Parity and Time-Reversal Violating Moments of Light Nuclei

Jordy de Vries

Theory Group, KVI, University of Groningen

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University of Arizona

university of groningen

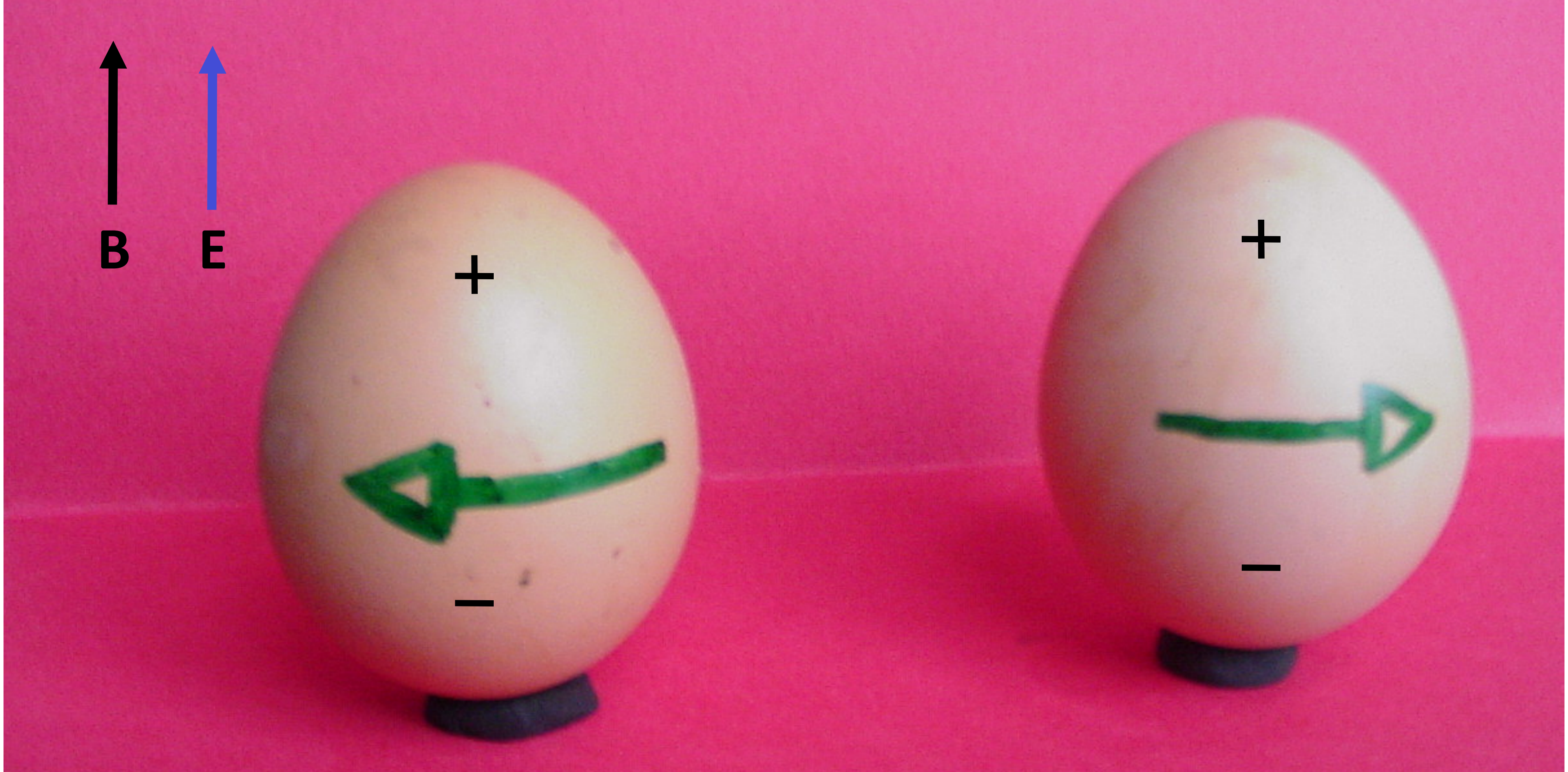
FOM

KVI

Outline of this talk

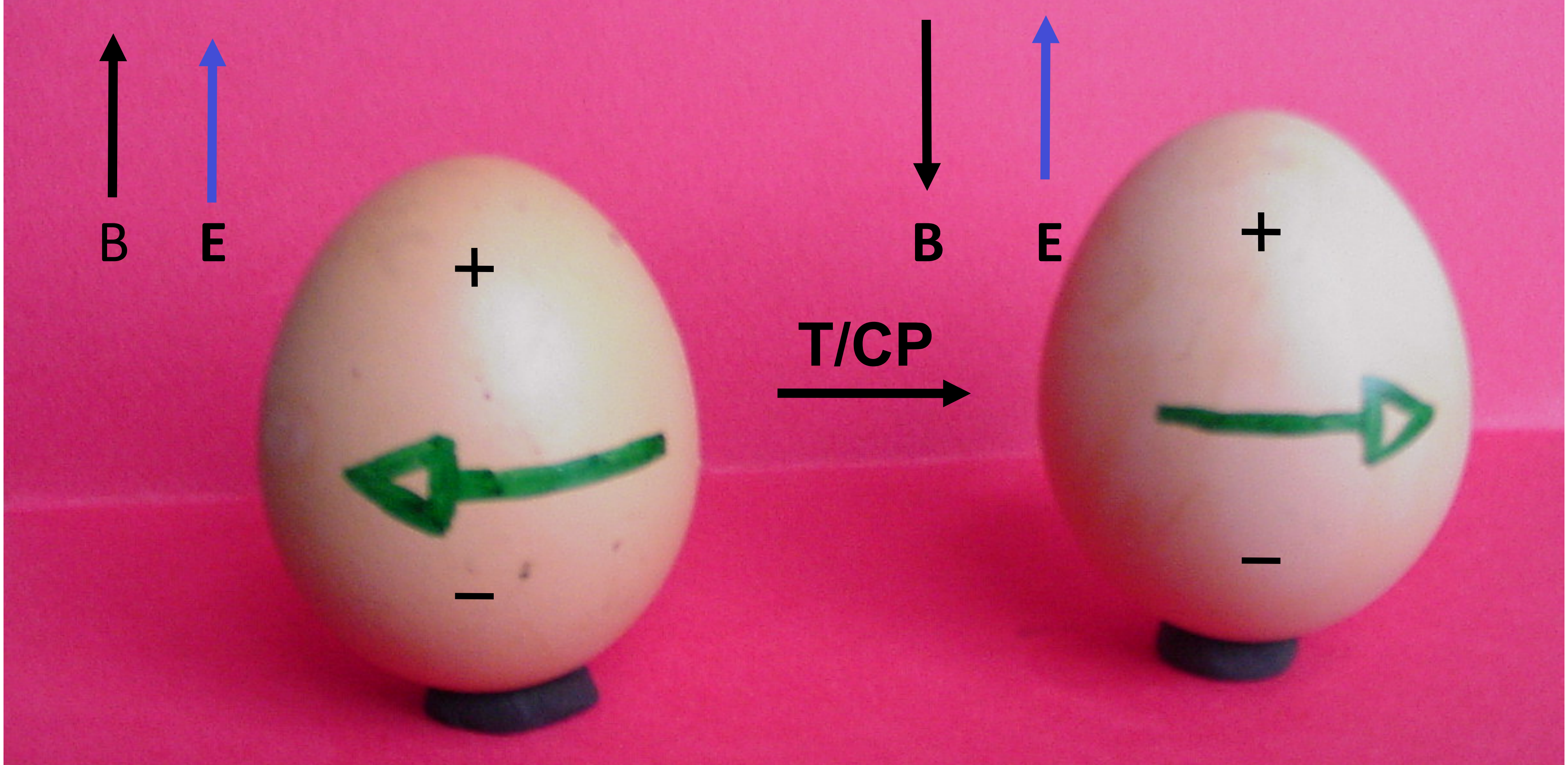
- **Part I: Electric Dipole Moments in the Standard Model**
- Part II: Standard Model as an Effective Field Theory
- Part III: Observables
  - IIIa: Nucleon
  - IIIb: Deuteron

Electric Dipole Moments

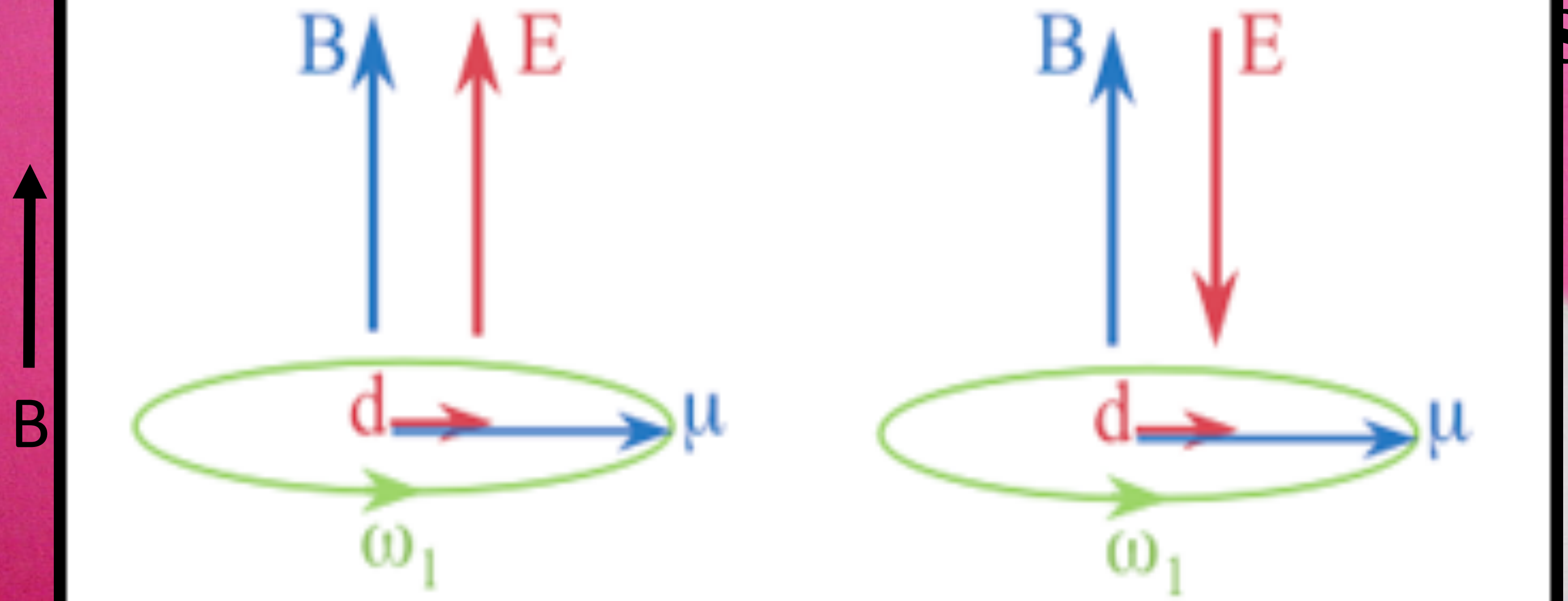


$$H = -\mu(\vec{\sigma}\cdot\vec{B}) - d(\vec{\sigma}\cdot\vec{E})$$

Electric Dipole Moments



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

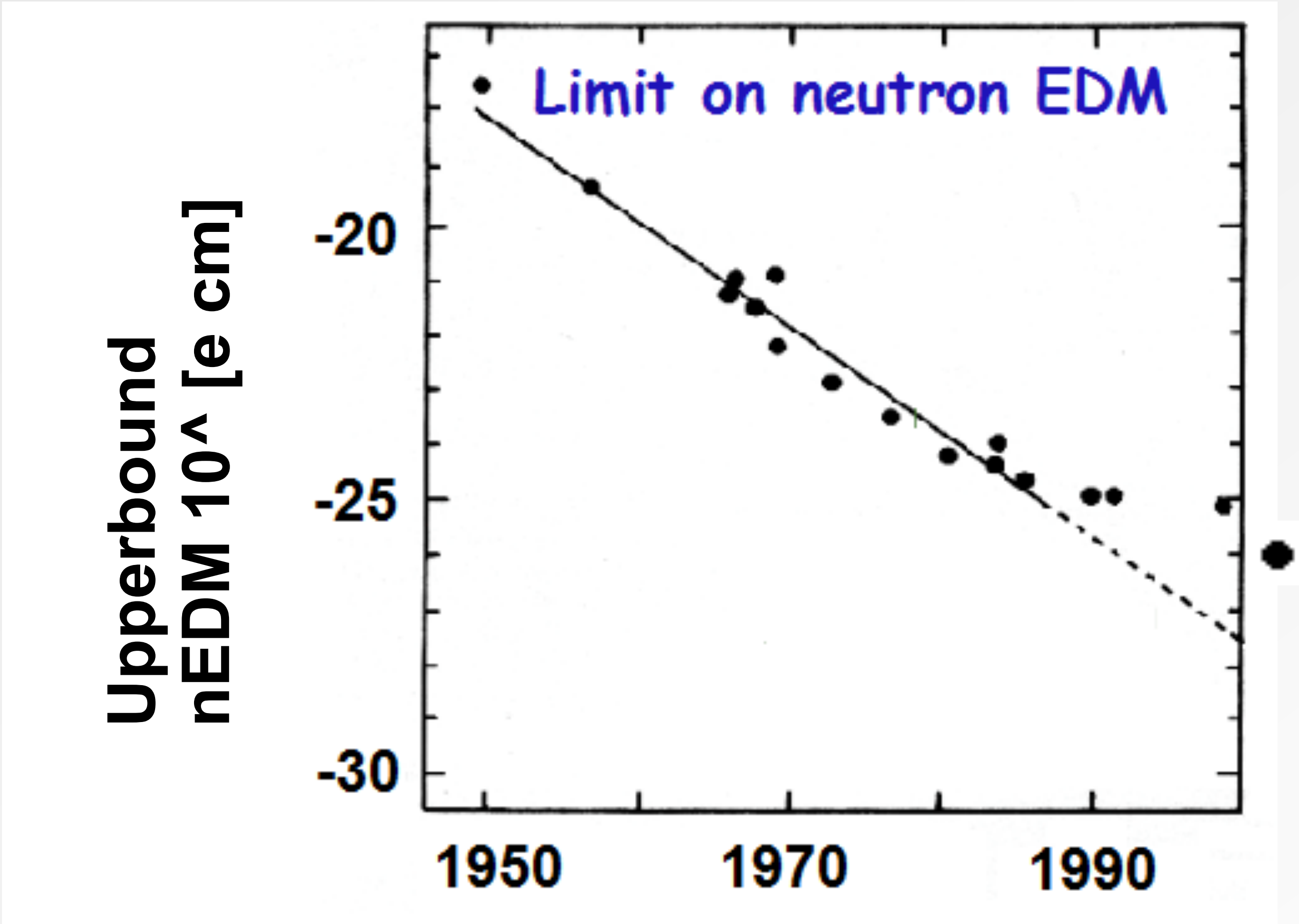


$$\omega_1 = \frac{2\,\mu B + 2dE}{\hbar} \qquad \omega_2 = \frac{2\mu B - 2dE}{\hbar}$$

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

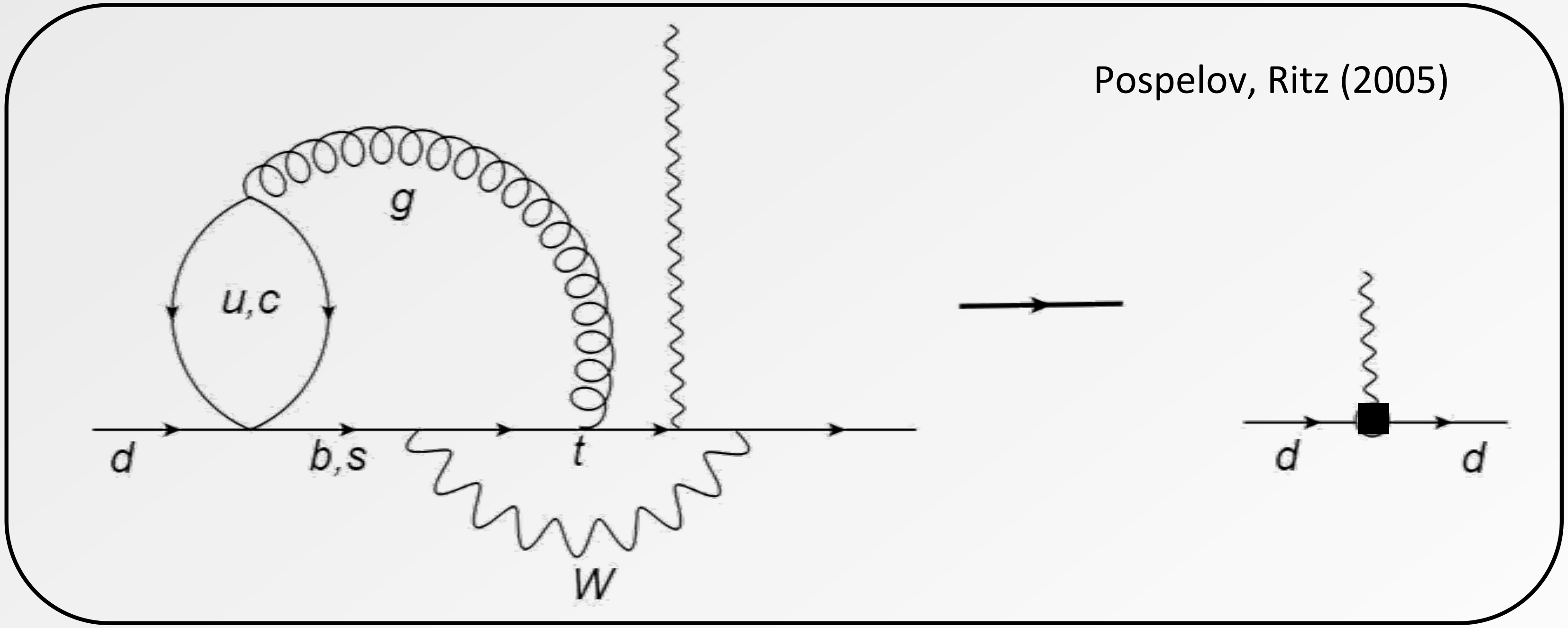
$$H = -\mu(\vec{\sigma}\cdot\vec{B}) + d(\vec{\sigma}\cdot\vec{E})$$

Experimental Upper Bound



EDM's in the Standard Model

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



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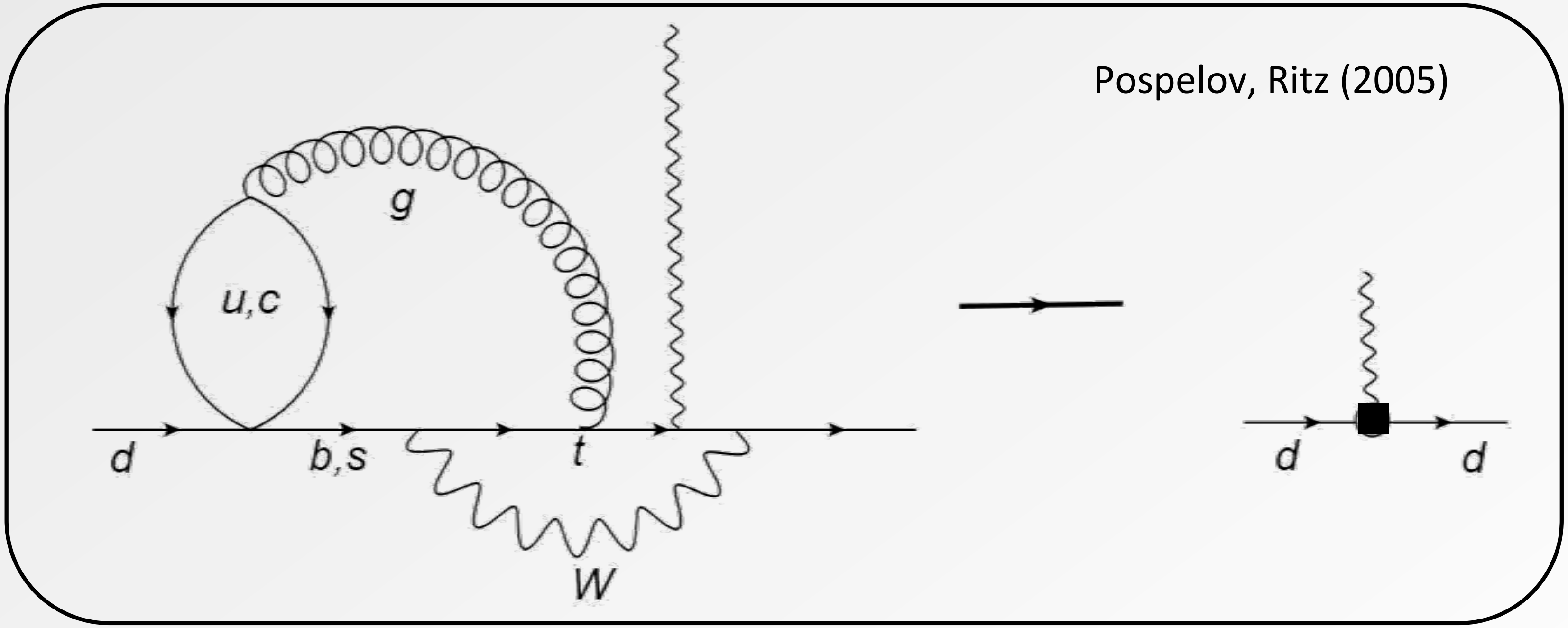
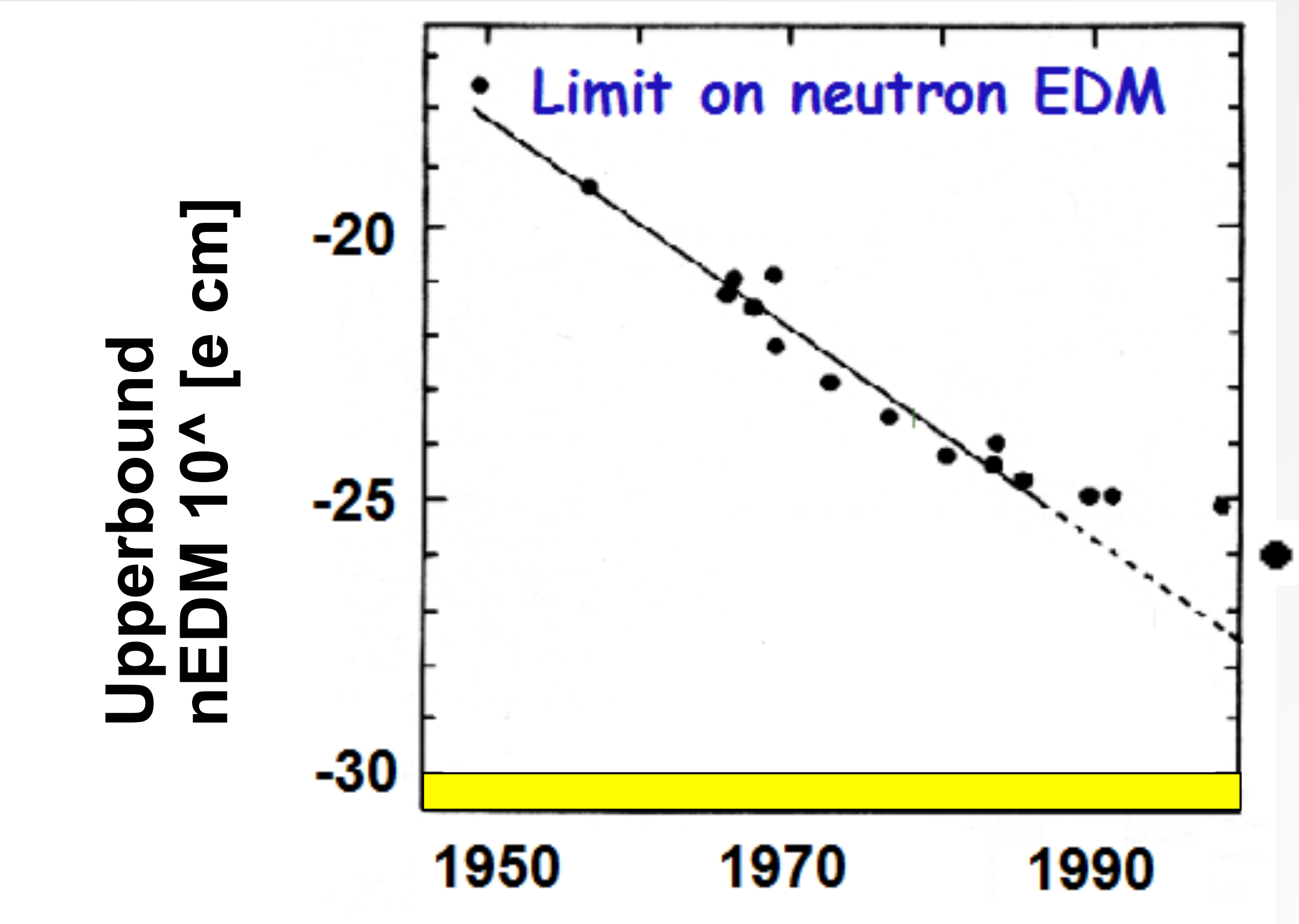


Highly Suppressed

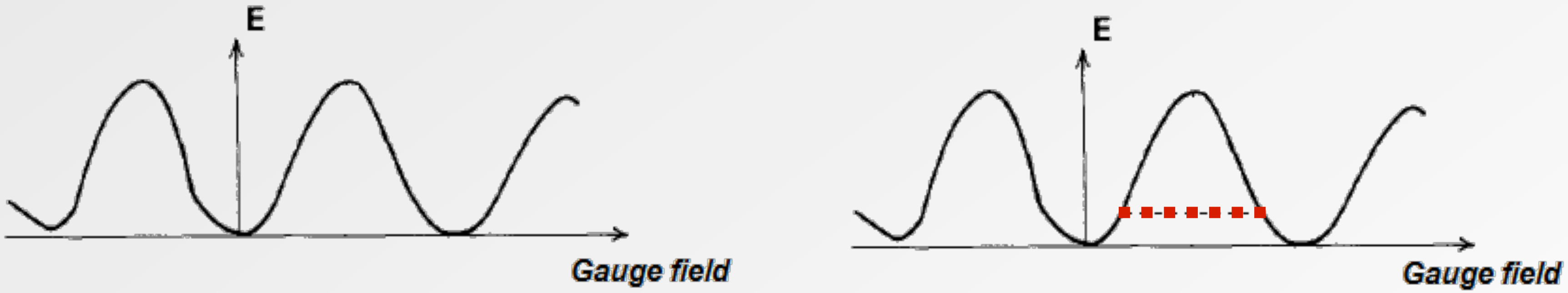
Electroweak CP-violation



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

EDM's in the Standard Model

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

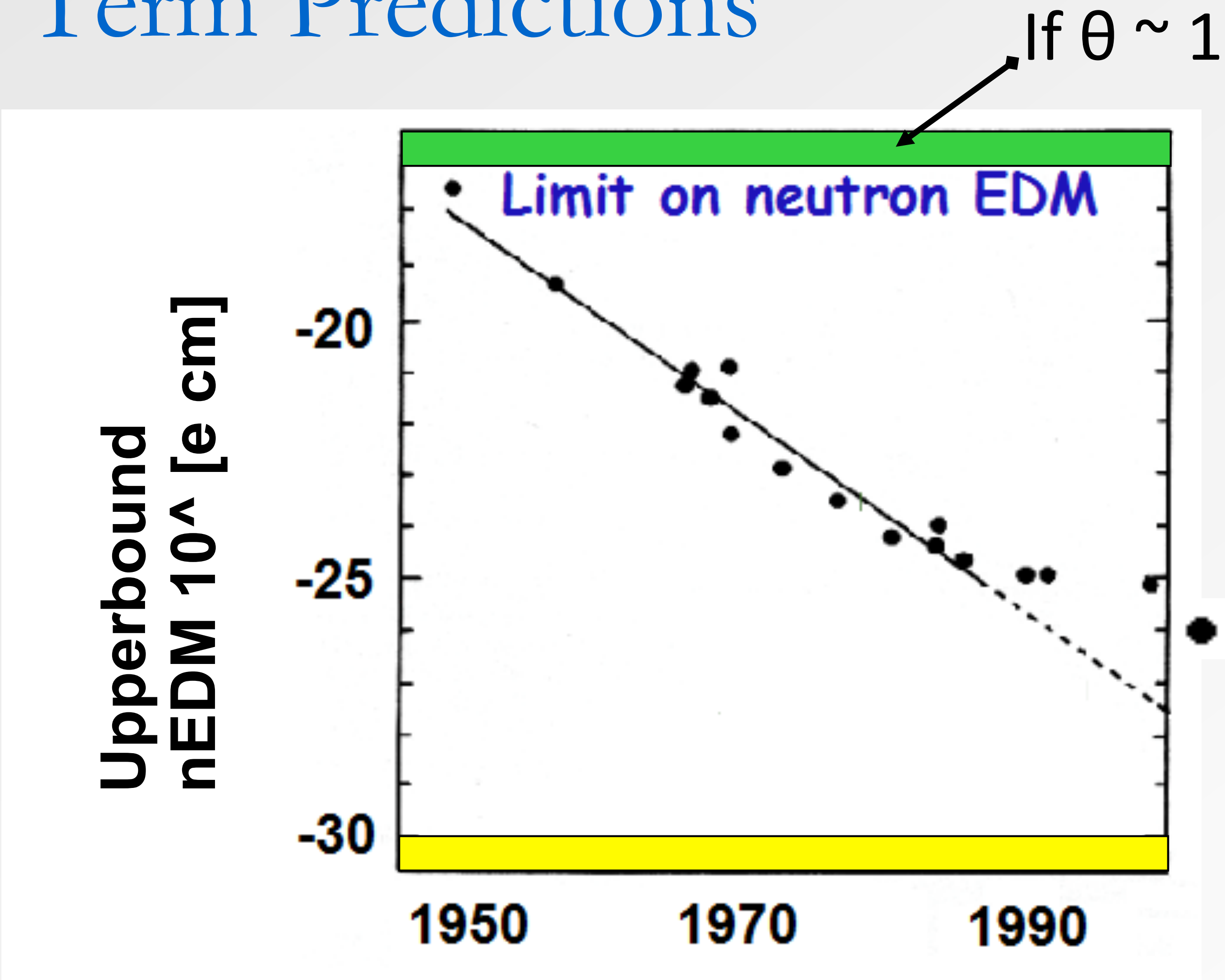


- Causes a 'new' CP-violating interaction with **coupling constant** θ

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

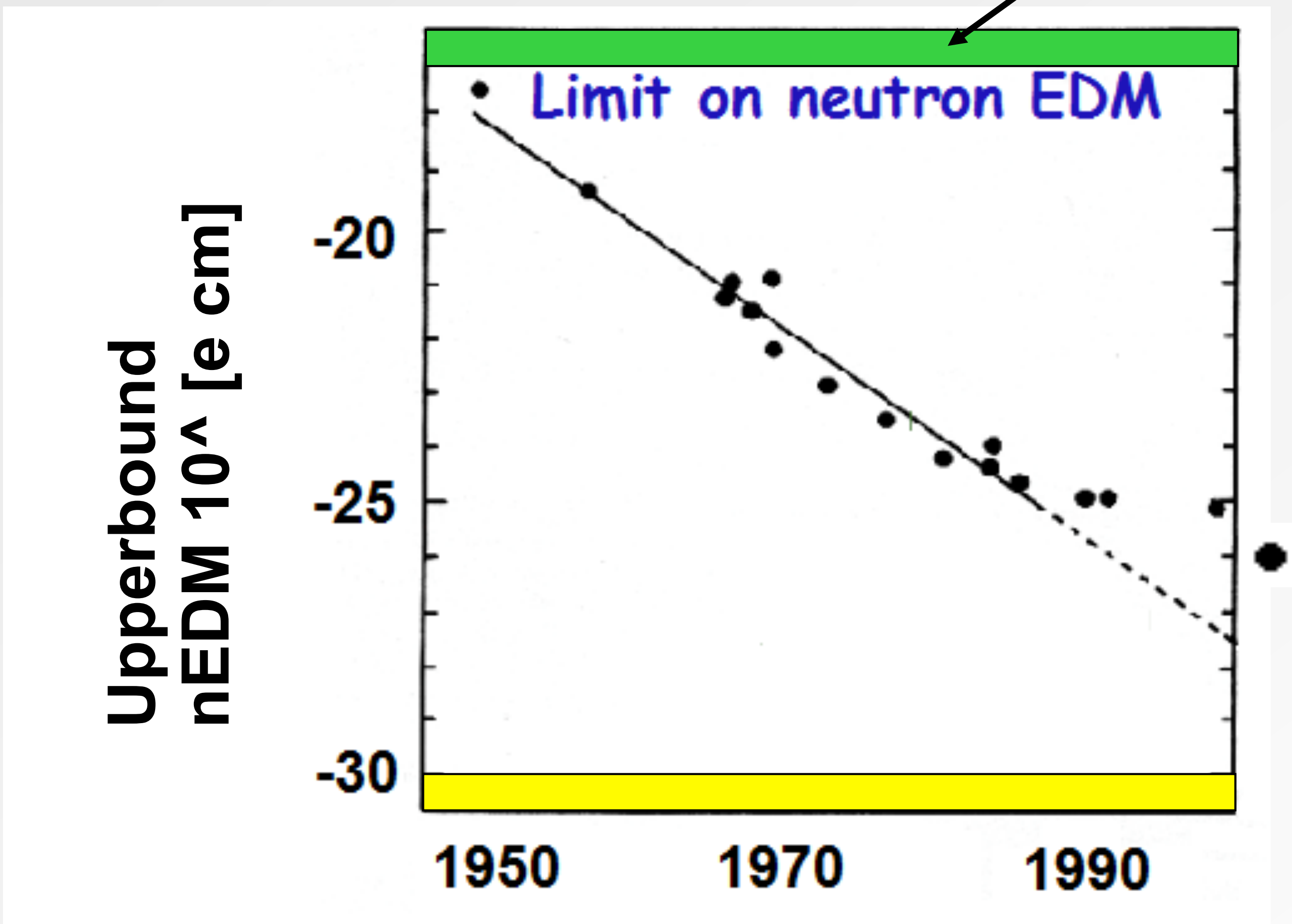
- Size of θ is **unknown**

Theta Term Predictions



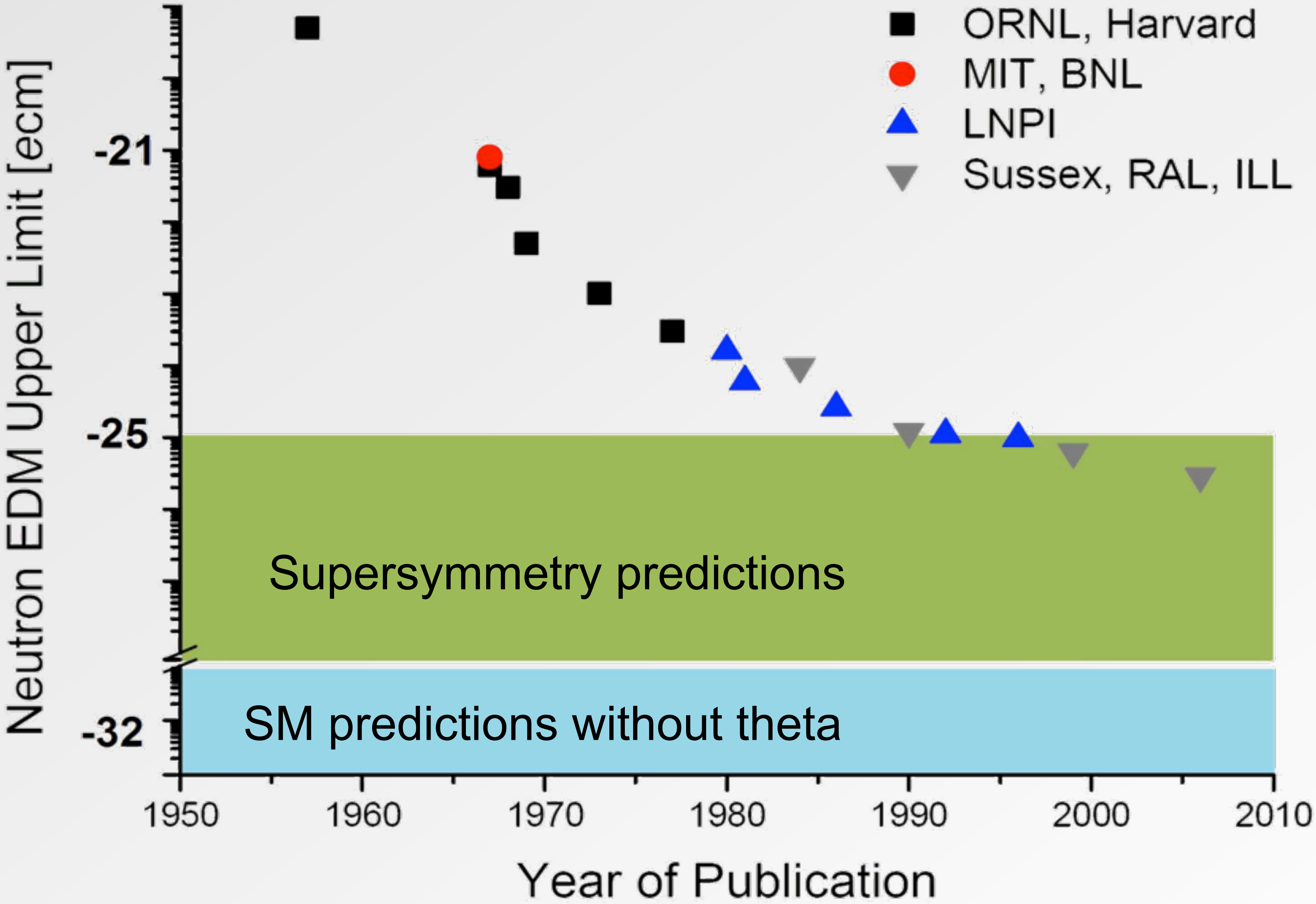
Theta Term Predictions

If θ ~ 1



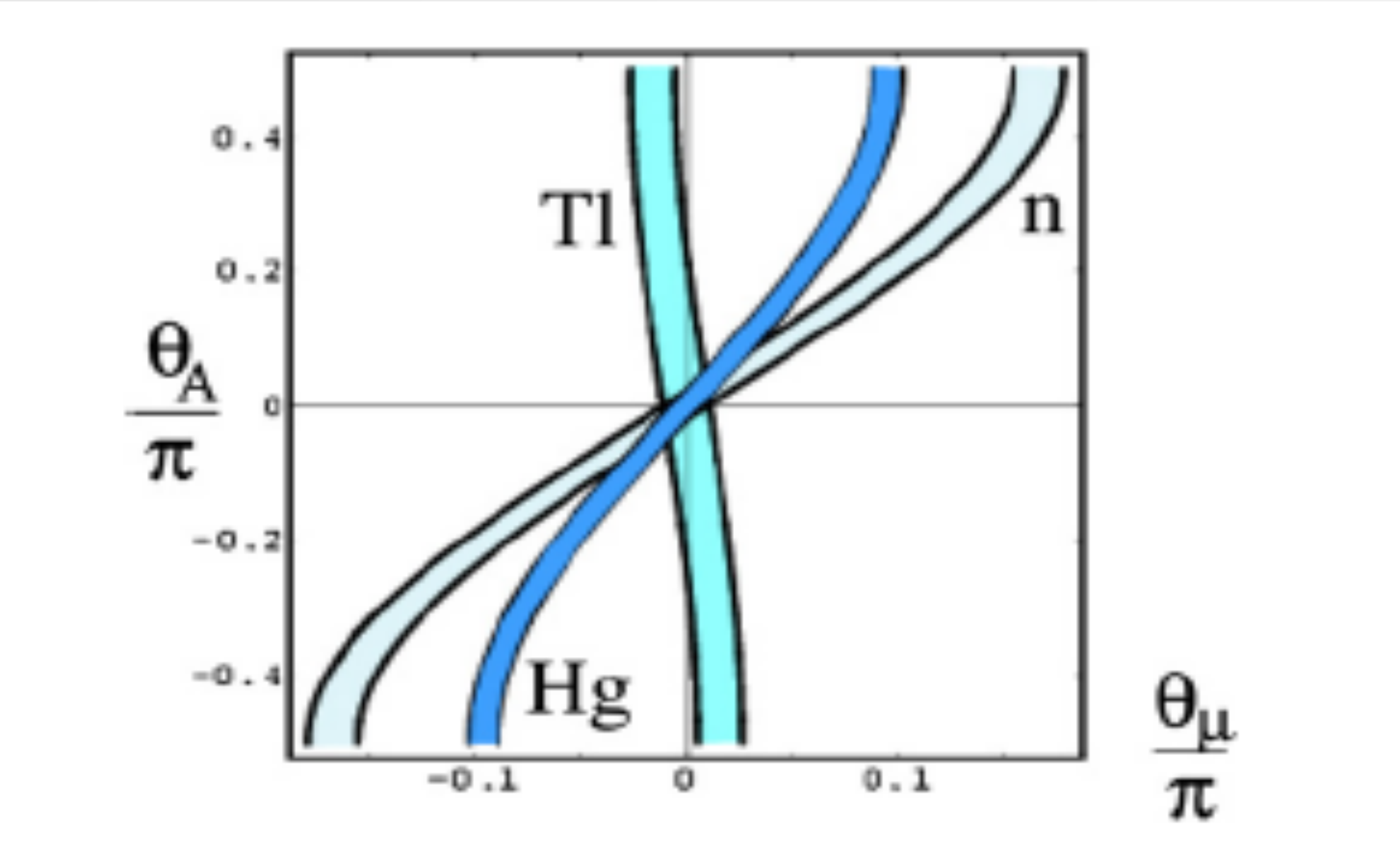
Crewther et al. (1979)

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



ORNL, Harvard
MIT, BNL
LNPI
Sussex, RAL, ILL
Neutron EDM Upper Limit [ecm]
-21
-25
-32
Supersymmetry predictions
SM predictions without theta
1950
1960
1970
1980
1990
2000
2010
Year of Publication

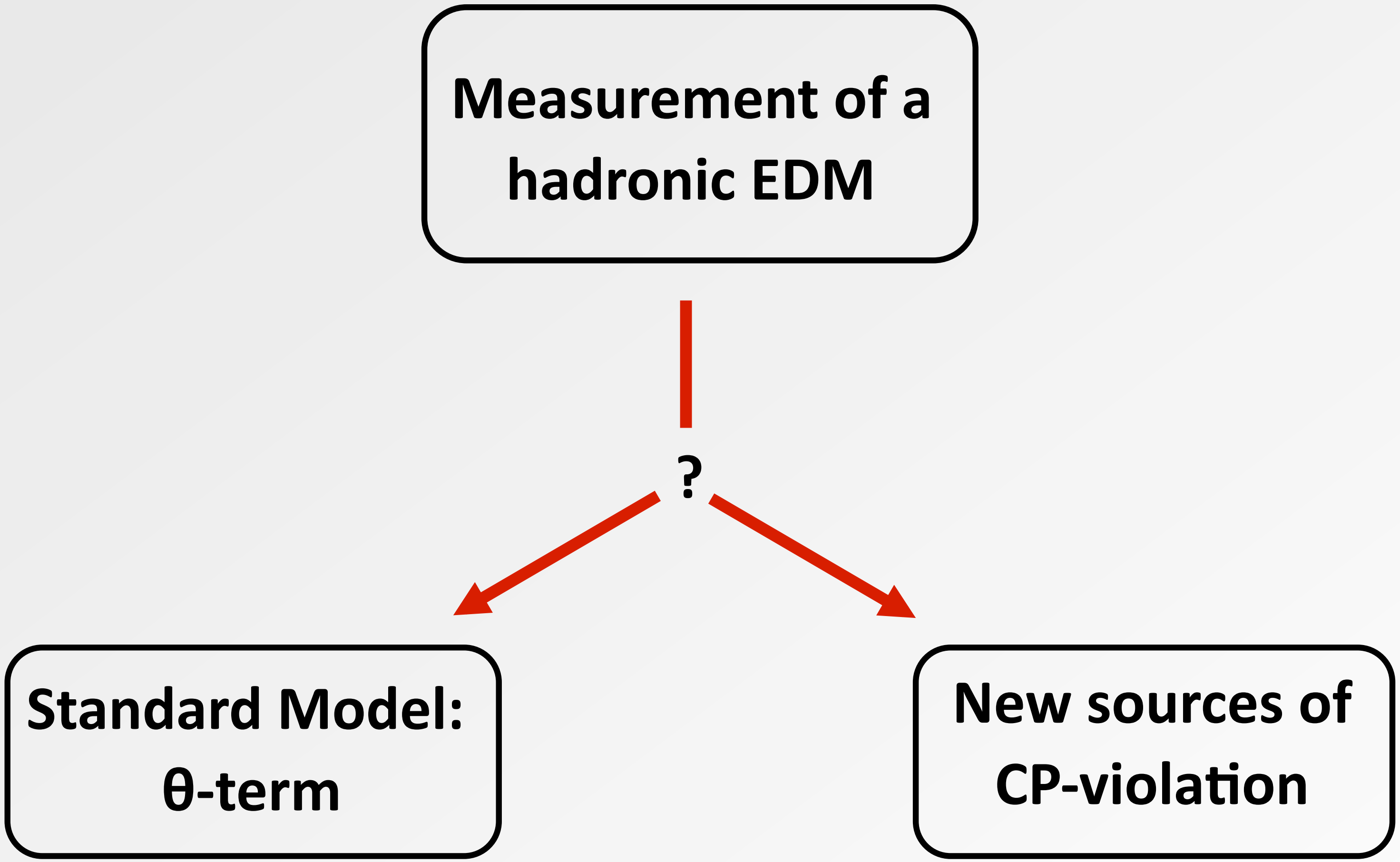
Constraining SUSY



(very constrained) MSSM: $\tan\beta = 3,\ M_{SUSY} = 500\ GeV$

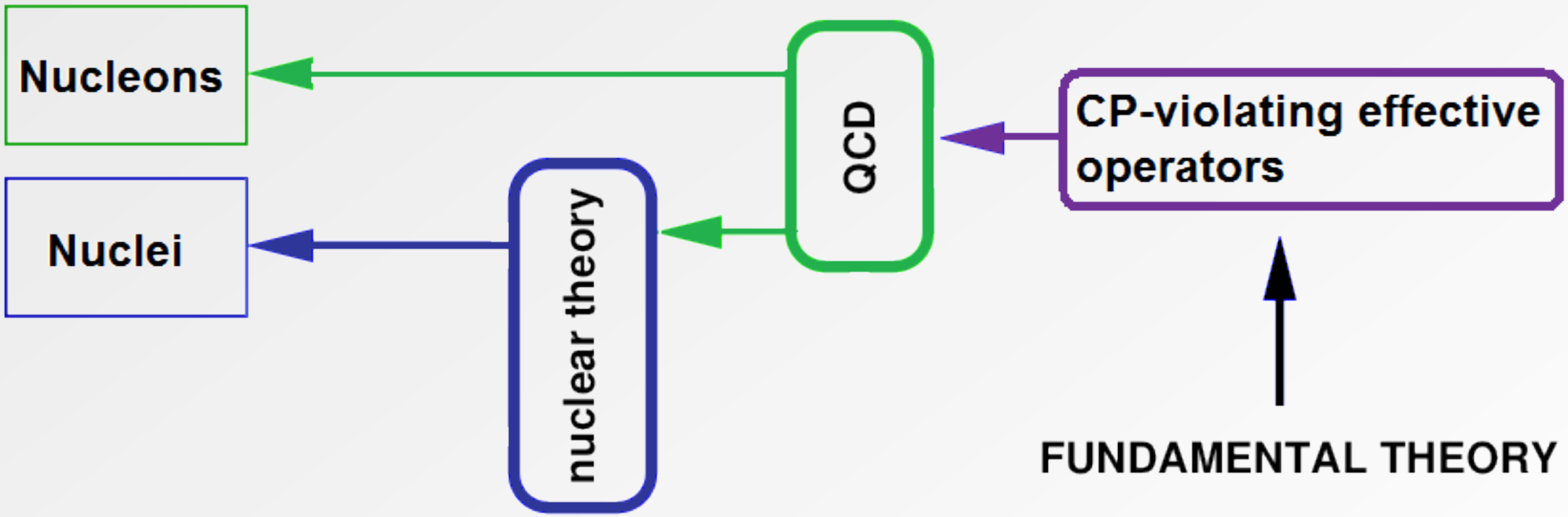
Pospelov, Ritz, Annals of Physics (2005)

Current Situation



Finding the **Source**

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



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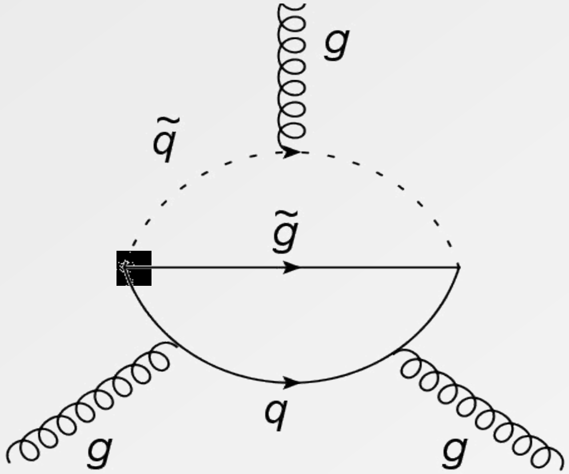
Standard Model as an EFT

1 TeV ?

SUSY?

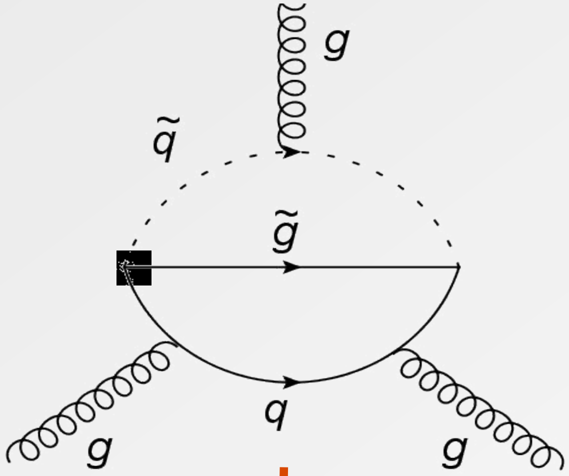


Energy

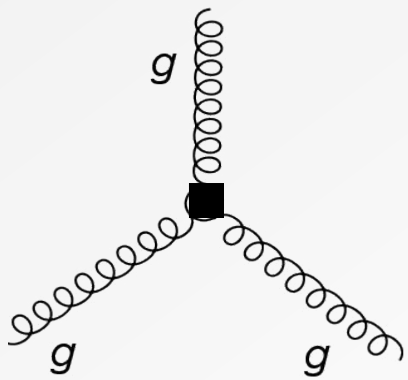
Standard Model as an EFT

1 TeV ?

SUSY?



Effectively becomes



$$\propto \frac{1}{M^2_{\not{T}}}$$

100 GeV

Standard Model

Energy

Standard Model as an EFT

- Add to the SM **all possible T+P-odd** contact interactions
- **Symmetry requirements**: Lorentz + SM gauge symmetries

100 GeV **Standard Model**

Energy

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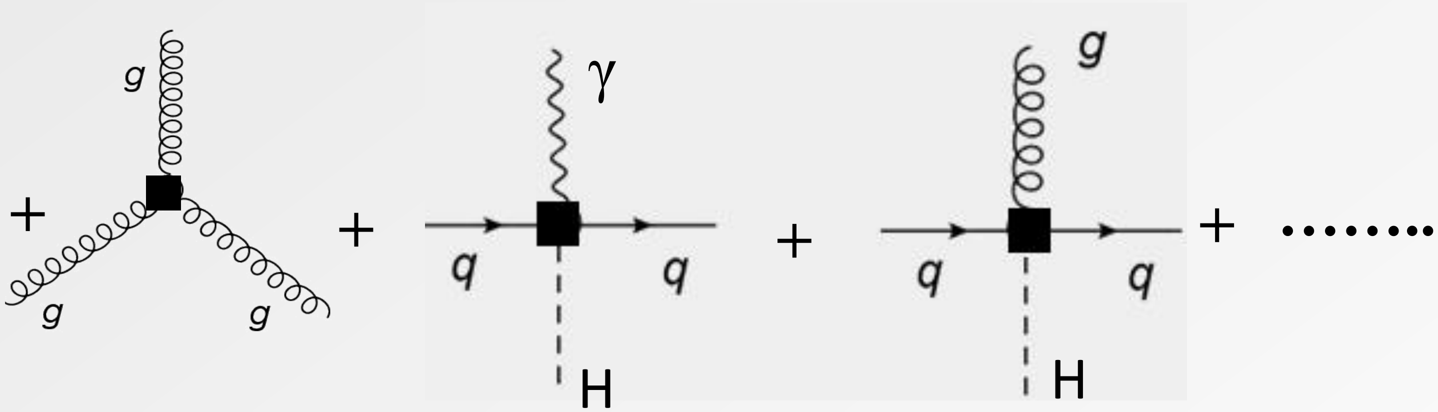
100 GeV **Standard Model**



(Gradzkowski, Iskrzynski, Misiak, Rosiek (2010))

Energy

Standard Model as an EFT

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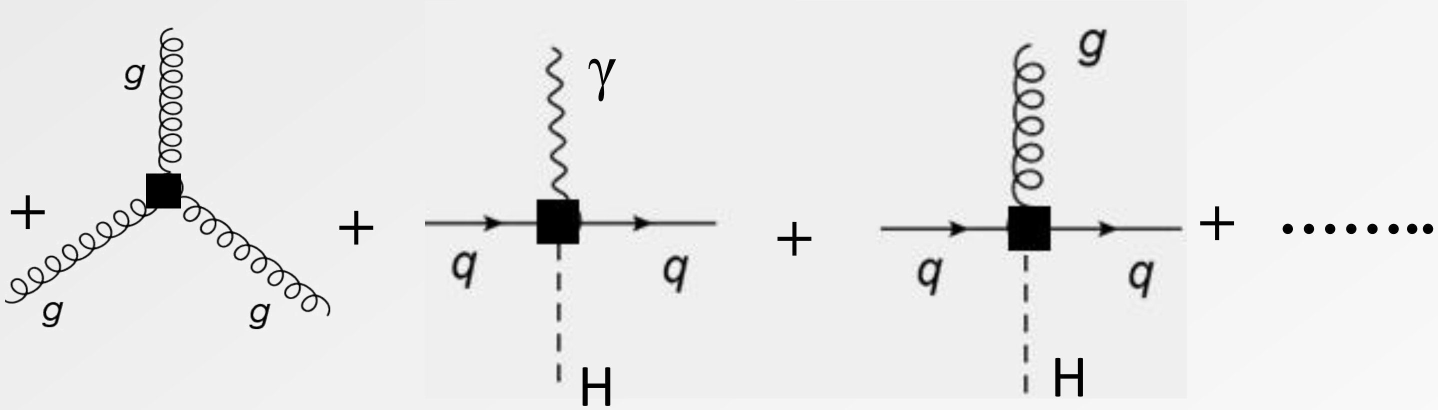
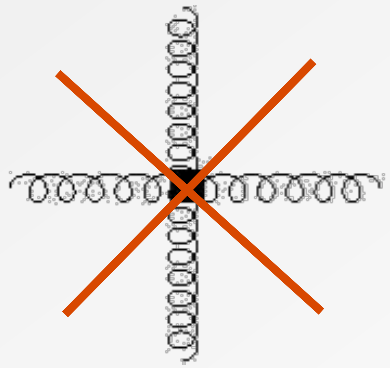
100 GeV **Standard Model**



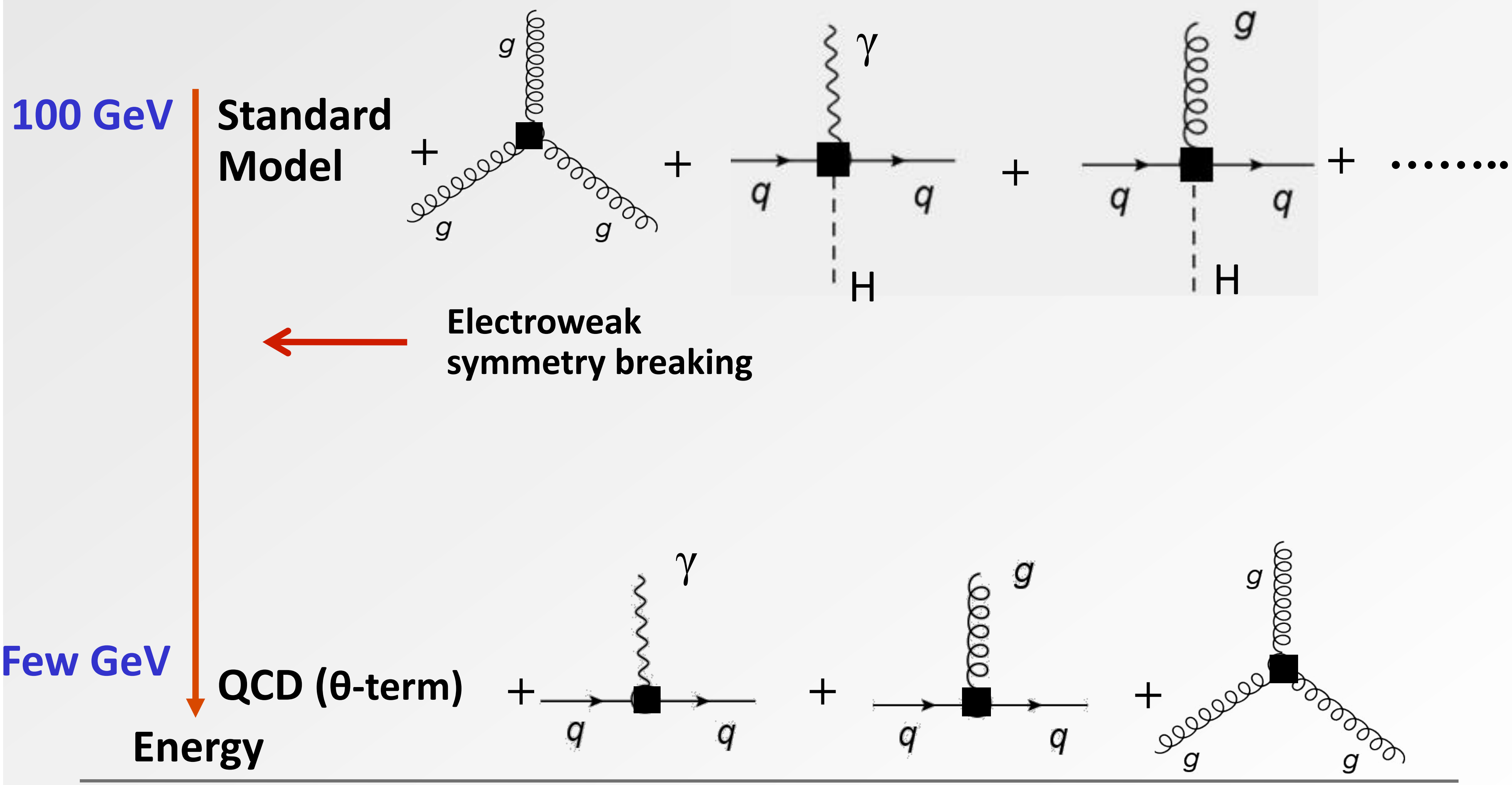


$$\propto \frac{1}{M_{\not T}^4}$$

Energy

Standard Model as an EFT

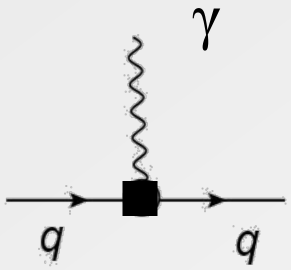
- Add to the SM **all possible T+P-odd** contact interactions
- **Symmetry requirements**: Lorentz + SM gauge symmetries



Effective P- and T-violation

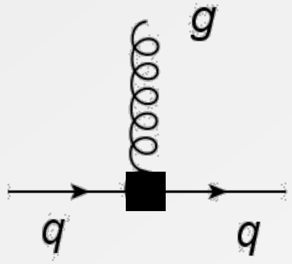
Few GeV

QCD(θ-term) +



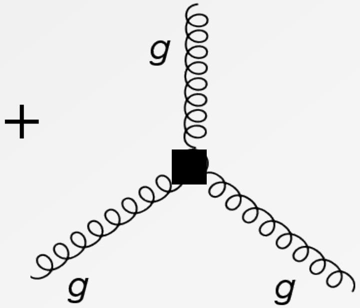
Quark EDM

+



Quark chromo-EDM

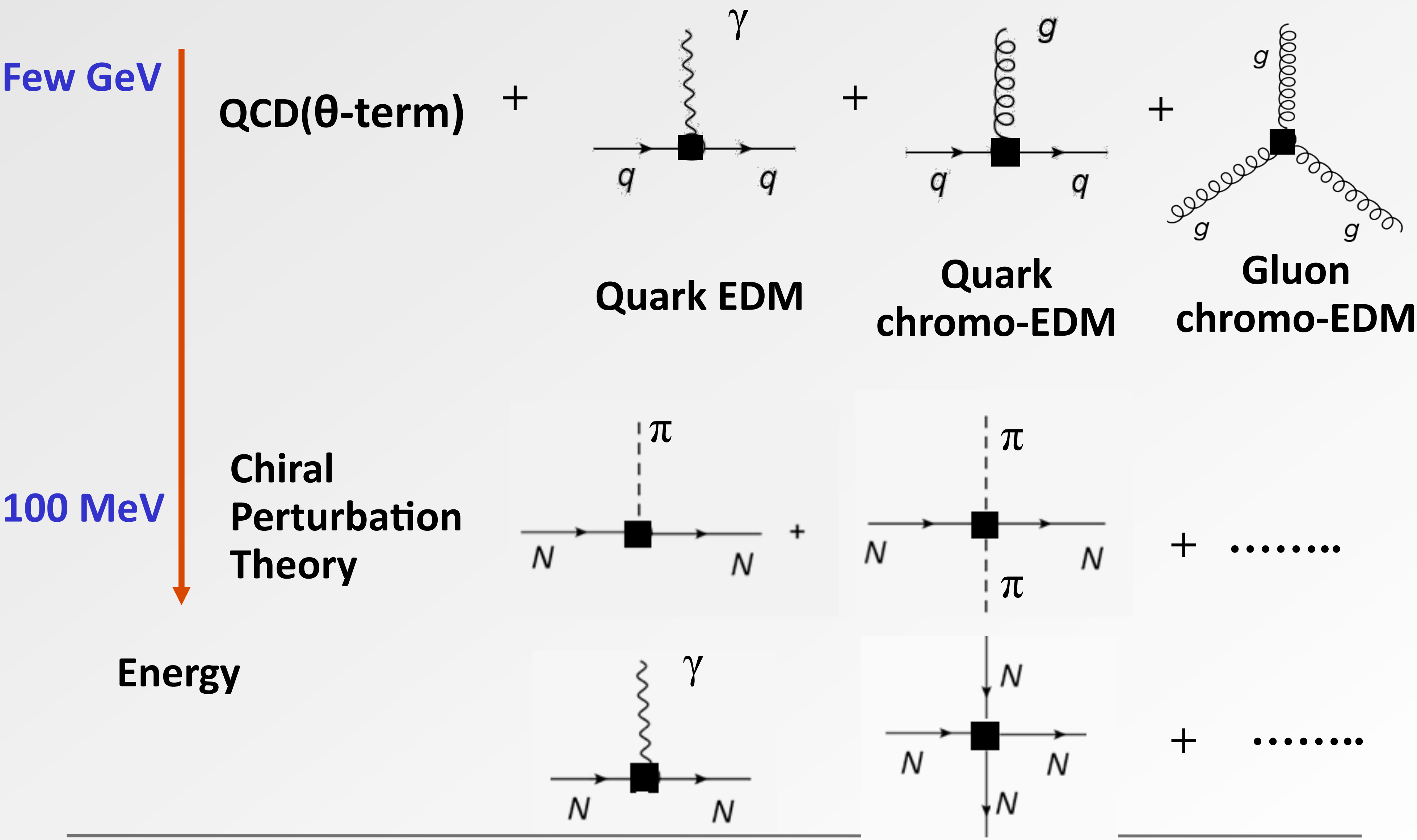
+



Gluon chromo-EDM

Energy

Effective P- and T-violation



Hierarchy among the sources

Each source transforms **differently** under chiral symmetry

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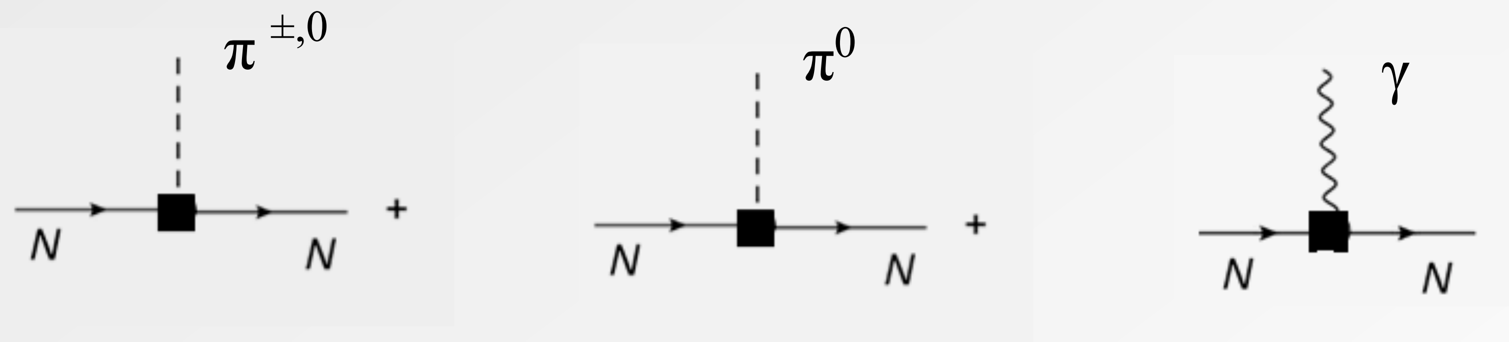
Each source transforms **differently** under chiral symmetry

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



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

Hierarchy among the sources

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$\left\lvert\frac{\bar{g}_1}{\bar{d}_0}\right\rvert / M_{QCD}^2$	$\left(\frac{m_\pi}{M_{QCD}}\right)^2$	1	$\left(\frac{\alpha_{em}}{4\pi}\right)$	$\left(\frac{m_\pi}{M_{QCD}}\right)^2$

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The Nucleon Electric Dipole Moment

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

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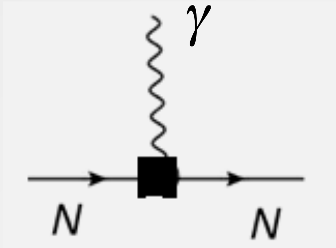
- θ-term + quark chromo-EDM

Nucleon EDM



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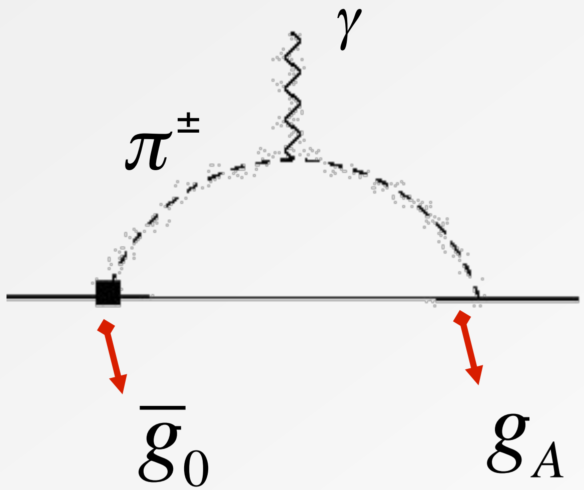

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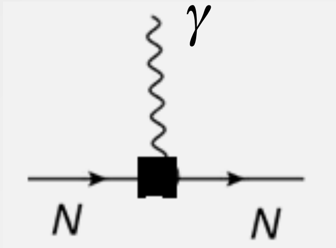

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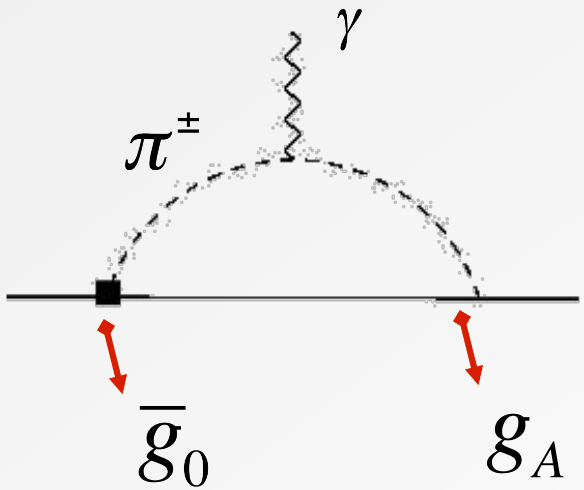


$$d_n = \bar{d}_0 - \bar{d}_1 + \frac{e g_A}{(2\pi F_\pi)^2} \ln\left(\frac{m_\pi^2}{m_n^2}\right) \bar{g}_0$$

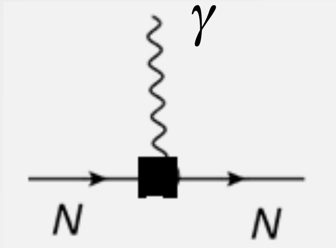
$$d_p = \bar{d}_0 + \bar{d}_1 - \frac{e g_A}{(2\pi F_\pi)^2} \ln\left(\frac{m_\pi^2}{m_n^2}\right) \bar{g}_0$$

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 (loops are suppressed)

Nucleon EDM



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

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The Nucleon Electric Dipole Moment

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

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

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

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Describing the deuteron

- Measurement of neutron and proton EDM not enough for disentangling the source → **Need more observables**
- Deuteron can be described **within same framework** as the nucleon
- Experiment planned!

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$$\gamma = \sqrt{m_N E_b} \approx 45\ MeV < m_\pi$$

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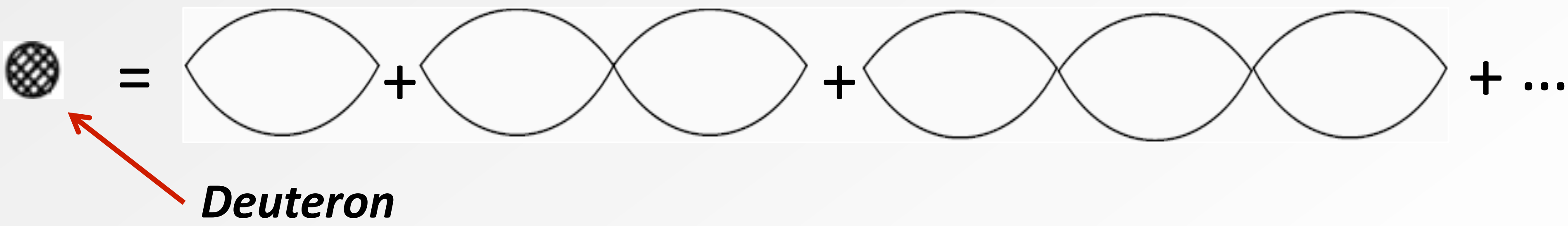
- Deuteron can be described **within same framework** as the nucleon
- Experiment planned!

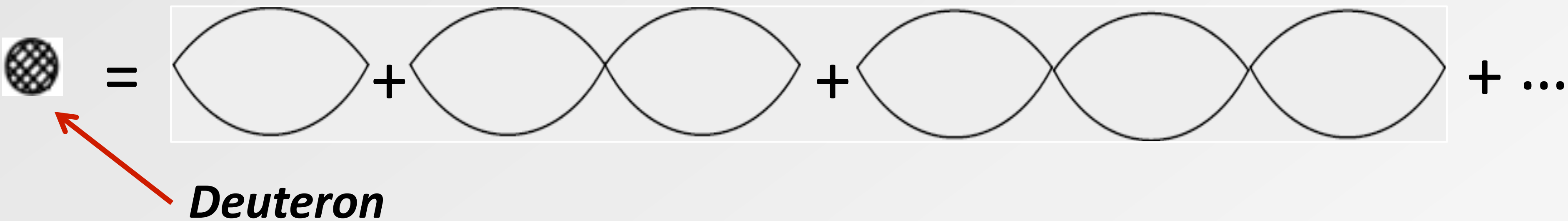
- Problem: the **small** binding momentum

$$\gamma = \sqrt{m_N E_b} \approx 45\ MeV < m_\pi$$

- We use a perturbative pion approach (Kaplan, Savage, Wise (1996))
- **S-wave nucleon-nucleon** interactions are **enhanced** and need to be summed



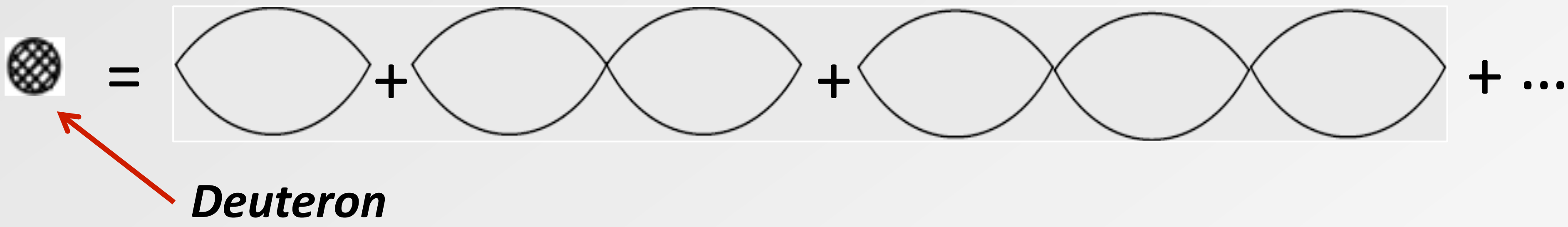
Describing the deuteron



Deuteron

- All other interactions are treated **perturbatively**

Describing the deuteron



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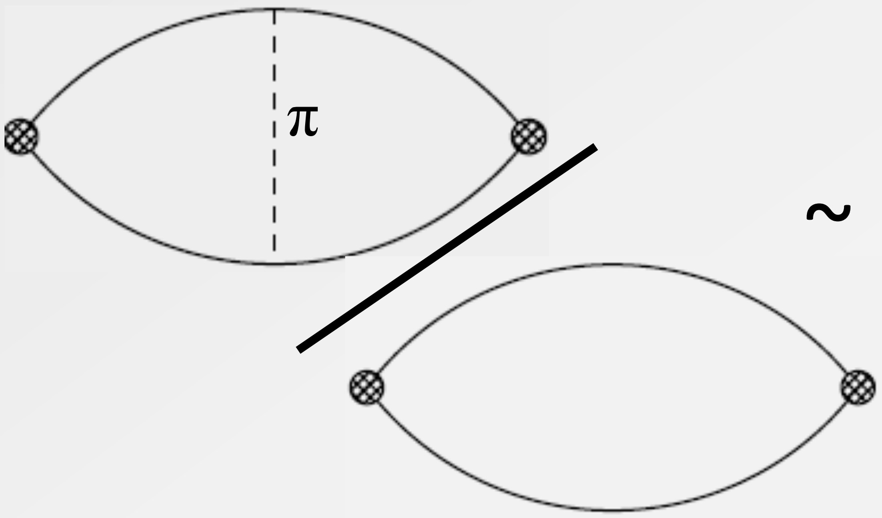
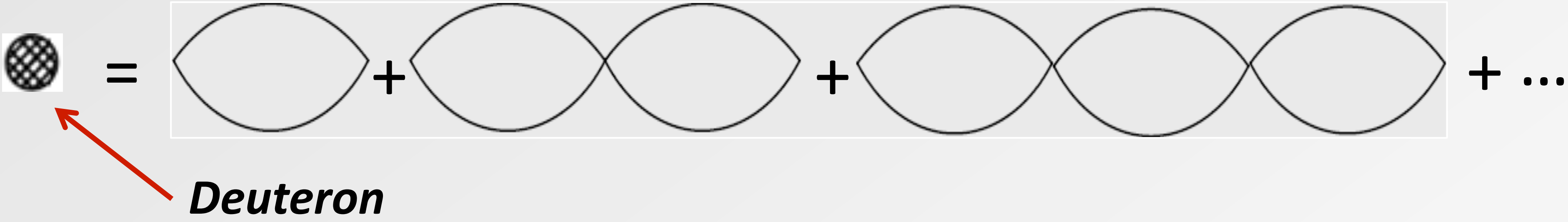


$$\sim \quad m_\pi \left(\frac{g_A^2 m_N}{4\pi F_\pi^2} \right) \equiv \frac{m_\pi}{M_{NN}} \approx 0.3$$

Describing the deuteron



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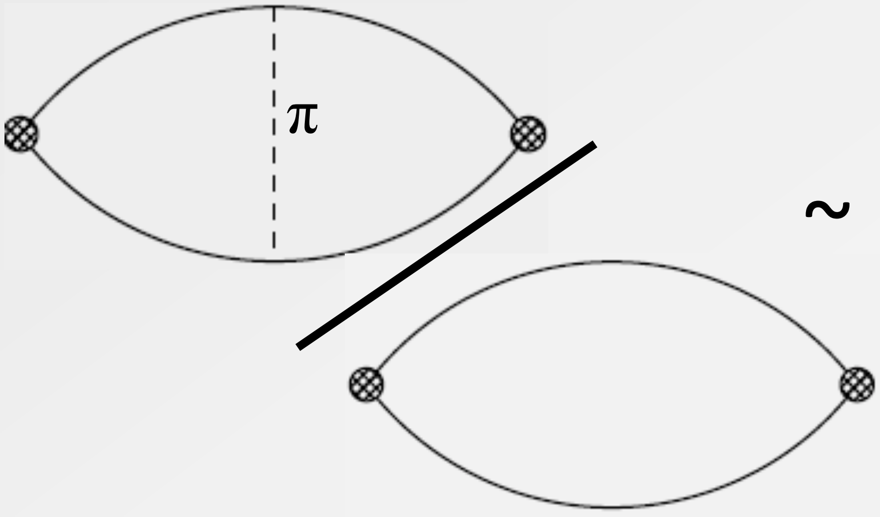
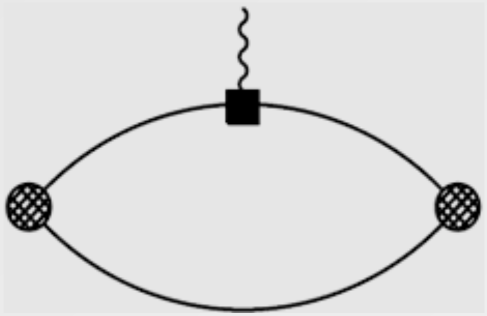


$$\sim \quad m_\pi \left(\frac{g_A^2 m_N}{4\pi F_\pi^2} \right) \equiv \frac{m_\pi}{M_{NN}} \approx 0.3$$

- The calculated P+T-conserving electromagnetic form factors agree well with experiments *Kaplan, Savage, Wise* (1999)

The deuteron EDM

- The deuteron EDM at leading order comes from 2 diagrams



One-body: $d_D = 2\bar{d}_0 = d_n + d_p$

The deuteron EDM

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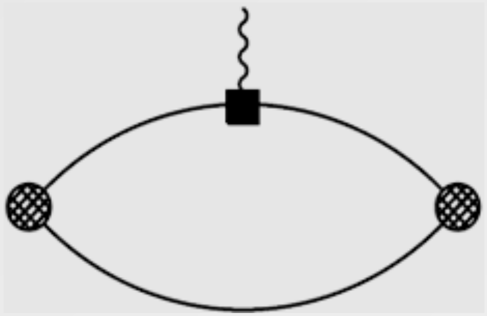

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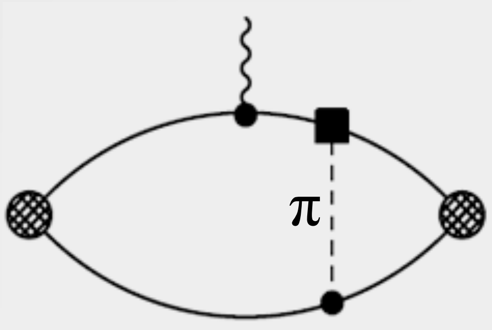

P+T-violating pion-exchange

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

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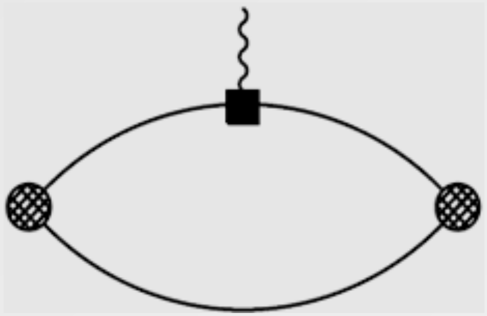
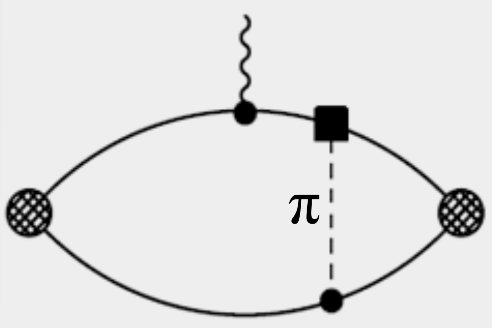


One-body: $d_D = 2\bar{d}_0 = d_n + d_p$



P+T-violating pion-exchange

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

$$^3S_1 \xrightarrow{\bar{g}_0} {}^1P_1 \xrightarrow{\gamma} \not{{}^3S_1}$$

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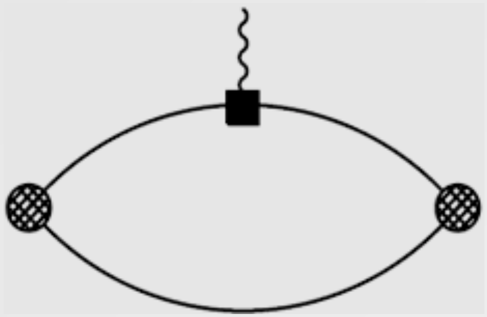
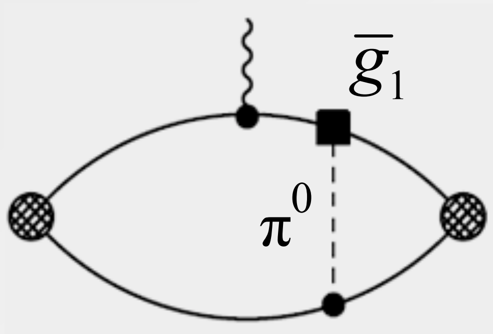
The deuteron EDM





- Easy to calculate the diagrams

$$d_d = d_n + d_p$$

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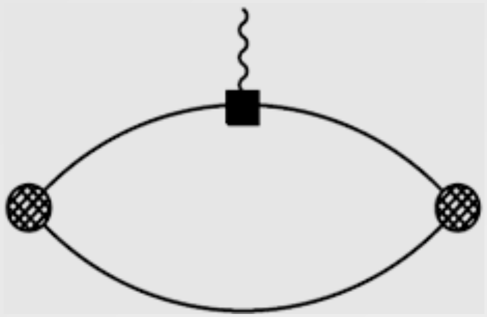
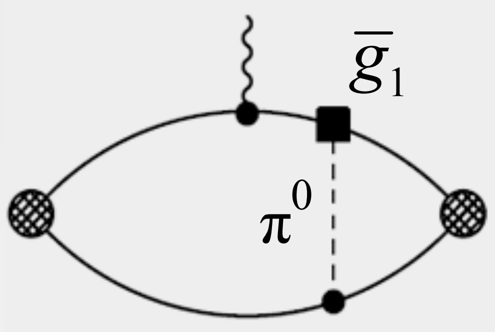


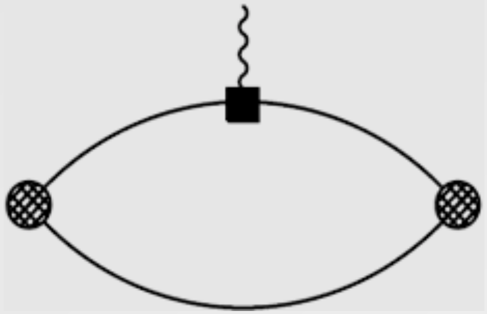


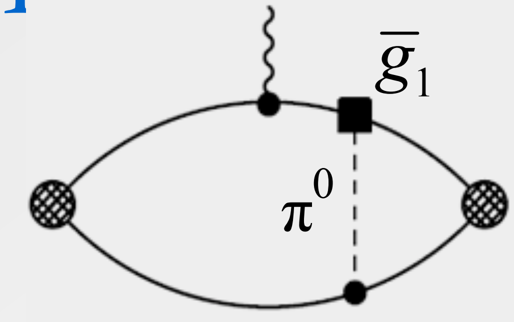
- Easy to calculate the diagrams

$$d_d = d_n + d_p$$

$$d_d = \bar{g}_1 \frac{2e\, g_A}{3 m_\pi M_{NN}} \frac{1+\gamma/m_\pi}{(1+2\gamma/m_\pi)^2}$$

The deuteron EDM

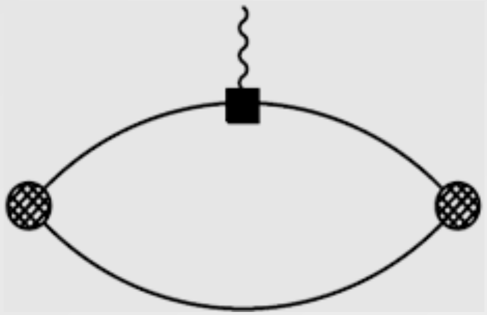


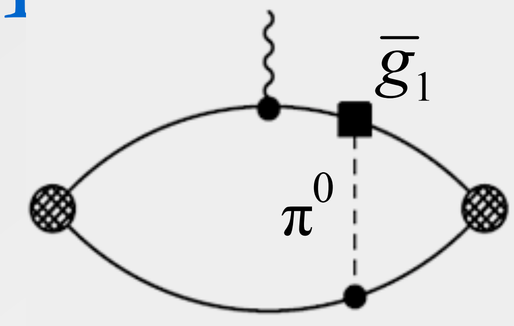


- Which effect **dominates** depends on the ratio of the diagrams

$$R \approx \left|\frac{\bar{g}_1}{\bar{d}_0}\right| \frac{1}{m_\pi M_{NN}}$$

The deuteron EDM





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

$$R \approx \left| \frac{\bar{g}_1}{\bar{d}_0} \right| \frac{1}{m_\pi M_{NN}}$$

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

	Theta term	Quark CEDM	Quark EDM	Gluon CEDM
$\left\| \frac{\bar{g}_1}{\bar{d}_0} \right\| / M_{QCD}^2$	$\left(\frac{m_\pi}{M_{QCD}} \right)^2$	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
Deuteron EDM/ (neutron+proton EDM)	1	$\left(\frac{M_{QCD}^2}{m_\pi M_{NN}}\right)$	1	1

- For 3 out of 4 sources d_D **is dominated by** $d_n + d_p$
- For quark chromo-EDM **pion-exchange** dominates d_D

JdV, Mereghetti, Timmermans, van Kolck, PRL (2011)

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~ 6

- A measurement of d_D **significantly larger** than $d_n + d_p$ indicates **new physics** in the shape of a **quark chromo-EDM**

JdV, Mereghetti, Timmermans, van Kolck, PRL (2011)

The deuteron MQM

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

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

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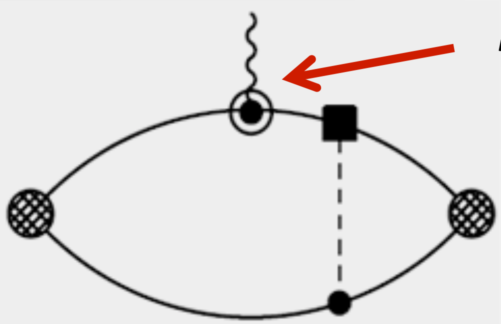

Sensitive to **both** $\bar{g}_0$ and $\bar{g}_1$ exchange

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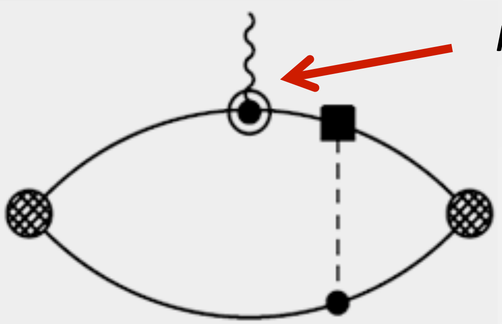

nucleon magnetic moment

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

- Dominant effect for both **theta** and **quark chromo-EDM**

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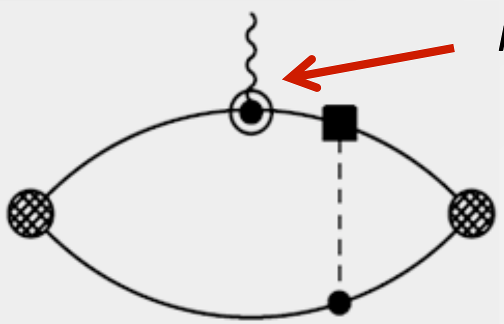


Sensitive to **both** $\bar{g}_0$ and $\bar{g}_1$ exchange

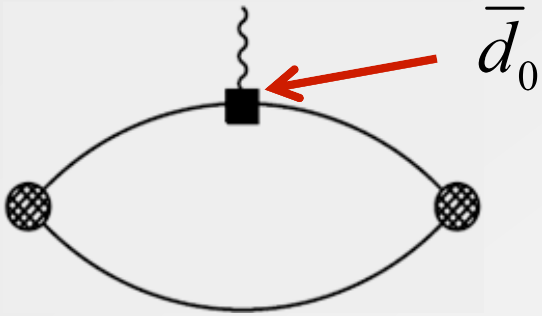
For quark chromo-EDM: $\frac{\overline{\mathrm{M}}_d}{d_d} m_N = (\mu_p - \mu_n) + \frac{3\bar{g}_0}{\bar{g}_1}(\mu_p + \mu_n)$

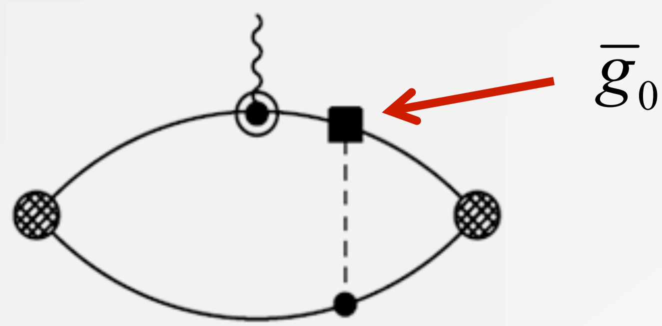
The deuteron MQM

deuteron EDM

deuteron MQM

For theta:





The deuteron MQM

deuteron EDM

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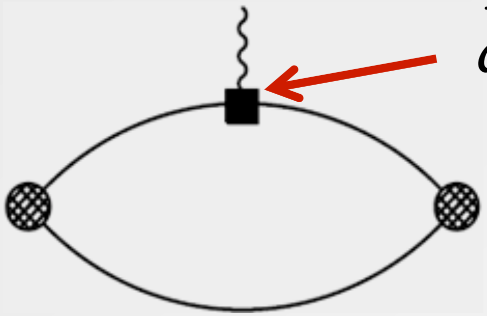
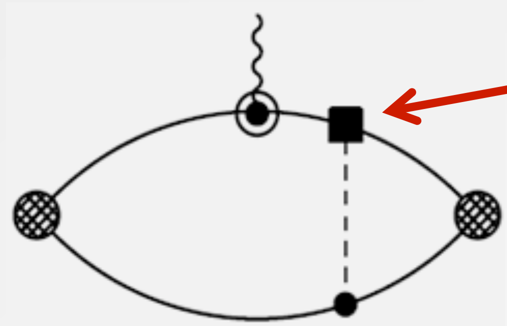
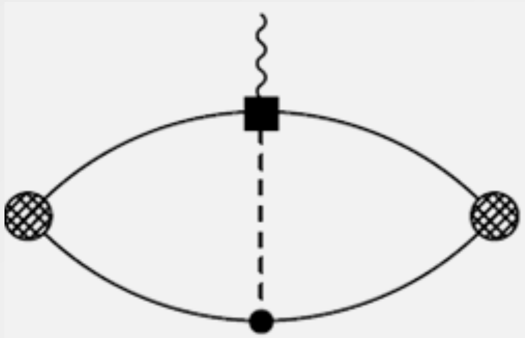


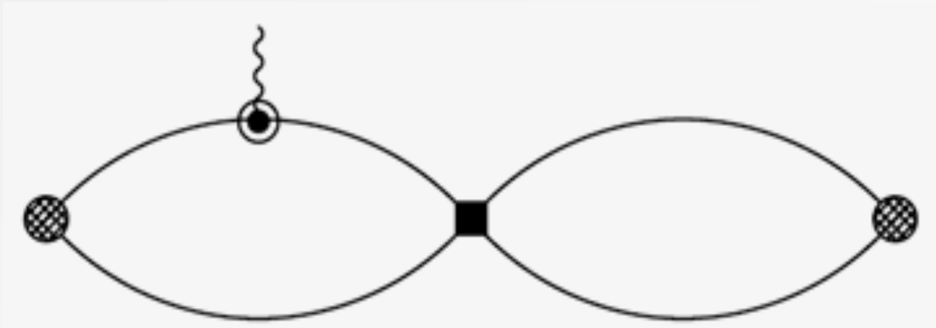


$$\frac{\overline{\mathbf{M}}_d}{d_d} m_N \propto \left|\frac{\bar{g}_0}{\bar{d}_0}\right| \frac{(\mu_p + \mu_n)}{m_\pi M_{NN}} \approx \frac{M_{QCD}^2}{m_\pi M_{NN}} \approx 10$$

The deuteron MQM

- Unfortunately for **quark EDM** and **gluon chromo-EDM** new interactions appear
- More coupling constants so less predictive power





The deuteron EDM and MQM

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mN*Deuteron MQM/ (Deuteron EDM)	$\left(\frac{M_{QCD}^2}{m_\pi M_{NN}}\right)$	1	$\left(\frac{m_\pi}{M_{NN}}\right)$	1

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

JdV, Mereghetti, Timmermans, van Kolck, PRL (2011)

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

JdV, Mereghetti, Timmermans, van Kolck, PRL (2011)

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 **three effective interactions of dimension-six**
- A deuteron EDM **significantly larger** than nucleon EDM points to new physics (quark chromo-EDM)
- A deuteron MQM is sensitive to the **theta-term**

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- A deuteron EDM **significantly larger** than nucleon EDM points to new physics (quark chromo-EDM)
- A deuteron MQM is sensitive to the **theta-term**
- Measuring the EDMs of **3He or 3H** (after nucleon+deuteron) is enough to **separate the sources**

JdV, Higa, Liu, Mereghetti, Stetcu, Timmermans, van Kolck, PRC (2011)