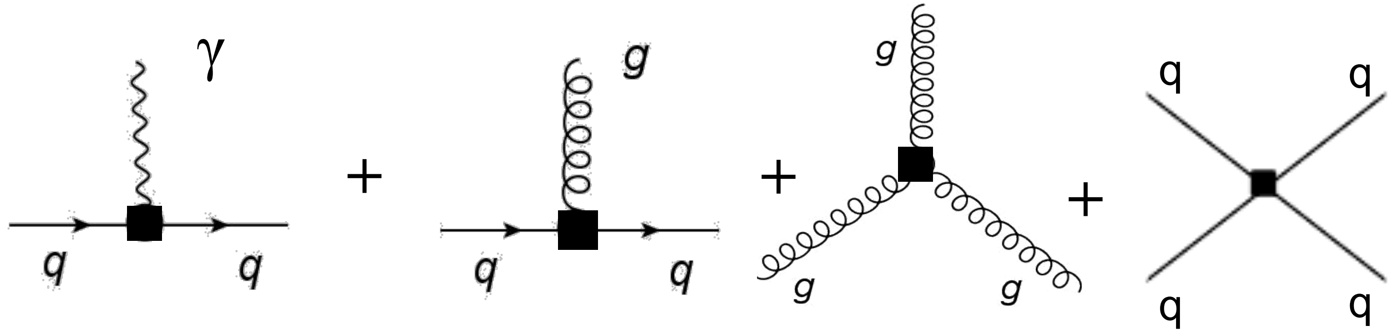

**CP-odd quark-Higgs vertices**



# When the dust settles….

**Few GeV**

**QCD (θ-term)** +




**Quark EDM** | **Quark chromo-EDM** | **Gluon chromo-EDM** | **3*4quark operators**

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

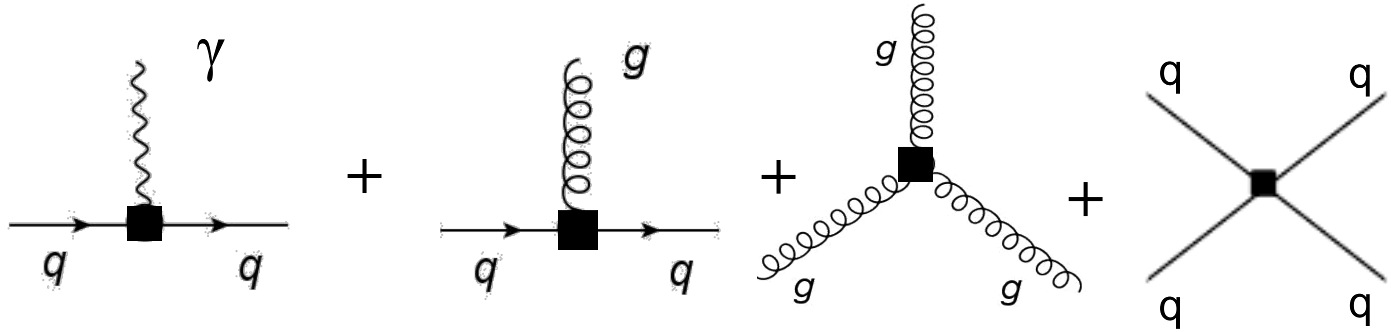
$$\mathcal{L}_{\not P \not T} = -\bar\theta \frac{g^2}{64\pi^2}\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta} - \frac{1}{2}\sum_{q=u,d}\left(d_q\,\bar q i\sigma^{\mu\nu}\gamma_5 q\,F_{\mu\nu} + \tilde d_q\,\bar q i\sigma^{\mu\nu}\gamma_5 t_a q\,G^a_{\mu\nu}\right)$$

$$+\frac{d_W}{6} f_{abc}\epsilon^{\mu\nu\alpha\beta}G^a_{\alpha\beta}G^b_{\mu\rho}G^{c\,\rho}_{\nu} + \sum_{i,j,k,l=u,d} C_{ijkl}\,\bar q_i\Gamma q_j\,\bar q_k\Gamma' q_l \ ,$$

# Crossing the barrier

Few GeV

QCD
(θ-term) +




Quark EDM

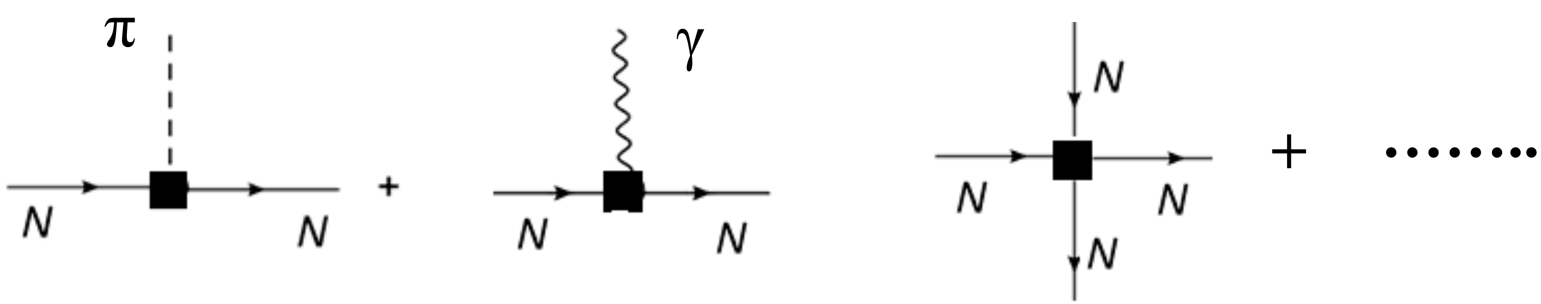
Quark
chromo-EDM

Gluon
chromo-EDM

3*4quark
operators

***Chiral Perturbation Theory***

100 MeV



# Chiral effective field theory

- Use the symmetries of QCD to obtain chiral Lagrangians

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

- Massless QCD Lagrangian has a global *SU(2)xSU(2)* symmetry spontaneously broken to *SU(2)*

$$q \rightarrow \left( e^{i\vec{\theta}_V \cdot \vec{\tau} + i\vec{\theta}_A \cdot \vec{\tau}\, \gamma^5} \right) q \qquad q = (u \;\; d)^T$$

- Pions are the corresponding **Goldstone** bosons (small pion mass due to small quark mass)

Weinberg, Gasser, Leutwyler, ….

# Chiral effective field theory

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

- The chiral Lagrangian can be constructed **order by order**
- Form of interactions **fixed by symmetry** considerations

- Each interaction associated with **unknown** LEC (needs to be fitted or from **lattice QCD**)

- Provides a **perturbative** expansion in $Q/\Lambda_\chi \quad \Lambda_\chi \cong 1\, GeV$

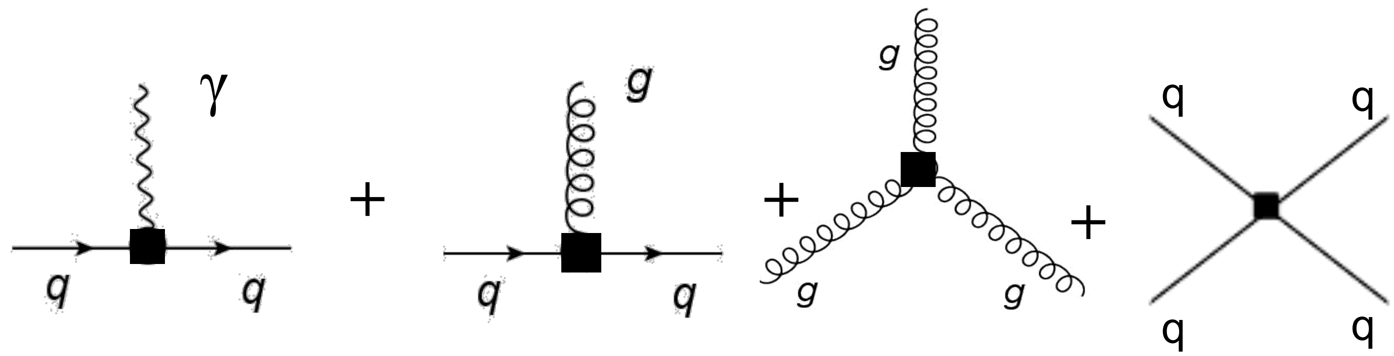
- Extremely successful in CP-even case (See for instance talk by Evgeny Epelbaum last monday)

Weinberg, Gasser, Leutwyler, Meißner, Kaiser, Bernard, van Kolck, Epelbaum….

# ChiPT with CP violation

- After integrating out new physics (***whatever it is***) at low energies:

**QCD (θ-term)** +




- They all break CP
- But **transform differently** under chiral symmetry

↓

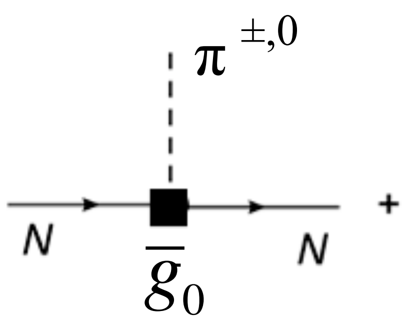
Different CP-odd chiral Lagrangians!

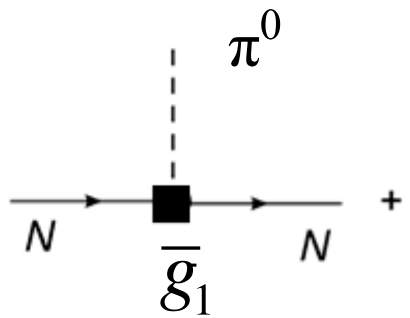
**This is the key to unravel them !**

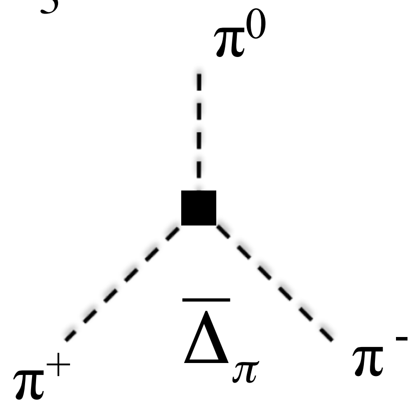
# Seven interactions up to N2LO

- We extend chiPT to include **CP-odd interactions**

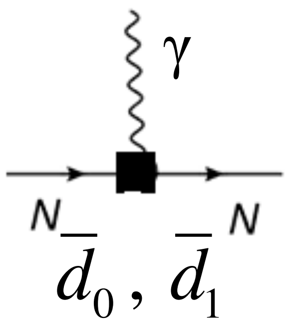
$$L = \bar{g}_0\, \bar{N}(\vec{\pi}\cdot\vec{\tau})N + \bar{g}_1\, \bar{N}\pi_3 N + \bar{\Delta}_\pi\, \pi^2\pi_3$$



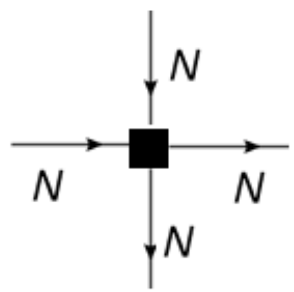




$$L = \bar{d}_0\, \bar{N}(\vec{\sigma}\cdot\vec{E})N + \bar{d}_1\, \bar{N}(\vec{\sigma}\cdot\vec{E})\tau^3 N$$




$$L = \bar{C}_1\, (\bar{N}\vec{\sigma}N)\cdot\vec{\partial}(\bar{N}N) + \bar{C}_2\, (\bar{N}\vec{\sigma}\boldsymbol{\tau}N)\cdot\vec{\partial}(\bar{N}\boldsymbol{\tau}N)$$



# Hierarchy among the sources

- Example: CP-odd pion-nucleon interactions

$$L = \bar{g}_0 \bar{N}(\vec{\pi}\cdot\vec{\tau})N + \bar{g}_1 \bar{N}\pi_3 N$$

---

❖ θ-term **breaks chiral** symmetry but **conserves isospin** symmetry

- $\bar{g}_0 >> \bar{g}_1$ because $\bar{g}_1$ is isospin-breaking

$$\bar{g}_0 = \frac{(m_n - m_p)^{strong}}{4F_\pi \varepsilon}\bar{\theta} = -0.018(7)\bar{\theta}$$

$$\bar{g}_1 = \frac{8c_1(\delta m_\pi^2)^{strong}}{F_\pi}\frac{1-\varepsilon^2}{2\varepsilon}\bar{\theta} = 0.003(2)\,\bar{\theta}$$

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

$$\varepsilon = (m_u - m_d)/2\bar{m} \cong 1/3$$

Lebedev et al '04
Bsaisou et al '12

# Hierarchy among the sources

- Example: CP-odd pion-nucleon interactions

$$L = \bar{g}_0 \bar{N}(\vec{\pi}\cdot \vec{\tau})N + \bar{g}_1 \bar{N}\pi_3 N$$

---

❖ Quark chromo-EDM: **both** isospin-breaking and –conserving part

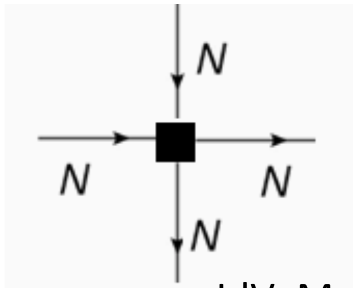
$$|\bar{g}_0| \approx |\bar{g}_1|$$

Relatively **large** uncertainty in LECs
e.g. from QCD sum rules

Pospelov, Ritz '02 '05

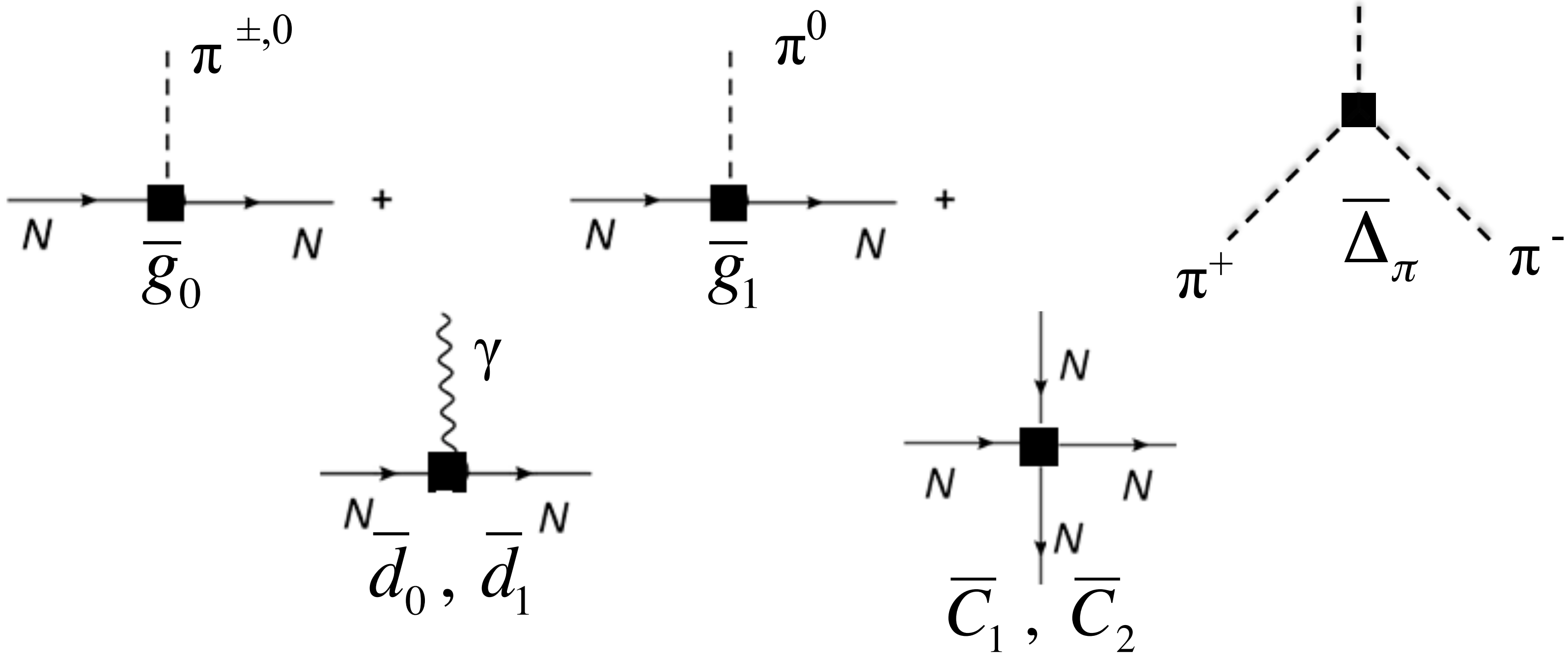
❖ Gluon chromo-EDM, LECs suppressed due to **chiral symmetry** .
Contributions from short-range NN interactions.

$$L = \bar{C}\,(\bar{N}\vec{\sigma}\,N)\cdot \vec{\partial}(\bar{N}N)$$




JdV, Mereghetti et al '12

# The magnificent seven




**Different sources of CP-violation (theta, quark EDM, gluon CEDM…. )**

**Induce different hierarchies between these interactions**

↓

**Probe these hierarchies experimentally**

JdV, Mereghetti et al '12

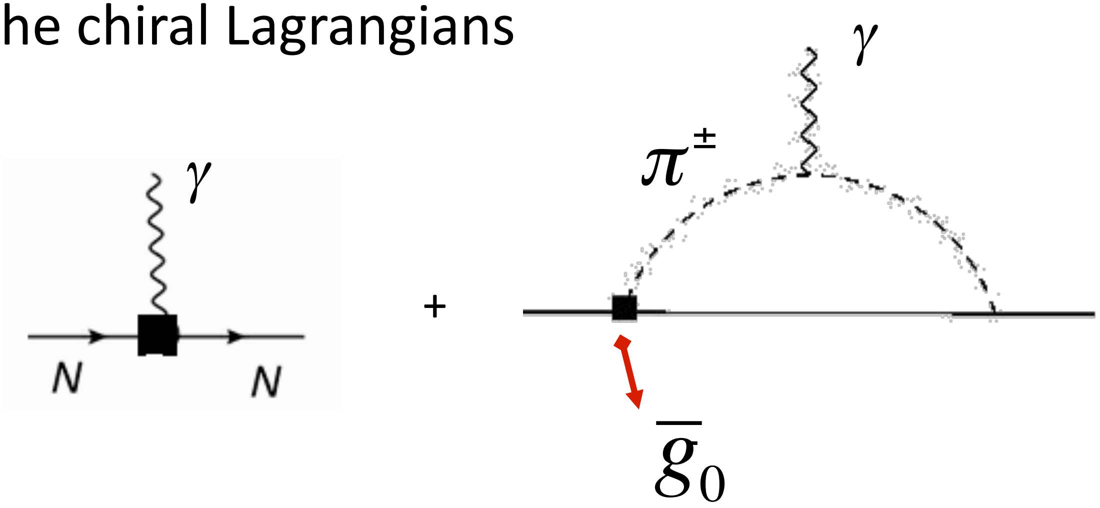
# Outline of this talk

- Part I: What are EDMs and why are they interesting in the first place ?
- Part II: Effective field theory framework
- **Part III: EDMs of nucleons and nuclei**

# The Nucleon EDM

- Calculate directly from the chiral Lagrangians

**Nucleon EDM**




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

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

Crewther et al., PLB ‘79
Pich, Rafael, NPB ‘91

Pallante, Bijnens, PLB ’96
Hockings, van Kolck, PLB ’05

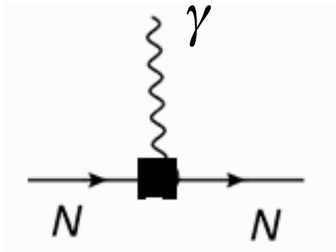
Ottnad et al, PLB ‘10
JdV, Mereghetti et al, PLB ’11 ’14

# The Nucleon EDM



- Calculate directly from the chiral Lagrangians

**Nucleon EDM**

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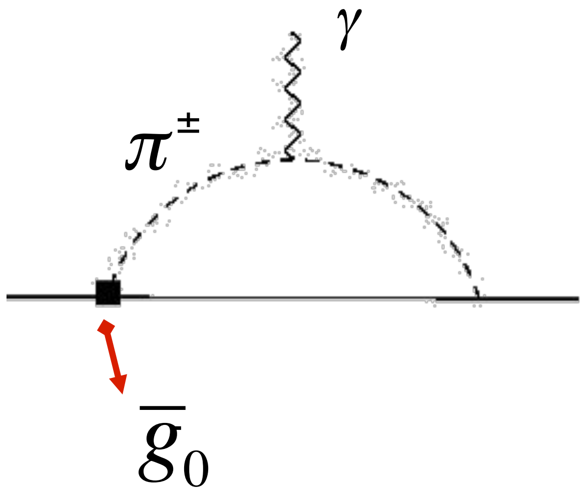


$$d_n = \bar{d}_0 - \bar{d}_1 + (0.13+0.01)\,\bar{g}_0\; e\ fm$$

$$d_p = \bar{d}_0 + \bar{d}_1 - (0.13+0.03)\,\bar{g}_0\; e\ fm$$

**Very similar and 3 LECs….**

***Hard to probe the hierarchy with only neutron and proton EDMs***

Crewther et al., PLB '79
Pich, Rafael, NPB '91

Pallante, Bijnens, PLB '96
Hockings, van Kolck, PLB '05

Ottnad et al, PLB '10
JdV, Mereghetti et al, PLB '11 '14

# Lattice QCD to the rescue

JÜLICH FORSCHUNGSZENTRUM

Test for the QCD theta term. With lattice input for LECs

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

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

Shintani ’12 ’13
Guo, Meißner ‘13 ’14

Could provide **strong hint** for theta term!

New lattice approach for theta

Talk by Andrea Shindler

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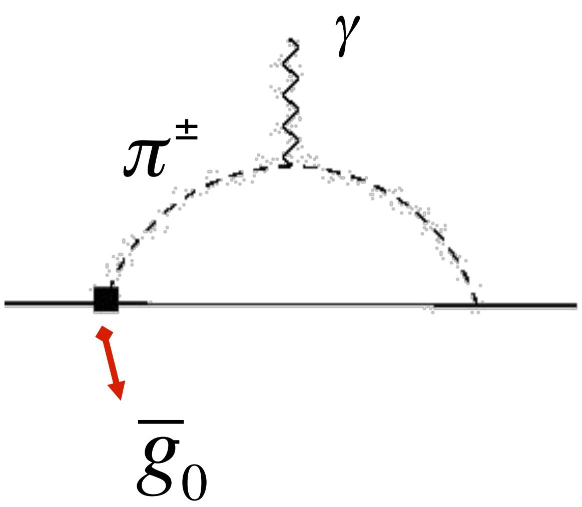
Talk by Andrea Shindler

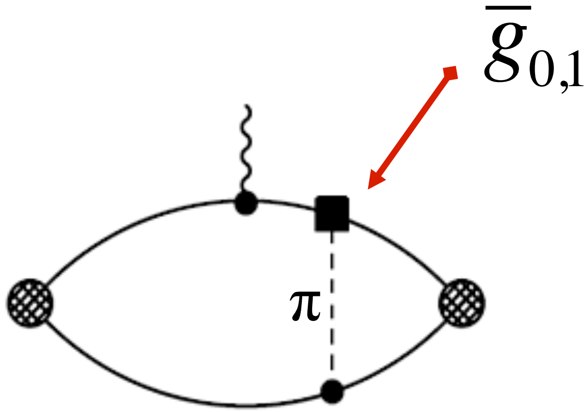
But…… No lattice data yet for other CPV scenarios
Work in progress (e.g. Cirigliano et al , Shindler et al)

**Generally: Need more observables to unravel sources !**

# Nuclear EDMs

- Nuclear EDMs: **tree-level dependence** !




- **No loop suppression and no counter terms!**

- Possible to calculate light-nuclear EDMs with **high accuracy!**

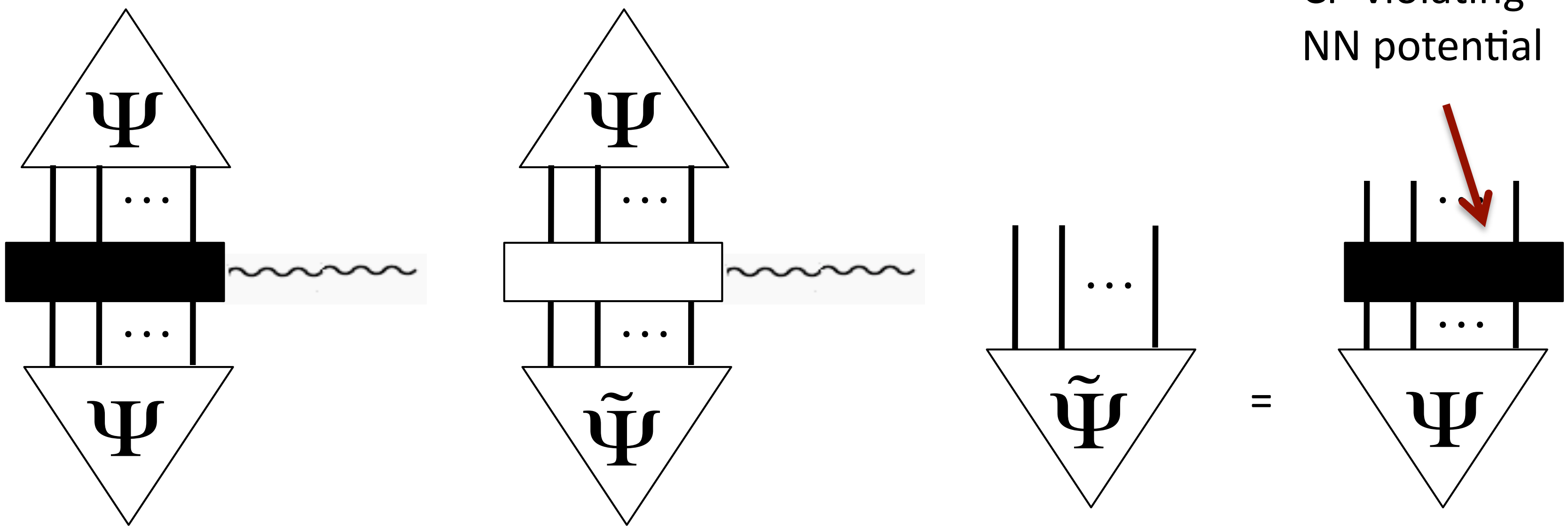
# EDM of a general light nucleus

- EDM of a nucleus with A nucleons can be separated in 2 contributions

**CP-odd admixtured wave-function**

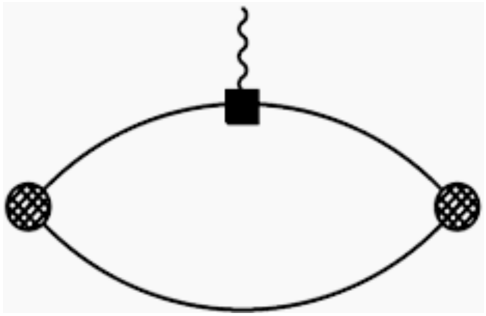
$$d_A = <\Psi_A \,||\, \vec{J}_{\cancel{CP}} \,||\, \Psi_A> \;+\; 2 <\Psi_A \,||\, \vec{J}_{CP} \,||\, \tilde{\Psi}_A>$$

CP-violating
NN potential

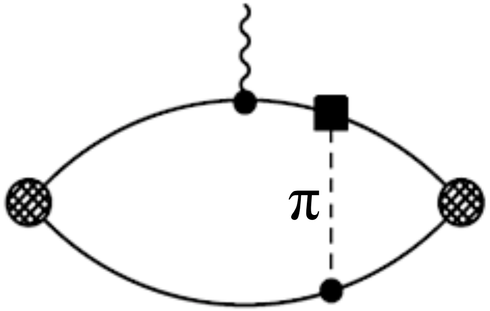



JdV et al '11
Bsaisou et al '12
Song et al '13

# The deuteron EDM



One-body: $d_D = d_n + d_p$




T-violating pion-exchange

$$L = \bar{g}_0 \bar{N}(\vec{\pi}\cdot\vec{\tau})N + \bar{g}_1 \bar{N}\pi_3 N$$

Khriplovich+Korkin NPA '00
Liu+Timmermans PRC '04
JdV et al PRL '11
Bsaisou et al '12

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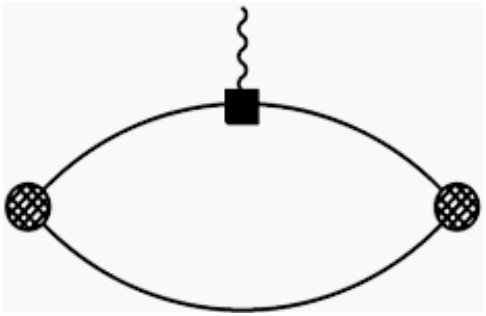

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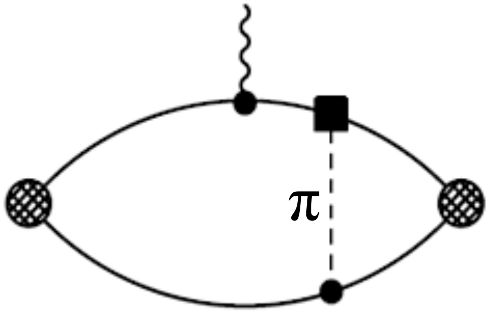


T-violating pion-exchange

$$L = \bar{g}_0 \bar{N}(\vec{\pi} \cdot \vec{\tau})N + \bar{g}_1 \bar{N}\pi_3 N$$

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

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

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

Khriplovich+Korkin NPA ’00
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JdV et al PRL ’11
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# The deuteron EDM



Obtain deuteron wave function from **chiral EFT potential**

$$(E - H_{PT})\,|\Psi_A> = 0$$

$$(E - H_{PT})\,|\tilde{\Psi}_A> = V_{\not{CP}}\,|\Psi_A>$$

Both consistently derived
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Both consistently derived in chiral EFT

Strong isospin filter

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

Theoretical accuracy is excellent !

# Do the same for 3He and 3H

No isospin filter in these nuclei, both g0 and g1 dependence

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

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

**Still good accuracy**, can most likely be improved by using N3LO

Stetcu et al, PLB ’08
JdV et al, PRC ’11
Song et al, PRC ‘13
Bsaisou et al, in prep

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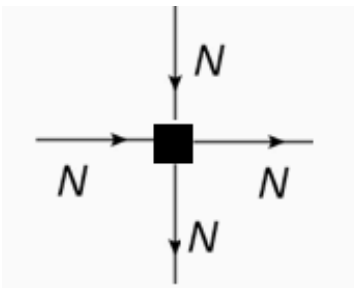
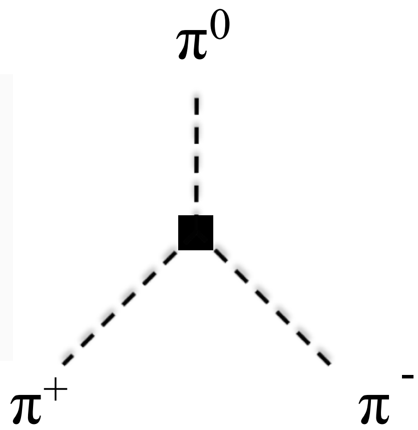
**Still good accuracy**, can most likely be improved by using N3LO

**$^3$H probably not a candidate for storage rings**

And dependence on:

*Not discussed now*




Stetcu et al, PLB '08
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# What would this tell us ?

JÜLICH FORSCHUNGSZENTRUM

- From measurements of dn, dp, dD, and/or d3He we can:

1) Extract the (relative) sizes of the couplings $\bar{g}_1 \quad \bar{g}_0 \quad (\bar{\Delta}_\pi)$

2) The size of the two- and three-body contributions, e.g.

$$\left|\frac{d_D}{d_p}\right| \qquad \left|\frac{d_D - d_n - d_p}{d_n + d_p}\right| \qquad \left|\frac{d_{3He}}{d_p}\right| \qquad \left|\frac{d_{3He} - d_n}{d_n}\right|$$

- These quantities point towards underlying source (theta, quark chromo-EDM, etc )

# Heavier EDMs

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- **Can't we get this info from EDMs of Hg, Ra, Rn…. ??**

Strong bound on atomic EDM: $d_{^{199}Hg} < 3.1 \cdot 10^{-29}\ e\ cm$

Griffiths et al, PRL '09

- The **atomic** part of the calculation is well under control

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

Dzuba et al, PRA '02, '09

**Nuclear Schiff moment**

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Dzuba et al, PRA '02, '09

**Nuclear Schiff moment**

- But the **nuclear** part isn't…..

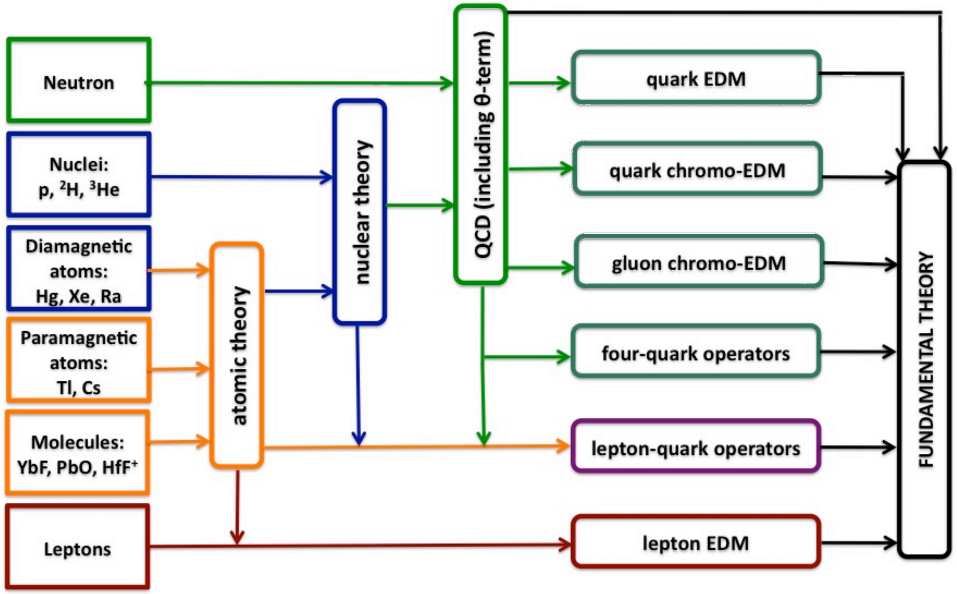
$$S_{^{199}Hg} = \left[(0.3 \pm 0.4)\bar{g}_0 + (0.4 \pm 0.8)\bar{g}_1\right] e\ fm^3$$

Engel et al, PPNP '13

- There is no **power counting** for nuclei with so many nucleons

# Footprint ?

JÜLICH
FORSCHUNGSZENTRUM




Big questions :

Do **different** models of CP-violation leave behind a **different** ‘EDM-footprint’

Can we **pinpoint** the microscopic source of CP-violation from **EDM measurements**?

# Unraveling models of CPV

- In recent work we studied 4 popular scenarios of CP-violation

**1) Standard Model including QCD theta term**
**2) The minimal left-right symmetric model** Mohapatra et al '08

3) The aligned two-Higgs-Doublet model Pich & Jung '13
4) The MSSM ( well, specific versions of it )

- Can we **unravel** these models with EDM experiments?

Dekens, JdV, Bsaisou, et al, JHEP '14

# Two scenarios of CPV



Crewther et al. (1979)

1) We first look at the QCD theta term

$$L = L_{QCD} + \frac{\theta}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

$\overline{m} = (m_u + m_d)/2$

Axial U(1) transformation

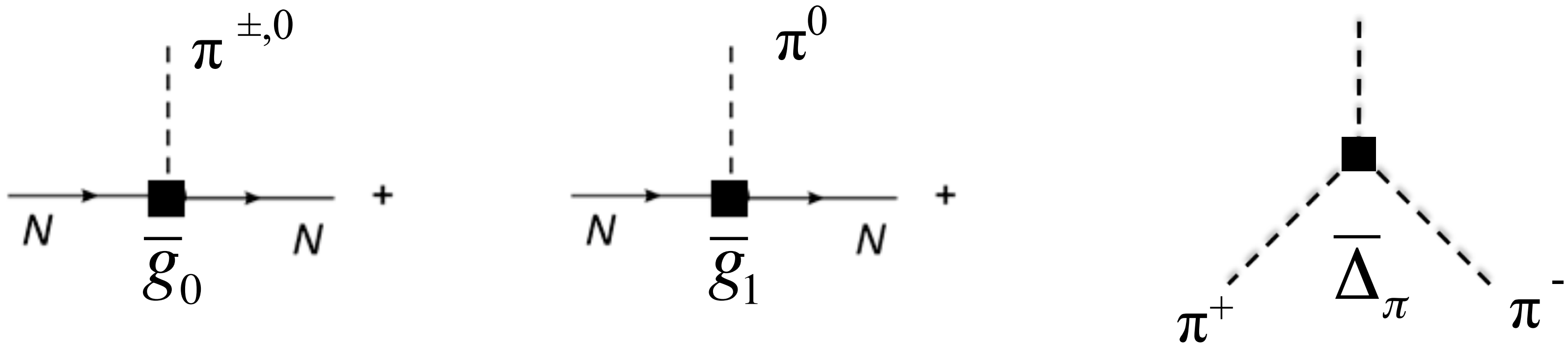
$$L = L_{QCD} + i\frac{\overline{m}}{2}\theta\, \overline{q} i \gamma^5 q$$

a CP-odd quark mass
**Isospin-symmetric!!**

Leads to a very **specific** hadronic CP-odd Lagrangian

# Two scenarios of CPV

1) Chiral Lagrangian for theta term




$$\bar{g}_0 = \frac{(m_n - m_p)^{strong}}{4F_\pi \varepsilon}\bar{\theta} = -0.018(7)\bar{\theta}$$

$$\varepsilon = (m_u - m_d)/2\overline{m} \cong 1/3$$

$$\bar{g}_1 = \frac{8c_1(\delta m_\pi^2)^{strong}}{F_\pi}\frac{1-\varepsilon^2}{2\varepsilon}\bar{\theta} = 0.003(2)\,\bar{\theta}$$

**Accuracy will improve!**

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

$\bar{\Delta}_\pi$ **Is N2LO effect**

# Two scenarios of CPV

2) Now the minimal left-right symmetric model

Mohapatra et al '08

- Based on unbroken Parity symmetry at high energies
- Gauge group: $SU_R(2)$ x $SU_L(2)xSU_c(3)xU(1)$
- Additional Higgs fields to break $SU_R(2)$
- Additional **heavy** right-handed gauge bosons $W_R^{+-}$ and $Z_R$

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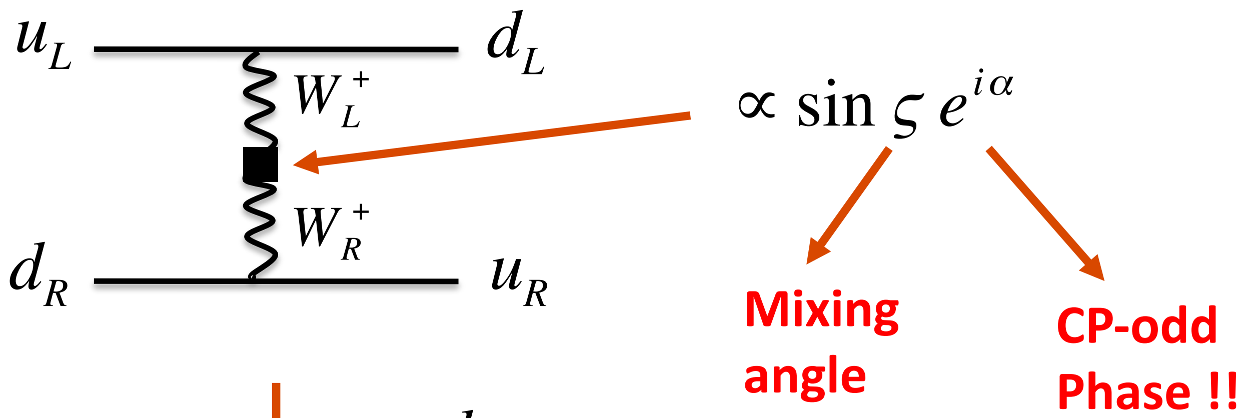


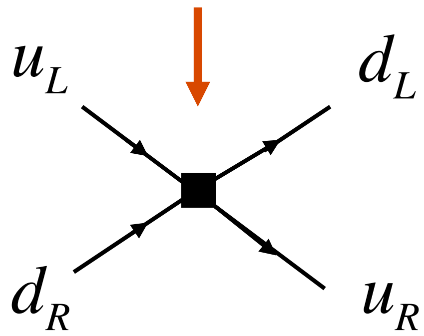


CP-odd **isospin-breaking** four-quark operator

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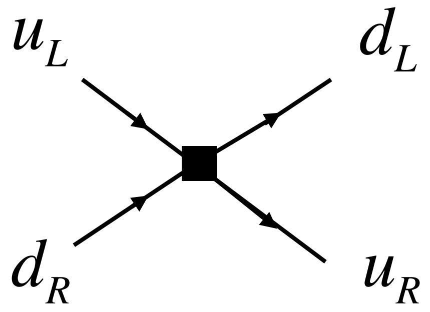
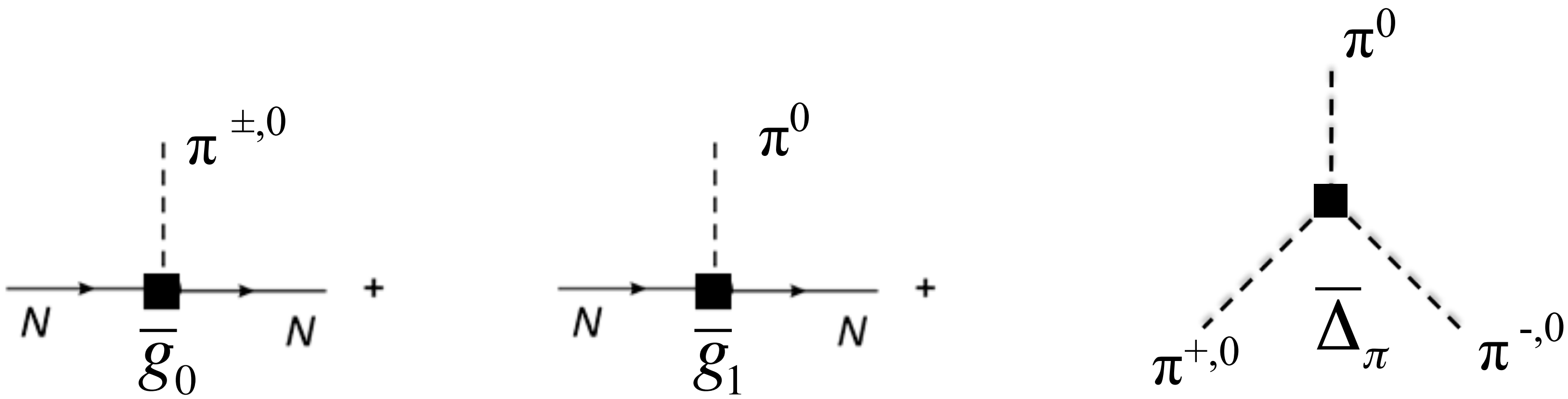



CP-odd **isospin-breaking** four-quark operator




Completely **opposite** behavior with respect tot theta term

$$\frac{\bar{g}_0}{\bar{g}_1} = \frac{(m_n - m_p)^{str}}{8c_1 m_\pi^2} - (0.02 \pm 0.01)$$

$\bar{\Delta}_\pi$ **Leading order interaction!**

# “EDM sum rules”

JÜLICH FORSCHUNGSZENTRUM

1) Theta term

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

2) mLRSM

$$\frac{\bar{g}_0}{\bar{g}_1} = -(0.02 \pm 0.01)$$

Deuteron EDM, sensitive mainly to $\bar{g}_1$

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

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$$\left|\frac{d_D - d_n - d_p}{d_n}\right| < 1$$

$$d_D - d_n - d_p \cong \frac{d_n}{6}$$

$$\left|\frac{d_D - d_n - d_p}{d_n}\right| > 1$$

**Rather big Uncertainty**

$$d_D - d_n - d_p \cong (3 - 10)\, d_n$$

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

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$$d_{3He} - 0.9 d_n \cong \frac{d_n}{2}$$

$$\cong 3\,(d_D - d_n - d_p)$$

$$d_{3He} - 0.9 d_n \cong 0.7\, d_D$$

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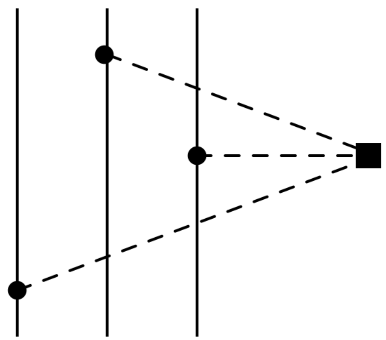
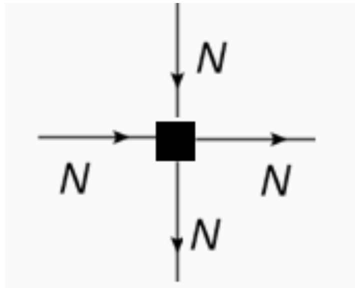


$\bar{\Delta}_\pi$ **?**

# Unraveling models of CPV

- Multi-Higgs and the MSSM leave different hierarchies behind

$$\left|\frac{\bar{g}_1}{\bar{g}_0}\right| \cong 1$$




- And give rise do different **electron/nucleon EDM ratio**

- **EDM experiments can tell us a lot about new physics**

**(or its absence….)**

# To-do list

***Light nuclei***

Wrap up some things (i.e. 3-body interactions)

***Reduce hadronic uncertainties***

**Lattice QCD** determinations of CP-odd LECs from theta and BSM.
In particular: nucleon EDMs and pion-nucleons

***Increase the number of nucleons***

Can we extend the framework to heavier systems ?

$$d_A(d_n, d_p, \bar{g}_0, \bar{g}_1, \bar{\Delta}_\pi, \bar{C}_{1,2})$$

Perhaps with nuclear lattice EFT ?

# Conclusion/Summary

1) EDMs are very good probes of new CP-odd physics
2) Probe **similar energy scales** as LHC, strong bounds on new physics

***EFT approach***

a) Framework exists for CP-violation (EDMs) from 1$^{st}$ principles

b) Keep track of **symmetries** from multi-Tev to few MeV

***The chiral filter***

a) Chiral symmetry determines form of hadronic interactions

b) n, p, D, 3He can be used to **unravel** the CP-odd source (if existing..)

***Quantified uncertainties***

a) Hadronic uncertainties dominate for nucleons & light nuclei → LQCD

b) Nuclear uncertainties dominate for heavy systems