Andreas Wirzba and the quest for the violation of CP symmetry

Jordy de Vries

University of Amsterdam, Nikhef

Time-line

- From 2009-2012 I was working on my PhD in Groningen

- I worked on computations of electric dipole moments (later more)
- I was happily working in my own little world, until february 2010…

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> *From Christoph Hanhart (February 2010)*
>
> *... here in Juelich there is a strong interest into EDMs (we are thinking of preparing for an experiment to get the deuteron EDM measurement together with the BNL people who will do the proton) and thus your paper comes at just the right time ....*

- I worked on computations of electric dipole moments (later more)
- I was happily working in my own little world, until february 2010…

First Contact

- **We were all working on the same thing using similar techniques**

My perspective

- Pretty excited on the one hand (other people care about my work/topic)

- Pretty scared on the other hand ……

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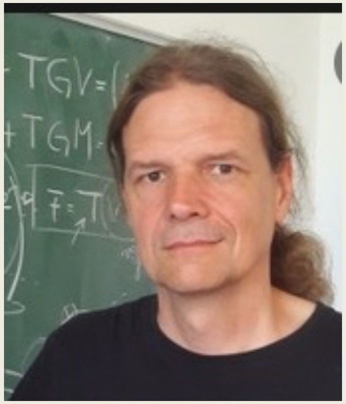

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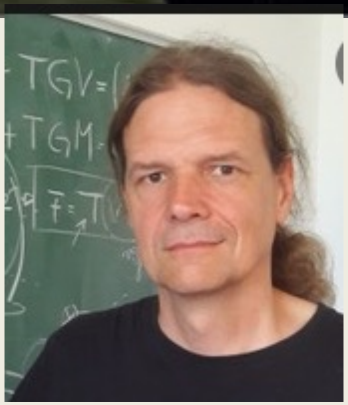


My perspective

- Pretty excited on the one hand (other people care about my work/topic)
- Pretty scared on the other hand ……
- **But that was not necessary,** I was invited to several workshops and a seminar by Andreas and we had a lot of discussions (also with Jan)
- **It was a tremendous boost for me:** meeting new people and new methods. Learning how to discuss physics beyond my own group

My perspective

- First discussions with Andreas and Jan

1 Induces Homomorphisms on Bilinear Forms

Let

$$F_g : G \times V \to V \quad \text{and} \quad B = \{e_i | i \in I\} \tag{1}$$

be a group action of the linear Lie group G on the vector space V and B its basis. A general bilinear form $f : V \times V \to \mathbb{K}$, $\mathbb{K} = \mathbb{R}, \mathbb{C}$ factorizes uniquely via the tensor product

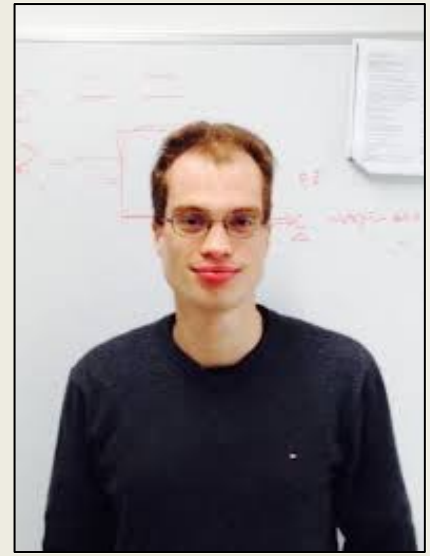
$$f = f_\otimes \circ (i_1 \times i_2) : V \times V \to V \otimes V \to \mathbb{K}, \tag{2}$$

where

$$i_1 : V \hookrightarrow V \otimes V, v \mapsto v \otimes \mathbf{1}, \tag{3}$$
$$i_2 : V \hookrightarrow V \otimes V, v \mapsto \mathbf{1} \otimes v. \tag{4}$$

The bilinear form is thus uniquely determined by the images of $f_\otimes$in $\mathbb{K}$ of the basis states of $V \otimes V$. The homomorphism $f_\otimes$ is an element of the dual space $(V \otimes V)^*$ of $V \otimes V$. Since the a vector space and its dual are isomorphic, say by the isomorphism $i : V \otimes V \to (V \otimes V)^*$, there is an isomorphism between the set of homomorphisms

$$F_g \otimes F_g \in Hom(V \otimes V, V \otimes V) \quad \text{and} \quad G_g'^{-1} \in Hom((V \otimes V)^*, (V \otimes V)^*), \tag{5}$$



Hi, here are the questions and notes from Jan Bsaisou, the PhD student from Bonn/FZJ. **It requires an actual understanding of group theory............**

- We had some technical, but important, differences in the number of effective operators one could construct → but resolved in the end

My perspective

- In summer of 2012 I got an offer from Christoph and Ulf to join FZJ as a postdoc.

- I moved to Julich in 2013 and had 3 wonderful years there.

Would often drive in Andrea’s car to Bonn (better than Christoph’s….)

Talk about music (Jazz and Kraftwerk), movies, and physics

- Many trips all over the world (from Schleching to Santa Barbara to Tbilisi)

My perspective

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My perspective

- During that time, FZJ was starting an experimental program to measure EDMs of protons and deuterons.

- With Andreas (and others af FZJ) we tried to build a theoretical basis for this program (put experiments into the landscape of particle physics)

My perspective

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- With Andreas (and others af FZJ) we tried to build a theoretical basis for this program (put experiments into the landscape of particle physics)

- Was a very important time for me: I felt like a **real physicist** working on problems in particle/hadronic/nuclear physics. The atmosphere at FZJ was great.

Nuclear Electric Dipole Moments in Chiral Effective Field Theory #2

J. Bsaisou (IAS, Julich and JCHP, Julich and Julich, Forschungszentrum), J. de Vries (IAS, Julich and JCHP, Julich and Julich, Forschungszentrum), C. Hanhart (IAS, Julich and JCHP, Julich and Julich, Forschungszentrum), S. Liebig (IAS, Julich and JCHP, Julich and Julich, Forschungszentrum), Ulf-G. Meissner (Bonn U. and Bonn U., HISKP and IAS, Julich and JCHP, Julich and Julich, Forschungszentrum) et al. (Nov 21, 2014)

Published in: *JHEP* 03 (2015) 104, *JHEP* 05 (2015) 083 (erratum) • e-Print: 1411.5804 [hep-ph]

pdf DOI cite 78 citations

Unraveling models of CP violation through electric dipole moments of light nuclei #3

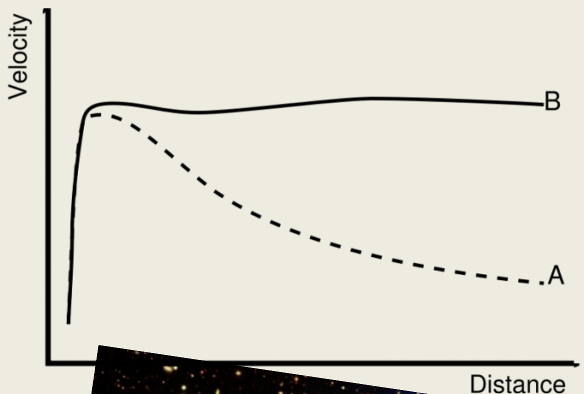
W. Dekens (Groningen U.), J. de Vries (IAS, Julich and Julich, Forschungszentrum and JCHP, Julich), J. Bsaisou (IAS, Julich and Julich, Forschungszentrum and JCHP, Julich), W. Bernreuther (RWTH Aachen U.), C. Hanhart (IAS, Julich and JCHP, Julich and Julich, Forschungszentrum) et al. (Apr 24, 2014)

Published in: *JHEP* 07 (2014) 069 • e-Print: 1404.6082 [hep-ph]

pdf DOI cite 109 citations

The search for something non-Standard…

13.x billion years



Theoretical puzzles

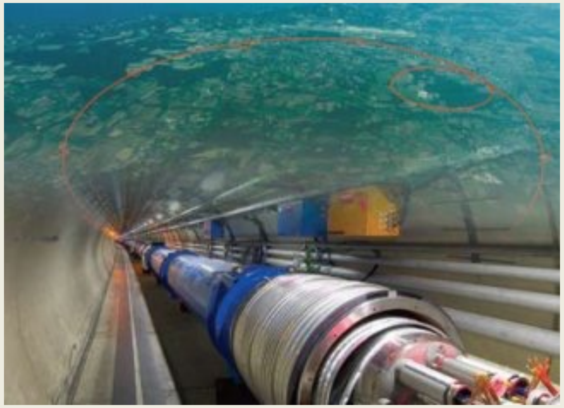
$$\frac{m_{Higgs}}{m_{Planck}} \sim 10^{-16}$$

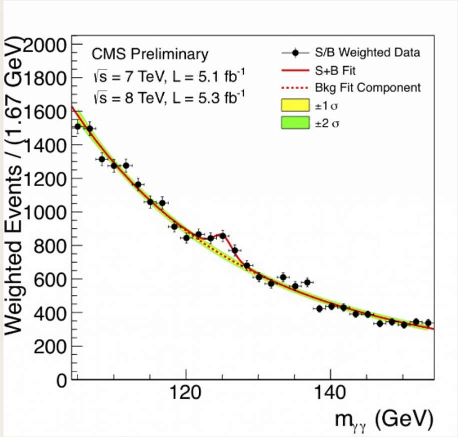
$$\theta_{CP} < 10^{-10}$$

The search for something non-standard…

Try to create something new directly

Energy





Reach ~ collider energy

LHC, FCC, CEPC, ….

Indirect effects with precisely known (sometimes no) SM background

Examples are: Flavor, g-2, EDMs, 0ν2β …..

Colliders if BSM scale is too high

Reach ~ experimental and **theoretical** accuracy

Magnetic dipole moments

- A non-relativistic particle with spin (i.e. electron) in magnetic field

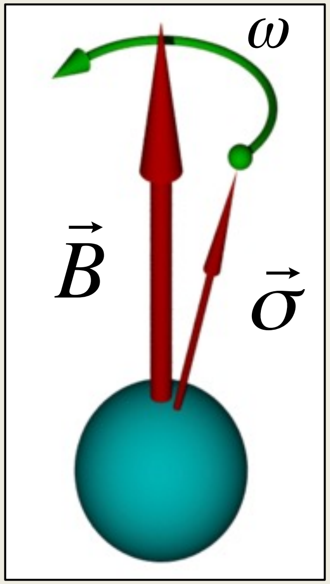
$$H = -\mu(\vec{S} \cdot \vec{B}) \qquad \vec{S} = \vec{\sigma}/2$$

Hamiltonian

Magnetic dipole moment

Spin

Magnetic Field



- The B-field puts a torque on the system → spin precession

$$\omega = 2\mu B \sin\theta$$

Magnetic dipole moments

- From Dirac equation: $$(i\gamma^\mu D_\mu - m)\,\Psi_e(p) = 0$$

$$H = -\frac{\mu}{2}(\vec{\sigma}\cdot\vec{B}) \qquad \mu = \frac{eg}{2m} \qquad g = 2$$

- g is the gyromagnetic ratio (clasically g=1), triumph of QM !

- Measurements in 1940's: g_e = 2*(1.00118+-0.00003)…..
- **Important to measure precisely !**

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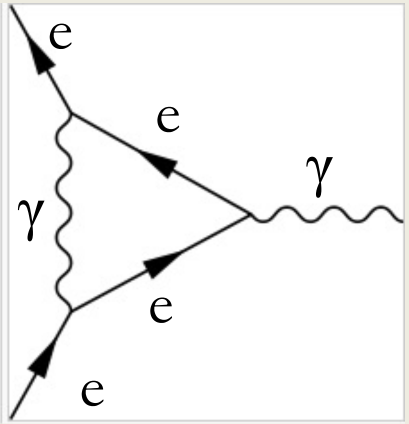
$$a_e = \frac{g_e - 2}{2}$$



$$a_e = \frac{\alpha_{em}}{2\pi} + \mathcal{O}(\alpha_{em}^2)$$

~~Magnetic~~ Electric dipole moments

- Let's remind ourselves about **electric** dipole moments
- A particle with spin (i.e. neutron) in an **electric** field is described by

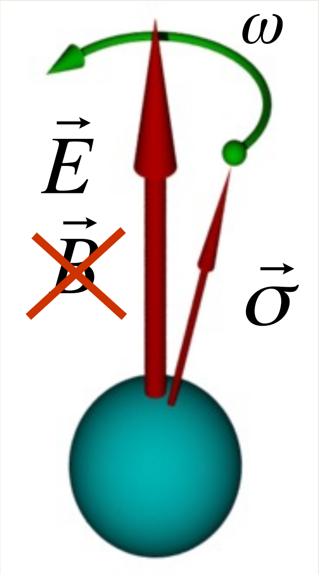
$$H = -d(\vec{S} \cdot \vec{E}) \qquad \vec{S} = \vec{\sigma}/2$$

Hamiltonian

Spin

Electric Field

~~Magnetic~~ Electric dipole moment



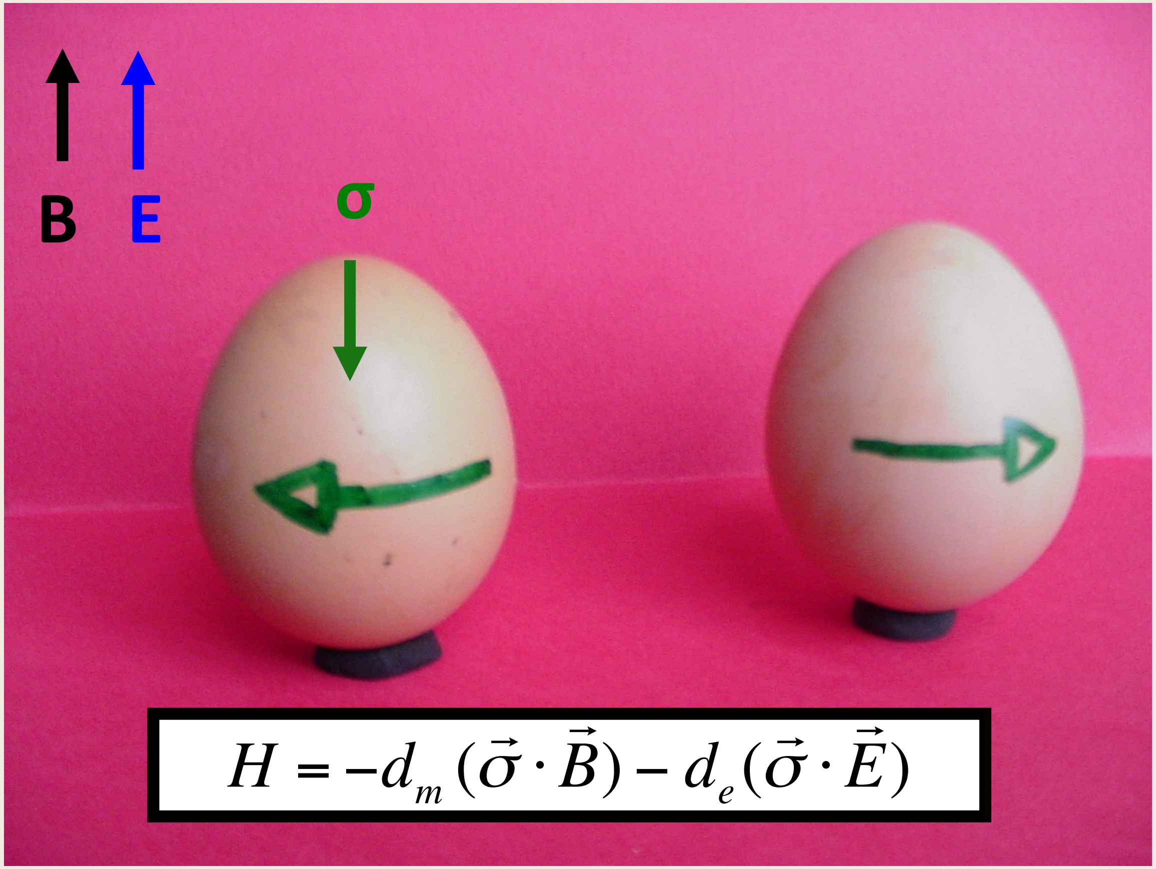
- The **E-field** puts a torque on the system → spin precession

$$\omega = 2\mu \cancel{B} \sin\theta \qquad \omega = 2dE \sin\theta$$

- How large is the **electric** dipole moment ?

Symmetry considerations

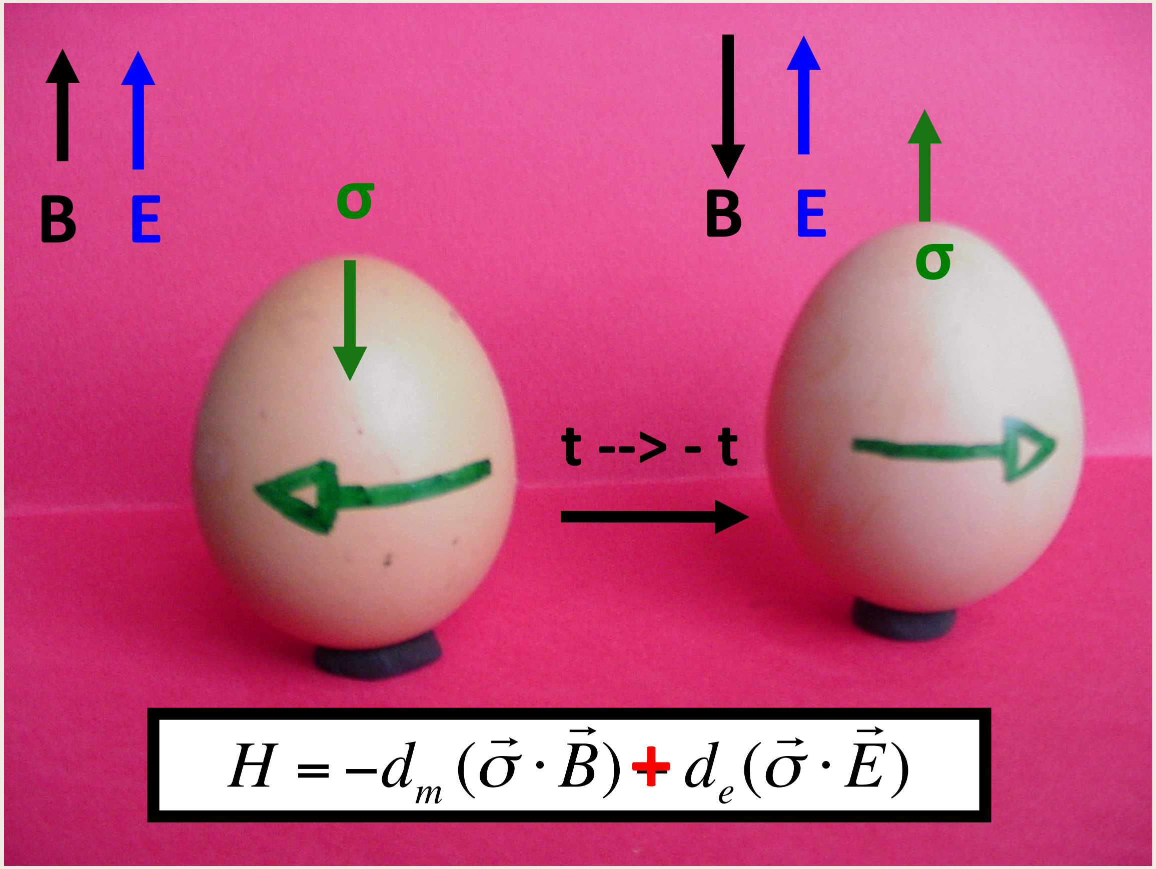
- Electric and Magnetic Dipole Moment (EDM and MDM)



PhD Thesis: Hudson

Symmetry considerations

- Electric and Magnetic Dipole Moment (EDM and MDM)



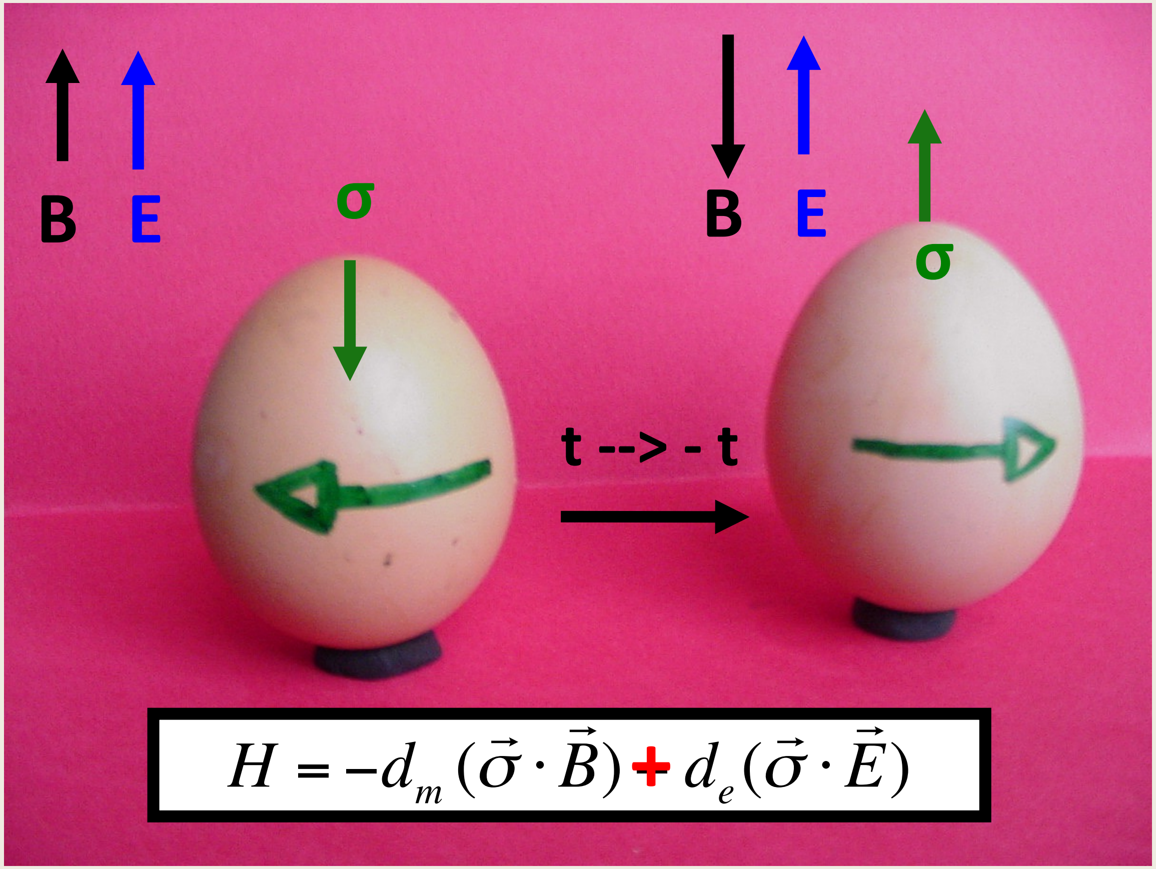
- The EDM, breaks time-reversal symmetry ! No EDM in QED at all !

PhD Thesis: Hudson

Symmetry considerations

- Electric and Magnetic Dipole Moment (EDM and MDM)

Pauli

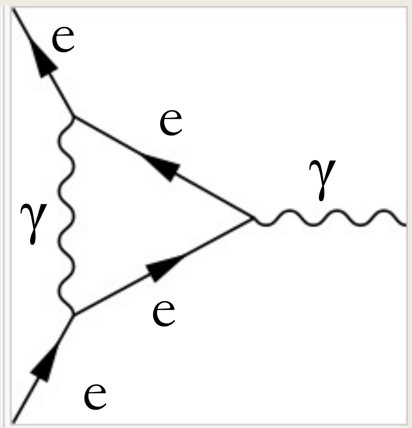


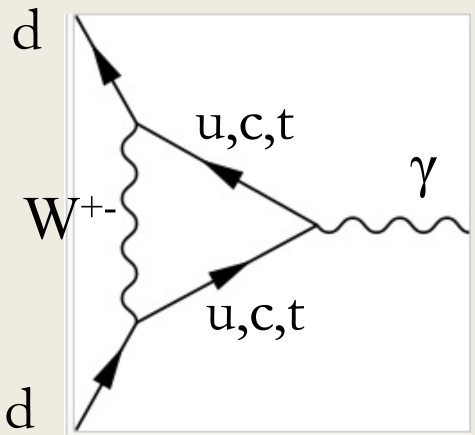
- The EDM, breaks time-reversal symmetry ! No EDM in QED at all
- **CPT theorem:** T violation $\longleftrightarrow$ CP violation

PhD Thesis: Hudson

CP violation in the Standard Model

- We can try to calculate EDMs from SM CKM phase





$$\mu = \frac{e}{2m_e}\frac{\alpha_{em}}{2\pi} \qquad d = 0$$

$$d_d \sim Im\left[V_{qd}V_{qd}^*\right] = 0$$

- **Vanishes at one-loop order!** Need to go to higher orders !

Naive nucleon-EDM estimate from known physics

(apart from measured bound $|d_n^{\rm exp}| < 10^{-26}\,e\,$cm) Khriplovich & Lamoreaux (1997); Kolya Nikolaev (2012)

- CP & P conserving (magnetic) moment $\sim$ nuclear magneton μ_N

$$\mu_N = \frac{e}{2m_p} \sim 10^{-14}\,e\,\text{cm}\,.$$

- Nonzero EDM requires

parity P violation: price to pay $\sim 10^{-7}$

$(G_F \cdot F_\pi^2 \sim 10^{-7}$ with $G_F \approx 1.166 \cdot 10^{-5}\text{GeV}^{-2})$,

and *additionally* **CP violation**: price to pay $\sim 10^{-3}$

$(|\eta_{+-}| \equiv |\mathcal{A}(K_L^0 \to \pi^+\pi^-)|/|\mathcal{A}(K_S^0 \to \pi^+\pi^-)| = (2.232 \pm 0.011) \cdot 10^{-3})$.

- In summary: $|d_N| \lesssim 10^{-7} \times 10^{-3} \times \mu_N \sim 10^{-24}\,e\,\text{cm}$

- In SM (without θ): extra $G_F F_\pi^2$ factor to *undo* flavor change of CKM-matrix

$$\hookrightarrow \quad |d_N^{\rm SM}| \lesssim 10^{-7} \times 10^{-24}\,e\,\text{cm} \sim 10^{-31}\,e\,\text{cm}$$

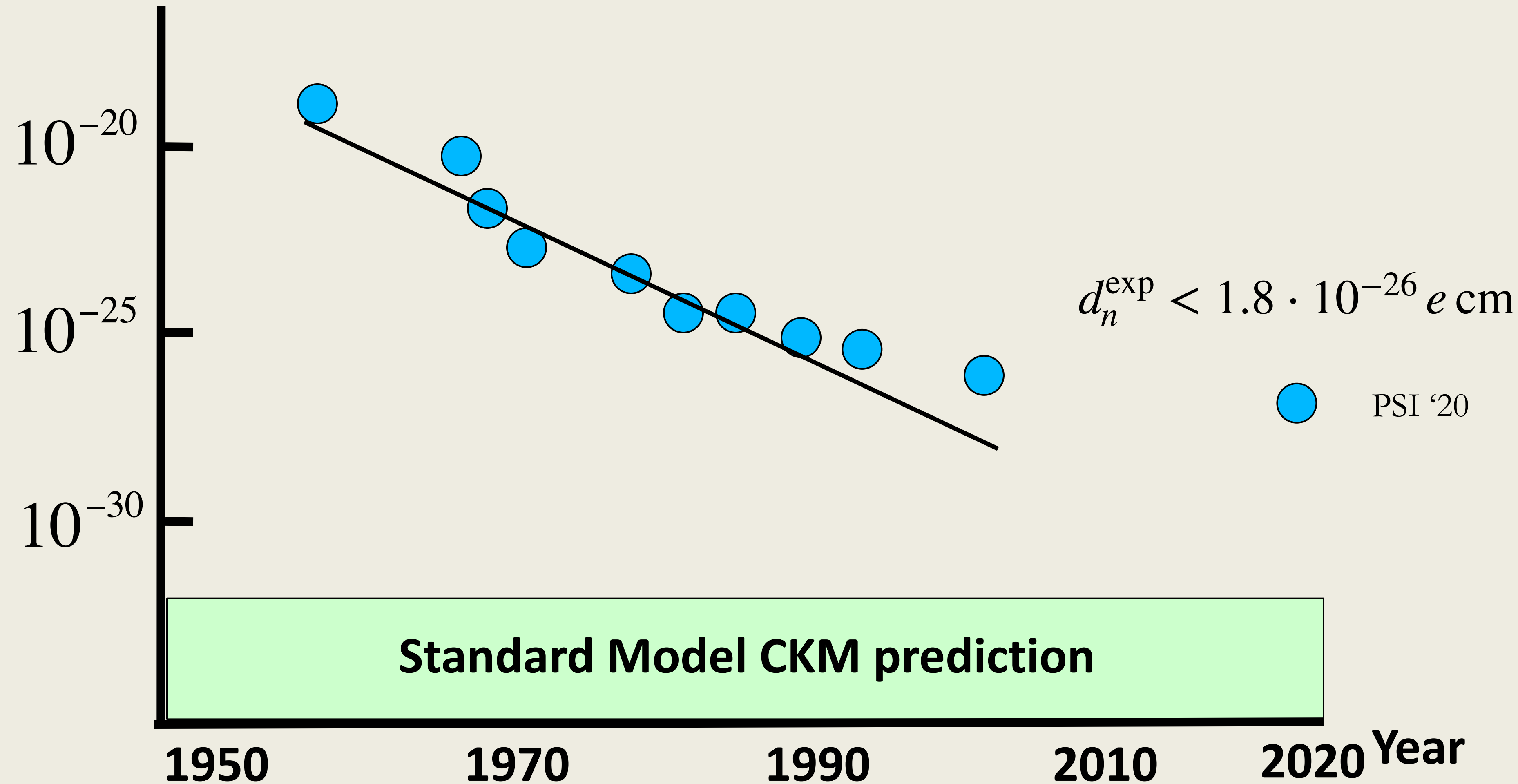
$\hookrightarrow$ BSM *window* for physics search beyond SM @θ:=0

▸ Hare ◂ Theta

$$10^{-24}\,e\,\text{cm} \gtrsim |d_N| \gtrsim 10^{-30}\,e\,\text{cm}$$

Electric dipole moments and the CKM matrix

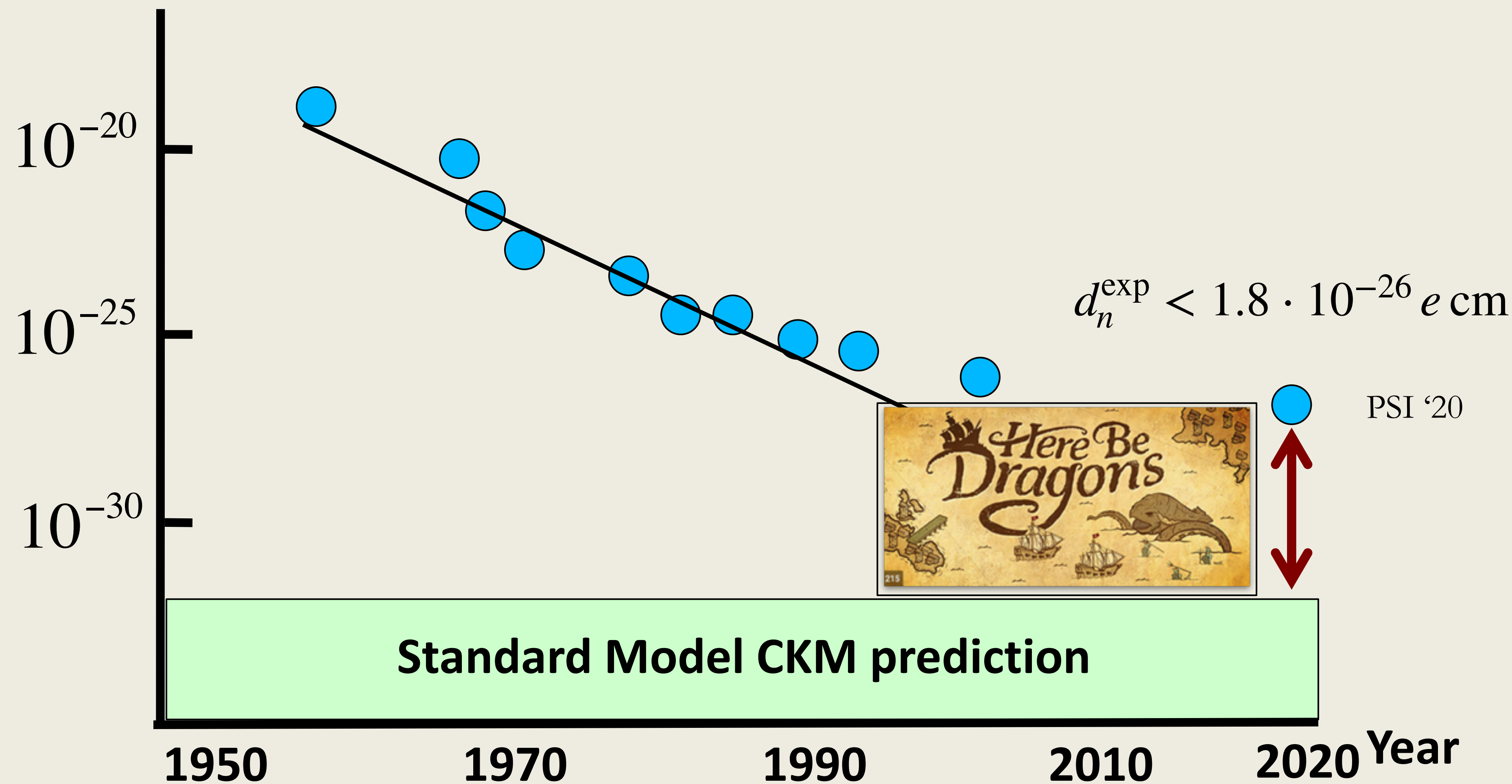
Limit on **neutron** EDM in e cm



More progress on electron EDM in recent times (factor 100 in 10 years)

Electric dipole moments and the CKM matrix

Limit on **neutron** EDM in e cm



Why do EDM experiments ?

- Just because CKM predictions are small, is not enough motivation

1. **EDMs are not crazy !**

Why do EDM experiments ?

- Just because CKM predictions are small, is not enough motivation

1. EDMs are not crazy !

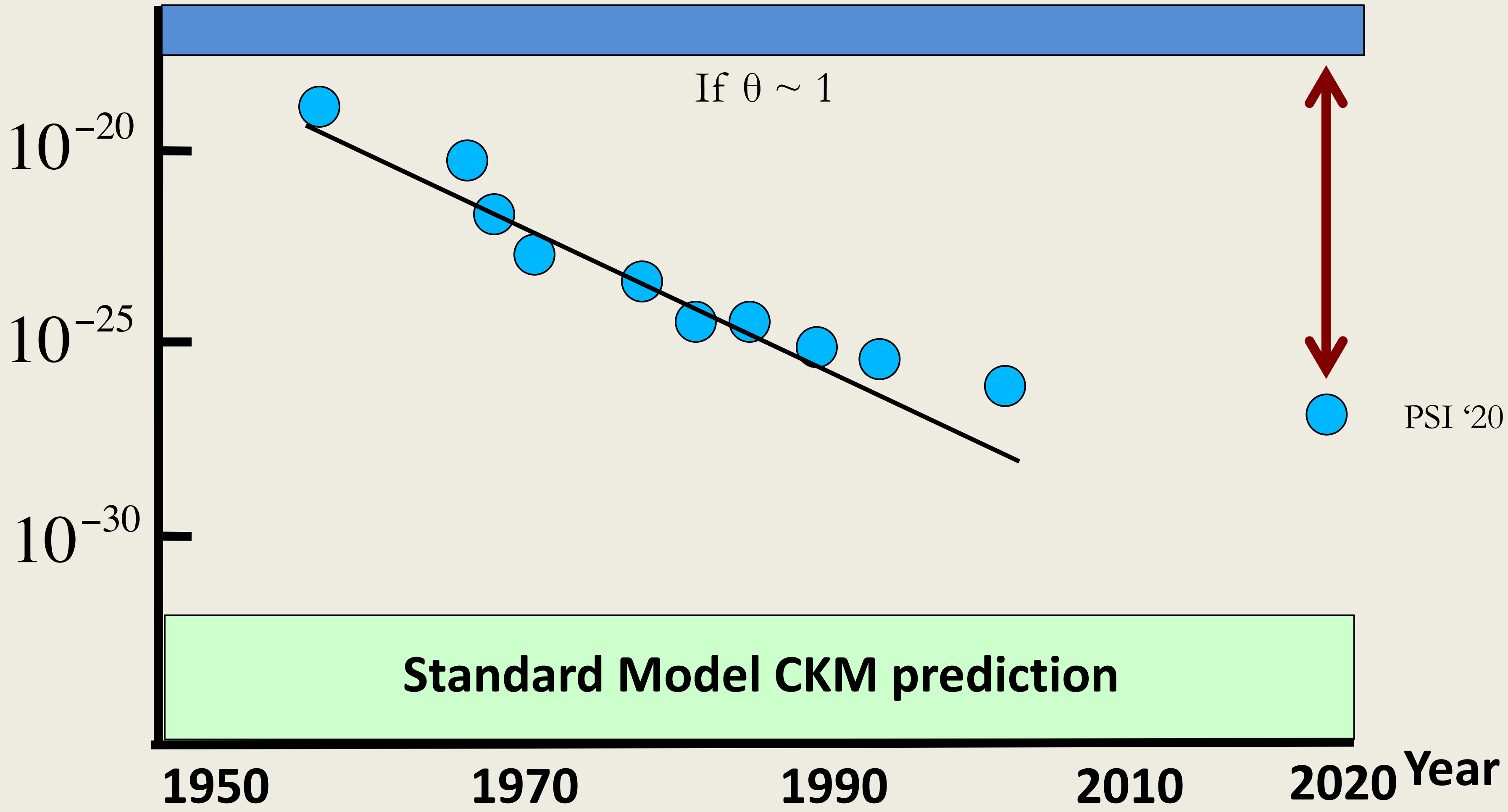
2. **There is another source of CP violation in the Standard Model**

$$+\theta \frac{g_s^2}{32\pi^2} \varepsilon^{\alpha\beta\mu\nu} G_{\alpha\beta} G^{\mu\nu} \xleftrightarrow{\text{axial U(1) transformation}} -\left(\frac{m_u m_d}{m_u + m_d}\right)\theta\, \bar{q} i \gamma^5 q$$

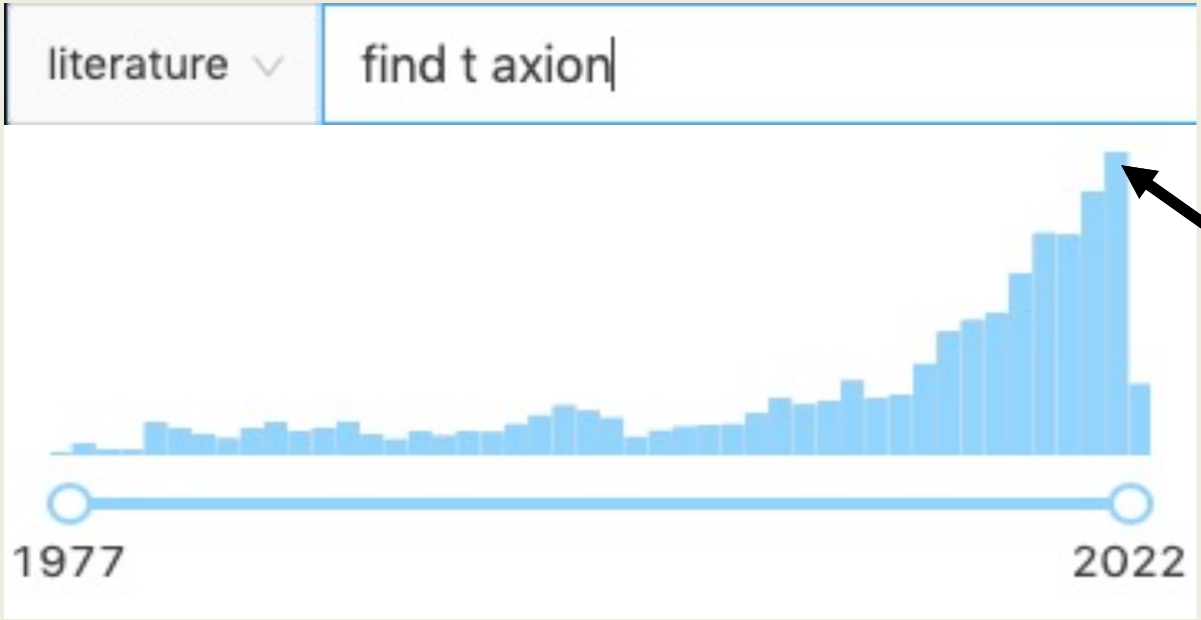
Theta itself is unknown → **Have to measure it**

Electric dipole moments and the CKM matrix

Limit on **neutron** EDM in e cm



Why do EDM experiments ?



341 papers

Theta itself is unknown → **Have to measure it** $\theta < 10^{-10}$

This is called the strong CP problem (driven by EDM searches)

Lead to a lot of theorizing: popular solutions are **axions** (could be dark matter)

Why do EDM experiments ?

- Just because CKM predictions are small, is IMO not enough motivation

1. EDMs are not crazy: predictions of the Standard Model

2. There is another source of CP violation in the Standard Mode

3. **We live in a universe with more matter than anti-matter**

Why might there be more CP violation

13.x billion years

- Entire observable universe made up of matter (no anti-matter regions)
- Cosmic microwave background: baryons about 5% universal energy budget

$$N_B \sim 10^{80} \qquad \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$

- Popular models of **baryogenesis** (there are many many many more)

1. Leptogenesis (new L violation and CP violation)
2. Post-sphaleron (new B violation and CP violation)
3. **Electroweak baryogenesis (New CP violation)**

Tested by EDMs

Why do EDM experiments ?

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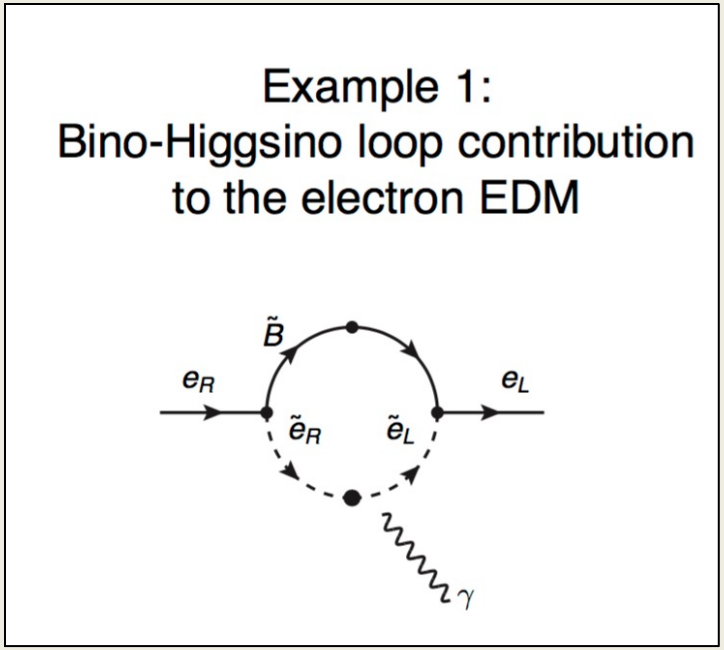
1. EDMs are not crazy: predictions of the Standard Model

2. There is another source of CP violation in the Standard Model

3. We live in a universe with more matter than anti-matter

4. **CP is a broken symmetry: SM extensions tend to violate it !**

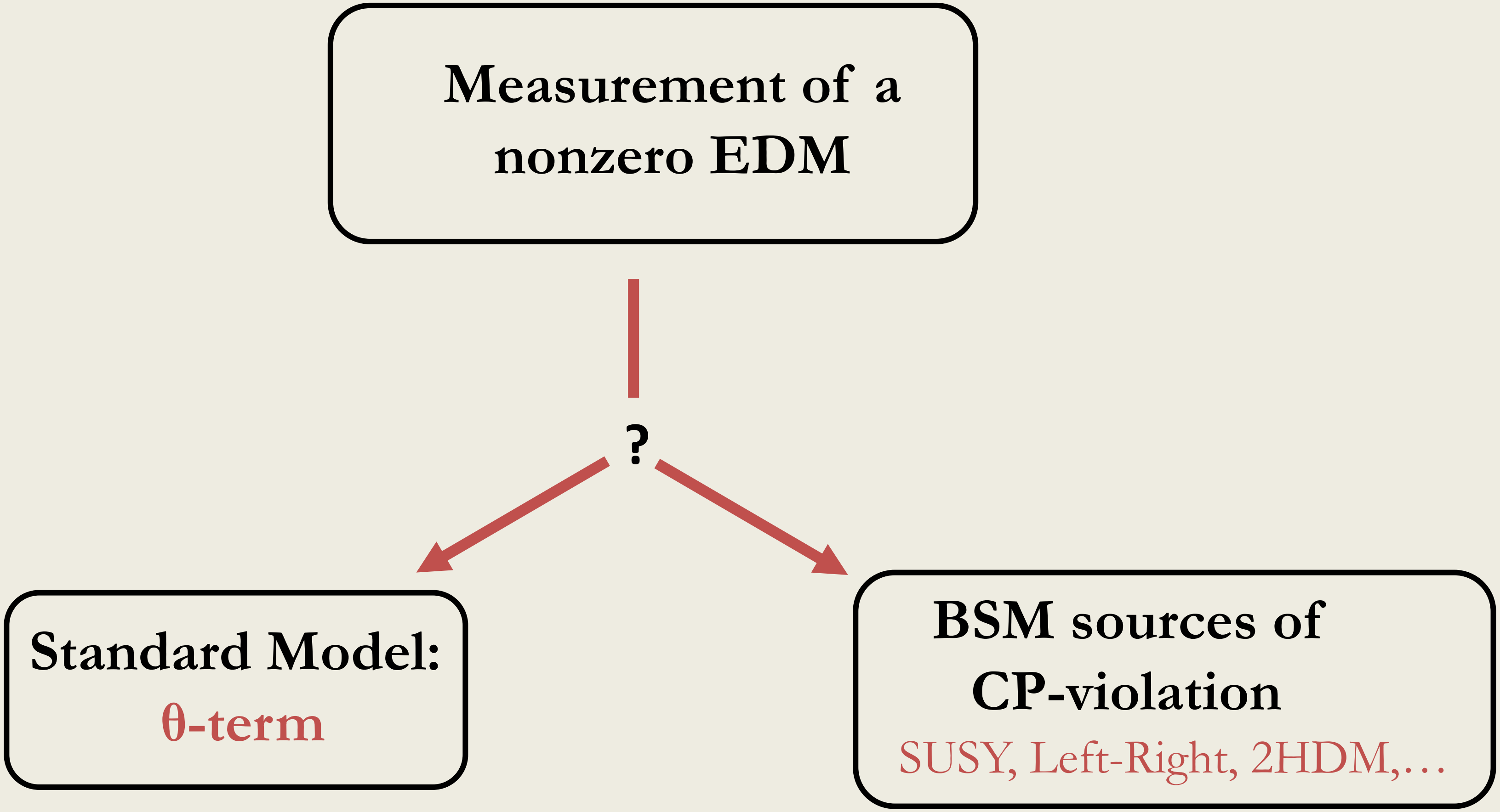
The SUSY CP problem



- CPV phase already at one-loop !
- **Typical size of EDM**

$$d_e \sim \left(\frac{\alpha_{em}}{\pi}\right)^n \frac{m_e}{\Lambda^2} \sin\phi$$

If phase = O(1): $\Lambda > 30$ TeV (n=1)



Forseeable future: EDMs are **'background-free'** searches for new physics

1. Can we disentangle theta from 'whatever' BSM physics
2. Can we disentangle different 'whatevers' ?

EDMs of charged particles

Farley *et al* PRL '04

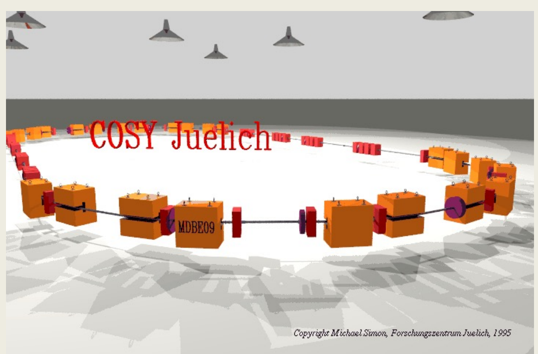
Anomalous magnetic moment

Electric dipole moment

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

All-purpose ring (^1H, ^2H, …) $\quad \sim 10^{-28,29}\ e\,cm$

100-1000 x current neutron EDM sensitivity!

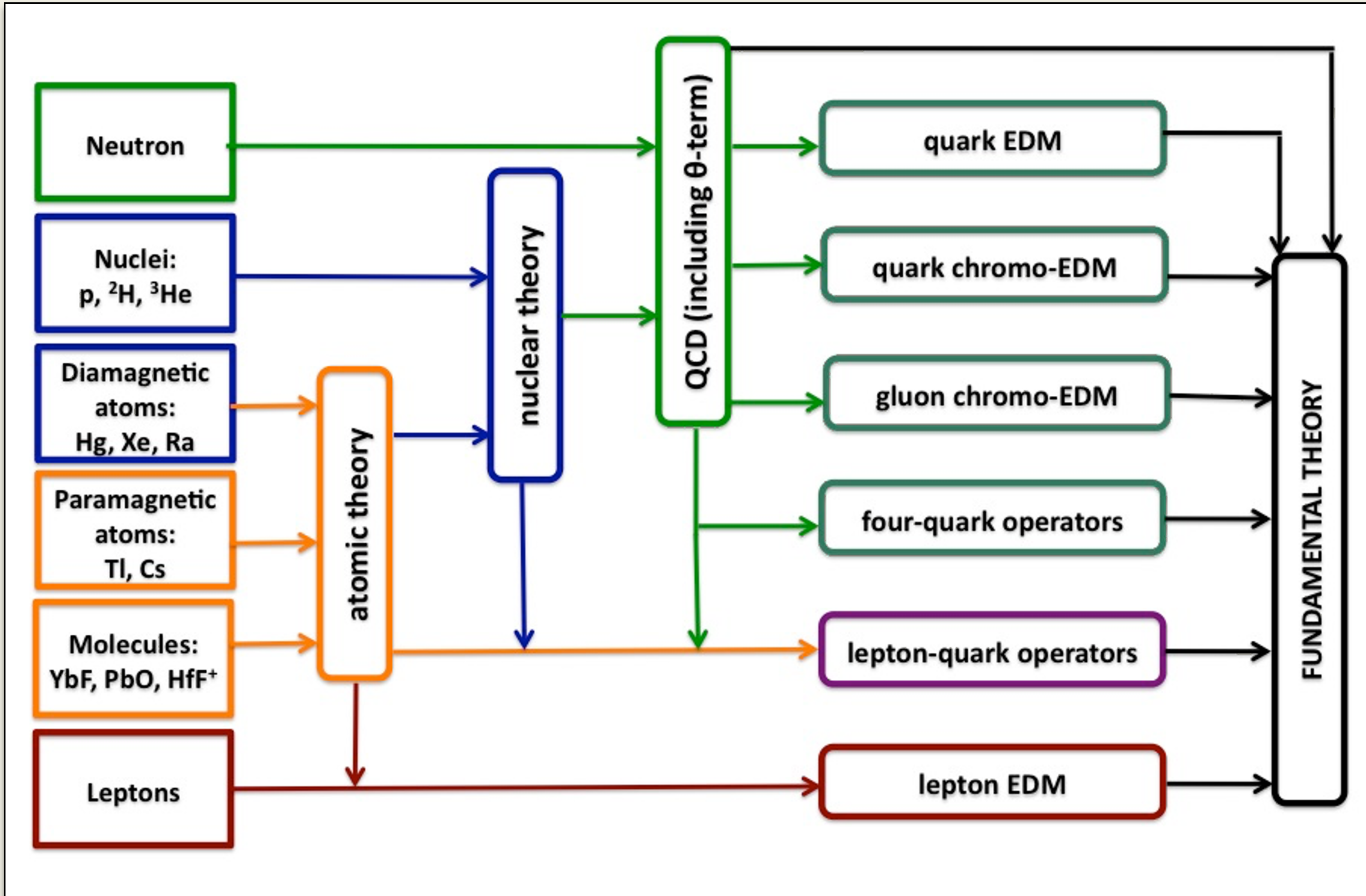


Already used for muon EDM

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

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

The EDM metromap

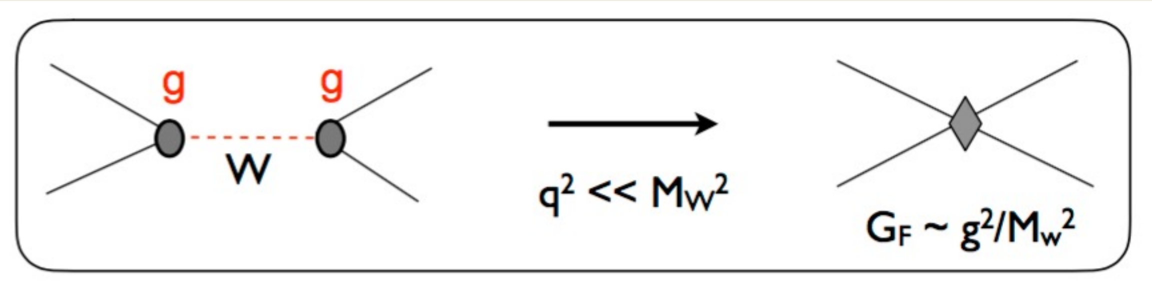


Describing the unknown

- **“In chemistry we do not care about top quarks”**

- At a certain energy scale, we can ‘integrate out’ fields associated with higher energies (smaller distances) → Effective Field Theory

- Very well-known example: Fermi-theory of beta decay

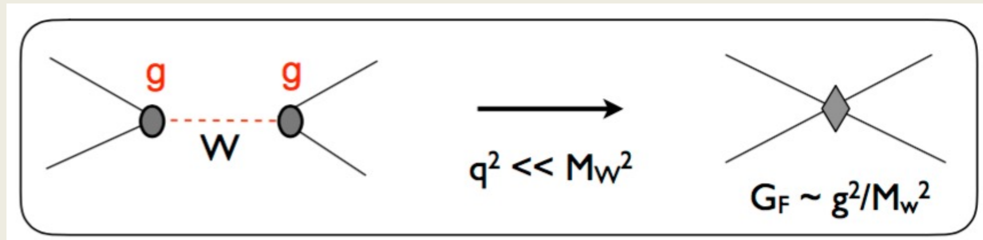


- We don’t need ‘high-energy details’, i.e. the W boson, at low energies !

Heavy BSM physics and the SM EFT

- Assume BSM fields exists but are heavy → **Integrate them out**

Fermi's theory:



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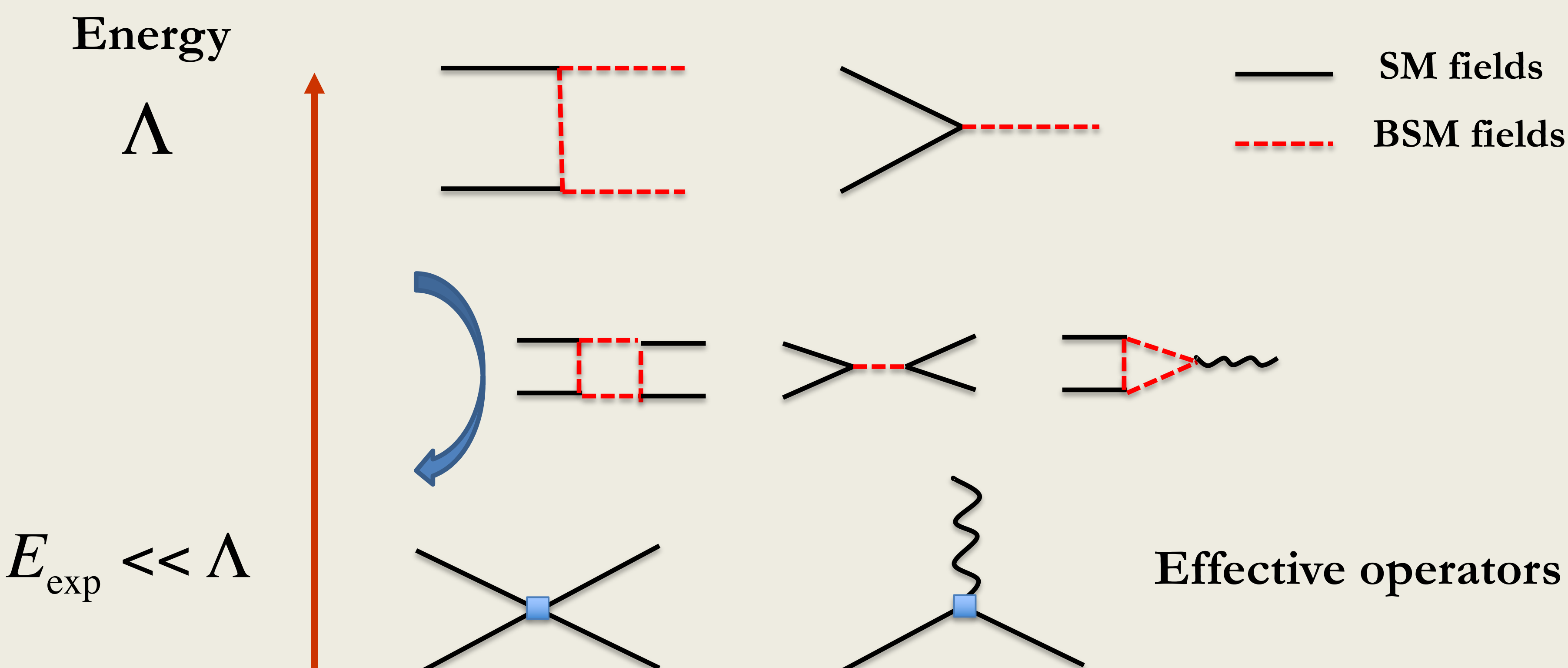

Standard model as an EFT

- Assume any BSM physics lives at scales $\Lambda >> M_{EW} \sim 100$ GeV
- Match to set of **effective** operators (model independent)

1) Degrees of freedom: Only Standard Model fields ! !

2) Symmetries: Lorentz, **SU(3)xSU(2)xU(1), nothing else**

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

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

- **At energy E, operators of dimension (4+n) contribute as**

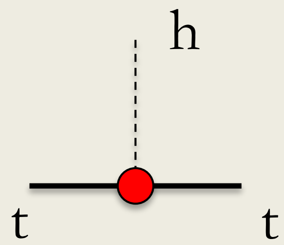
$$\left(\frac{E}{\Lambda}\right)^n$$ so at low energy: lowest-dim operators are relevant !

- Roughly 25 CP-violating structures at dimension six (more flavor assignments)

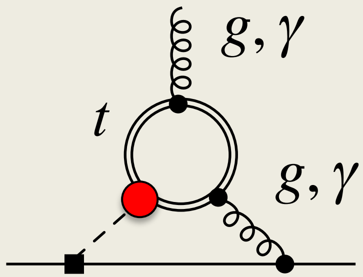
Example

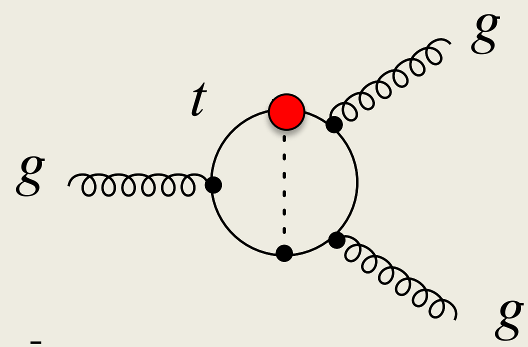
$$C_Y \; y_t \overline{t_L} t_R \tilde{\varphi} \, (\varphi^\dagger \varphi \;) + h.c.$$

Λ



$\mathbf{m_t}$

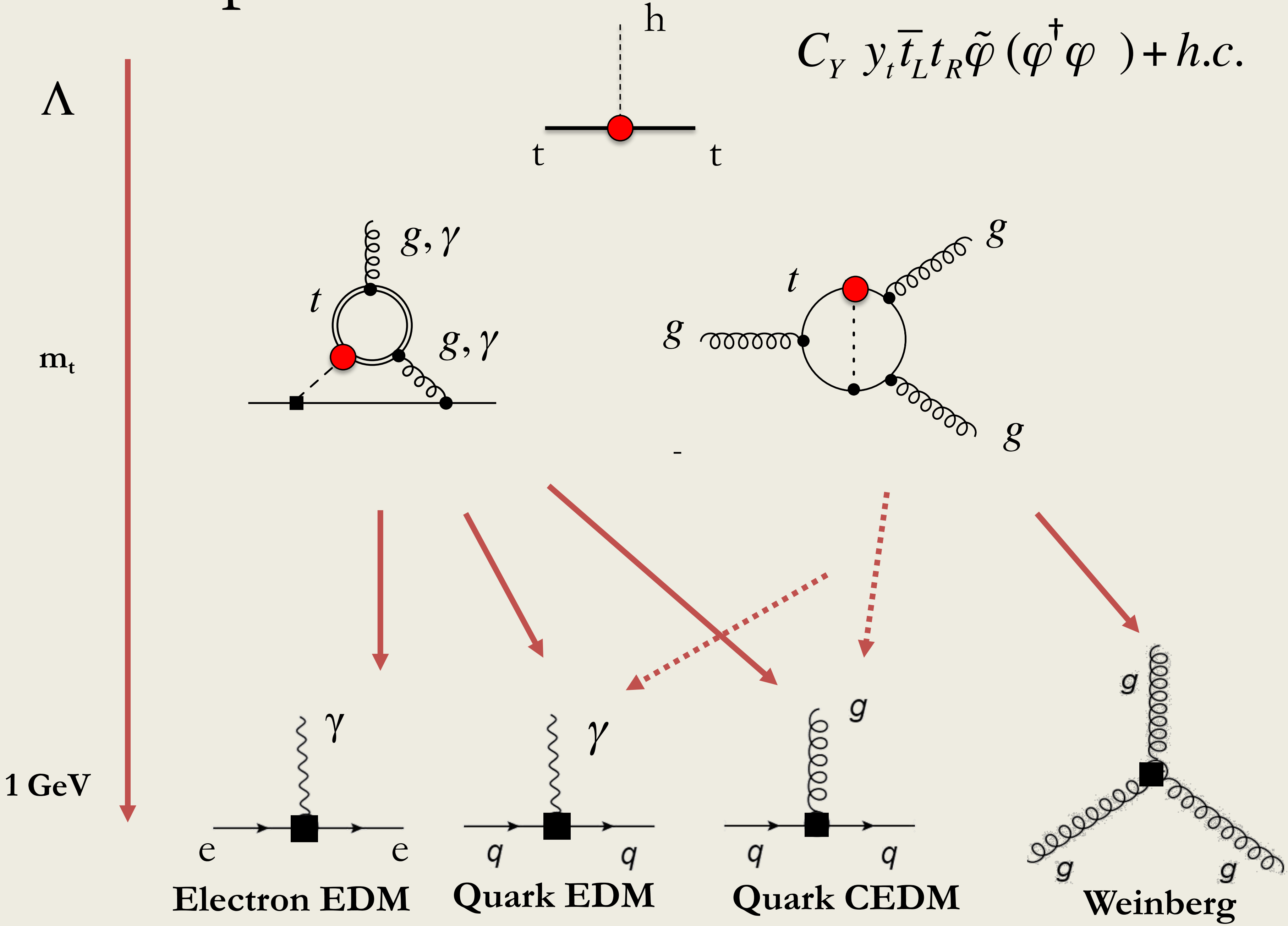




1 GeV

Example

$$C_Y \; y_t \overline{t}_L t_R \tilde{\varphi} \, (\varphi^\dagger \varphi \;) + h.c.$$

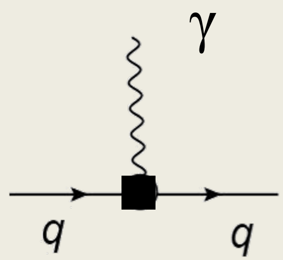


Plus others… But when the dust settles…..

Few GeV

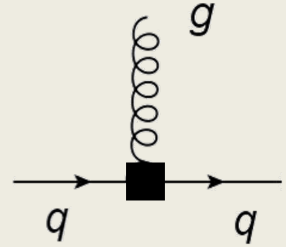
QCD
(θ-term)

+



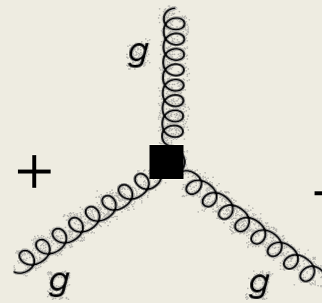
Quark EDM

+



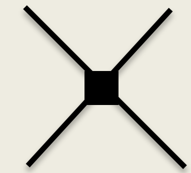
Quark C-EDM

+



Gluon C-EDM

+

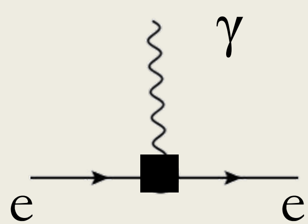


FQ operators

Just u,d quarks: 10 operators (without SU(2) would be ~20)

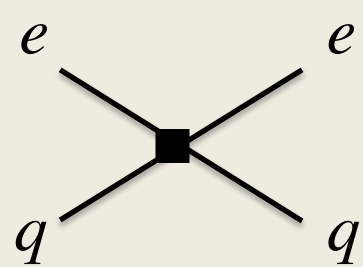
Handful more with strange quarks

(semi-)leptonic interactions (1 + 3)



Electron EDM

(muon + tau)



Intermediate summary I

- Parametrized BSM CP violation by **dim6** operators -> evolved down

- **Quite a mess.** Everything mixes under SM interactions.

- If nonzero EDMs are measured:

  Can they tell us anything about the underlying physics?

Study several BSM scenarios and see if they can be unraveled

Dekens, JdV, Bsaisou, Bernreuther, Hanhart, Meißner, Nogga, Wirzba, JHEP '14

Unraveling models

1. **SM + theta, obvious….**

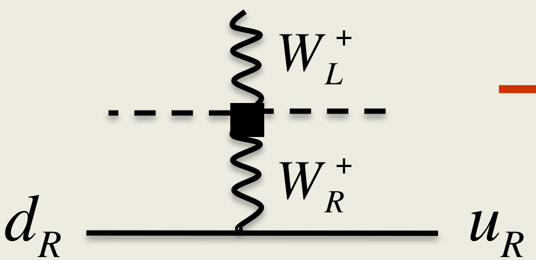
Unraveling models

1. **SM + theta, obvious….**
2. **Minimal left-right symmetric model**

Mohapatra, Senjanovic '75
Zhang et al' 08
Xu, An, Ji '10

- Parity restored at high energies: $SU_R(2)$ x $SU_L(2)$x$SU_c(3)$x$U(1)$

- Tree-level CP violation in W_L-W_R mixing



$$\Xi\, \bar{u}_R \gamma^\mu d_R \,(\tilde{\varphi}^\dagger i D_\mu \varphi) + \text{h.c.}$$

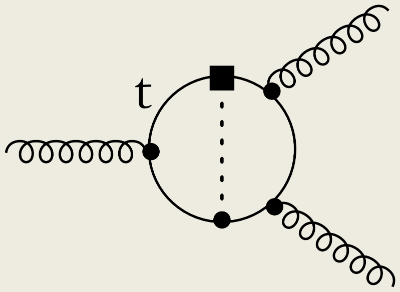
$$\Xi \sim \frac{1}{v_R^2} e^{i\alpha}$$

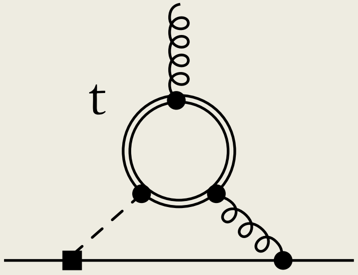
- **Dominant four-quark operator (FQLR) at low energies**

Unraveling models

1. **SM + theta, obvious….**
2. **Minimal left-right symmetric model**
3. **Aligned 2HDM**

- Simple SM extension with another Higgs doublet
- CP violation in Yukawa interactions -> Bar-Zee diagrams





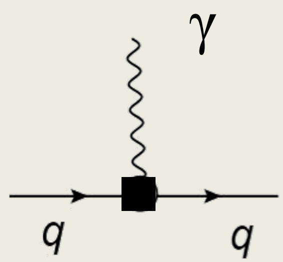
- At low energies: mainly **quark (C)EDMs + electron EDM**

Onwards to hadronic CPV

Few GeV

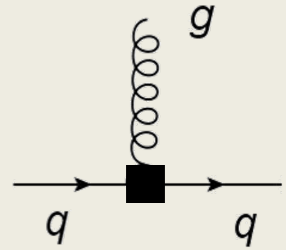
QCD
(θ-term)

+



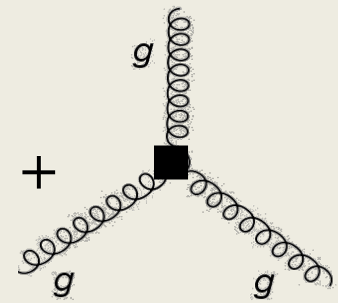
Quark EDM

+

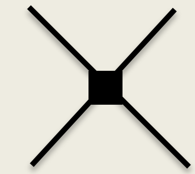


Quark chromo-
EDM

+



Weinberg
operator

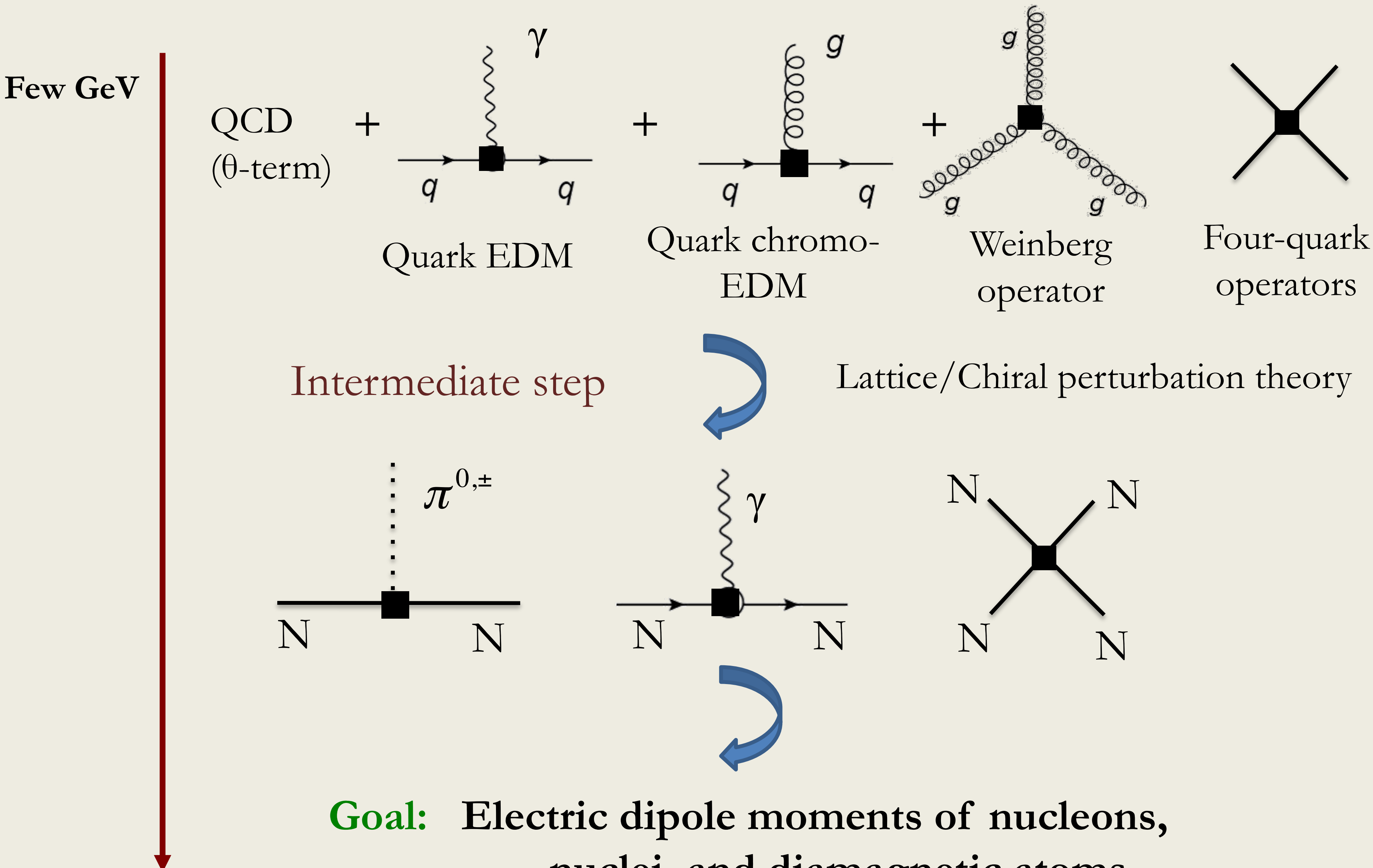


Four-quark
operators

Hadronic/Nuclear CP-violation

Goal: **Electric dipole moments of nucleons,
nuclei, and diamagnetic systems**

Onwards to hadronic CPV



Goal: Electric dipole moments of nucleons, nuclei, and diamagnetic atoms

Let's start with hadronic CPV

- Can learn a lot from chiral perturbation theory

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

- Quark masses = 0 → $SU(2)_L x SU(2)_R$ symmetry
  - Spontaneously broken to SU(2)-isospin (pions = Goldstone)
  - Explicit breaking (quark mass) → pion mass

- ChPT has systematic expansion in $Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi$ $\Lambda_\chi \cong 1\,GeV$
  - Chiral symmetry fixes 'form' of hadronic interaction
  - Each interactions comes with an unknown constant (LEC)
  - **Extended to include CP violation**

Weinberg, Gasser, Leutwyler, and many many others

Let's start with hadronic CPV

- Can learn a lot from chiral perturbation theory

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

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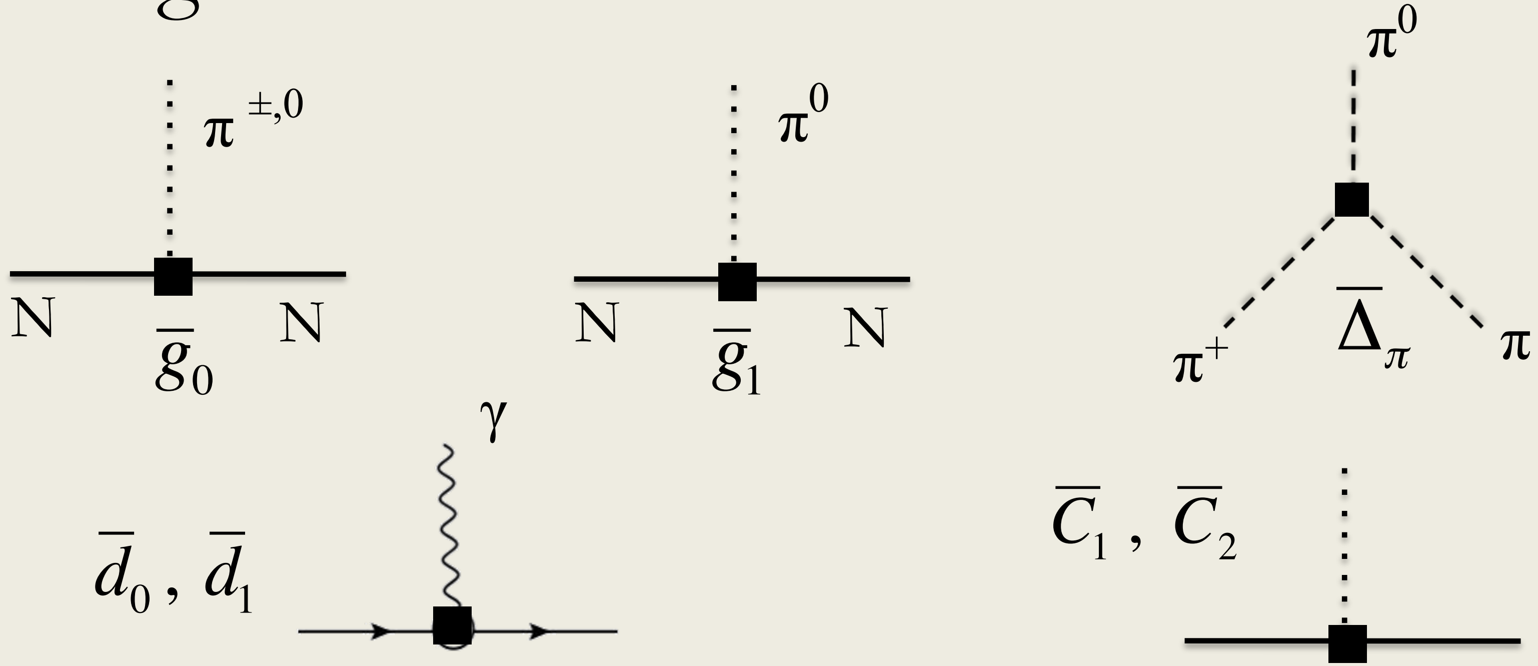
- ChPT has systematic expansion in $Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi \qquad \Lambda_\chi \cong 1\,GeV$

P- and T-Violating Lagrangians in Chiral Effective Field Theory and Nuclear Electric Dipole Moments #13

J. Bsaisou (IAS, Julich and JCHP, Julich and Julich, Forschungszentrum), Ulf-G. Meißner (Bonn U. and Bonn U., HISKP and IAS, Julich and JCHP, Julich and Julich, Forschungszentrum), A. Nogga (Julich, Forschungszentrum and IAS, Julich and JCHP, Julich), A. Wirzba (IAS, Julich and JCHP, Julich and Julich, Forschungszentrum) (Dec 17, 2014)

Published in: *Annals Phys.* 359 (2015) 317-370 • e-Print: 1412.5471 [hep-ph]

The magnificent seven



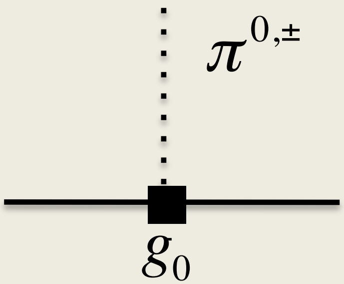
- 2 pion-nucleon (no g_2 !)
- 1 pion-pion-pion
- 2 nucleon-nucleon
- 2 nucleon-photon (EDM)

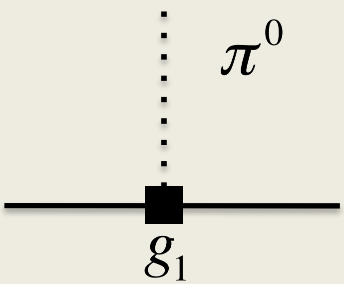
- Up to **NLO,** seven interactions for **all CP-odd** dim4-6 sources
- **Each hadronic/nuclear CPV observables probes a linear combination**

Separating mechanism

- Lowest-order interactions: **CPV pion-nucleon couplings (2x)**

$$L = g_0\,\bar{N}\boldsymbol{\pi}\cdot\boldsymbol{\tau}N + g_1\,\bar{N}\pi^0 N$$





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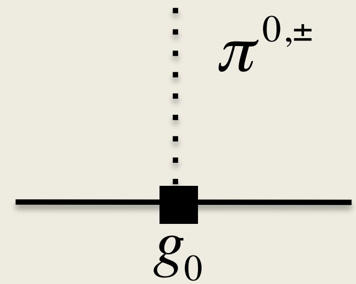
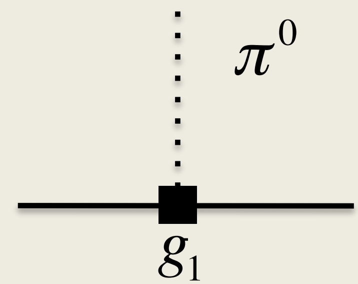




Key idea

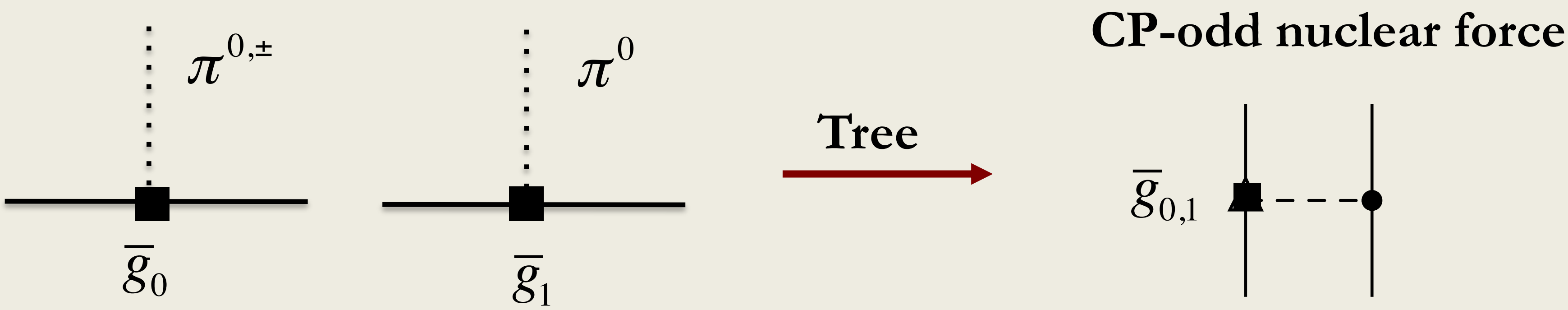
- The theta-term and dim-6 operators have different chiral properties
- **Different models -> Different g_0/g_1 ratios**

	Theta	2HDM	mLRSM	
	Theta term	**Quark CEDMs**	**FQLR**	**Quark EDM and Weinberg**
$\dfrac{\bar{g}_1}{\bar{g}_0}$	-0.2	≈ 1	$+50$	Both couplings are suppressed !

- **How to measure these ratios?**

Nucleon and nuclear EDMs up to NLO

- **Chiral power counting:** handful interactions dominate hadronic EDMs
- Lowest-order interactions: **CPV pion-nucleon couplings (2x)**



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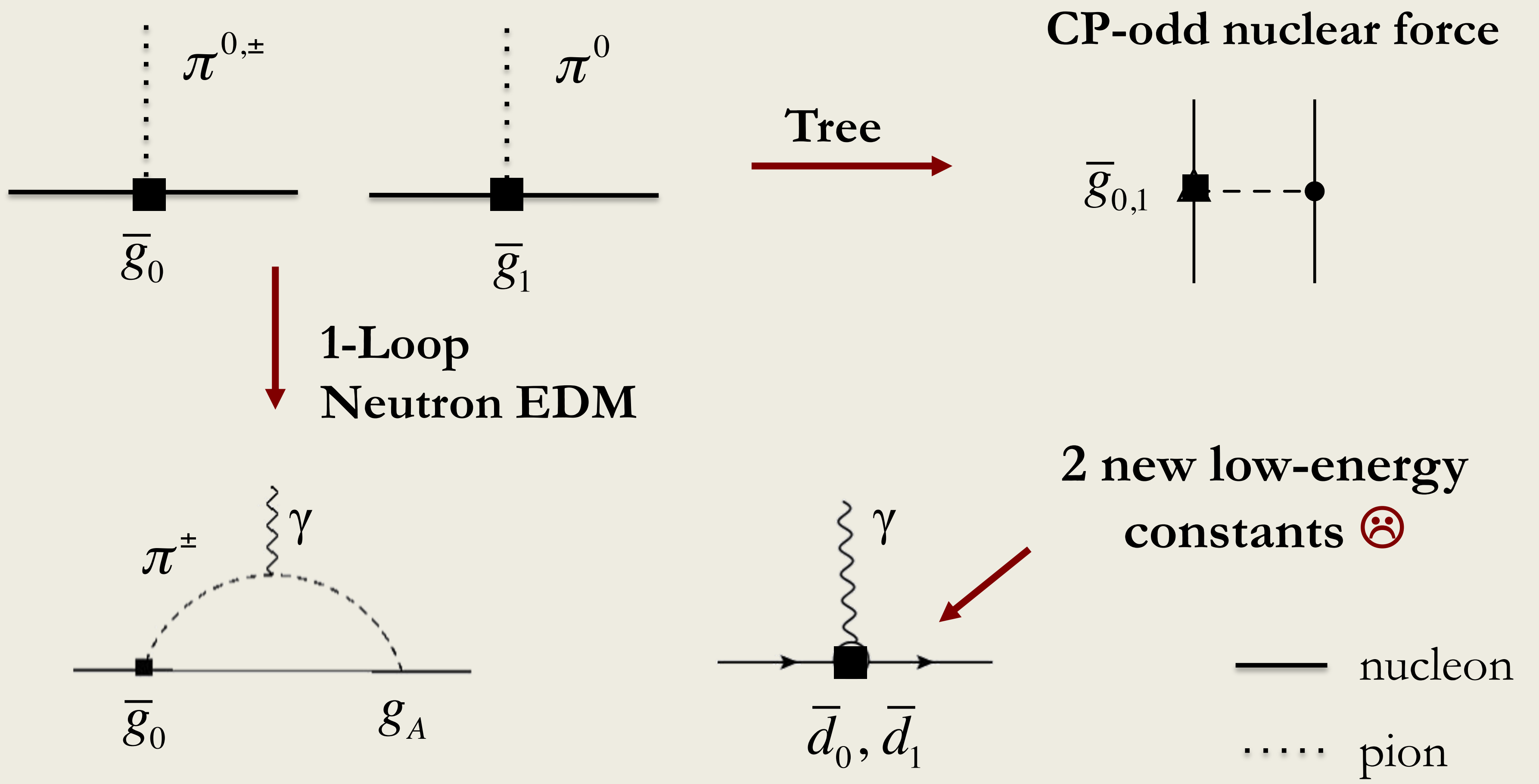
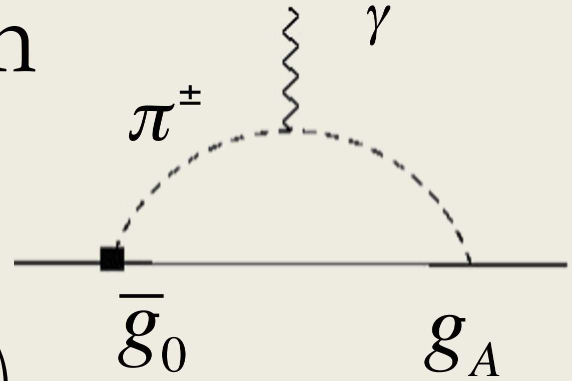


The strong CP problem



Nucleon EDM

Crewther ‘79 Borasoy ’02
Guo et al, ’10 ’12 ’14,
JdV et al ‘10 ’11 ‘14

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

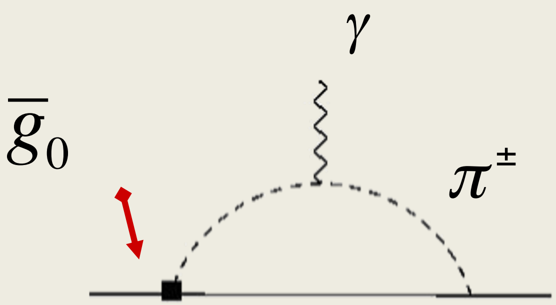
$$d_p = \bar{d}_0 + \bar{d}_1 + \frac{e g_A \bar{g}_0}{4\pi^2 F_\pi}\left(\ln\frac{m_\pi^2}{m_N^2} - 2\pi\frac{m_\pi}{m_N}\right) - \frac{e g_A \bar{g}_1}{8\pi F_\pi}\frac{m_\pi}{m_N}$$

- **No clear hierarchy** although hint for $d_n \sim -d_p$ for theta term

- Need non-perturbative computations
- Lattice QCD exists for only a few CP-odd mechanisms

- **Main conclusion: need more than nucleons to unravel the source**

More than one nucleon

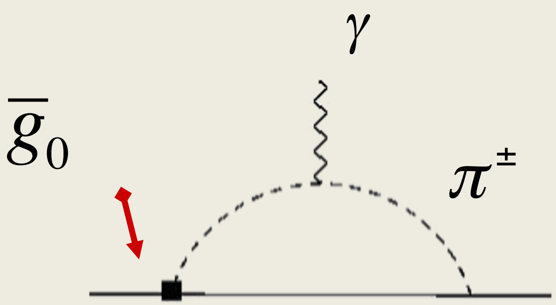


Nucleon EDM

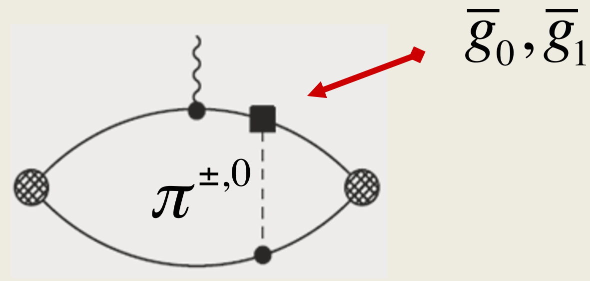
$$d_A = < \Psi_A \parallel \vec{J}_{\cancel{CP}} \parallel \Psi_A >$$

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

More than one nucleon



Nucleon EDM



Nuclear EDM

- New contribution from CP-odd pion exchange: **no loop** suppression

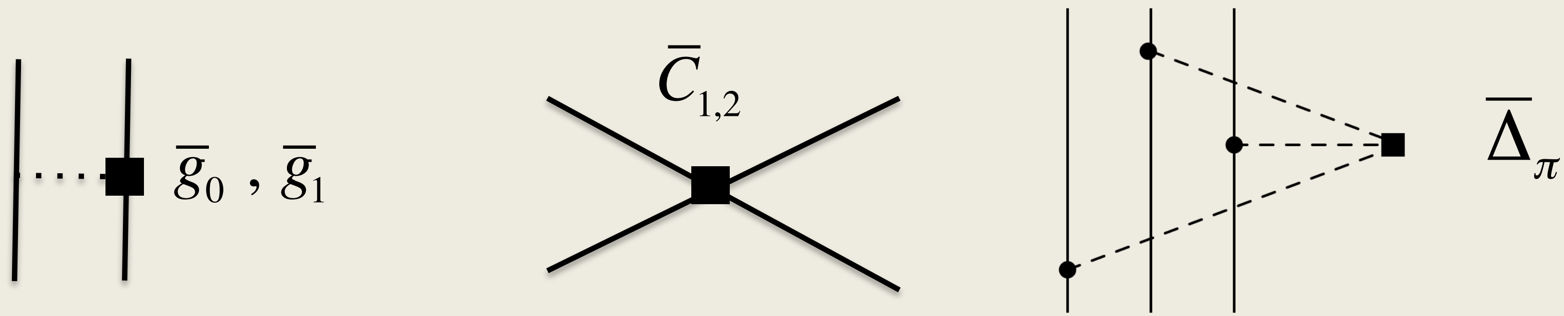
$$d_A = \langle \Psi_A \| \vec{J}_{\cancel{CP}} \| \Psi_A \rangle + 2 \langle \Psi_A \| \vec{J}_{CP} \| \tilde{\Psi}_A \rangle$$

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

- **Pion-exchange contribution can be larger than nucleon EDMs !**
- Chiral calculation of wave functions + CPV potential and currents

The CPV NN +NNN potential

For all dim4 + dim6 sources, NN + NNN CPV potential is subset of



- Long-range (pions): $\bar{g}_0$ $\bar{g}_1$
- Short range $\bar{C}_{1,2}$
- CPV three-body force at NLO $\bar{\Delta}_\pi$

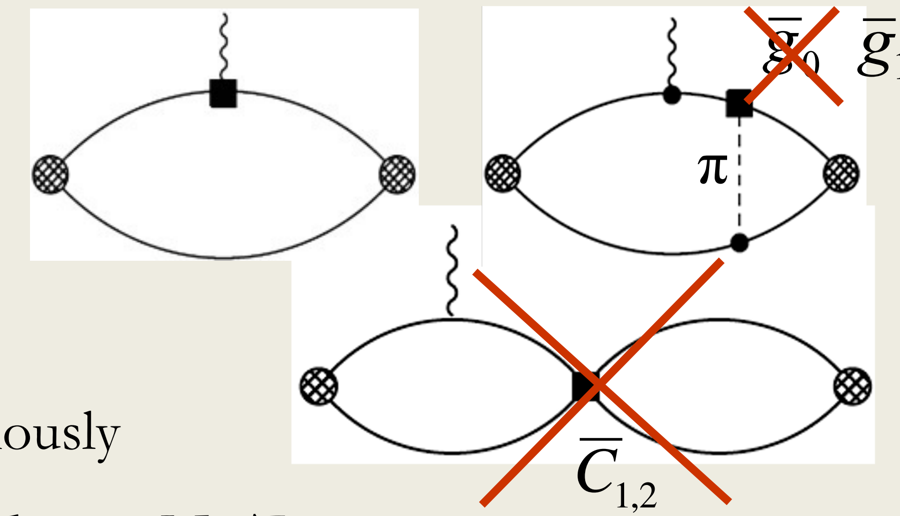
$$(E - H_{PT})\,|\tilde{\Psi}_A> = V_{\cancel{CP}}\,|\Psi_A>$$

Very different from traditional boson-exchange models

EDM of the deuteron

Target of storage ring measurement

- Three contributions (NLO)
  1. Sum of nucleon EDMs
  2. CP-odd pion exchange
  3. CP-odd NN interactions
  4. No three-body force obviously



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

$$^3S_1 \xrightarrow{\bar{g}_0,\,\bar{C}_{1,2}} {}^1P_1 \xrightarrow{\gamma} \cancel{{}^3S_1}$$

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

The chiral filter

Khriplovich/Korkin '00
Liu/Timmermans '04
Lebedev et al '04
JdV et al '11
Bsaisou et al '14

Chiral filter

- Deuteron EDM results

$$d_D = 0.9(d_n + d_p) + \left[(0.18 \pm 0.02)\,\bar{g}_1 + (0.0028 \pm 0.0003)\,\bar{g}_0\right] e\ fm$$

- Error estimate from cut-off variations + higher-order terms

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- Error estimate from cut-off variations + higher-order terms

	Theta term	**Quark CEDMs**	**Four-quark operator**	**Quark EDM and Weinberg**
$\left\lvert \frac{d_D - d_n - d_p}{d_n} \right\rvert$	0.5 ± 0.2	5 ± 3	20 ± 10	$\cong 0$

- Ratio suffers from hadronic (not nuclear!) uncertainties **(need lattice)**
- EDM ratio hint towards **underlying CP-odd operator**!

The chiral filter

Khriplovich/Korkin '00
Liu/Timmermans '04
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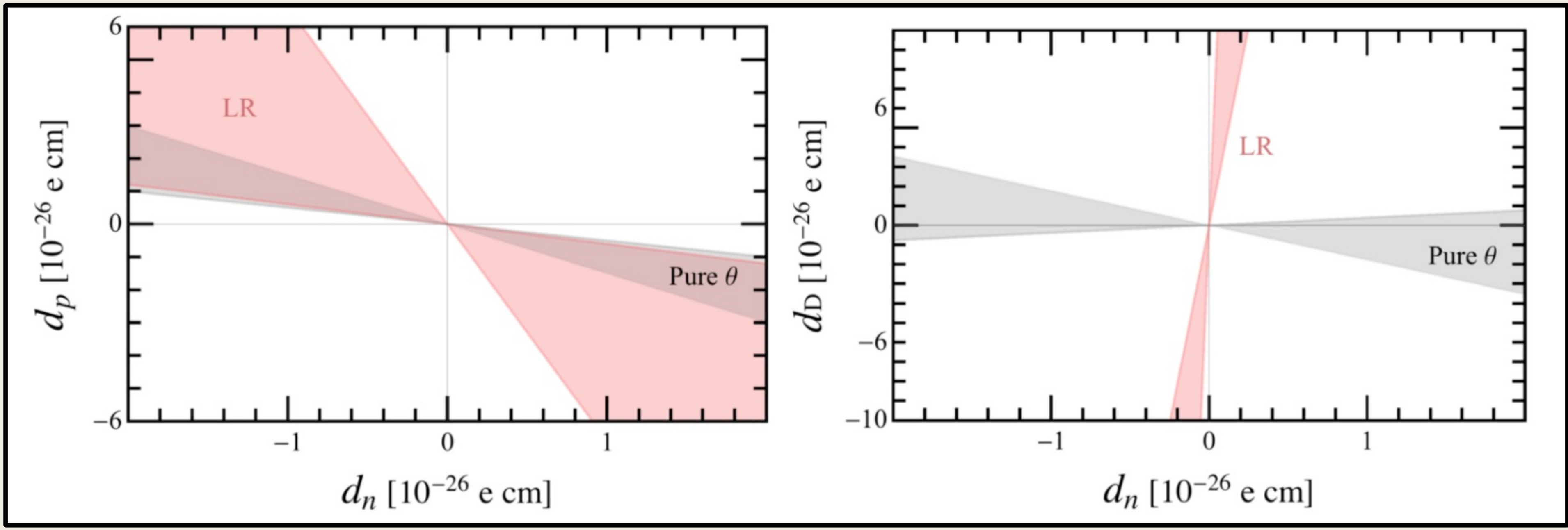

EDMs of the tri-nucleon system

Stetcu et al '08
JdV et al '11
Song et al '13
Bsaisou et al '14

- 3He can be put in a ring as well (3H too but radioactive…)
- More contributions than deuteron:
  1. Nucleon EDMs
  2. Both g_0 and g_1 pion exchange

$$d_{3He} = 0.9\, d_n - 0.05\, d_p + \left[(0.14 \pm 0.04)\, \bar{g}_1 + (0.10 \pm 0.03)\, \bar{g}_0 \right] e\ fm + \ldots.$$

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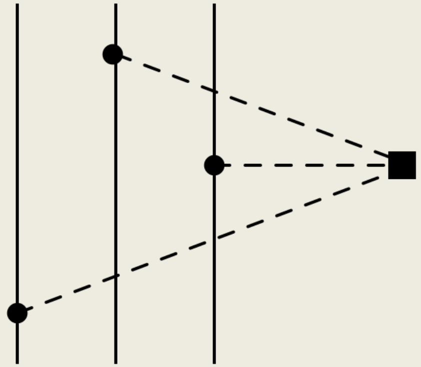
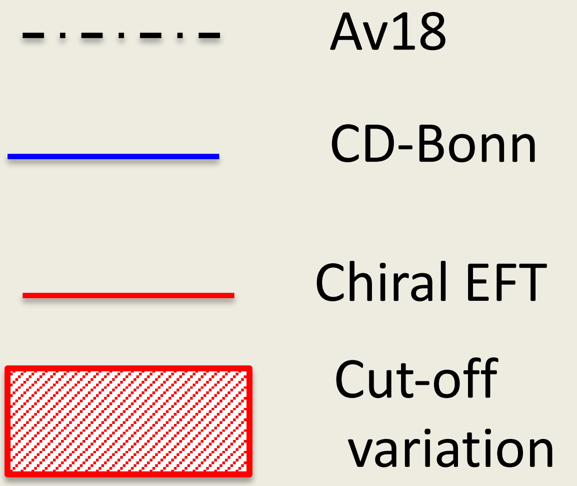


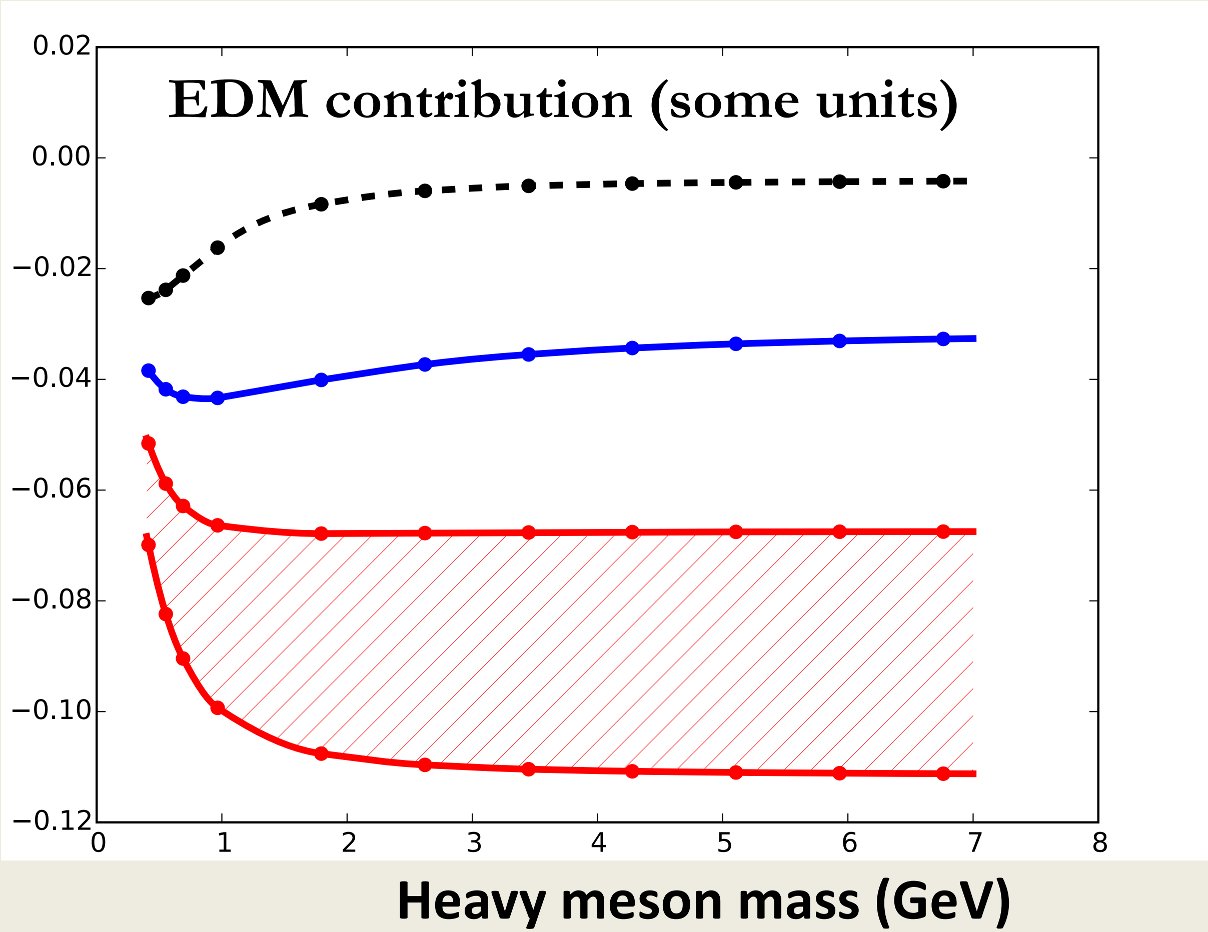
- Found to give small contributions (smaller than expectations) Bsaisou et al '14
- Unclear why, related to 3He structure?
- Viviani + Gnech reinvestigated this and found a larger and significant contribution! (2019)
- No calculations include this for heavier nuclei

Cut-off dependence

Plot from Bsaisou et al JHEP '14

$$\frac{m_1^2 \overline{C}_1}{4\pi\, r}\, e^{-m_1 r} \rightarrow \overline{C}_1\, \delta^{(3)}(\vec{r})$$





- Quite a large spread ….
- Only 10-20% for most CPV sources but leading for Weinberg operator
- **What to make of this ?**

Cut-off dependence

Plot from Bsaisou et al JHEP '14

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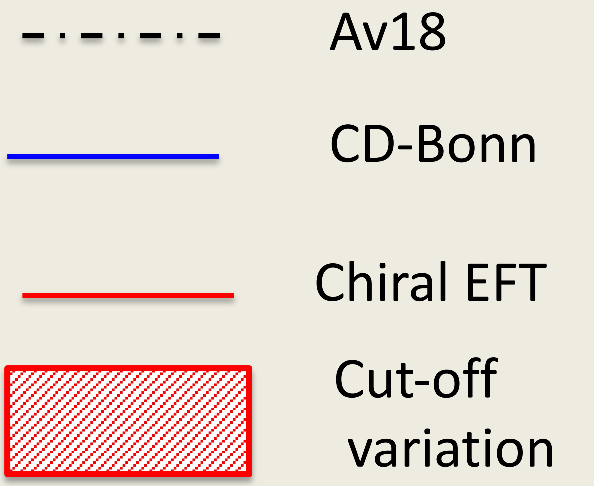
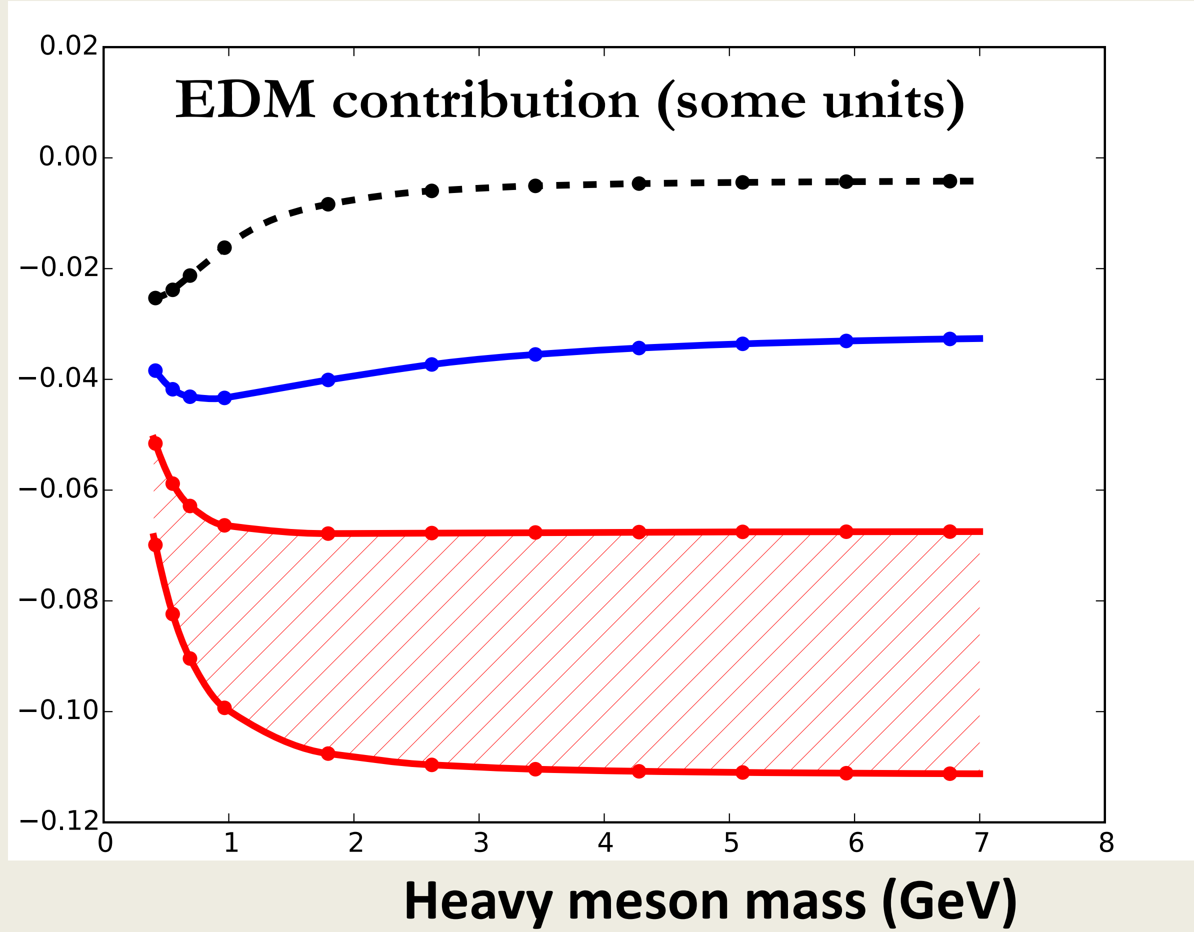


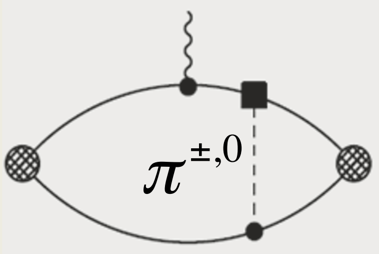


- Spread for different wave functions → different short-range NN force
- For a given regulator Λ : fit $\overline{C}_1(\Lambda)$ to data . Requires nonzero EDMs…
- **Better: calculate S ←→ P transitions on lattice → fit** $\overline{C}_1(\Lambda)$

Onwards to heavy systems

Graner et al, '16

Strongest bound on atomic EDM: $d_{^{199}Hg} < 8.7 \cdot 10^{-30}\ e\ cm$



Contribution from CP-odd nuclear force

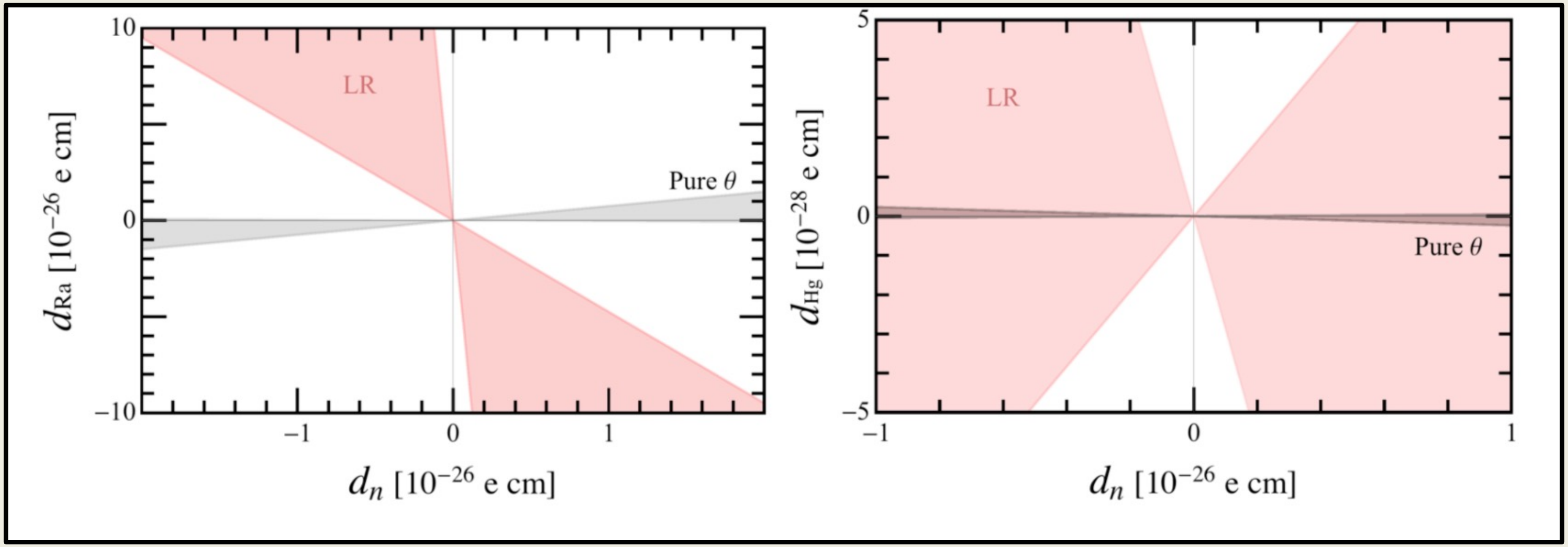
Screening incomplete: nuclear finite size (Schiff moment **S**)

$$S = g(a_0 \bar{g}_0 + a_1 \bar{g}_1)\ e\ fm^3$$

	a_0 range	**a_1 range**
^{199}Hg	0.3±0.4	0.45±0.7
^{225}Ra	2.5±7.5	65±40

Hadronic and nuclear uncertainties make interpretation difficult !

Reduced discriminatory power



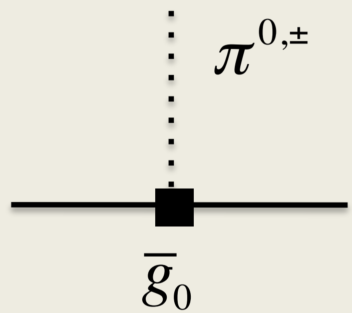
Goal for theory: matrix elements with 25-50% uncertainty

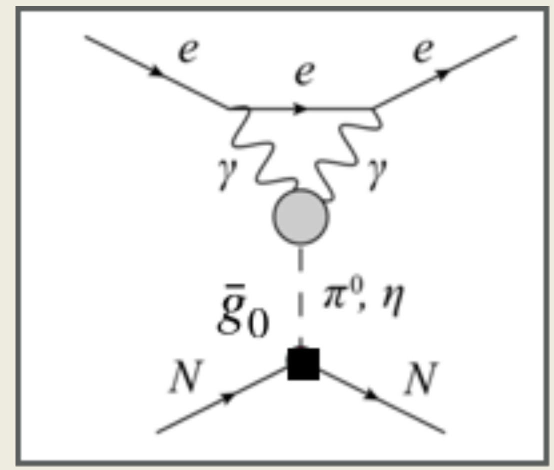
Similar to program for Dark Matter detection and neutrinoless double beta decay

A more inclusive picture

- Division in para- and diamagnetic systems is artifical

QCD
(θ-term)





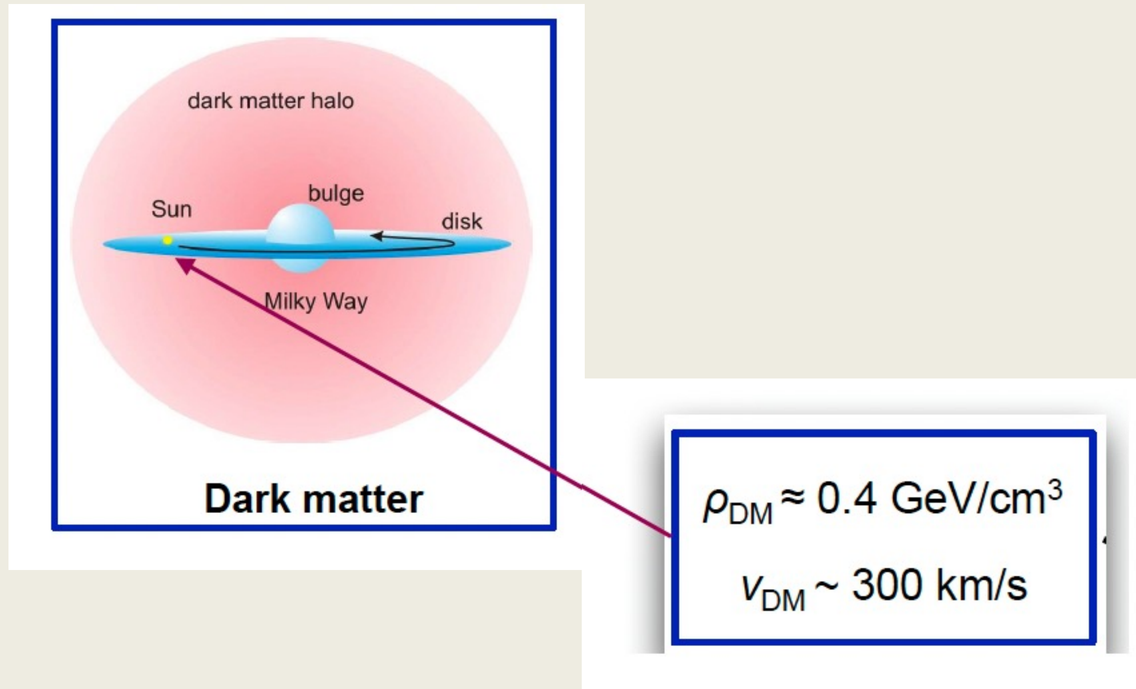
- Contribution suppressed by α_{em}^2 but still relevant !
- For instance, limit from polar molecule ThO $\quad \bar{\theta} < 10^{-8}$
- Only factor 100 away! Could be overcome in next generation!

A connection to axion searches

- If axions form Dark Matter they lead to oscillating EDMs

$$
\begin{aligned}
a(t,\cancel{\vec{x}}) &\approx a_0 \cos\left(m_a\left(1+\frac{v_{\rm DM}^2}{2c^2}\right)(t-t_0)+\phi_0\right)\\
&\approx a_0 \cos(m_a(t-t_0)+\phi_0)
\end{aligned}
$$

$$
\theta_a \equiv \frac{a_0}{f_a} \sim \frac{\sqrt{2\rho^{\rm local}}}{m_a f_a} \sim \frac{\sqrt{2\rho_{\rm DM}^{\rm local}}}{0.5\, m_\pi f_\pi}
$$



- Same expressions we derived for EDMs are necessary to look for these oscillating EDM searches → also in storage rings

Coming to the end

- Andreas made crucial contributions in connecting EDM experiments to the underlying particle physics

- I only talked about a **tiny fraction** of Andreas' work
- He worked on skyrmions, Casimir effect, eta decays, pion-nucleus absorption, neutron stars, nuclear matter, QM scattering problems….

- Extremely broad and interested, and superb mathematical physicist.
- Very well connected to the experimental program at FZJ

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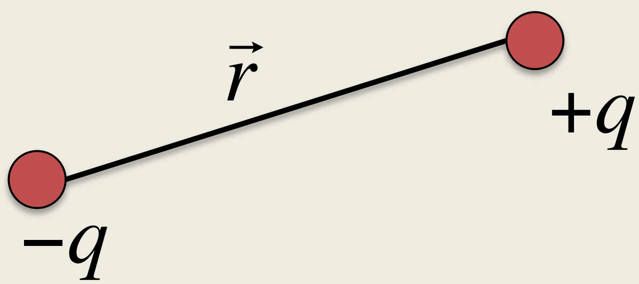
- Very well connected to the experimental program at FZJ

- **Maybe more important: Andreas was extremely kind to a young physicist joining FZJ → I am very grateful**

Other electric dipole moments

- Take a classical dipole configuration
- Electric dipole ~ d ~ q r
- Does not violate **anything**



- So we mean with an EDM: the coupling of **spin** and the **E-field**.

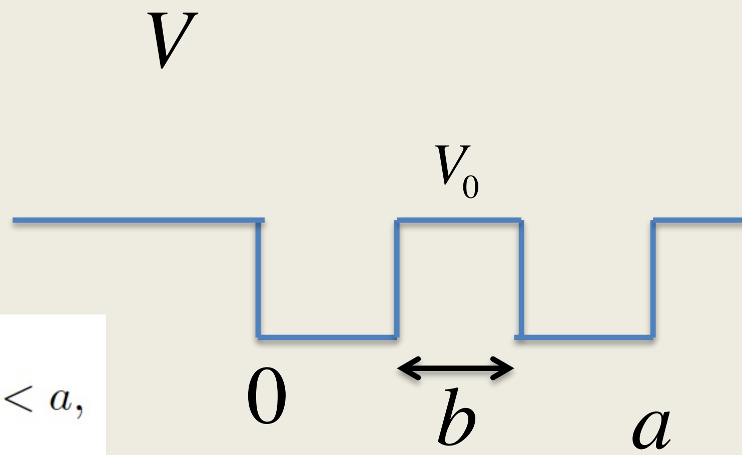
- For electron, neutron, atom, the only quantity available is the spin.
  So there is no 'r' around

- So where does the non-CPV EDM of molecules come from ?

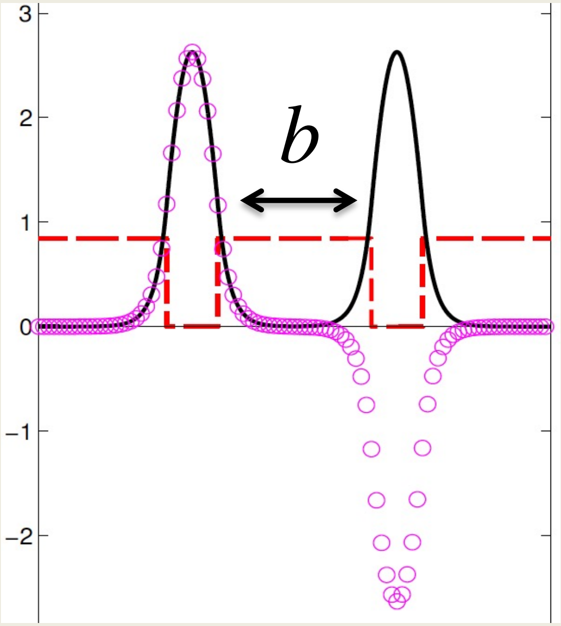
Double-well potential

- Analogy take a double-well potential
- If V_0 is very small, get usual solutions

$$\psi_n(x) = \begin{cases} \sqrt{\frac{2}{a}} \sin\left(\frac{n\pi x}{a}\right) & \text{if } 0 < x < a, \\ 0 & \text{otherwise,} \end{cases}$$



Double-well potential



- Analogy take a double-well potential

- If V_0 is very large, get usual solutions

$$\psi_n(x) = \begin{cases} \sqrt{\frac{2}{a}} \sin\left(\frac{n\pi x}{a}\right) & \text{if } 0 < x < a, \\ 0 & \text{otherwise,} \end{cases}$$

- With nonzero V_0 , two solutions appear with different parity and a small enery difference (tunneling effect !). $\mathbf{E_+ - E_- \sim b}$

- A molecule like water has indeed **a nearly-degenerate** ground state with opposite parity

Fake EDMs

- So we have 2 states which we call $\left|\pm\right\rangle$
- Turn on Electric field E (mixing of states)

$$H = \begin{pmatrix} \mathcal{E}^{+} & 0 \\ 0 & \mathcal{E}^{-} \end{pmatrix} + \begin{pmatrix} 0 & Eb \\ Eb & 0 \end{pmatrix}$$

- Diagonalize matrix to get energy eigenvalues

$$\mathcal{E}_{1,2} = \frac{1}{2}(\mathcal{E}_{+} + \mathcal{E}_{-}) \pm \sqrt{(\mathcal{E}_{+} - \mathcal{E}_{-})^2/4 + E^2 b^2}$$

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- If the E field is smaller than the energy gap

$$\mathcal{E}_{1,2} = \frac{1}{2}(\mathcal{E}_+ + \mathcal{E}_-) \pm \frac{1}{2}(\mathcal{E}_+ - \mathcal{E}_-)\left(1 + \frac{2E^2 b^2}{(\mathcal{E}_+ - \mathcal{E}_-)^2}\right)$$

- The energy shift is quadratic in the E field !! So no P or T violation
- If the E field is larger than the gap: **degenerate ground state**

$$\mathcal{E}_{1,2} = \frac{1}{2}(\mathcal{E}_+ + \mathcal{E}_-) \pm Eb$$

EDM theorem

- Nonzero EDMs imply P and T (and CP) violation if the system has a **nondegenerate ground state**
- Note: all subatomic particles are non-degenerate

1. Uuuuh, what about H_2O or NH_3 molecules. HUGE EDMs. ~ 10^{-8} e cm

   Degenerate ground states, no signal for CP violation !

2. What about CP violation in the Standard Model (SM) ?
   How large are EDMs expected to be ?

Some musings

Is there really a problem ?

- Not really. **It is just a parameter**. No inconsistencies.
- **Could it have been larger?**
- Seems yes, nothing really changes in the universe if θ ~ **0.1** **No anthropic argument.**

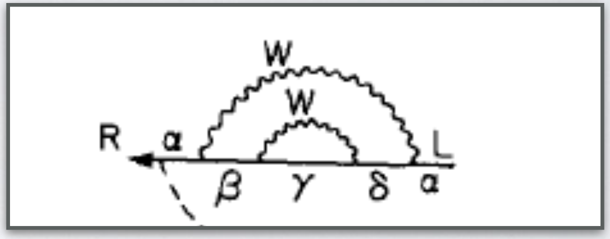
Ubaldi '08, Inka Hammer '15, Lee et al '20,

Is small theta radiatively stable?

- SM has a remarkable property: **theta is technically natural**
- **Ellis/Gaillard '79: tiny CKM contributions**

$$\Delta\bar{\theta} \sim 10^{-16}$$

- This property is lost in generic BSM extensions !



If we do think it is a problem, can we solve it ?

- **UV solutions:** P or CP is a symmetry of UV theory. Break at some scale to generate CKM phase —> Avoid generating a large theta term is not easy!
- **IR solution:** Use a Peccei-Quinn mechanism to dynamically set theta to zero. **AXIONS**
- **Ruled out solution:** massless up quark

EDMs of charged particles

Farley *et al* *PRL* '04

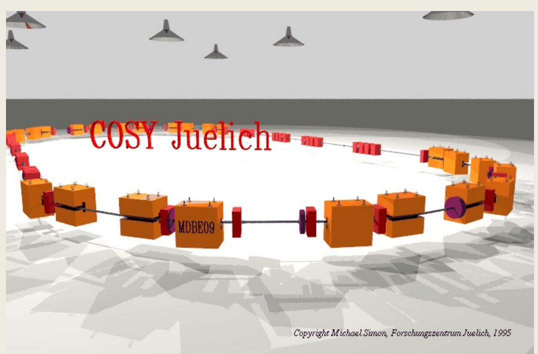
Anomalous magnetic moment

Electric dipole moment

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

All-purpose ring (^{1}H, ^{2}H, ^{3}He, …) $\sim 10^{-28,29}\ e\ cm$

100-1000 x current neutron EDM sensitivity! (takes a while tough….)



Already used for muon EDM

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

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

Major progress in:

JEDI collaboration, '15, '16

Test d_D measurement in 2019

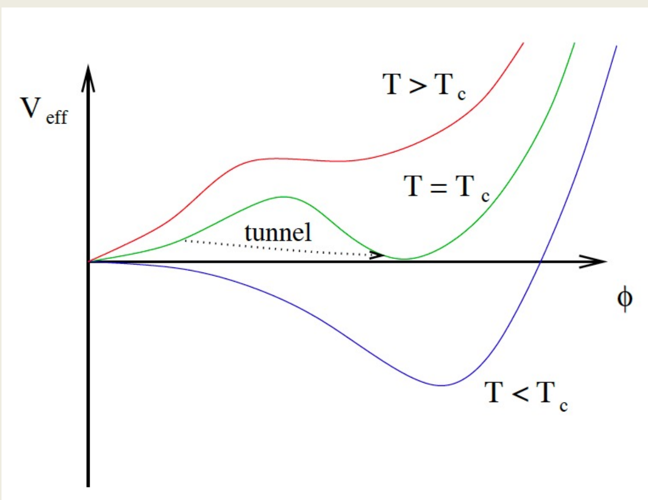
Electroweak baryogenesis in a nut-shell

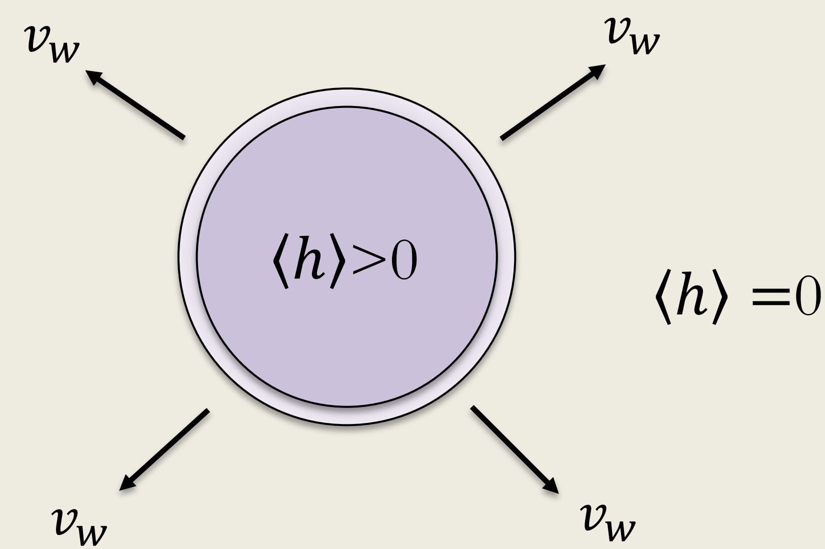
- Many BSM models for electroweak baryogenesis

Kuzmin, Kubakov, Shaposhnikov ‘85
Cohen, Kaplan, Nelson ‘93

1. A strong first-order EW phase transition

Does not happen for m_h > 60 GeV → need new physics ~ TeV or lower





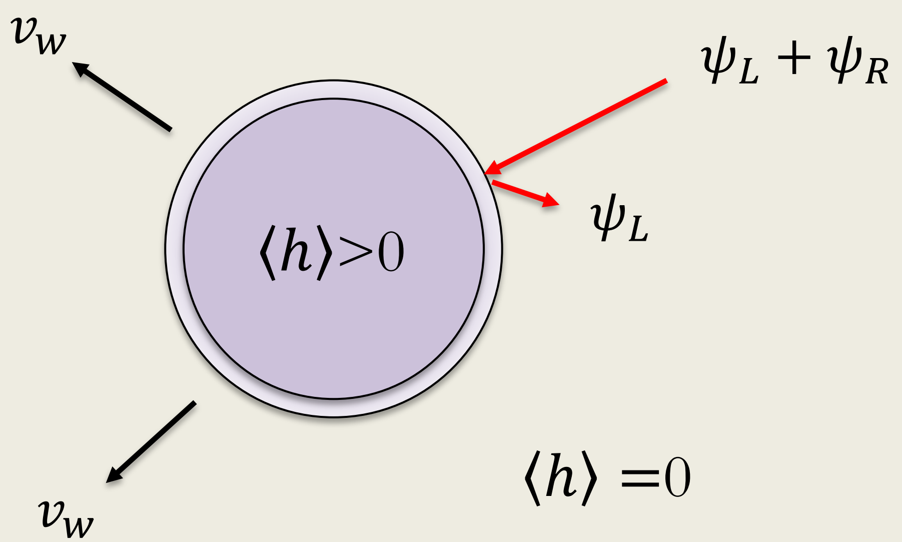
Experimental probes: di-Higgs production, new scalars, Higgs couplings, Gravitational waves

Electroweak baryogenesis in a nut-shell

- Generation of matter happens during EW phase transition

  2. Additional CP-violation. CKM phases + theta term not enough.

CP-violation ~ Higgs field to create **overdensity of left-handed particles** in front of bubble

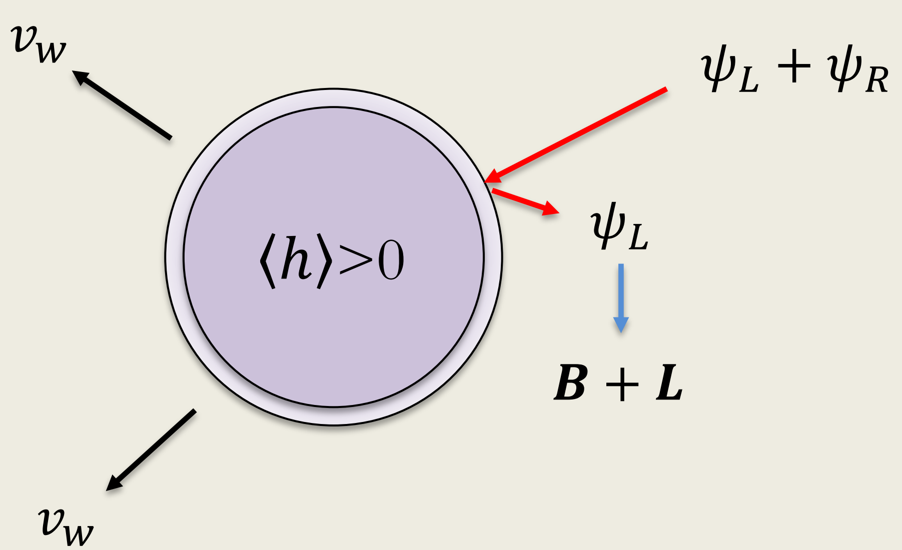


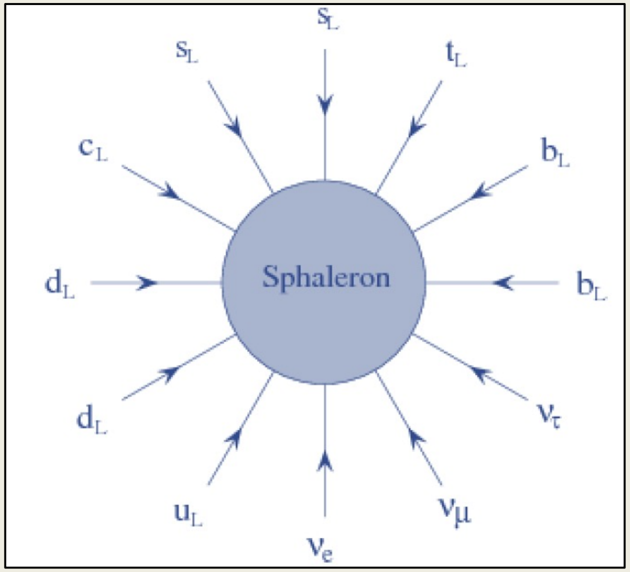
Electroweak baryogenesis in a nut-shell

- Generation of matter happens during EW phase transition

  2. Additional CP-violation. CKM phases + theta term not enough.

Chiral asymmetry transformed into **Baryon asymmetry** by electroweak sphaleron processes (efficient for T>M_W)





Electroweak baryogenesis in a nut-shell

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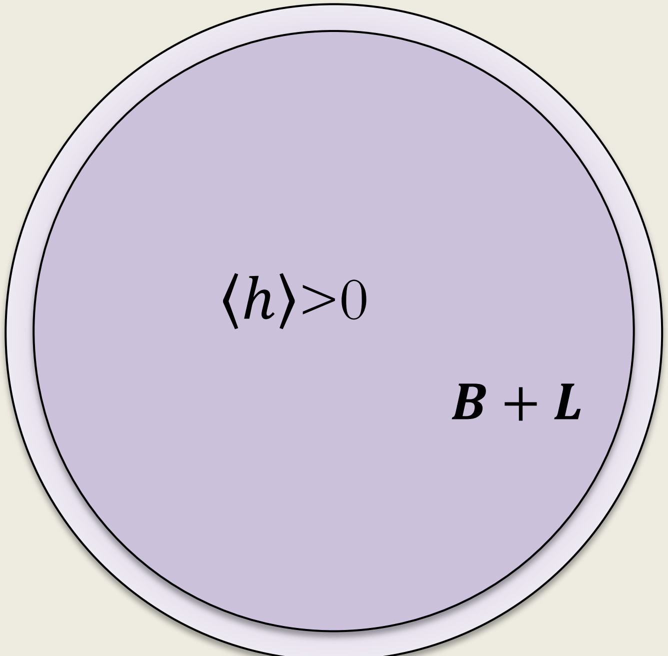
  2. Additional CP-violation. CKM phases + theta term not enough.

B+L is captured by expanding bubble as sphalerons turn off at nonzero v



Complicated calculations and large associated uncertainties

Order-of-magnitude level predictions

Lee, Cirigliano, Ramsey-Musolf ‘05
Postma, van de Vis ‘19
Cline, Kainulainen ‘20

Electroweak baryogenesis and the SM-EFT

- Can we do EWBG with the SM-EFT to capture a lot of models at once?

- Attempt 1: phase transition and CPV via SM-EFT dim-6 operators
- EFT inconsistent: phase transition needs **light BSM physics**

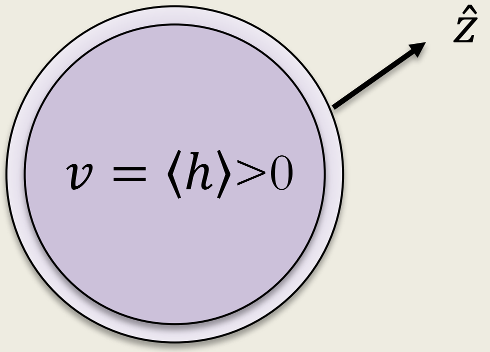
JdV, Postma, van de Vis, White '17

- Second attempt: assume strong first-order transition occurs
- Describe CPV by effective dim-6 Yukawa couplings JdV, Postma, van de Vis, '18

$$L = -y_f \bar{f} f \, h - \frac{y_f}{\Lambda_f^2} \bar{f} i\gamma^5 f \, (v^2 h + \cdots)$$

- The CPV source (interference SM and dim-6) scales as

$$S_{CPV} \sim \frac{y_f^2}{\Lambda_f^2} \times v^3 \frac{dv}{dz}$$

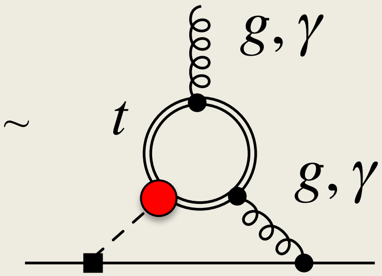


- Main focus in literature on top quark

Does it work ?

$$L = -y_f \bar{f} f\, h - \frac{y_f}{\Lambda_f^2}\, \bar{f} i\gamma^5 f\, (v^2 h + \cdots)$$

- Observed Baryon asymmetry requires 5-10% CPV in top-Yukawa
- Corresponds to $\Lambda_t \lesssim 1$ TeV
- LHC data can still accommodate this, but

Electron EDM ~ 

$\Lambda_t \geq 7$ TeV

- Strongly constrains lot of models (e.g. 2 Higgs-doublet models)

Does it work ?

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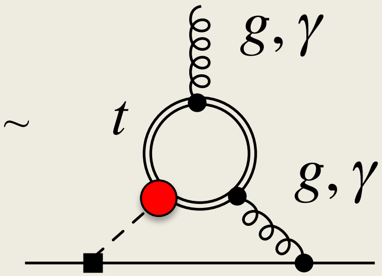
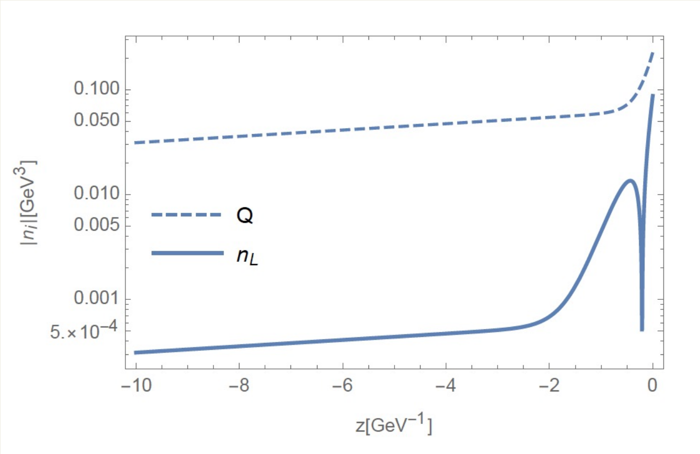
Electron EDM $\sim$

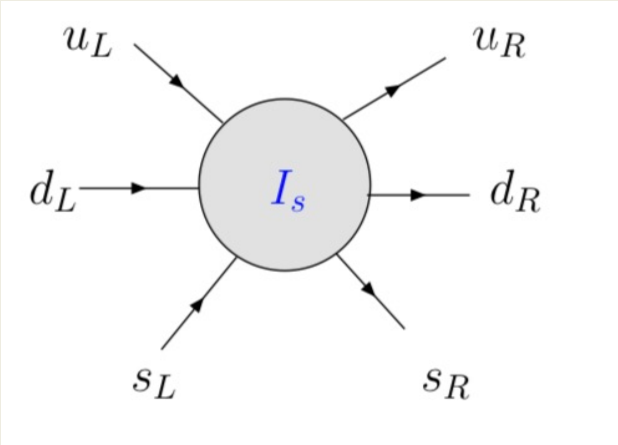


$\Lambda_t \geq 7$ TeV

- Lighter fermions hopeless since CPV source scales as y_f^2 ?
- No! quark chiral asymmetry washed out by strong sphalerons + Yukawa !

Giudice, Shaposhnikov '94



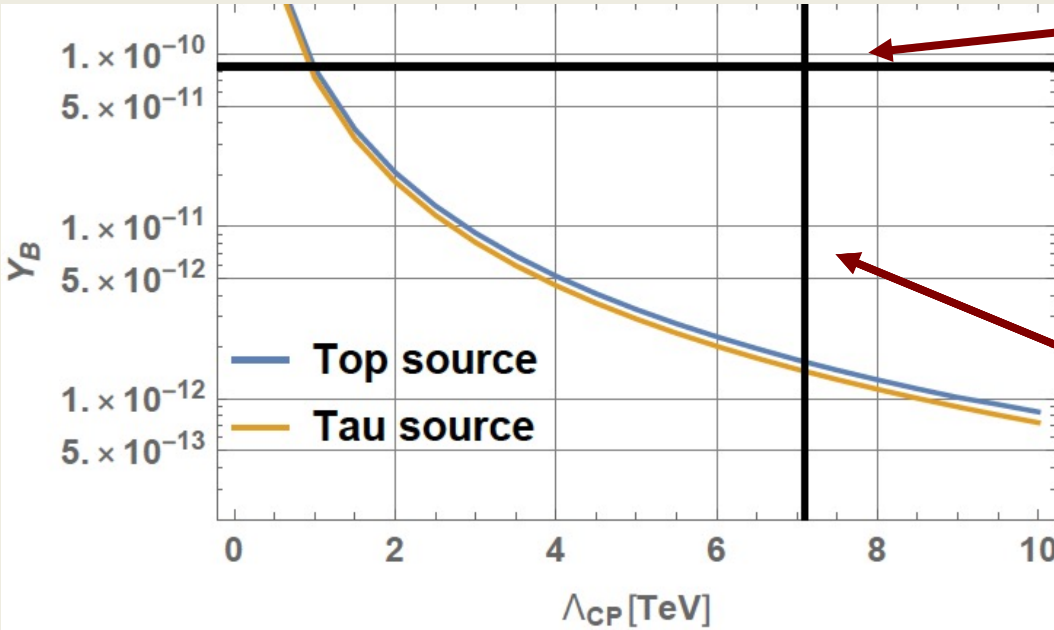


Does it work ?

- Despite small Yukawa: **tau as efficient as top**
- Requires roughly $\Lambda_\tau \lesssim 1$ TeV

JdV, Postma, van de Vis, '18

- **Consistent with all data**



Observed asymmetry

EDM limit for top

- Weizmann group extended calculations to muons
- But Yukawa couplings too small ….

Fuchs et al '19

Does it work ?

- Despite small Yukawa: **tau as efficient as top**
- Requires roughly $\Lambda_\tau \lesssim 1\,\mathrm{TeV}$

JdV, Postma, van de Vis, '18

- **Consistent with all data**

- Test: electron EDM improves by 2 orders of magnitude
- Measure $h \to \tau + \bar{\tau}$ at 1% level (seems possible at CLIC or FCC-ee)
- Measure τau-EDM at fixed-target collisions at LHC?

Coupling modifier (precision in %)	HL-LHC + CLIC$_{380}$	FCC-ee$_{365}$
κ_W	0.73	0.41
κ_Z	0.44	0.17
κ_g	1.5	0.90
κ_γ	1.4 *	1.3
$\kappa_{Z\gamma}$	10 *	10 *
κ_c	4.1	1.3
κ_t	3.2	3.1
κ_b	1.2	0.64
κ_μ	4.4	3.9
κ_τ	1.4	0.66

PHYSICAL REVIEW LETTERS **123,** 011801 (2019)

Novel Method for the Direct Measurement of the τ Lepton Dipole Moments

J. Fu,[1] M. A. Giorgi,[2] L. Henry,[3] D. Marangotto,[1] F. Martínez Vidal,[3] A. Merli,[1] N. Neri,[1] and J. Ruiz Vidal[3]
[1]*INFN Sezione di Milano and Università di Milano, 20133 Milano, Italy*
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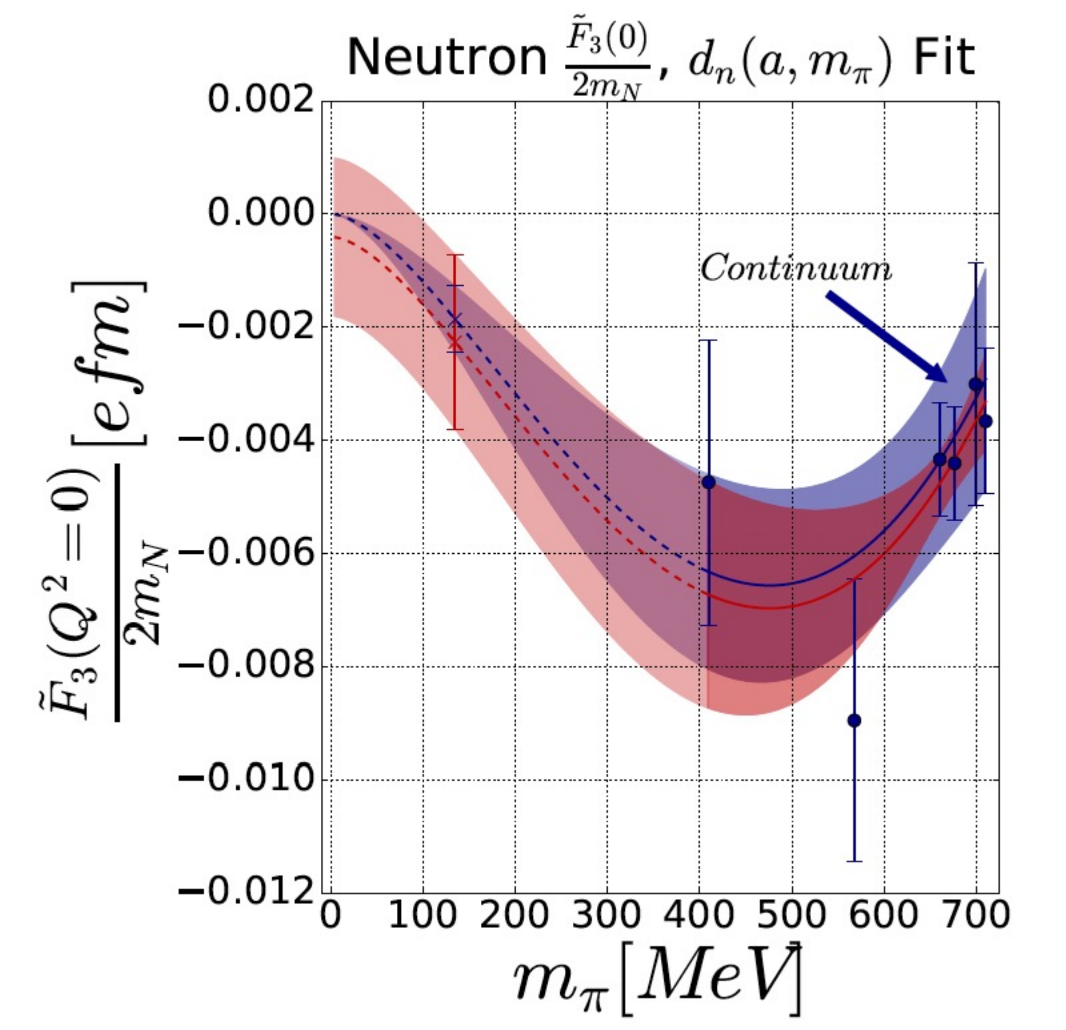
Charting the European Course to the High-Energy Frontier 1912:13466

Just got out

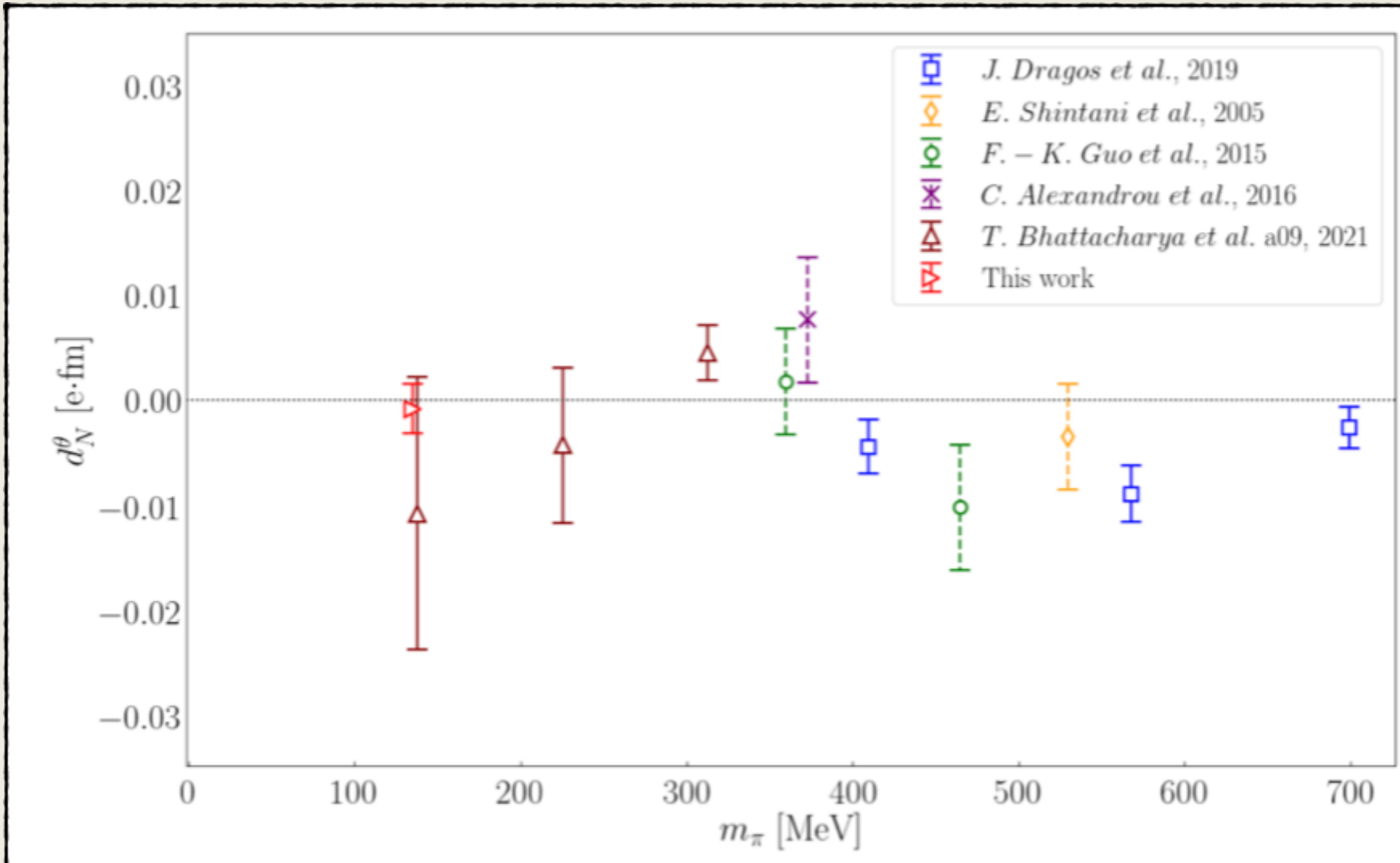


- Method based on Gradient Flow
- Three pion masses and three lattice spacings
- Fit to physical point based on ChPT

$$d_n = -(1.5 \pm 0.7) \cdot 10^{-16}\ \bar{\theta}\ e\ cm$$

- Still not that convincing…

Jack Dragos, Andrea Shindler, Tom Luu, JdV, Ahmed Yousif , ArXiv: 1902.03254



J. Dragos et al., 2019
E. Shintani et al., 2005
F. – K. Guo et al., 2015
C. Alexandrou et al., 2016
T. Bhattacharya et al. a09, 2021
This work
d_N^θ [e·fm]
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
0
100
200
300
400
500
600
700
m_π [MeV]