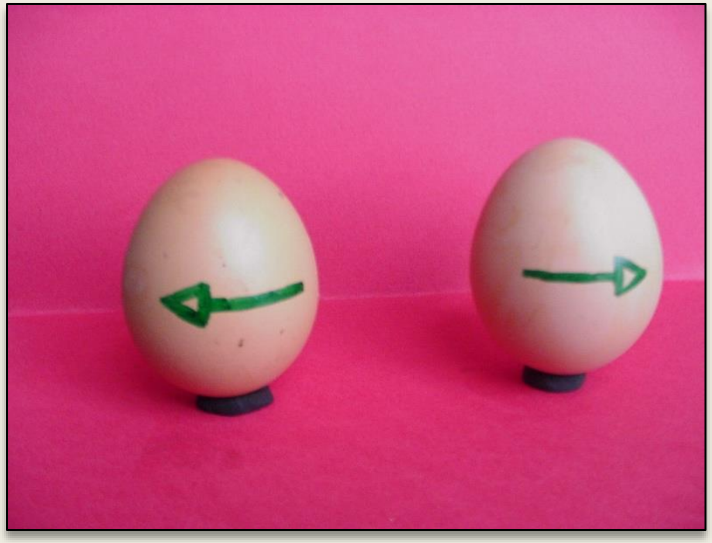
Electric Dipole Moments: a view from above

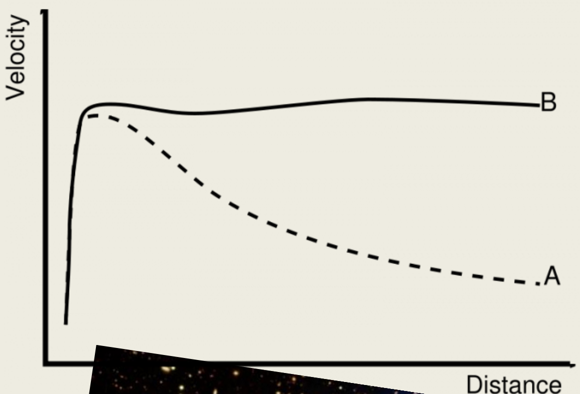


Jordy de Vries

University of Amsterdam, Nikhef

The search for something non-Standard…

13.799 billion years



Theoretical puzzles

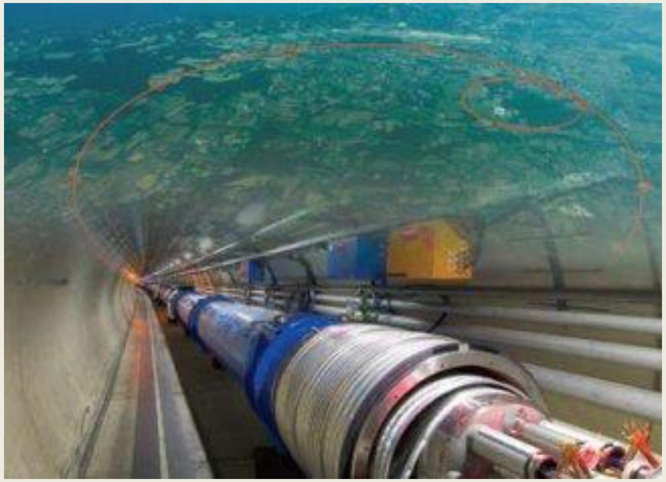
$$\frac{m_{Higgs}}{m_{Planck}} \sim 10^{-16}$$

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

Particle Physics at a Crossroads

- Where do we go from here ? More energy ? More precision ?

Try to create something new directly

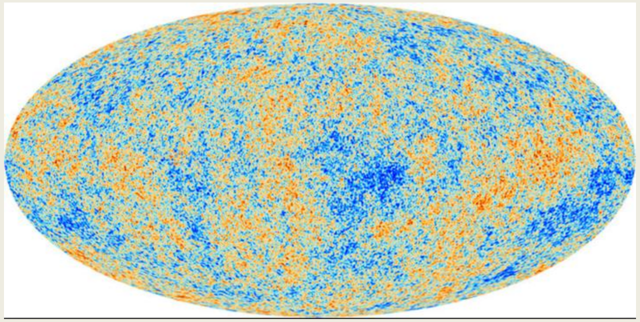


Large Hadron Collider (LHC)

FCC, ILC, …..

Reach ~ energy

Cosmological/astrophys probes



Cosmic microwave background

Dark Matter detection

Gravitational waves

Reach ~ background control + experimental sensitivity

Precision measurements

Magnetic and electric dipole moment

Neutrino physics

…....................

Reach ~ experimental and theoretical accuracy

Magnetic dipole moments

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

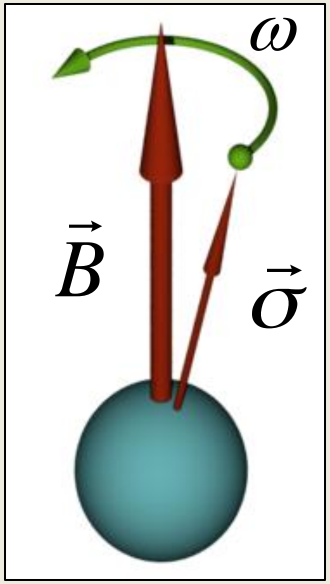
$$H = -\mu(\vec{S} \cdot \vec{B}) \qquad \vec{S} = \vec{\sigma}/2$$

Hamiltonian

Spin

Magnetic Field

Magnetic dipole moment



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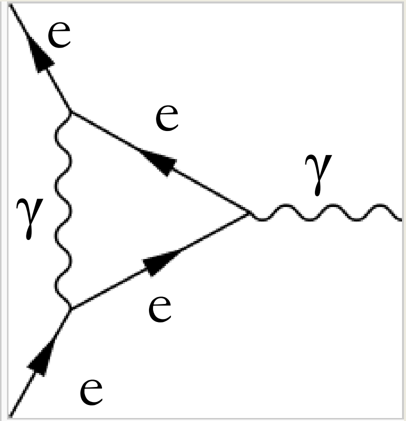
$$a_e = \frac{g_e - 2}{2}$$



- **Exercise: compute this loop !**

Magnetic dipole moments

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

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

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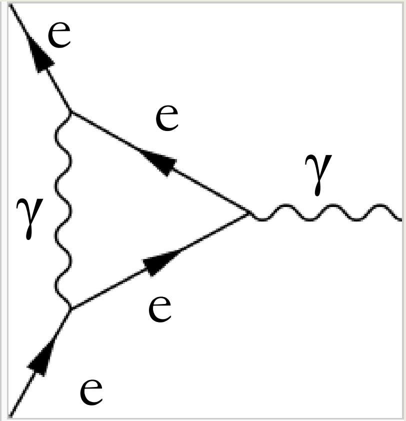

$$a_e = \frac{\alpha_{em}}{2\pi} + \mathcal{O}(\alpha_{em}^2)$$

A crash course in loop diagrams

- I counted the number of loop diagrams in these lectures as ~ 100
- Calculation diagrams is 'straightforward' but tedious .
- But estimating them is very very easy (apart from a O(1) factor)

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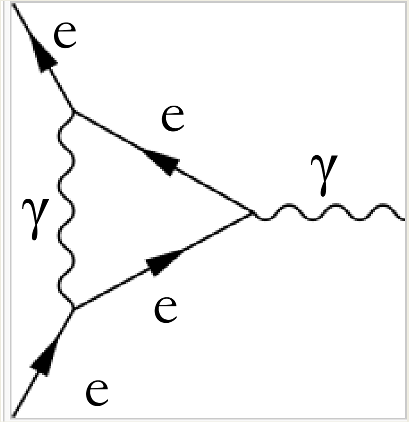

- 3 'rules'

- 1) multiply the vertices coupling strenghts
- 2) for each loop add $1/(4\pi)^2$
- 3) hardest step: 'adjust the dimension'

A crash course in loop diagrams

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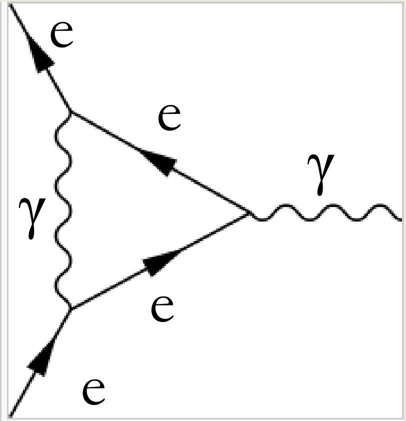

- Example 1: one-loop correction to electron magnetic moment (μ)

$$L_{dip} = -\frac{1}{2}\bar{e}\sigma^{\mu\nu}(\mu + i\gamma^5 d)eF_{\mu\nu}$$

- Step 1: ?
- Step 2: ?
- Step 3: ?

A crash course in loop diagrams

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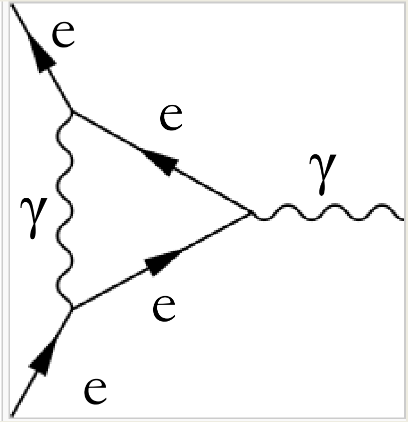

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A crash course in loop diagrams

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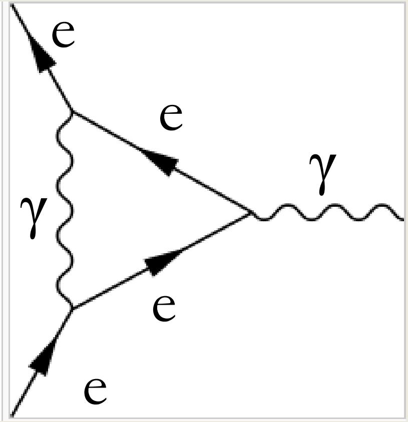

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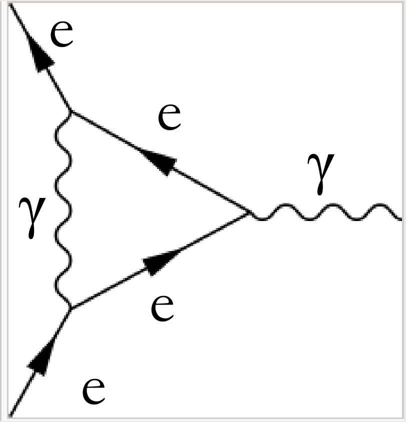

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A crash course in loop diagrams

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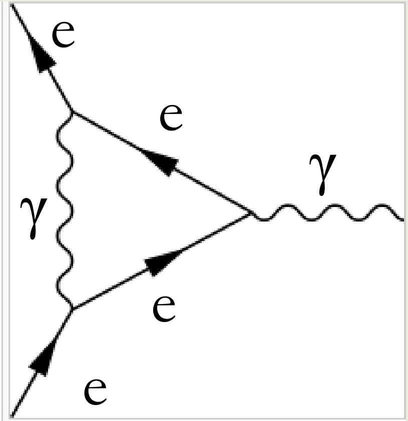


- Example 1: one-loop correction to electron magnetic moment (μ)

$$L_{dip} = -\frac{1}{2}\bar{e}\sigma^{\mu\nu}(\mu + i\gamma^5 d)eF_{\mu\nu}$$

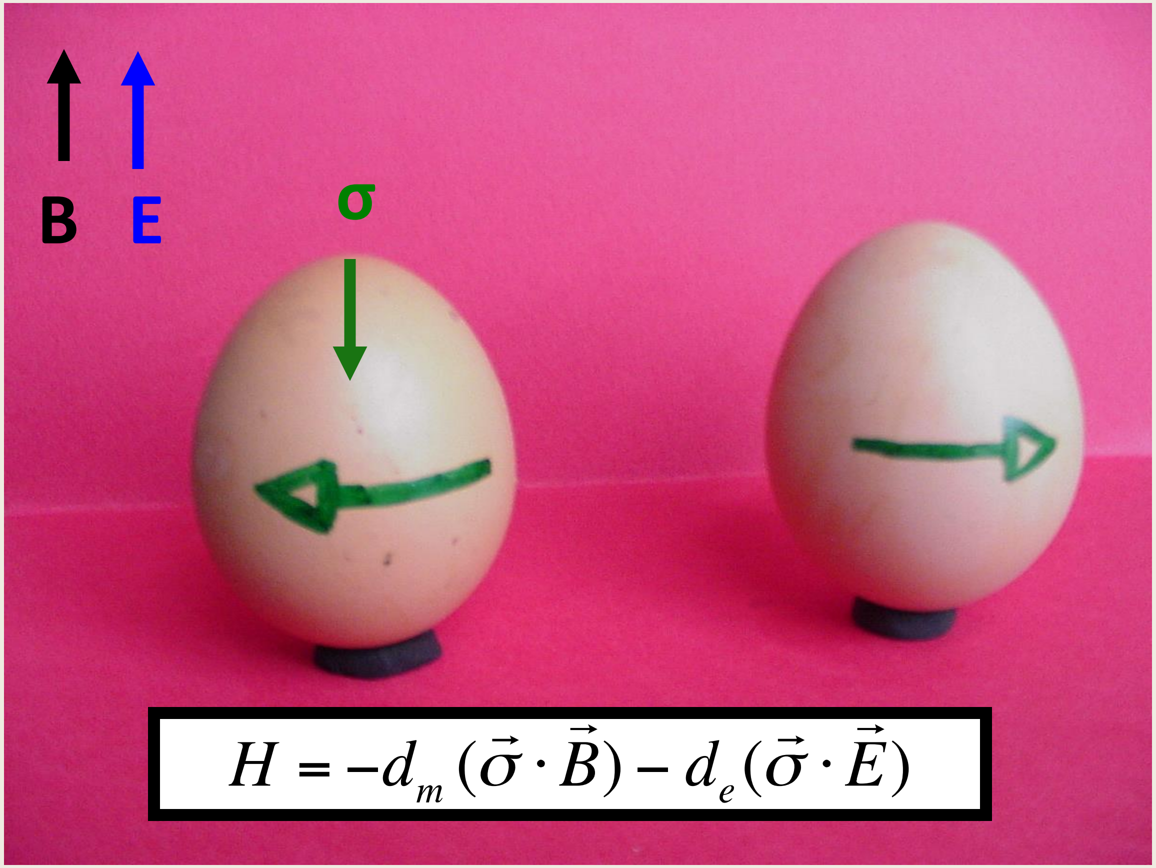
$$\mu \propto e\frac{\alpha_{em}}{4\pi}\frac{1}{m_e}$$

- Step 1: e^3
- Step 2: $1/(4\pi)^2$
- Step 3: What does this mean? **Blackboard**

$$g = \frac{\alpha}{4\pi}$$

Symmetry considerations

- Electric and Magnetic Dipole Moment (EDM and MDM)



$$H = -d_m(\vec{\sigma}\cdot\vec{B}) - d_e(\vec{\sigma}\cdot\vec{E})$$

Symmetry considerations

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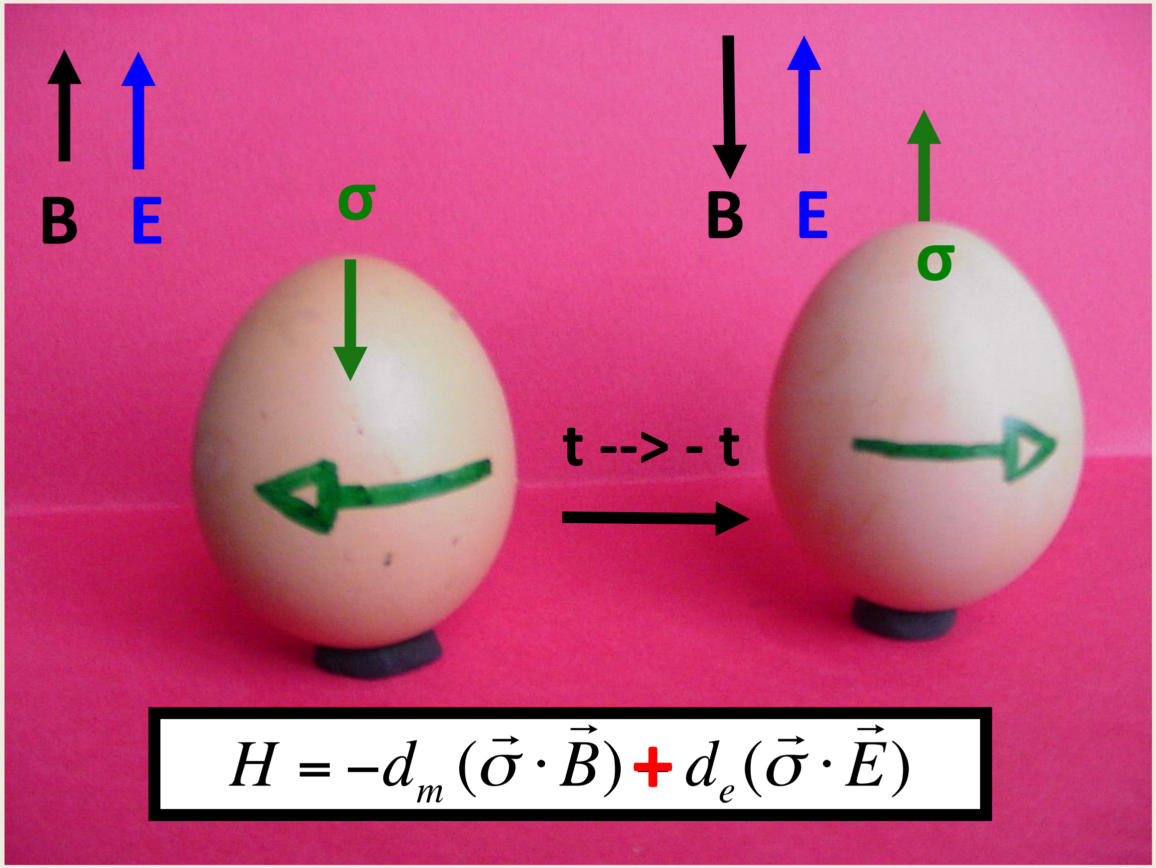


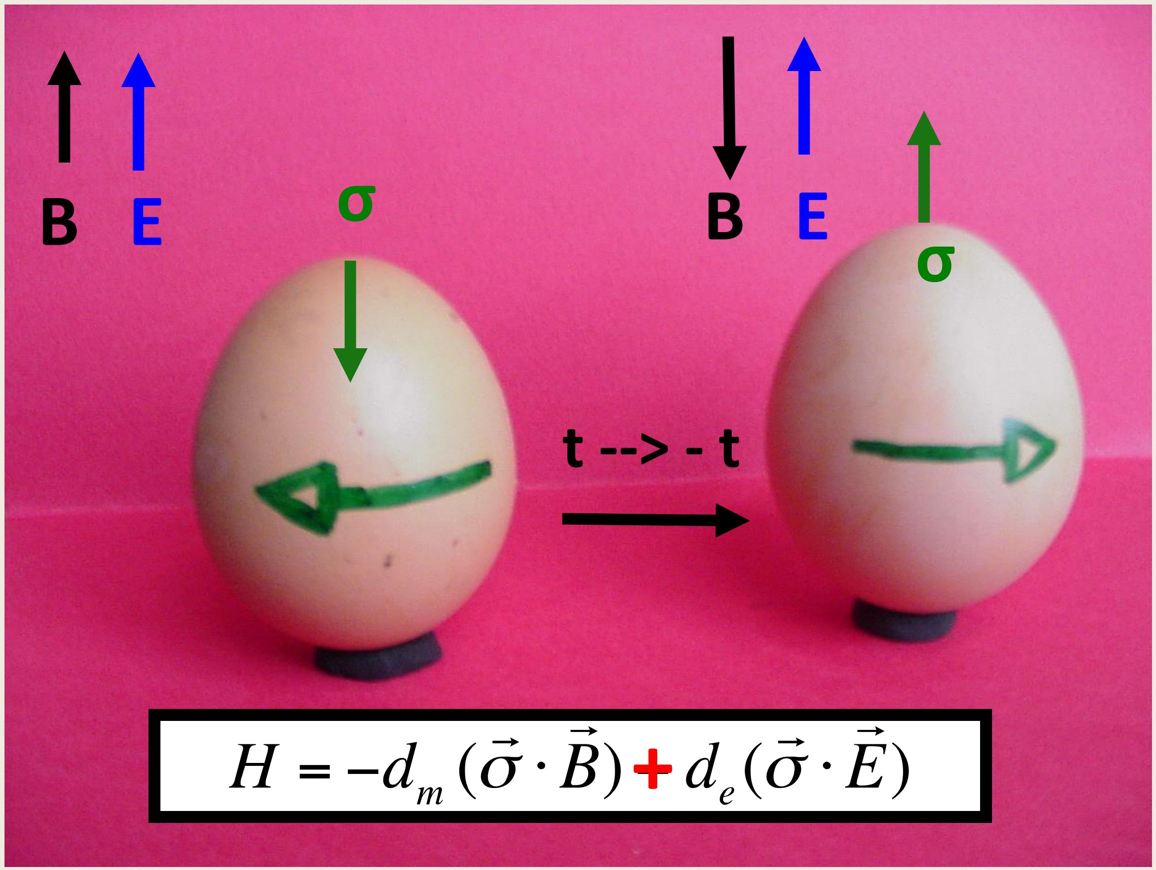
- The EDM, breaks time-reversal symmetry ! No EDM in QED at all !

PhD Thesis: Hudson

Symmetry considerations

- Electric and Magnetic Dipole Moment (EDM and MDM)

Pauli



- **CPT theorem:** T violation ⟷ CP violation

PhD Thesis: Hudson

CP violation in weak interactions

- Violation of CP was first measured in 1964 (Nobel prize 1980)

ER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

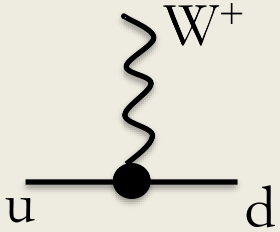
- Discovery of CP violation lead Kobayashi and Maskawa to predict (1973) a third generation of quarks → Nobel prize '08

- CP violation manifests in 'flavor-changing' weak interaction

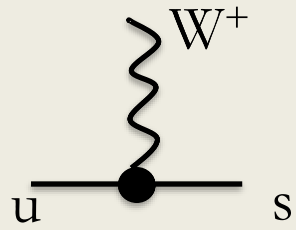
- **Describes all measurements of CP violation so far (excluding neutrinos)**

CP violation in weak interactions

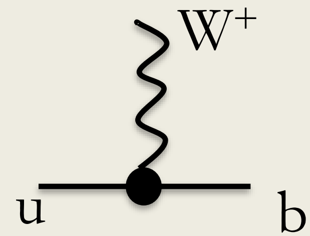
- **Strenght of weak transition proportional to 'CKM' matrix**



V_{ud}



V_{us}



V_{ub}

$V_{CKM} = (N \times N)$ matrix

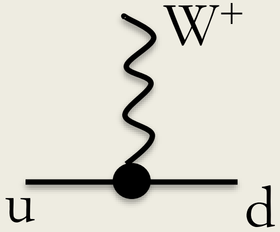
N = # of quark generations

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

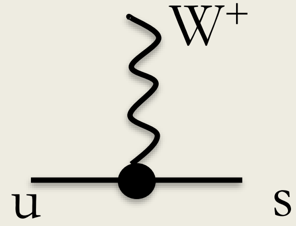
- **9 complex numbers but not all are independent**
  - N(N-1)/2 CP conserving angles → 3 for N = 3
  - (N-1)(N-2)/2 **CP violating phases** → 1 for N = 3

CP violation in weak interactions

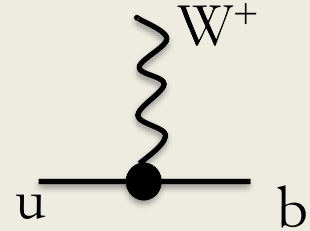
- **Strenght of weak transition proportional to 'CKM' matrix**



V_{ud}



V_{us}



V_{ub}

$$V_{CKM} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}$$

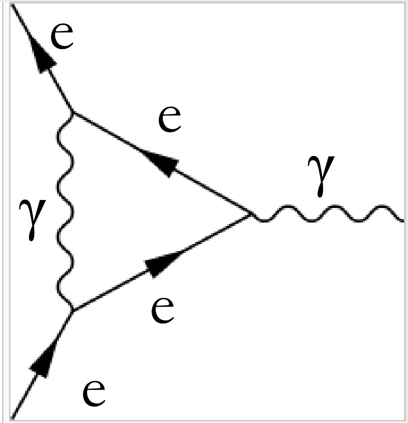
$$\frac{-g}{\sqrt{2}}(\bar{u}_L,\, \bar{c}_L,\, \bar{t}_L)\gamma^\mu V_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_\mu^+ + \text{h.c.}$$

- Note, CPV phase is not small at all: Sin(δ_{13}) ~ O(1)
- But the off-diagonal elements are small: $s_{13} \sim 10^{-3}$ (not understood)

SM CKM EDMs (too many acronyms!)

- Analogously to g-2 magnetic moment corrections we can calculate SM EDMs.

$$L_{dip} = -\frac{1}{2}\bar{\Psi}\sigma^{\mu\nu}(\mu + i\gamma^5 d)\Psi F_{\mu\nu}$$



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

Why ?

SM CKM EDMs (too many acronyms!)

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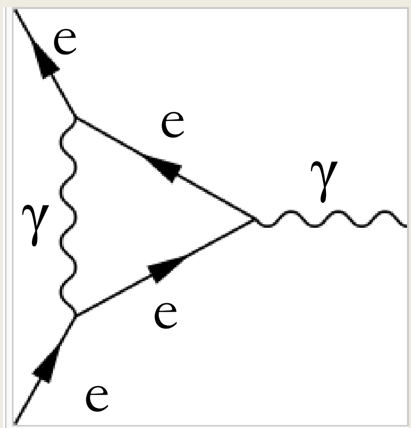
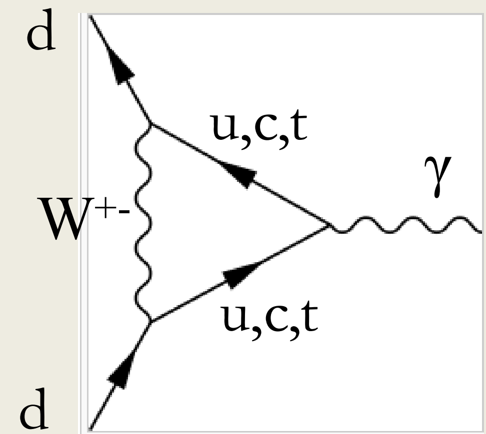




$$\mu = \frac{e}{2m_e}\frac{\alpha_{em}}{2\pi}$$

$$d = 0$$

Why ?

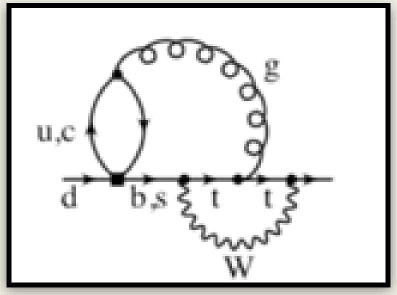
$$\mu \propto \frac{m_d}{m_W^2}\frac{\alpha_{weak}}{2\pi}(V_{qd}V_{qd}^*)$$

$$d = 0$$

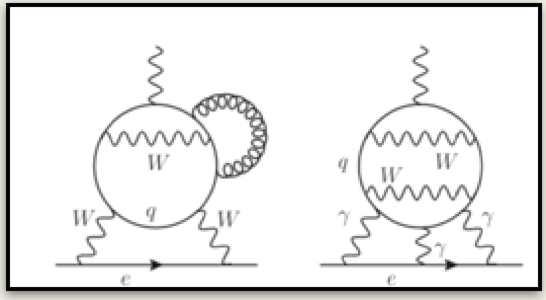
Why ?

EDMs from the Standard Model

- At two loops: individual diagrams contribute but sum vanishes
- Quark EDMs induced at three loops



$d_q \sim 10^{-34} e\,\text{cm}$



- Electron EDM at 4 loops $\qquad d_e \sim 10^{-44} e\,\text{cm}$
- Compare with magnetic dipole moment: $\qquad \mu_e \sim 10^{-11} e\,\text{cm}$

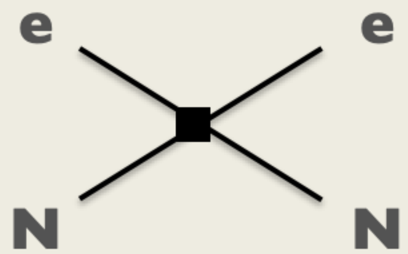
- Disclaimer 1: electron EDM can be a bit larger due to hadronic loops
- Disclaimer 2: EDMs of composite objects can be larger (still small)

CKM EDMs are really very very very very small

Molecular EDM from CKM

- In atoms/molecular must include CP-odd electron-nucleon interaction

$$\mathscr{L}_{eN} = \bar{C}_S G_F \bar{N}N \bar{e}i\gamma^5 e$$



- Induces a contribution to the measured energy shift $\omega_X \sim (d_e + r_X \bar{C}_S)$

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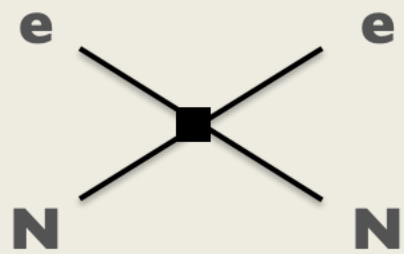
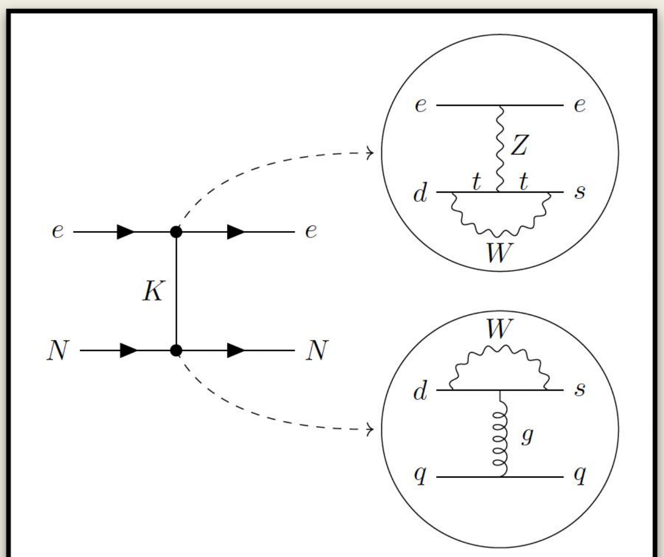


- Induces a contribution to the measured energy shift $\omega_X \sim (d_e + r_X \bar{C}_S)$
- To compare, useful to write: $\bar{d}_e(\text{ThO}) = d_e + \bar{C}_S \cdot 2.1 \cdot 10^{-9}\, e\,\text{cm}$



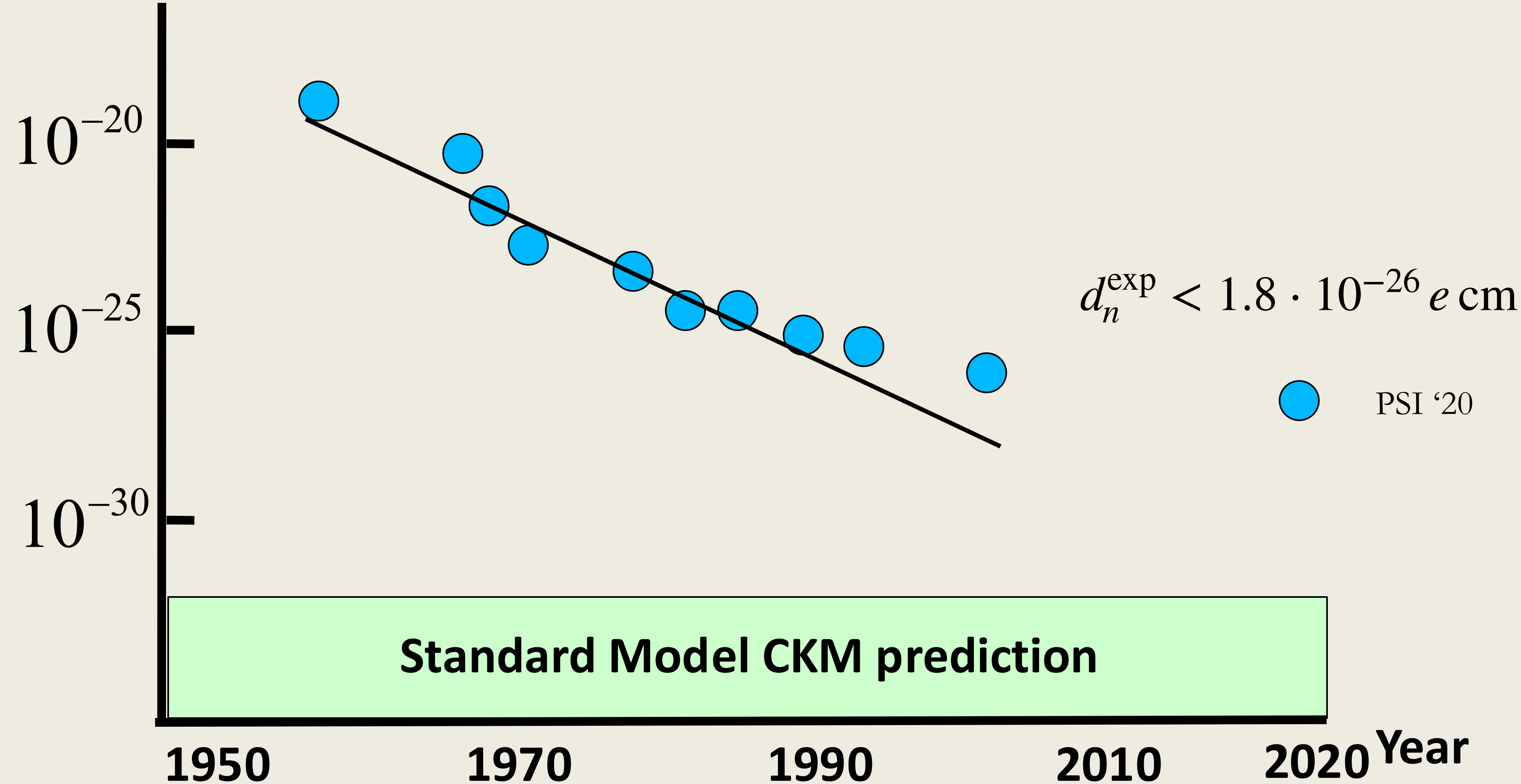
- Ema et al (PRL '22) found a new 'kaon exchange' contribution

$$\bar{d}_e(\text{ThO}, CKM) \simeq 1.0 \cdot 10^{-35}\, e\,\text{cm}$$

- 5 orders down… Can we reach it?

Electric dipole moments and the CKM matrix

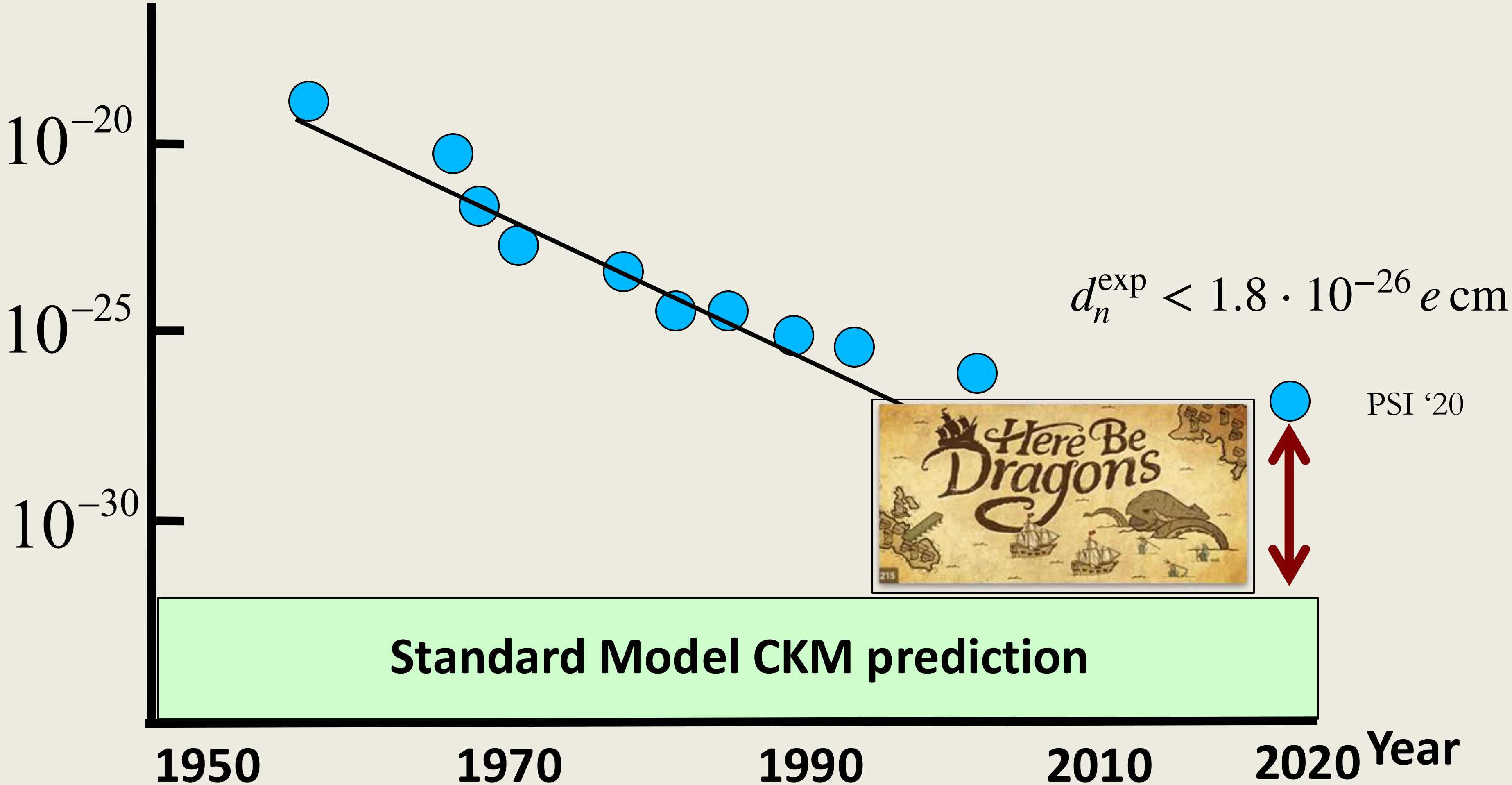
Limit on **neutron** EDM in e cm



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



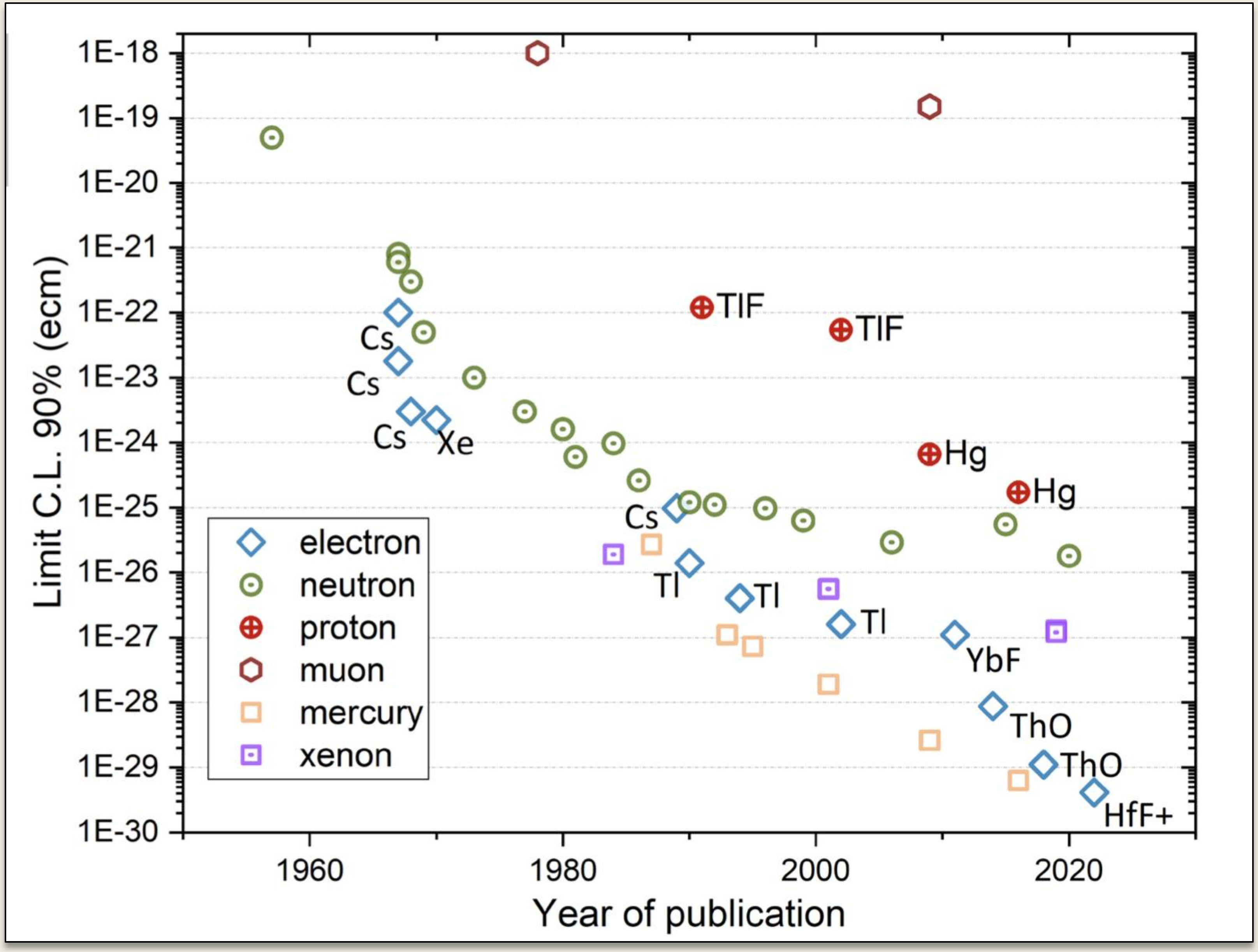
Thriving experimental field

Community input to the European Strategy on particle physics: Searches for Permanent Electric Dipole Moments

edited by:
M. Athanasakis-Kaklamanakis (*Imperial College London, United Kingdom*), M. Au (*CERN, Geneva, Switzerland*), R. Berger (*University of Marburg, Germany*), S. Degenkolb (*Heidelberg University, Germany*), J. De Vries (*University of Amsterdam, The Netherlands*) S. Hoekstra (*University of Groningen, The Netherlands*), A. Keshavarzi (*University of Manchester, United Kingdom*), N. Neri (*University of Milan and INFN Milan, Italy*), D. Ries (*Paul Scherrer Institute, Villigen, Switzerland*), P. Schmidt-Wellenburg (*Paul Scherrer Institute, Villigen, Switzerland*), and M. Tarbutt (*Imperial College London, United Kingdom*)
endorsed by the
European EDM projects and collaborations:

Collaboration	Species	Method	Sensitivity (10^{-29} $e$cm)	Status	Duration (years)	Ref
PanEDM I	n	UCN	380	Commissioning	5	[43]
PanEDM II	n	UCN	79	Commissioning	8	[43]
Beam EDM	n	beam	500	proof-of-principle	?	[44]
n2EDM	n	UCN	110	Start data-taking	4	[45]
n2EDMagic	n	UCN	50	Construction	5	[45]
nEDMsf	n	UCN	20	Development	7	[42]
ACME III	ThO ($^3\Delta_1$)	Beam	0.1	Commissioning		[93]
JILA III	ThF^+ ($^3\Delta_1$)	Ion trap		Commissioning		[94]
Imperial II	YbF ($^2\Sigma$)	μK beam	0.1	Commissioning	3	[47]
Imperial III	YbF ($^2\Sigma$)	Lattice	0.01	Construction	6	[47]
NL-eEDM I	BaF ($^2\Sigma$)	Slow beam	0.5	Commissioning	3	[48]
NL-eEDM II	BaOH ($^2\Sigma$)	Lattice	0.1	Construction	6	[50]
PolyEDM	SrOH ($^2\Sigma$)	Lattice		Construction		[51]
EDM^3	BaF ($^2\Sigma$)	Matrix		Construction		[52]
DOCET	BaF ($^2\Sigma$)	Matrix		Construction	3	[53]
CeNTREX	^{205}TlF	Beam		Commissioning		[58]
HeXe	^{129}Xe	^{3}He-comagnetometer	10	Construction	4	[57]
quMercury	^{199}Hg	ultracold atoms	1	Construction	5	[61]
ALADDIN	Λ_c^+, Ξ_c^+	collider	1×10^{13}	Development	?+2	[64]
muEDM I	μ	frozen-spin	4×10^8	Commissioning	3	[67]
muEDM II	μ	frozen-spin	6×10^6	Conception	10	[67]
pEDM I	p	frozen-spin	1	Development	5	[69]
pEDM II	p	frozen-spin	0.01	Conception	5	[69]

Thriving experimental field



Why do EDM experiments ?

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

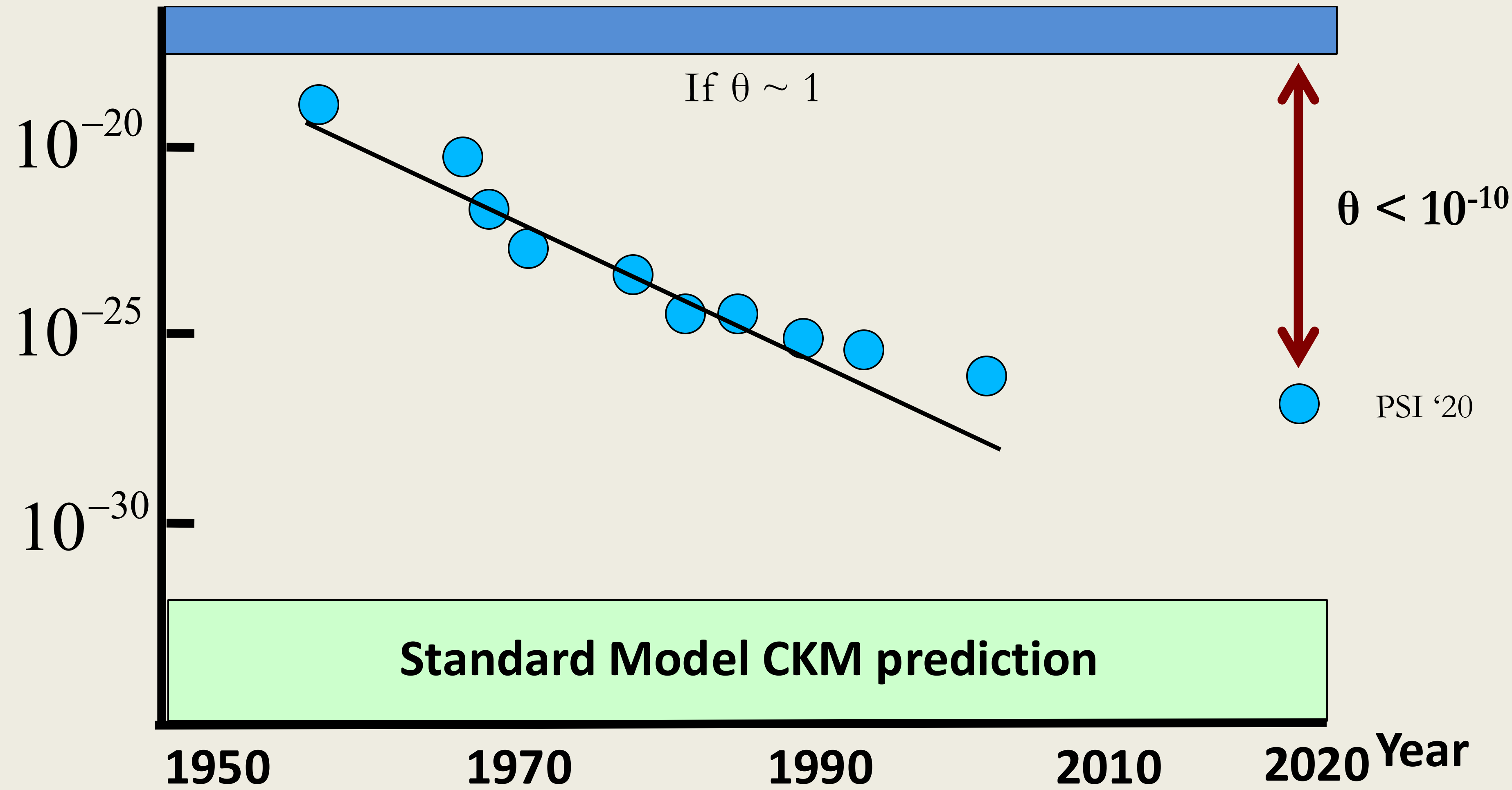
1. There is another source of CP violation in the Standard Model

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

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

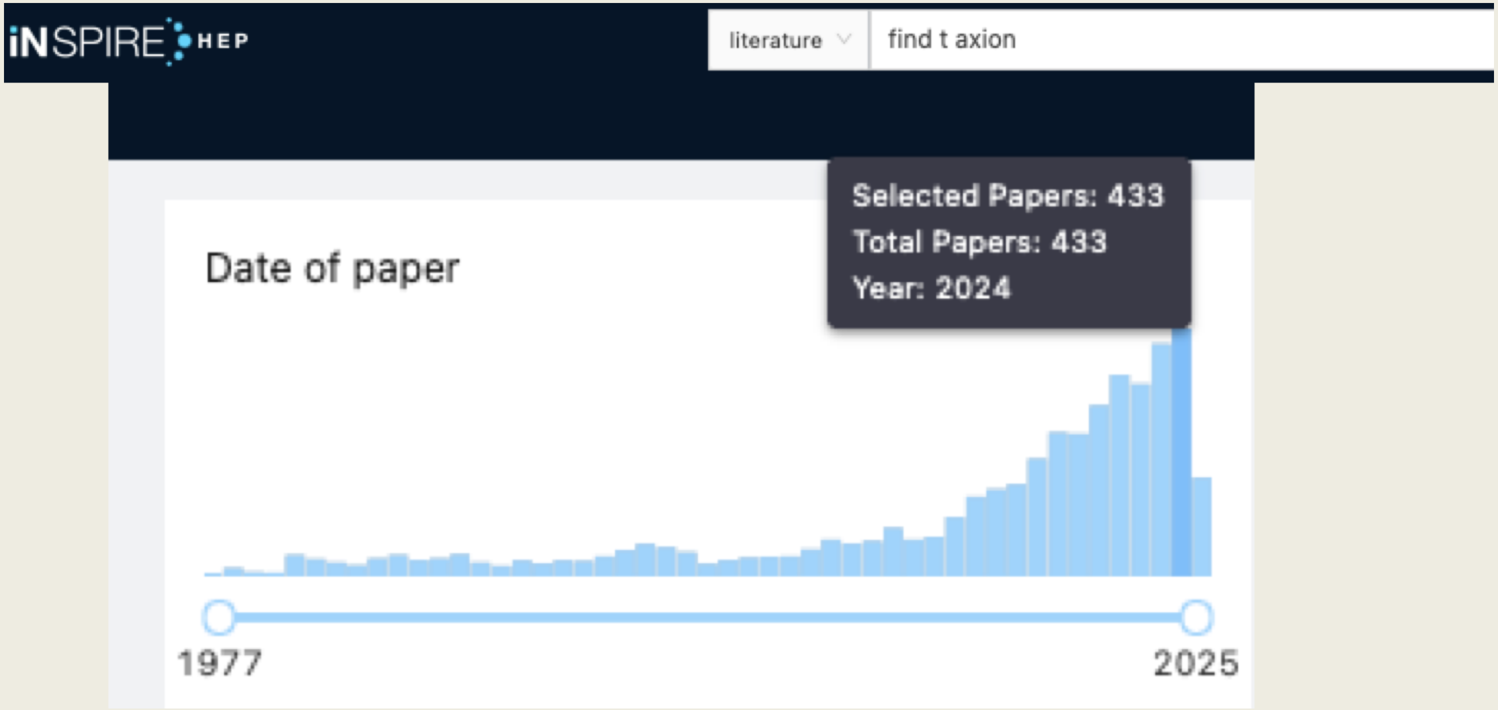
Strong CP violation

Limit on **neutron** EDM in e cm



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

Why do EDM experiments ?



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

2. **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

$$N_B \sim 10^{80}$$

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

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- 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 ?

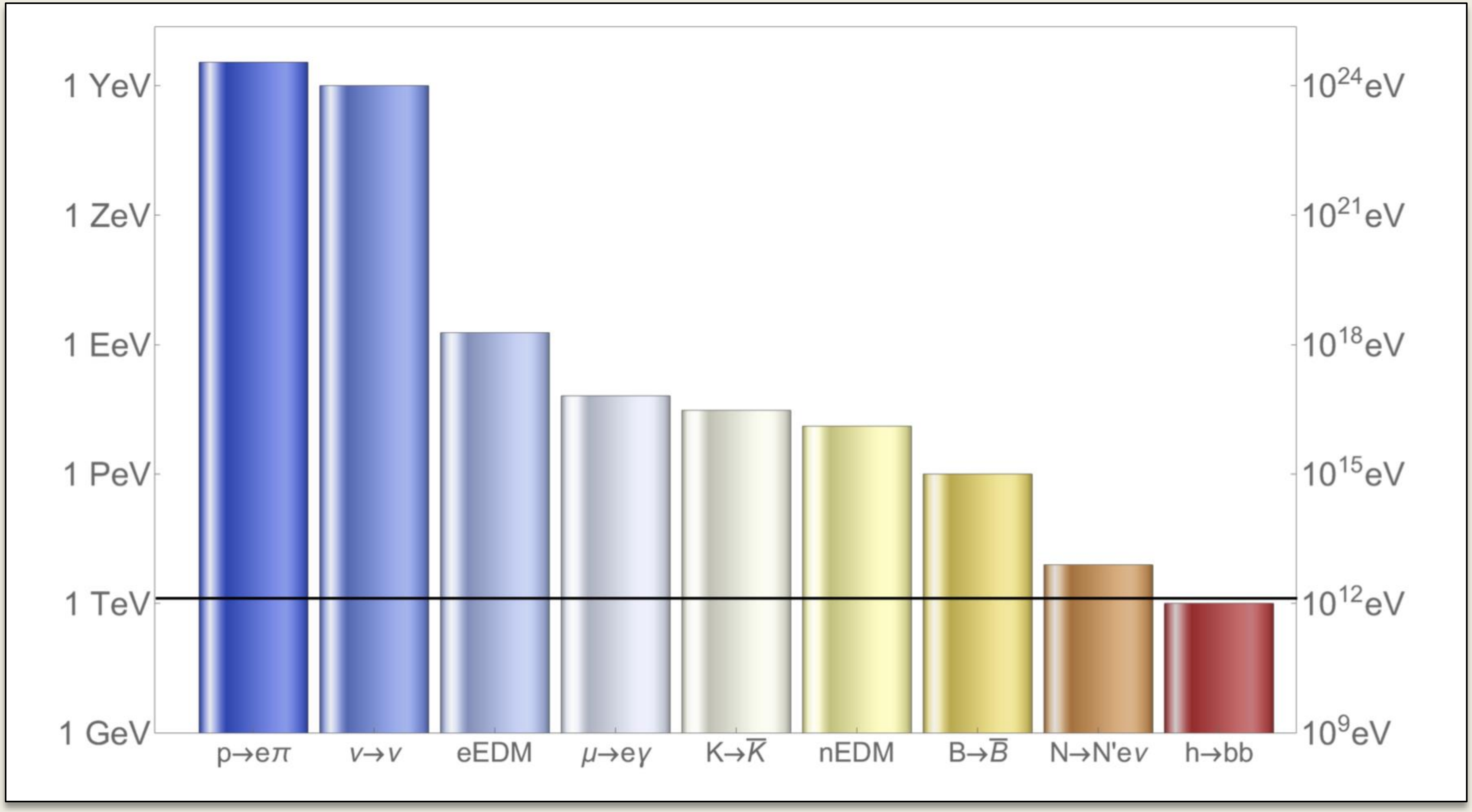
- Just because CKM predictions are small, is IMO not enough motivation

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

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

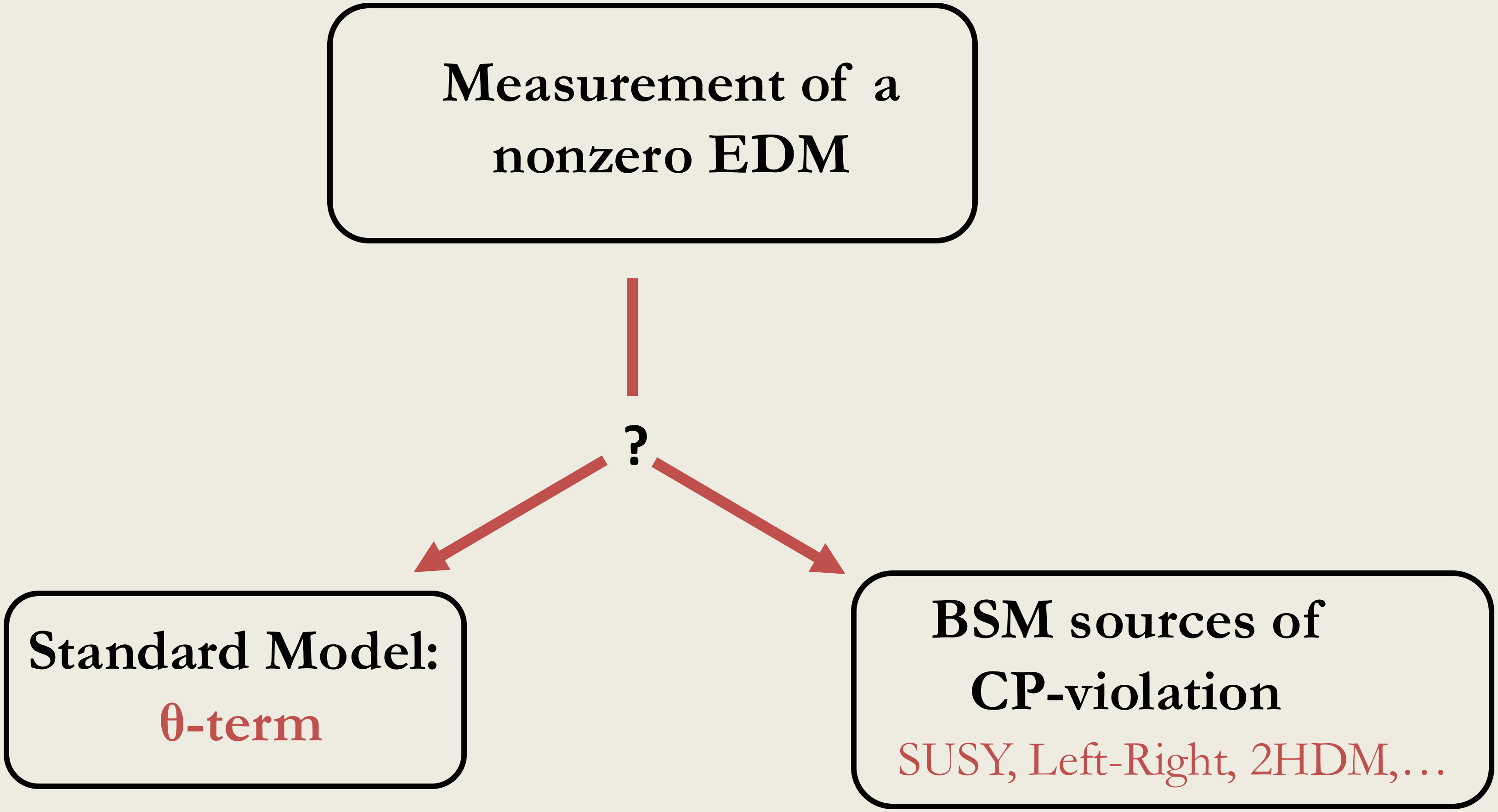
3. **CP is a broken symmetry: SM extensions tend to violate it !**
   EDMs are extreeeeeemely sensitive !

Indirect scale

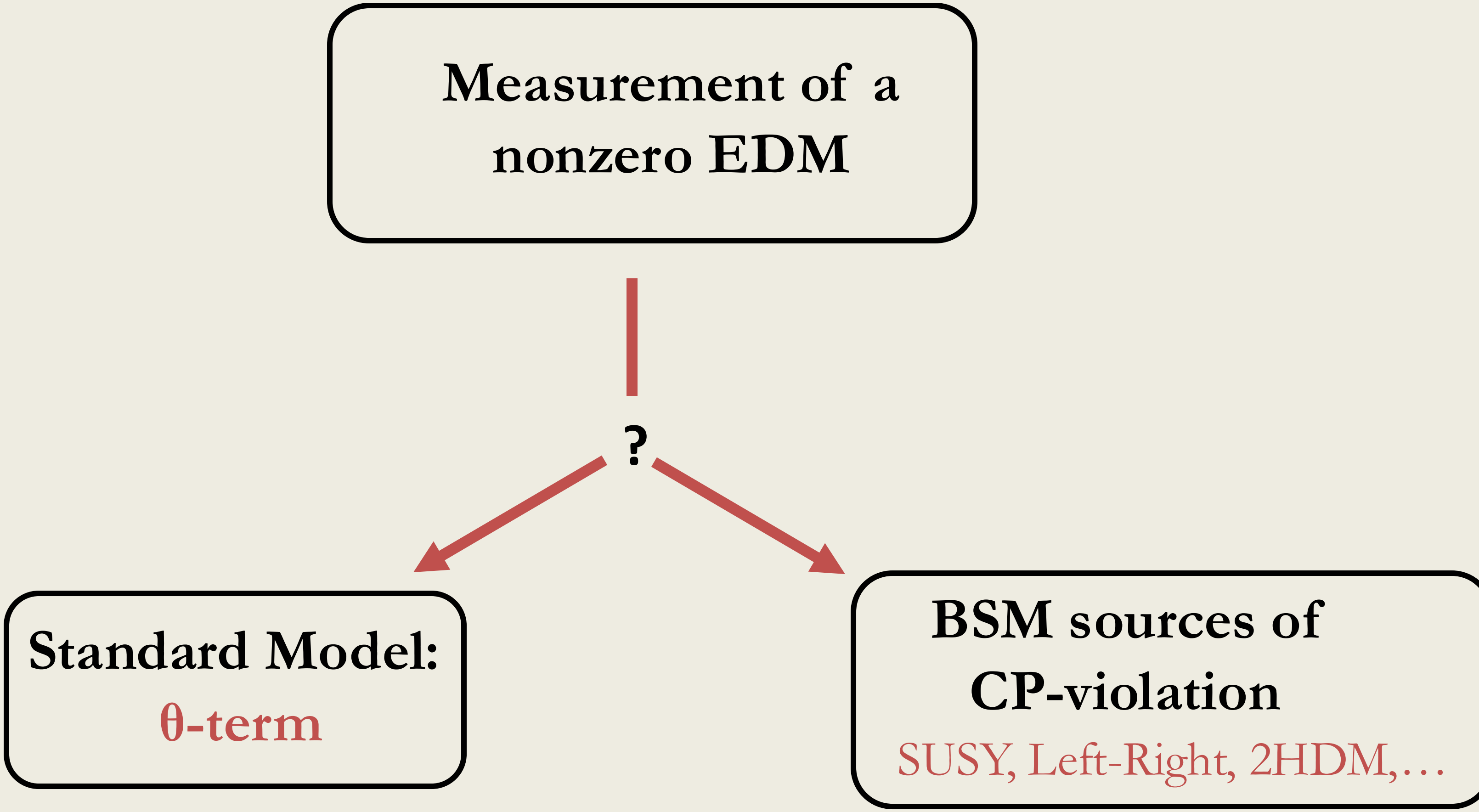


Picture from Adam Falkowski

We have to spend some more time to understand this plot (later)



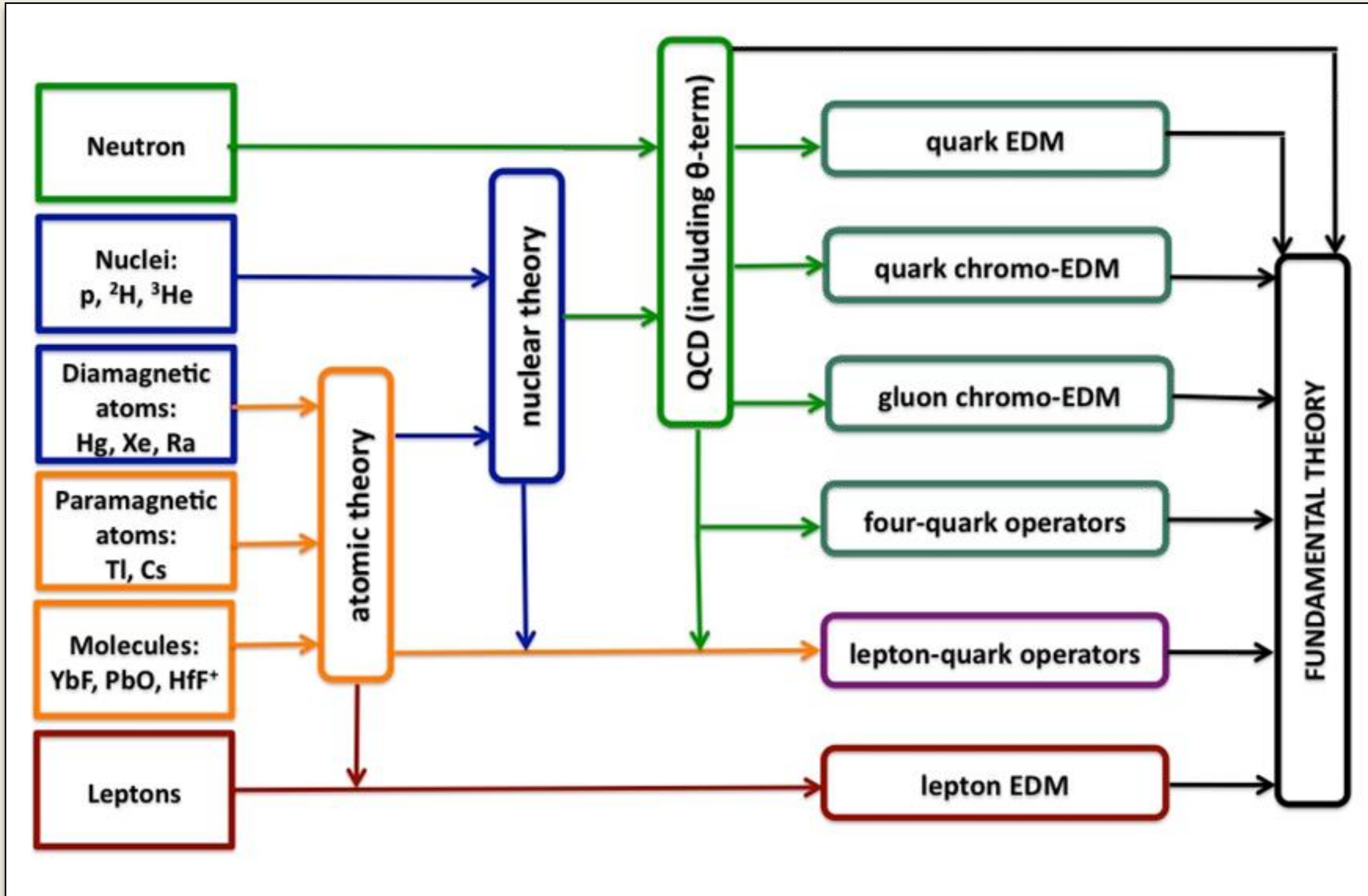
Forseeable future: EDMs are **‘background-free’** searches



Forseeable future: EDMs are **‘background-free’** searches

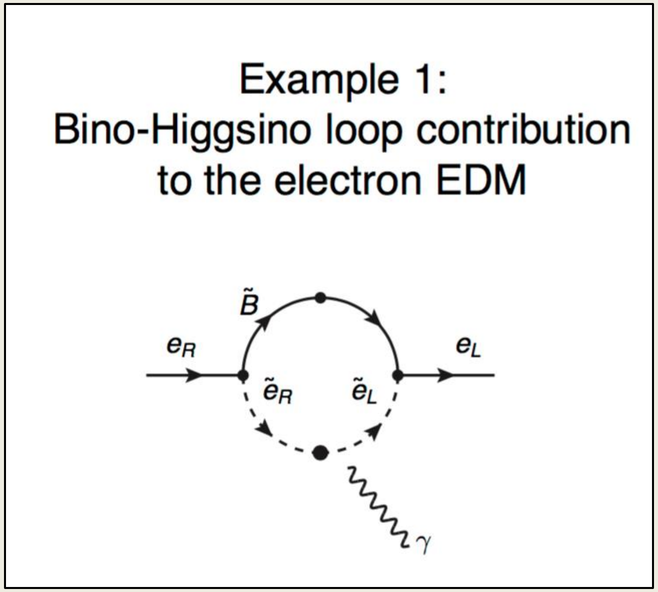
1. How to interpret EDM experiments in terms of particle physics
2. Can we disentangle source of CP violation from experiments
3. Can we connect this to cosmological problems (matter/antimatter)

The EDM metromap



An historic example

- Historically, supersymmetry played a big role in particle physics



An historic example

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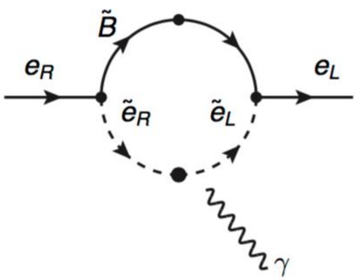
Example 1:
Bino-Higgsino loop contribution to the electron EDM



- We use our loop skills to find

$$d_e \sim \frac{m_e}{M_{\mathrm{SUSY}}^2} \frac{\alpha_{\mathrm{em}}}{4\pi} \sin\phi_{CP}$$

- Let's plug in some numbers

$$d_e < 4.1 \cdot 10^{-30}\, e\,\mathrm{ecm}$$

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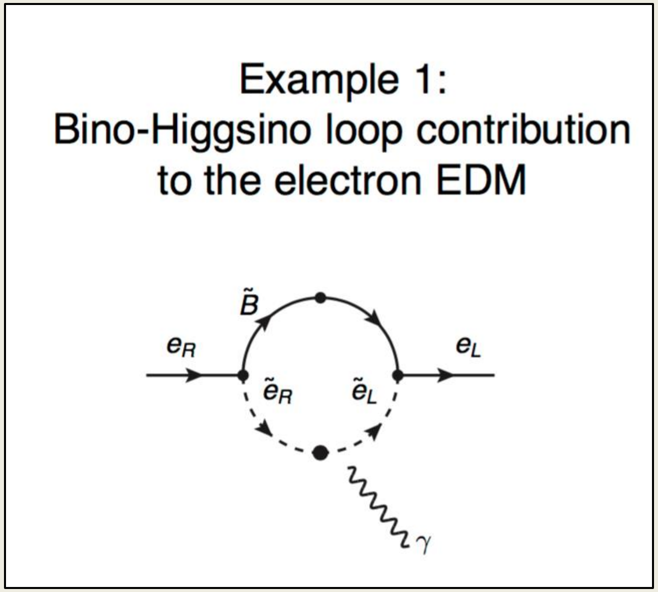

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- Let's plug in some numbers

$$d_e < 4.1 \cdot 10^{-30}\, e\,\mathrm{ecm}$$

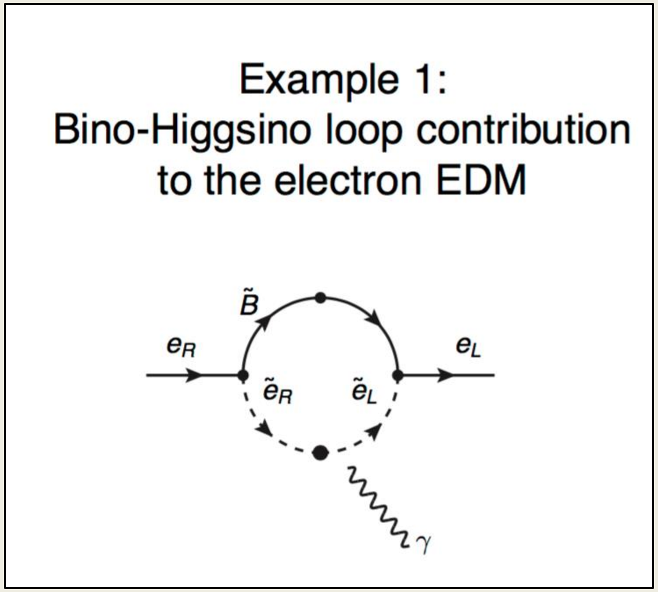
↓

$$M_{\rm SUSY} > 35\,\mathrm{TeV} \times \sqrt{\sin\phi_{CP}}$$

- Either SUSY lives at large scales or it conserves CP somehow

An historic example

- Historically, supersymmetry played a big role in particle physics



- We use our loop skills to find

$$d_e \sim \frac{m_e}{M_{\rm SUSY}^2}\frac{\alpha_{\rm em}}{4\pi}\sin\phi_{CP}$$

- Turn back the clock to pre-LHC times

$$d_e < 1.6 \cdot 10^{-27}\, e\,\text{ecm}$$

$$\downarrow$$

$$M_{\rm SUSY} > 2\,\text{TeV} \times \sqrt{\sin\phi_{CP}}$$

- These limits were, roughly speaking, ignored (close your eyes)
- SUSY at LHC was never favored by EDM limits

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2024

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

	Model	Signature			$\int \mathcal{L}\,dt$ [fb^{-1}]	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{q}$ [1×, 8× Degen.] 1.0 1.85	m($\tilde{\chi}_1^0$)<400 GeV	2010.14293
		mono-jet	1-3 jets	E_T^{miss}	140	$\tilde{q}$ [8× Degen.] 0.9	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{g}$ 2.3	m($\tilde{\chi}_1^0$)=0 GeV	2010.14293
						$\tilde{g}$ Forbidden 1.15-1.95	m($\tilde{\chi}_1^0$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}_1^0$	1 e,μ	2-6 jets		140	$\tilde{g}$ 2.2	m($\tilde{\chi}_1^0$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee,\mu\mu$	2 jets	E_T^{miss}	140	$\tilde{g}$ 2.2	m($\tilde{\chi}_1^0$)<700 GeV	2204.13072
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	E_T^{miss}	140	$\tilde{g}$ 1.97	m($\tilde{\chi}_1^0$) <600 GeV	2008.06032
		SS e,μ	6 jets		140	$\tilde{g}$ 1.15	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	2307.01094
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	E_T^{miss}	140	$\tilde{g}$ 2.45	m($\tilde{\chi}_1^0$)<500 GeV	2211.08028
		SS e,μ	6 jets		140	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1909.08457
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	E_T^{miss}	140	$\tilde{b}_1$ 1.255	m($\tilde{\chi}_1^0$)<400 GeV	2101.12527
						$\tilde{b}_1$ 0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}_1^0$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	E_T^{miss}	140	$\tilde{b}_1$ Forbidden 0.23-1.35	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	140	$\tilde{b}_1$ 0.13-0.85	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{t}_1$ 1.25	m($\tilde{\chi}_1^0$)=1 GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	1 e,μ	3 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$ Forbidden 1.05	m($\tilde{\chi}_1^0$)=500 GeV	2012.03799, 2401.13430
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$ Forbidden 1.4	m($\tilde{\tau}_1$)=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$ 0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	140	$\tilde{t}_1$ 0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_2^0$, $\tilde{\chi}_2^0\to Z/h\tilde{\chi}_1^0$	1-2 e,μ	1-4 b	E_T^{miss}	140	$\tilde{t}_1$ 0.067-1.18	m($\tilde{\chi}_2^0$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	140	$\tilde{t}_2$ Forbidden 0.86	m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.96	m($\tilde{\chi}_1^0$)=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.205	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW	2 e,μ		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}$ 0.42	m($\tilde{\chi}_1^0$)=0, wino-bino	1908.08215
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ Forbidden 1.06	m($\tilde{\chi}_1^0$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}$ 1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	140	$\tilde{\tau}$ [$\tilde{\tau}_R\tilde{\tau}_R$] 0.35 0.5	m($\tilde{\chi}_1^0$)=0	2402.00603
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	E_T^{miss}	140	$\tilde{\ell}$ 0.7	m($\tilde{\chi}_1^0$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{\ell}$ 0.26	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	E_T^{miss}	140	$\tilde{H}$ 0.94	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	2401.14922
		4 e,μ	0 jets	E_T^{miss}	140	$\tilde{H}$ 0.55	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	$\geq$ 2 large jets	E_T^{miss}	140	$\tilde{H}$ 0.45-0.93	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	2108.07586
		2 e,μ	$\geq$ 2 jets	E_T^{miss}	140	$\tilde{H}$ 0.77	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=BR($\tilde{\chi}_1^0\to h\tilde{G}$)=0.5	2204.13072
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	E_T^{miss}	140	$\tilde{\chi}_1^{\pm}$ 0.66	Pure Wino	2201.02472
						$\tilde{\chi}_1^{\pm}$ 0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$ 2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns] 2.2	m($\tilde{\chi}_1^0$)=100 GeV	2205.06013
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		E_T^{miss}	140	$\tilde{e}$,$\tilde{\mu}$ 0.74	$\tau(\tilde{\ell})$ = 0.1 ns	ATLAS-CONF-2024-011
						$\tilde{\tau}$ 0.36	$\tau(\tilde{\ell})$ = 0.1 ns	ATLAS-CONF-2024-011
		pixel dE/dx		E_T^{miss}	140	$\tilde{\tau}$ 0.36	$\tau(\tilde{\ell})$ = 10 ns	2205.06013
RPV	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0$, $\tilde{\chi}_1^{\pm}\to Z\ell\to\ell\ell\ell$	3 e,μ			140	$\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0$, $\lambda_{12k}\neq 0$] 0.95 1.55	m($\tilde{\chi}_1^0$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$		$\geq$8 jets		140	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=50 GeV, 1250 GeV] 1.6 2.34	Large λ''_{112}	2401.16333
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^{\pm}\to bbs$		$\geq 4b$		140	$\tilde{t}$ Forbidden 0.95	m($\tilde{\chi}_1^{\pm}$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		140	$\tilde{t}_1$ 0.4-1.85	BR($\tilde{t}_1\to be/b\mu$)>20%	2406.18367
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_1^0$, $\tilde{\chi}_{1,2}^0\to tbs$, $\tilde{\chi}_1^+\to bbs$	1-2 e,μ	$\geq$6 jets		140	$\tilde{\chi}_1^0$ 0.2-0.32	Pure higgsino	2106.09609

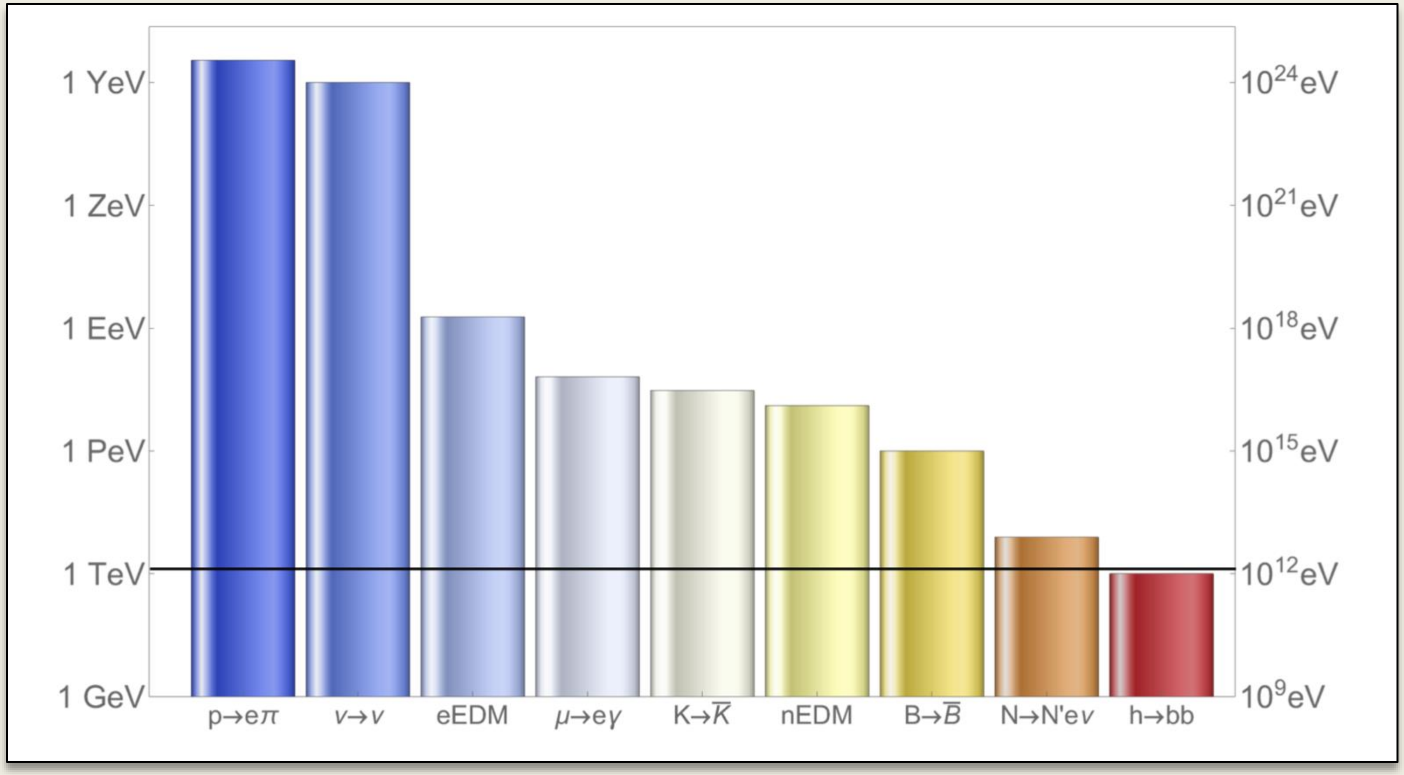
10^{-1} 1 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Scales

- Seems very different from my earlier picture

$$M_{\rm SUSY} > 35\,{\rm TeV} \times \sqrt{\sin \phi_{CP}}$$



- This picture assumes

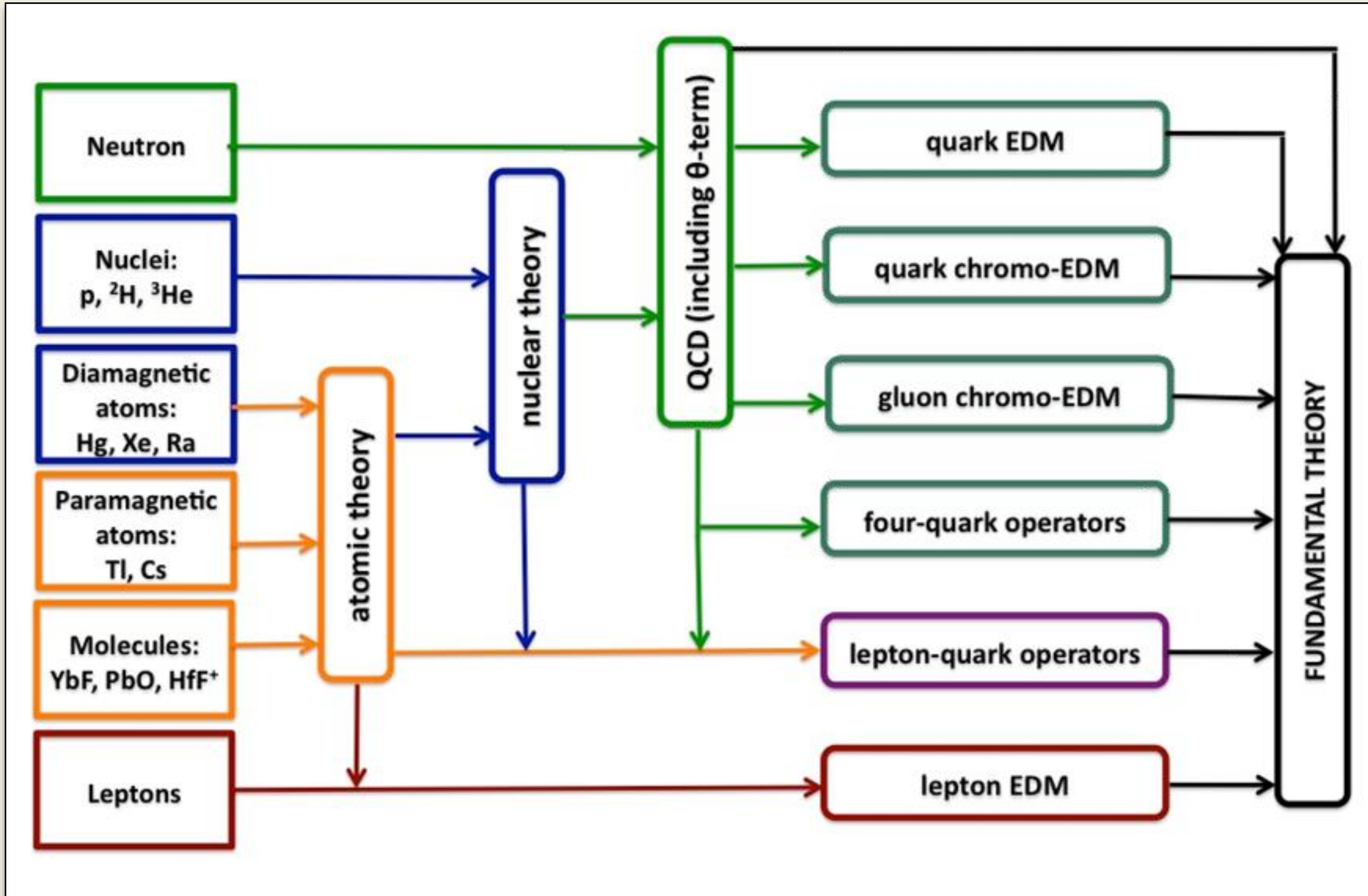
$$\mathcal{L} = C_e \bar{e}_L \sigma^{\mu\nu} \varphi e_R F_{\mu\nu}$$

$$d_e \sim v\,{\rm Im}\, C_e \sim \frac{v}{\Lambda^2}$$

- In SUSY there is a chiral and loop suppression

$$\frac{m_e}{v}\frac{\alpha_{em}}{4\pi} \sim 10^{-9}$$

I ignored some intermediate steps



Paramagnetic systems

e

System	Group	Limit	C.L.	Value	Year
^{205}Tl	Berkeley	1.6×10^{-27}	90%	$6.9(7.4) \times 10^{-28}$	2002
YbF	Imperial	10.5×10^{-28}	90	$-2.4(5.7)(1.5) \times 10^{-28}$	2011
ThO	ACME	1.1×10^{-29}	90	$4.3(3.1)(2.6) \times 10^{-30}$	2018
HfF^{+}	Boulder	4.1×10^{-30}	90	$-1.3(2.0)(0.6) \times 10^{-30}$	2022

- Why these complicated systems ? Cannot use free electrons….
- **Why not simply use Hydrogen ?**

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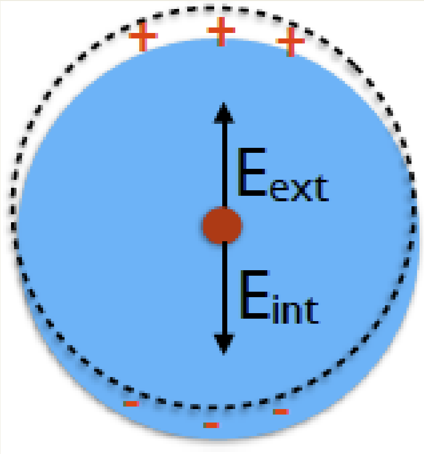
HfF^{+}	Boulder	4.1×10^{-30}	90	$-1.3(2.0)(0.6) \times 10^{-30}$	2022

- Why these complicated systems ? Cannot use free electrons….
- **Why not simply use Hydrogen ?**

Schiff Theorem: EDMs of charged constituents are screened in a neutral atom Schiff, '63

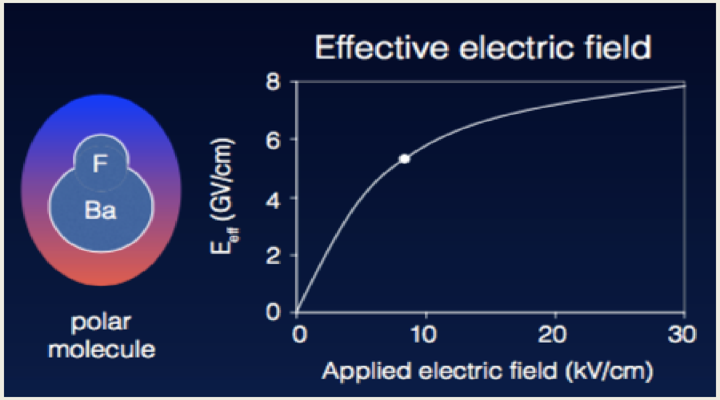


- Assumption : **non-relativistic constituents**
- **Invalid in heavy atoms/molecules**

$$d_A(d_e) = K_A d_e \qquad K_A \propto Z^3 \alpha_{em}^2$$

Sandars '65

Probing the leptonic interactions



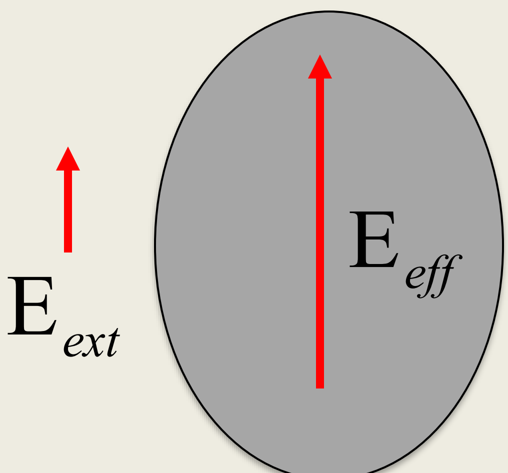
Polar molecules:

Convert small external to **huge** internal E field

$$E_{eff} \propto 10^6 E_{ext}$$

Requires high-accuracy electronic structure computations

See work by our organizer: Anastasia Borschevsky

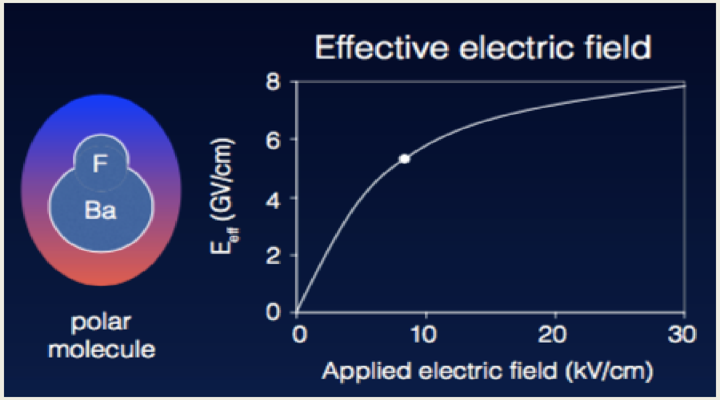


$$\Delta E_{ThO} = (80 \pm 10) \cdot GeV \left(\frac{d_e}{e\,cm} \right)$$

$$d_e < 1.4 \square 10^{-29}\ e\,cm$$ Andreev et al ’18

Similar story for HfF with factor 2 better limit

Probing the leptonic interactions



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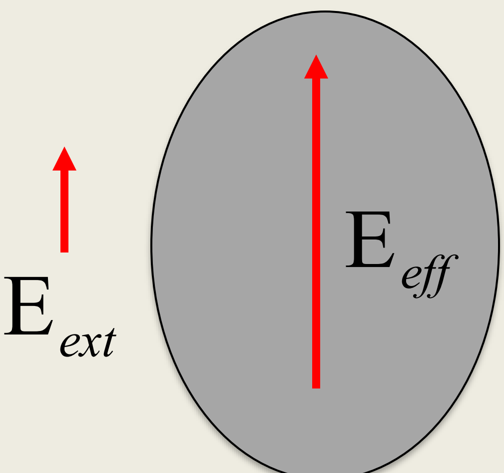
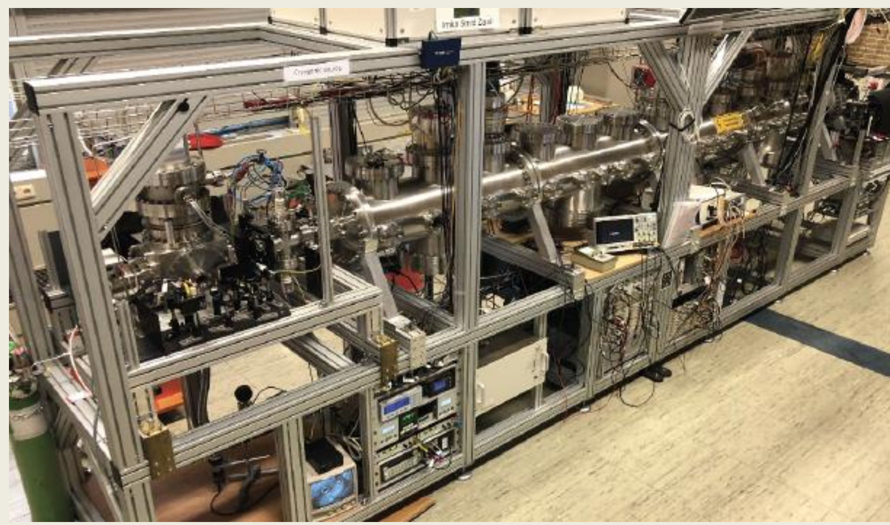
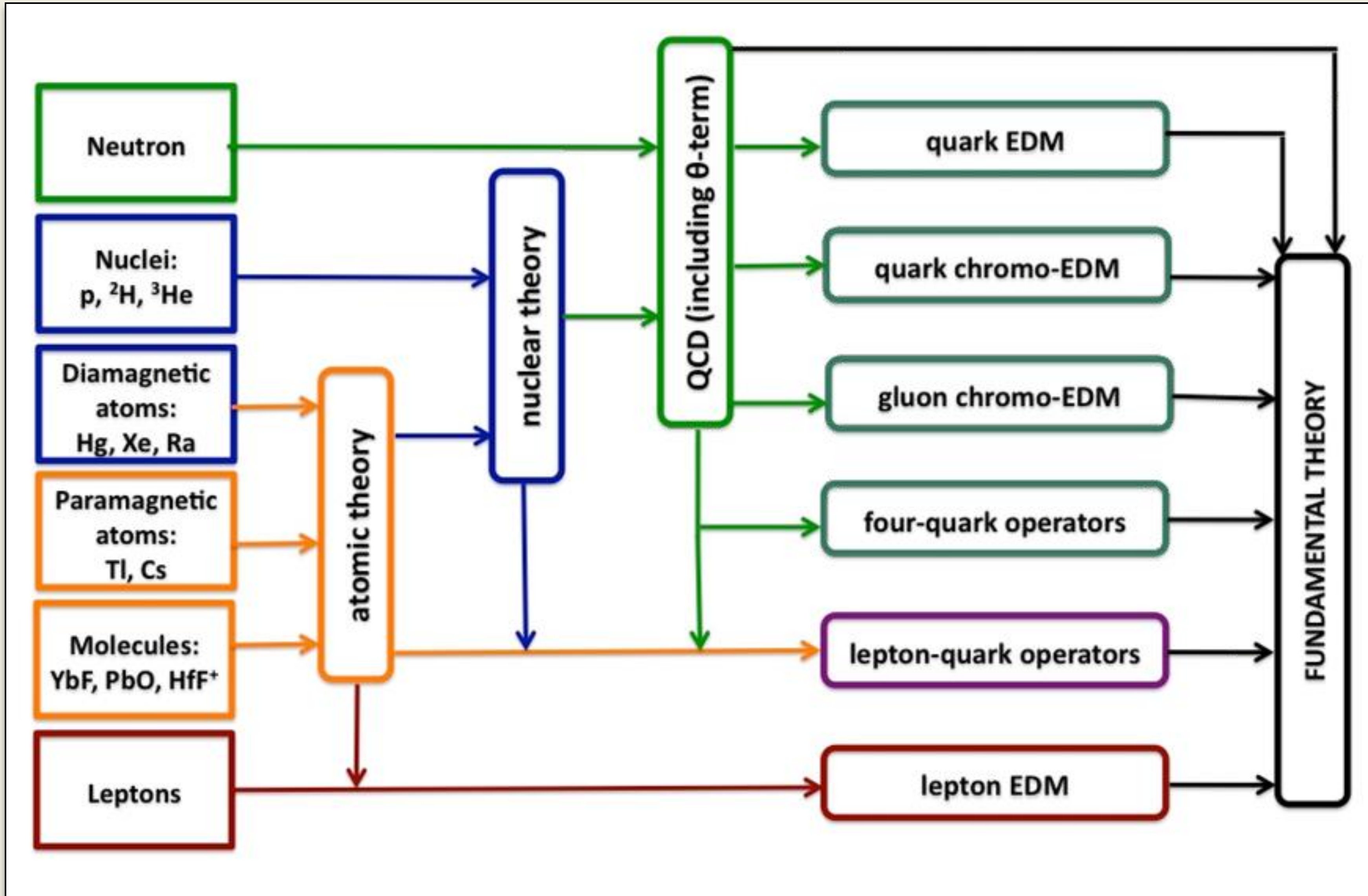




8

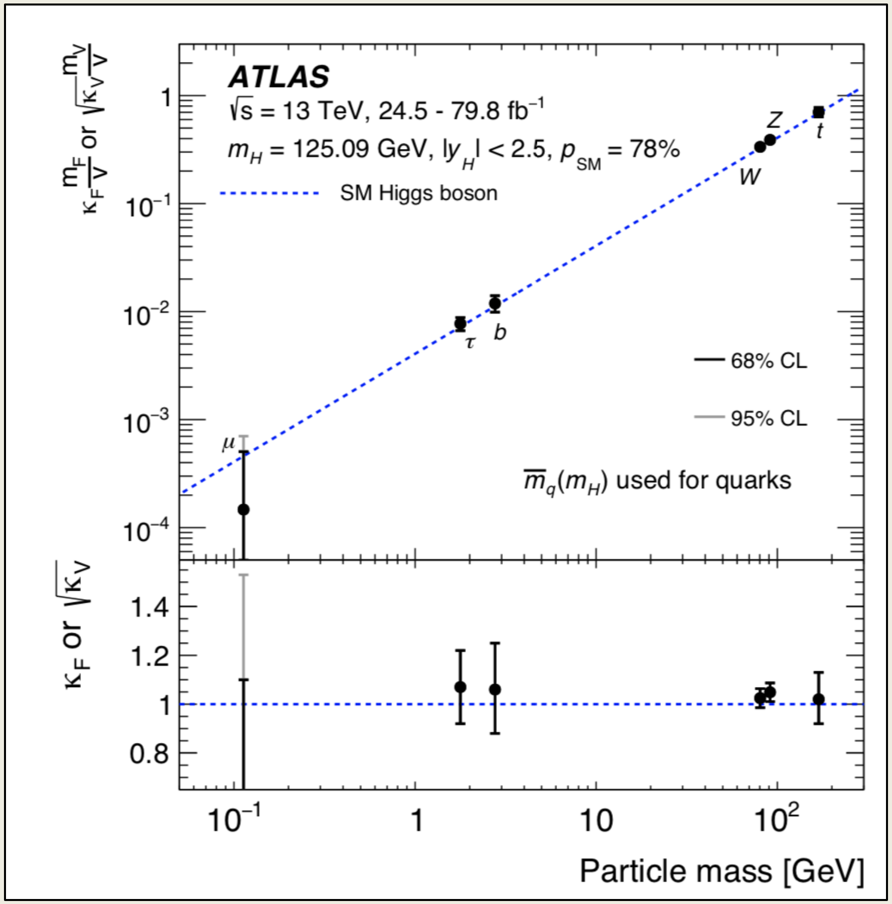
RUG/VU/Nikhef use laser-cooled BaF molecules

I ignored some intermediate steps



Testing the Higgs sector

- Discovery of fundamental scalar boson opens a new era
- So far: Higgs properties **in rough agreement** with Standard Model



SM predictions

1. Higgs couples ~ to mass
2. Higgs is a scalar:
No CP violating interactions

Consequences of a minimal Higgs sector

Can EDMs help with testing this?

Applications to electroweak baryogenesis

13.x billion years →

Generation of matter happens during EW phase transition

BSM physics to fulfill Sakharov conditions

1. A strong first-order EW phase transition (out-of-equilibrium)
2. Additional CP-violation (CKM phase + theta not enough)

Applications to electroweak baryogenesis

13.x billion years →

Generation of matter happens during EW phase transition

BSM physics to fulfill Sakharov conditions

1. Minimal option: couple Higgs to quarks with CP violation

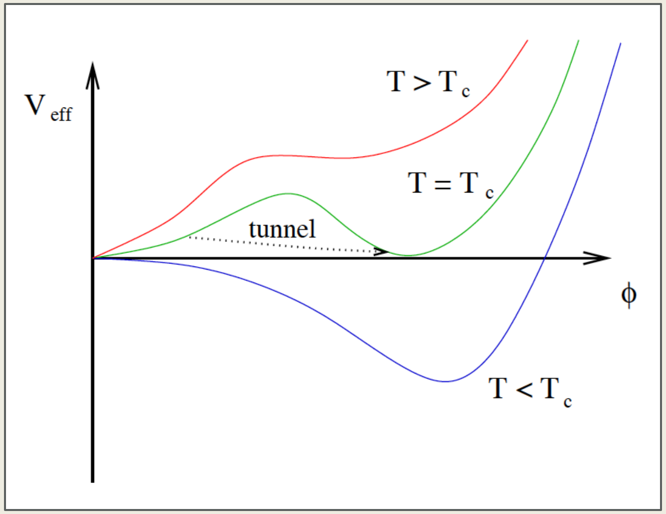
$$\mathcal{L} = y_t \bar{t}\, t\, h + \tilde{y}_t \bar{t}\, i\gamma^5 t\, h$$

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



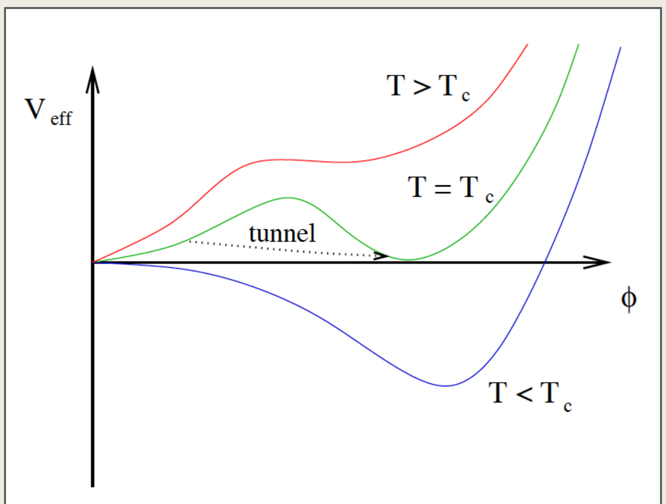
Electroweak baryogenesis in a nut-shell

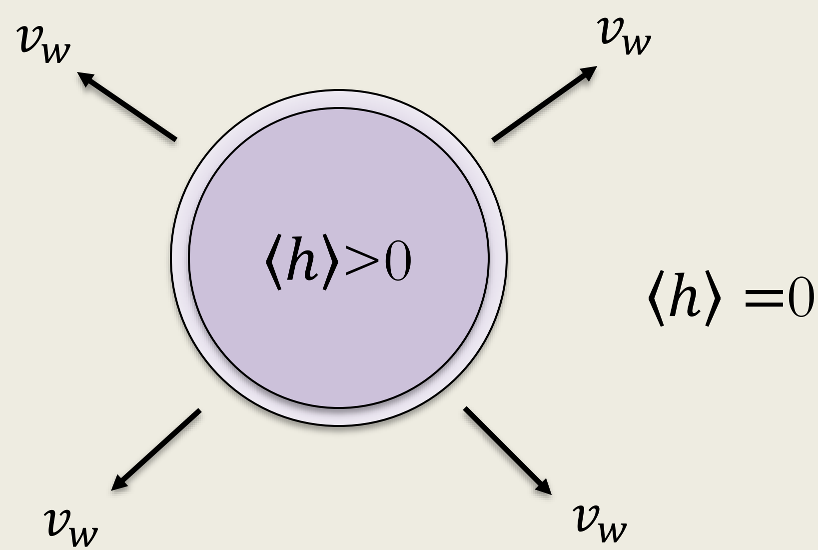
- Many BSM models for electroweak baryogenesis

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





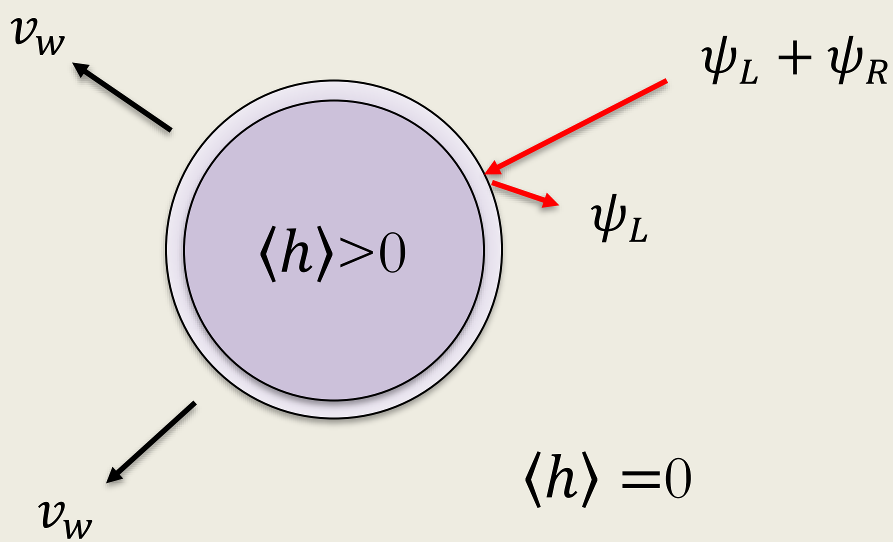
Experimental probes: di-Higgs production, new scalars, Higgs couplings, Gravitational waves

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

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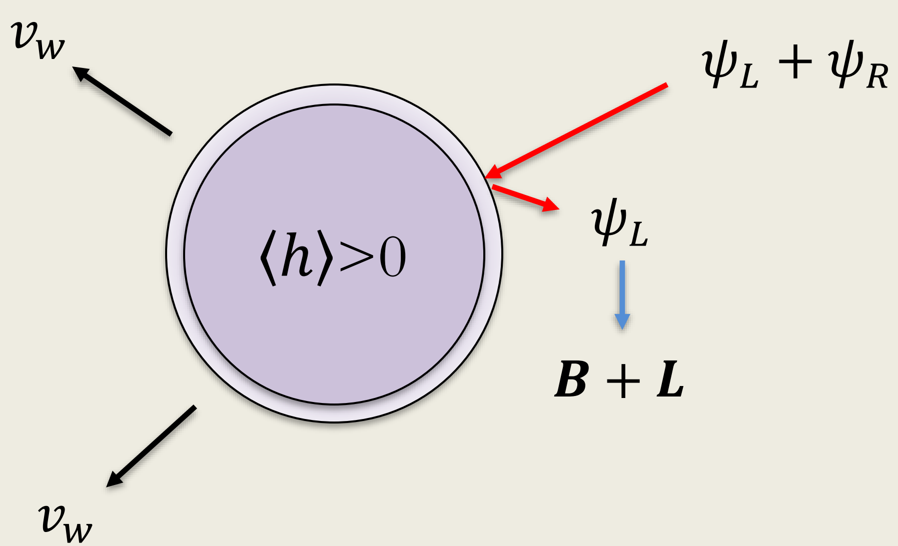
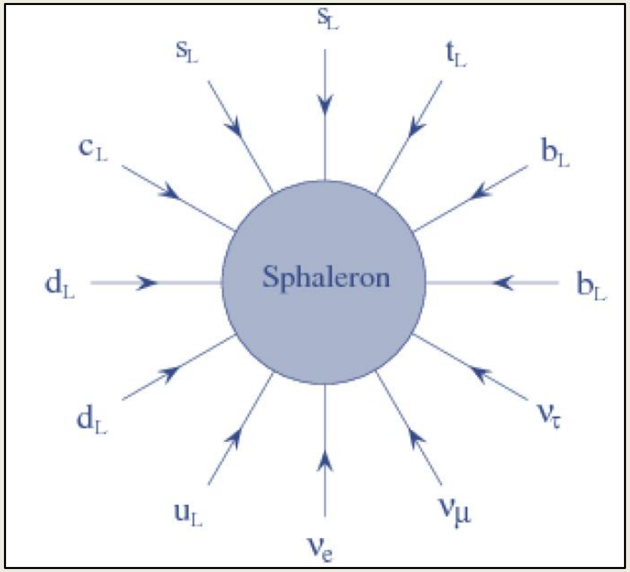
Chiral asymmetry transformed into **Baryon asymmetry** by electroweak sphaleron processes (efficient for $T>M_W$)





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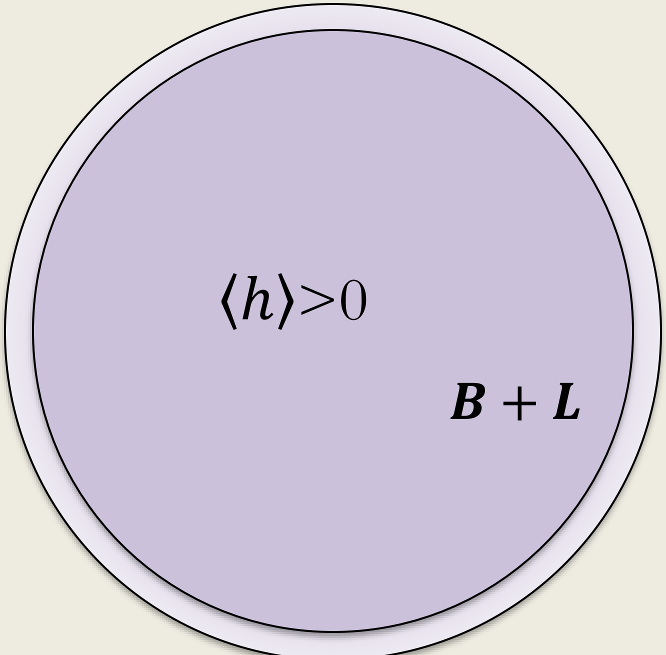
B+L is captured by expanding bubble as sphalerons turn off at nonzero v



Complicated calculations and large associated uncertainties

Order-of-magnitude level predictions

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

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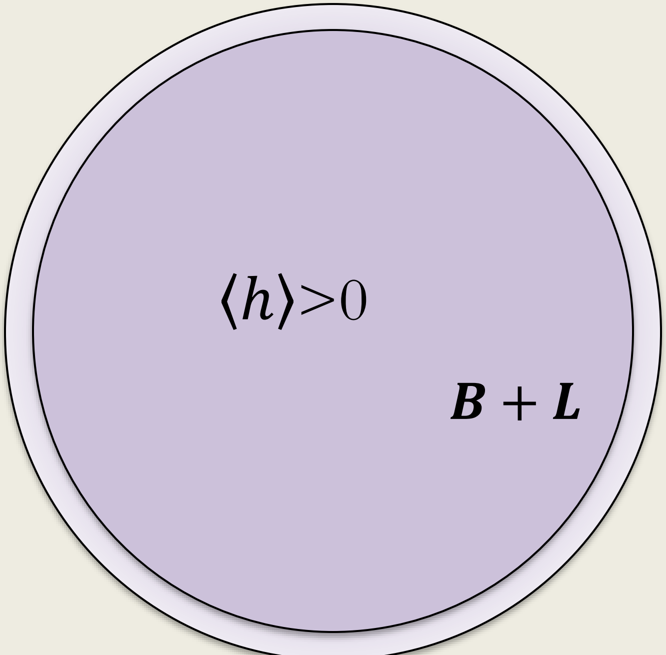
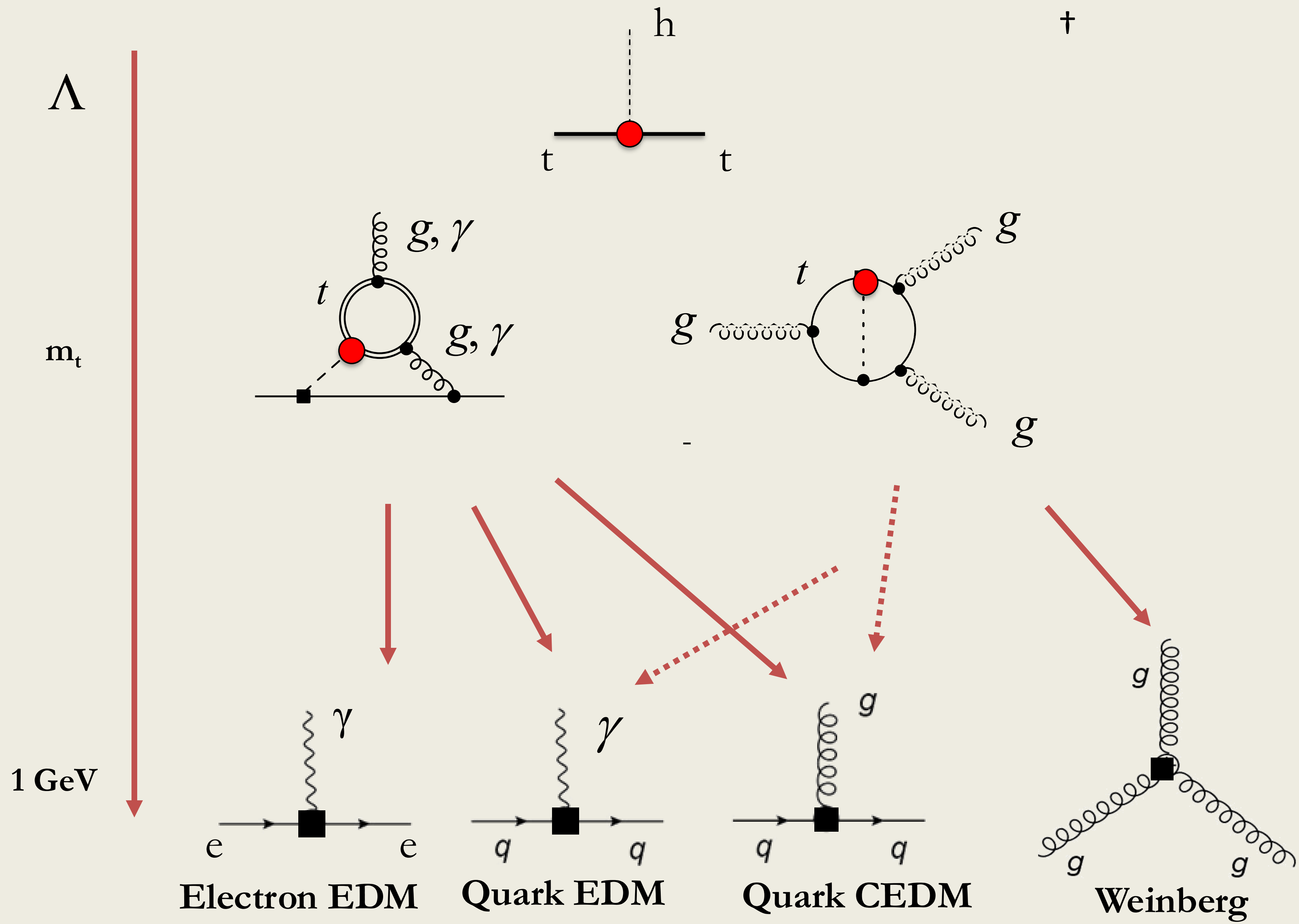


Complicated calculations and large associated uncertainties

Order-of-magnitude level predictions

Detailed calculations (JdV, Postma, van de Vis): $\tilde{y}_t \simeq 0.03$

Can we test this with EDMs ?



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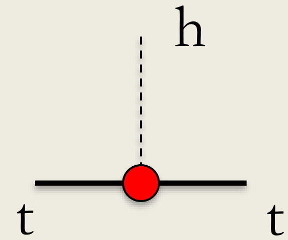
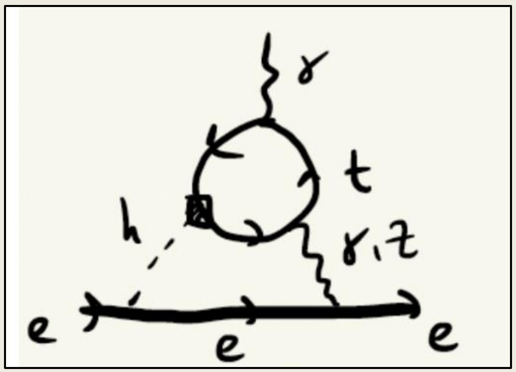
Λ

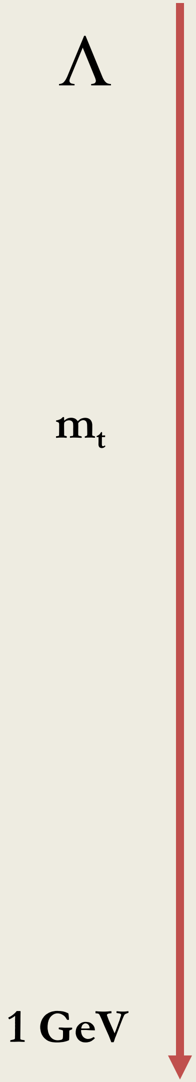


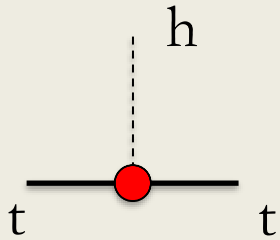
m_t

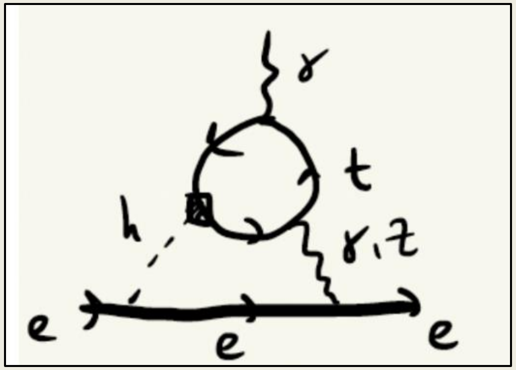


1 GeV

Can we test this with EDMs ?



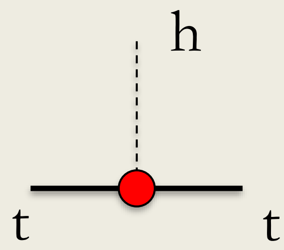




$$d_e \sim \frac{e^3 y_e \tilde{y}_t}{(4\pi)^4} \frac{1}{m_t}$$

Can we test this with EDMs ?

Λ



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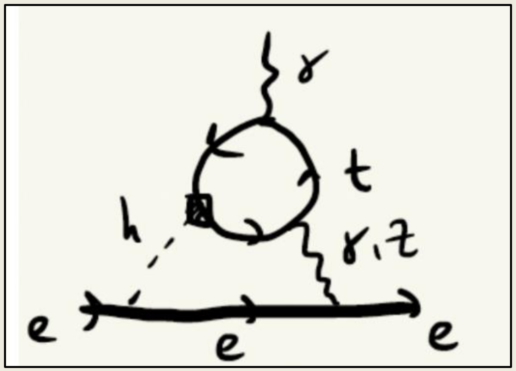


$$d_e \sim \frac{e^3 y_e \tilde{y}_t}{(4\pi)^4}\frac{1}{m_t}$$

Full answer:

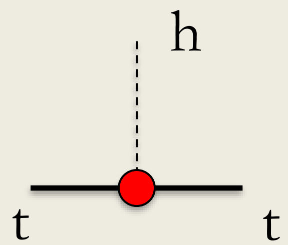
$$\frac{d_e}{e} = -m_e \frac{8N_c Q_t^2 \alpha_{\rm em}}{(4\pi)^3} g(x_t) \times {\rm Im}(Y_t)\,, \qquad g(x_t) = \frac{x_t}{2}\int_0^1 {\rm d}x \frac{1}{x(1-x)-x_t}\ln\left(\frac{x(1-x)}{x_t}\right)$$

1 GeV

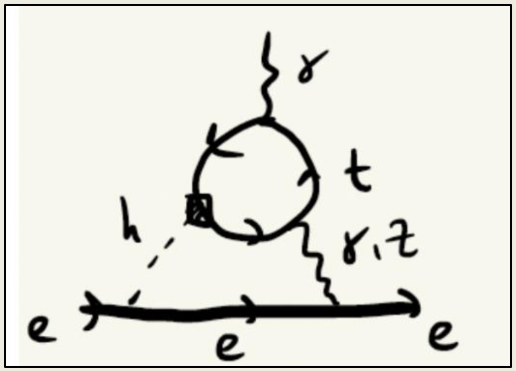
Estimate within 40% !

Can we test this with EDMs ?

Λ



m_t



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EDMs constrain $\tilde{y}_t \lesssim 10^{-3}$

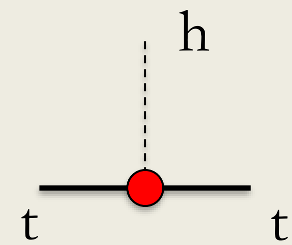
This then rules out this model of EWBG $\tilde{y}_t \simeq 0.03$

There are many ways to avoid this in more complicated models but the *'minimal'* models are ruled out

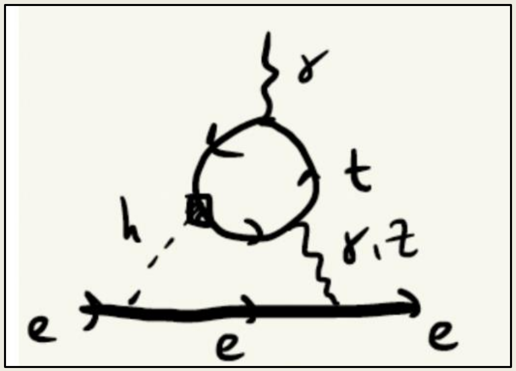
1 GeV

Can we test this with EDMs ?

Λ



m_t



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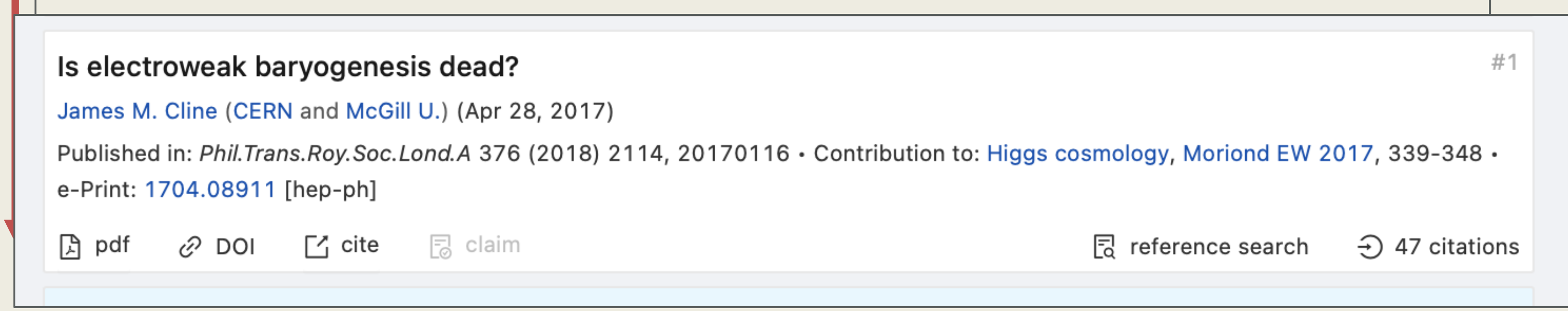
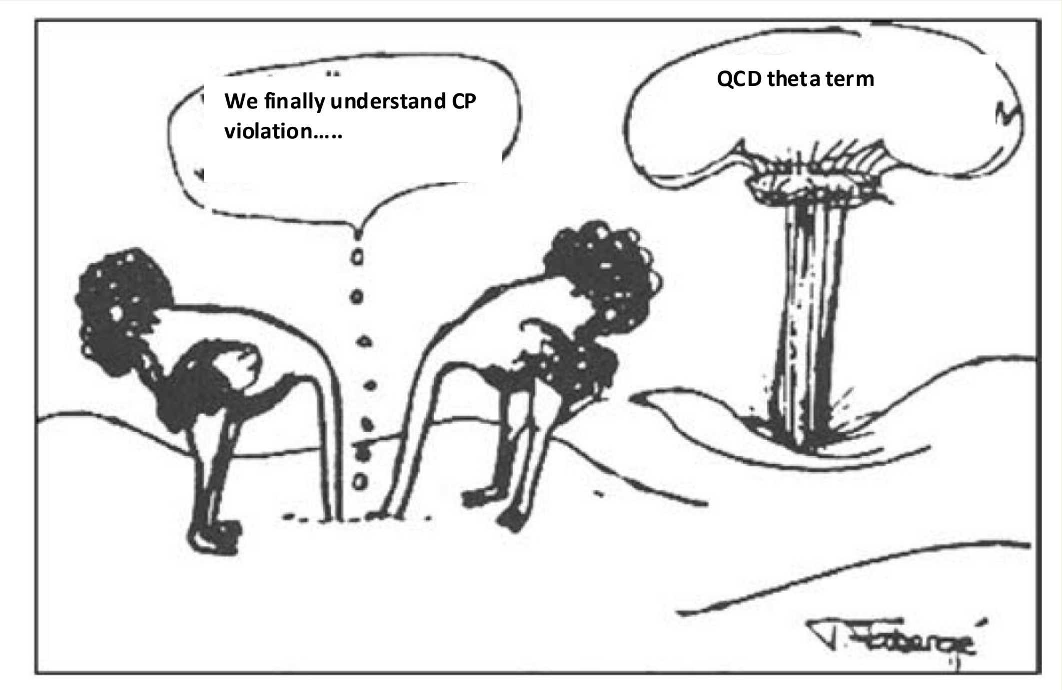

Is electroweak baryogenesis dead? #1

James M. Cline (CERN and McGill U.) (Apr 28, 2017)

Published in: *Phil.Trans.Roy.Soc.Lond.A* 376 (2018) 2114, 20170116 • Contribution to: Higgs cosmology, Moriond EW 2017, 339-348 • e-Print: 1704.08911 [hep-ph]

pdf DOI cite claim reference search 47 citations

Electric Dipole Moments and the strong CP problem



Introductory remarks

- Strong CP violation is a technical subject. **Here outline the main ideas.**
- Start by considering the QED Lagrangian

$$L = \overline{q}(i\gamma^{\mu} D_{\mu} - m_q)q - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \qquad D_{\mu} = \partial_{\mu} - iQ_q A_{\mu}$$

- Why these terms? They are **almost all** gauge-invariant terms (U(1) gauge) with terms up to 'dimension 4'.
- **SM = all renormalizable terms that obey SU(3)xSU(2)xU(1) gauge invariance involving known degrees of freedom (quarks , leptons,..)**

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- Why these terms? They are **almost all** gauge-invariant terms (U(1) gauge) with terms up to 'dimension 4'.
- **SM = all renormalizable terms that obey SU(3)xSU(2)xU(1) gauge invariance involving known degrees of freedom (quarks , leptons,..)**
- However one term is missing.....
- $F_{\mu\nu}$ is a gauge-invariant quantity.... So we could have added a term:

$$\theta \frac{e^2}{32\pi^2} \varepsilon^{\alpha\beta\mu\nu} F_{\alpha\beta} F^{\mu\nu} \equiv \theta \frac{e^2}{32\pi^2} \tilde{F}_{\mu\nu} F^{\mu\nu}$$

$\varepsilon^{\alpha\beta\mu\nu}$

= 4 dimensional Levi-Civita tensor

= 0 if 2 indices are equal

Total derivatives

- So why don't we have this term in QED ?

$$\theta \frac{e^2}{32\pi^2} \varepsilon^{\alpha\beta\mu\nu} F_{\alpha\beta} F^{\mu\nu} \equiv \theta \frac{e^2}{32\pi^2} \tilde{F}_{\mu\nu} F^{\mu\nu}$$

- First of all, what does it even describe ?

$$\theta \frac{e^2}{32\pi^2} \varepsilon^{\alpha\beta\mu\nu} F_{\alpha\beta} F^{\mu\nu} \sim \vec{E} \cdot \vec{B}$$

Total derivatives

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- First of all, what does it even describe ?

$$\theta\frac{e^2}{32\pi^2}\varepsilon^{\alpha\beta\mu\nu}F_{\alpha\beta}F^{\mu\nu} \sim \vec{E}\cdot\vec{B}$$

Parity or Time-reversal: $\vec{E}\cdot\vec{B} \to -\vec{E}\cdot\vec{B}$

Note: $F_{\mu\nu}F^{\mu\nu} \sim \vec{E}^2 - \vec{B}^2 \to \vec{E}^2 - \vec{B}^2$

- So it describes a CP-odd interaction! Whoho !
- But.... This term has no physical consequences ! Why ?

- **Cause its a total derivative:** $\varepsilon^{\alpha\beta\mu\nu}F_{\alpha\beta}F^{\mu\nu} = \Box_\mu(\varepsilon^{\alpha\beta\mu\nu}A_\nu F_{\alpha\beta})$

QCD makes life complicated …

- This explains why we do not have a QED theta term
- QCD is more complicated, non-Abelian group, still total derivative

$$\varepsilon^{\alpha\beta\mu\nu} G_{\alpha\beta} G^{\mu\nu} = \partial_\mu \varepsilon^{\alpha\beta\mu\nu} (A_\nu F_{\alpha\beta} + A_\alpha A_\beta A_\nu)$$

- For a long time it was though that this has no consequences as well....

- Now I am going to wave hands .....

QCD makes life complicated …

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$$\varepsilon^{\alpha\beta\mu\nu} G_{\alpha\beta} G^{\mu\nu} =$$

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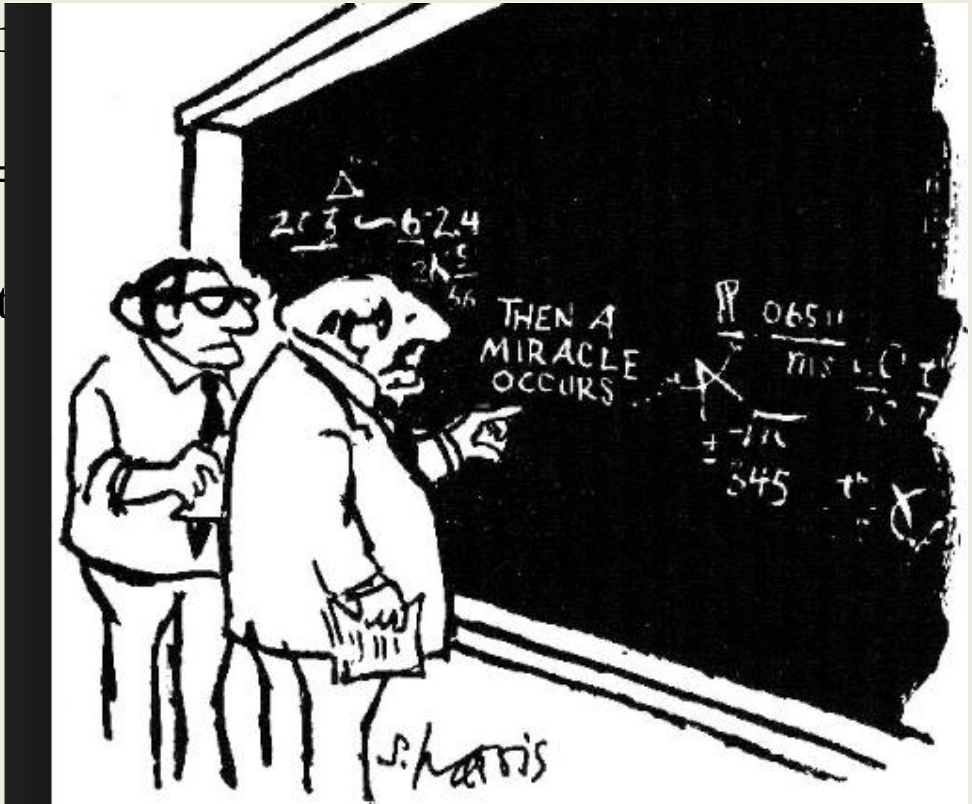

"I think you should be more explicit here in step two."

QCD makes life complicated …

- This explains why we do not have a QED theta term
- QCD is more complicated, non-Abelian group

$$\varepsilon^{\alpha\beta\mu\nu} G_{\alpha\beta} G^{\mu\nu} = \square_{\mu} \varepsilon^{\alpha\beta\mu\nu} (A_{\nu} F_{\alpha\beta} + A_{\alpha} A_{\beta} A_{\nu})$$

- For a long time it was though that this has no consequences as well....

- Now I am going to wave hands .....

- There are instanton solutions where A ~ 1/r only for very large r
- These solutions do not drop off fast enough to ignore the surface terms

$$\square d^4x \, \varepsilon^{\alpha\beta\mu\nu} G_{\alpha\beta} G^{\mu\nu} \, \square \, 0$$

- **The QCD theta term has physical consequences !**

The eta-eta' puzzle

- Let us look at 3-flavor QCD

$$L = \sum_{u,d,s} \bar{q}(i\gamma^{\mu} D_{\mu} - m_q)q - \frac{1}{4} G_{\mu\nu} G^{\mu\nu}$$

- The u,d,s quark masses are much smaller than the hadron masses, so let us consider the 'chiral limit' $m_q \to 0$
- The very simple Lagrangian has a number of **global** symmetries

$q \to e^{i\alpha} q$ U(1) symmetry $\qquad$ $q \to e^{i\beta^a \lambda^a} q$ SU(3) symmetry

$q \to e^{i\alpha_5 \gamma^5} q$ $U_A(1)$ symmetry $\qquad$ $q \to e^{i\beta^a \lambda^a \gamma^5} q$ $SU_A(3)$ symmetry

- **But do we actually see any of these symmetries in QCD ?**

Symmetry hunting

- Let's hunt these symmetries in the spectrum of mesons and baryons

$$q \to e^{i\alpha} q$$ U(1) symmetry

Symmetry hunting

- Let's hunt these symmetries in the spectrum of mesons and baryons

$q \rightarrow e^{i\alpha} q$ U(1) symmetry **Check !** Baryon number conservation !

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$$q \Box \; e^{i\alpha} q$$ U(1) symmetry **Check !** Baryon number conservation !

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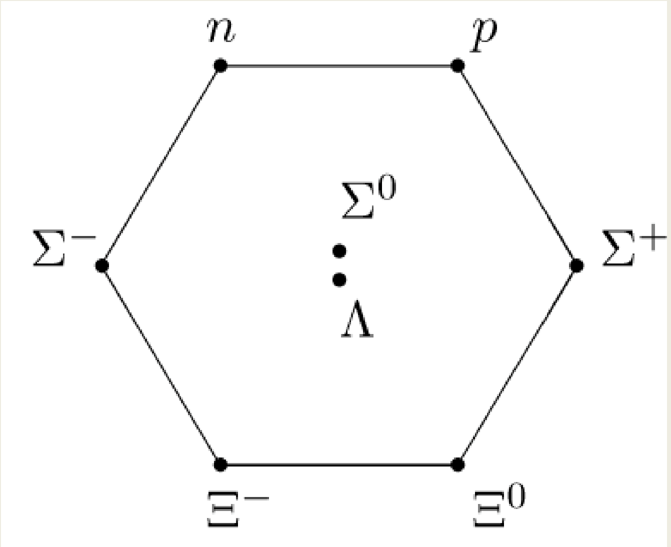
$q \to e^{i\beta^a \lambda^a} q$ SU(3) symmetry **Check !** Octet baryons with very similar properties (neutron, proton, Lambda, ...)



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$q \square \; e^{i\beta^a \lambda^a \gamma^5} q$ $SU_A(3)$ symmetry ???? ????? No P-odd neutron …

$q \square \; e^{i\alpha_5 \gamma^5} q$ $U_A(1)$ symmetry ???? ?????

- What is going on? Does QCD even describe hadrons ?

Nambu-Goldstone to the rescue !

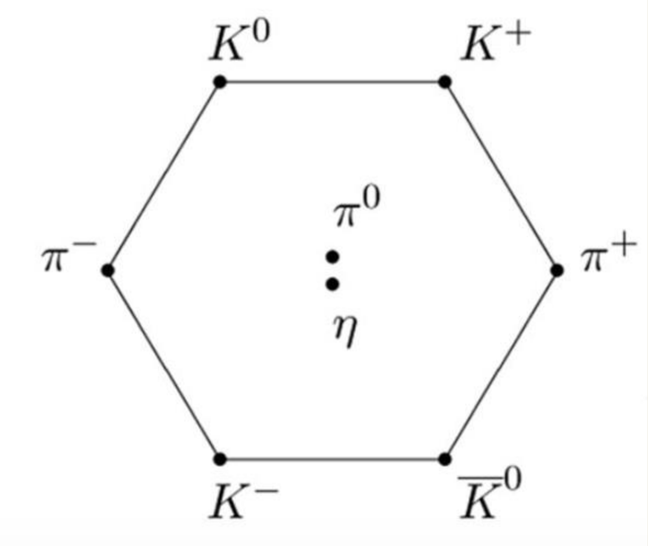
- But wait ! Maybe these symmetries are **spontaneously** broken !
- What does this imply? Goldstone theorem: for each **spontaneously broken global symmetry** there appears a **massless** boson .

- Well, QCD has no massless bosons.....

Nambu-Goldstone to the rescue !

- But wait ! Maybe these symmetries are **spontaneously** broken !
- What does this imply? Goldstone theorem: for each **spontaneously broken global symmetry** there appears a **massless** boson .

- Well, QCD has no massless bosons….. But there are very light bosons !
- Pions (3), Kaons (4), eta (1) are much lighter than ~ 1 GeV (baryon mass)
- They are **Pseudo-Goldstone** bosons of $SU_A(3)$ (because of quark mass)



Symmetry hunting

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$q \to e^{i\alpha} q$ U(1) symmetry **Check !** Baryon number conservation !

$q \to e^{i\beta^a \lambda^a} q$ SU(3) symmetry **Check !** Octet baryons with very similar Masses (neutron, proton, Lambda, ...) !

$q \to e^{i\beta^a \lambda^a \gamma^5} q$ $SU_A(3)$ symmetry **Check!** Spontaneously broken !

$q \to e^{i\alpha_5 \gamma^5} q$ $U_A(1)$ symmetry ???? ?????

- **What about the last one ?** There are no more light mesons....
- The eta' is there but it is massive ~ 1 GeV >> $m_{\text{pion,Kaon,eta}}$
- This was a big problem in the early days of QCD

Anomalous symmetry

- Anomalous symmetries are classical symmetries that are broken by QM
- Action (or Lagrangian) invariant but path-integral not
- **We forgot about the Jacobian !**

$$\int [d\psi][d\bar{\psi}]\; e^{iS[\psi,\bar{\psi}]}$$

$$\psi \to \psi' \qquad \bar{\psi} \to \bar{\psi}'$$

$$S[\psi,\bar{\psi}] = S[\psi',\bar{\psi}']$$

$$\int [d\psi][d\bar{\psi}] = \int [d\psi'][d\bar{\psi}']\, \mathcal{J} \qquad \mathcal{J} \neq 1$$

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$$\int [d\psi][d\bar{\psi}] = \int [d\psi'][d\bar{\psi}']\,\mathcal{J} \qquad \mathcal{J} \neq 1$$

- The $U_A(1)$ symmetry is not a symmetry at al !

Axial transformation induces a shift in the θ term

$$\log \mathcal{J} = -\alpha \int d^4x\ \frac{g_s^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$$

Total derivative but nonzero !

- No reason to expect another Goldstone Boson ! **Eta' mass 'explained'**

Complex masses

- Let us look at 2-flavor QCD with masses + theta term

$$L = \sum_{u,d} \bar{q}(i\gamma^{\mu} D_{\mu} - m_q)q \quad + \theta \frac{g_s^2}{32\pi^2} \varepsilon^{\alpha\beta\mu\nu} G_{\alpha\beta} G^{\mu\nu}$$

- We assumed the masses to be real, but there is **no** reason to do so
- To **make** the masses real, we do a $U_A(1)$ transformation

$$q \to e^{i\alpha_5 \gamma^5} q$$

Complex masses

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- To **make** the masses real, we do a $U_A(1)$ transformation

$$q \rightarrow e^{i\alpha_5 \gamma^5} q$$

- But this induces a theta term from the anomaly ! $\theta \rightarrow \theta + 2i \; Arg(m_q)$
- So we can **'trade'** the theta term for a complex mass or vice versa

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

- One 'physical' combination

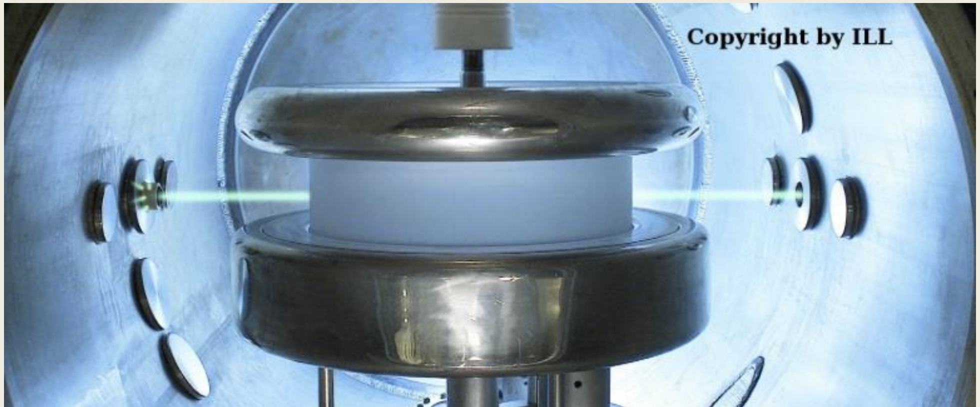
$$\bar{\theta} = \theta + n_f Arg(m_q)$$

Let's take a breath…..

- QCD contains a theta term, a CP-violating interaction
- Total derivative but still contributes via 'instantons'
- The effect is real because we are missing a Goldstone boson

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

- We can trade the theta term for a complex quark mass
- Theta itself is unknown! One of the SM parameters !
- **We should measure it ! Let's do it !**



How do we measure the theta term ?

- Difficult problem. Not unlike measuring the normal quark mass…
- Only **two** feasible ways that I know and one is much better
- **Electric dipole moments of hadrons and nuclei**

- **Problem: low-energy QCD is nonperturbative.**
- How to calculate the nucleon EDM from CPV at quark-gluon level ?

$$L_{dip} = -\frac{d_n}{2}\bar{\Psi}_n \sigma^{\mu\nu} i\gamma^5 \Psi\, F_{\mu\nu} \qquad \text{from} \quad -\left(\frac{m_u m_d}{m_u + m_d}\right)\bar{\theta}\, \bar{q} i\gamma^5 q \;= -\left(m^*\right)\bar{\theta}\, \bar{q} i\gamma^5 q$$

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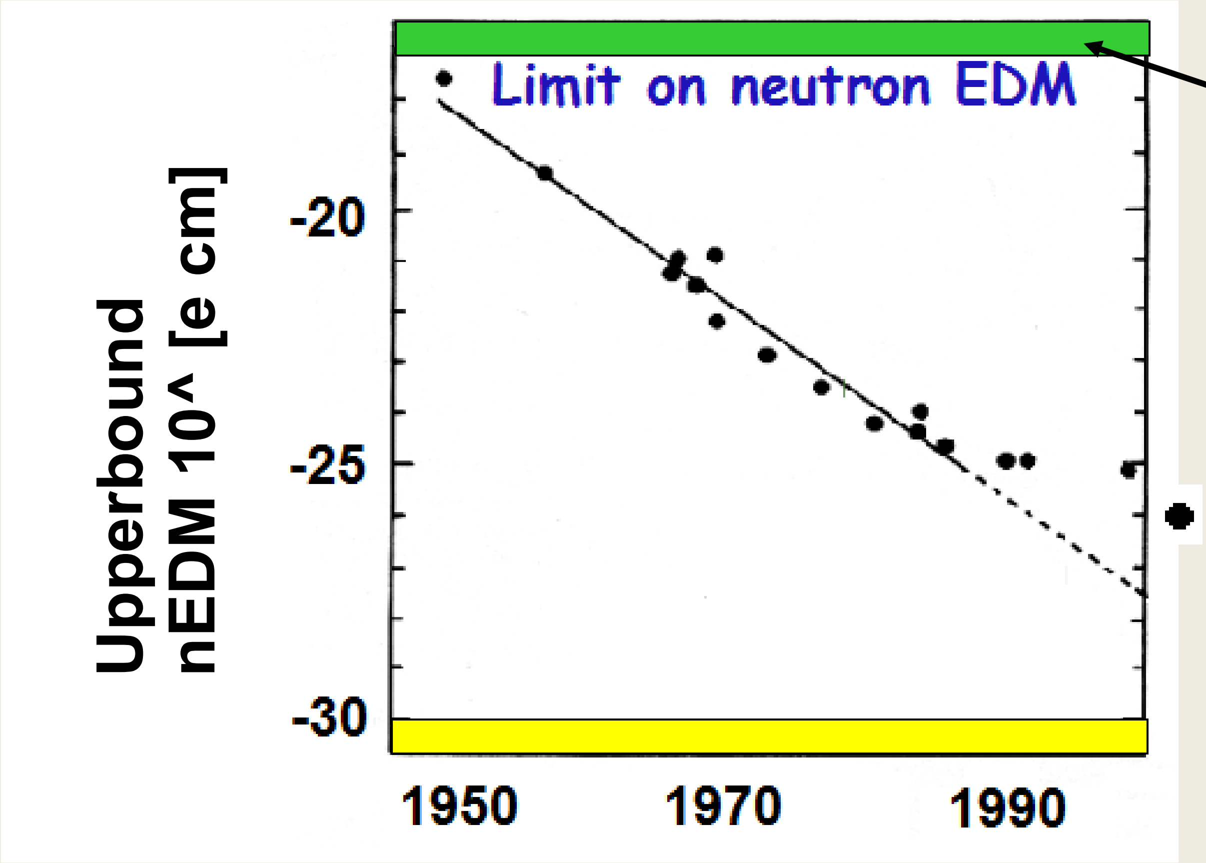
- Let's guess something: d_n should be proportional to ~ $(m^*\theta)$
- There should be a coupling to a photon somewhere ~ e
- To get dimensions right we need 1/mass^2, let's say nucleon mass....

$$d_n \sim e\frac{m^*}{m_N^2}\bar{\theta} \sim e\frac{10\ MeV}{(1\ GeV)^2}\bar{\theta} \sim 10^{-3}\bar{\theta}\ e\ fm$$

Limiting theta

$$d_n \sim e\frac{m^*}{m_N^2}\bar{\theta} \sim e\frac{10\ MeV}{(1\ GeV)^2}\bar{\theta} \sim 10^{-3}\bar{\theta}\ e\ \ fm$$

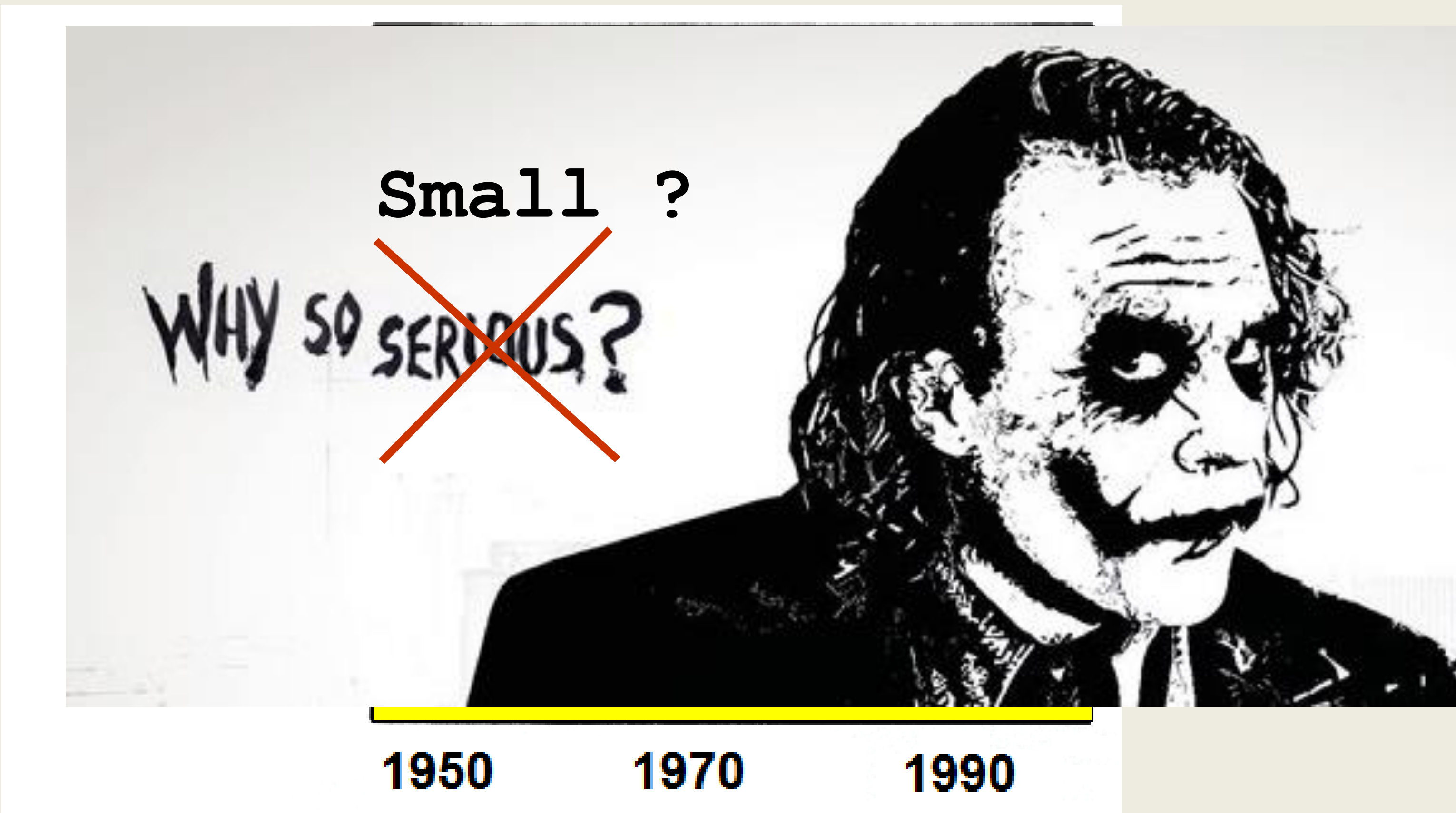


If θ ~ 1, just like the CKM phase

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

Limiting theta

$$d_n \sim e\frac{m^*}{m_N^2}\bar{\theta} \sim e\frac{10\ MeV}{(1\ GeV)^2}\bar{\theta} \sim 10^{-3}\bar{\theta}\ e\ \ fm$$



~ 1,
like
KM
ase

Sets θ upper bound: **θ < 10^-10^**

Perhaps the estimate is stupid….

- The estimate was based on inserting some quasi-random factors

$$\mathcal{L}_{\rm QCD} = \mathcal{L}_{\rm kin} - \bar{m}\bar{q}q - \varepsilon\bar{m}\,\bar{q}\tau^3 q \;+m_\star\,\bar{\theta}\,\bar{q}i\gamma^5 q$$

$$\bar{m} = \frac{m_u + m_d}{2}$$

$$\varepsilon = \frac{m_u - m_d}{m_u + m_d}$$

- We use 'chiral perturbation theory' to match this to the hadronic level. Skip all details.

Perhaps the estimate is stupid….

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$$\mathcal{L}_{\rm QCD} = \mathcal{L}_{\rm kin} - \boxed{\bar{m}\bar{q}q} - \varepsilon\bar{m}\,\bar{q}\tau^3 q \;\; +m_\star\,\bar{\theta}\,\bar{q}i\gamma^5 q$$

$$\bar{m} = \frac{m_u + m_d}{2}$$

$$\mathcal{L}'_\chi = \mathcal{L}_\chi - \boxed{\frac{m_\pi^2}{2}\pi^2} - \delta m_N\,\bar{N}\tau^3 N \quad +\bar{g}_0\,\bar{N}\tau\cdot\pi N$$

Pion mass

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Strong proton-neutron mass splitting

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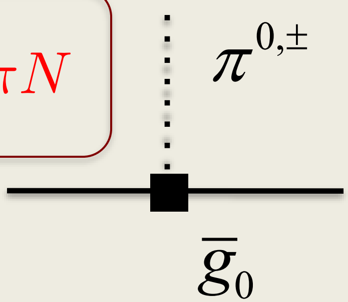

CP-odd pion-nucleon interaction

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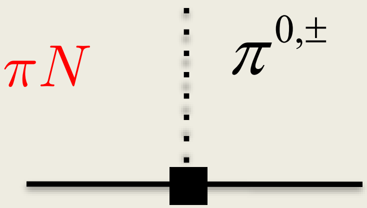
$$\mathcal{L}_{\text{QCD}} = \mathcal{L}_{\text{kin}} - \bar{m}\bar{q}q - \varepsilon\bar{m}\,\bar{q}\tau^3 q \;\; +m_\star\,\bar{\theta}\,\bar{q}i\gamma^5 q$$

$$m_\star = \frac{m_u m_d}{m_u + m_d}$$

Linked via $SU_A(2)$ rotation

$$\mathcal{L}'_\chi = \mathcal{L}_\chi - \frac{m_\pi^2}{2}\pi^2 - \delta m_N\,\bar{N}\tau^3 N \quad +\bar{g}_0\,\bar{N}\tau\cdot\pi N$$

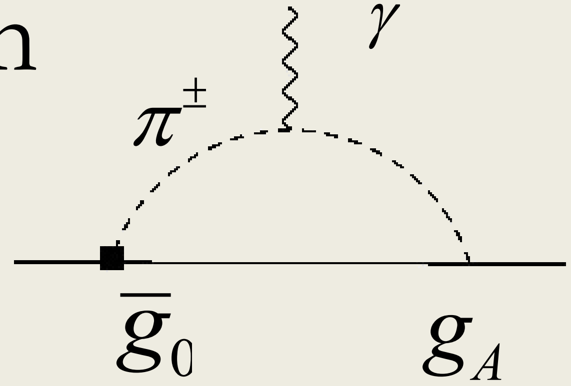


Nucleon mass splitting (strong part, no EM!) ⟷ **CP-odd pion-nucleon interaction**

Use **lattice** for mass splitting

$$g_0 = -\frac{\delta m_N}{2f_\pi}\frac{m_*\bar{\theta}}{\bar{m}\varepsilon} = -(15.5 \pm 2.5)\Box 10^{-3}\;\bar{\theta}$$

The strong CP problem



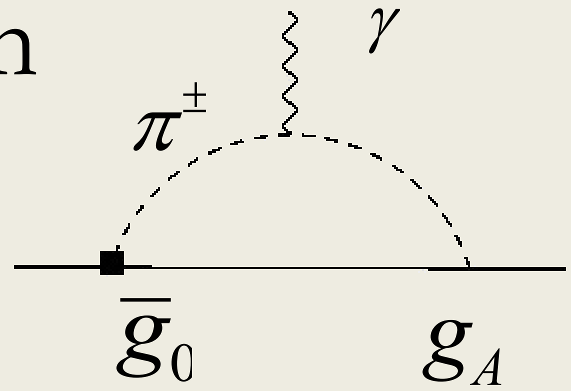
Neutron EDM

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

$$\bar{g}_0 = -(15.5 \pm 2.5)\cdot 10^{-3}\,\bar{\theta} \quad \xrightarrow{\mu = m_N} \quad d_n \simeq -2.5\cdot 10^{-16}\,\bar{\theta}\, e\,\mathrm{cm}$$

- Experimental constraint: $\longrightarrow$ $\bar{\theta} < 10^{-10}$

The strong CP problem



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- Experimental constraint: $\longrightarrow$ $\bar{\theta} < 10^{-10}$

A proper assessment requires a non-perturbative calculation !

Lattice QCD (Shindler et al '19) $d_n = -(1.5 \pm 0.7)\cdot 10^{-16}\,e\,\bar{\theta}$ cm

Lattice QCD (Liang et al '23) $d_n = -(1.4 \pm 0.5)\cdot 10^{-16}\,e\,\bar{\theta}$ cm

Some musings

Is there really a problem ?

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

- Not really. **It is just a parameter**. No inconsistencies.
- **Could it have been larger?**
- Nothing really changes in the universe if $\boldsymbol{\theta} \sim \mathbf{0.1}$ **No anthropic argument.**

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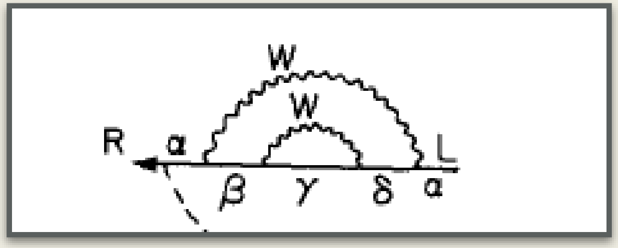
Is small theta radiatively stable?

- 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 !

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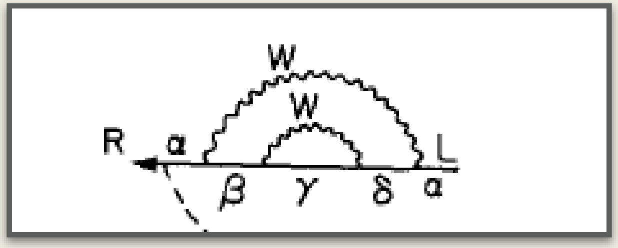

- This property is lost in generic BSM extensions !

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:** Peccei-Quinn mechanism to dynamically set theta to zero. (**AXIONS**)
- **Ruled out solution:** massless up quark

Can we just ignore theta ?

- Since its so small, can't we just ignore it ?
- Short answer: no. We are comparing to stuff that scales as $1/M^2$ so also small

- Fine-tuning: theta could be anything below current limit….

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- High scale P (or CP) invariance: ***theta reintroduced once CP spontaneously broken***.

Do Minimal Parity Solutions to the Strong *CP* Problem Work?

Jordy de Vries,[1,2,*] Patrick Draper,[3,†] and Hiren H. Patel[4,‡]

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- Fine-tuning: theta could be anything below current limit….
- High scale P (or CP) invariance: ***theta reintroduced once CP spontaneously broken***.
- Peccei-Quinn mechanism kills theta exactly *(if it is the only CP-odd source)*.

Axions

Peccei Quinn '77
Weinberg '78, Wilczek '78

- **Lecture set on its own**, but the idea is not too hard
- We saw: theta term connected to $U_A(1)$ anomaly

- Add to the SM some new SU(3)-charged fields which have a new $U_A(1)$ symmetry
- Assume this symmetry is spontaneously broken (axion=goldstone)

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{a(x)}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G}$$

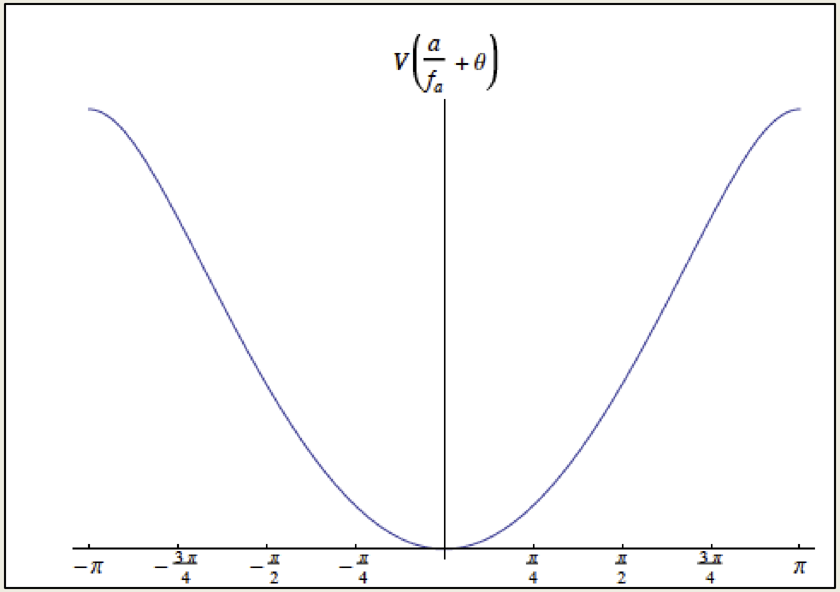
- The theta term becomes a pseudoscalar 'field'

$$\bar{\theta} \rightarrow \bar{\theta} + \frac{a}{f_a}$$

- This field has a **potential,** just like the Higgs

Axions

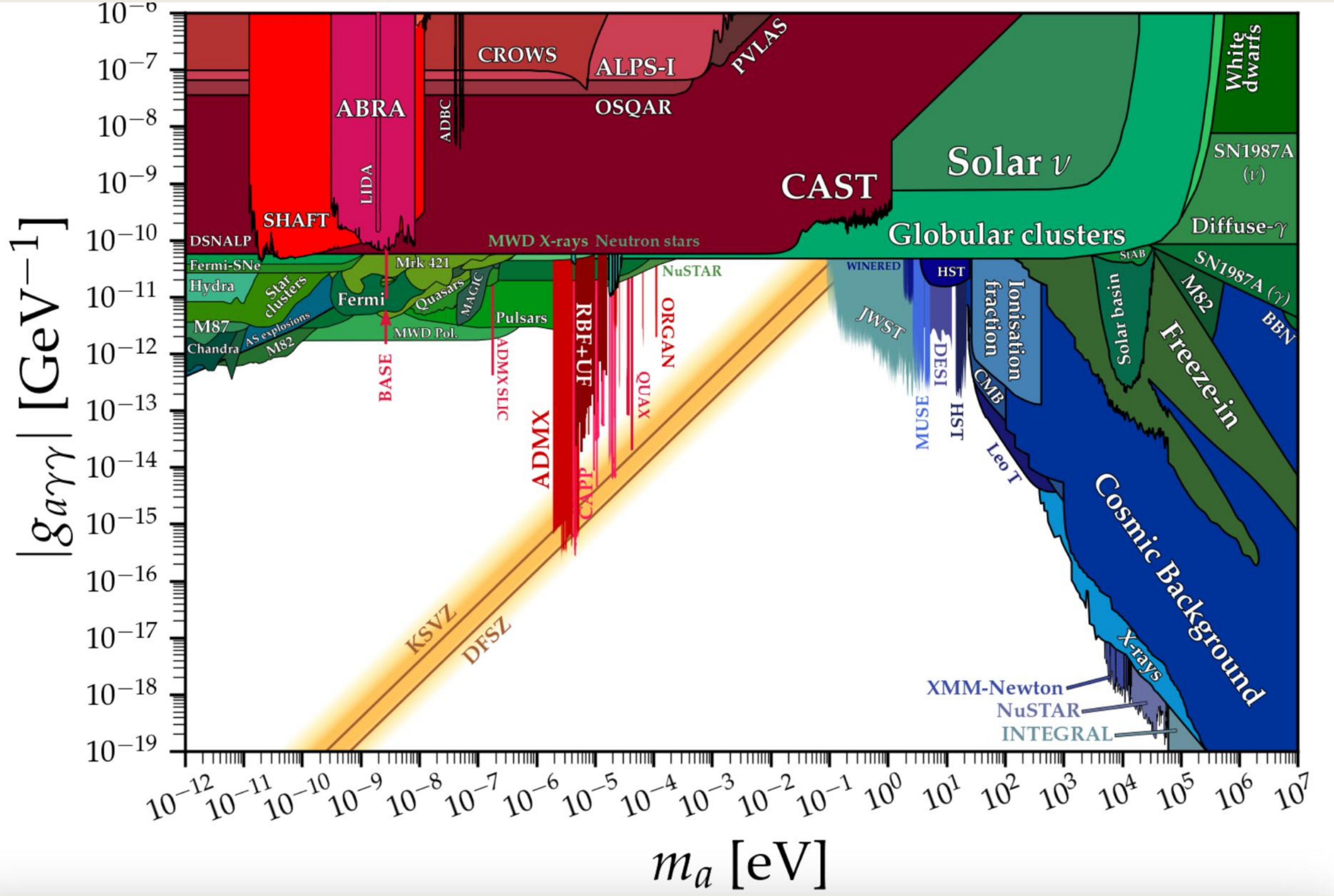
- Potential gets a minimum $$\theta_{total} = \frac{<a>}{f_a} + \bar{\theta} = 0$$



- This solves the CP-problem **independent of the starting value of the theta term !**
- **Very nice, but where is the axion?**
- Mass inversely proportional to f_a which can be huge ! So axion could be **very very light**

$$m_a^2 \propto \frac{m_\pi^2 f_\pi^2}{f_a^2}$$

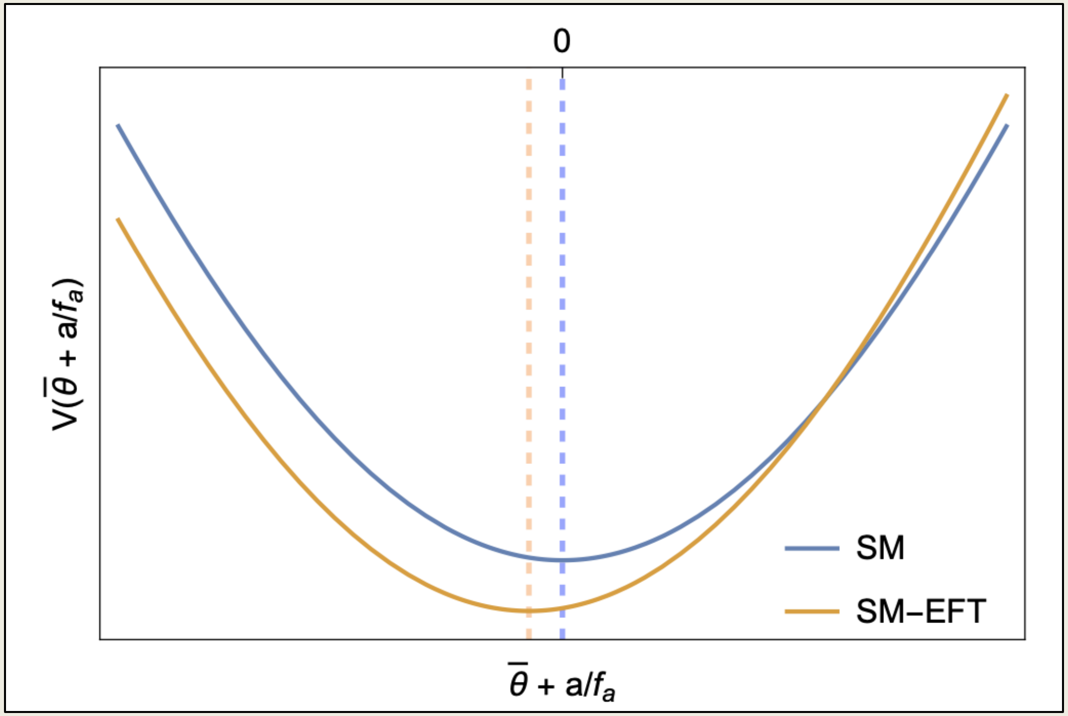
Where is the axion ?



This is a huuuuuuuuuuge field by now

BUT CAN WE IGNORE THETA ?

- PQ is exact for a single source of CPV but minimum shifts if another source is present. *So a remnant theta is left behind.*



Pospelov, Ritz ‘05

V. Plakkot, JdV, Dekens, Shain ‘23

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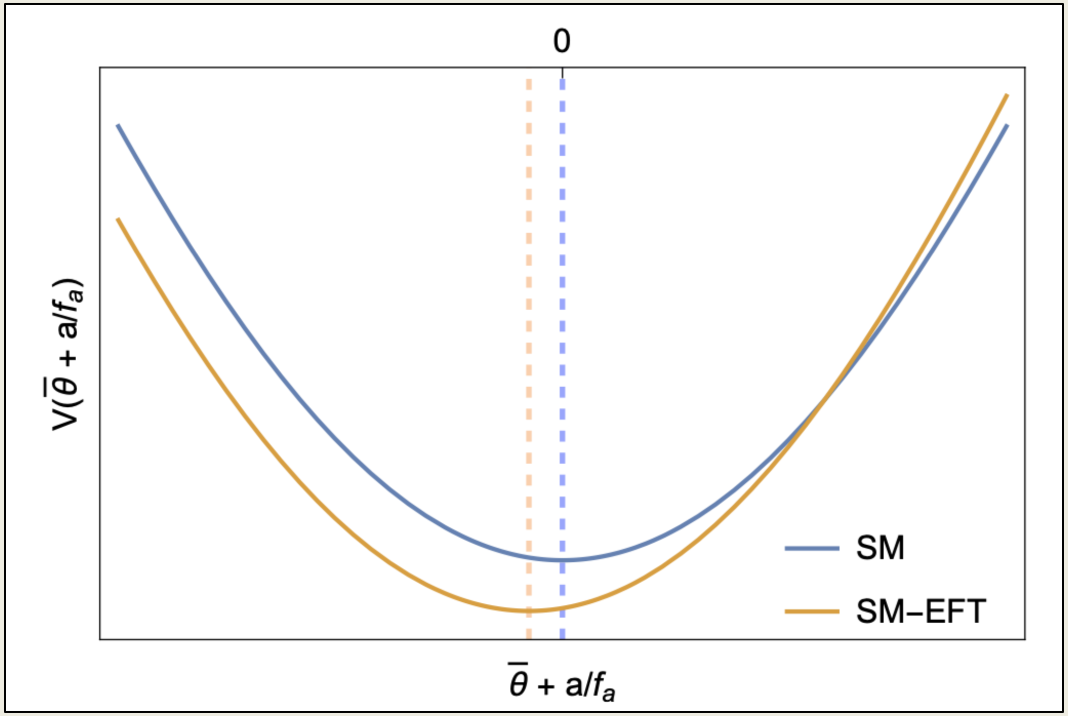
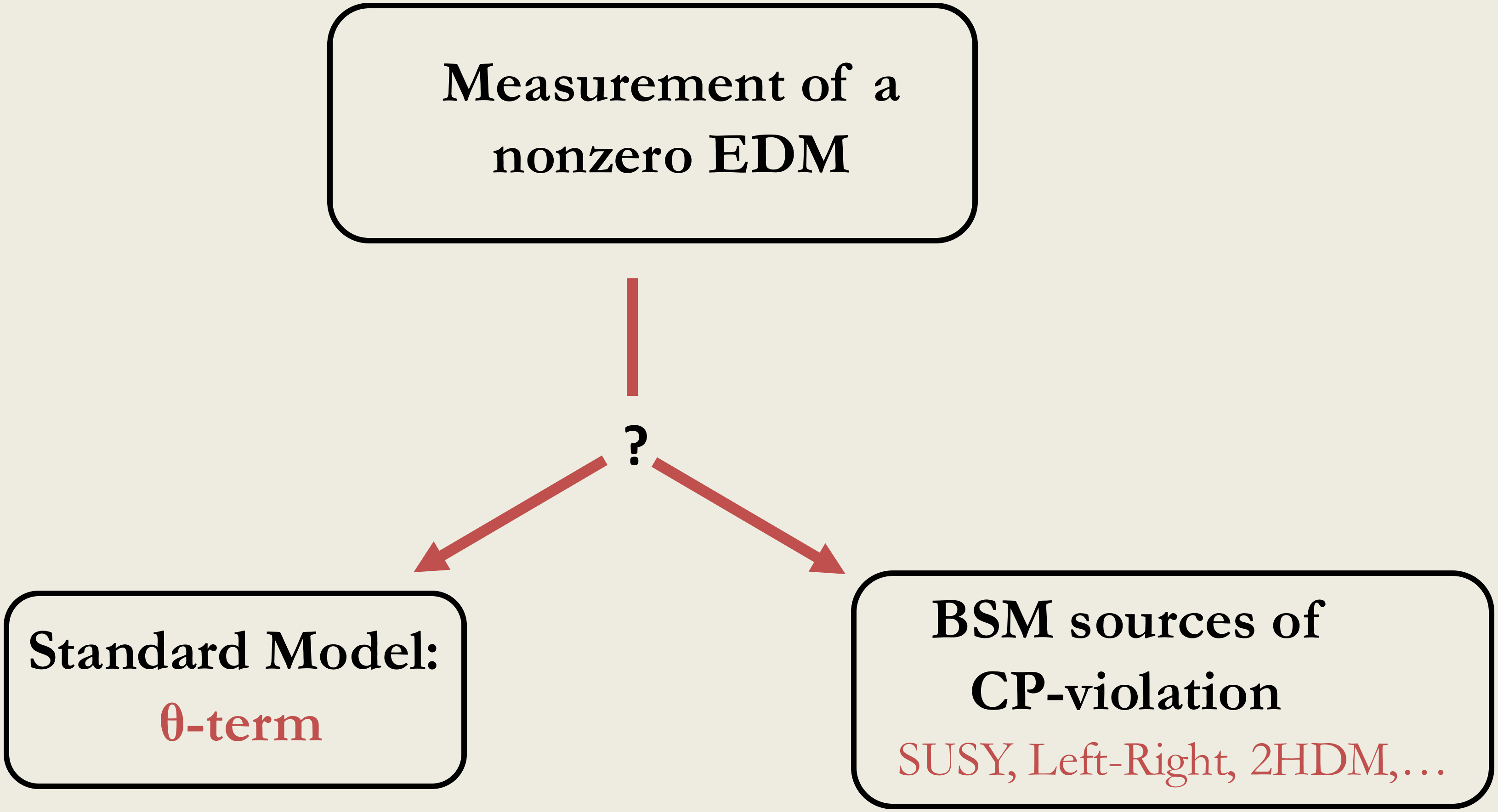


Pospelov, Ritz '05

V. Plakkot, JdV, Dekens, Shain '23

$$\theta \sim \frac{m_\pi^2}{M^2}$$

Explains the smallness but means EDMs can still be dominated by theta



Forseeable future: EDMs are **‘background-free’** searches

Caveat: some recent work claims theta is unphysical

Consequences of the order of the limit of infinite spacetime volume and the sum over topological sectors for CP violation in the strong interactions

Wen-Yuan Ai (Louvain U., CP3), Juan S. Cruz (Munich, Tech. U.), Björn Garbrecht (Munich, Tech. U.), Carlos Tamarit (Munich, Tech. U.)

Jan 20, 2020

rameter $\bar{\theta}$. However, based on the reasoning that the quantization of the topological sectors comes from the fact that the path integral receives its nonvanishing contributions from saddle points of finite action and fluctuations about these, boundary conditions in Euclidean space should be imposed at infinity before the summation over topological sectors. The conclusion then is that the theory of strong interactions with massive fermions does not predict CP-violating phenomena, irrespective of the value of $\bar{\theta}$.

Caveat: some recent work claims theta is unphysical

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Jan 20, 2020

But this paper claims that this is wrong….

Lattice techniques to investigate the strong *CP* problem: lessons from a toy model

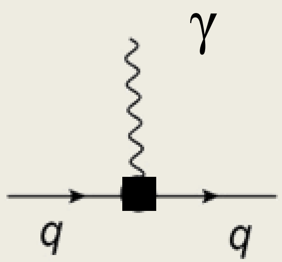
David Albandea, Guilherme Catumba, Alberto Ramos

Onwards to hadronic CPV

Few GeV

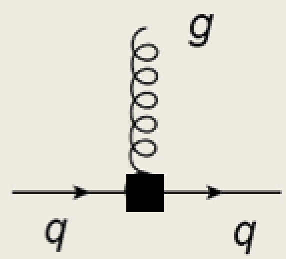
QCD
(θ-term)

+



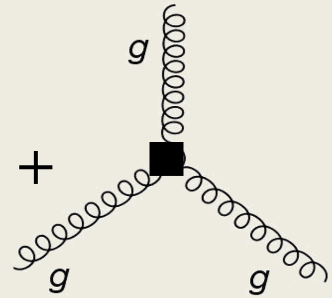
Quark EDM

+

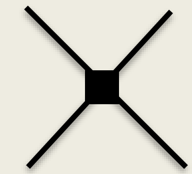


Quark chromo-
EDM

+



Weinberg
operator



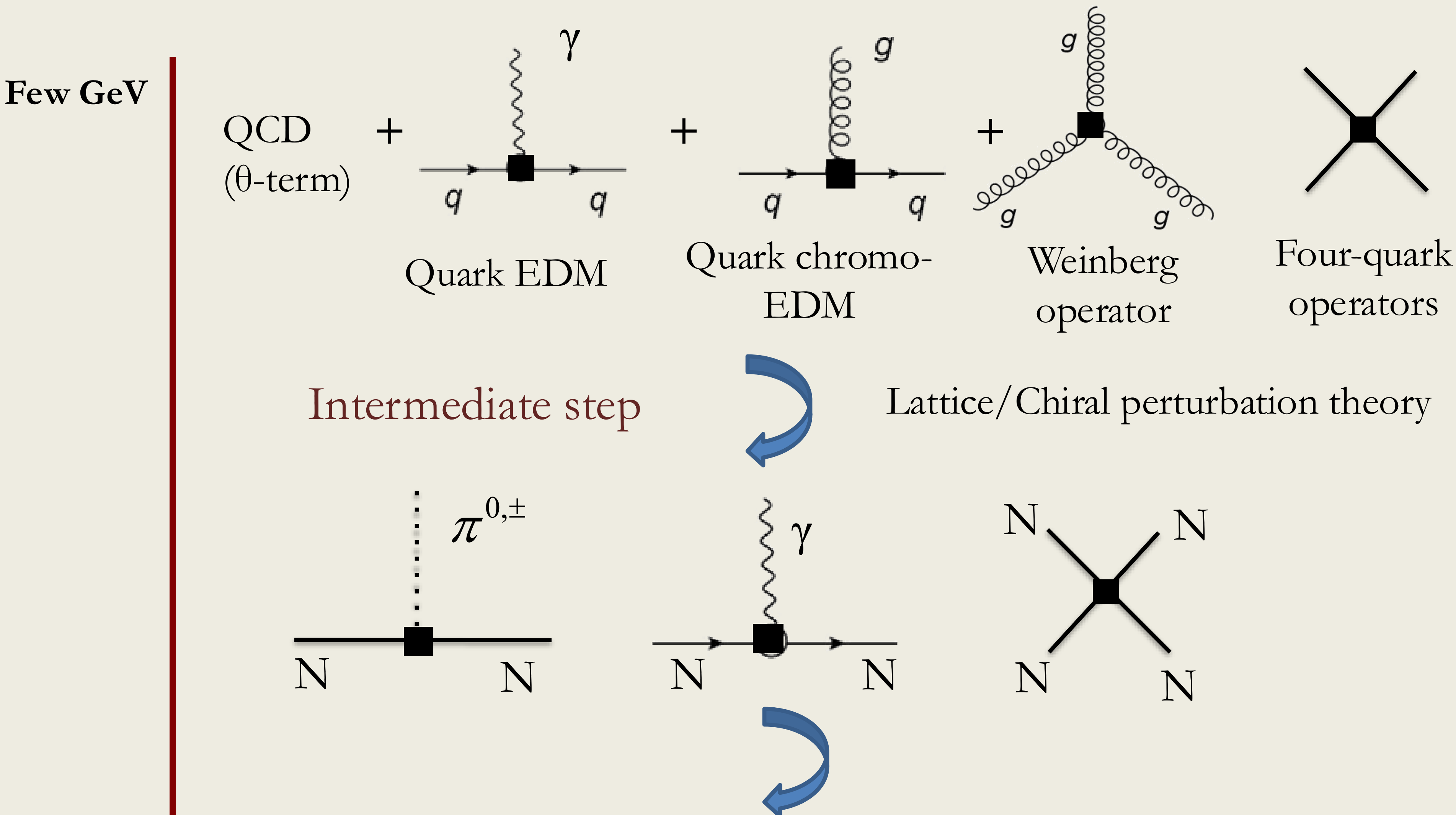
Four-quark
operators

Hadronic/Nuclear CP-violation

Theoretically more difficult

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

Onwards to hadronic CPV

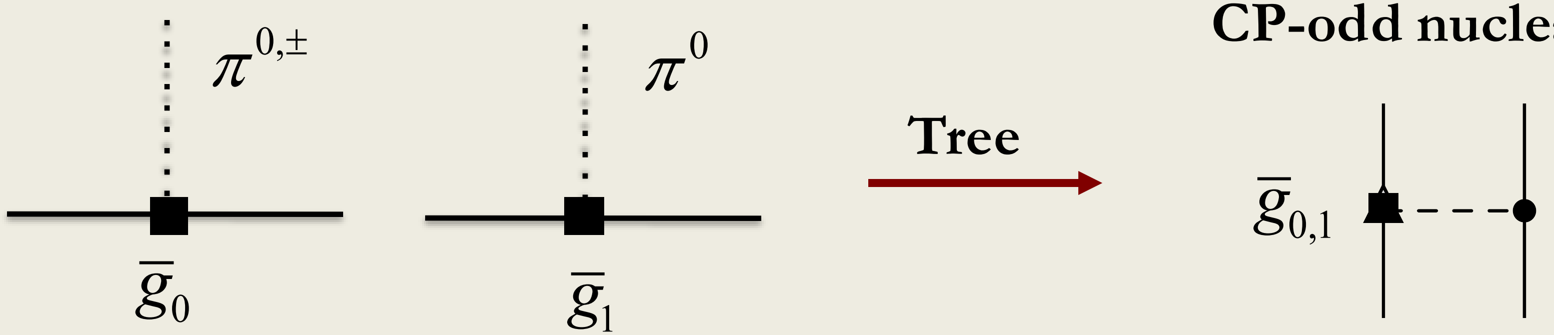


Goal: **Electric dipole moments of nucleons, nuclei, and diamagnetic atoms**

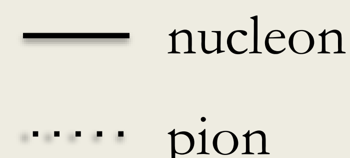
Nucleon and nuclear EDMs up to NLO

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

CP-odd nuclear force



- CPV force dominates EDMs of nuclei and diamagnetic atoms
- **Crucial for current/upcoming measurements of Hg, Xe, Ra, Rn, …**



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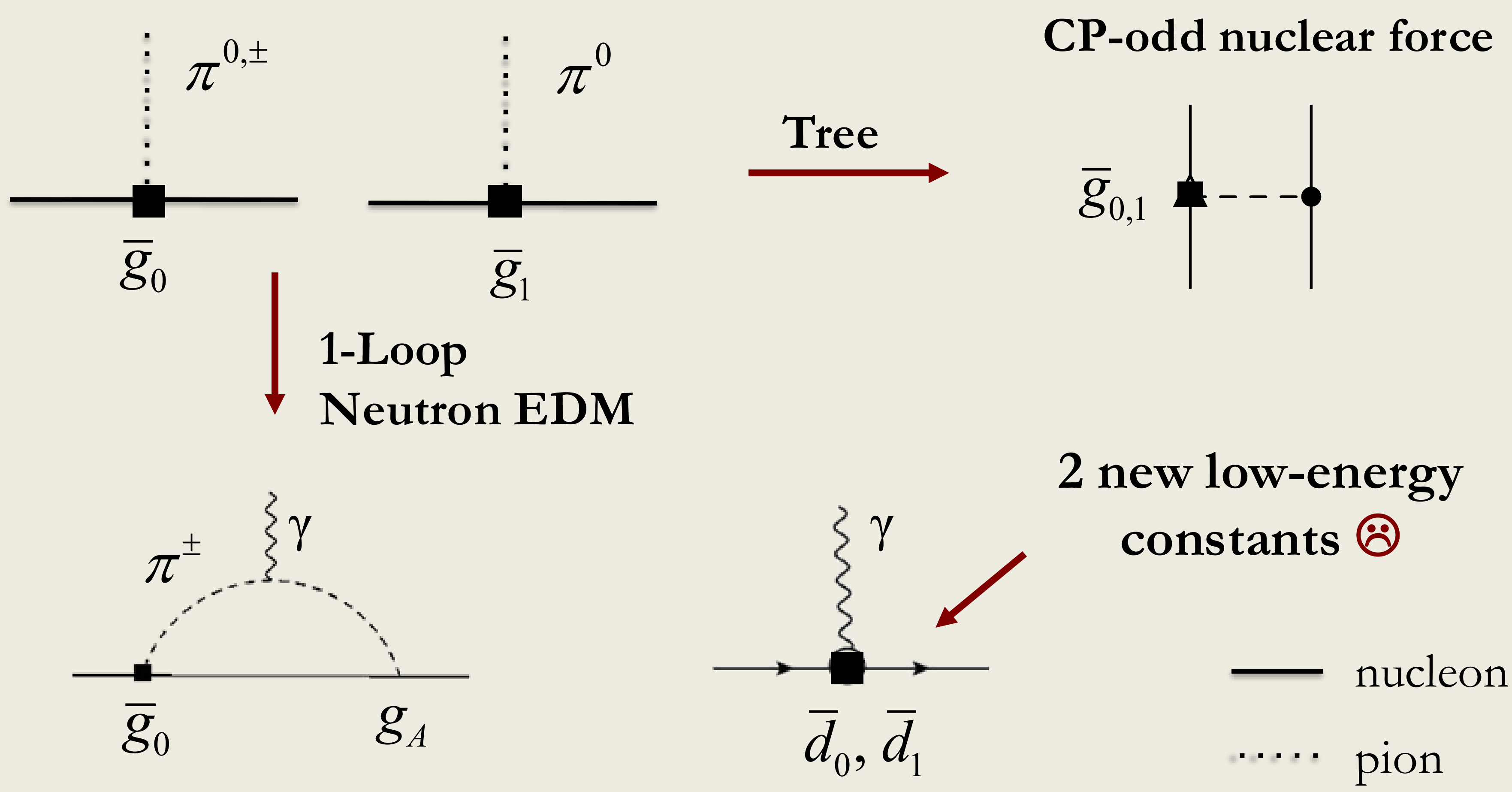


EDMs of charged particles

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

$$d_\mu \leq 1.8\times10^{-19}\ e\,cm \quad (95\%\ C.L.)$$

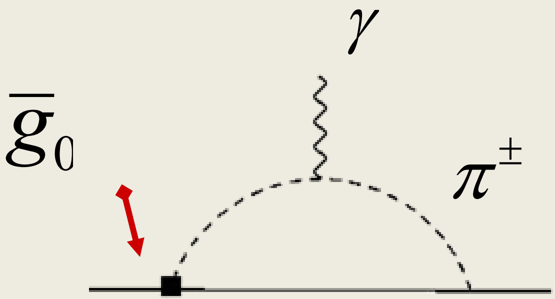
Bennett *et al* (BNL g-2) PRL '09

A compact frozen-spin trap for the search for the electric dipole moment of the muon

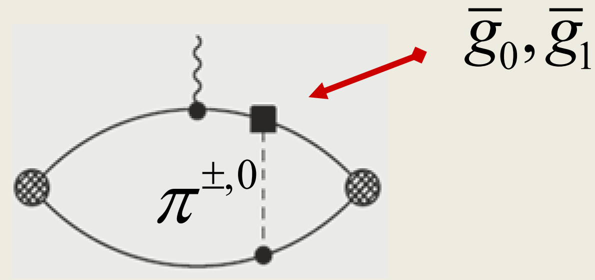
Ring ~ 0.1 m circumference, muEDM at 10^{-22} e cm

P. Schmidt-Wellenburg et et al, 2501.18979

The CPV NN force and nuclear EDMs



Nucleon EDM



Nuclear EDM

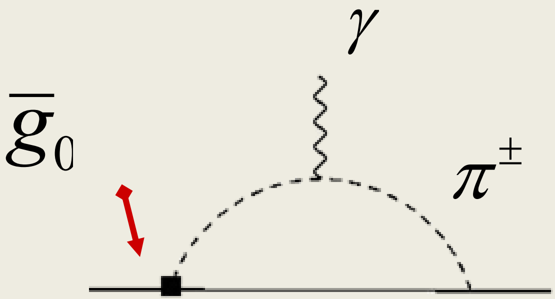
- Tree-level: **no loop** suppression → EDM predictions
- Orthogonal to nucleon EDMs, sensitive to different CPV structures

Recent review: arXiv:2001.09050

Parity- and Time-Reversal-Violating Nuclear Forces

Jordy de Vries[1,2], Evgeny Epelbaum[3], Luca Girlanda[4,5], Alex Gnech[6], Emanuele Mereghetti[7] and Michele Viviani[8*]

The CPV NN force and nuclear EDMs



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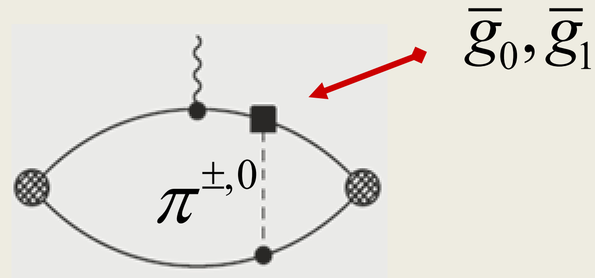


Nuclear EDM

- Tree-level: **no loop** suppression → EDM predictions
- Orthogonal to nucleon EDMs, sensitive to different CPV structures

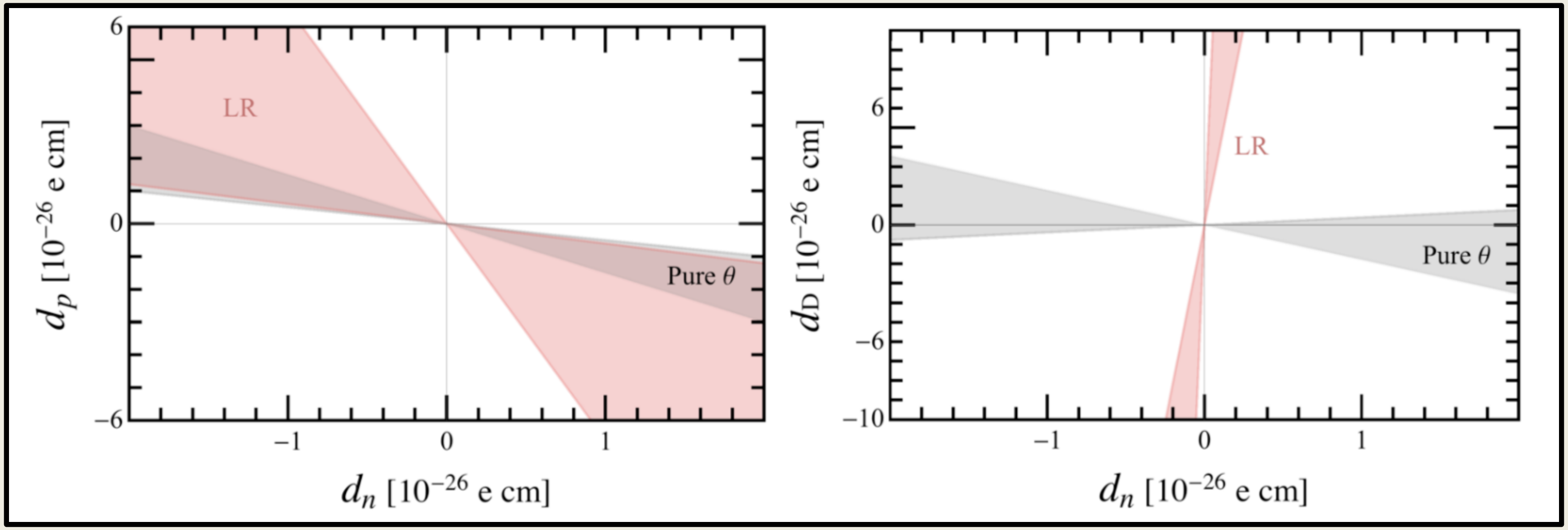
JdV et al '11 '15

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

`	**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	$\cong 0$

Unraveling sources with 2 EDMs

- Compare EDM ratios for theta term and BSM dim-6 four-quark operator



- **Nuclear EDMs complementary to nucleon EDMs**
- Deuteron is just a placeholder: other nuclear systems are similar
- **If we can control nuclear matrix elements !**

Nuclear theory…. Uuugh…

- Very complicated many-body calculation
- Use nuclear model and mean-field theory

$$S = g(a_0 \bar{g}_0 + a_1 \bar{g}_1)\, e\, fm^3 \qquad g = 13.5$$

	a_0 range (best)	a_1 range (best)
^{199}Hg	0.03±0.025 (0.01)	0.030±0.060 (±0.02)
^{225}Ra	-3.5±2.5 (-1.5)	14±10 (6)
^{129}Xe	-0.03±0.025 (-0.008)	-0.03±0.025 (-0.009)

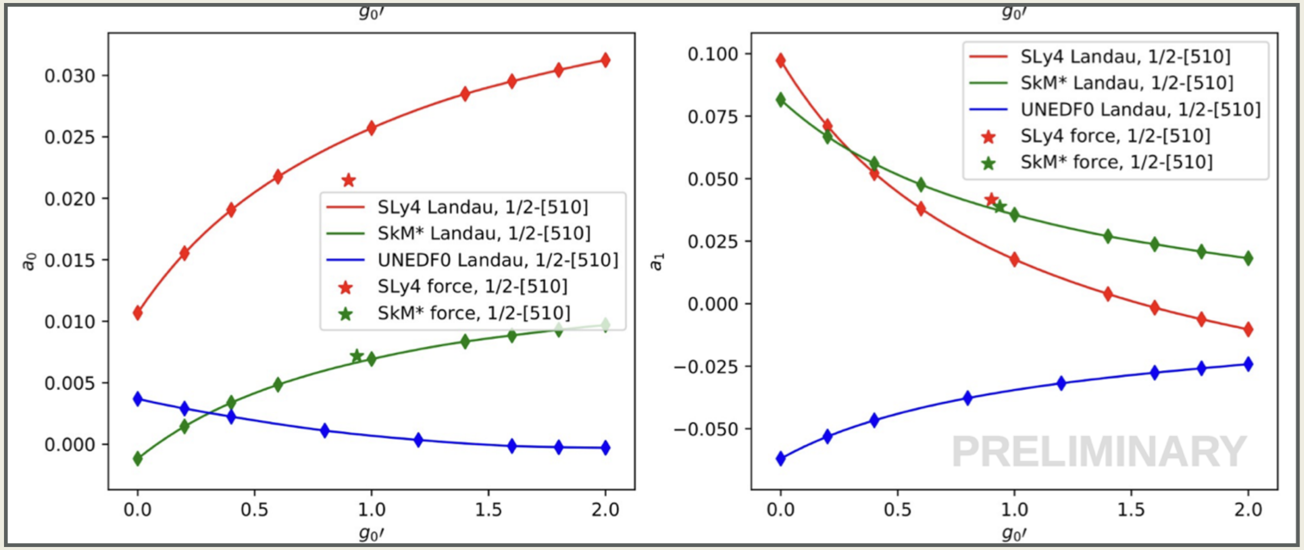
Flambaum, de Jesus,Engel, Dobaczewski,,….

- Based on calculations from various groups
- Hg & Xe: spread >100% (unclear why, difficult 'soft' nuclei)
- **Difficult** to interpret the limits on BSM parameters.

table from review: Engel et al, '13

Nuclear theory…. Uuugh…

- New calculations don't really seem to to help….



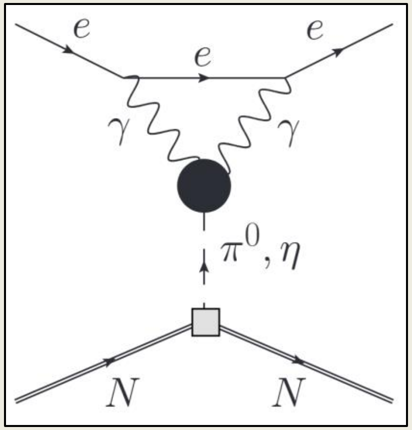
Talk by Markus Kortelainen at ECT* '24

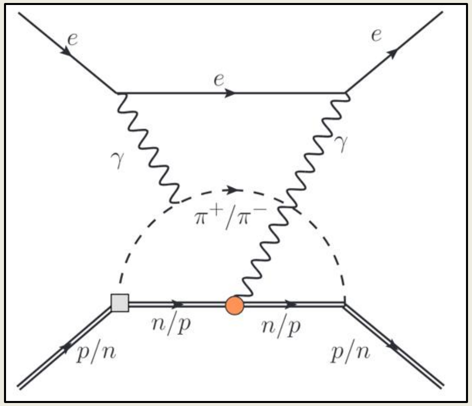
Flambaum, de Jesus,Engel, Dobaczewski,,….

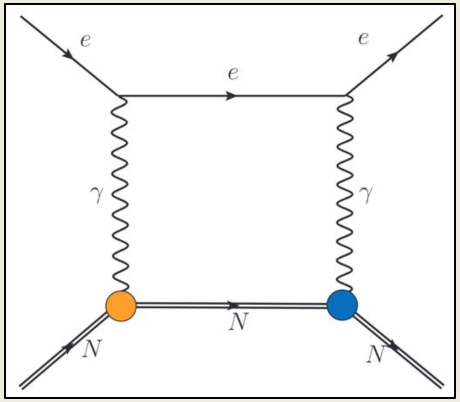
New developments

- Constraining hadronic CP-violation with paramagnetic EDMs

Flambaum, Stadnik, Pospelov, Ritz PRD '19







- Effective field theory calculations to compute induced CP-odd electron-nucleus interactions

Heleen Mulder, JdV, Rob Timmermans '25

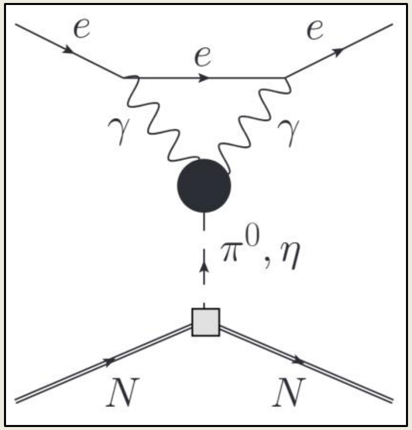
$$C_{\rm SP}^{\rm ME+PL}\frac{G_F}{\sqrt{2}} = \frac{\alpha^2}{4\pi^2}\frac{m_e}{F_\pi m_\pi^2}\left\{\left[\frac{Z-N}{Z+N}\bar{g}_0+\bar{g}_1\right]\mathcal{B}^\pi(0,m_e)+\frac{F_\pi}{\sqrt{3}F_\eta}\frac{m_\pi^2}{m_\eta^2}\bar{g}_{0\eta}\mathcal{B}^\eta(0,m_e)\right.$$
$$\left.+\,\bar{g}_0\frac{\pi g_A m_\pi}{m_N}\frac{Z\mu_n-N\mu_p}{(Z+N)\mu_N}\left[\log\left(\frac{m_\pi}{m_e}\right)+1.77\right]\right\}.$$

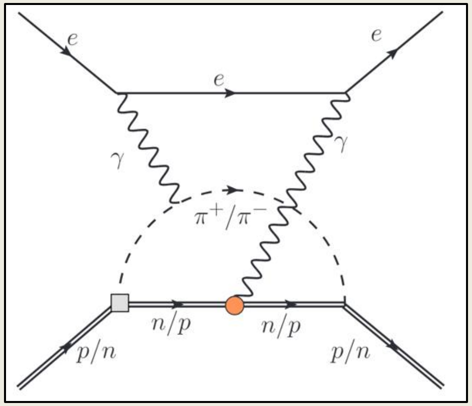
+ work in progress with Lemonia Gialidi

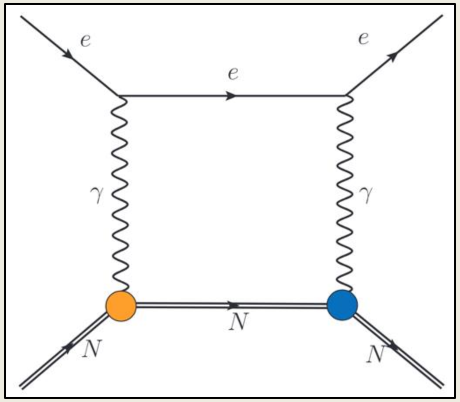
New developments

- Constraining hadronic CP-violation with paramagnetic EDMs

Flambaum, Stadnik, Pospelov, Ritz PRD '19







$$|\bar{\theta}|_{\mathrm{HfF}^+} < 1.5 \cdot 10^{-8}$$

- Polar molecules EDMs not competitive yet, **but experimental progress is rapid.**