Parity and Time-Reversal Violating Moments of Light Nuclei

Jordy de Vries
Theory Group, KVI, University of Groningen

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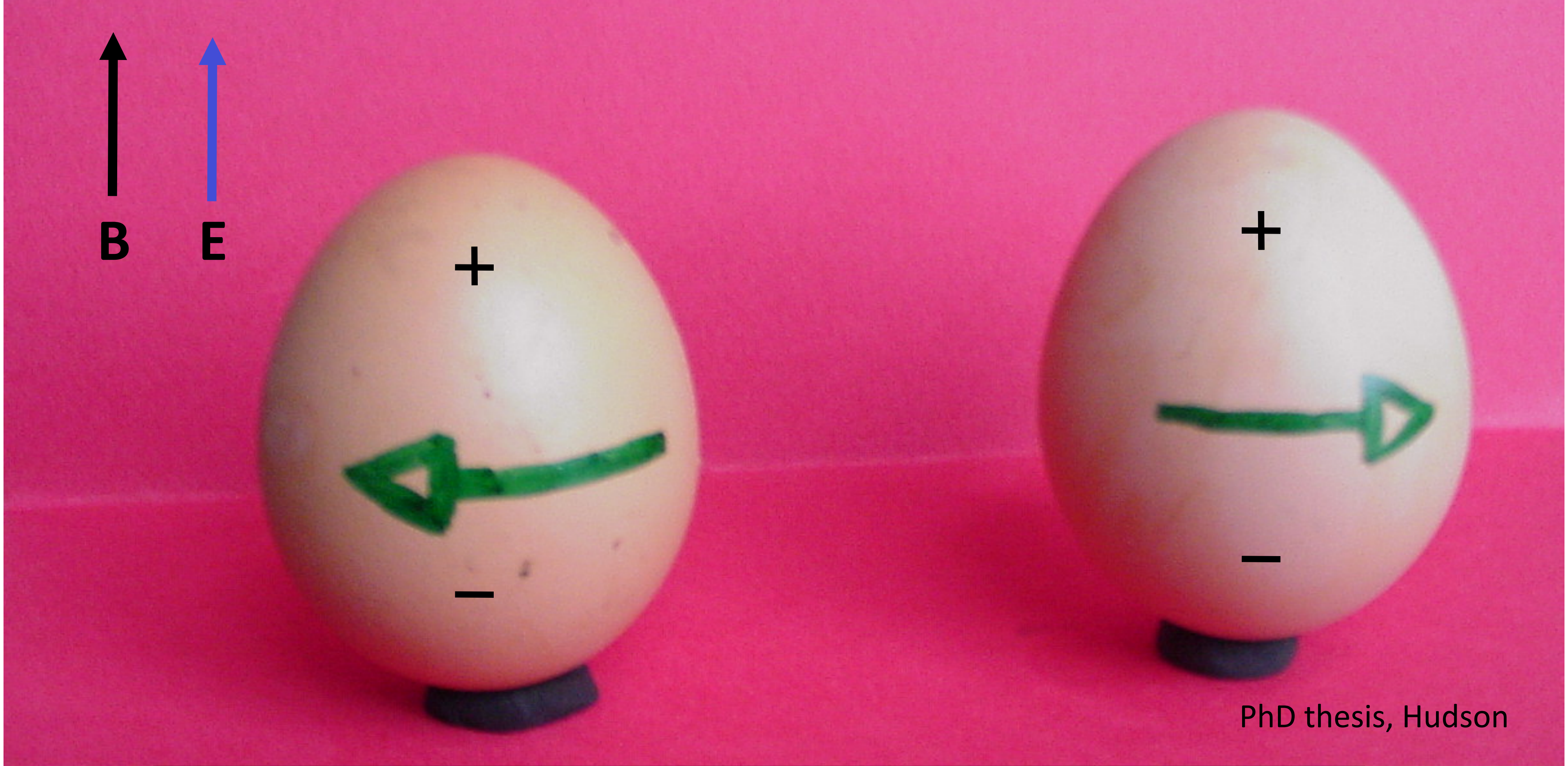
Jordy de Vries & Rob Timmermans
Theory Group, KVI, University of Groningen

Emanuele Mereghetti & Bira van Kolck & C.-P. Liu

Outline of this talk

- **Part I: Electric Dipole Moments in the Standard Model**
- Part II: Standard Model as an Effective Field Theory
- Part III: Observables
  - IIIa: Nucleon EDM
  - IIIb: Deuteron EDM and MQM
  - IIIc: 3He + 3H EDMs

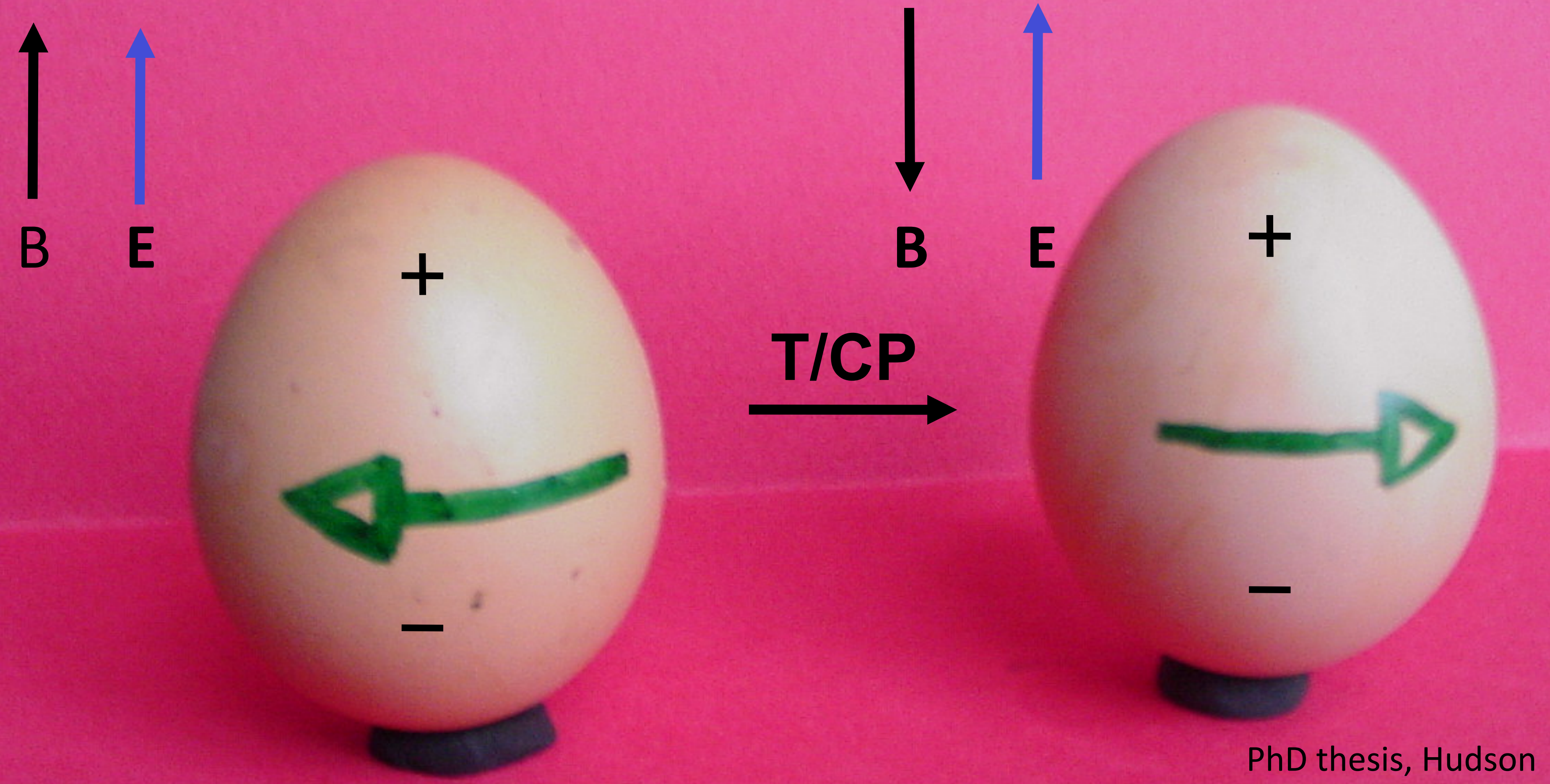
Electric Dipole Moments



PhD thesis, Hudson

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

Electric Dipole Moments



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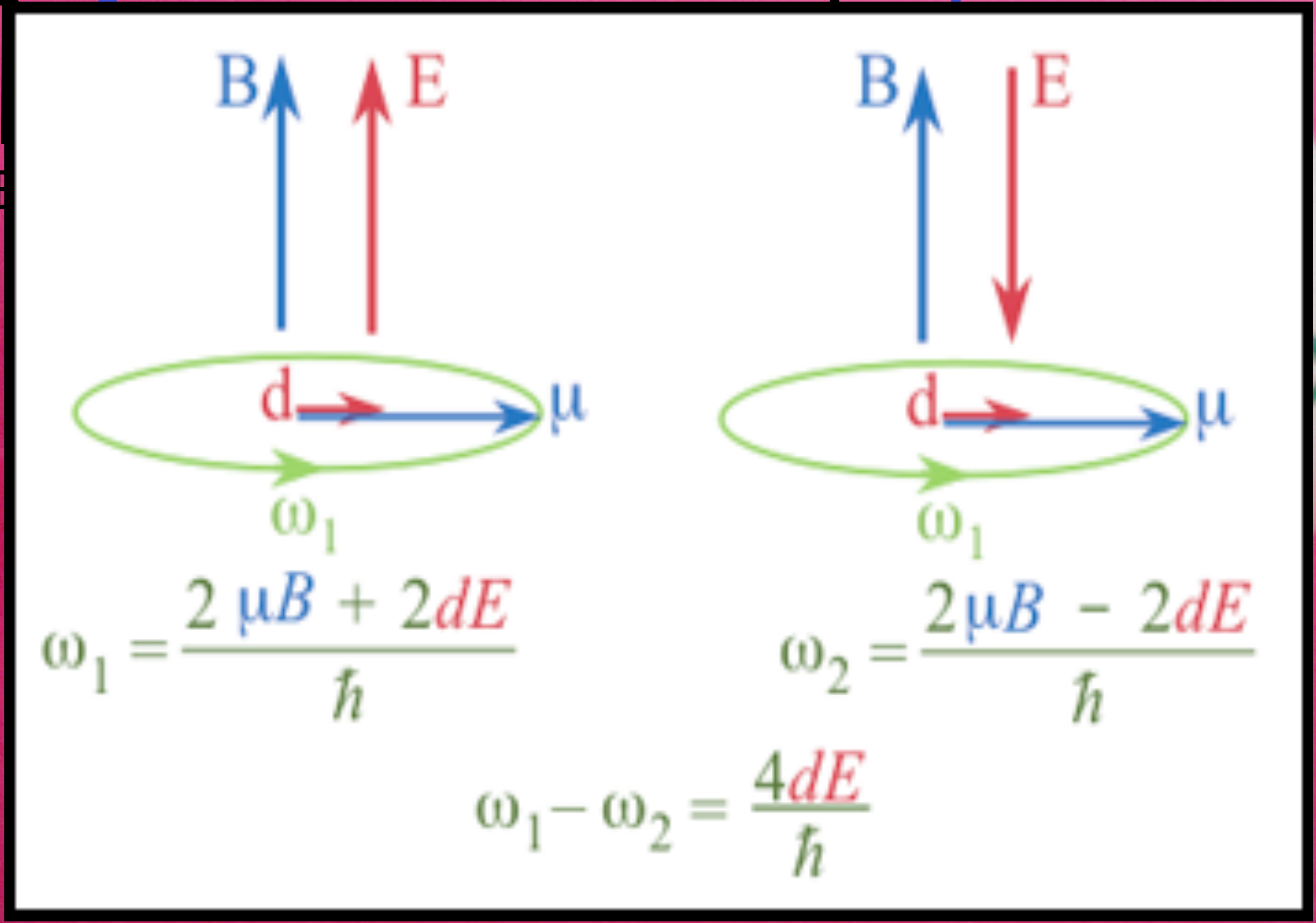
Electric Dipole Moments



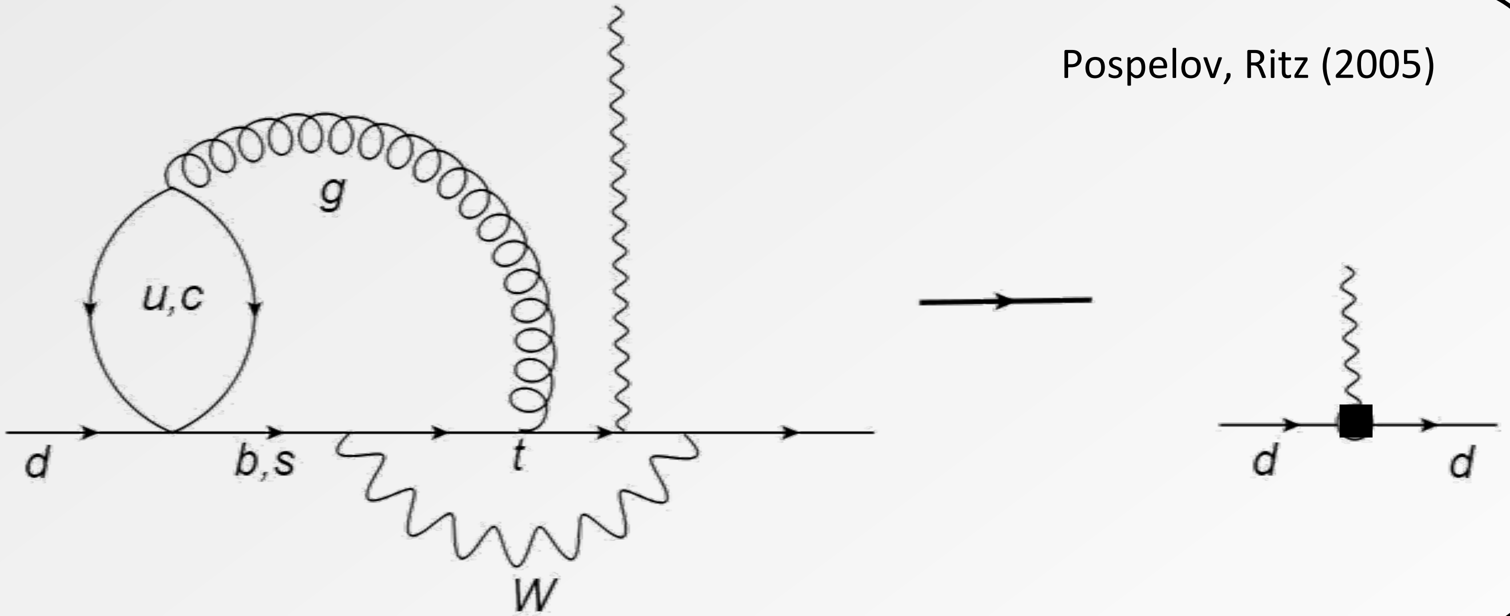
$$\omega_1 = \frac{2\,\mu B + 2dE}{\hbar}$$

$$\omega_2 = \frac{2\mu B - 2dE}{\hbar}$$

$$\omega_1 - \omega_2 = \frac{4dE}{\hbar}$$

EDM's in the Standard Model

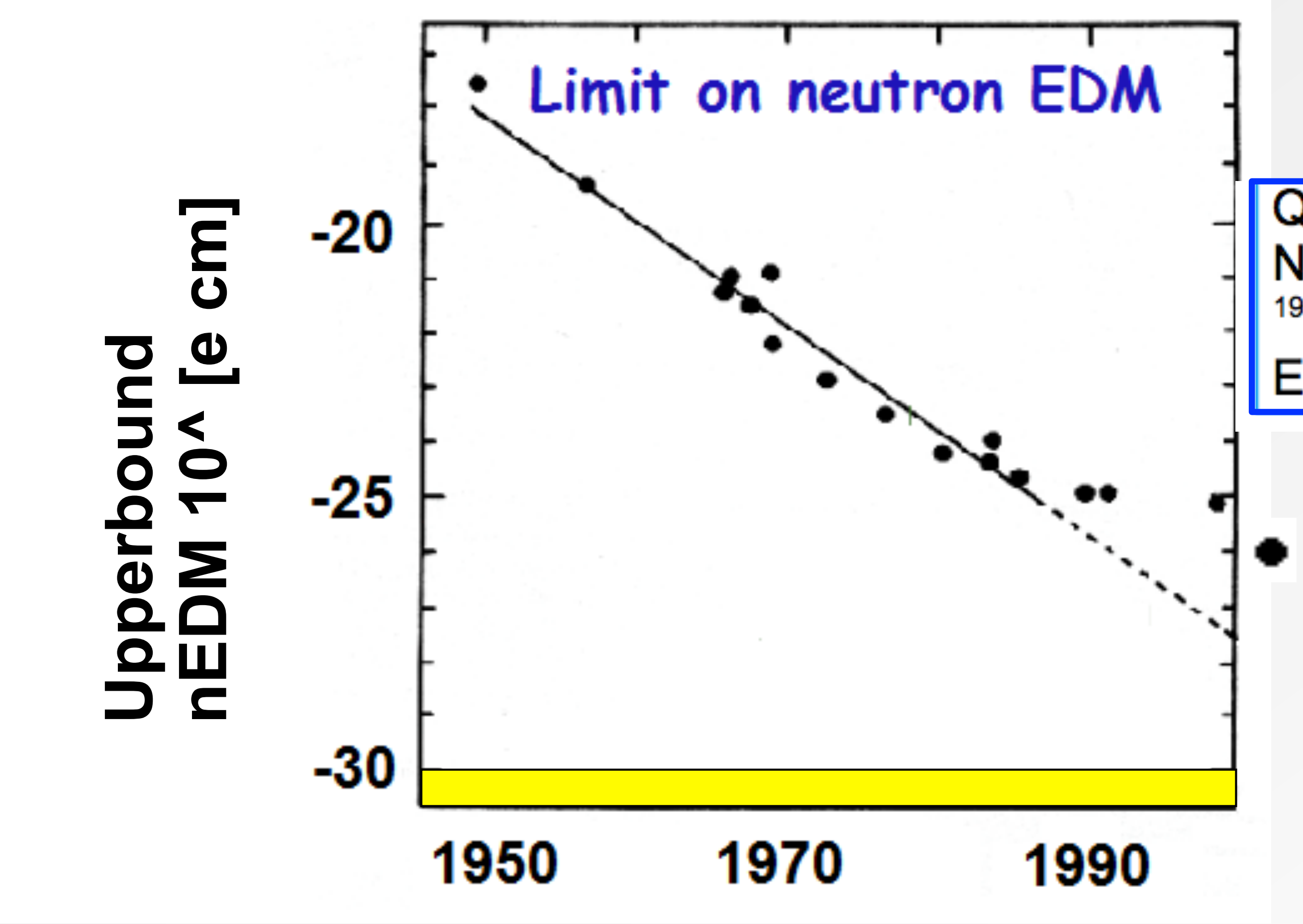
- Electroweak CP-violation
- Nobel prize for predicting **third** generation



Pospelov, Ritz (2005)

Highly Suppressed

Electroweak CP-violation



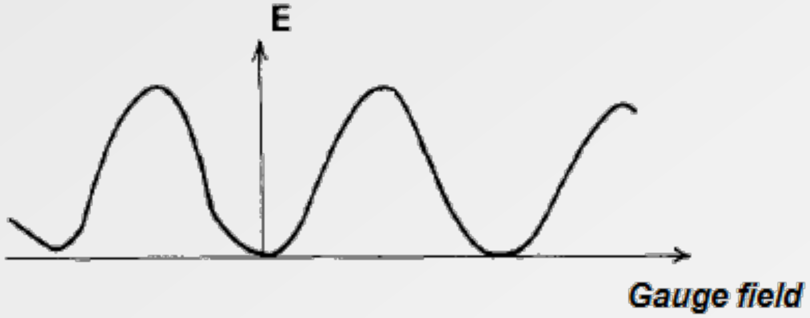
Quarks : $\sim 10^{-33 \cdots 34}$ $e \cdot$cm
Neutron : $\sim 10^{-31 \cdots 32}$ $e \cdot$cm
^{199}Hg : $\sim 10^{-33 \cdots 34}$ $e \cdot$cm
Electron : $< 10^{-40}$ $e \cdot$cm

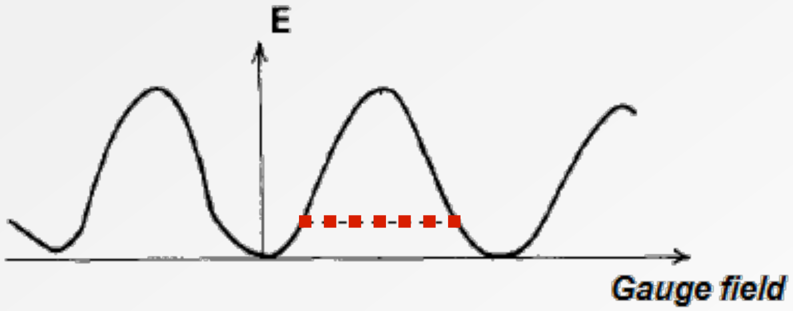
5 to 6 orders **below** upper bound ⟷ **Out of reach!**

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



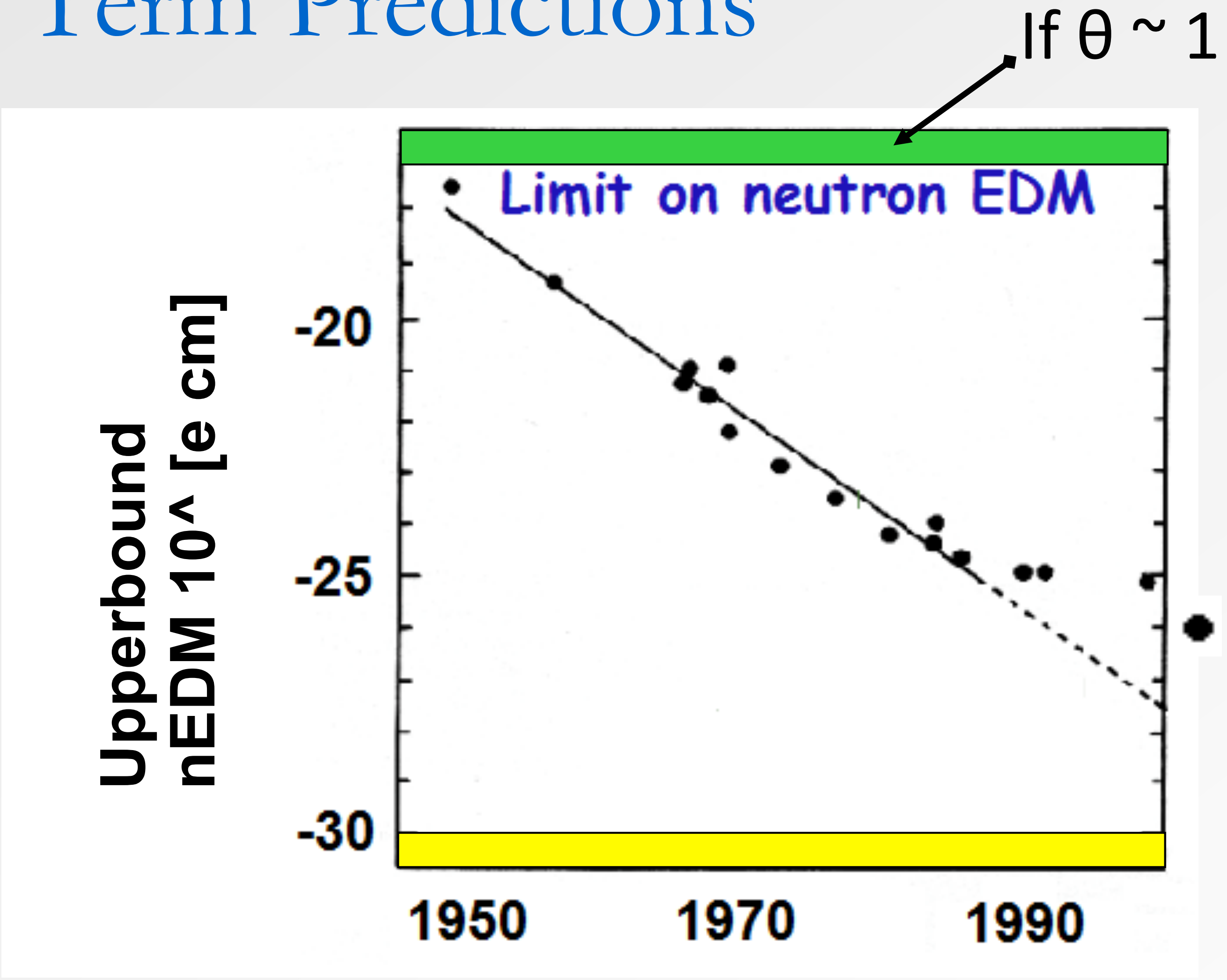


- Causes a 'new' CP-violating interaction with **coupling constant** θ

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

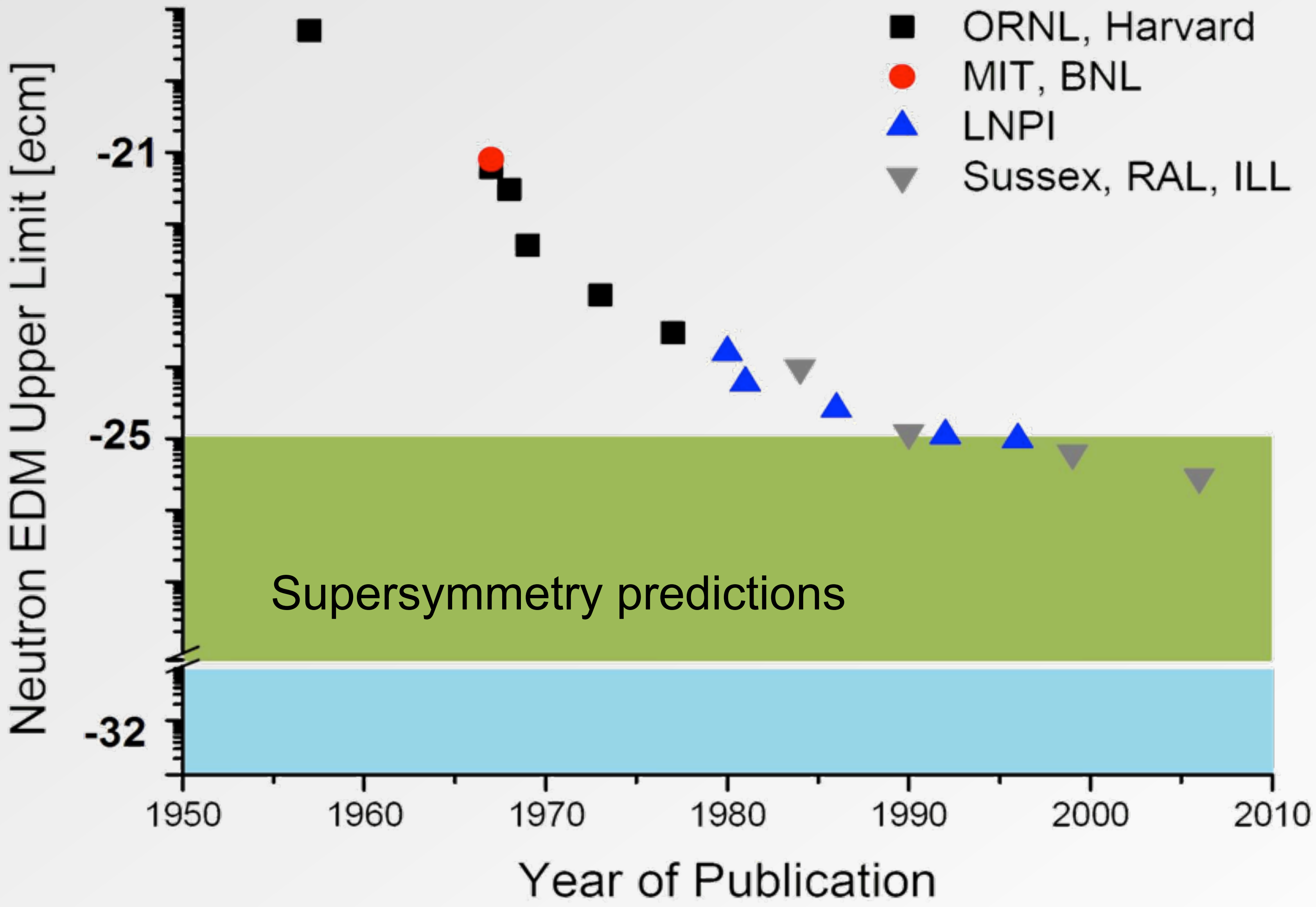
- Size of θ is **unknown**

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)**

Experiments on hadronic EDMs

- New neutron EDM experiments at ILL, SNS, PSI, TRIUMF

Baker *et al PRL* ’06 (ILL)

current $$d_n = \left(0.2 \pm 1.5(stat) \pm 0.7(sys)\right) \cdot 10^{-26}\ e\ cm$$

proposed → $$\sim 10^{-28}\ e\ cm$$

Talks on Wednesday and Friday!

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proposed → $$\sim 10^{-28}\ e\ cm$$

Talks on Wednesday and Friday!

- Proton EDM inferred from diamagnetic atoms

Griffith *et al PRL* ’09 (UW)

current $$d(^{199}Hg) \le 3.1\cdot 10^{-29}\ e\ cm \quad (95\%\ \ C.L.)$$

↘

Dmitriev + Sen’kov PRL ’03

$$d_p \le 7.9\cdot 10^{-25}\ e\ cm$$

Ongoing experiments on Ra, Rn, Xe….

Experiments on hadronic EDMs

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

Farley *et al PRL* ’04

Anomalous magnetic moment

Electric dipole moment

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

Bennett *et al* (BNL g-2) PRL ‘09

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

Experiments on hadronic EDMs

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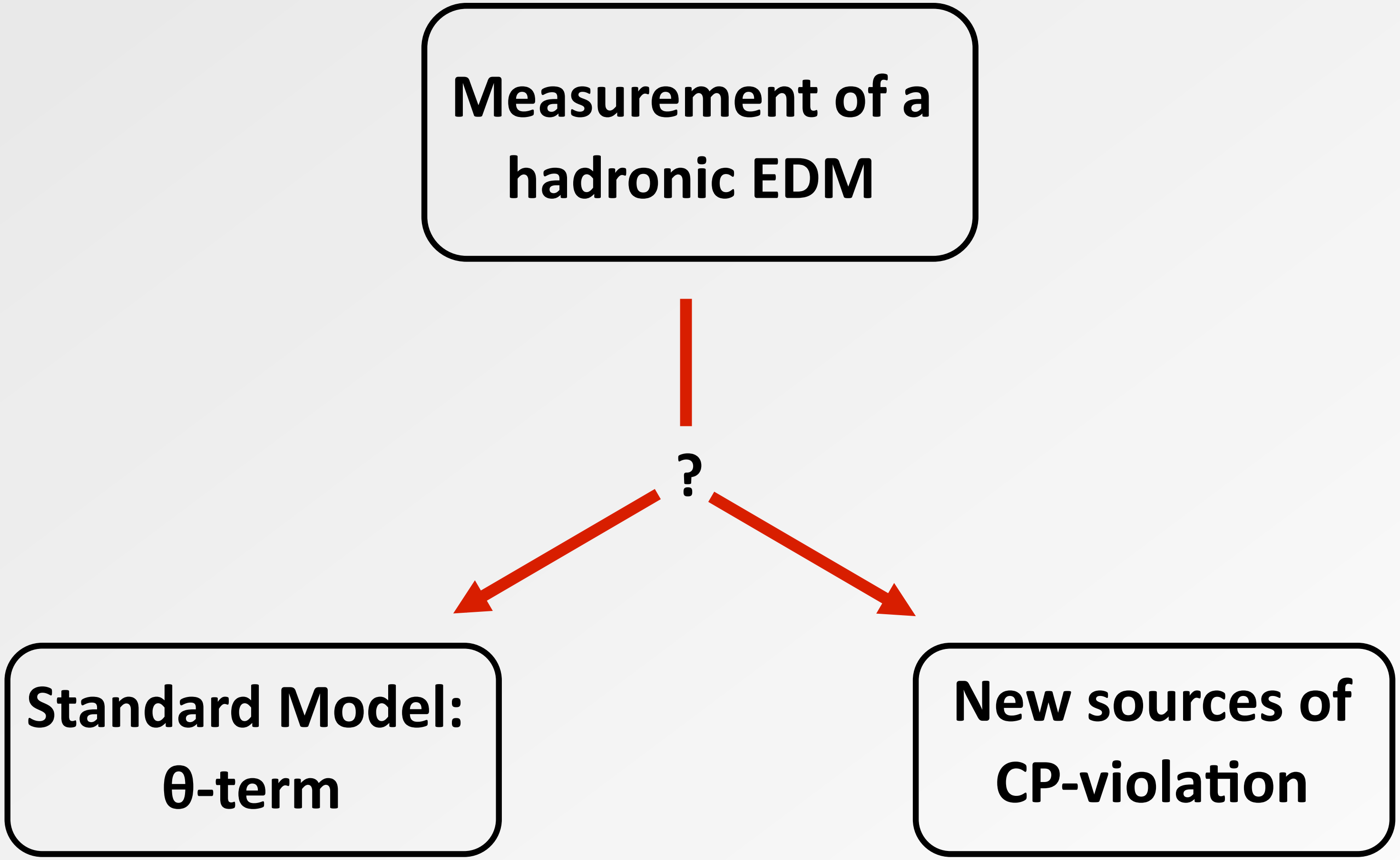
- Limit on muon EDM $d_\mu \leq 1.8 \cdot 10^{-19}\ e\ cm \quad (95\%\ \ C.L.)$

Talk on Friday by Joerg Pretz

- **Proposals to measure EDMs of proton and deuteron at level** $\sim 10^{-29}\ e\ cm$
- Other light nuclei? 3He or 3H?

Current Situation



Measurement of a hadronic EDM

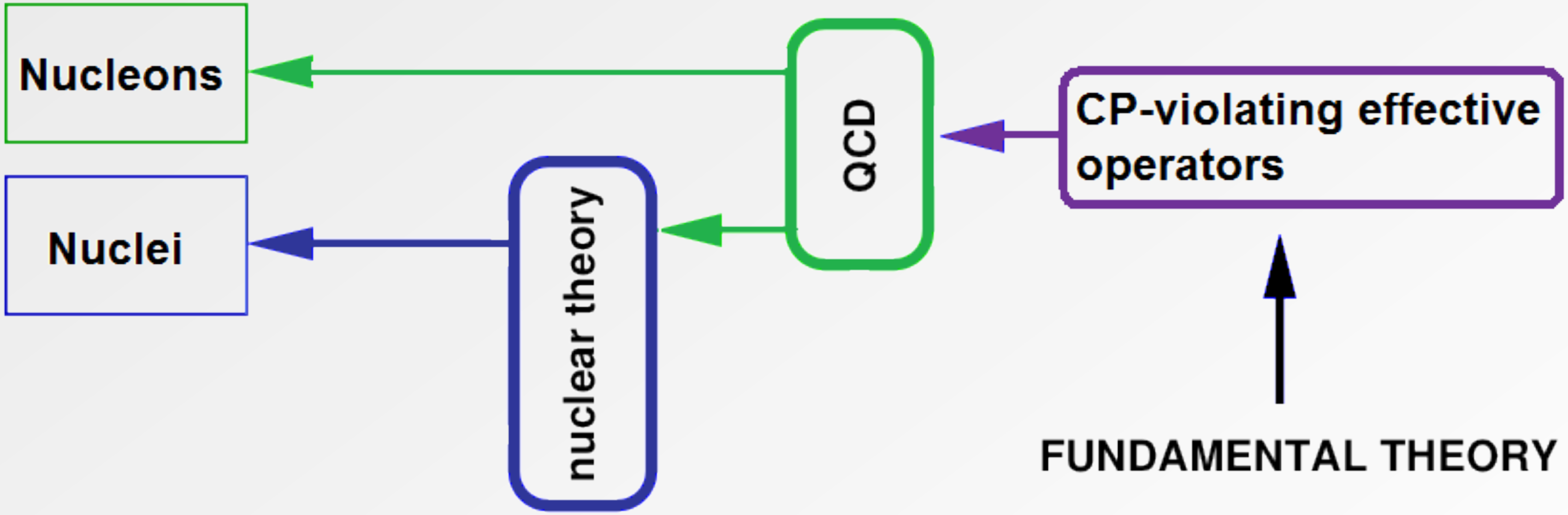
?

Standard Model: θ-term

New sources of CP-violation

Finding the **Source**

Can we **pinpoint** the microscopic source of P+T-violation from **hadronic EDM measurements**?



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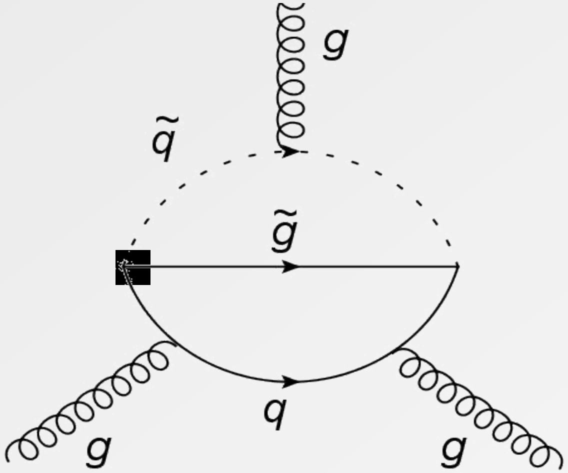
Standard Model as an EFT

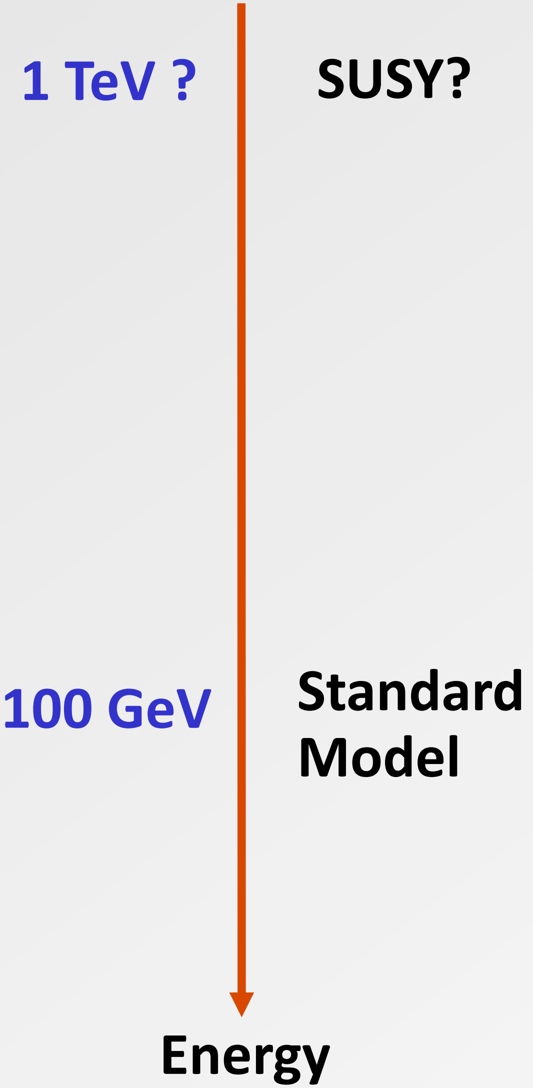
1 TeV ?

SUSY?



Energy

Standard Model as an EFT



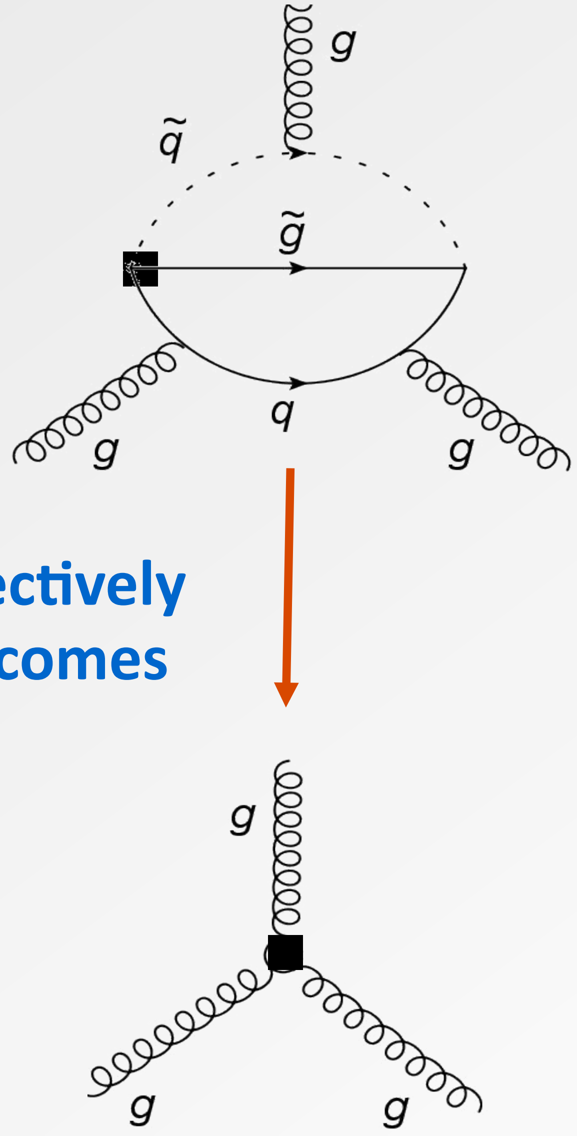
1 TeV ?

SUSY?

100 GeV

Standard Model

Energy



Effectively becomes

$$\propto \frac{1}{M_{\not{T}}^{2}}$$

Standard Model as an EFT

- Add to the SM **all possible T+P-odd** contact interactions

$$L = L_{SM} + \frac{1}{M_{\not{T}}} L_5 + \frac{1}{M_{\not{T}}^2} L_6 + \cdots$$

Standard Model as an EFT

- Add to the SM **all possible T+P-odd** contact interactions

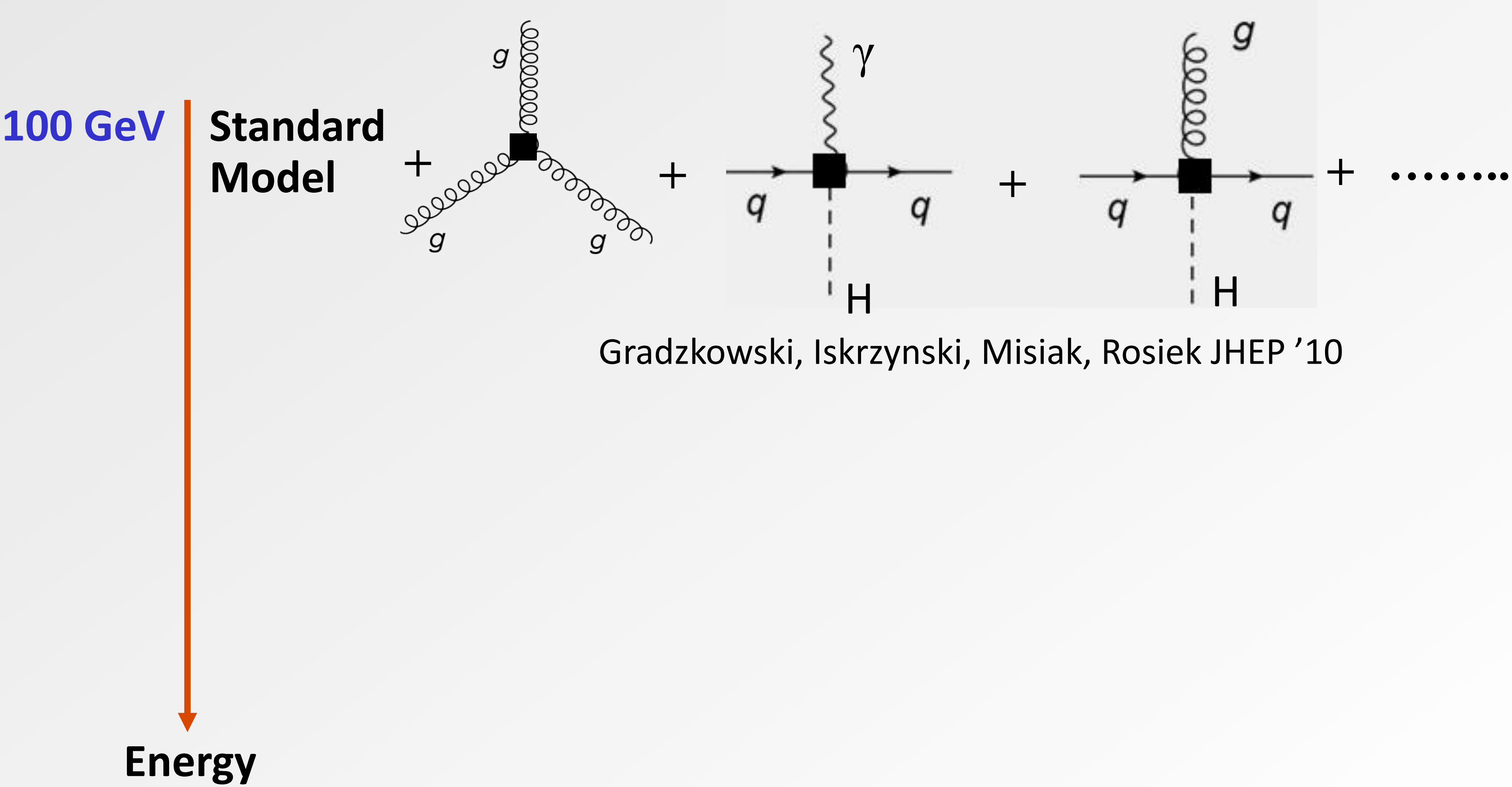
$$L = L_{SM} + \frac{1}{M_{\not T}} L_5 + \frac{1}{M_{\not T}^2} L_6 + \cdots$$

- **Symmetry requirements**: Lorentz + SM gauge symmetries

$$L = L_{SM} + \xcancel{\frac{1}{M_{\not T}} L_5} + \frac{1}{M_{\not T}^2} L_6 + \cdots$$

Standard Model as an EFT

- Add to the SM **all possible T+P-odd** contact interactions
- **They start at dimension six** $\propto 1/M_{\not T}^2$



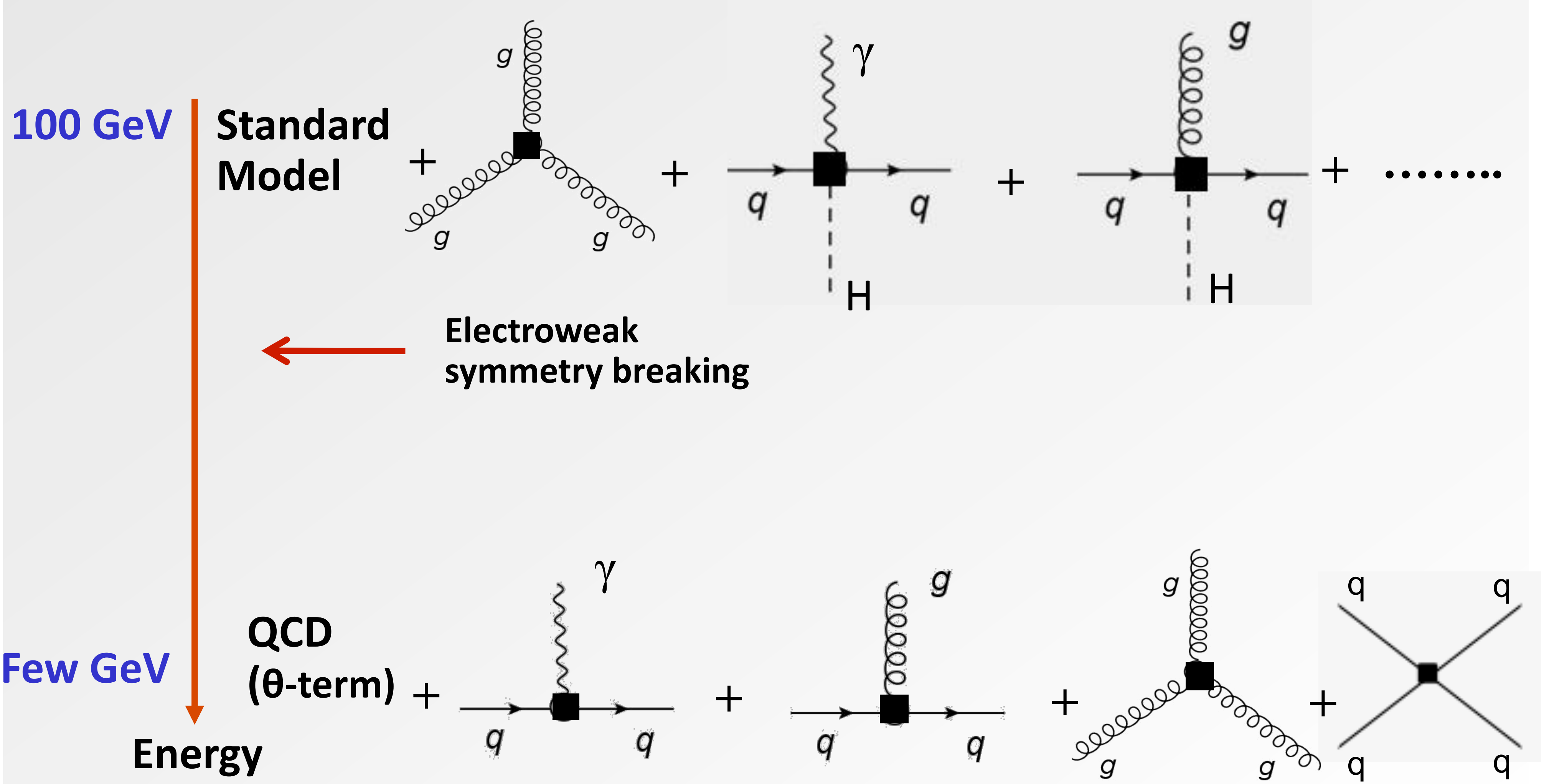
100 GeV **Standard Model** + + + + ……..

Energy

Gradzkowski, Iskrzynski, Misiak, Rosiek JHEP ’10

Standard Model as an EFT

- Add to the SM **all possible T+P-odd** contact interactions
- **They start at dimension six** $\propto 1/M_T^2$



100 GeV **Standard Model** + + + + ……..

Electroweak symmetry breaking

Few GeV **QCD (θ-term)** + + + +

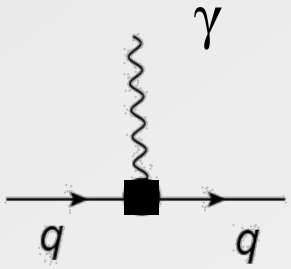
Energy

Effective P- and T-violation

Few GeV

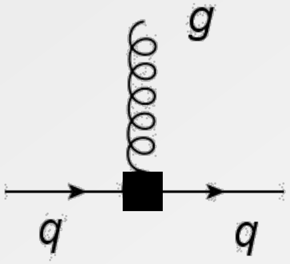
QCD (θ-term)

+



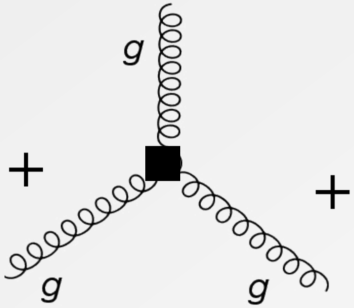
Quark EDM

+



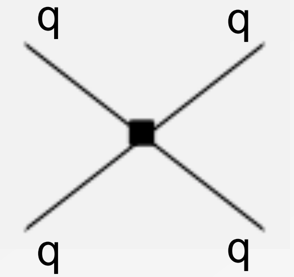
Quark chromo-EDM

+



Gluon chromo-EDM

+



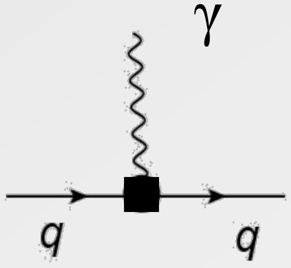
2*4quark operators

Energy

Effective P- and T-violation

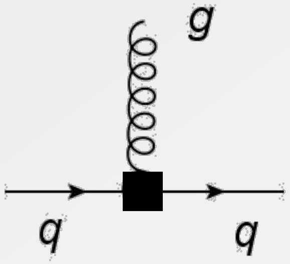
Few GeV

QCD (θ-term) +



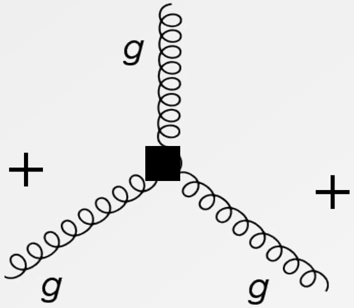
Quark EDM

+



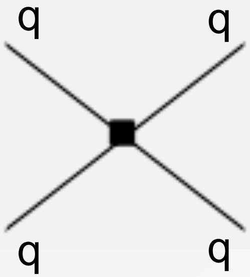
Quark chromo-EDM

+



Gluon chromo-EDM

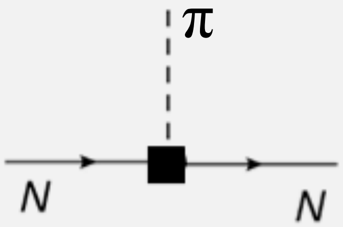
+



2*4quark operators

100 MeV

Chiral Perturbation Theory



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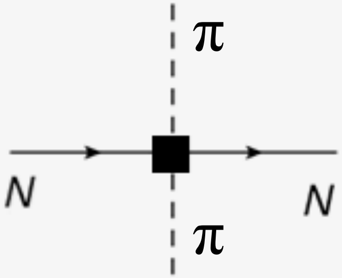
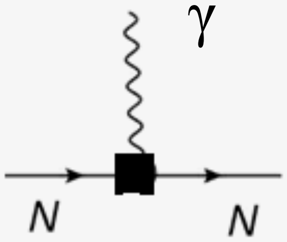
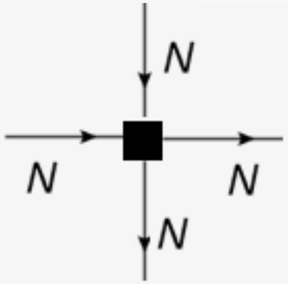


+ ....

Energy



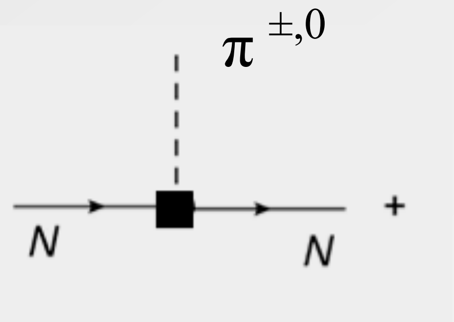


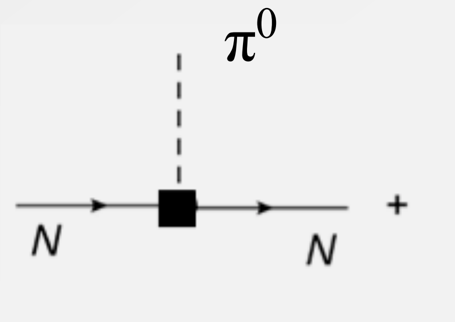
+ ....

Hierarchy among the sources

Each source transforms **differently** under chiral and isospin symmetry

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





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

- θ-term **breaks chiral** symmetry but **conserves isospin** symmetry
  - $\bar{g}_0 \gg \bar{g}_1$ because $\bar{g}_1$ is isospin-breaking

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$$|\bar{g}_1| = \frac{\delta m_q}{M_{QCD}} |\bar{g}_0| \approx 0.01\, |\bar{g}_0|$$

Here NDA, for QCD
sum rules: Pospelov
+Ritz ‘05

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Here NDA, for QCD sum rules: Pospelov +Ritz '05

- Quark chromo-EDM **breaks chiral and isospin** symmetry
  - $|\bar{g}_0| \approx |\bar{g}_1|$

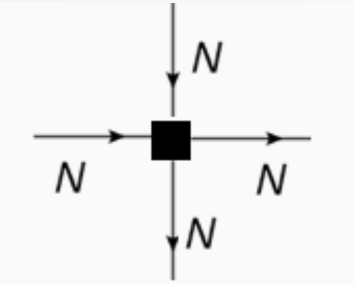
Hierarchy among the sources

Each source transforms **differently** under chiral and isospin symmetry

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

- Gluon chromo-EDM + 4Q **conserve chiral and isospin** symmetry
  - Both $\overline{g}_0$ and $\overline{g}_1$ break chiral symmetry.
  - Suppressed by m_q / M_{QCD} and $\delta m_q / M_{QCD}$
  - Chiral symmetric nucleon-nucleon interactions become important

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



Hierarchy among the sources

Each source transforms **differently** under chiral and isospin symmetry

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

❖ Gluon chromo-EDM + 4Q **conserve chiral and isospin** symmetry

- Both $\bar{g}_0$ and $\bar{g}_1$ break chiral symmetry.
- Suppressed by m_q / M_{QCD} and $\delta m_q / M_{QCD}$

❖ For quark EDM $N\pi$ and NN -interactions are suppressed by

$$\alpha_{em} /(4\pi)$$

Hierarchy among the sources

Each source transforms **differently** under chiral symmetry

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

	Theta term	**Quark CEDM**	**Quark EDM**	**Gluon CEDM +4Q**
$\left\lvert \frac{\bar{g}_1}{\bar{g}_0} \right\rvert$	$\left(\frac{m_\pi}{M_{QCD}}\right)^2$	1	1	1

Mereghetti, Hockings, van Kolck, *Ann. of. Phys. (2010)*, JdV, Mereghetti, Hockings, van Kolck, *In prep.*

Hierarchy among the sources

Each source transforms **differently** under chiral symmetry

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

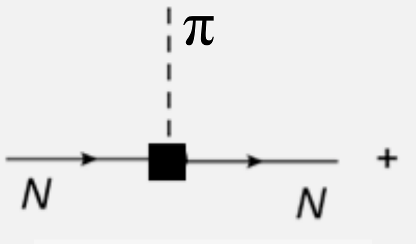
	Theta term	**Quark CEDM**	**Quark EDM**	**Gluon CEDM +4Q**
$\left\|\frac{\bar{g}_1}{\bar{g}_0}\right\|$	$\left(\frac{m_\pi}{M_{QCD}}\right)^2$	1	1	1
$\left\|\frac{\bar{g}_1}{\bar{d}_0}\right\| / M_{QCD}^2$	$\left(\frac{m_\pi}{M_{QCD}}\right)^2$	1	$\left(\frac{\alpha_{em}}{4\pi}\right)$	$\left(\frac{m_\pi}{M_{QCD}}\right)^2$

Mereghetti, Hockings, van Kolck, *Ann. of. Phys. (2010)*, JdV, Mereghetti, Hockings, van Kolck, *In prep.*

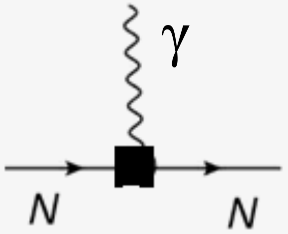
Six important interactions

- EDMs of light nuclei at LO depend on **six** low-energy constant (LECs)

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

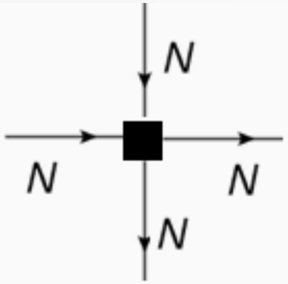


$$+\ \bar{d}_0\bar{N}(\vec{\sigma}\cdot\vec{E})N+\ \bar{d}_1\bar{N}(\vec{\sigma}\cdot\vec{E})\tau^3N$$



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

$$+\ \cdots$$



- Which of the six are important depends on the **PT-odd source and the nucleus under consideration!**

JdV, Higa, Liu, Mereghetti, Stetcu, Timmermans, van Kolck, PRC '11

Six important interactions

- EDMs of light nuclei at LO depend on **six** low-energy constant (LECs)

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

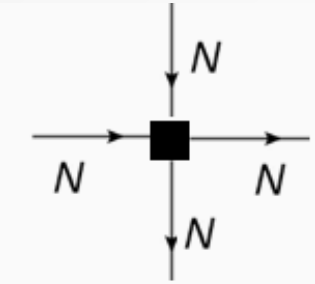
$$+\frac{\bar{g}_2}{F_\pi}\bar{N}\pi_3\tau_3 N$$

Higher order for all sources

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

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

$$+\cdots$$



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JdV, Higa, Liu, Mereghetti, Stetcu, Timmermans, van Kolck, PRC ‘11

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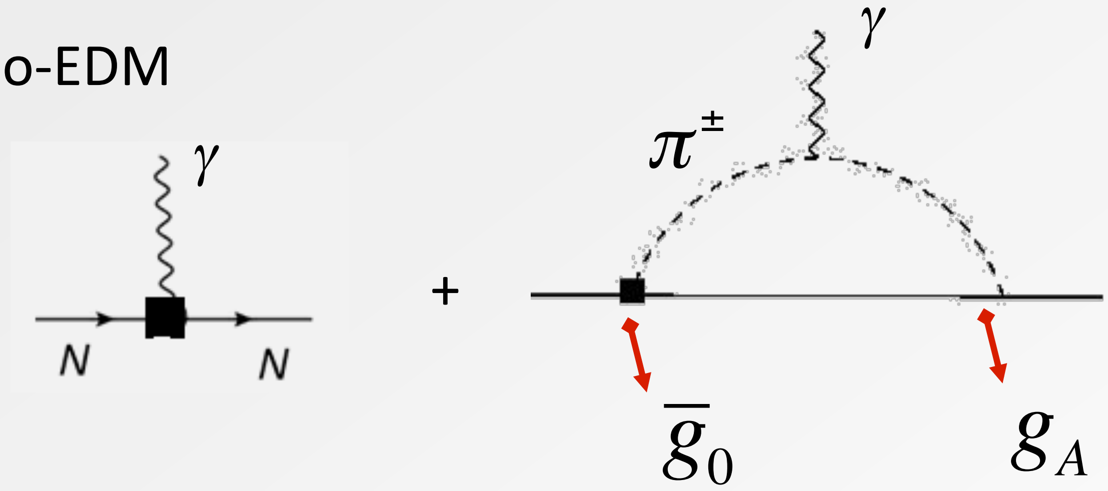
The Nucleon Electric Dipole Moment

- Calculated for each source from the PT-odd chiral Lagrangian
- θ-term + quark chromo-EDM

Nucleon EDM

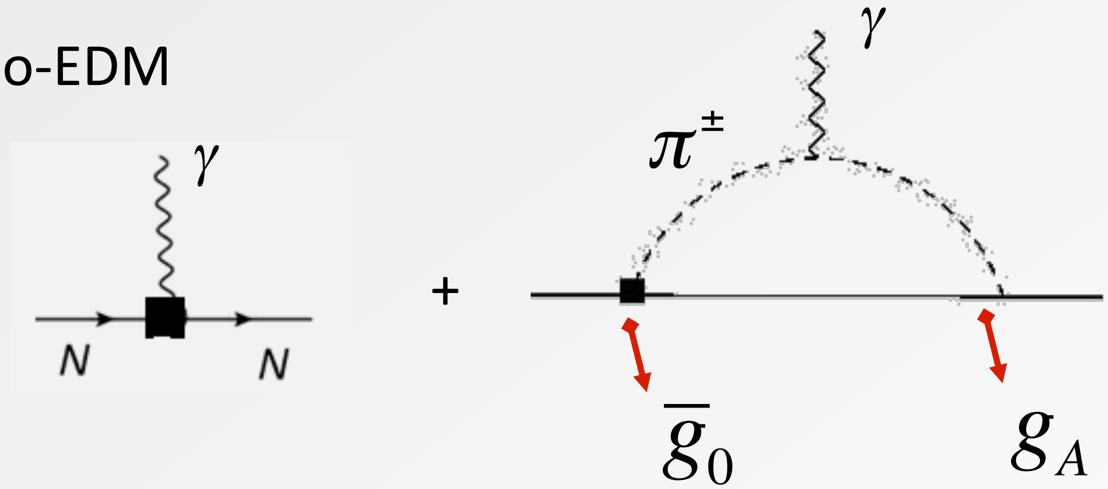


The Nucleon Electric Dipole Moment

- Calculated for each source from the PT-odd chiral Lagrangian

- θ-term + quark chromo-EDM

Nucleon EDM



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

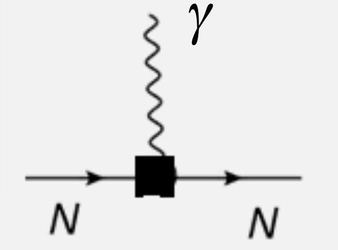
$$d_p = \bar{d}_0 + \bar{d}_1 - \frac{e g_A}{(2\pi F_\pi)^2} \ln\left(\frac{m_\pi^2}{m_n^2}\right) \bar{g}_0$$

Crewther et al., PLB (1979)
Pich, Rafael, NPB (1991)
Hockings, van Kolck, PLB(2005)

The Nucleon Electric Dipole Moment

- Calculated for each source from the PT-odd chiral Lagrangian
- quark EDM + gluon chromo-EDM + 4Q (loops are suppressed)

Nucleon EDM



$$d_n = \bar{d}_0 - \bar{d}_1$$

$$d_p = \bar{d}_0 + \bar{d}_1$$

The Nucleon Electric Dipole Moment

	Theta term	Quark CEDM	Quark EDM	Gluon CEDM + 4Q
$M_n d_n / e$	$\theta \left(\frac{m_\pi}{M_{QCD}} \right)^2$	$\tilde{\delta} \left(\frac{m_\pi}{M_{\not T}} \right)^2$	$\delta \left(\frac{m_\pi}{M_{\not T}} \right)^2$	$w \left(\frac{M_{QCD}}{M_{\not T}} \right)^2$
Proton EDM/ Neutron EDM	O(1)	O(1)	O(1)	O(1)

- Measurement of neutron or proton EDM can be fitted by **any source**
- For each source proton EDM is **of same order** as neutron EDM

JdV, Mereghetti, Timmermans, van Kolck, *PLB. (2011)*

The Nucleon Electric Dipole Moment

	Theta term	Quark CEDM	Quark EDM	Gluon CEDM + 4Q
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- Current limit: $d_n < 2 \cdot 10^{-13} e\, fm$ Baker et al, PRL (2006)

$$\theta < 10^{-10}, \qquad \tilde{\delta} / M_{\not T}^2 < (10^5\ GeV)^{-2}$$

JdV, Mereghetti, Timmermans, van Kolck, *PLB. (2011)*

The Nucleon Electric Dipole Moment

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$$\theta < 10^{-10}, \qquad \tilde{\delta} / M_{\not{T}}^2 < (10^5\ GeV)^{-2}$$

Pospelov, Ritz (2005)

- Certain SUSY-models $\tilde{\delta} \approx \sin \phi$, if natural $\sin \phi \sim 1$

$$\xrightarrow{\qquad\qquad} \quad M_{\not{T}} > 100\ TeV$$

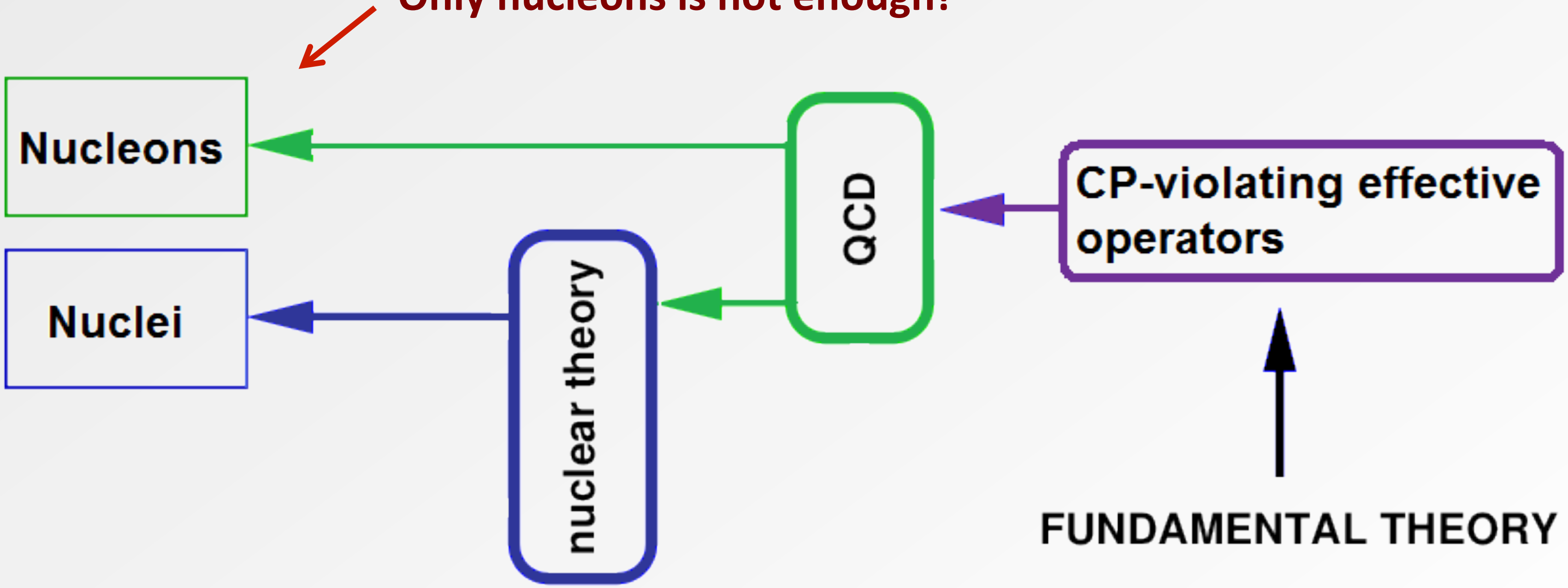
JdV, Mereghetti, Timmermans, van Kolck, *PLB. (2011)*

EDMs of light nuclei

- Measurement of neutron and proton EDM not enough for disentangling the source → **Need more observables**

- Light nuclei can be described **within same framework** as the nucleon using *chiral effective field theory*

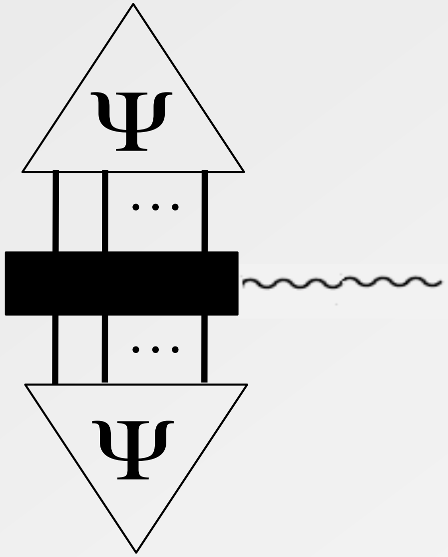
Only nucleons is not enough!



EDM of a general light nucleus

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

$$d_A = < \Psi_A \parallel \vec{J}_{\cancel{PT}} \parallel \Psi_A >$$



EDM of a general light nucleus

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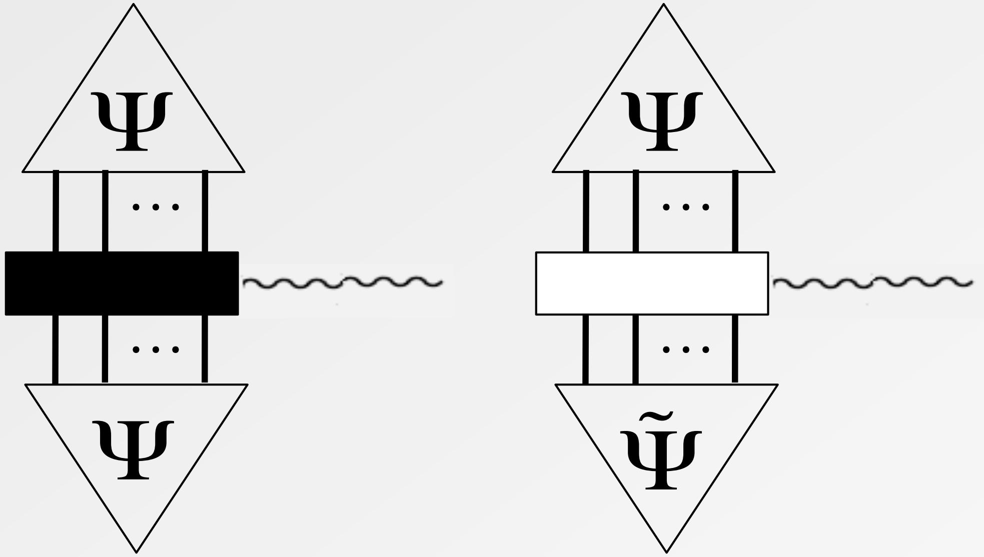
PT-odd admixtured wave-function

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



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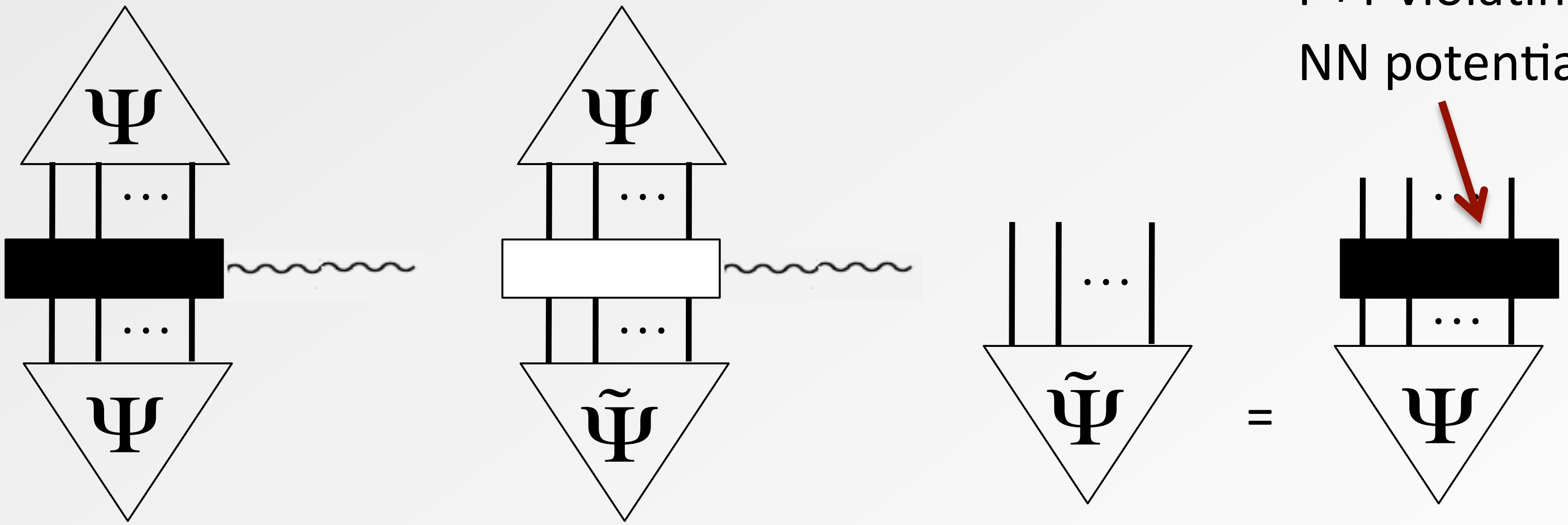

P+T violating
NN potential

EDM of a general light nucleus

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

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

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

Phenomenological Potentials

Argonne 18, Nijmegen II, Reid93

EDM of a general light nucleus

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

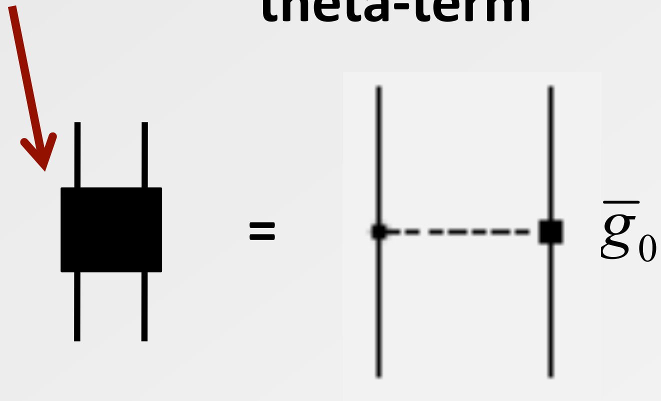
Different for every source!

EDM of a general light nucleus

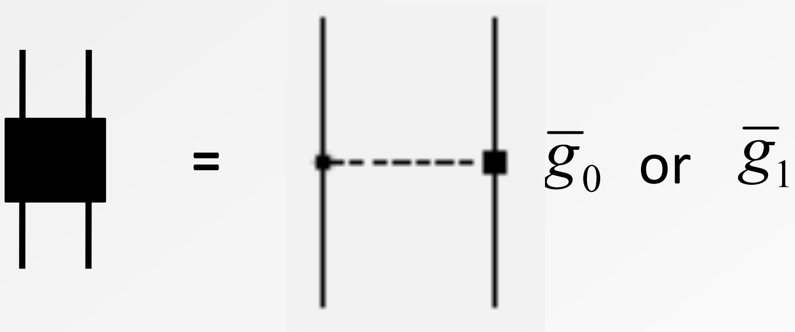
- The most important ingredients are the **PT-odd Potential + Currents**
- They are derived from the PT-odd Lagrangian **(unique for each source)**

~~PT~~-potential

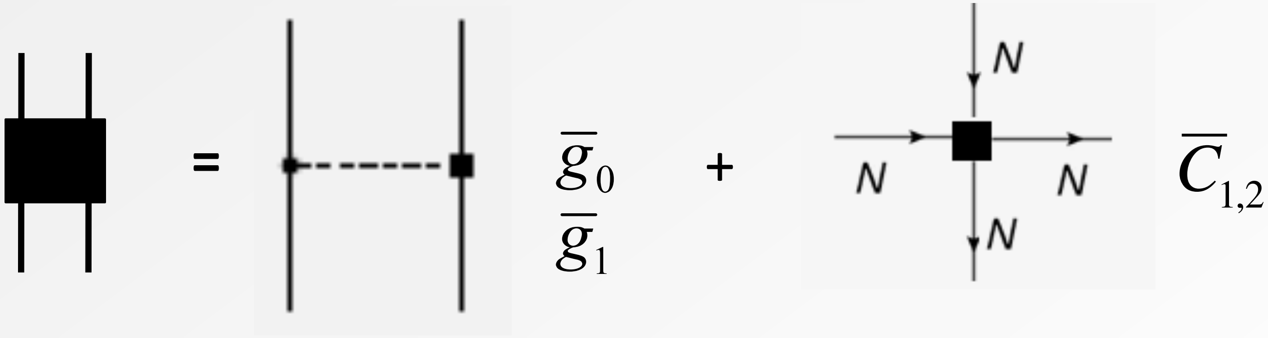
theta-term



quark colour-EDM



gluon color-EDM + 4Q



Maekawa, Mereghetti, JdV, van Kolck, NPA (2011)

EDM of a general light nucleus

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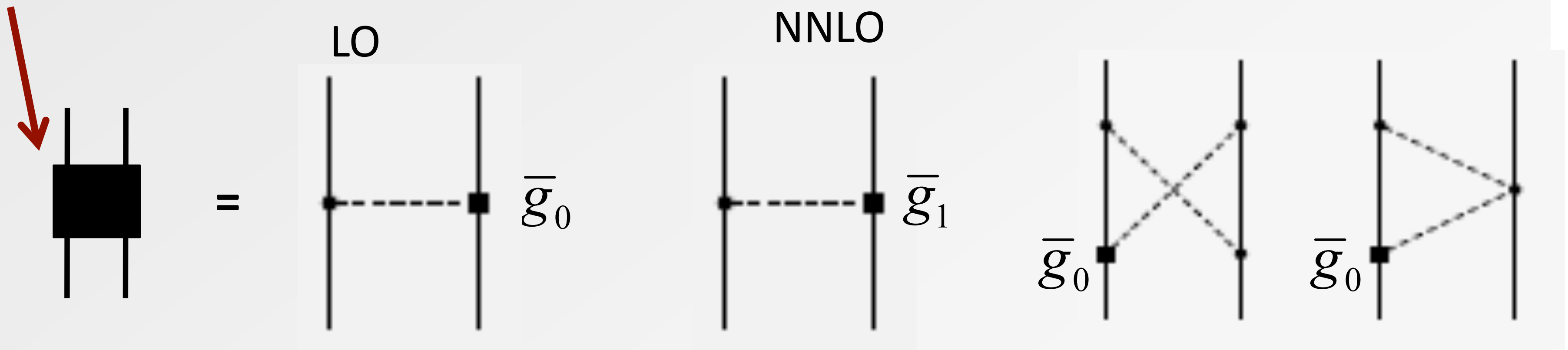
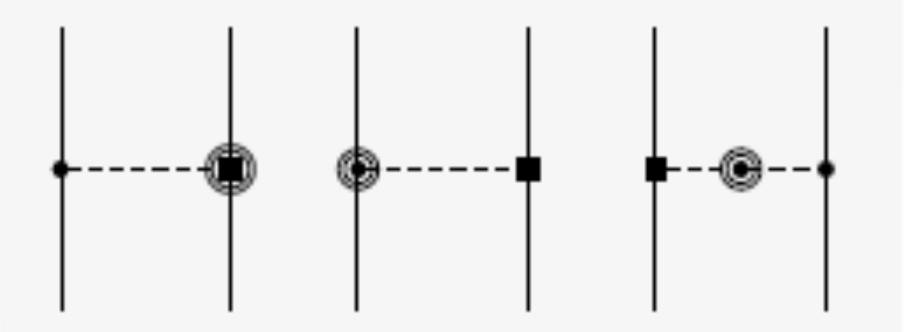
~~PT~~-potential **theta-term**



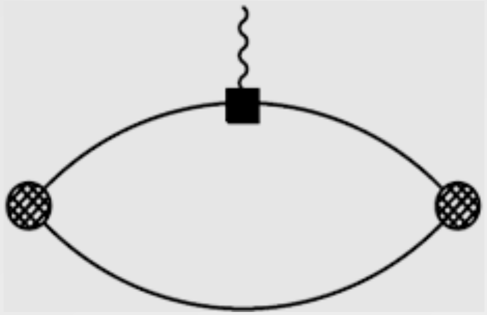
Isospin breaking and relativistic corrections



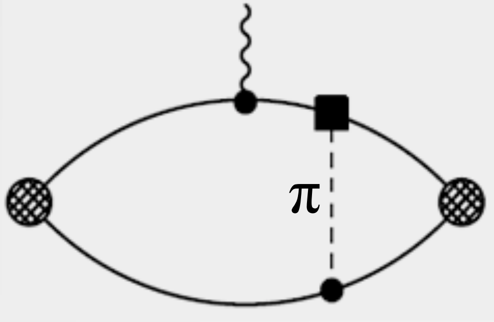
Maekawa, Mereghetti, JdV, van Kolck, NPA (2011)

The deuteron EDM

- Deuteron EDM at LO **in principle** 3 contributions

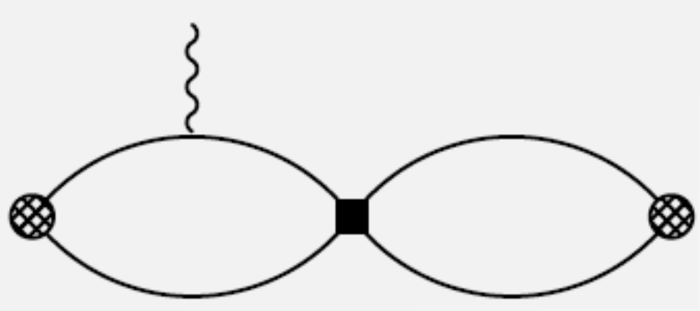


One-body: $d_D = 2d_0 = d_n + d_p$



T-violating pion-exchange

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



T-violating NN interactions

$$\bar{C}_1 (\overline{N}\vec{\sigma} N) \cdot \vec{\partial}(\overline{N}N)$$

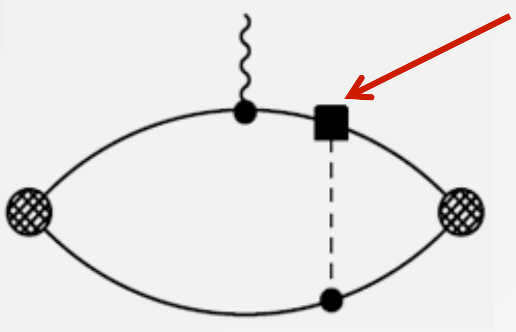
$$+\bar{C}_2 (\overline{N}\vec{\sigma} \tau N) \cdot \vec{\partial}(\overline{N}\tau N)$$

The deuteron EDM

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

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

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



Must be Isovector!

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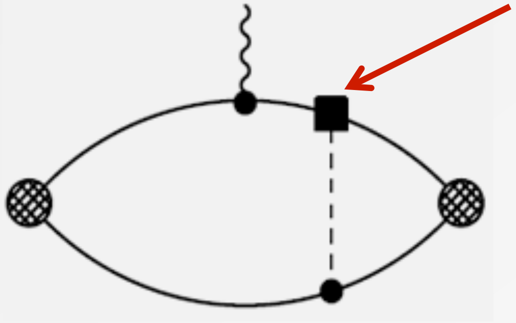
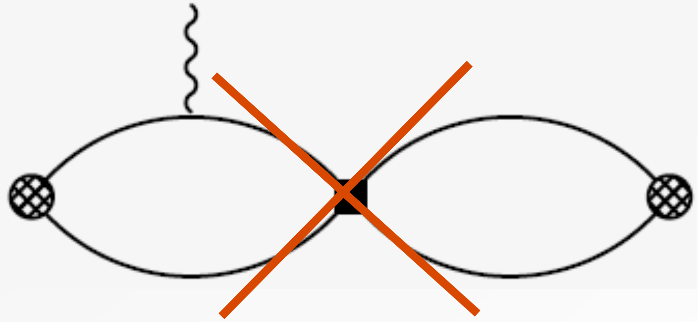
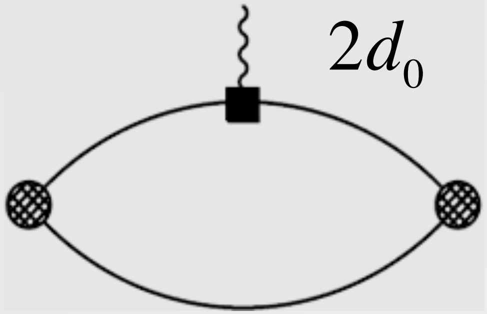


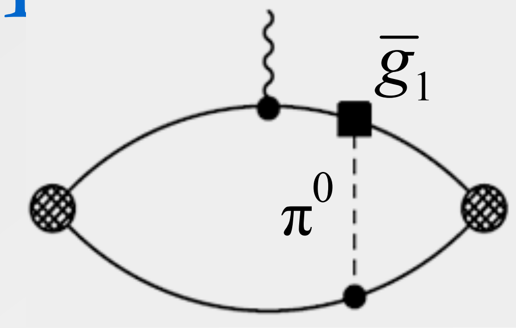
Must be Isovector!

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



The deuteron EDM



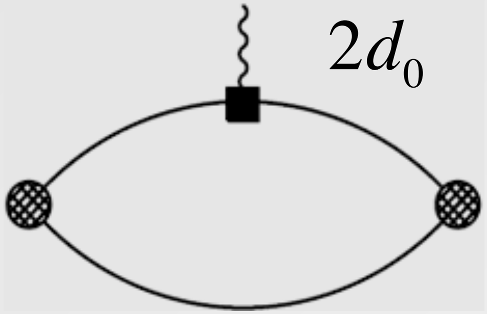


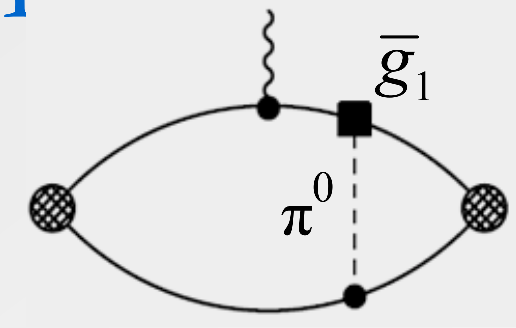
- We recycle the work of Liu+Timmermans PRC ‘04
- Obtain deuteron wave function from phenomenological potentials (Argonne 18, Nijmegen II, Reid93)

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

- Results differ within 5% for different potentials   Afnan, Gibson PRC ‘10

The deuteron EDM





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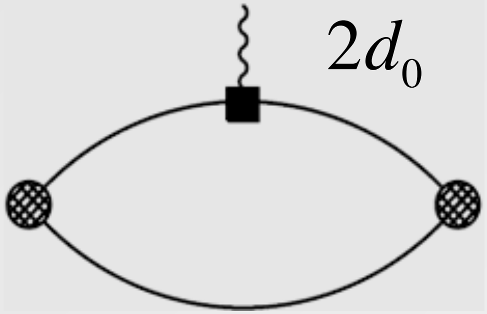
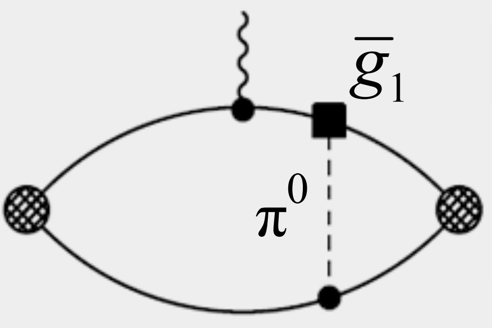
Afnan, Gibson PRC ‘10

$$d_D = d_n + d_p - 0.19\,\frac{\bar{g}_1}{F_\pi}\,e\ fm\ + 2\cdot 10^{-4}\,\frac{\bar{g}_0}{F_\pi}\,e\ fm$$

Khriplovich+Korkin NPA ’00
Liu+Timmermans PRC ’04
JdV et al PRC ‘11

The deuteron EDM

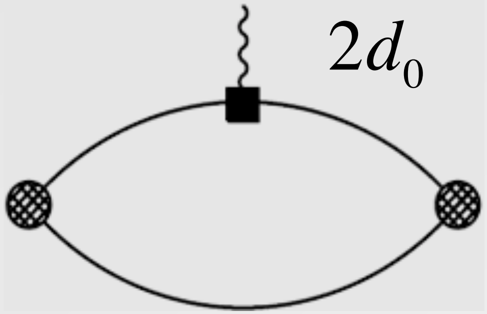


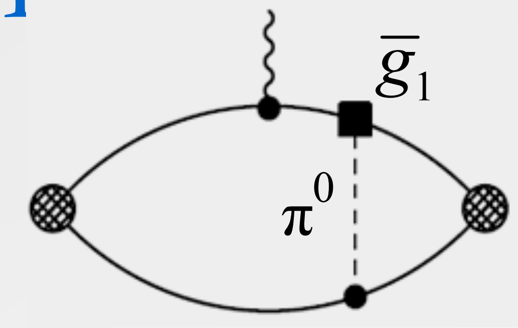


- Which effect **dominates** depends on the ratio of the LECs

$$R \propto \left| \frac{\bar{g}_1}{d_0} \right|$$

The deuteron EDM





- Which effect **dominates** depends on the ratio of the LECs

$$R \propto \left|\frac{\bar{g}_1}{d_0}\right|$$

- **This depends on the fundamental source!**

	Theta term	**Quark CEDM**	**Quark EDM**	**Gluon CEDM + 4Q**
$\left\|\frac{\bar{g}_1}{\bar{d}_0}\right\| / M_{QCD}^2$	$\left(\frac{m_\pi}{M_{QCD}}\right)^2$	1	$\left(\frac{\alpha_{em}}{4\pi}\right)$	$\left(\frac{m_\pi}{M_{QCD}}\right)^2$

The deuteron EDM

	Theta term	**Quark CEDM**	**Quark EDM**	**Gluon CEDM + 4Q**
Deuteron EDM/ (neutron+proton EDM)	1	$\left(\frac{M_{QCD}^2}{m_\pi^2}\right)$	1	1

- For 3 out of 4 sources d_D is approximately $d_n + d_p$
- For qCEDM $d_D = -0.19 \frac{\bar{g}_1}{F_\pi} e \ fm$

JdV, Mereghetti, Timmermans, van Kolck, PRL ‘11

The deuteron EDM

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- For qCEDM $d_D = -0.19\,\frac{\bar{g}_1}{F_\pi}\,e\ fm\ \boxed{+\left(d_n + d_p\right)} \leftarrow$ **O(20%)**
- For qCEDM: d_D **significantly larger than** $d_n + d_p$

JdV, Mereghetti, Timmermans, van Kolck, PRL ‘11

The deuteron EDM

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- For qCEDM $d_D = -0.19 \frac{\bar{g}_1}{F_\pi} e\ fm$ $\boxed{+\left(d_n + d_p\right)}$ ← **O(20%)**
- For qCEDM: d_D **significantly larger than** $d_n + d_p$
- If $d_d = d_n + d_p$ more observables are needed to separate theta from quark EDM and gluon CEDM

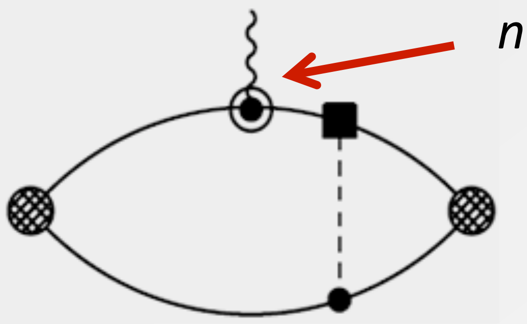
JdV, Mereghetti, Timmermans, van Kolck, PRL '11

The deuteron MQM

- 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

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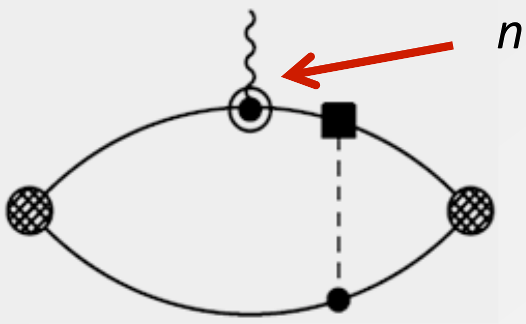

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Sensitive to **both** $\bar{g}_0$ and $\bar{g}_1$ exchange

Khriplovich+Korkin NPA '00

Liu+Timmermans PRC '04

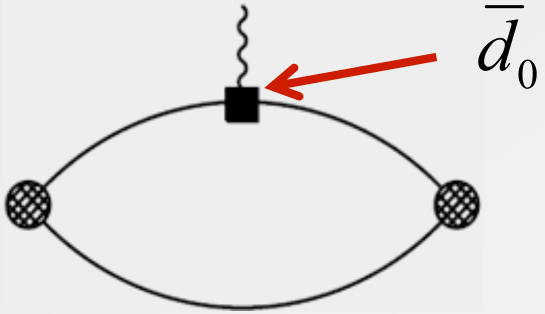
Liu et al PLB '12

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

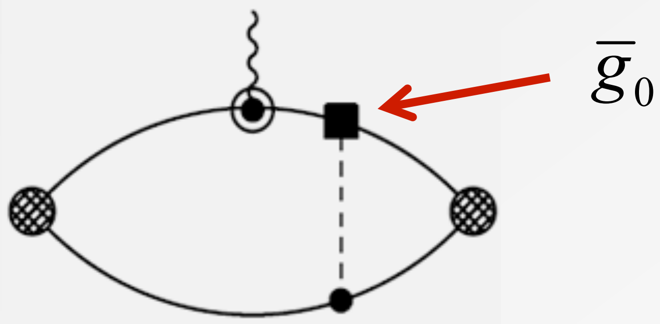
The deuteron MQM

For theta:

deuteron EDM



deuteron MQM



$$\overline{M}_d = -0.044\frac{\bar{g}_0}{F_\pi}(\mu_p+\mu_n)\,e\ fm^2 \cong 0.7\cdot 10^{-3}\,\bar{\theta}\ e\ fm^2$$

$$\frac{\overline{\mathrm{M}}_d}{d_d}m_d = 0.22(\mu_p+\mu_n)\left|\frac{\bar{g}_0}{F_\pi d_0}\right| e\ fm \ \propto 21(\mu_p+\mu_n)$$

Liu, JdV, Mereghetti, Timmermans, van Kolck PLB ‘12

The deuteron EDM and MQM

	Theta term	**Quark CEDM**	**Quark EDM**	**Gluon CEDM**
Deuteron EDM/ (neutron+proton EDM)	1	$\left(\frac{M_{QCD}^2}{m_\pi^2}\right)$	1	1
mD*Deuteron MQM/ (Deuteron EDM)	$\left(\frac{M_{QCD}^2}{m_\pi^2}\right)$	1	1	1

- **Only for the Standard Model is the MQM larger than the EDM**

- MQM experiment?

Liu, JdV, Mereghetti, Timmermans, van Kolck PLB '12

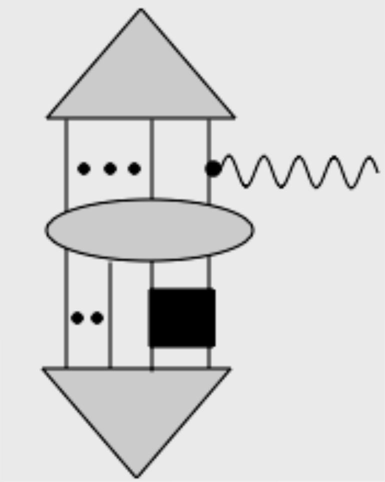
Helion (3He) and Triton (3H) EDMs

- We recycle the work of *Stetcu, Liu, Friar, Hayes, Navratil PLB (2008)*
- Obtain wave function in no-core shell model
- Use phenomenological PT-even potential (Argonne 18, CD-Bonn)

- Results differ less than 25% for different potentials (pion exchange)

Helion and Triton EDMs

theta



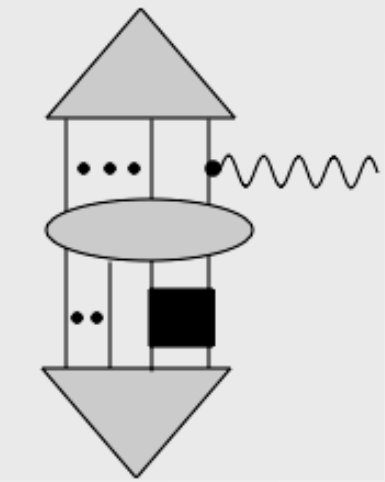
~~PT~~-potential

$$d_{^3He} = \left(-0.15 \frac{\bar{g}_0}{F_\pi} \right) e \ fm$$

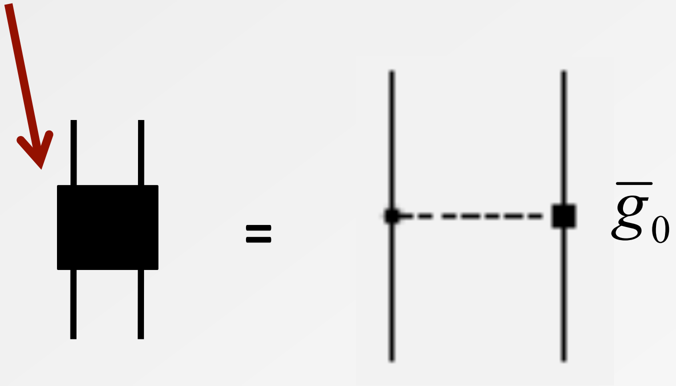
$$d_{^3H} = \left(0.15 \frac{\bar{g}_0}{F_\pi} \right) e \ fm$$

Helion and Triton EDMs

theta



~~PT~~-potential



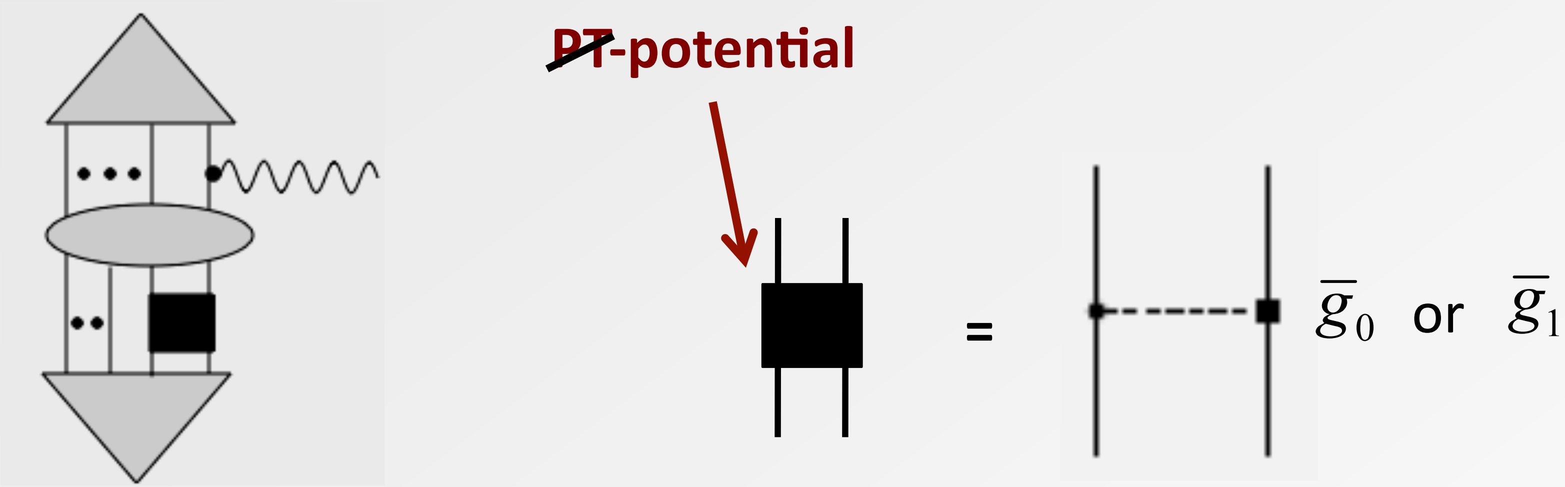
$$d_{3He} = \left(-0.15\frac{\bar{g}_0}{F_\pi}\right) e\ fm \quad + \left(0.88\ d_n - 0.05\ d_p\right)$$

$$d_{3H} = \left(0.15\frac{\bar{g}_0}{F_\pi}\right) e\ fm \quad + \left(0.90\ d_p - 0.05\ d_n\right)$$

O(30%)

Helion and Triton EDMs

quark chromo-EDM



$$d_{3He} = \left(-0.15 \frac{\bar{g}_0}{F_\pi} - 0.28 \frac{\bar{g}_1}{F_\pi} \right) e \ fm$$

$$d_{3H} = \left(0.15 \frac{\bar{g}_0}{F_\pi} - 0.29 \frac{\bar{g}_1}{F_\pi} \right) e \ fm$$

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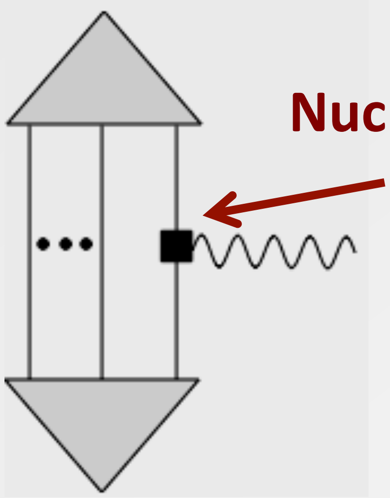


Nucleon EDM

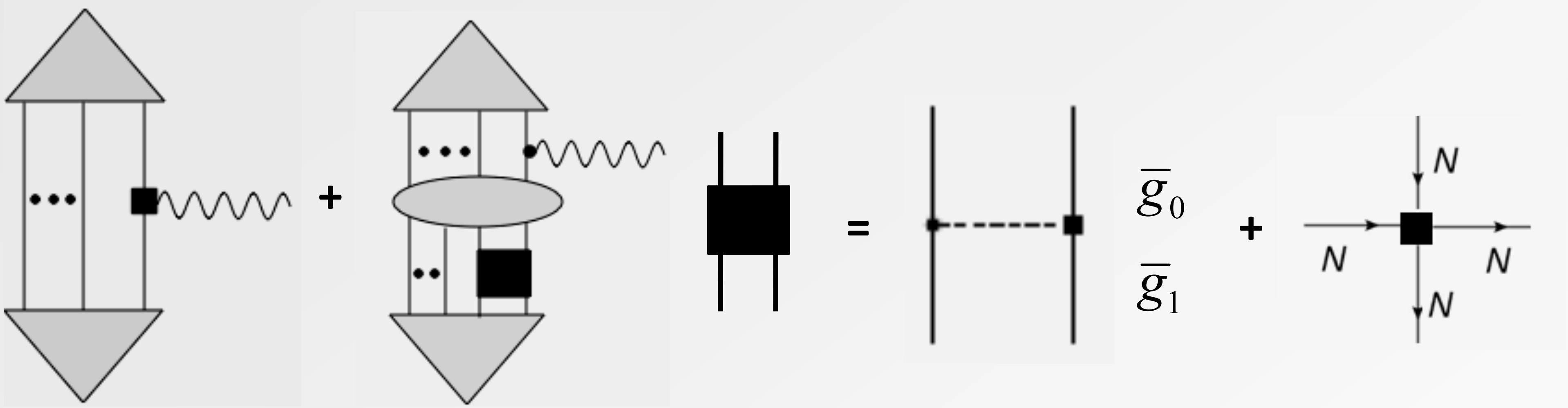
$$d_{3He} = 0.88\, d_n - 0.05\, d_p$$

$$d_{3H} = 0.90\, d_p - 0.05\, d_n$$

- In the case of quark EDM, $d_{3He} \approx d_n$ and $d_{3H} \approx d_p$
- For other light nuclei expect similar behaviour

Helion and Triton EDMs

gluon chromo-EDM + 4Q



$$d_{3He} = \left(0.88\ d_n - 0.05\ d_p\right) + \left[-0.15\frac{\bar{g}_0}{F_\pi} - 0.28\frac{\bar{g}_1}{F_\pi} - (0.01\ F_\pi^3\bar{C}_1 - 0.02\ F_\pi^3\bar{C}_2)\right] e\ fm$$

$$d_{3H} = \left(0.90\ d_p - 0.05\ d_n\right) + \left[0.15\frac{\bar{g}_0}{F_\pi} - 0.28\frac{\bar{g}_1}{F_\pi} + (0.01\ F_\pi^3\bar{C}_1 - 0.02\ F_\pi^3\bar{C}_2)\right] e\ fm$$

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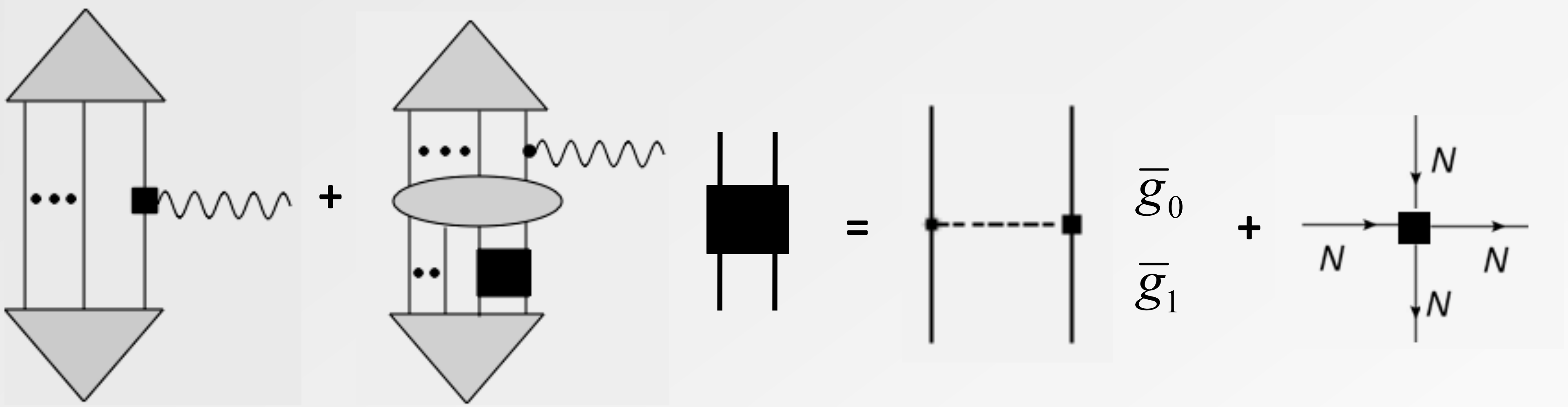

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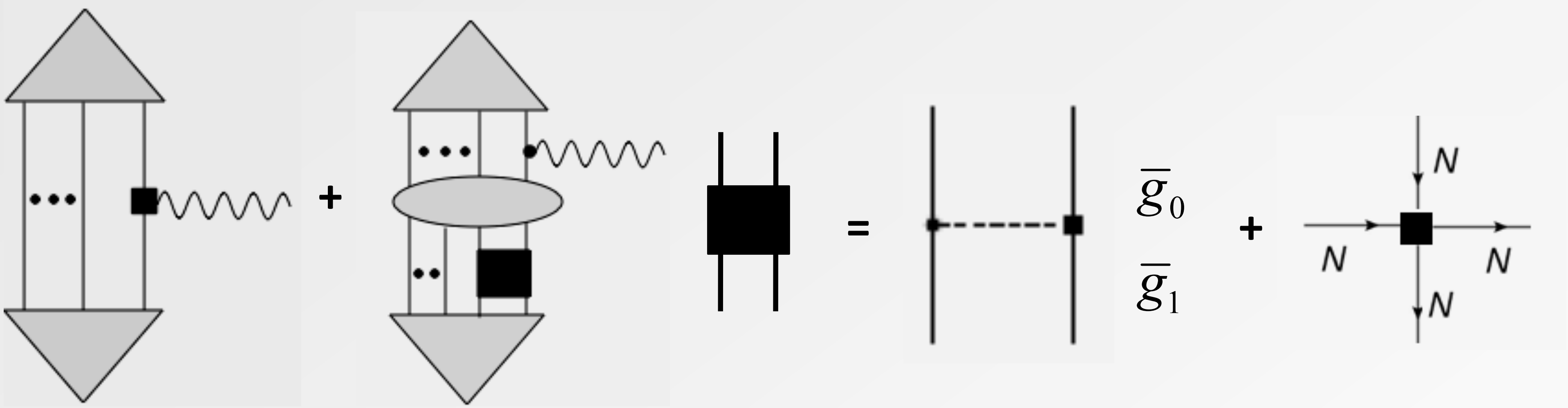
O(15%)

Helion and Triton EDMs

gluon chromo-EDM + 4Q



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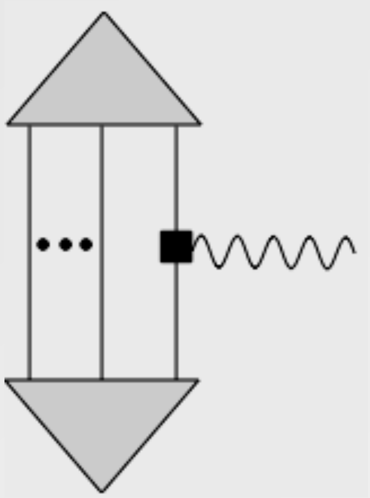
Unreliable, but small

Helion and Triton EDMs

gluon chromo-EDM + 4Q



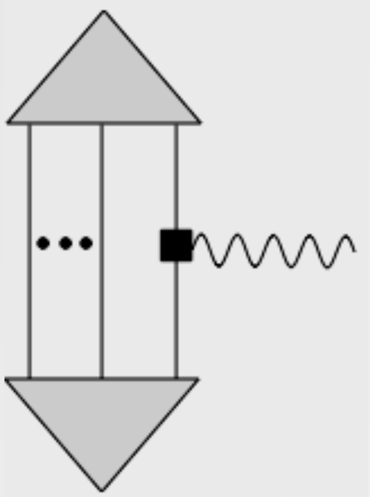
$$d_{3He} \approx \left(0.88\, d_n - 0.05\, d_p\right)$$

$$d_{3H} \approx \left(0.90\, d_p - 0.05\, d_n\right)$$

- Just as for quark EDM: the EDMs are dominated by the constituent nucleon EDMs
- **Hard to disentangle quark EDM from gluon CEDM + 4Q**

Helion and Triton EDMs

gluon chromo-EDM + 4Q



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We expect differences for heavier nuclei

Haxton, Henley, PRL ‘83

Separating the Sources

- We can now combine the predictions for different sources
- Assume **one source** is dominant

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→ Then we can rule out quark Chromo-EDM

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→ Point towards Standard Model (theta term)

JdV, Higa, Liu, Mereghetti, Stetcu, Timmermans, van Kolck, PRC '11

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Further tests

$$d_{3He} + d_{3H} = 0.84\left(d_n + d_p\right)$$

$$d_{3He} - d_{3H} = 0.94\left(d_n - d_p\right) - 0.30\frac{\bar{g}_0}{F_\pi} e\ fm$$

JdV, Higa, Liu, Mereghetti, Stetcu, Timmermans, van Kolck, PRC ‘11

Separating the Sources

- We can now combine the predictions for different sources
- Assume **one source** is dominant

- If **deuteron** EDM is much larger **neutron + proton** EDM

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JdV, Higa, Liu, Mereghetti, Stetcu, Timmermans, van Kolck, PRC ‘11

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$$d_{3He} + d_{3H} = -0.57 \, \frac{\bar{g}_1}{F_\pi} \, e \; fm \; \boxed{\approx 3 \, d_d}$$

JdV, Higa, Liu, Mereghetti, Stetcu, Timmermans, van Kolck, PRC ‘11

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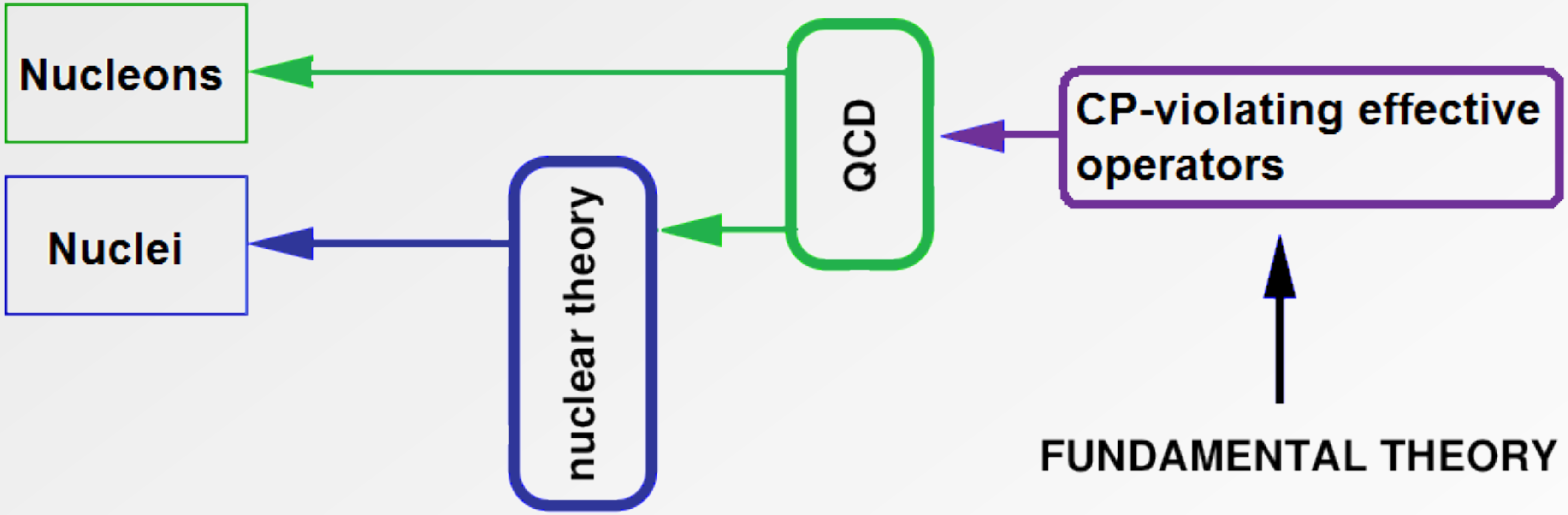
$$d_{{}^3He} - d_{{}^3H} = -0.3\,\frac{\bar{g}_0}{F_\pi}\,e\ fm$$

Predict deuteron MQM or EDMs of other nuclei

JdV, Higa, Liu, Mereghetti, Stetcu, Timmermans, van Kolck, PRC '11

So!

Measurements on nucleon and light nuclear EDMs can shed light on the mechanism of T-violation



What needs to be done

- Can heavier nuclei be described by the same six LECs? Hg, Ra?

  Can short-range NN interactions be included?

- Calculations of LECs in Lattice QCD

Berruto et al (RBC) PRD '05

Shintani *et al* (CP-PACS) PRD '05

- And, of course, measurements….

Conclusions/Summary

- A single hadronic EDM measurement can be fitted by **theta (Standard Model)** or by **new physics**

- At low energies the effects of new physics can be captured by **effective interactions of dimension-six**

- Chiral symmetry **dictates form** of effective hadronic interactions

- Measuring the EDMs of the nucleons + deuteron + helion and/or triton would allow us to (partially) **separate the sources**

- Deuteron EDM >> neutron + proton EDM **-> new physics (qCEDM)**

- Large deuteron MQM **-> Standard Model (theta-term)**

university of groningen

FOM

KVI