Theory of Electric Dipole Moments:

A (theorists) motivation for JEDI

Jordy de Vries

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

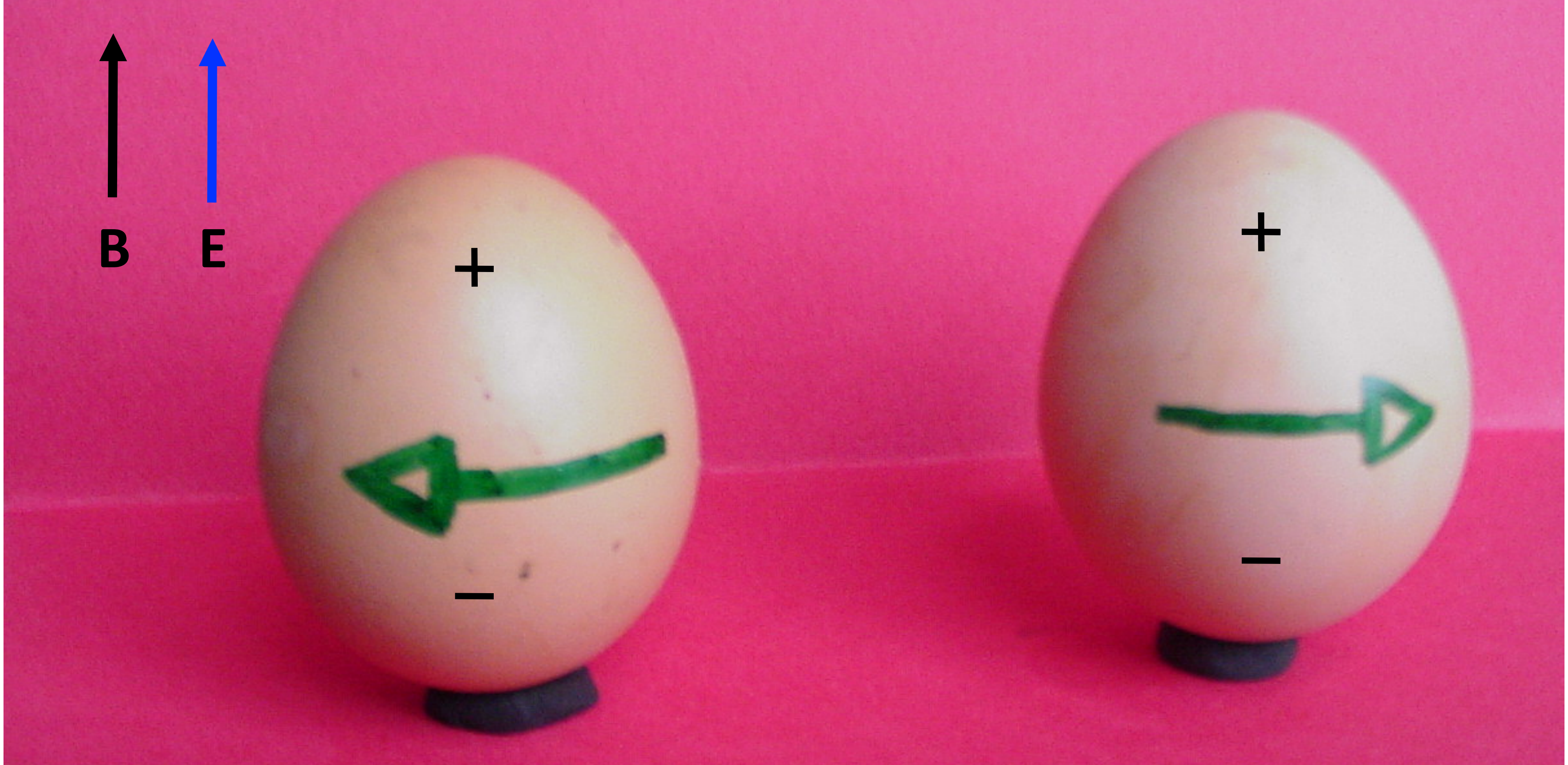
Outline of this talk

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

- Part II: EDMs of nucleons and (light) nuclei

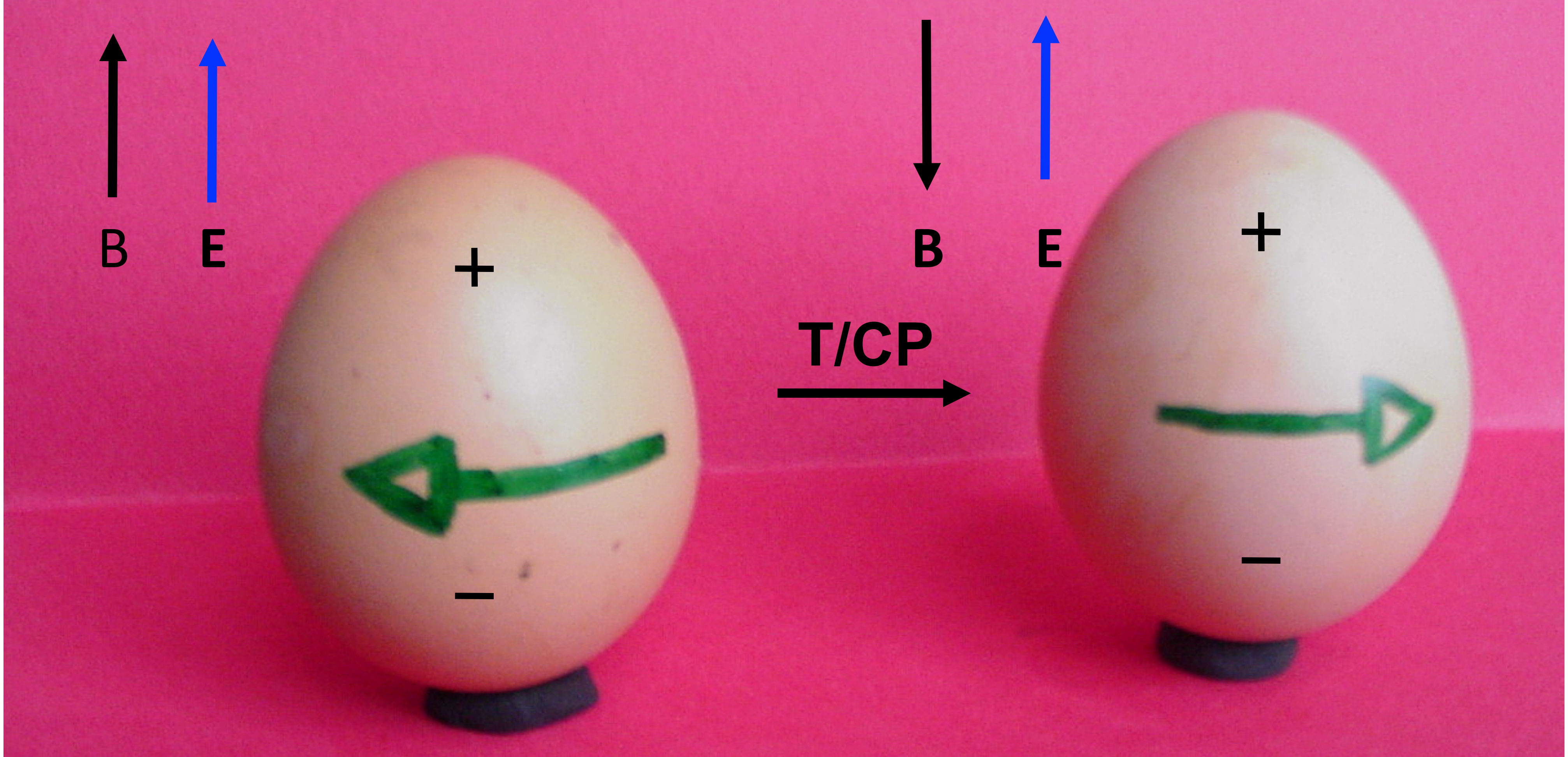
- Part III: Unraveling models of CP violation

Electric Dipole Moments



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

Electric Dipole Moments



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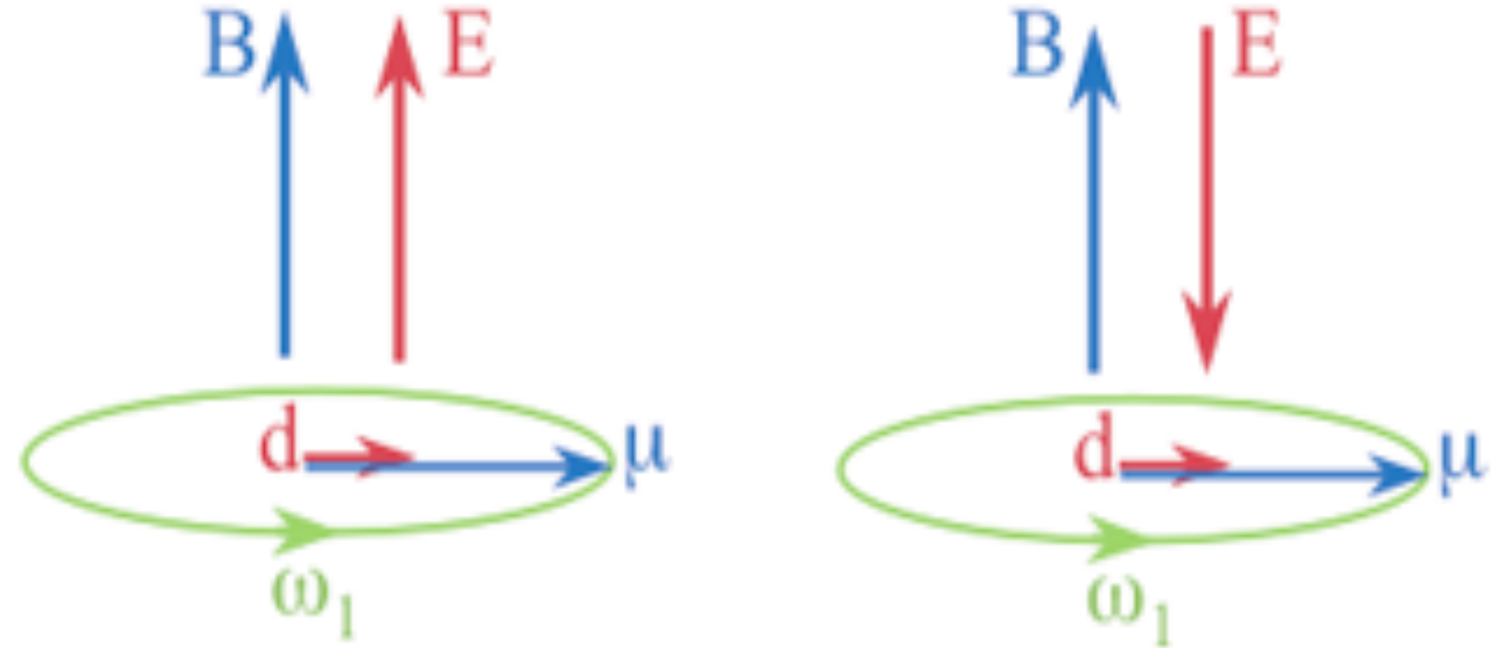
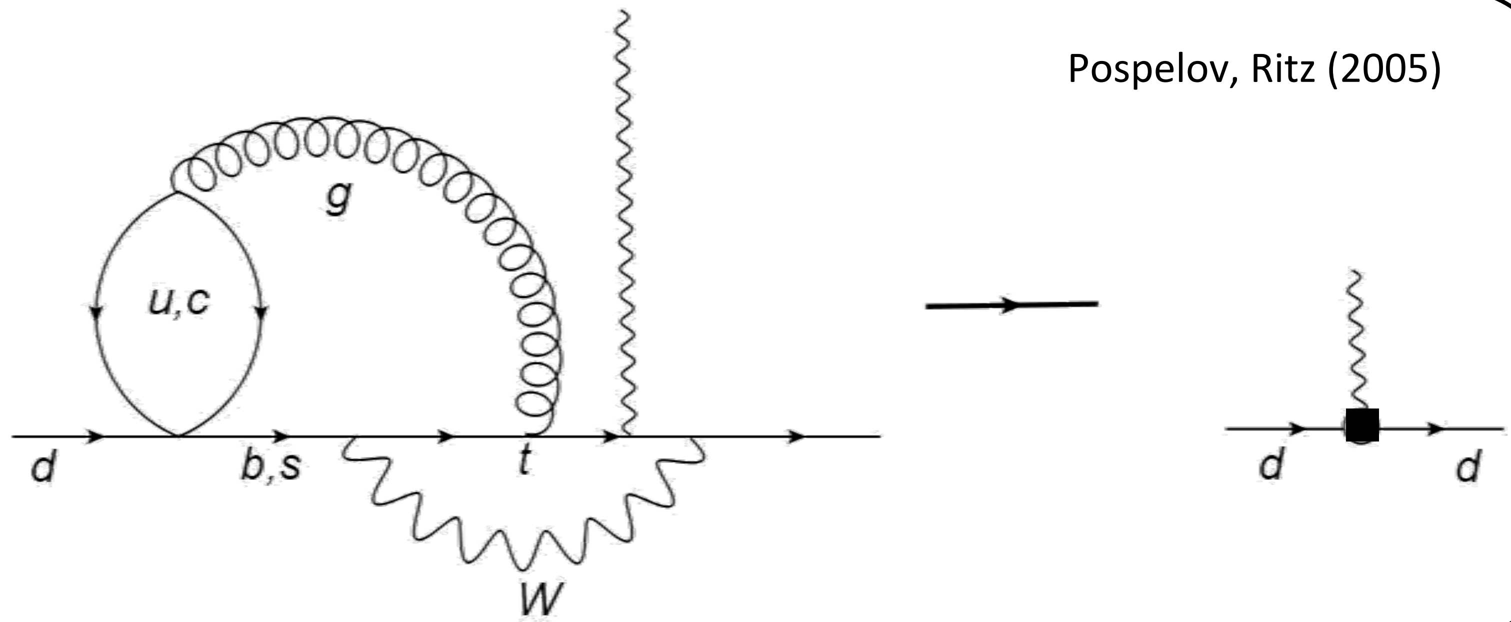


$$\omega_1 = \frac{2\,\mu B + 2dE}{\hbar} \qquad \omega_2 = \frac{2\mu B - 2dE}{\hbar}$$

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

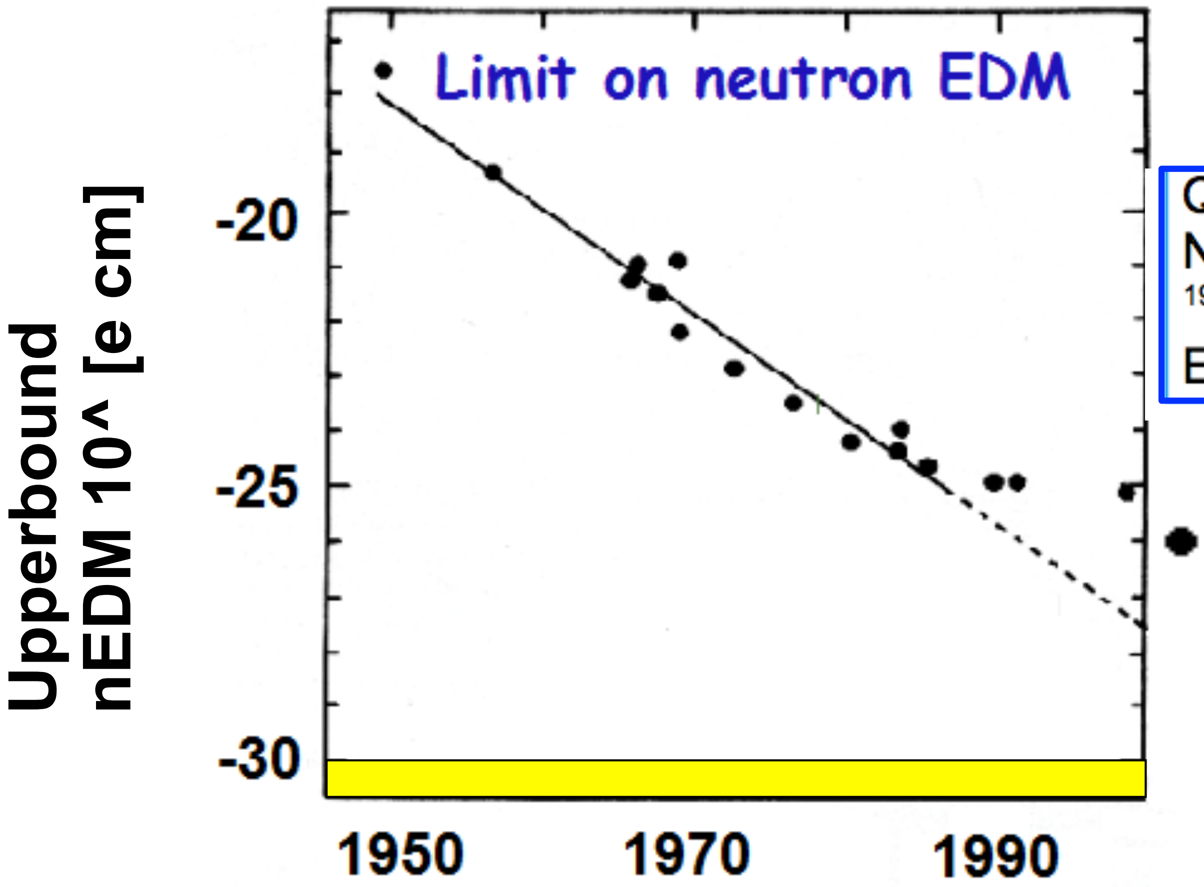
EDM's in the Standard Model

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



Highly Suppressed

Electroweak CP-violation

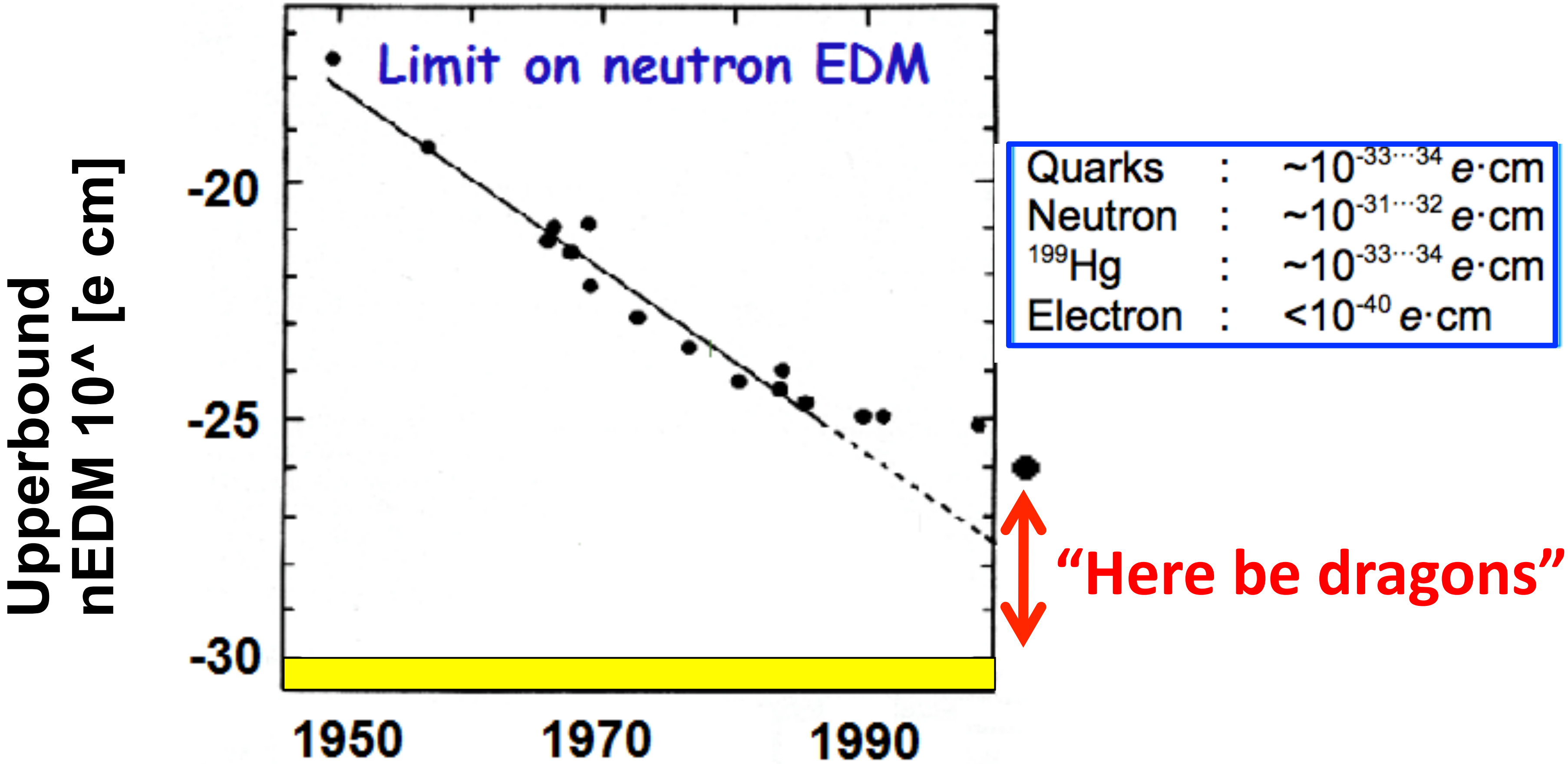


Quarks	:	$\sim 10^{-33 \cdots 34}\ e\cdot cm$
Neutron	:	$\sim 10^{-31 \cdots 32}\ e\cdot cm$
^{199}Hg	:	$\sim 10^{-33 \cdots 34}\ e\cdot cm$
Electron	:	$<10^{-40}\ e\cdot cm$

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

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

Electroweak CP-violation



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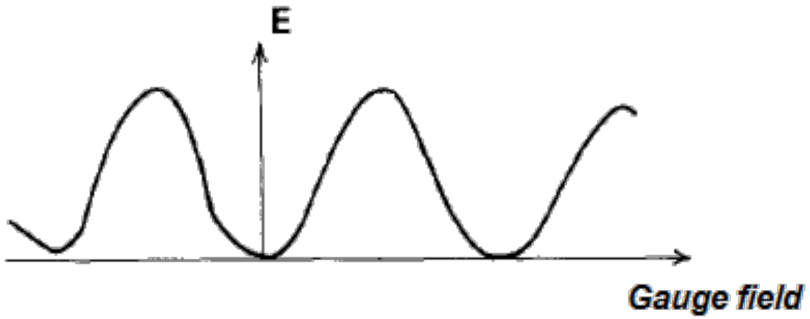
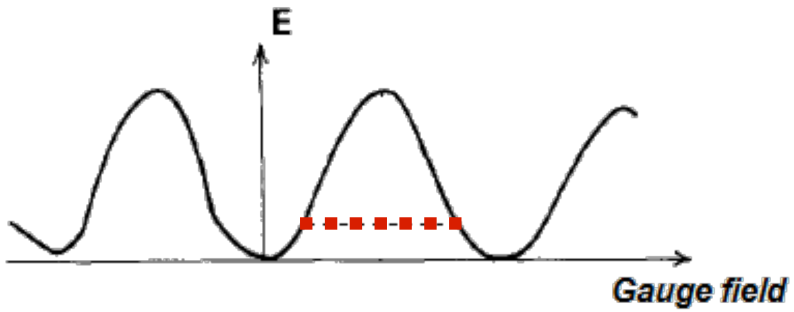
EDM's in the Standard Model

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





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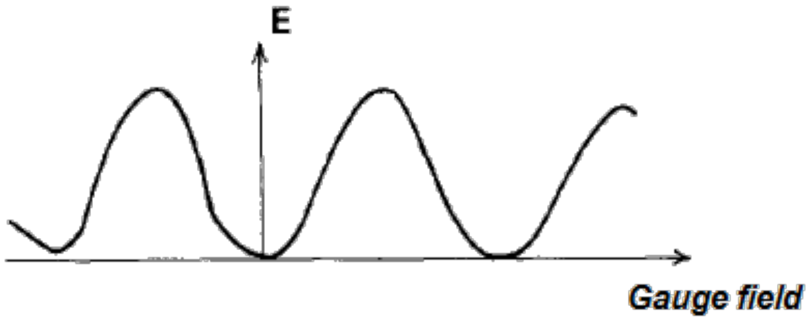
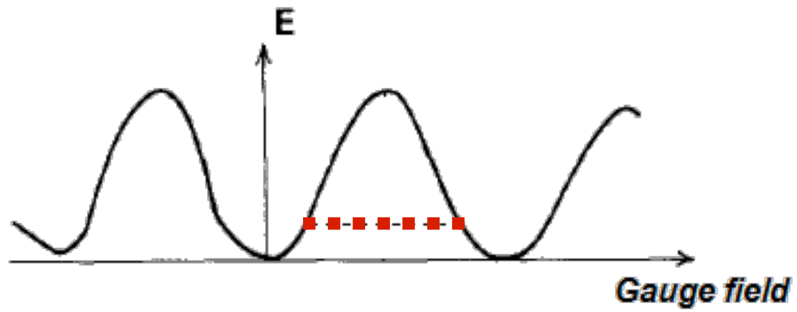


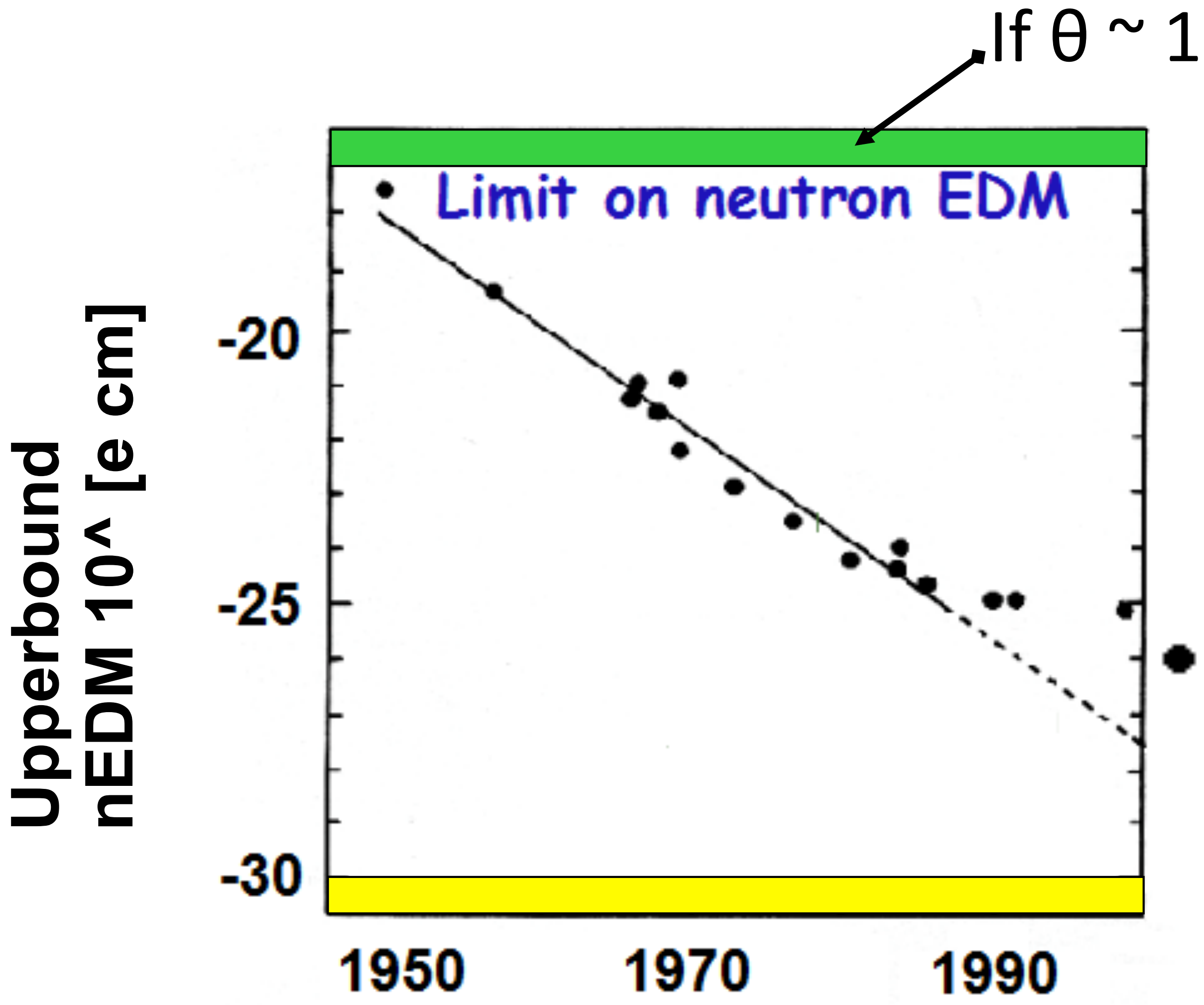


- Causes a 'new' CP-violating interaction with **coupling constant** θ

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

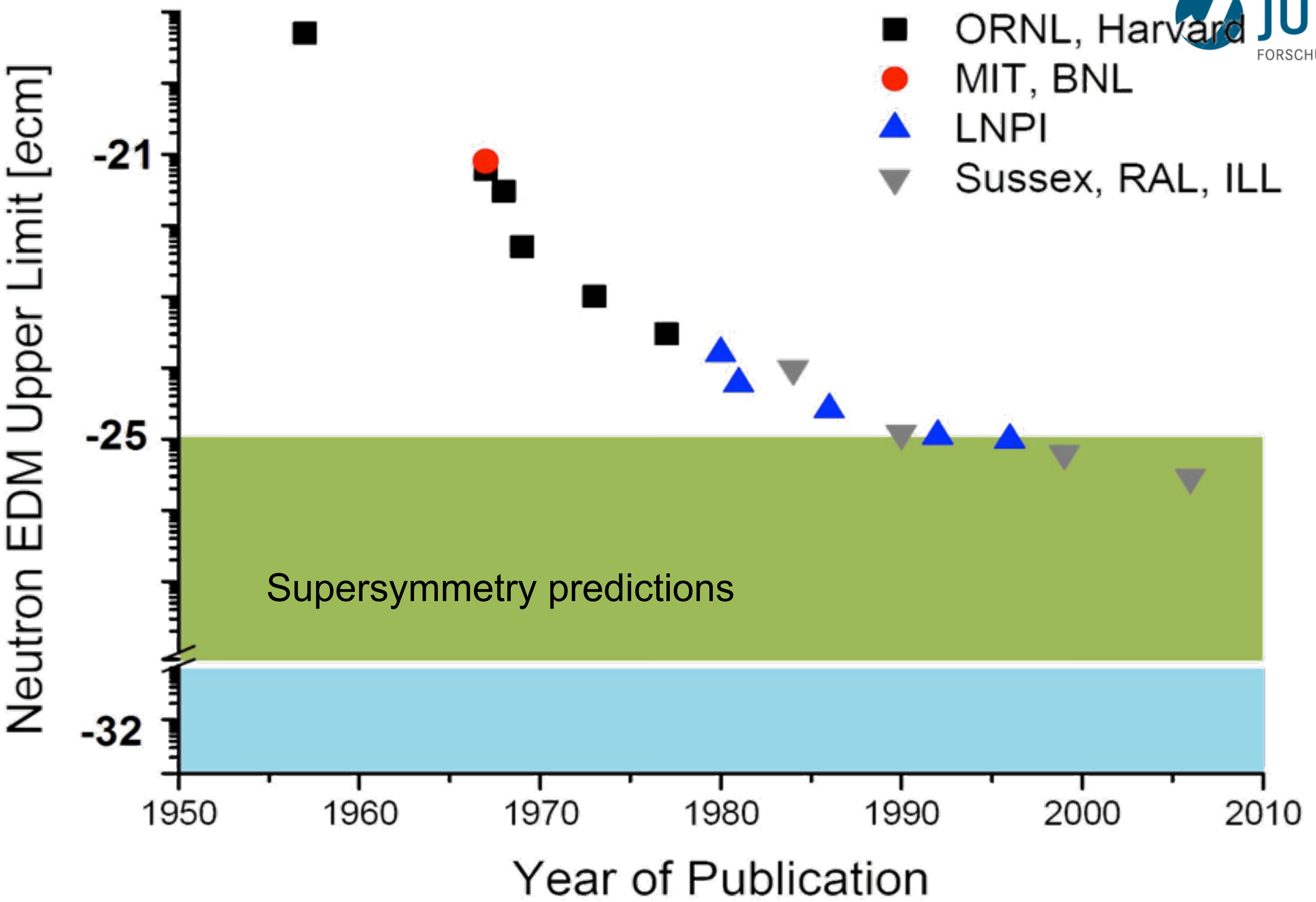
- Size of θ is **unknown**

Theta Term Predictions



Crewther et al. (1979)

Sets θ upper bound: **θ < 10^{-10}**



Electric Dipole Moments =

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

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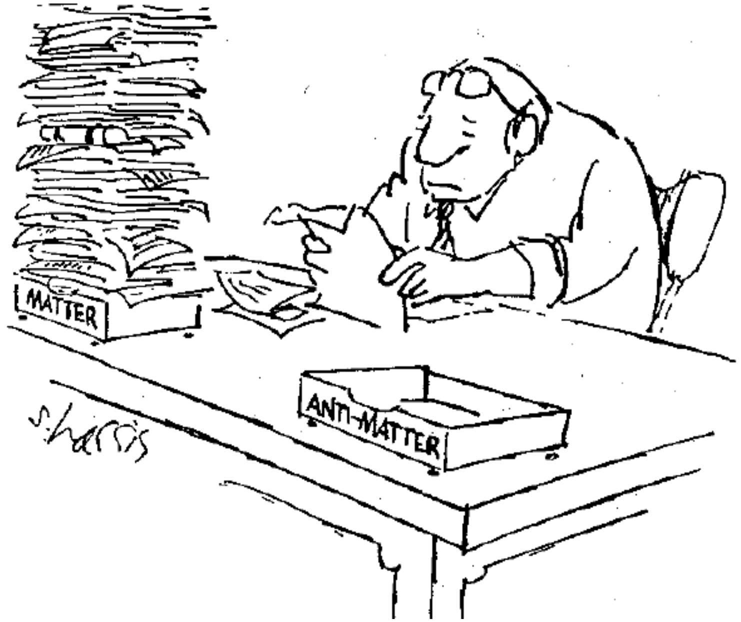
Problem of the Universe

Matter/Anti-Matter Asymmetry

13.7 billion years →



Observed: $$\frac{n(b)}{n(\gamma)} \approx 10^{-9}, \quad n(\bar{b}) \approx 0$$

Expected: $$\frac{n(b)}{n(\gamma)} \approx \frac{n(\bar{b})}{n(\gamma)} \approx 10^{-18}$$

Sakharov Conditions

- **Baryon number violation**

$$X \rightarrow Y + B$$

- **C- and CP-violation**

$$\Gamma(X \rightarrow Y + B) \neq \Gamma(\bar{X} \rightarrow \bar{Y} + \bar{B})$$

- **Out of thermal equilibrium**

$$\Gamma(X \rightarrow Y + B) \neq \Gamma(Y + B \rightarrow X)$$

Requires more CP-violation

Motivational Summary

Why are EDMs interesting to measure?

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

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

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

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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- 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

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Ongoing experiments on Ra, Rn, Xe….

- Electron EDM from ThO molecule: $d_e \leq 9 \cdot 10^{-29}\ e\ cm$

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

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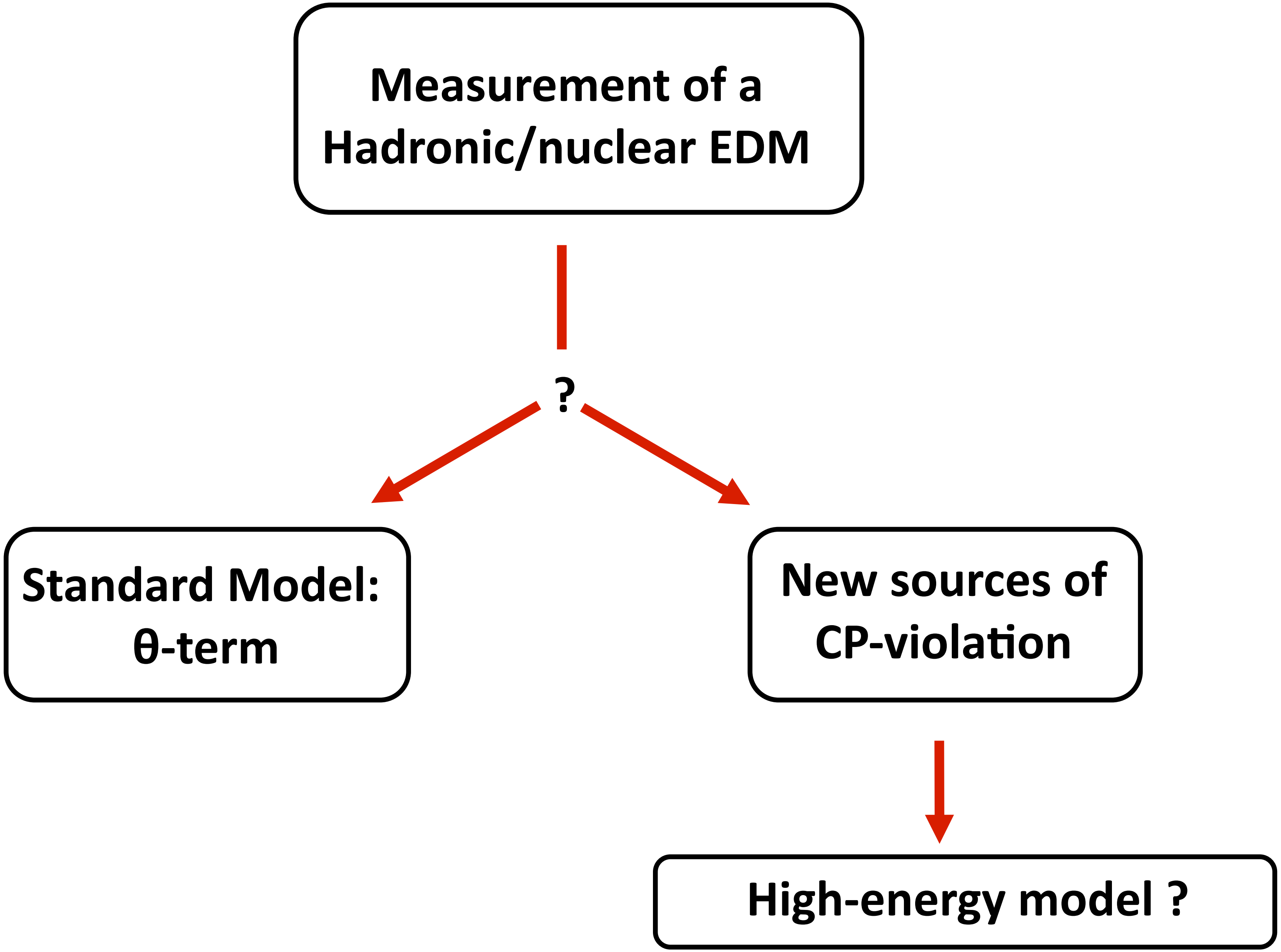
- Limit on muon EDM $d_\mu \leq 1.8 \cdot 10^{-19}\ e\ cm \quad (95\%\ \ C.L.)$

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

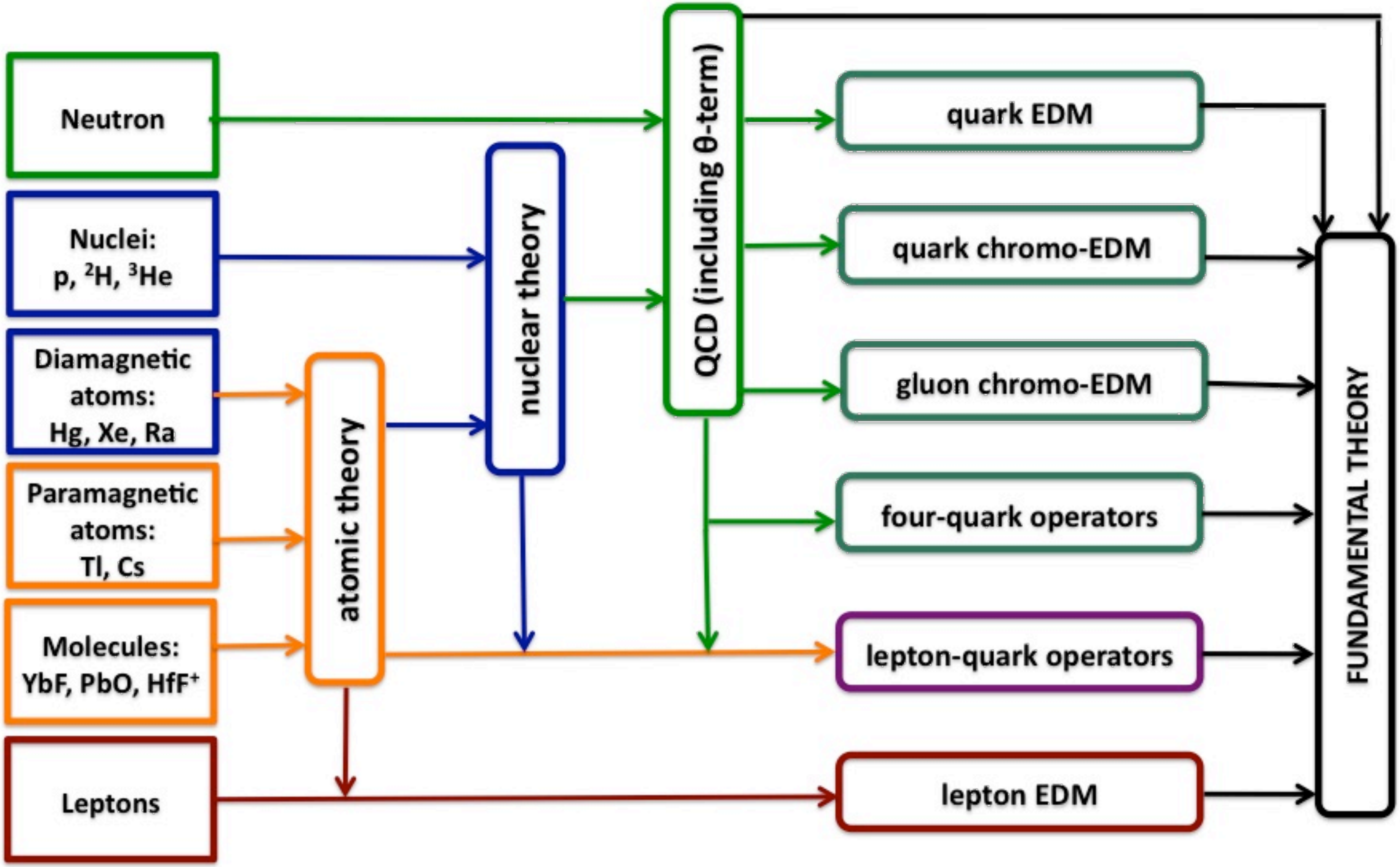
COSY @ Jülich
Brookhaven/Fermilab

- Other light nuclei? 3He ?

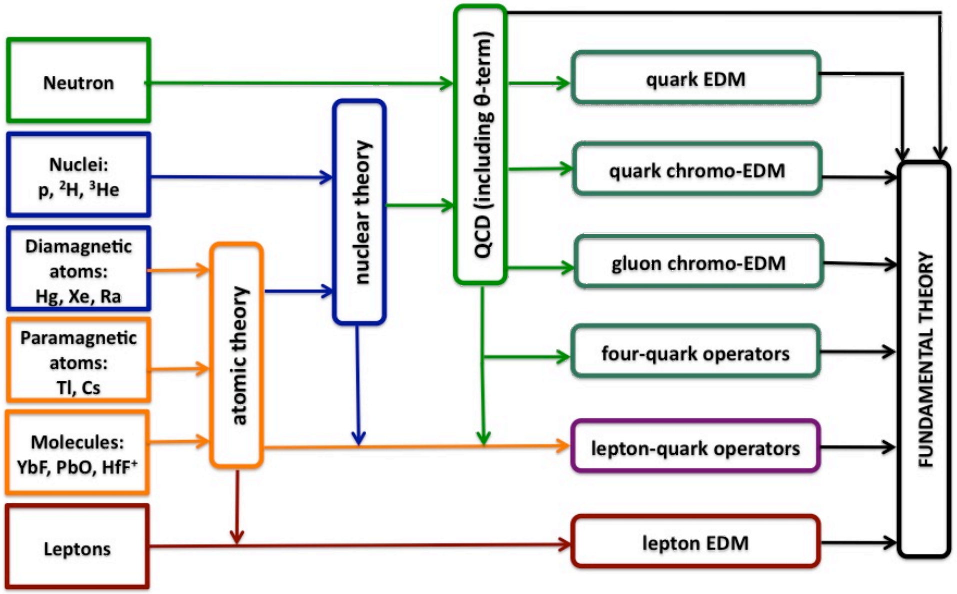
Not really background free……



Finding the **Source**



Footprint ?



Questions :

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

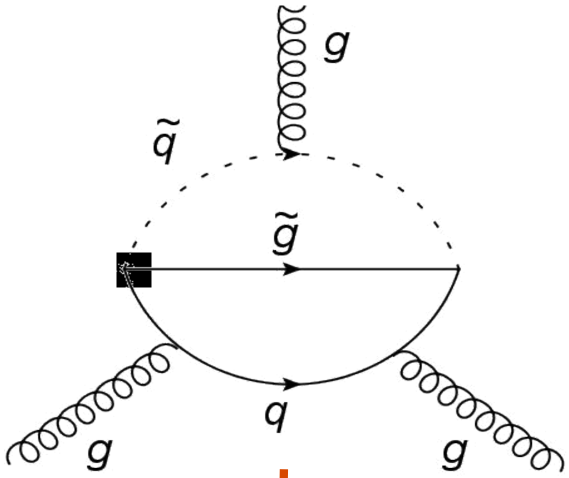
Can we **pinpoint** the microscopic source of CP-violation from **EDM measurements**?

General Idea

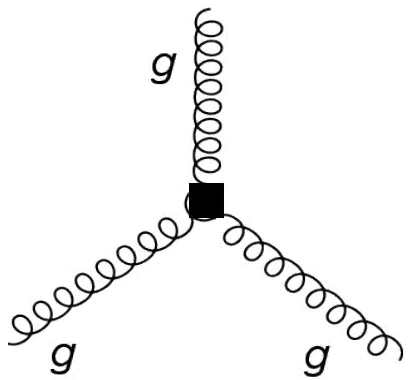
1 TeV ? SUSY?

100 GeV Standard Model

Energy



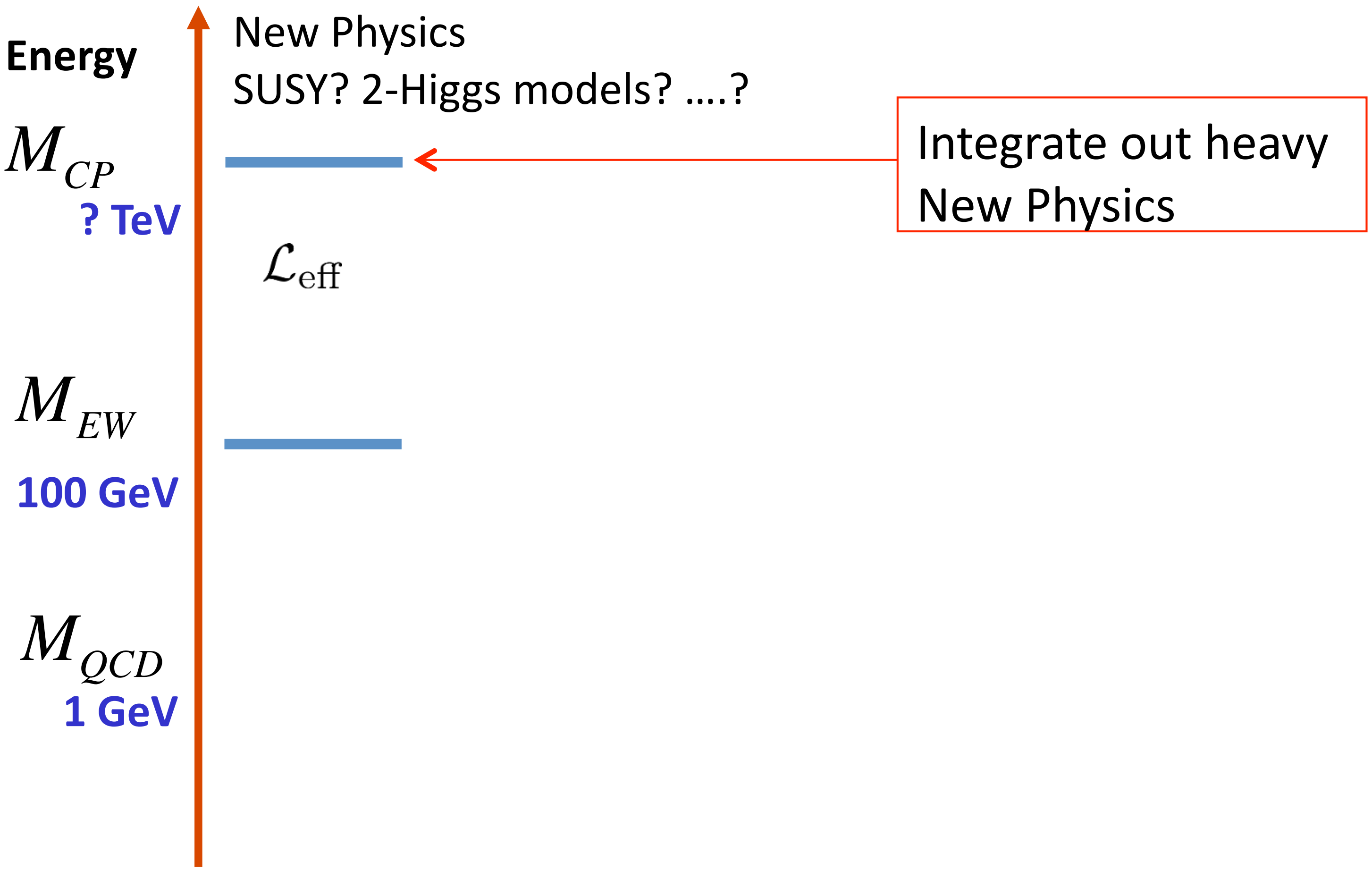
Effectively becomes



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

Running through the scales

Dekens & JdV, JHEP, ‘13



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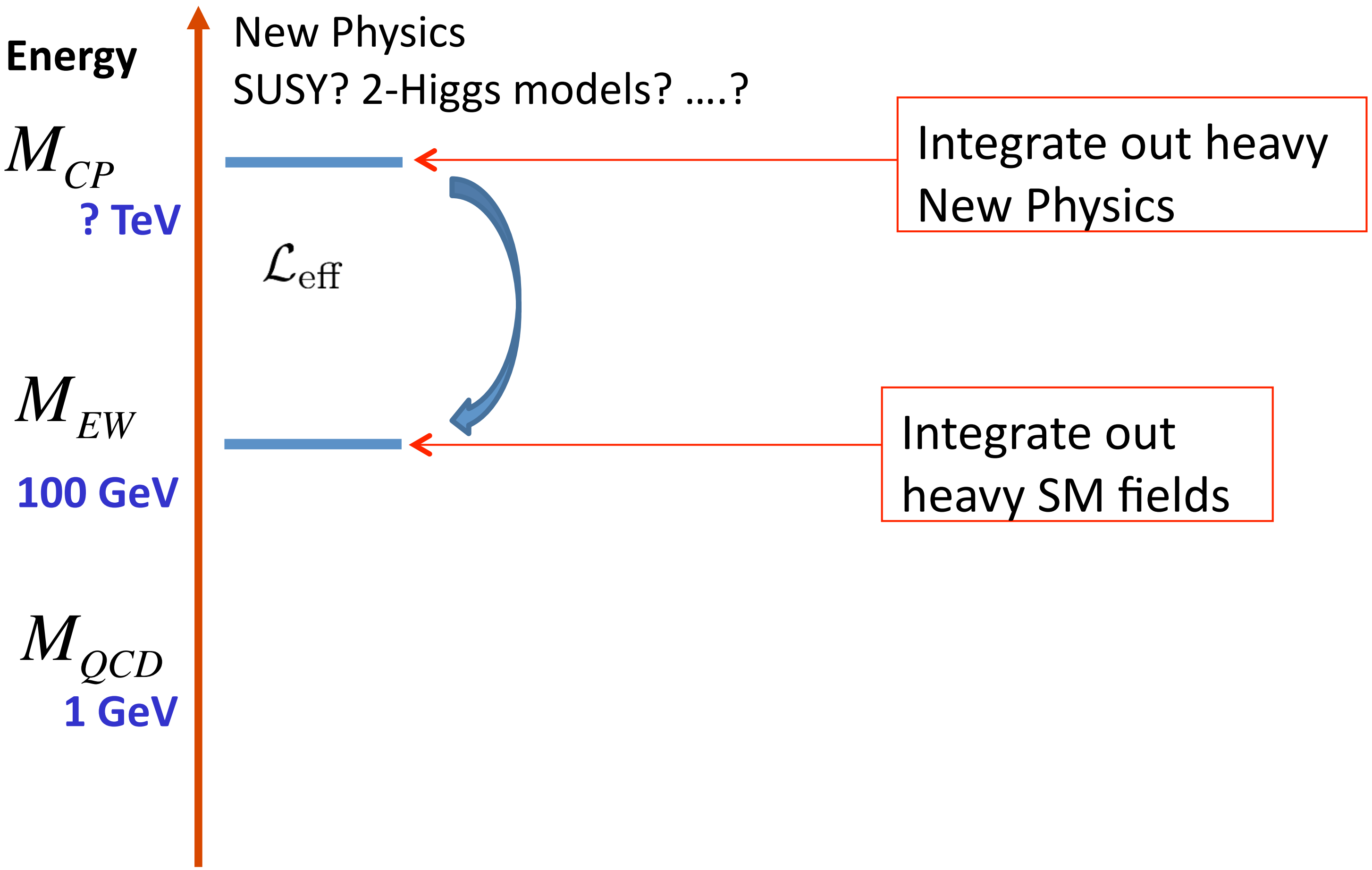

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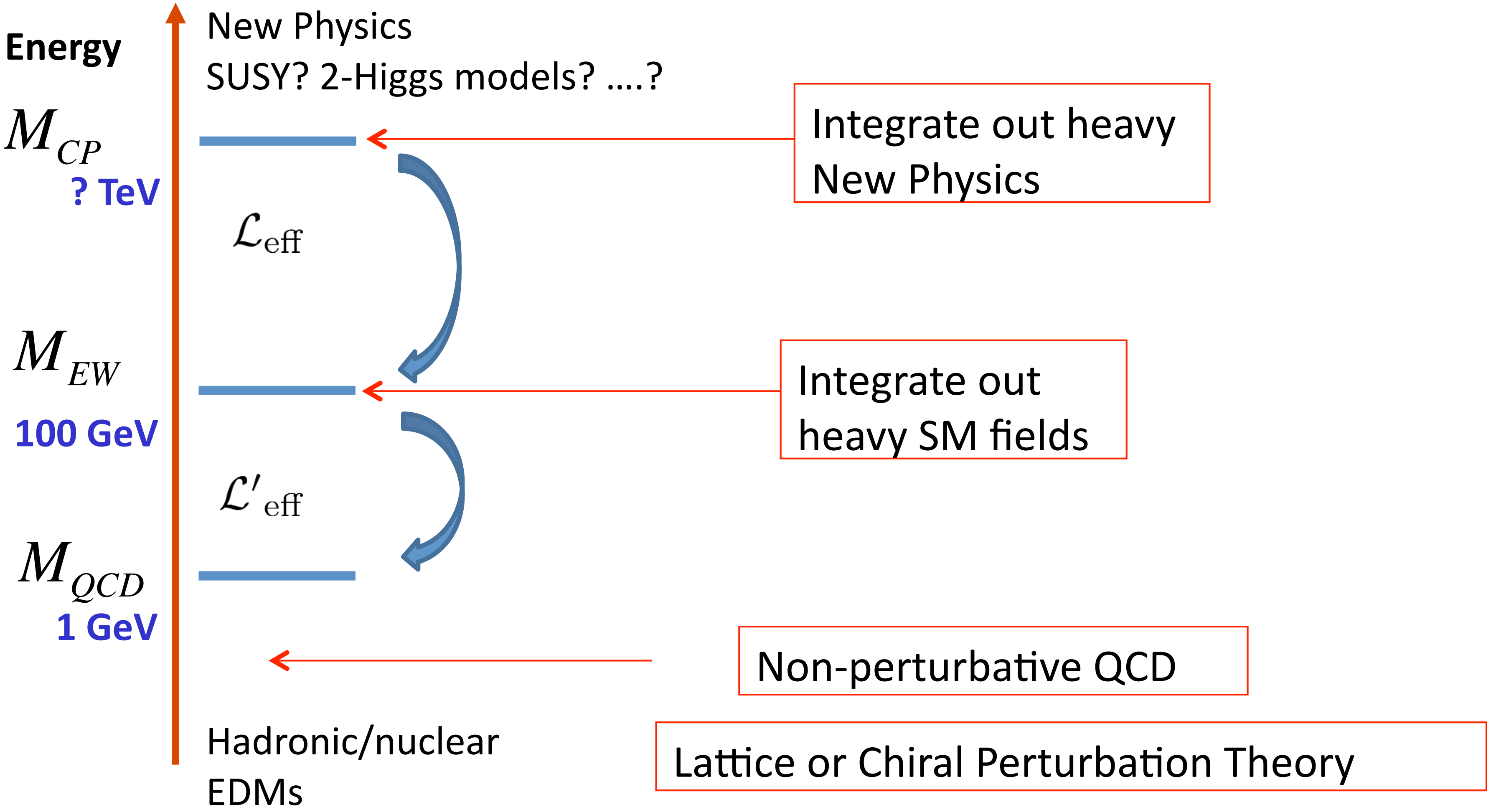

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- Part I: What are EDMs and why are they interesting in the first place ?

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Lower and lower energies

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

~ 1 GeV

$$L = L_{QCD} + \frac{\theta}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{1}{M_{CP}^2}\sum O^{(6)}$$

Effective CP-odd operators:
They encode Beyond-the-SM physics.

- **Different** BSM-models produce **different** effective operators

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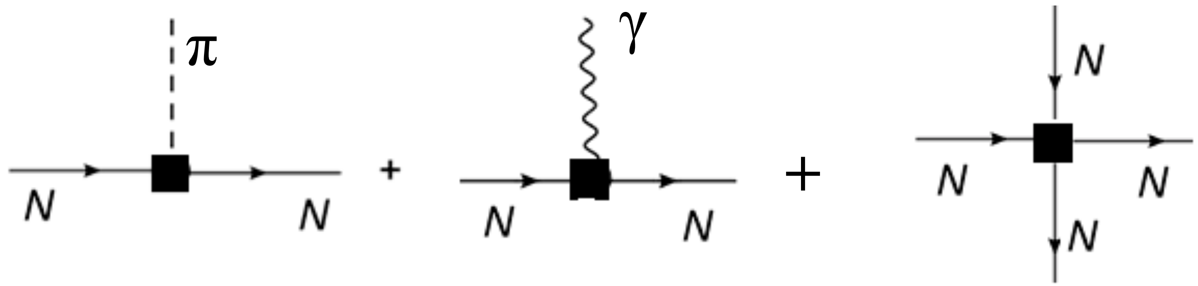
- At lower energies: QCD becomes nonperturbative

<< 1 GeV

Chiral Perturbation Theory



Chiral effective field theory

- Use the symmetries of QCD to get chiral Lagrangians

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

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

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

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

Chiral effective field theory

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

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

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

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

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

CP-violation in chiPT

- Repeat the exercise with the **CP-odd operators included:**

$$L = L_{QCD} + \frac{\theta}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{1}{M_{CP}^2}\sum O^{(6)}$$

Different models of CP-violation (theta, SUSY, Left-Right, multi-Higgs,....)

↓

Different effective CP-odd operators at quark level

↓

Different CP-odd hadronic interactions

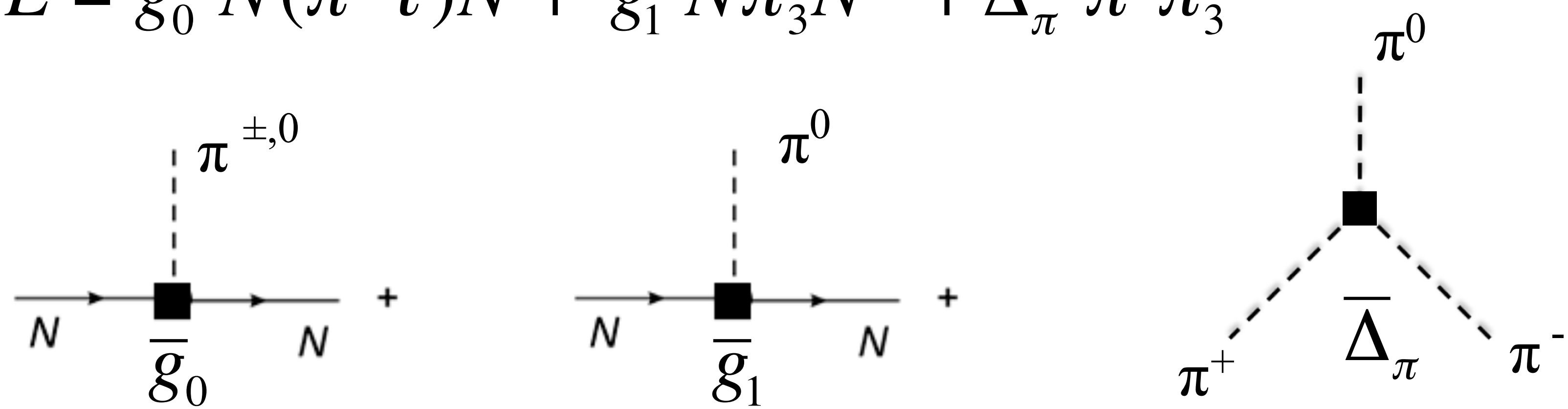
↓

Different pattern of observables (EDMs)

For now: keep it general

- The CP-odd terms induce **CP-odd hadronic interactions:**

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



JdV et al, '12

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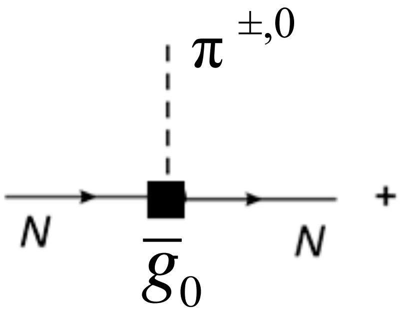
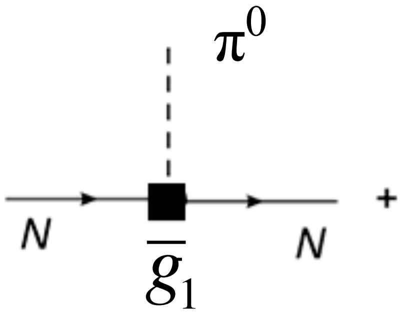
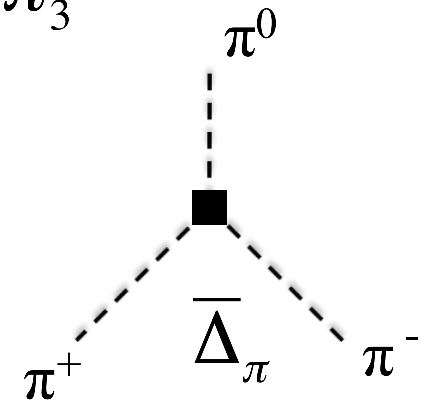
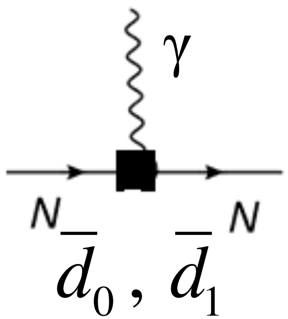


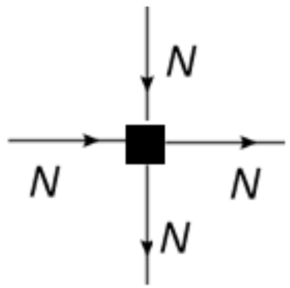




$$L = \bar{d}_0\, \bar{N}(\vec{\sigma}\cdot\vec{E})N + \bar{d}_1\, \bar{N}(\vec{\sigma}\cdot\vec{E})\tau^3 N$$

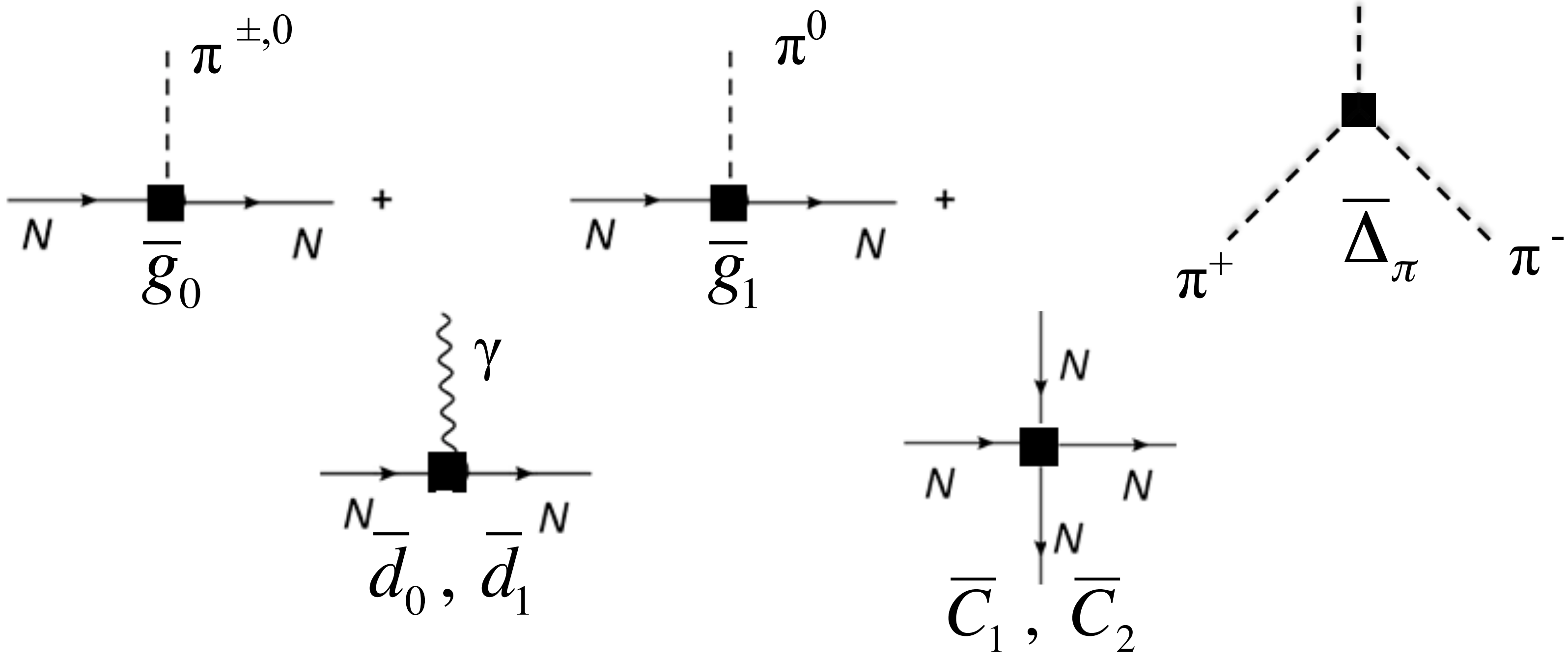
$$L = \bar{C}_1\, (\bar{N}\vec{\sigma}N)\cdot\vec{\partial}(\bar{N}N) + \bar{C}_2\, (\bar{N}\vec{\sigma}\tau N)\cdot\vec{\partial}(\bar{N}\tau N)$$





JdV et al, '12

The magnificent seven



Different models of CP-violation (theta, SUSY, Left-right, multi-higgs,….)

Predict a different hierarchy between these 7 terms !

Goal: probe these hierarchies experimentally

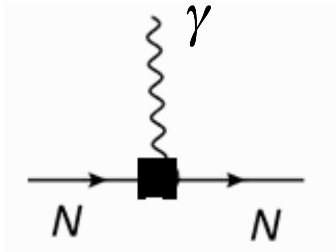
↓

JEDI

The Nucleon EDM

- Calculate from the chiral Lagrangians

Nucleon EDM



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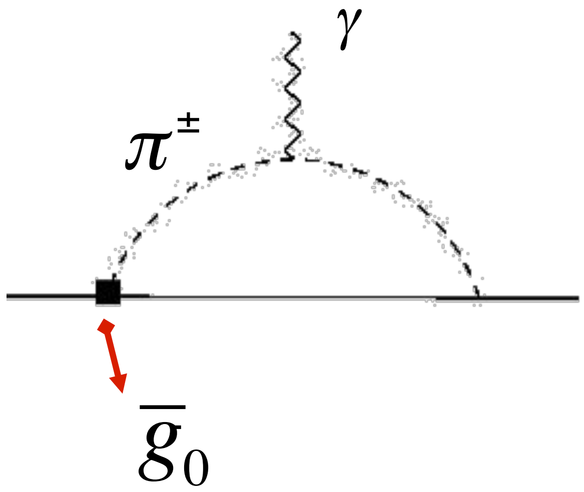

$$d_n = \bar{d}_0 - \bar{d}_1 + (0.13 + 0.01)\,\bar{g}_0\; e\; fm$$

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

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

Hockings, van Kolck, PLB ’05
Ottnad et al, PLB ‘10

JdV, Mereghetti et al, PLB ’11 ‘14

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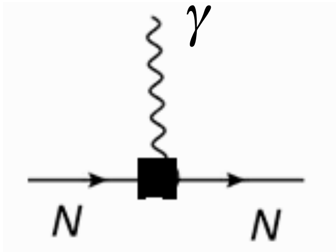

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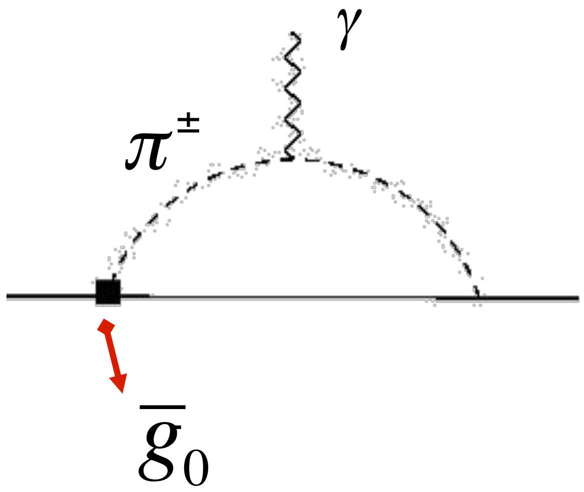

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Very similar and 3 LECs….

Hard to probe the hierarchy with only neutron and proton EDMs

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

Hockings, van Kolck, PLB '05
Ottnad et al, PLB '10

JdV, Mereghetti et al, PLB '11 '14
Mei

Proton EDM still important!

JÜLICH FORSCHUNGSZENTRUM

1) Potential high accuracy ! $\sim 10^{-29}\ e\ cm$

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

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

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

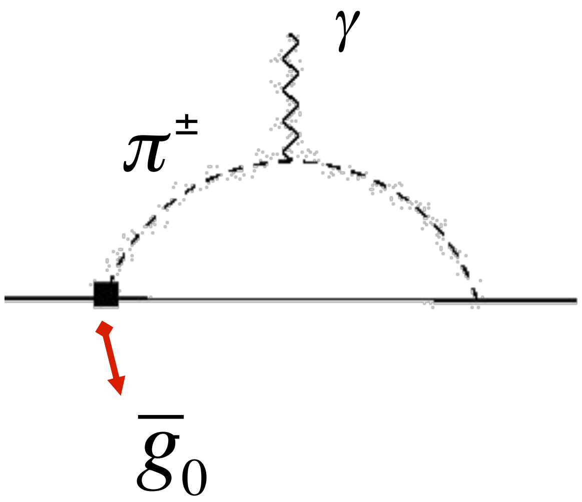
Shintani ’12 ’13
Guo, Meißner ‘13 ‘14

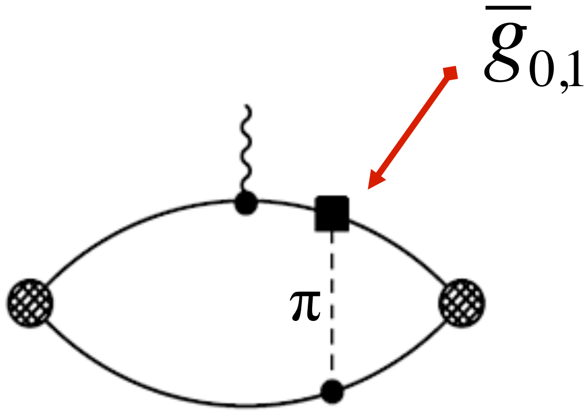
Could provide **strong hint** for theta term.
But…… No lattice data for other CPV scenarios

3) **Crucial** input for EDMs of nuclei !

Nuclear EDMs

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





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

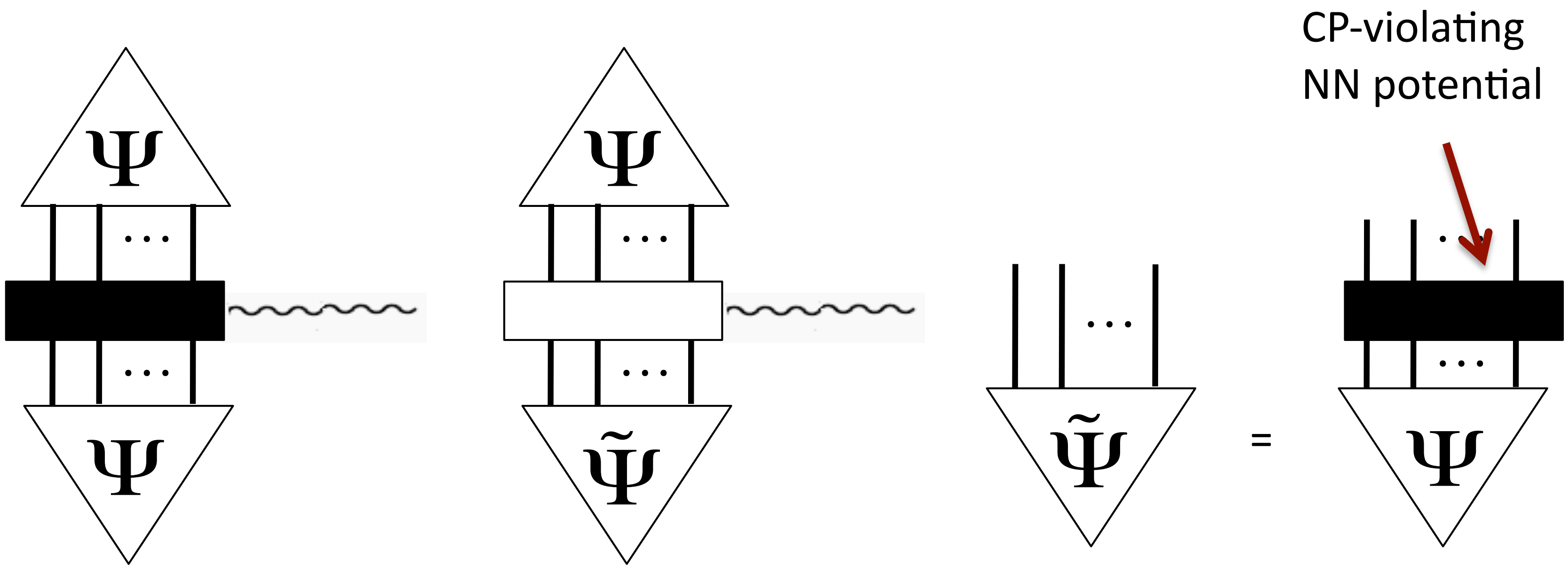
- Possible to calculate light-nuclear EDMs with high accuracy!

EDM of a general light nucleus

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

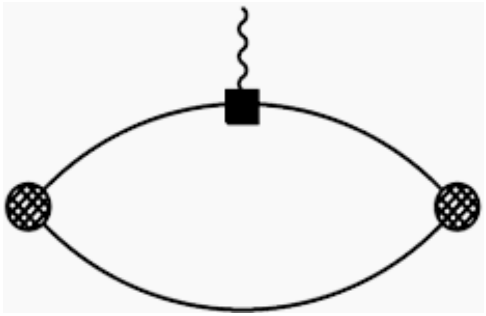
CP-odd admixtured wave-function

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

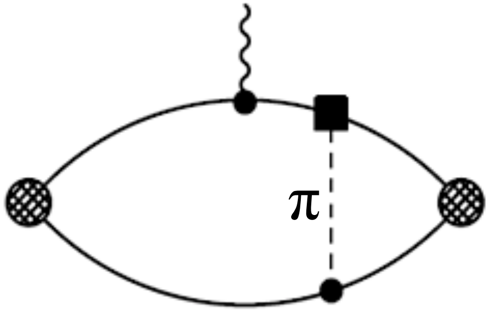


JdV et al ’11
Bsaisou et al ’12
Song et al ‘13

The deuteron EDM



One-body: $d_D = d_n + d_p$

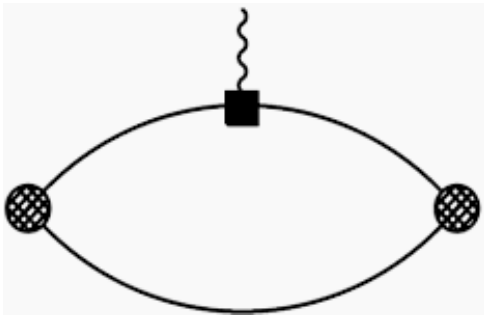


T-violating pion-exchange

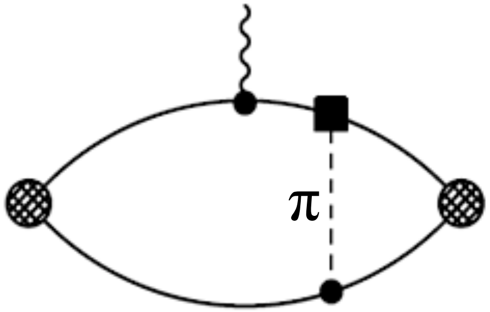
$$L = \bar{g}_0 \overline{N}(\vec{\pi}\cdot\vec{\tau})N + \bar{g}_1 \overline{N}\pi_3 N$$

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

The deuteron EDM



One-body: $d_D = d_n + d_p$



T-violating pion-exchange

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

- **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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The deuteron EDM

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

Bsaisou et al, in prep

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

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

Both consistently derived
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Both consistently derived in chiral EFT

Strong isospin filter

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

Theoretical accuracy is excellent !

Do the same for 3He and 3H

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

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

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

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

Stetcu et al, PLB ’08
JdV et al, PRC ’11
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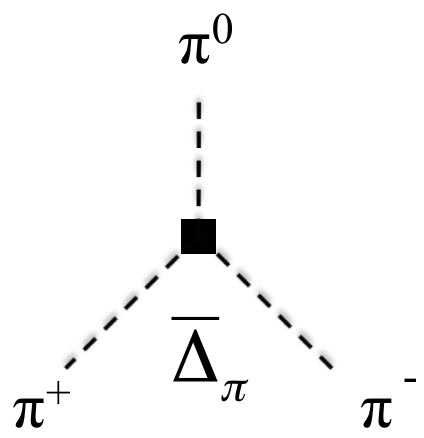
^{3}H probably not a candidate for JEDI

And dependence on:

Not in this talk



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What would this tell us ?

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

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

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

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

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- These quantities are very **indicative** of the CP-odd source
- What about **heavy nuclei ?**

Traditional EDMs

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

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

Griffiths et al, PRL '09

Traditional EDMs

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

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

  Dzuba et al, PRA '02, '09

  Nuclear Schiff moment

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  Nuclear Schiff moment

- But the **nuclear** part isn't…..

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

  Engel et al, PPNP '13

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

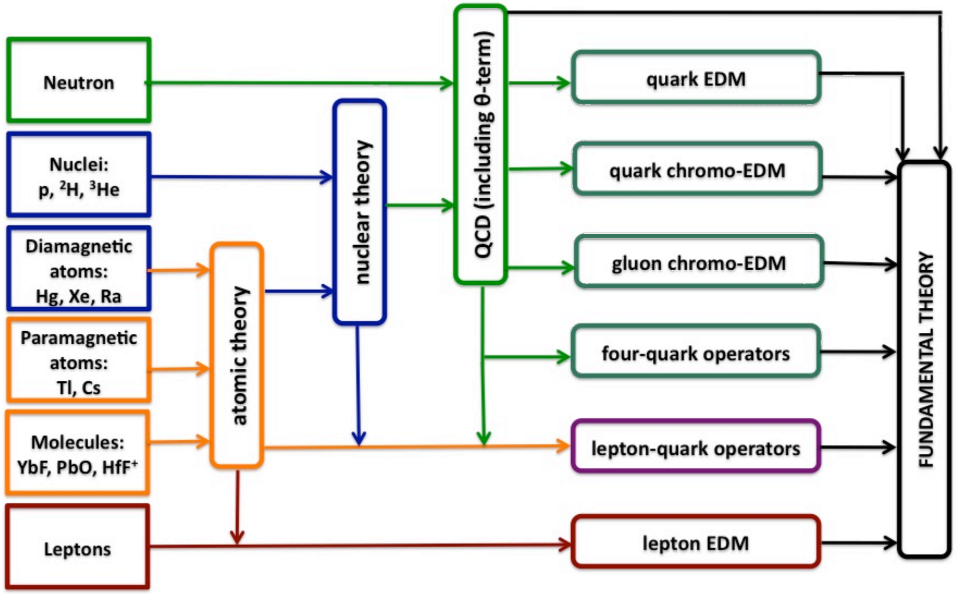
Outline of this talk

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

- Part II: EDMs of nucleons and (light) nuclei

- **Part III: Unraveling models of CP violation**

Footprint ?



Big questions :

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

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

Unraveling models of CPV

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

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

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

- Can we **unravel** these models using **JEDI** experiments?

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

Two scenarios of CPV

1) We first look at the QCD theta term

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

Axial U(1) transformation

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

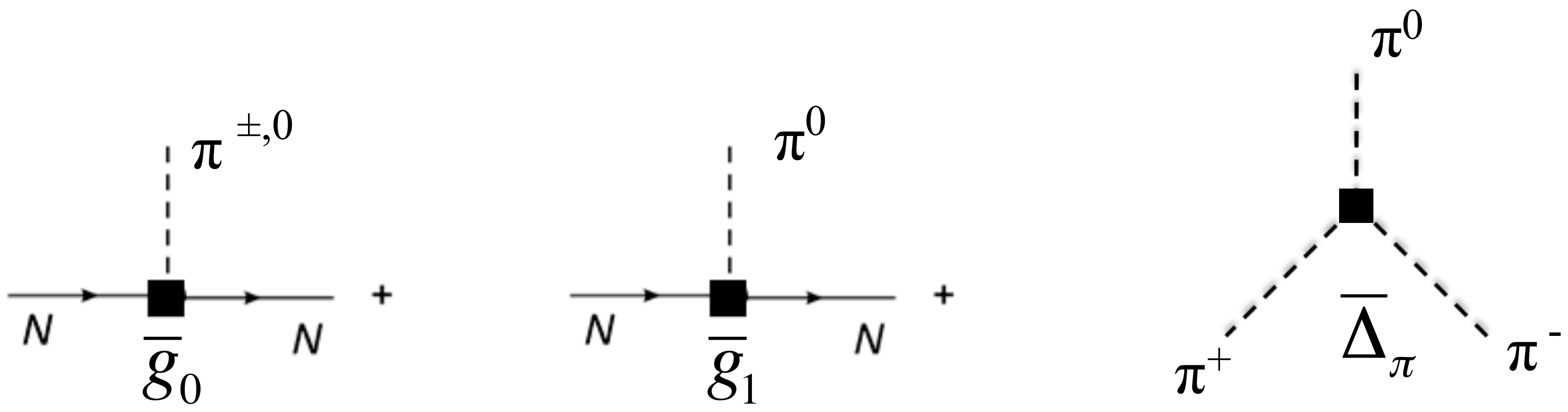
$$L = L_{QCD} + i\frac{\overline{m}}{2}\theta\, \overline{q} i\gamma^5 q$$

a CP-odd quark mass
Isospin-symmetric!!

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

Two scenarios of CPV

1) We first look at the QCD theta term $L = L_{QCD} + i\frac{\overline{m}}{2}\theta\,\overline{q}i\gamma^5 q$



Two scenarios of CPV

JÜLICH FORSCHUNGSZENTRUM

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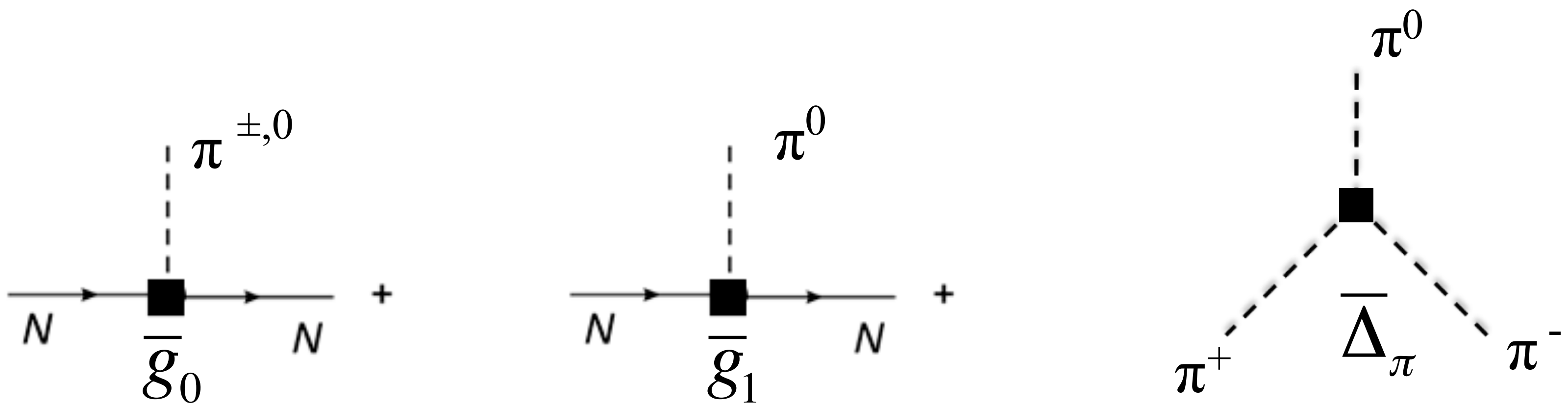

$$\varepsilon = (m_u - m_d)/2\overline{m} \cong 1/3$$

$$\bar{g}_0 = \frac{(m_n - m_p)^{strong}}{4F_\pi\varepsilon} = -(0.018 \pm 0.007)\theta$$

Accuracy will improve!

Similar (but more complicated) relations for $\bar{g}_1$ and $\bar{\Delta}_\pi$

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

$\bar{\Delta}_\pi$ **Too small to matter !**

Two scenarios of CPV

2) Now the minimal left-right symmetric model

Mohapatra et al '08

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

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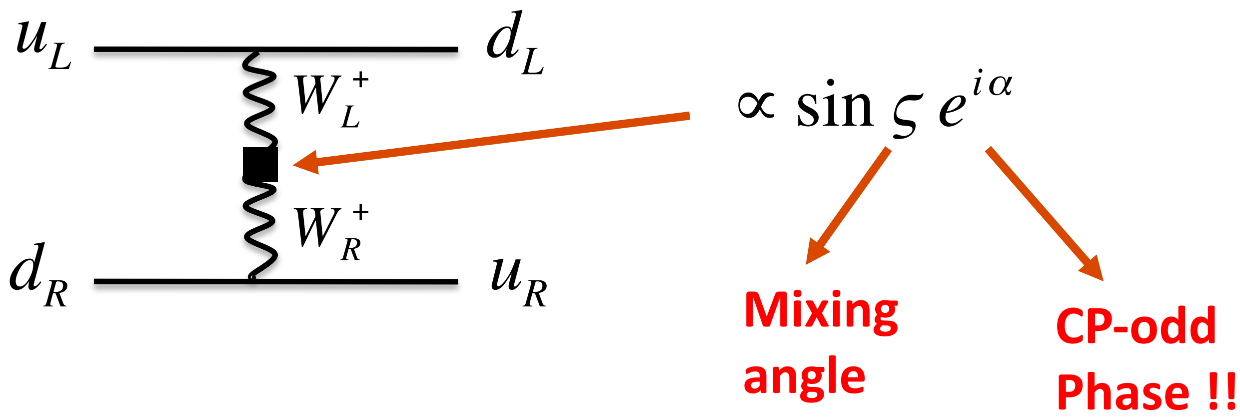

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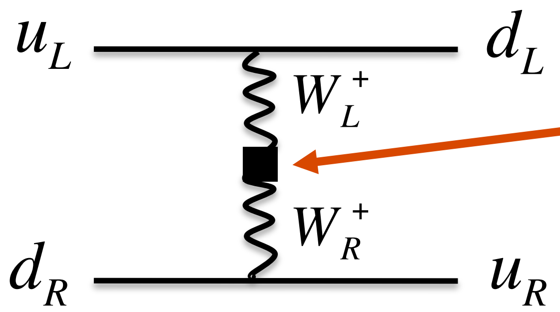
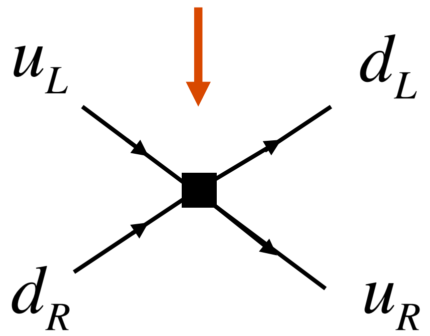


$\propto \sin \varsigma \, e^{i\alpha}$

Mixing angle

CP-odd Phase !!



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

Two scenarios of CPV

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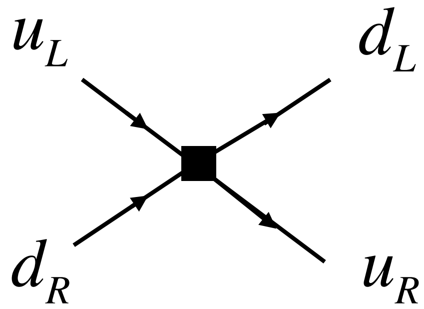

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Dekens, JdV, Nogga, et al, JHEP '14

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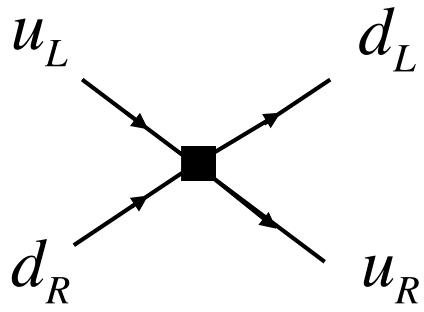

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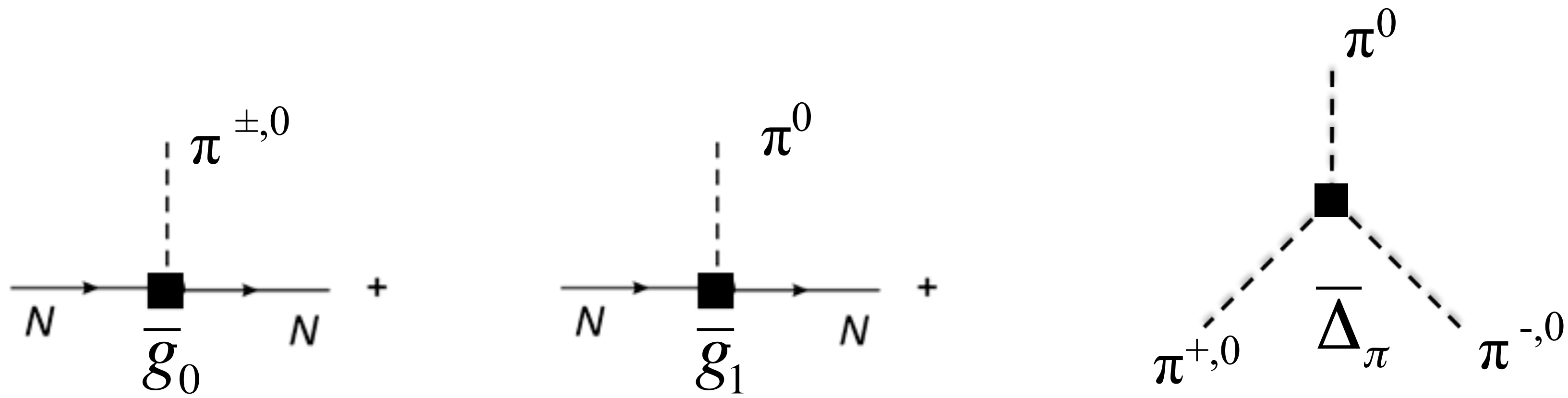

Completely **opposite** behavior with respect tot theta term

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

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

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

Two scenarios of CPV

1) Theta term

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

2) mLRSM

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

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

Theta term:

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

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

mLRSM:

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

Rather big uncertainty

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

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3He EDM, sensitive to $\bar{g}_1$ and $\bar{g}_0$

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

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

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

Two scenarios of CPV

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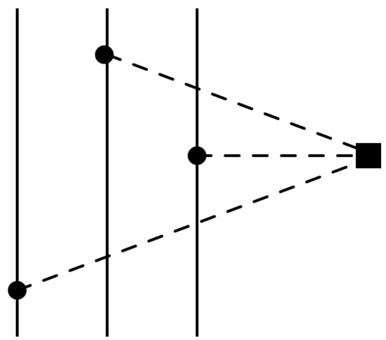

$\bar{\Delta}_\pi$

Unraveling models of CPV

- EDMs of nucleons and light nuclei can **identify** the theta term

- It can also provide strong hints for other models:
  e.g. left-right symmetric models

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

Unraveling models of CPV

JÜLICH FORSCHUNGSZENTRUM

- EDMs of nucleons and light nuclei can **identify** the theta term
- It can also provide strong hints for other models:
  e.g. left-right symmetric models
- Multi-Higgs and the MSSM leave different hierarchies behind

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

- And give rise do different **electron/nucleon EDM ratio**
- **JEDI could tell us a lot about high-energy physics !**

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

Conclusion/Summary

1) EDMs are very good probes of new CP-odd physics
2) Probe **similar energy scales** as LHC, strong bounds on new physics
3) However, if one EDM is measured: **not clear** what is responsible

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The motivation for JEDI (for me at least!)

1) Potential for very high accuracy $\sim 10^{-29}\ e\ cm$

2) The **light nuclear EDMs** are:

Simple enough to be well under control…….

But, complex enough to get non-trivial info on CP-odd source