Electric dipole moments of light nuclei from dimension-six operators

Jordy de Vries, Institute for Advances Simulation, Institut für Kernphysik, and Jülich center for hadron physics

In collaboration with: E. Mereghetti (LBL), U. van Kolck (University of Arizona),
R. Timmermans (KVI), W. Dekens (KVI),
C.-P. Liu(NDHU ,Taiwan)

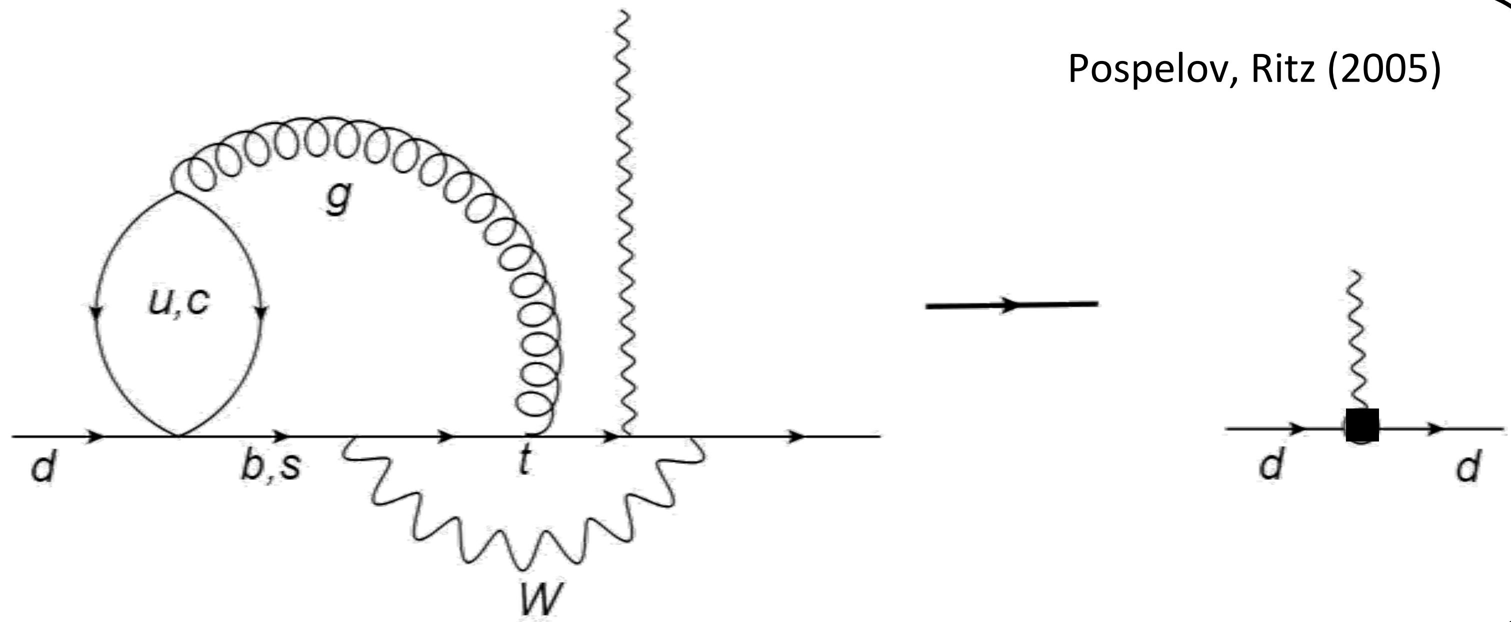
Outline of this talk

- **Part I: Different sources of Time-Reversal Violation**
- Part II: Chiral techniques
- Part III: Observables
  - IIIa: Nucleon EDM
  - IIIb: Light-Nuclear EDMs

EDM's in the Standard Model

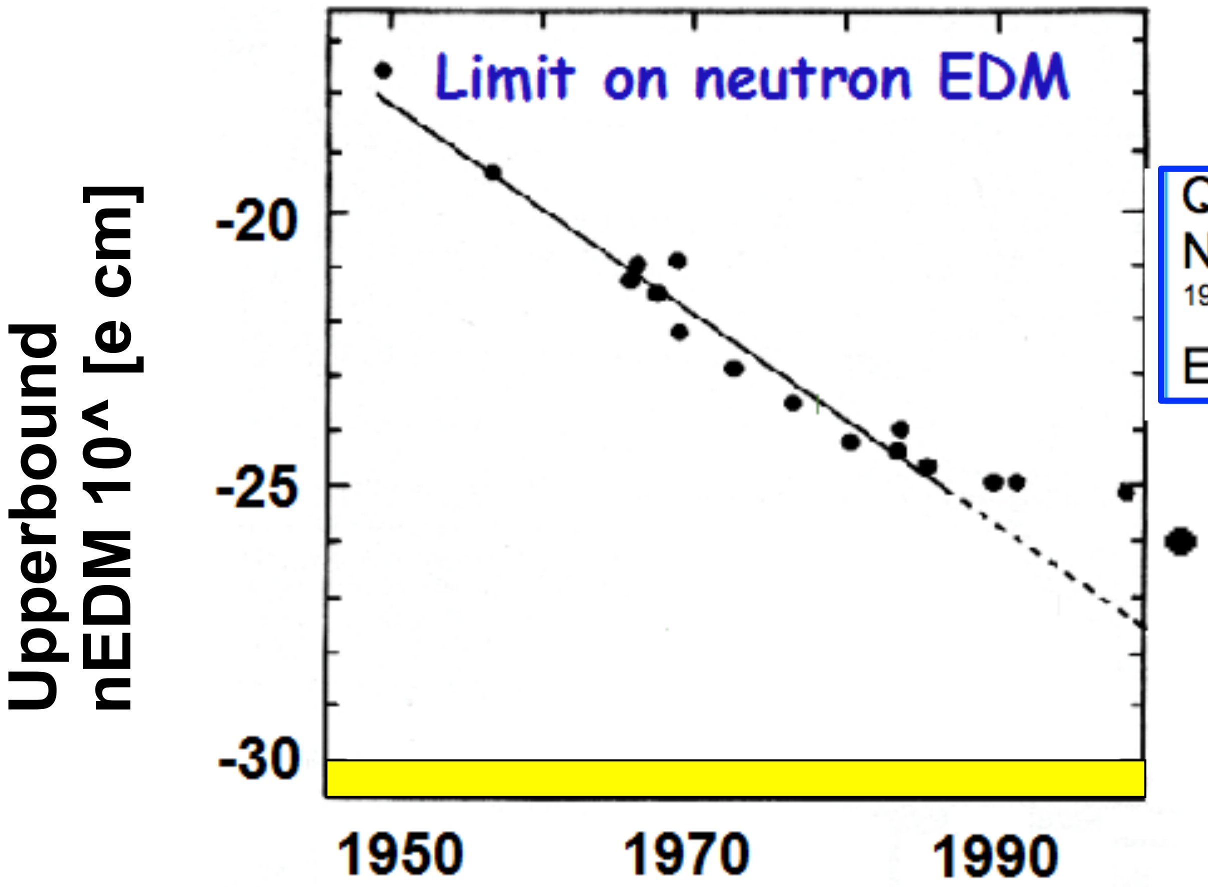
- Electroweak CP-violation
- Nobel prize for predicting **third** generation

Pospelov, Ritz (2005)



Highly Suppressed

Electroweak CP-violation



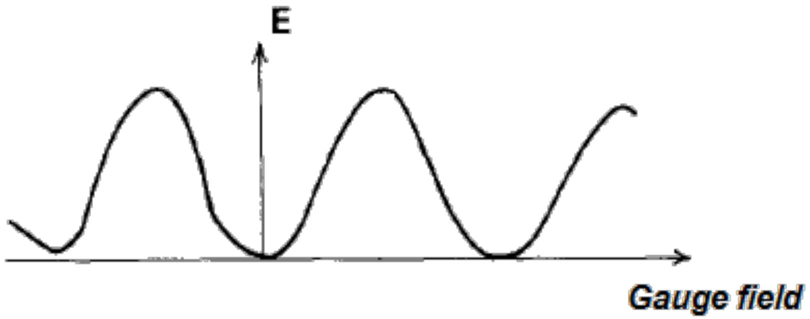
Quarks	:	$\sim 10^{-33\cdots 34}\, e\cdot\mathrm{cm}$
Neutron	:	$\sim 10^{-31\cdots 32}\, e\cdot\mathrm{cm}$
^{199}Hg	:	$\sim 10^{-33\cdots 34}\, e\cdot\mathrm{cm}$
Electron	:	$< 10^{-40}\, e\cdot\mathrm{cm}$

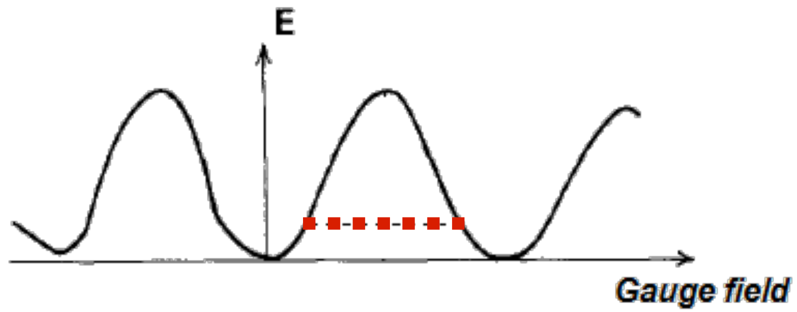
5 to 6 orders **below** upper bound ⟷ **Out of reach!**

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



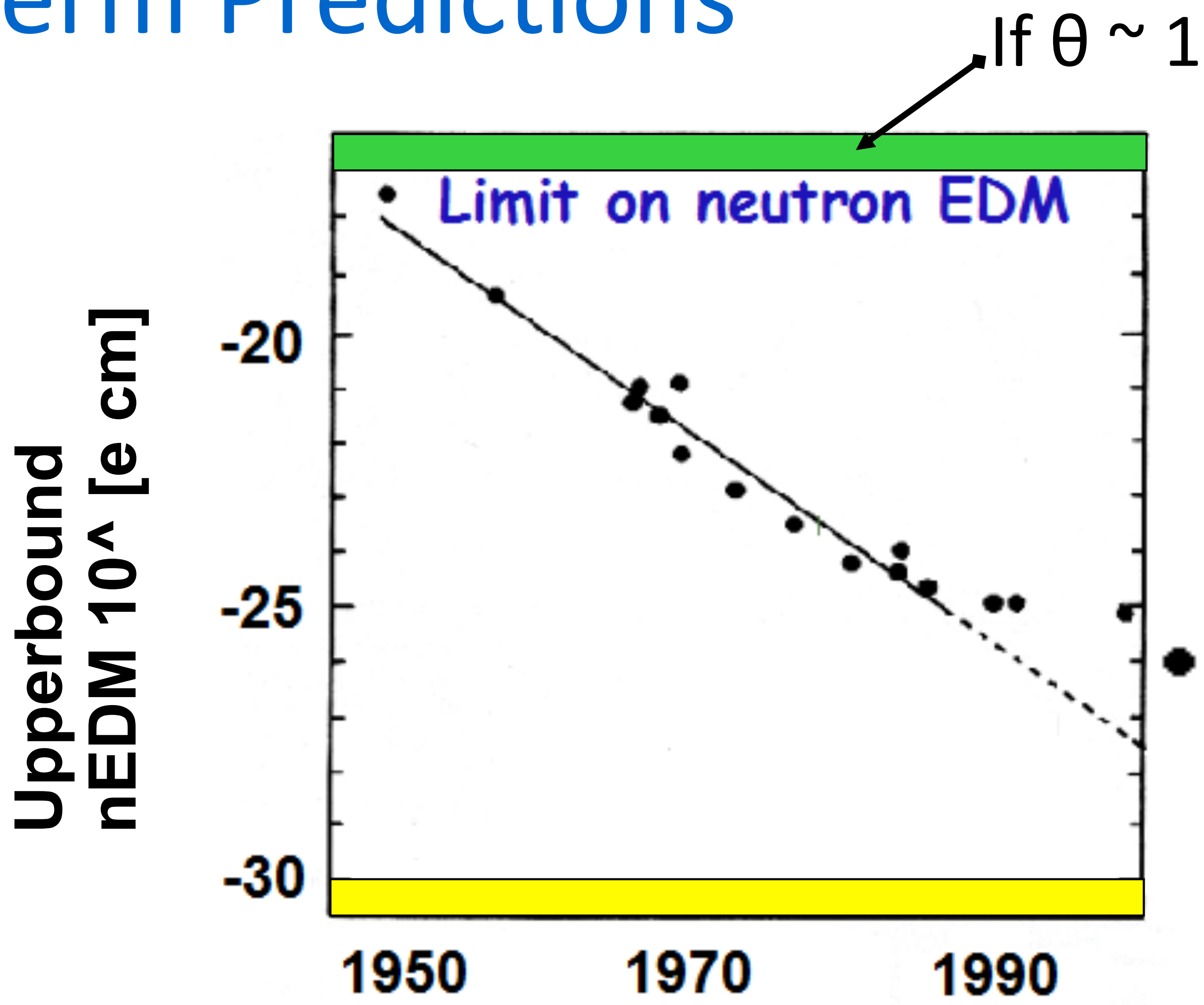


- Causes a 'new' CP-violating interaction with **coupling constant** θ

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

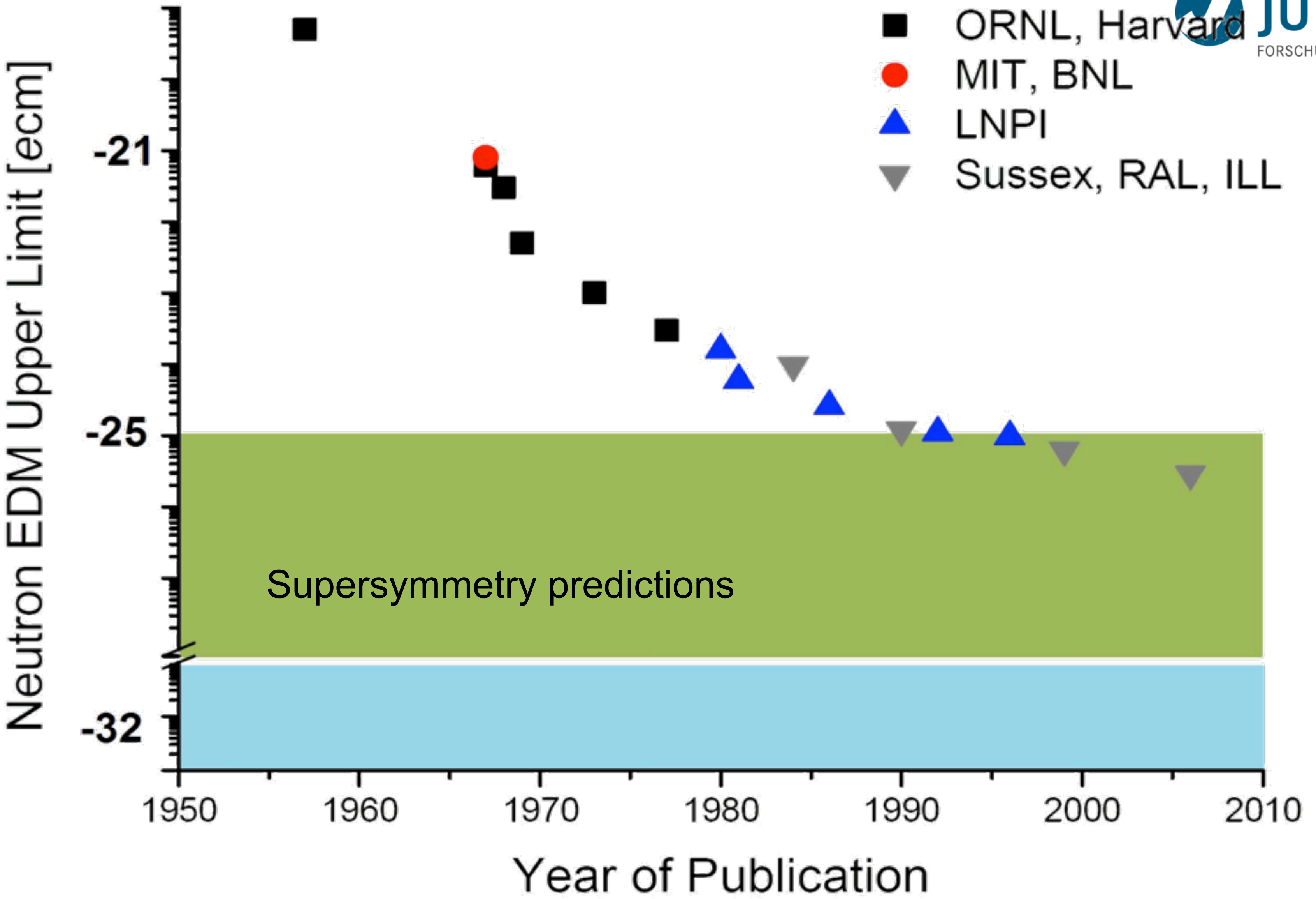
- Size of θ is **unknown**

Theta Term Predictions



Crewther et al. (1979)

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



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 → $$\sim 10^{-28}\ e\ cm$$

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proposed $\rightarrow$ $$\sim 10^{-28}\ e\ cm$$

- Proton EDM inferred from diamagnetic atoms

Griffith *et al PRL* '09 (UW)

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

Dmitriev + Sen'kov PRL '03

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

Ongoing experiments on Ra, Rn, Xe….

Experiments on hadronic EDMs

JÜLICH FORSCHUNGSZENTRUM

- 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 $\qquad d_\mu \leq 1.8 \cdot 10^{-19}\ e\,cm \quad (95\%\ \ C.L.)$

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

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

COSY @ Jülich

Brookhaven/Fermilab

- Other light nuclei? 3He or 3H?

Current Situation

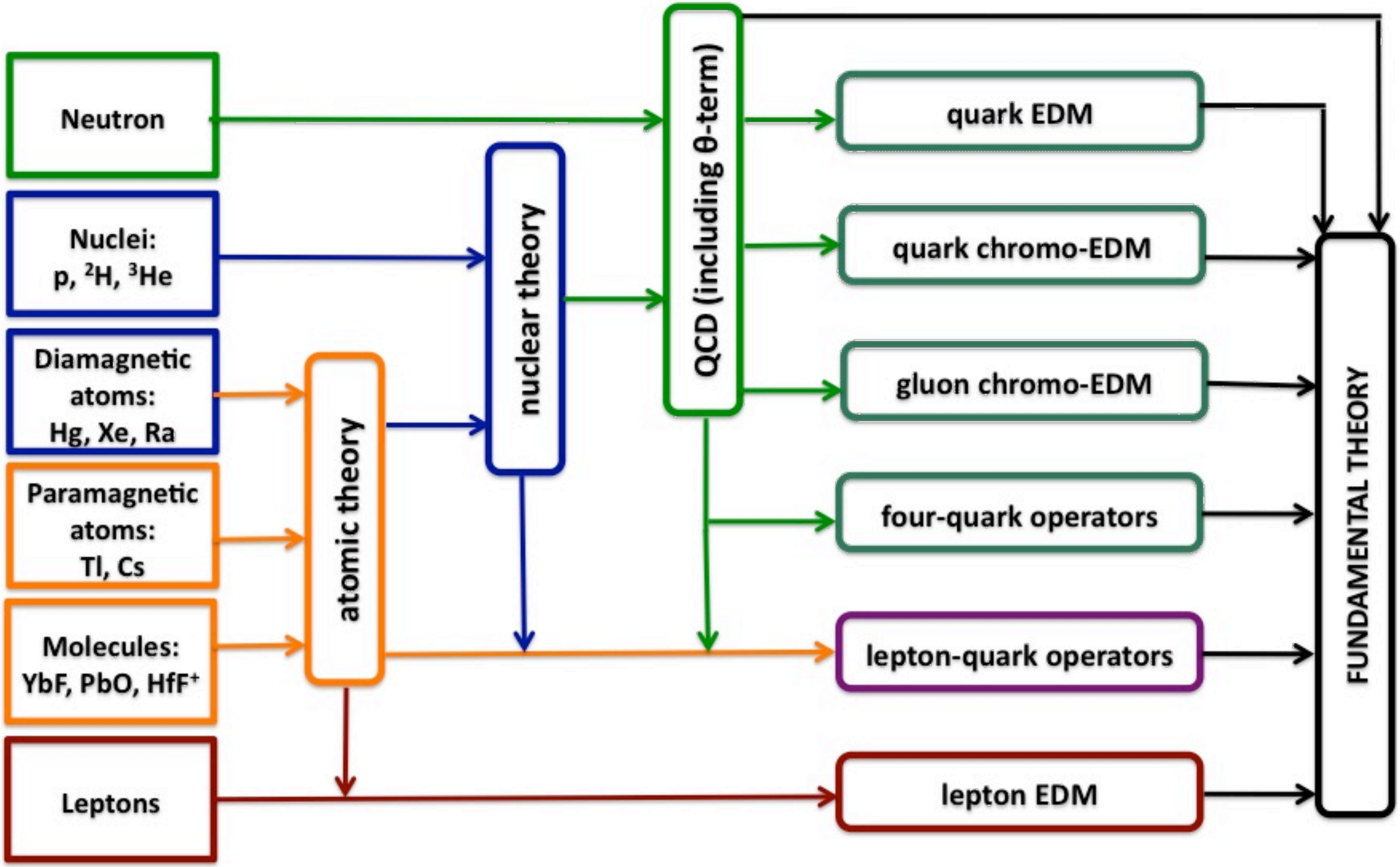
Measurement of a hadronic EDM

?

Standard Model: θ-term

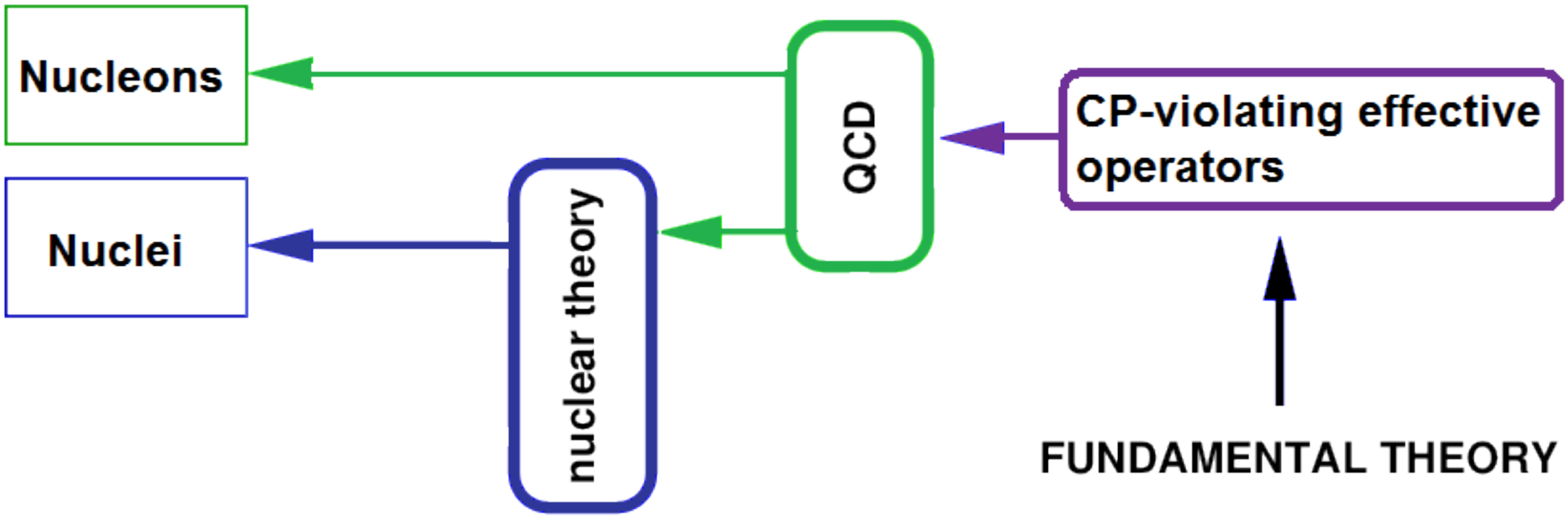
New sources of CP-violation

Finding the **Source**



Finding the **Source**

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

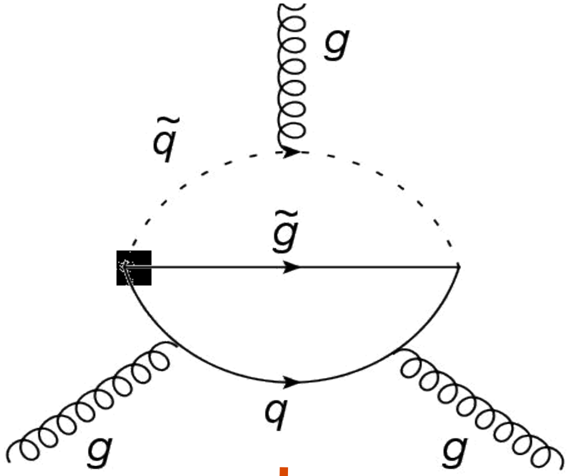


Standard Model as an EFT

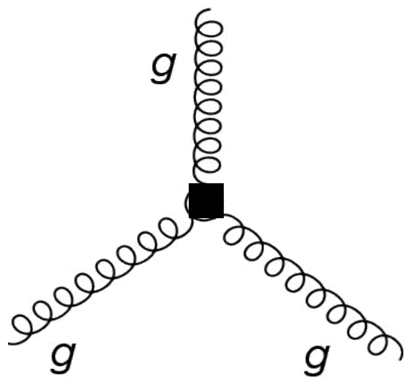
1 TeV ? — SUSY?

100 GeV — Standard Model

Energy



Effectively becomes



$$\propto \frac{1}{M_T^2}$$

Effective Field Theories

- Start the analysis right below: M_T >> 100 GeV
- Degrees of freedom: **Full SM field content**
- Symmetries: Lorentz, SU(3)xSU(2)xU(1) gauge symmetries

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

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Running through the scales

Dekens & JdV, JHEP, '13

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

Energy

New Physics
SUSY?

M_T
? TeV

Integrate out heavy New Physics

$\mathcal{L}_{\rm eff}$

M_{EW}
100 GeV

M_{QCD}
1 GeV

Running through the scales

Dekens & JdV, JHEP, ‘13

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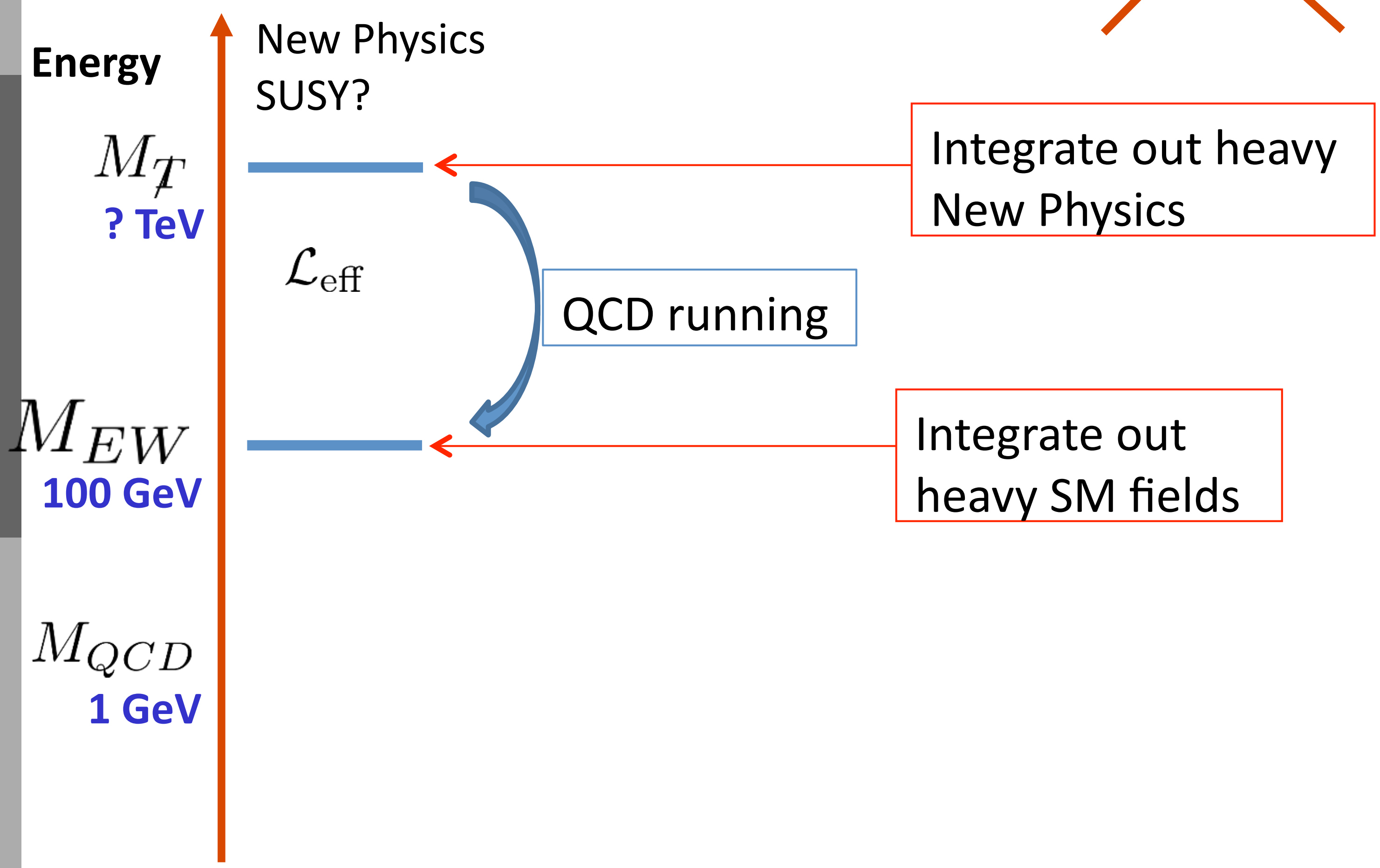

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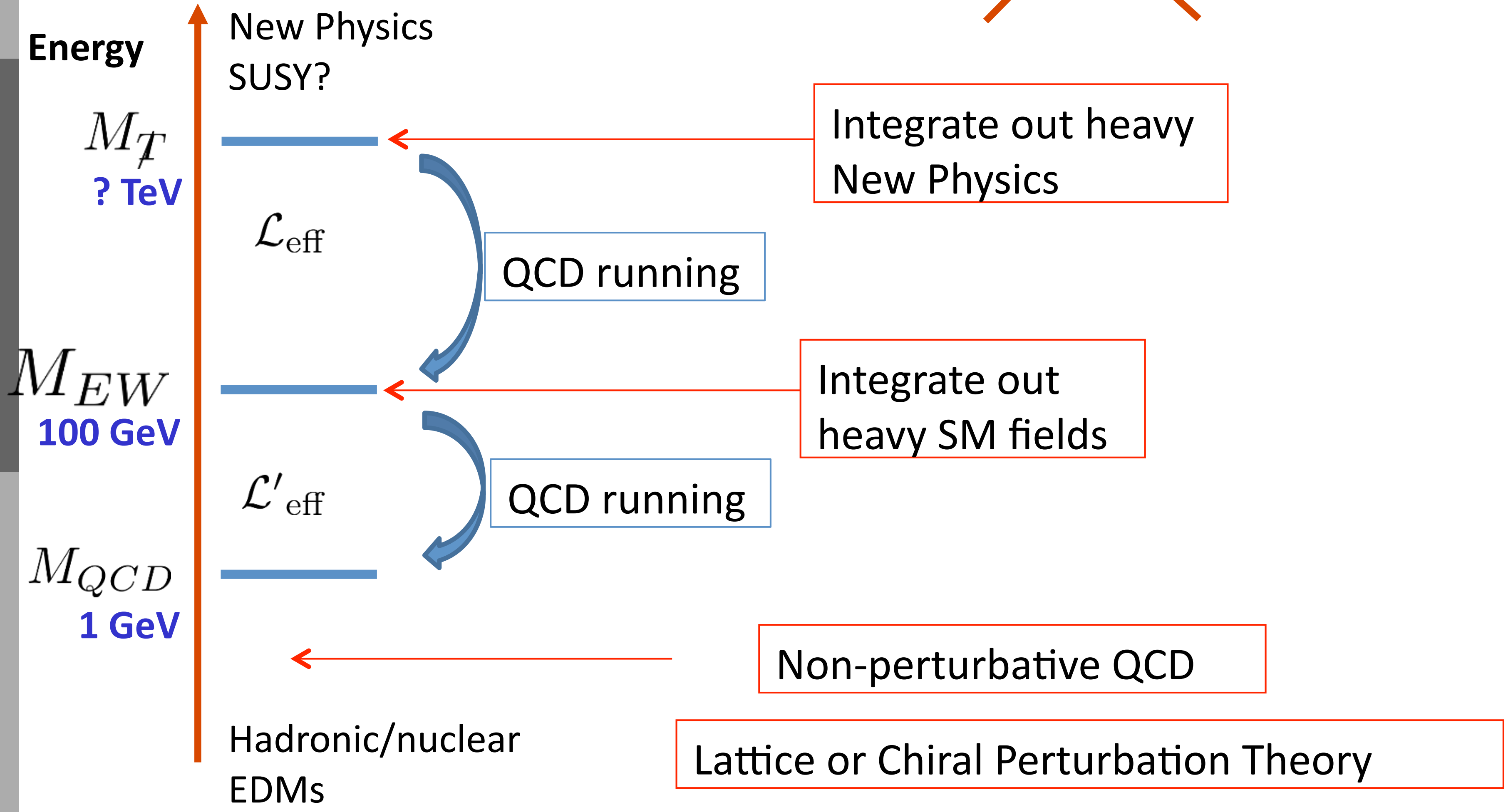
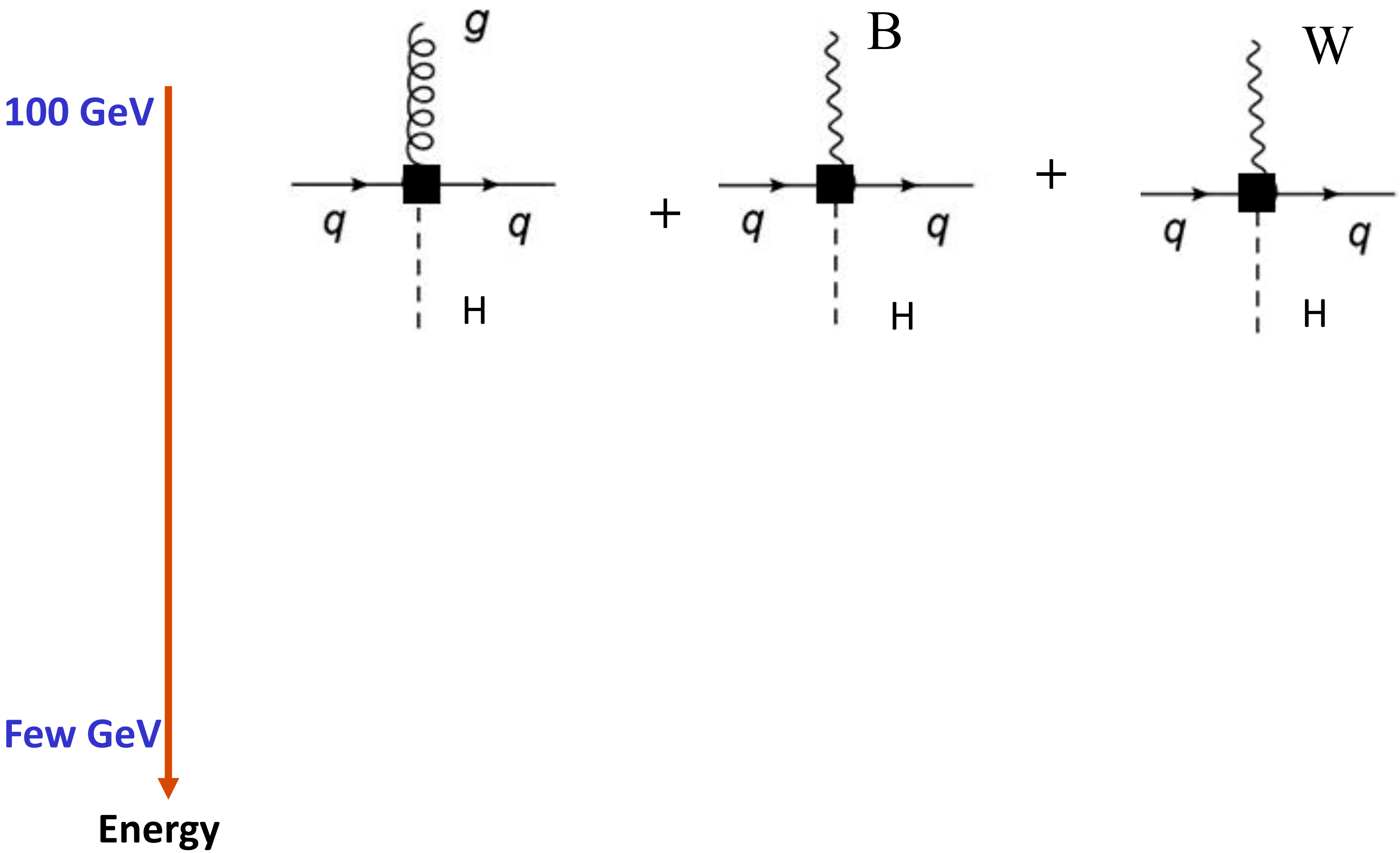


Dimension-six sources

- Add to the SM **all possible T+P-odd** contact interactions
- **They start at dimension six**

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

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



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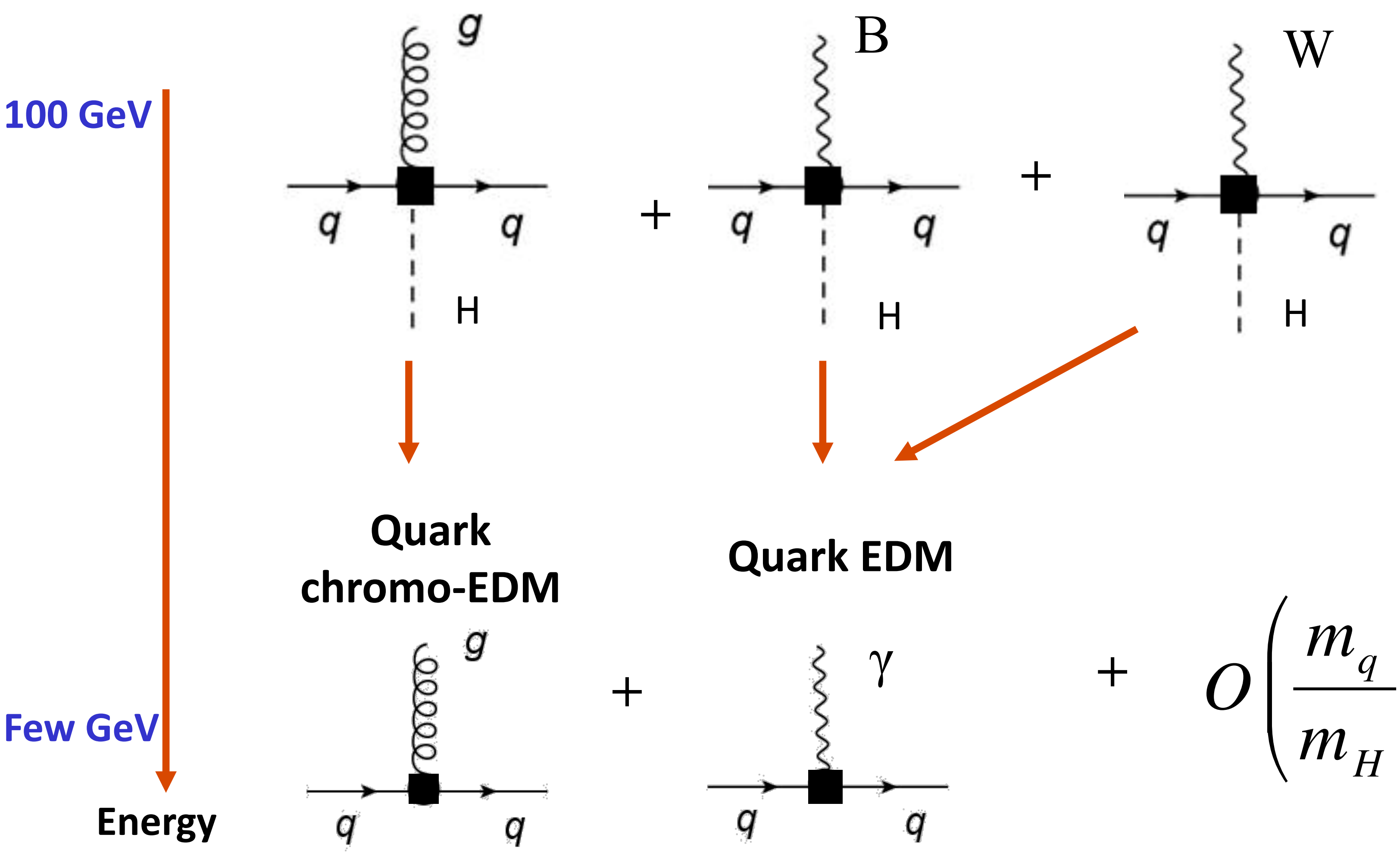

$$+ \; O\left(\frac{m_q}{m_H}, \frac{\alpha_w}{4\pi}\right)$$

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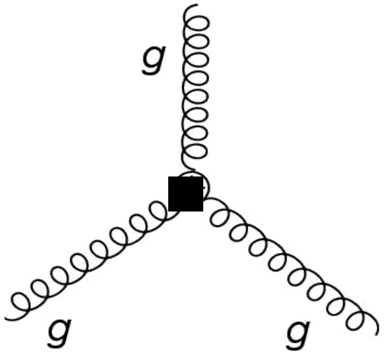
Weinberg PRL ‘89

100 GeV



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

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

Few GeV

Energy

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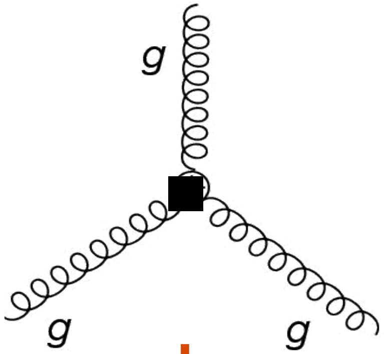

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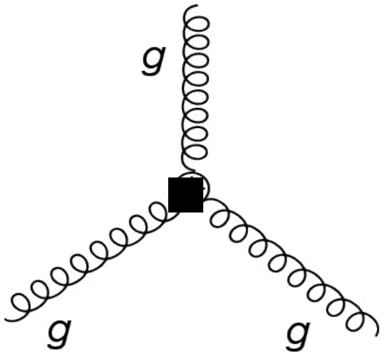
Gluon chromo-EDM

Braaten et al PRL '90



$+$

Quark (C)EDM

mixing

Few GeV

Energy

Four-quark operators

Ramsey-Musolf & Su Phys. Rep. '08
Maekawa et al NPA '11

Only **two** gauge-invariant **four-quark** interactions (u, d quarks only)

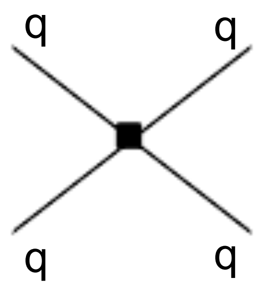
$$\Sigma_{1,8} \propto \frac{1}{M_T^2}$$

Energy

M_T

M_{EW}

M_{QCD}



$$\Sigma_1 \left(\bar{u}_L u_R\, \bar{d}_R d_L - \bar{d}_L u_R\, \bar{u}_R d_L\right) + h.c.$$

$$\Sigma_8 \left(\bar{u}_L \lambda^a u_R\, \bar{d}_R \lambda^a d_L - \bar{d}_L \lambda^a u_R\, \bar{u}_R \lambda^a d_L\right) + h.c.$$

Don't insist on SU(2) gauge symmetry -> you find 10 interactions!

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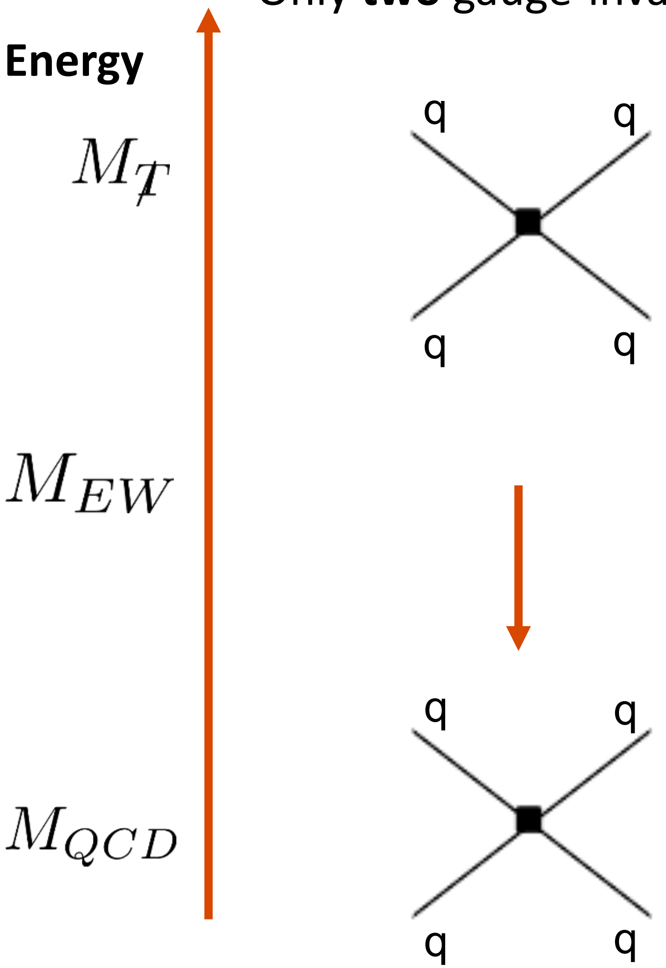


$$\Sigma_1\left(\bar{u}_L u_R\ \bar{d}_R d_L - \bar{d}_L u_R\ \bar{u}_R d_L\right) + h.c.$$

$$\Sigma_8\left(\bar{u}_L \lambda^a u_R\ \bar{d}_R \lambda^a d_L - \bar{d}_L \lambda^a u_R\ \bar{u}_R \lambda^a d_L\right) + h.c.$$

Hisano et al ’12
Dekens, JdV ‘13

Quite strong QCD enhancement:

$$\Sigma_1\left(1\, GeV\right) \cong 7\, \Sigma_1\left(1\, TeV\right)$$

Dimension-six sources

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

Ng & Tulin PRD '12

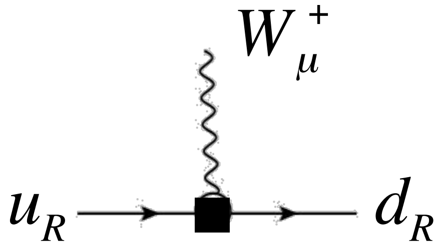
Finally:

100 GeV

One **quark-Higgs-Higgs** interaction

$$\Xi_1 \propto \frac{1}{M_{\not{T}}^2}$$

$$\Xi_1 \left(\bar{u}_R \gamma^\mu d_R\right) \tilde{\varphi}^{*T} i D_\mu \varphi + h.c. \longrightarrow \Xi_1 \, v^2 \left(\bar{u}_R \gamma^\mu d_R\right) W_\mu^+ + h.c.$$



Few GeV

Energy

Dimension-six sources

JÜLICH
FORSCHUNGSZENTRUM

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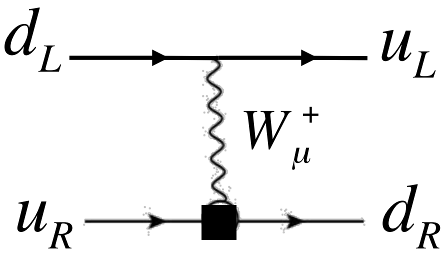
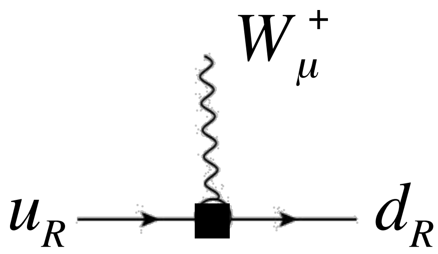
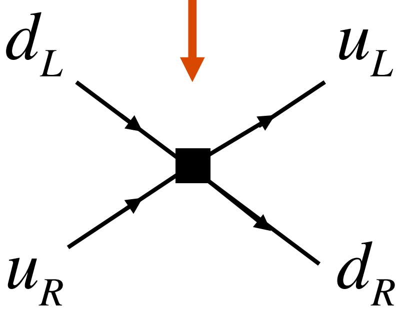






$$\propto \mathrm{Im}\,\Xi_1 \frac{v^2}{M_W^2} \approx \mathrm{Im}\,\Xi_1$$

An additional unsuppressed 4q term

Few GeV

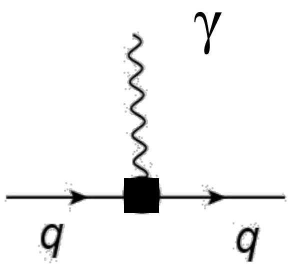
Energy

Mitglied der Helmholtz-Gemeinschaft

Dimension-four and -six sources

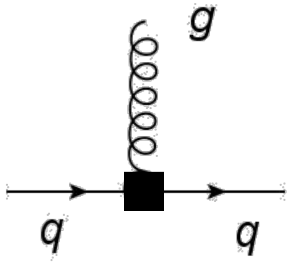
Few GeV

QCD
(θ-term) +



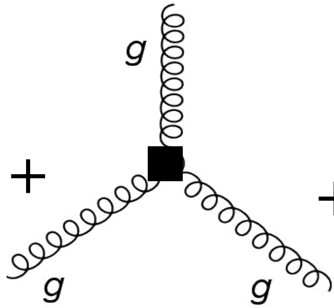
Quark EDM

+



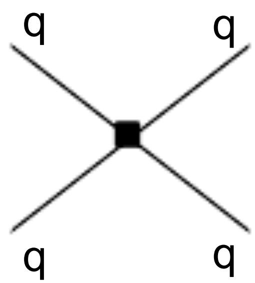
Quark
chromo-EDM

+



Gluon
chromo-EDM

+



3*4quark
operators

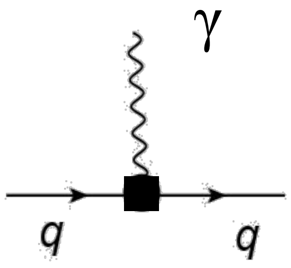
Different models predict different operator(s)!!!

Energy

Dimension-four and -six sources

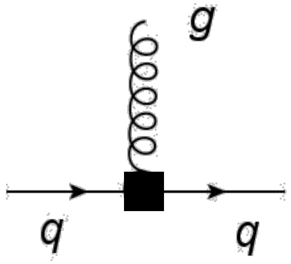
Few GeV

QCD
(θ-term)
+



Quark EDM

+



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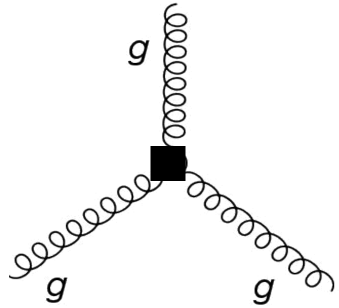
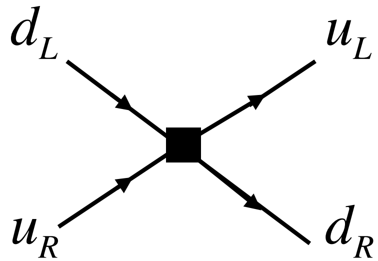
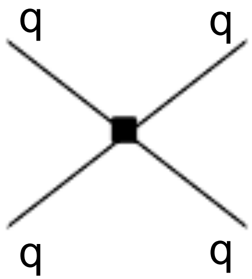


Gluon
chromo-EDM



four-quark
left-right term
(FQLR)

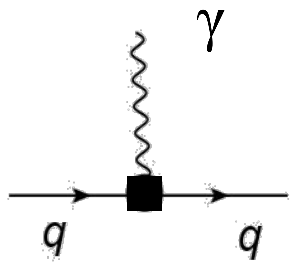


2 Chiral-invariant
four-q terms

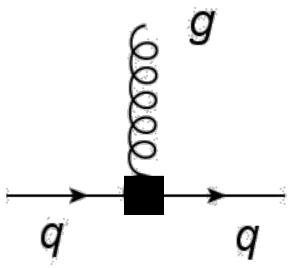
Energy

Dimension-four and -six sources

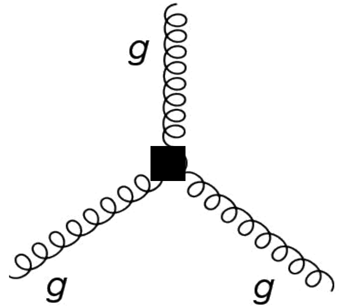
Few GeV

QCD (θ-term) + 

Quark EDM

\+ 

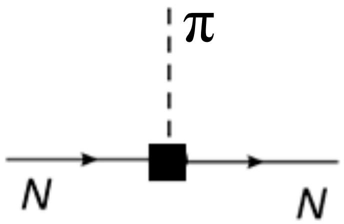
Quark chromo-EDM

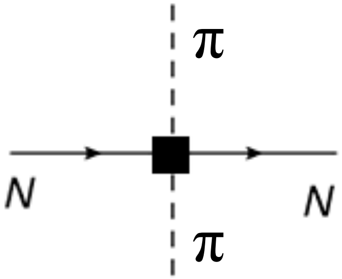
\+ 

Gluon chromo-EDM

100 MeV

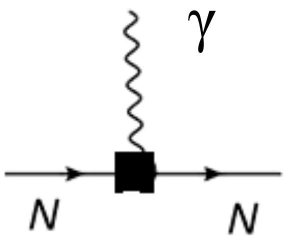
Chiral Perturbation Theory

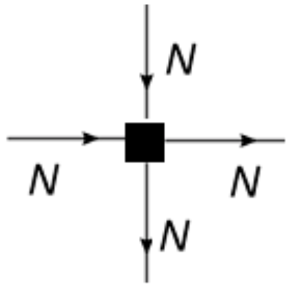


\+ 

\+ ....

Energy





\+ ....

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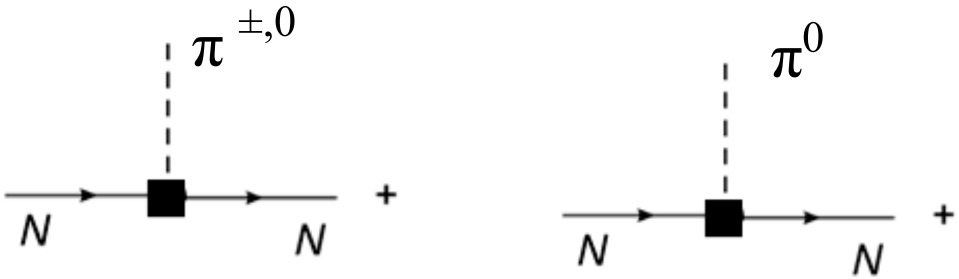
- Part I: Different sources of Time-Reversal Violation
- **Part II: Chiral techniques**
- Part III: Observables
  - IIIa: Nucleon EDM
  - IIIb: Light-Nuclear EDMs

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

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

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

Hierarchy among the sources

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

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

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

$$|\bar{g}_1| \approx 0.1\,|\bar{g}_0|$$

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

New estimate: Bsaisou et al '12

Mitglied der Helmholtz-Gemeinschaft

Hierarchy among the sources

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

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

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

❖ Quark chromo-EDM (+ FQLR) **breaks chiral and isospin** symmetry

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

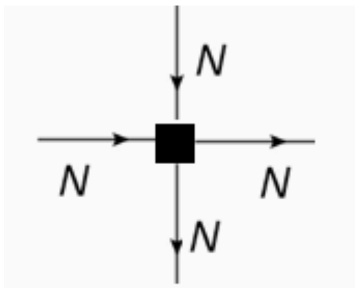
Hierarchy among the sources

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

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

- 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 $\delta m_q / M_{QCD}$
  - Chiral symmetric nucleon-nucleon interactions become important

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



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/Λ_χ and $\delta m_q/\Lambda_\chi$

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

$$\alpha_{em}/(4\pi) \sim 10^{-3}$$

Hierarchy among the sources

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

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

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

Mereghetti, Hockings, van Kolck, *Ann. of. Phys. (2010)*, JdV et al, *Ann. of. Phys. (2013)*

Hierarchy among the sources

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

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

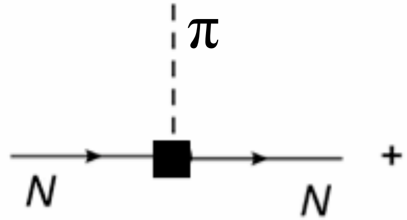
	Theta term	Quark CEDM +FQLR	Quark EDM	Gluon CEDM +4Q
$\left\lvert\frac{\bar{g}_1}{\bar{g}_0}\right\rvert$	$\left(\frac{m_\pi}{\Lambda_\chi}\right)^2$	1	1	1
$\left\lvert\frac{\bar{g}_1}{\bar{d}_0}\right\rvert / \Lambda_\chi^2$	$\left(\frac{m_\pi}{\Lambda_\chi}\right)^2$	1	$\left(\frac{\alpha_{em}}{4\pi}\right)$	$\left(\frac{m_\pi}{\Lambda_\chi}\right)^2$

Mereghetti, Hockings, van Kolck, *Ann. of. Phys. (2010),* JdV et al, *Ann. of. Phys. (2013)*

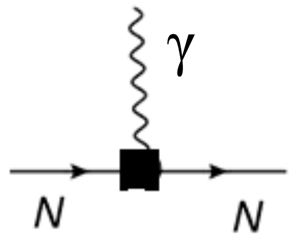
Six important interactions

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

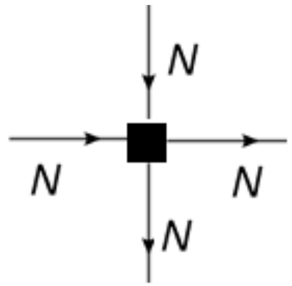
$$L = \frac{\bar{g}_0}{F_\pi}\bar{N}(\vec{\pi}\cdot\vec{\tau})N + \frac{\bar{g}_1}{F_\pi}\bar{N}(\pi_3)N$$



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



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



$$+\ \cdots$$

- 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

Outline of this talk

- Part I: Different sources of Time-Reversal Violation
- Part II: Chiral techniques
- Part III: Observables
  - **IIIa: Nucleon EDM**
  - IIIb: Light-Nuclear EDMs

The Nucleon Electric Dipole Moment

- In principle calculate on **lattice**

- Results available for theta term

Talks by Ulf-G. Meiβner
& G. Schierholz

Shintani et al. PRD ’05, ‘07 ‘08
Berruto et al. PRD ’06
Horsley et al. ‘08
Guo & Meiβner JHEP ‘12

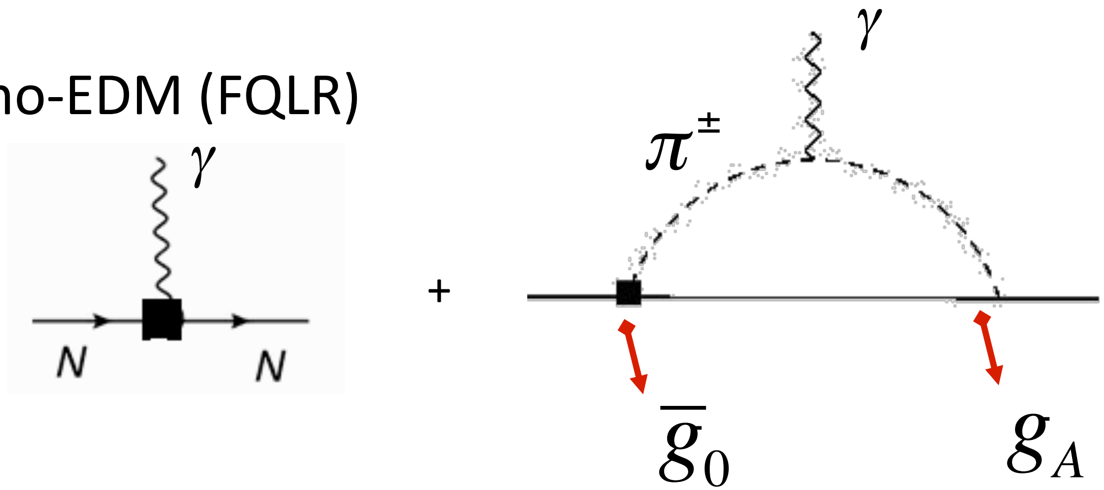
- Unfortunately: No results for dimension-six sources yet

The Nucleon Electric Dipole Moment

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

- θ-term + quark chromo-EDM (FQLR)

Nucleon EDM



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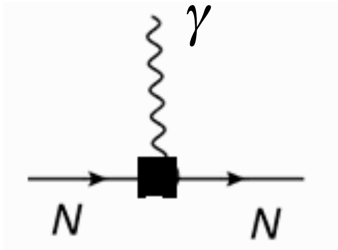
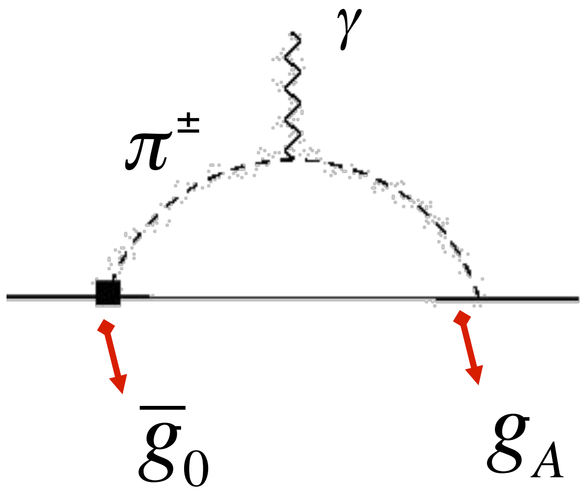
Nucleon EDM



+



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

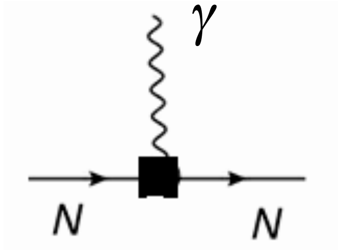
$$d_p = \bar{d}_0 + \bar{d}_1 - \frac{e g_A}{(2\pi F_\pi)^2} \ln\left(\frac{m_\pi^2}{m_n^2}\right) \bar{g}_0$$

Crewther et al., PLB ‘79
Pich, Rafael, NPB ‘91
Hockings, van Kolck, PLB ’05
Ottnad et al, PLB ‘10

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

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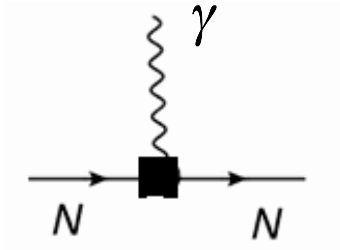
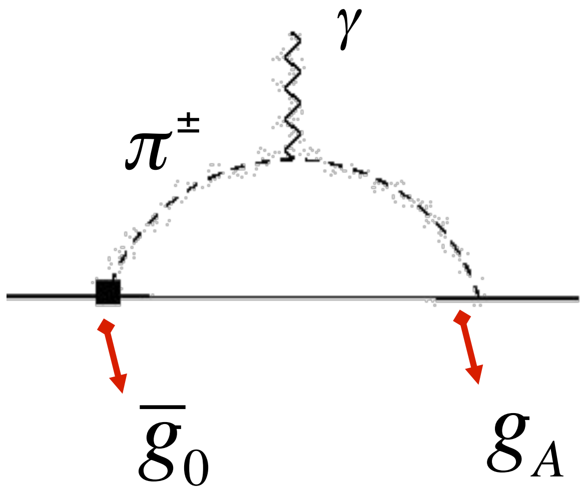
Nucleon EDM





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

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

Loops appear at next-to-next-to-leading order

The Nucleon Electric Dipole Moment

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

- 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 $\xrightarrow{\sin\phi \sim 1}$ $M_{\not T} > 100\ TeV$

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

The Nucleon Electric Dipole Moment

	Theta term	Quark CEDM +FQLR	Quark EDM	Gluon CEDM + 4Q
$M_n d_n / e$	$\theta \left(\frac{m_\pi}{\Lambda_\chi} \right)^2$	$\tilde{\delta} \left(\frac{m_\pi}{M_{\not T}} \right)^2$	$\delta \left(\frac{m_\pi}{M_{\not T}} \right)^2$	$w \left(\frac{\Lambda_\chi}{M_{\not T}} \right)^2$
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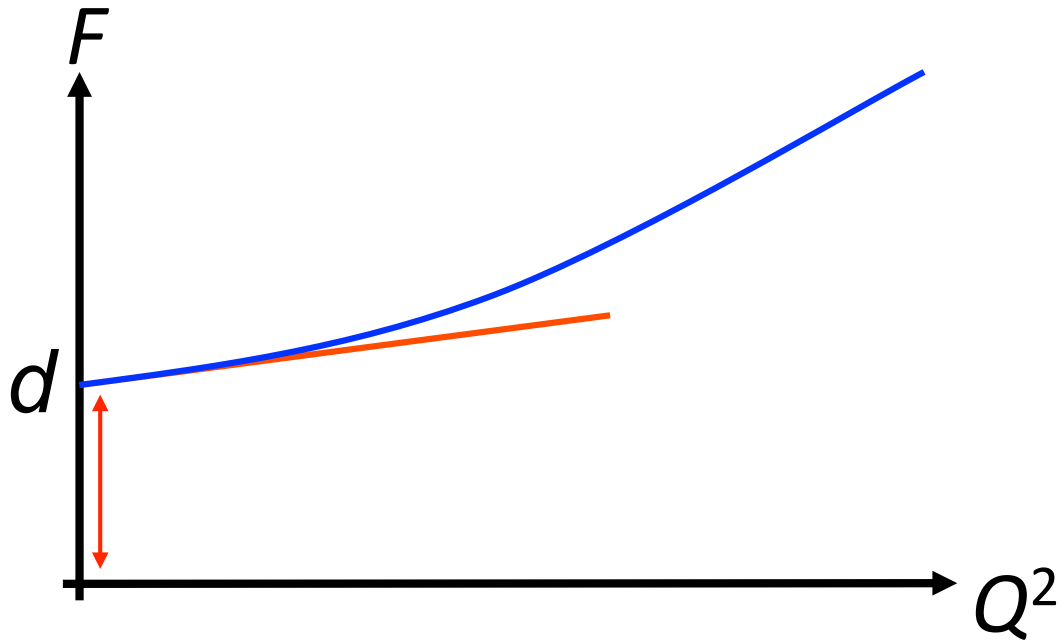
$$\theta < 10^{-10}, \qquad \tilde{\delta} / M_{\not T}^2 < (10^5\ GeV)^{-2}$$

Pospelov, Ritz (2005)

- Certain SUSY-models $\tilde{\delta} \approx \sin\phi$, if $M_{\not T} = 1\, TeV$ $\longrightarrow$ $\sin\phi < 10^{-4}$

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

The Nucleon Schiff Moment



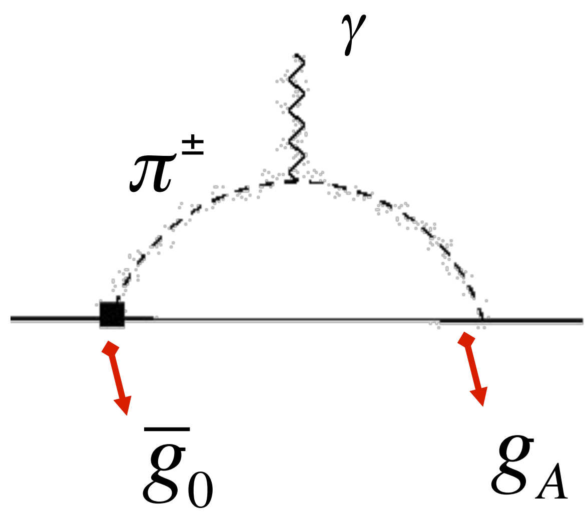
$$F(Q^2) = d + Q^2 S + Q^4 H + \ldots$$

EDM **Schiff Moment**

The Nucleon Schiff Moment

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

Schiff Moment



$$S_n = -\frac{e g_A \bar{g}_0}{6(2\pi F_\pi)^2}\frac{1}{m_\pi^2}\left(1 - \frac{m_\pi}{m_N}\frac{5\pi}{4}\right)$$

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

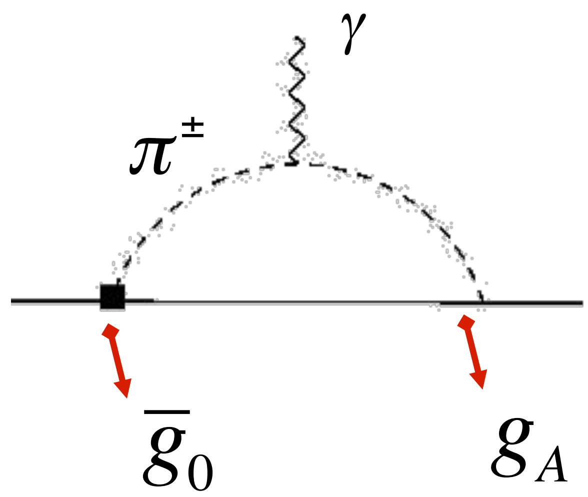
$$S_p \approx -S_n$$

Mitglied der Helmholtz-Gemeinschaft

The Nucleon Schiff Moment

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

Schiff Moment are very small



Loops appear at next-to-next-to-leading order

JdV et al, PLB '11

The Nucleon Schiff Moment

	Theta term	Quark CEDM	Quark EDM	Gluon CEDM
$M_n d_n / e$	$\theta \left(\frac{m_\pi}{\Lambda_\chi} \right)^2$	$\tilde{\delta} \left(\frac{m_\pi}{M_{\not{T}}} \right)^2$	$\delta \left(\frac{m_\pi}{M_{\not{T}}} \right)^2$	$w \left(\frac{\Lambda_\chi}{M_{\not{T}}} \right)^2$
Proton EDM/ Neutron EDM	O(1)	O(1)	O(1)	O(1)
$m_\pi^2 \left(S_{p,n} / d_{p,n} \right)$	O(1)	O(1)	$\left(\frac{m_\pi}{\Lambda_\chi} \right)^2$	$\left(\frac{m_\pi}{\Lambda_\chi} \right)^2$

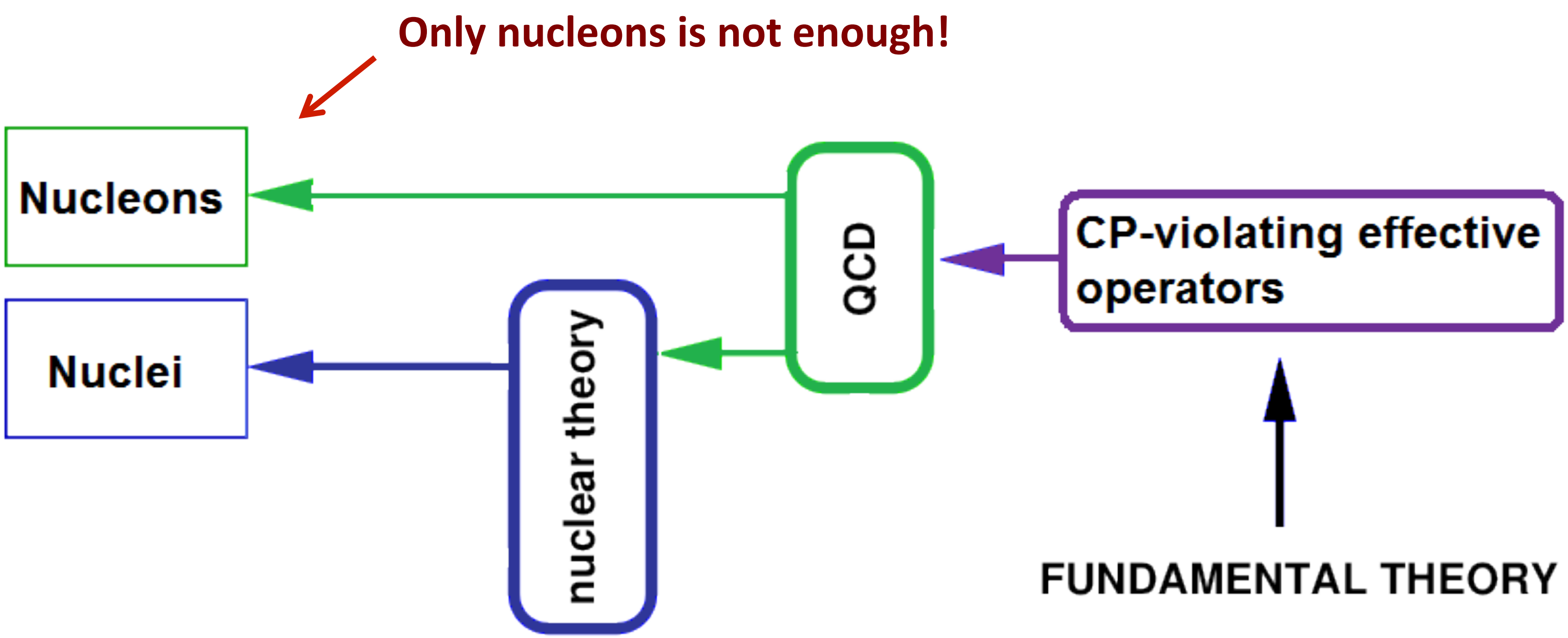
- Schiff Moments could **separate** (theta & qCEDM) from (qEDM & gCEDM)
- Can they be measured?

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*



Storage rings experiments

Farley *et al PRL* '04

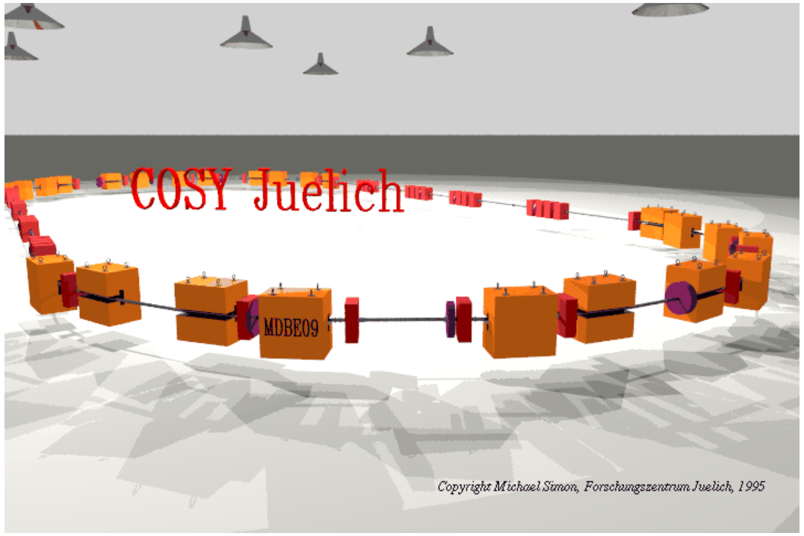
Anomalous magnetic moment

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?

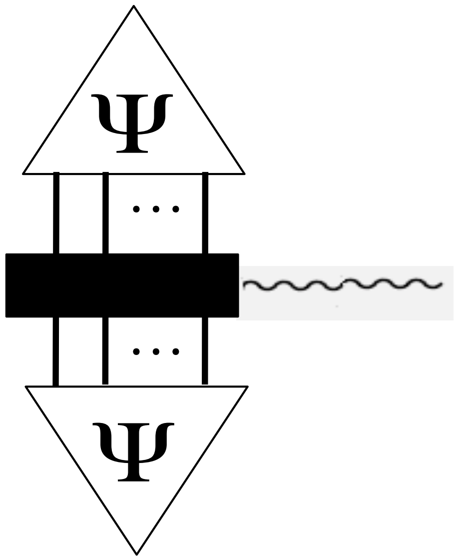
All-purpose ring (proton, deuteron, helion) at COSY?



EDM of a general light nucleus

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

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

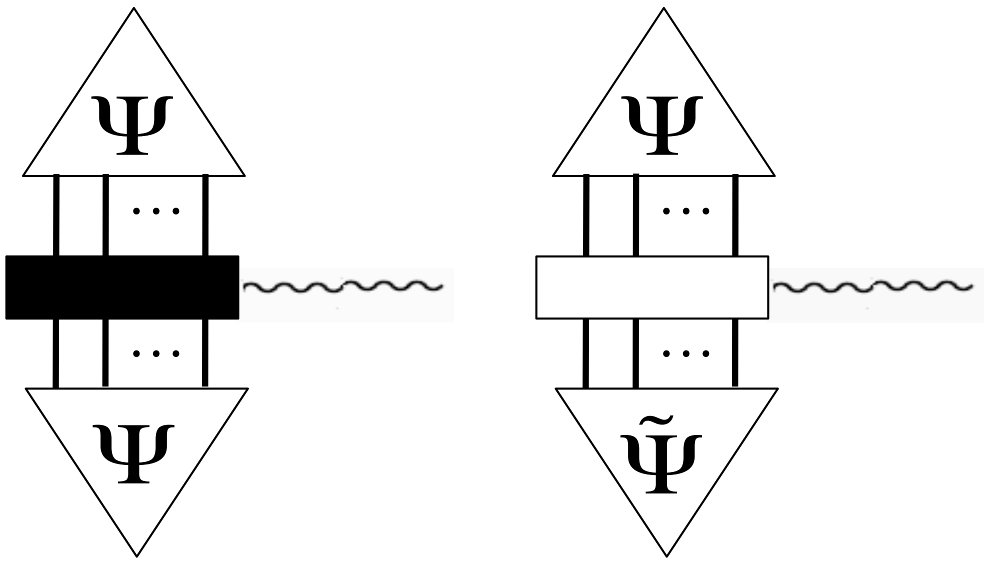


EDM of a general light nucleus

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

PT-odd admixtured wave-function

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



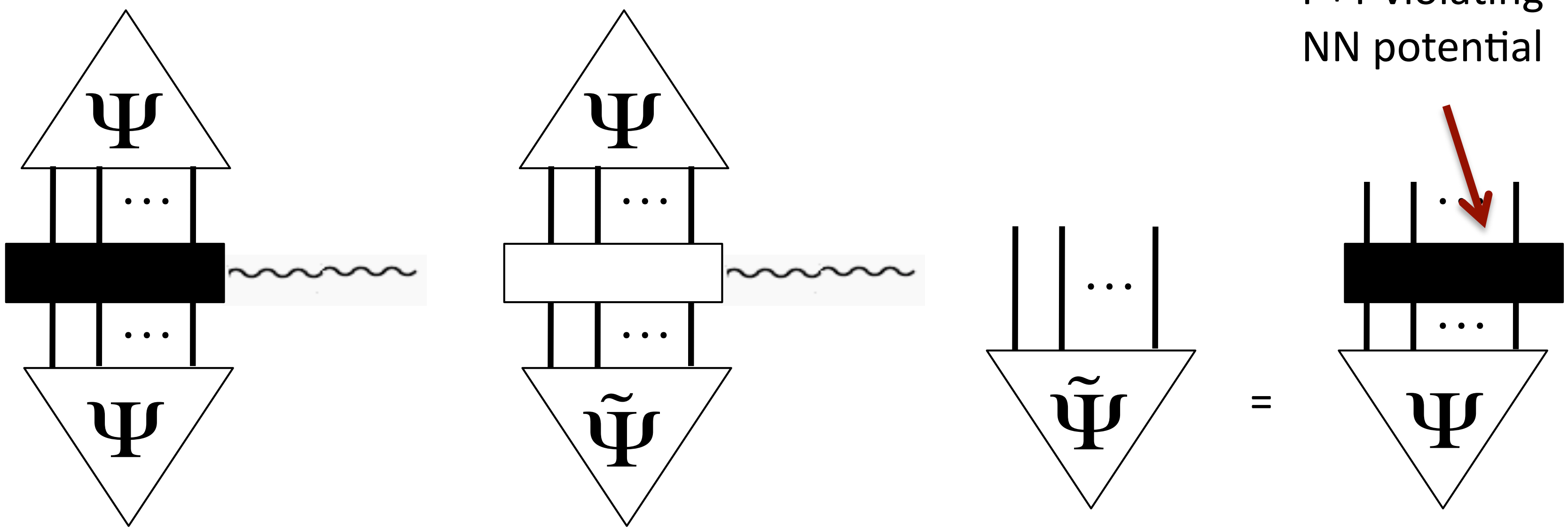
EDM of a general light nucleus

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

PT-odd admixtured wave-function

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

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

Should be replaced by chiral potentials

EDM of a general light nucleus

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

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

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

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

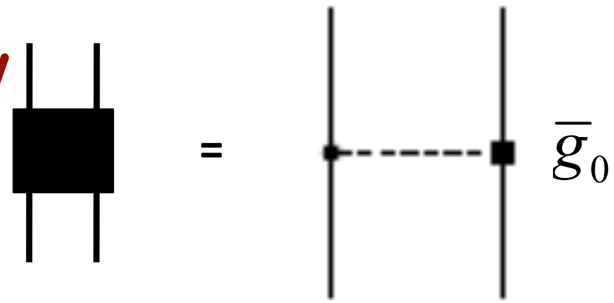
Different for every source!

EDM of a general light nucleus

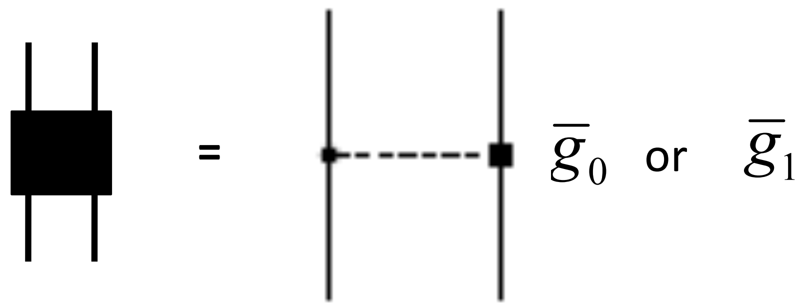
- The most important ingredients are the **PT-odd Potential + Currents**
- They are derived from the PT-odd Lagrangian **(unique for each source)**

~~PT~~-potential

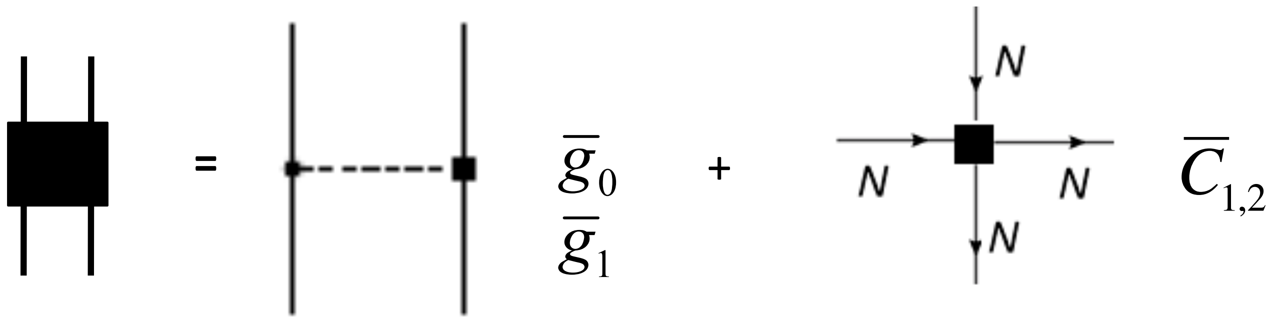
theta-term



quark colour-EDM + FQLR



gluon color-EDM + 4Q



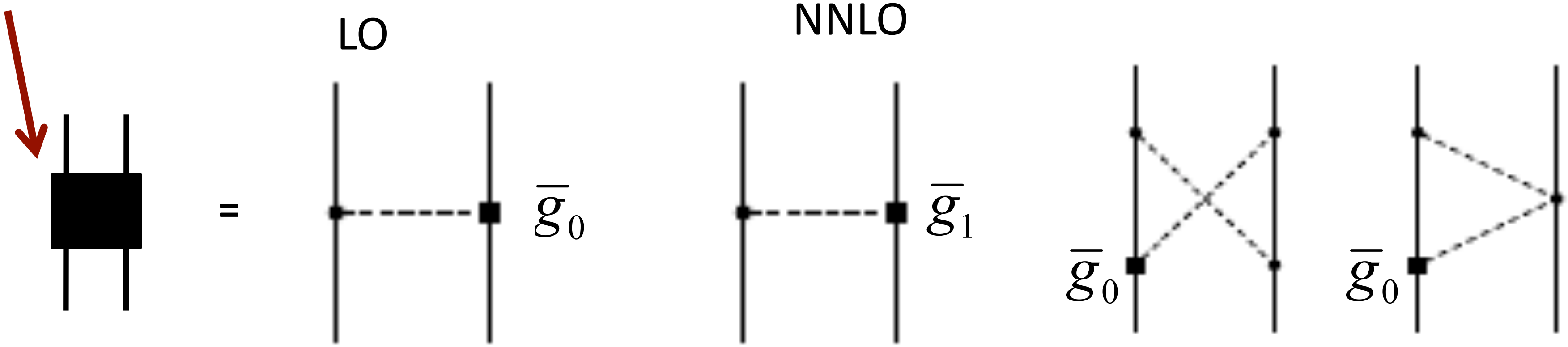
Maekawa, Mereghetti, JdV, van Kolck, NPA (2011)

EDM of a general light nucleus

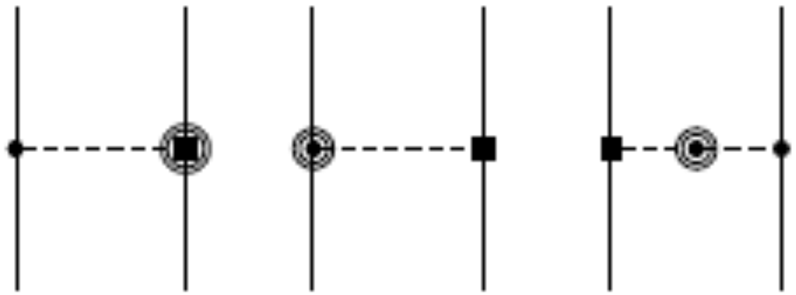
- The most important ingredients are the **PT-odd Potential + Currents**
- They are derived from the PT-odd Lagrangian **(unique for each source)**

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

LO NNLO



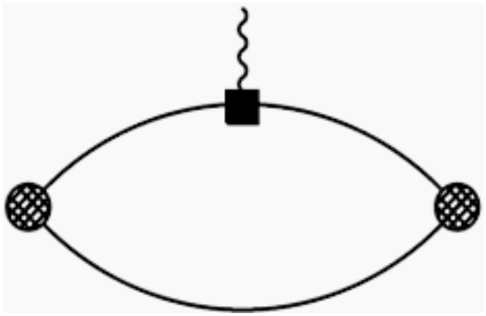
Isospin breaking and
relativistic corrections



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

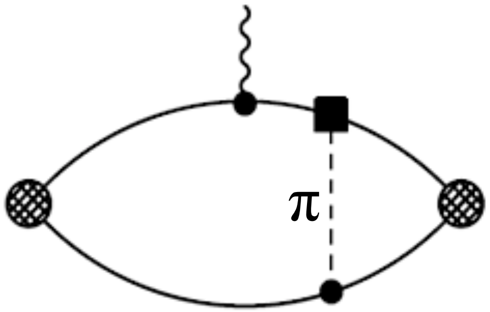
The deuteron EDM

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



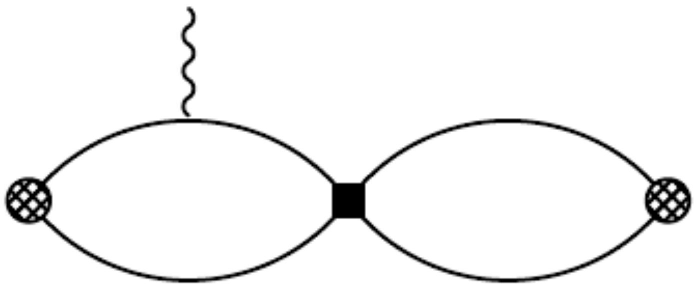
One-body:

$$d_D = 2d_0 = d_n + d_p$$



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

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

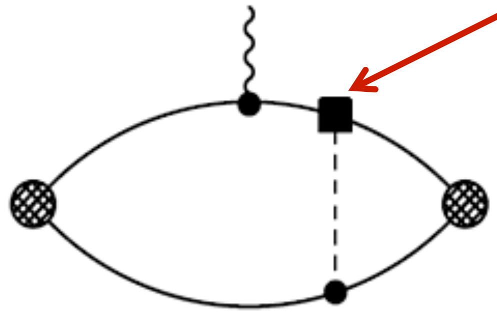
The deuteron EDM

- **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!



The deuteron EDM

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

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

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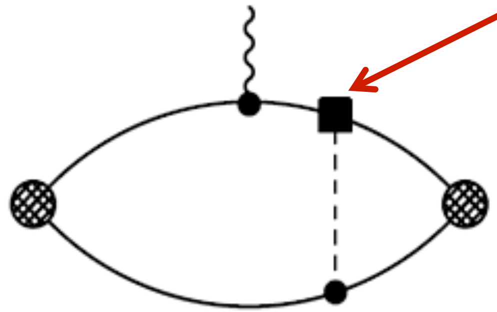
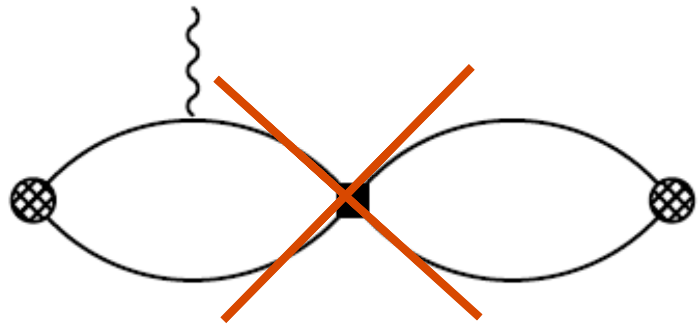
Must be Isovector!



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



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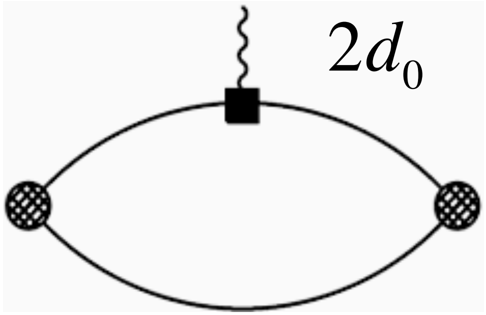

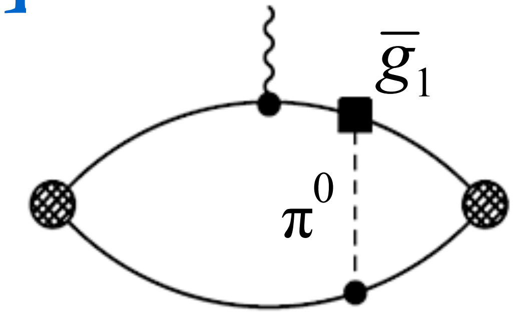

- We recycle the work of Liu+Timmermans PRC ‘04
- Obtain deuteron wave function from phenomenological potentials (Argonne 18, Nijmegen II, Reid93)

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

- Results differ within 5% for different potentials

Afnan, Gibson PRC ‘10

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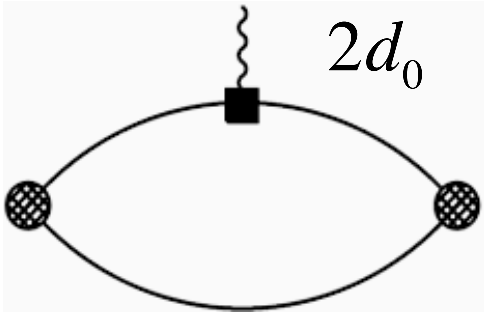

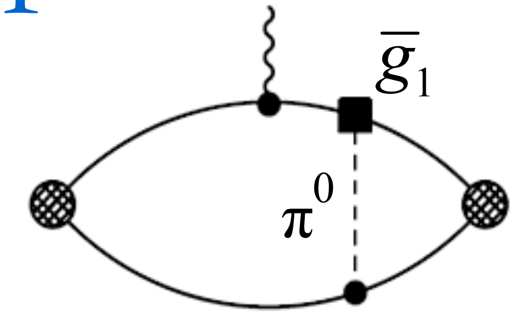

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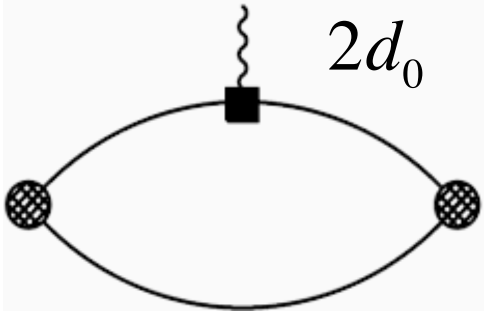
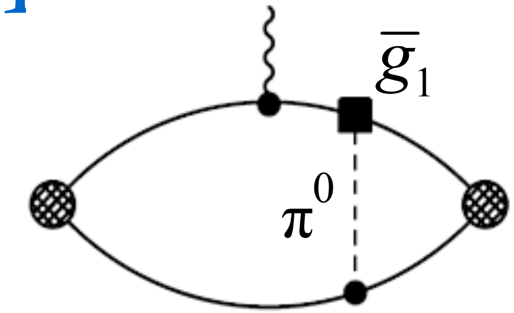
Afnan, Gibson PRC '10

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

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

The deuteron EDM

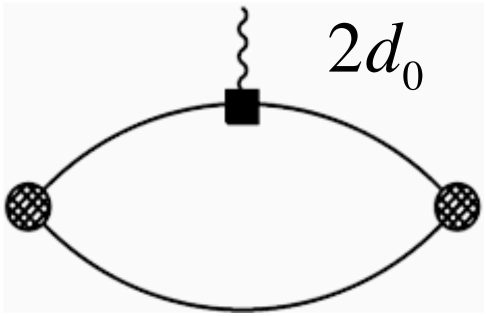


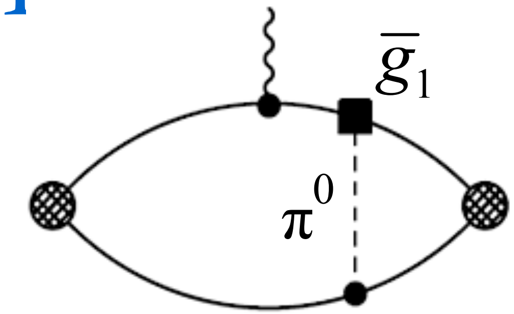


- Which effect **dominates** depends on the ratio of the LECs

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

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 +FQLR	Quark EDM	Gluon CEDM + 4Q
$\left\lvert\frac{\bar{g}_1}{\bar{d}_0}\right\rvert / \Lambda_\chi^2$	$\left(\frac{m_\pi}{\Lambda_\chi}\right)^2$	1	$\left(\frac{\alpha_{em}}{4\pi}\right)$	$\left(\frac{m_\pi}{\Lambda_\chi}\right)^2$

The deuteron EDM

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

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

Mitglied der Helmholtz-Gemeinschaft

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

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- For qCEDM/FQLR d_D **significantly larger than** $d_n + d_p$
- **Exact value of** $d_D - d_n - d_p$ **can be used to identify strong CP-violation**

Bsaisou et al, EJPA ‘13

Mitglied der Helmholtz-Gemeinschaft

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

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

- The same strategy as for the deuteron EDM has been employed to calculate the EDMs of 3He and 3H

Stetcu et al, PLB ’08
JdV et al PRC ’ 11
Song et al PRC ‘13
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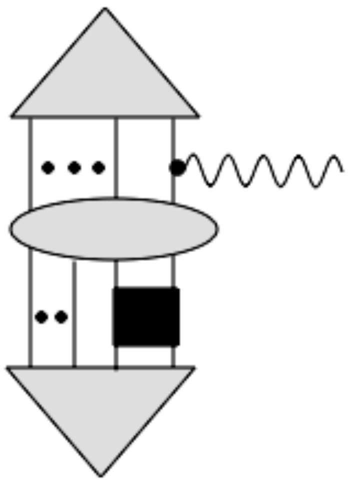
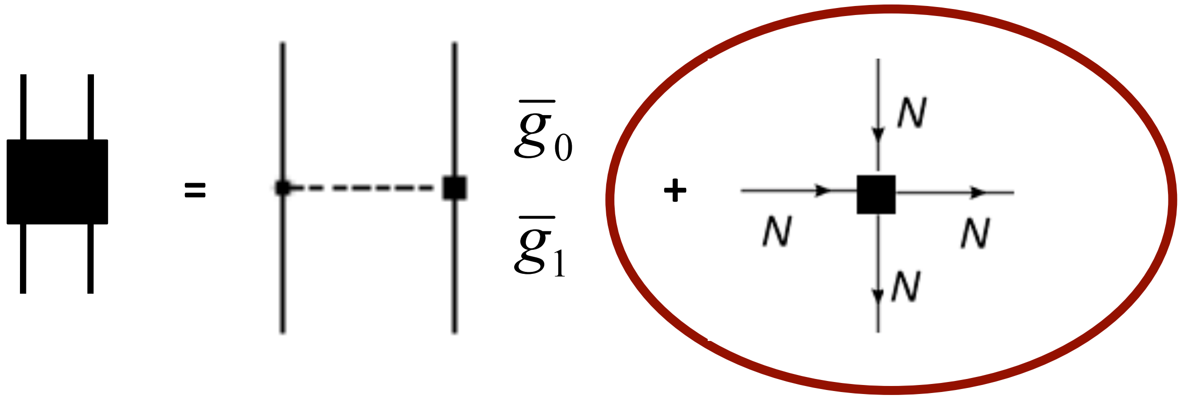
- Additional difficulties due to short-range interactions (but appear to be small)



Gluon chromo-EDM + 4Q



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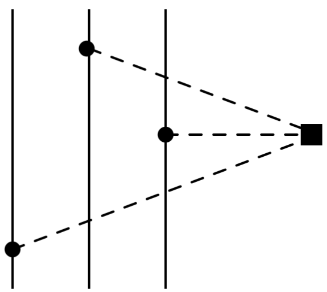
- Also **new features in 3-body system** for certain four-quark operators

- **Unique chiral properties** induce a PT-odd **three-body force** at LO

JdV et al AOP ’ 13

FQLR



Disclaimer: no quantitative calculations yet

Separating the sources

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

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- Assume **one source** is dominant

- If deuteron EDM is approx. **neutron + proton EDM**

  → Rule out **quark chromo-EDM** and certain **four-quark operators**

- If also **helion (triton)** EDM deviate significantly from **neutron (proton)** EDM

  → Point towards **Standard Model (theta term)**

Further quantitave tests

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

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

Separating the sources

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

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

→ **New physics** in form of **quark chromo-EDM** or four-quark operators

Further tests

$$d_{^3He} + d_{^3H} = -0.57\,\frac{\bar{g}_1}{F_\pi}\,e\ fm \approx 3\,d_d >> d_n + d_p$$

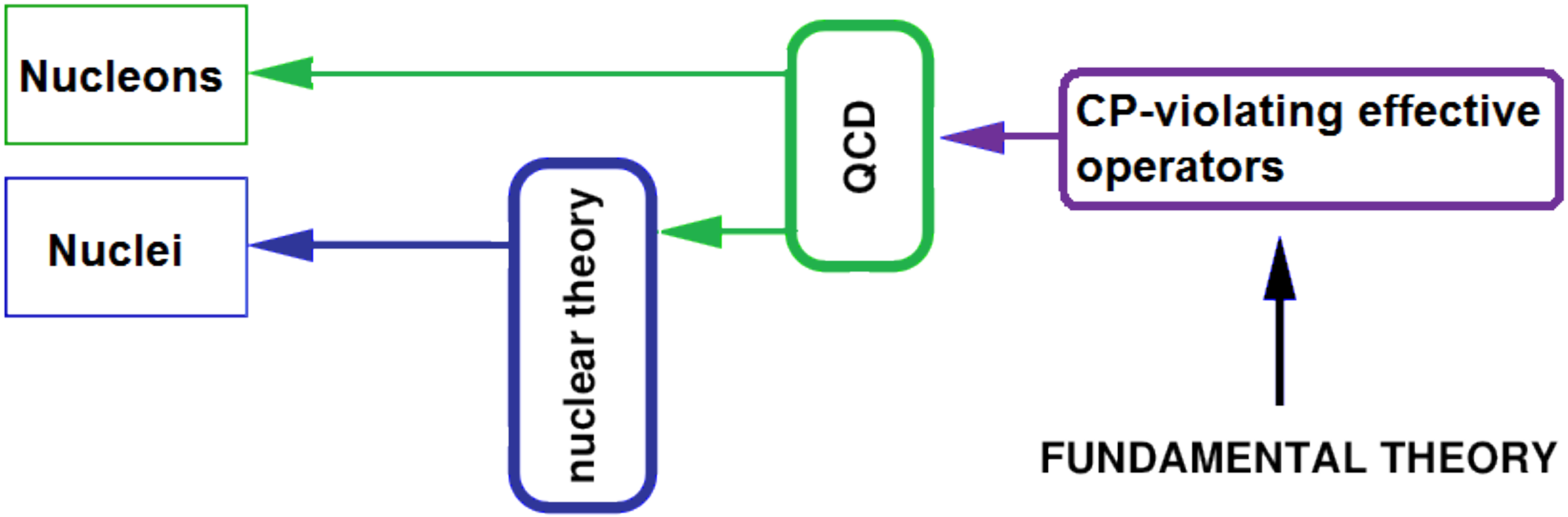
$$d_{^3He} - d_{^3H} = -0.3\,\frac{\bar{g}_0}{F_\pi}\,e\ fm$$

→ **Predict other EDMs or higher moments (i.e. Schiff or magnetic quadrupole)**

So!

Measurements on nucleon and light nuclear EDMs

can shed light on the mechanism of T-violation



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**

- Standard techniques used to build the chiral T-odd Lagrangian
  Different sources $\longrightarrow$ **Different** chiral Lagrangians

- We have built a **consistent framework for quantitative calculations** of T-odd observables in A=1,2,3,..? nuclear systems

- The framework allows the **disentanglement** of the various T-odd sources