Interpreting Electric Dipole Moments

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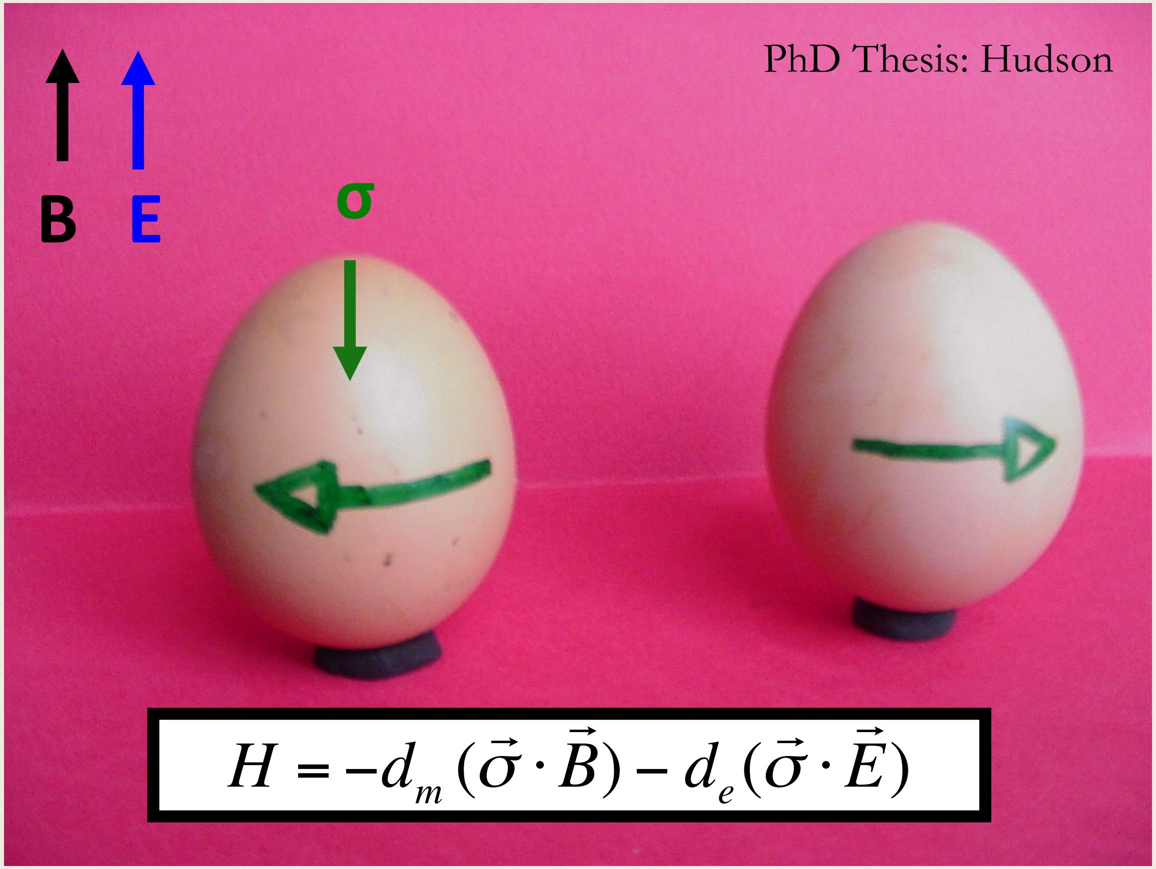
Outline

- **Part I: Why do we (I?) care about dipole moments ?**
- Part II: Interpreting Electric Dipole Measurement
- Part III: Interplay with high-energy experiments and cosmology

Symmetry considerations

- Electric and Magnetic Dipole Moment (EDM and MDM)



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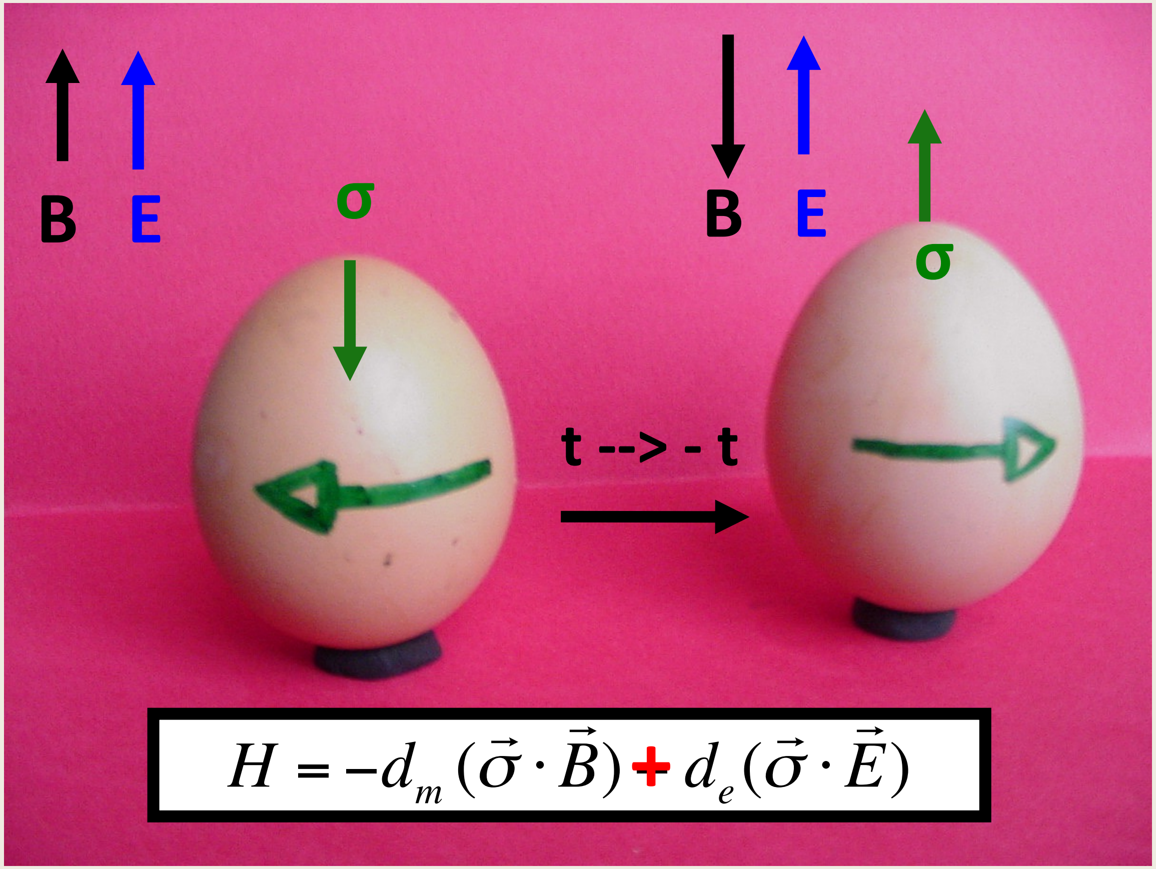
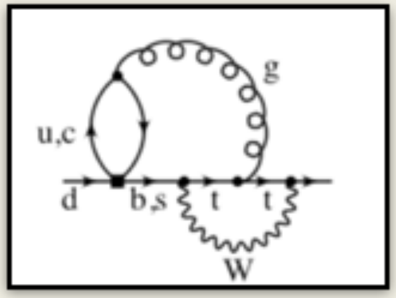


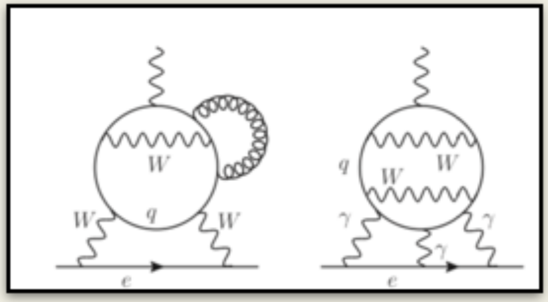
- The EDM, breaks time-reversal symmetry ! No EDM in QED at all
- **CPT theorem:** T violation ⟷ CP violation

EDMs from the Standard Model

- No EDMs at one loop
- At two loops: individual diagrams contribute but sum vanishes
- Quark EDMs induced at three loops



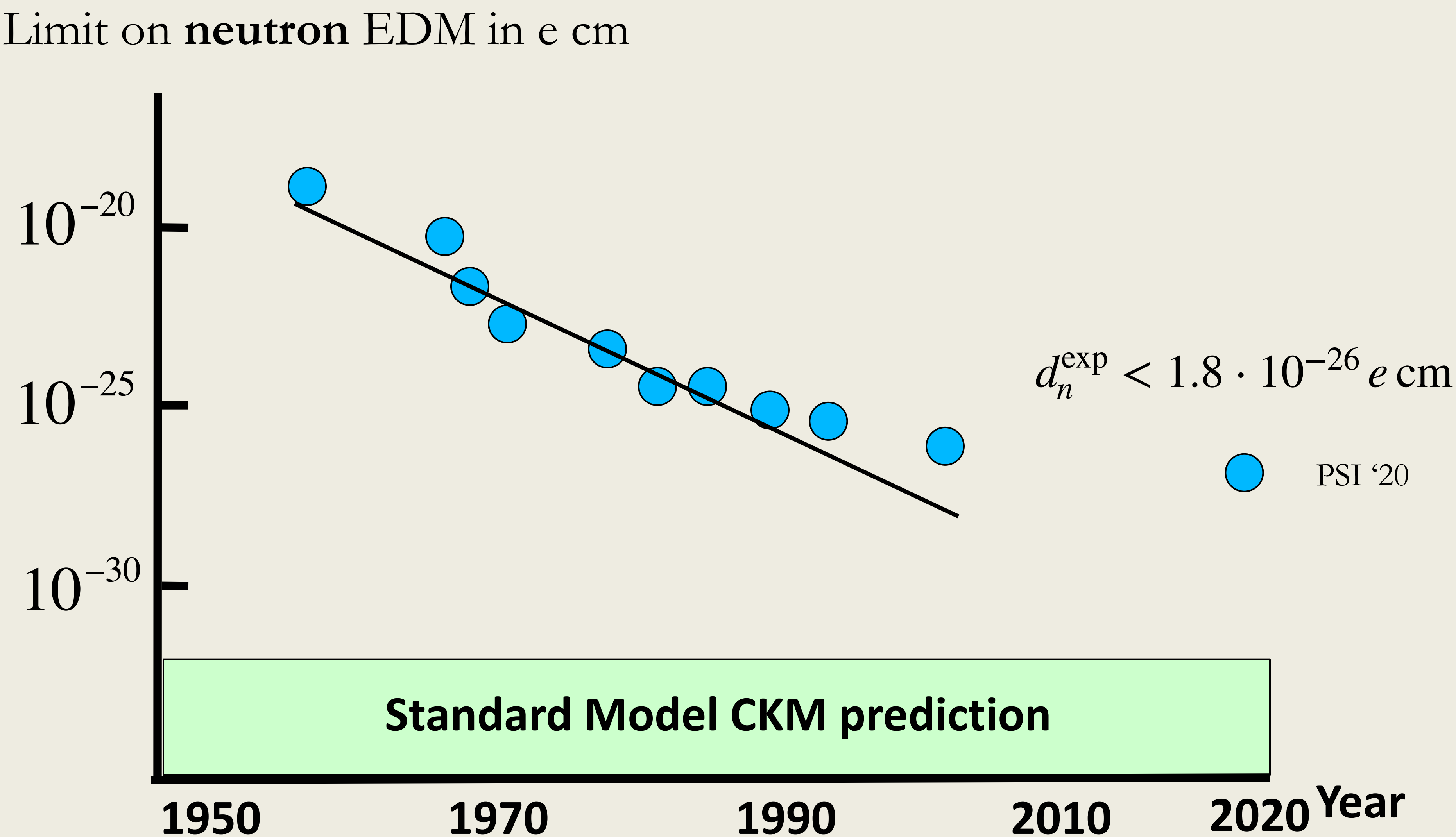
$$d_q \sim 10^{-34} e\,\mathrm{cm}$$



- Electron EDM at 4 loops
- Compare with magnetic dipole moment:

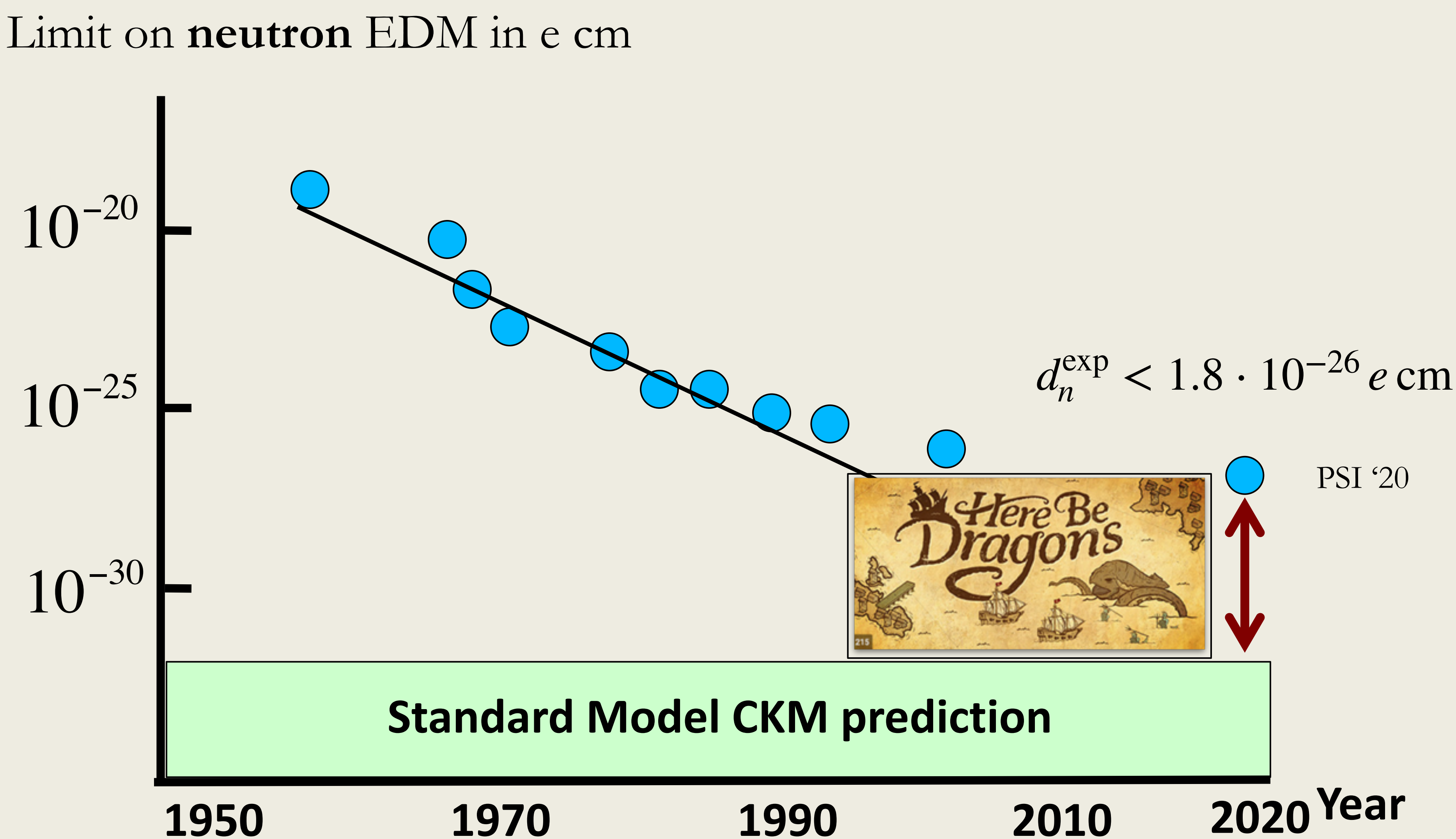
- **Disclaimer 1:** electron EDM can be a bit larger due to hadronic loops
- **Disclaimer 2:** EDMs of composite objects can be larger (still small)

Electric dipole moments and the CKM matrix



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

Electric dipole moments and the CKM matrix

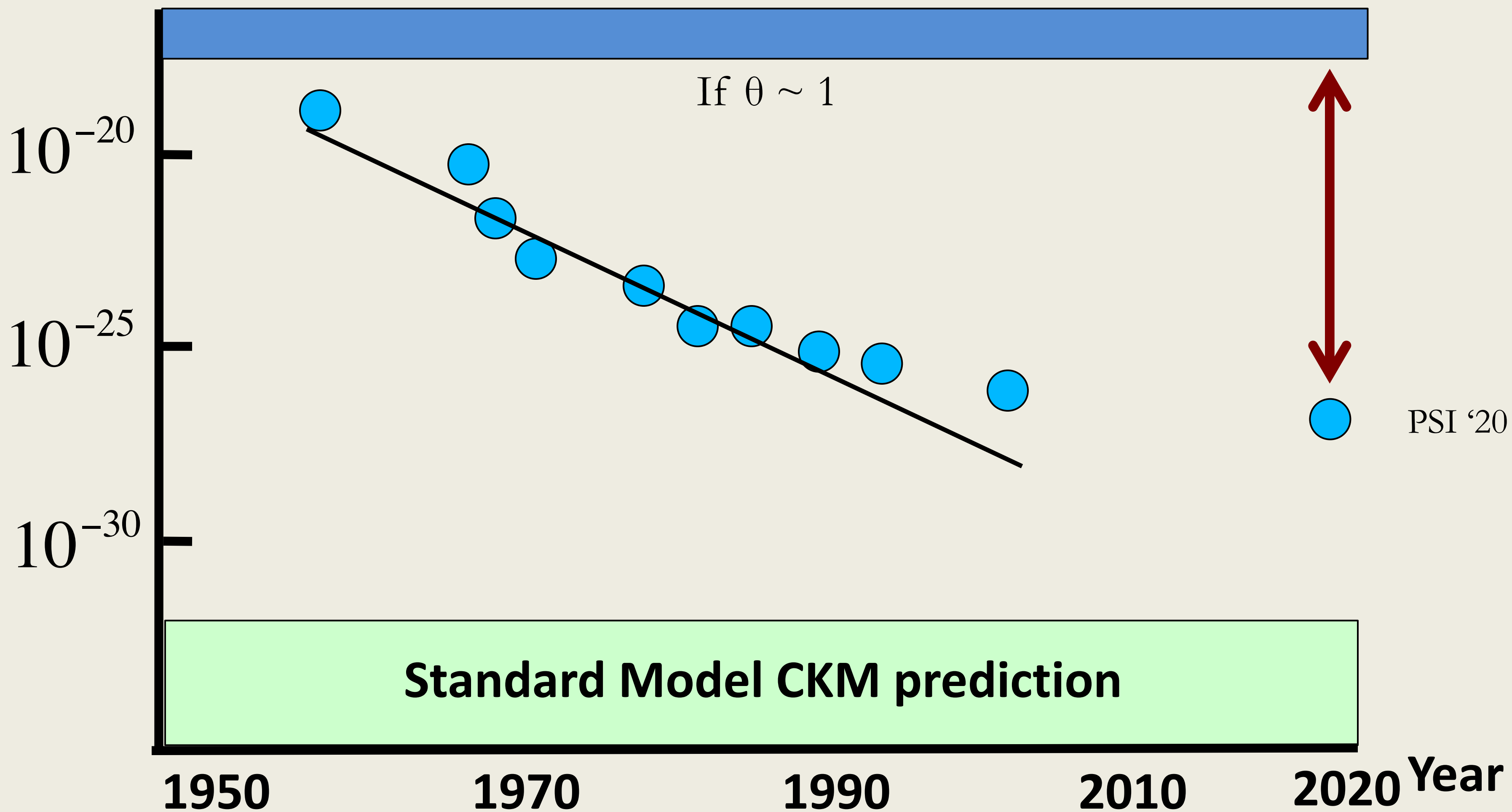


The strong CP problem

't Hooft '76, '78

$$\theta\,\varepsilon^{\mu\nu\alpha\beta}G_{\mu\nu}G_{\alpha\beta}$$

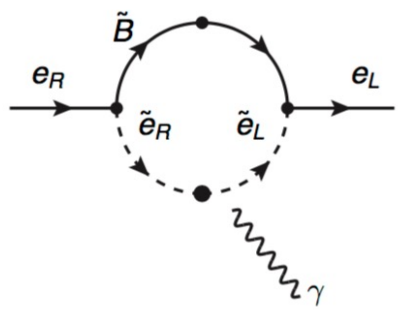
Limit on **neutron** EDM in e cm



Neutron EDM forces θ < 10^{-10} (the strong CP problem)

Unknown dragons

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

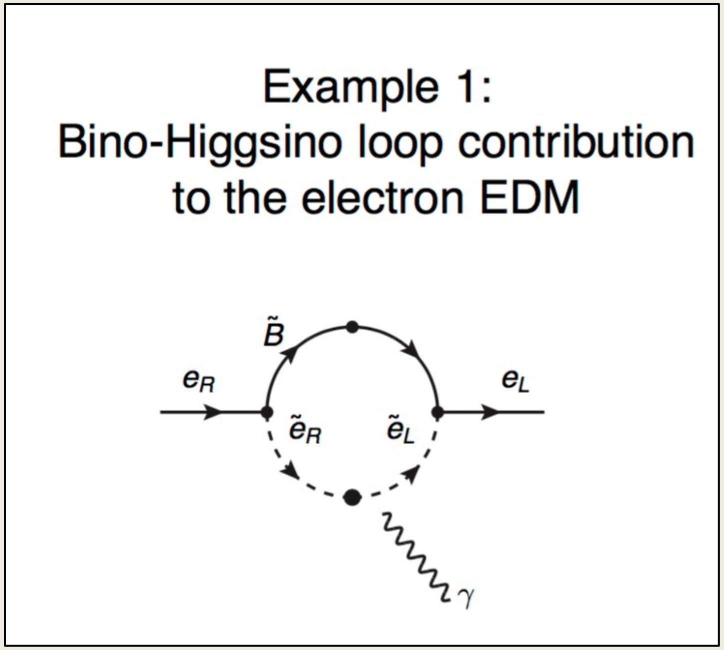


- CPV phase already at one-loop !
- **Typical size of EDM**

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

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

Unknown dragons



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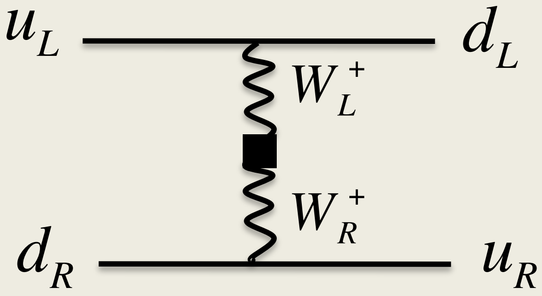
- **In left-right symmetric models**

$$L = i\Xi(\bar{u}_R\gamma_\mu d_R)(\bar{u}_L\gamma_\mu d_L) + \text{h.c.}$$

$$\Xi \sim \sin\alpha / \Lambda^2$$



- Tree-level CP violation, EDMs probe ~ 100 TeV scale

Very active experimental field

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
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HfF^{+}	Boulder	4.1×10^{-30}	90	$-1.3(2.0)(0.6) \times 10^{-30}$	2022
n	PSI	1.8×10^{-26}	90	$0.0(1.1)(0.2) \times 10^{-26}$	2020
^{129}Xe	UMich	4.8×10^{-27}	95	$0.26(2.3)(0.7) \times 10^{-27}$	2019
^{199}Hg	UWash	7.4×10^{-30}	95	$-2.2(2.8)(1.5) \times 10^{-30}$	2016
^{225}Ra	Argonne	1.4×10^{-23}	95	$4(6.0)(0.2) \times 10^{-24}$	2016
muon	E821 BNL g−2	1.8×10^{-19}	95	$0.0(0.2)(0.9) \times 10^{-19}$	2009

+ new electron, muon, neutron, proton, Xe, Ra, Rn, **BaF**….. experiments

- **How do we interpret these limits ?**

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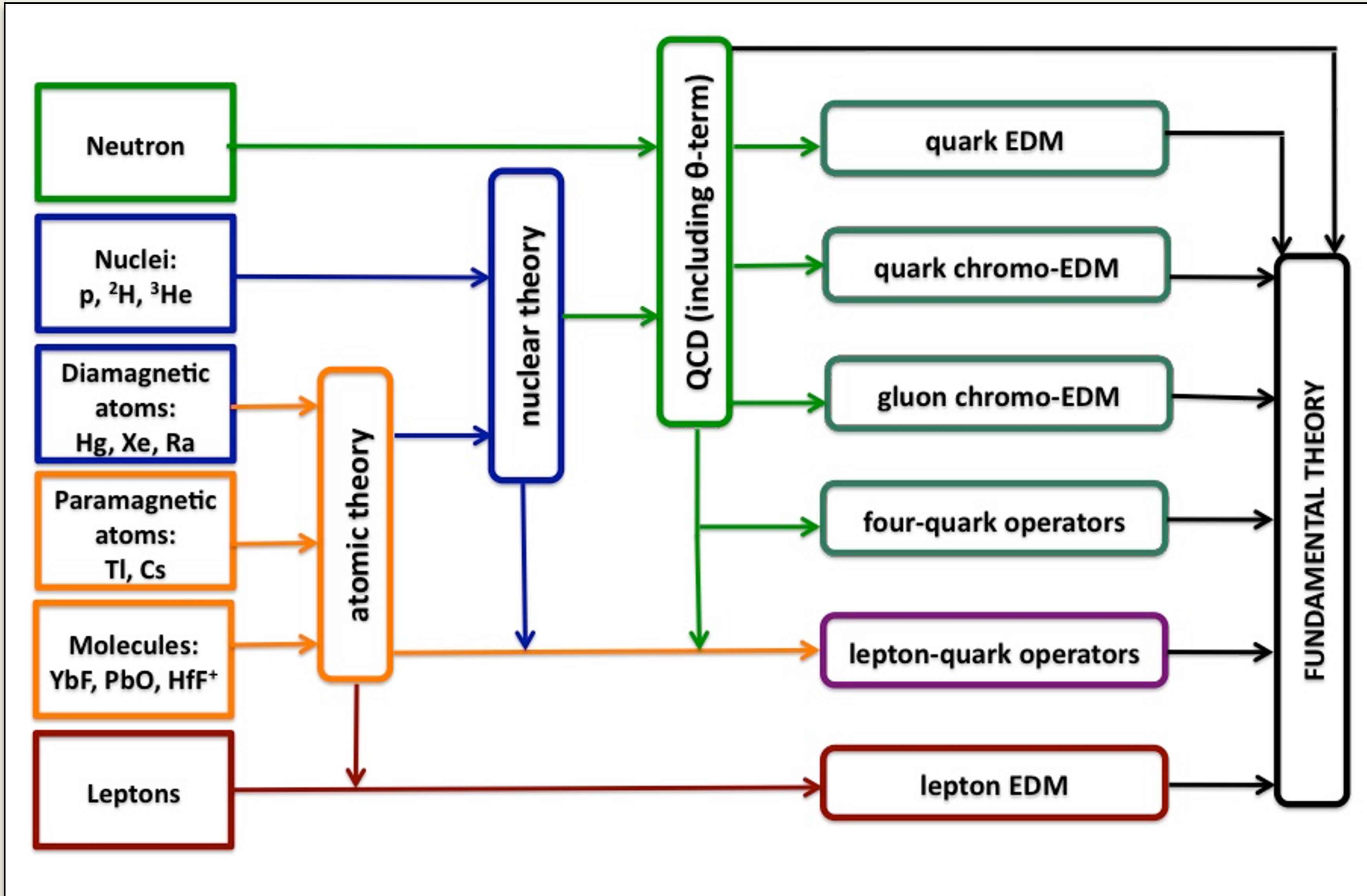
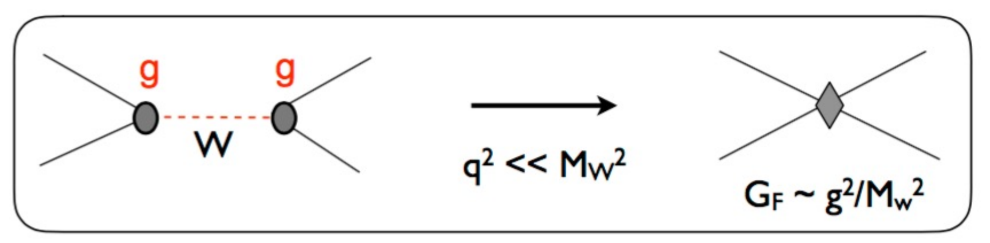
The EDM metromap



Heavy BSM physics and the SM EFT

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

Fermi's theory:



- We don't need 'high-energy details', the W boson, at low energies !

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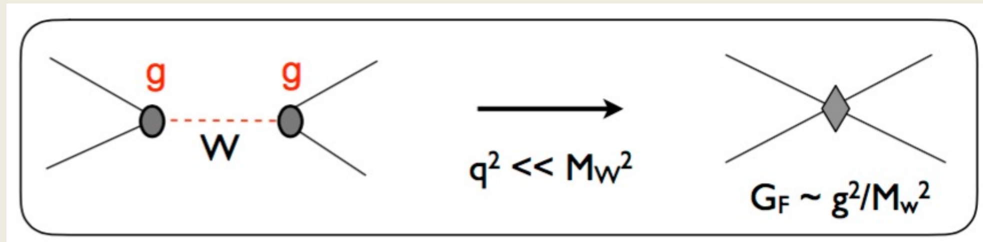

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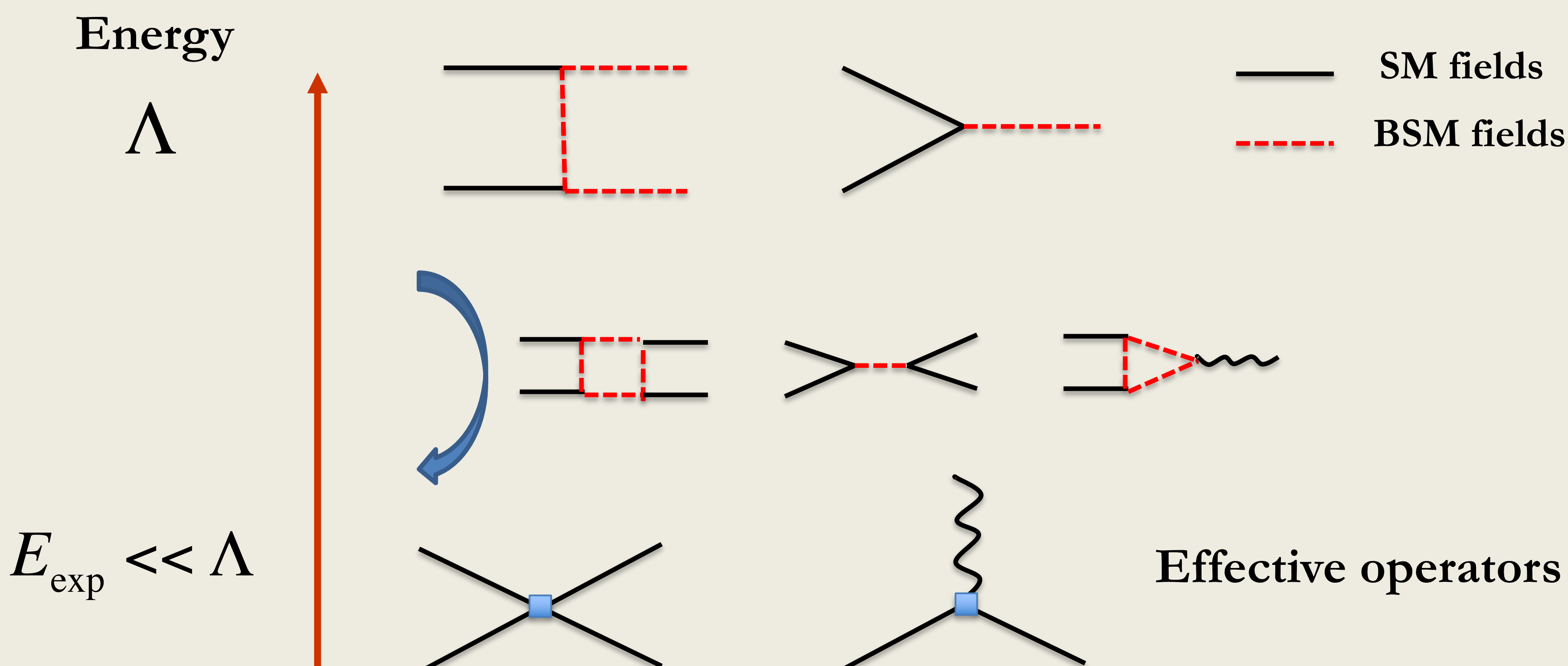

Standard model as an EFT

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

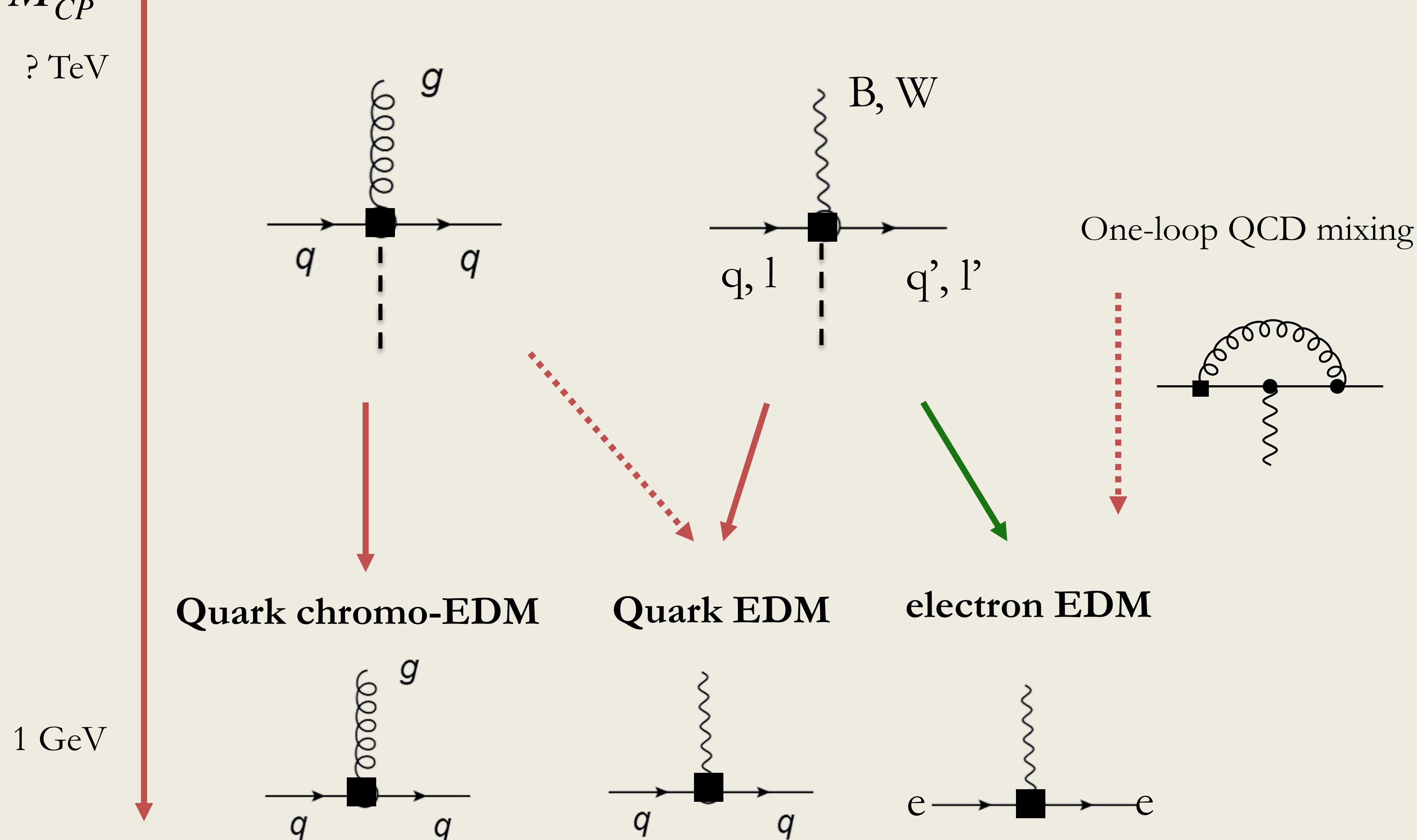
$$\left(\frac{E}{\Lambda}\right)^n$$ so at low energy: lowest-dim operators are relevant !

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

Fermion dipole operators

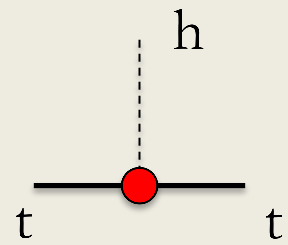
Electric and magnetic dipoles: **canonical dimension five**

Chirality flip → $SU_L(2)$ gauge symmetry requires Higgs



Example

Λ



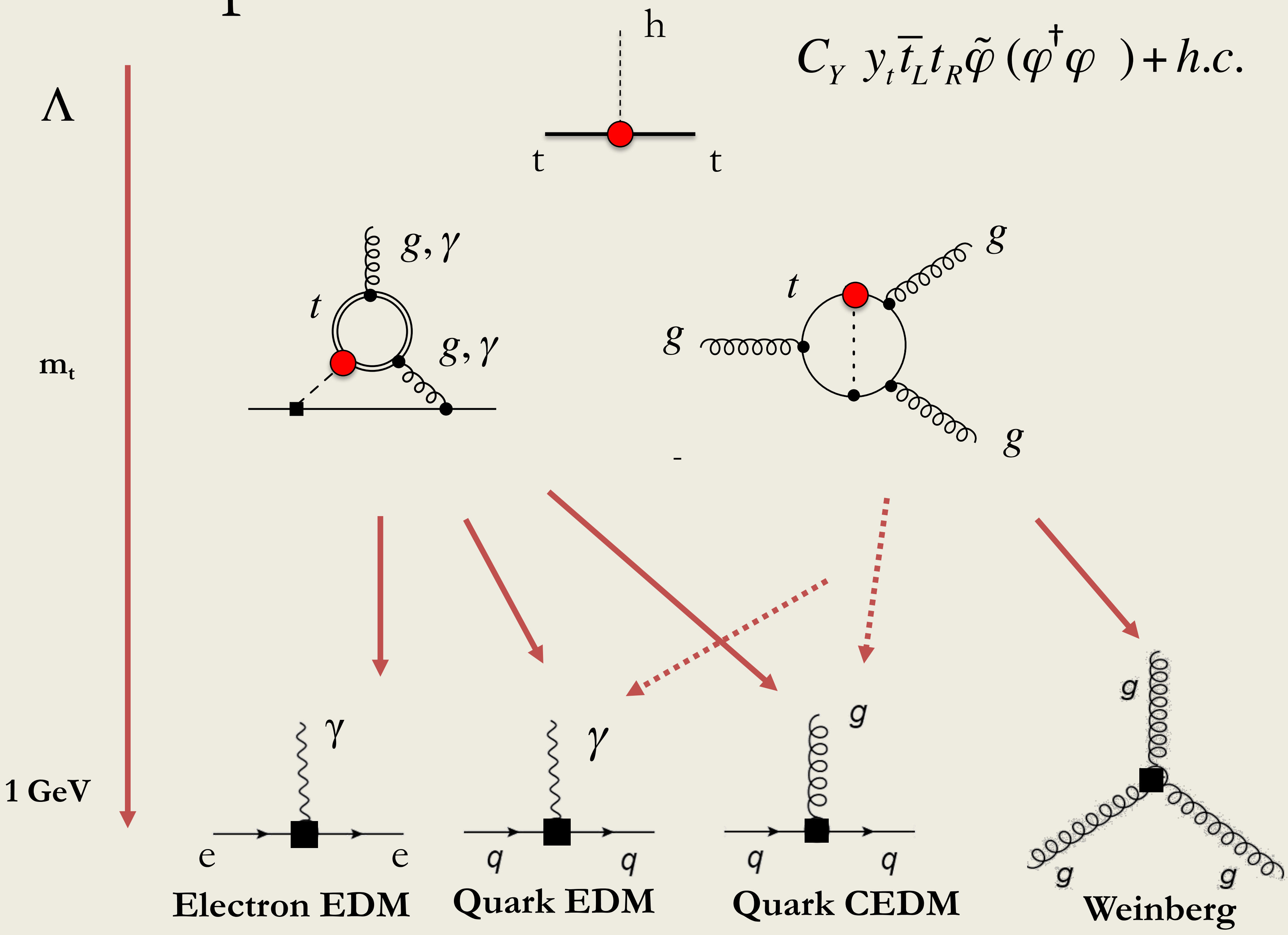
$$C_Y\, y_t \overline{t}_L t_R \tilde{\varphi} (\varphi^\dagger \varphi\ ) + h.c.$$

$\mathbf{m_t}$

1 GeV

Example

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

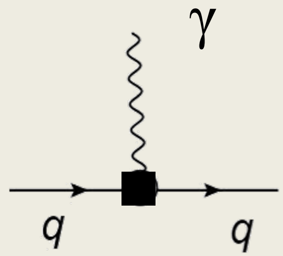


When the dust settles…..

Few GeV

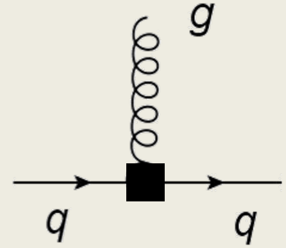
QCD
(θ-term)

+



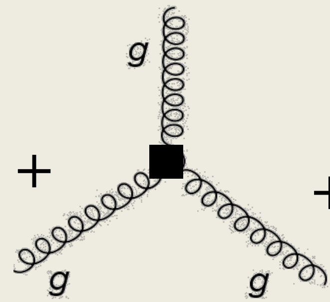
Quark EDM

+



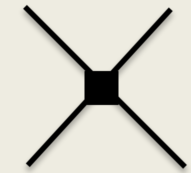
Quark chromo-EDM

+



Gluon chromo-EDM

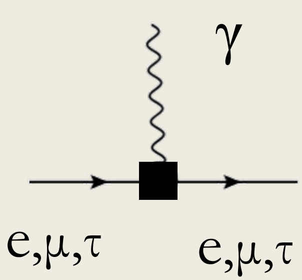
+

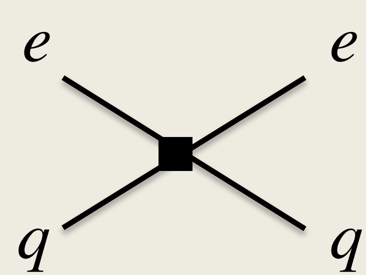


4quark operators

Different beyond-the-SM models predict different **dominant** operator(s)

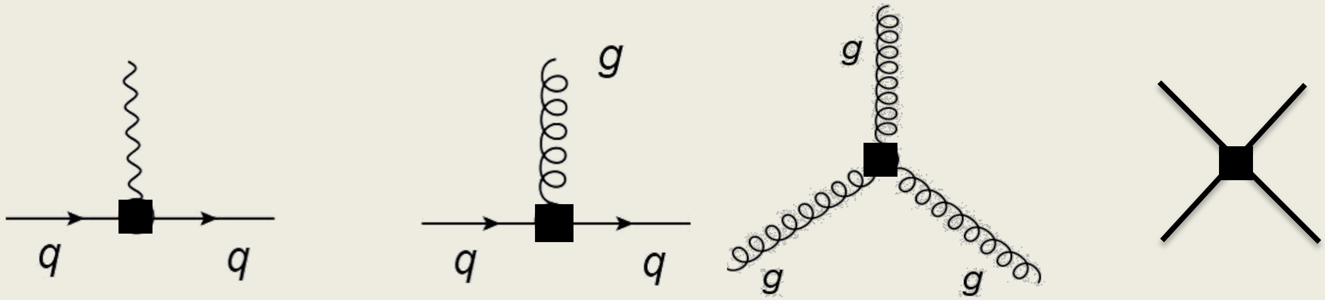
EFT p.o.v: just look at these low-energy structures





Traditional division of labor

QCD
(θ-term)



‘Diamagnetic’ EDMs. No electron spin and nonzero nuclear spin.

- Examples: neutron, deuteron, atoms such as ^{199}Hg, ^{225}Ra

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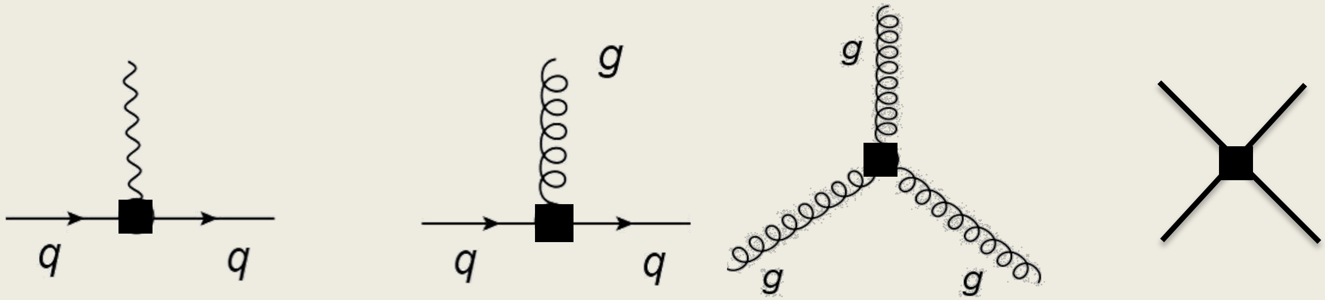

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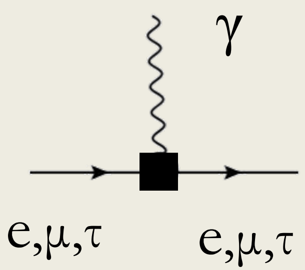

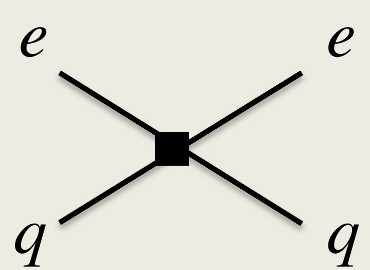

'Paramagnetic' EDMs. Nonzero electron spin and zero nuclear spin.

- Examples: ^{205}Tl, Molecules such as HfF, ThO, BaF, and muon EDM

Paramagnetic systems

e

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

Paramagnetic systems

e

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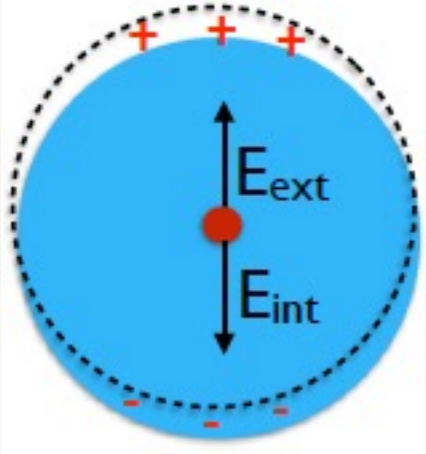
- **Why not simply use Hydrogen ?**

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

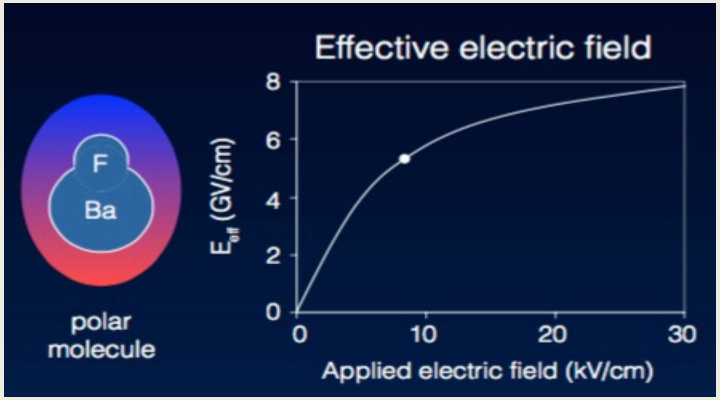


- Assumption : **non-relativistic constituents**
- **Invalid in heavy atoms/molecules**

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

Sandars '65

Probing the leptonic interactions

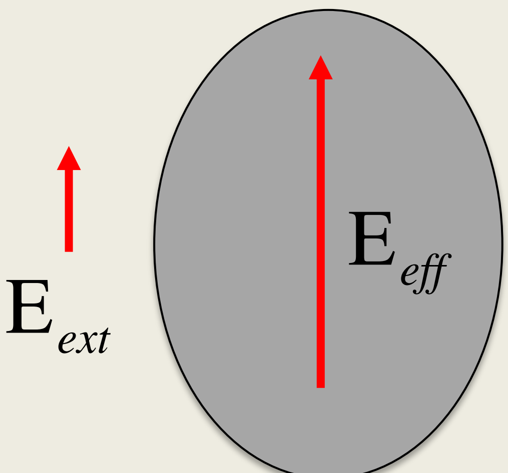


Polar molecules:

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

$$\mathrm{E}_{eff} \propto 10^{6} E_{ext}$$

Requires high-accuracy electronic structure computations

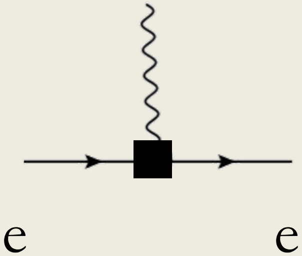


$$\Delta E_{ThO} = (80 \pm 10) \cdot GeV \left(\frac{d_e}{e\ cm} \right)$$

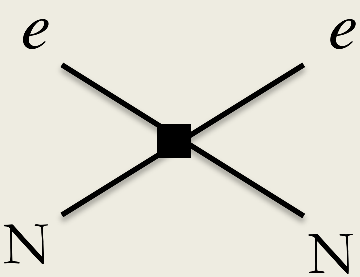
$$d_e < 1.4 \cdot 10^{-29}\ e\ cm$$ Andreev et al ’18

Similar story for HfF with factor 2 better limit

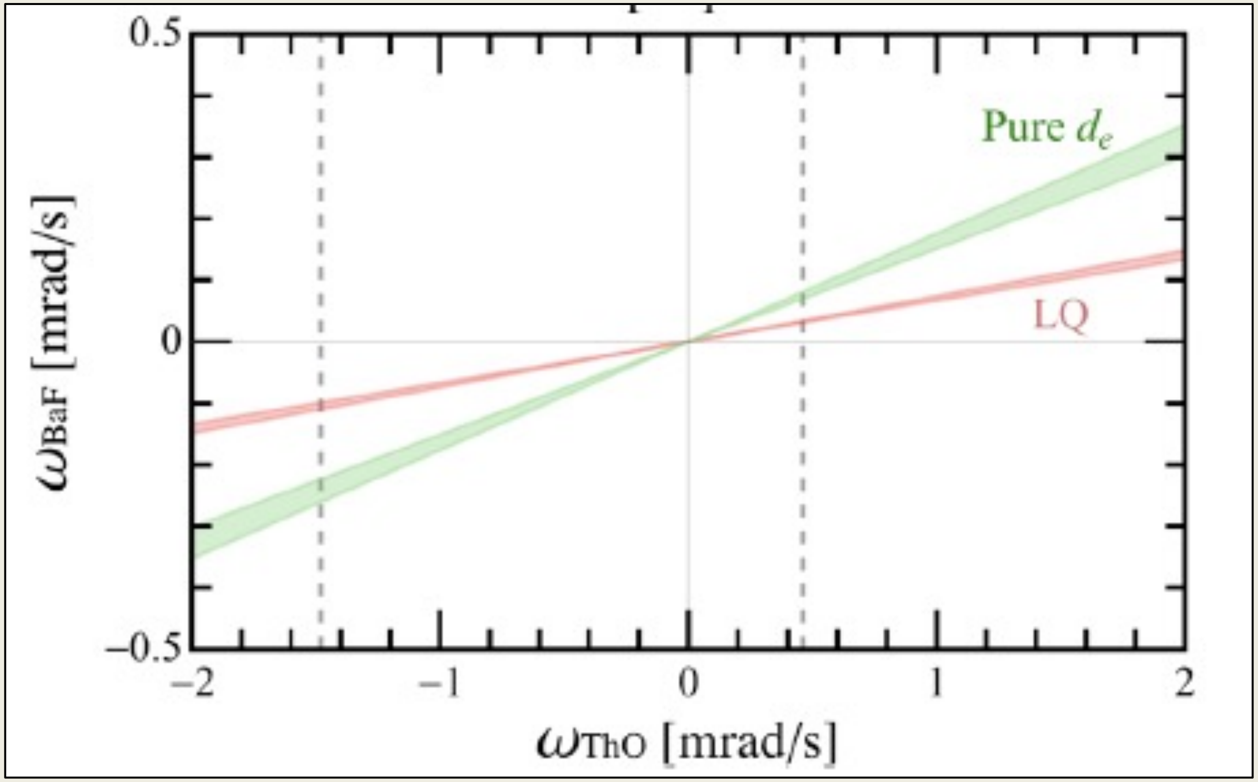
Complementary measurements



Electron EDM

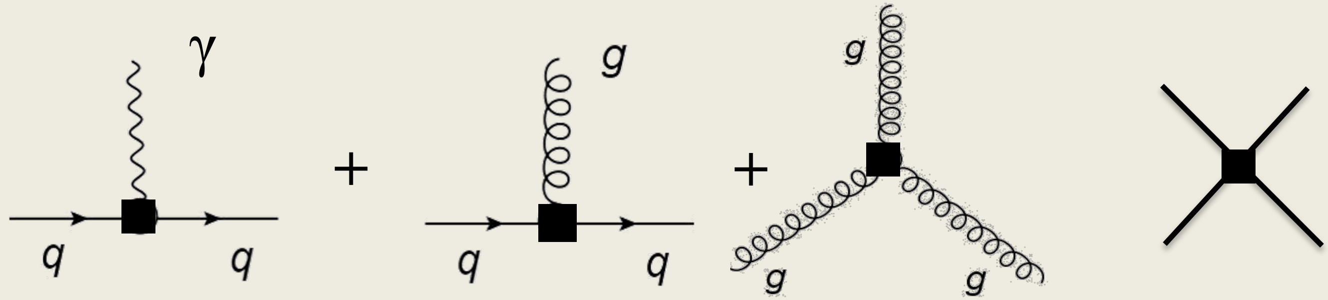


Electron-Nucleus interactions



Onwards to hadronic CPV

Few GeV

QCD (θ-term) + 

Quark EDM

Quark chromo-EDM

Weinberg operator

Four-quark operators

Hadronic/Nuclear CP-violation

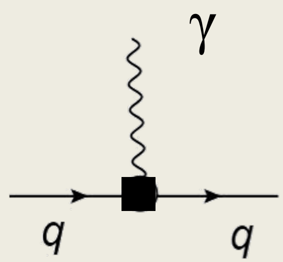
Theoretically more difficult

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

Onwards to hadronic CPV

Few GeV

QCD
(θ-term) +



Quark EDM

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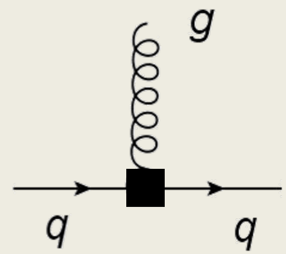

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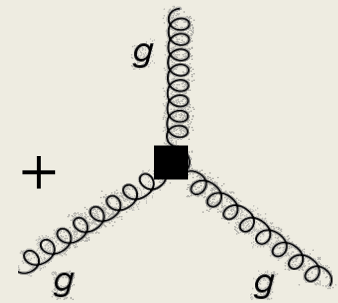
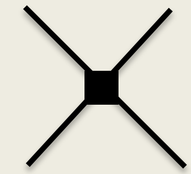


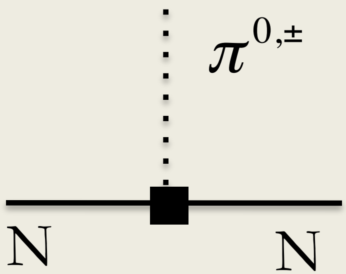
Weinberg operator

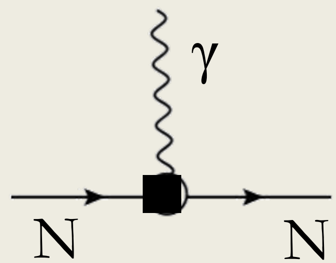


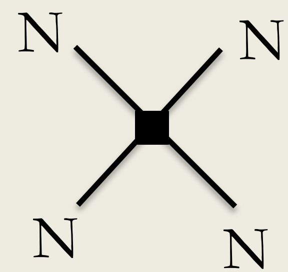
Four-quark operators

Intermediate step

Lattice/Chiral perturbation theory







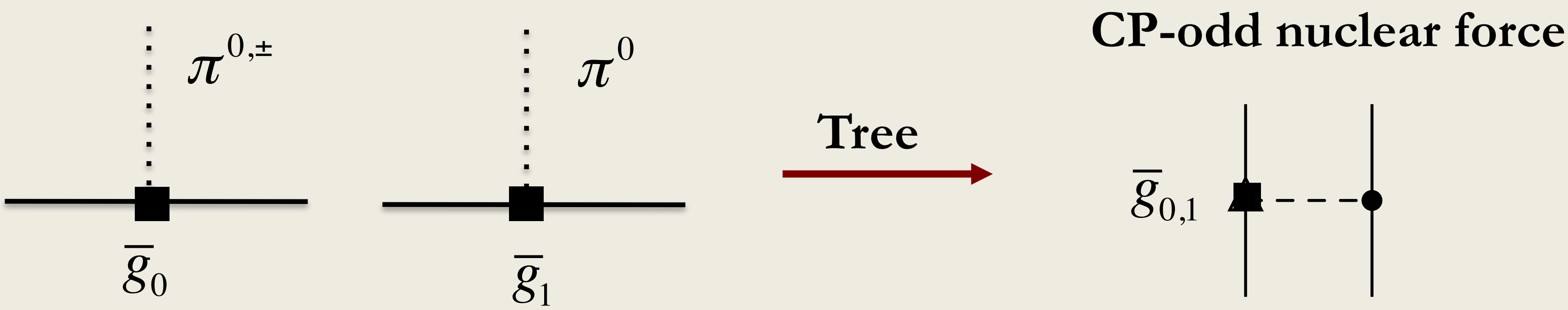
Mereghetti et al '10, JdV et al' 12, Bsaisou et al '15

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

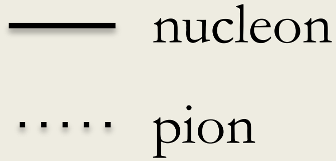
Nucleon and nuclear EDMs up to NLO

- **Chiral power counting:** handful interactions dominate hadronic EDMs

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



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



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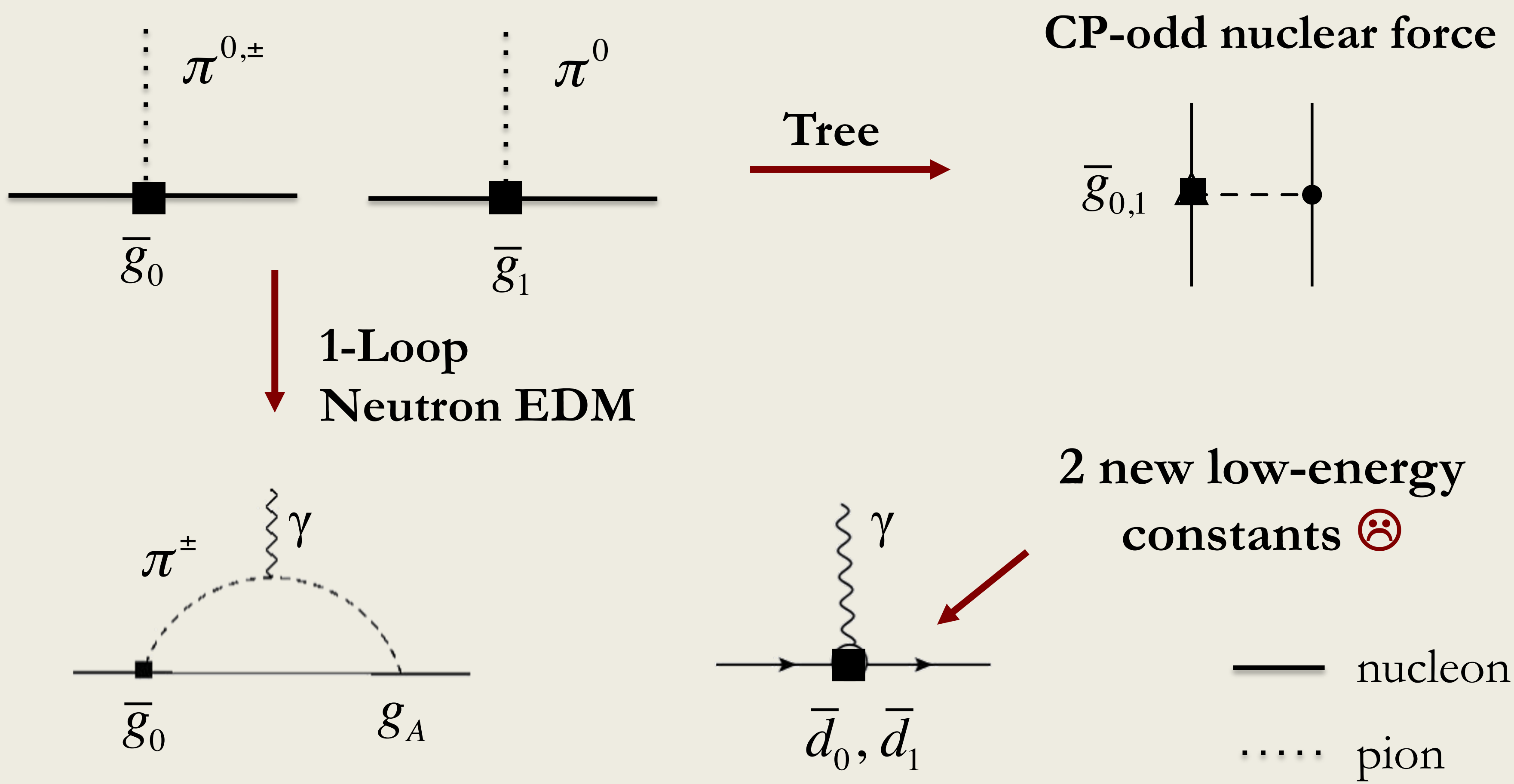
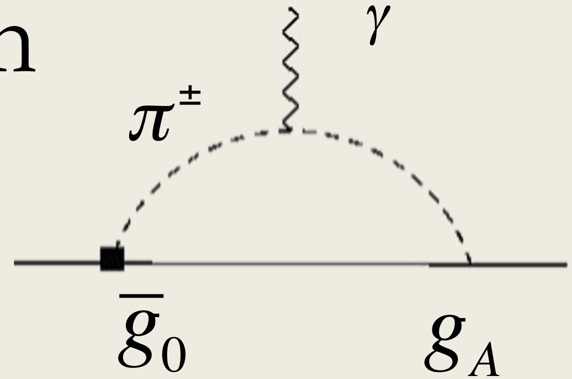


The strong CP problem



Neutron EDM

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

$$\mu = m_N$$

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

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

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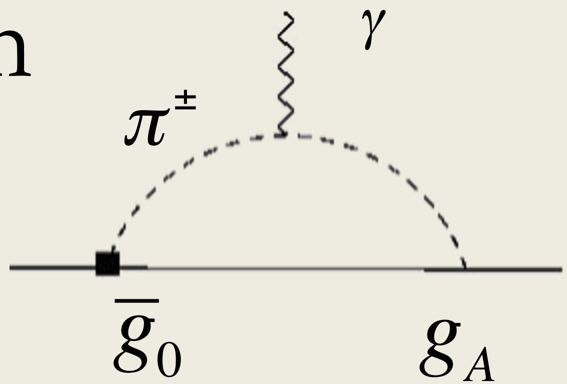

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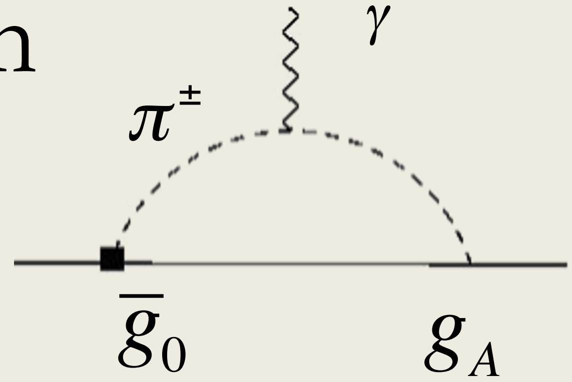
- Experimental constraint: $\longrightarrow$ $\bar{\theta} < 10^{-10}$

A proper assessment requires a non-perturbative calculation !

Lattice QCD (Shindler et al '19) $\quad d_n = -(1.52 \pm 0.7)\cdot 10^{-16}\, e\,\bar{\theta}$ cm

(Liang et al '23) $\quad d_n = -(1.48 \pm 0.4)\cdot 10^{-16}\, e\,\bar{\theta}$ cm

The strong CP problem



Neutron EDM

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

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

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

A proper assessment requires a non-perturbative calculation !

Large uncertainties for dimension-six operators (quark chromo-EDM, four-quark, Weinberg, etc)

EDMs of charged particles

Farley *et al* PRL '04

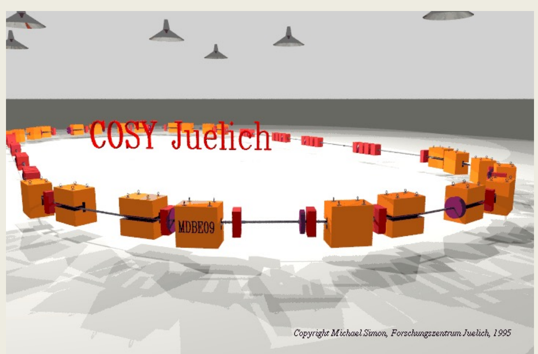
Anomalous magnetic moment

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….)

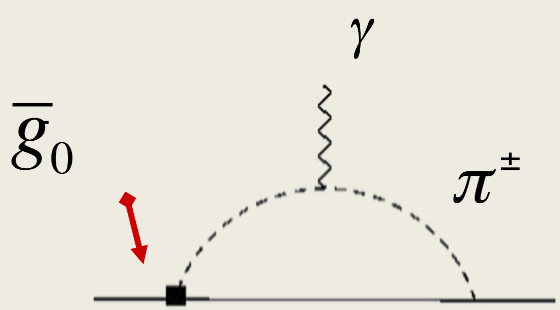


Already used for muon EDM

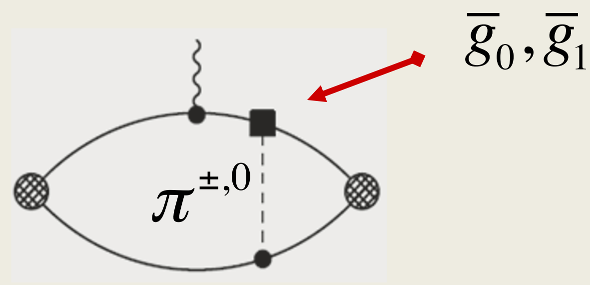
$$d_\mu \leq 1.8 \cdot 10^{-19}\ e\,cm \quad (95\%\ C.L.)$$

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

The CPV NN force and nuclear EDMs



Nucleon EDM



Nuclear EDM

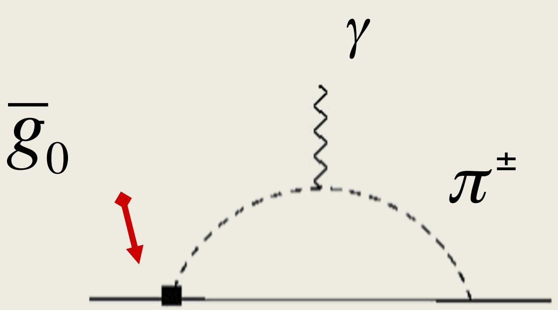
- Tree-level: **no loop** suppression → EDM predictions
- Orthogonal to nucleon EDMs, sensitive to different CPV structures

Recent review: arXiv:2001.09050

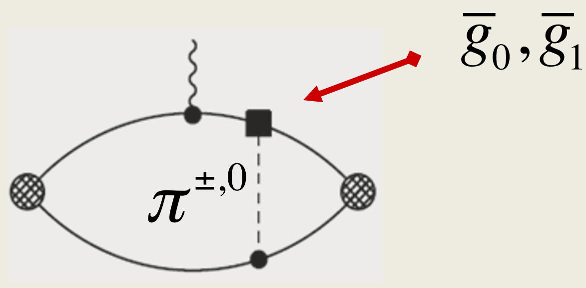
Parity- and Time-Reversal-Violating Nuclear Forces

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



Nucleon EDM



Nuclear EDM

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

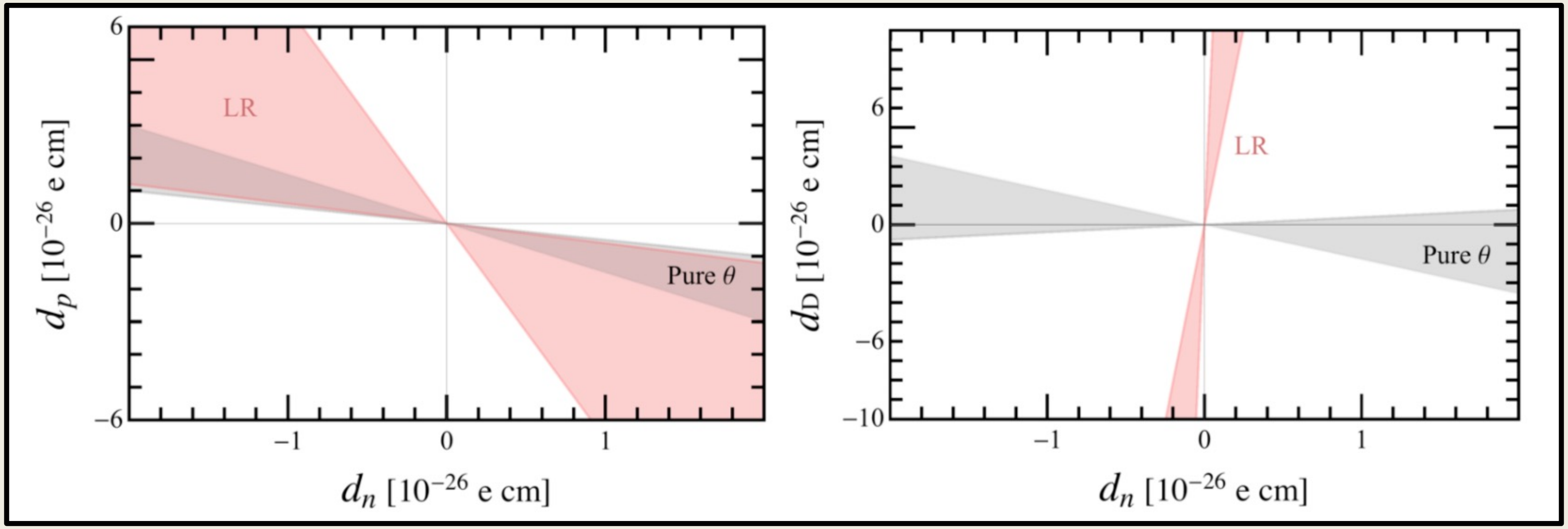
JdV et al '11 '15

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

\`	**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

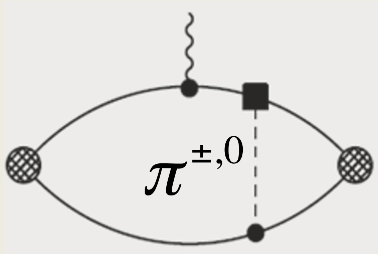


- **Nuclear EDMs complementary to nucleon EDMs**
- Deuteron is just a placeholder: other nuclear systems are similar
- **If we can control nuclear matrix elements !**

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 !

Outline

- Part I: Why do we (I?) care about dipole moments ?

- Part II: Interpreting Electric Dipole Measurement

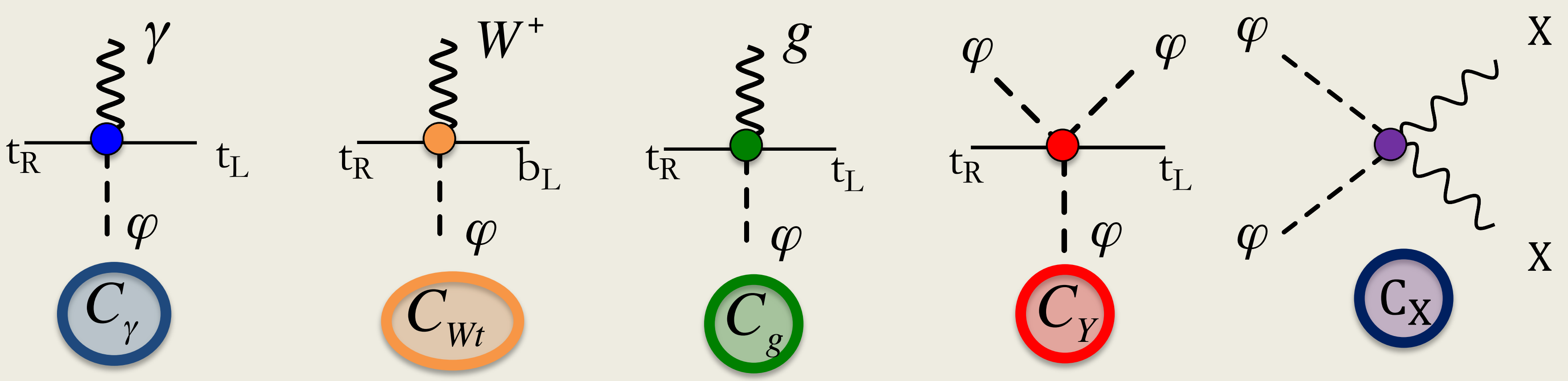
- **Part III: Interplay with high-energy experiments**

Colliders versus EDMs

- **Look at interactions with Higgs that violate CP**
- Time constraints: a subset of dim-6 operators

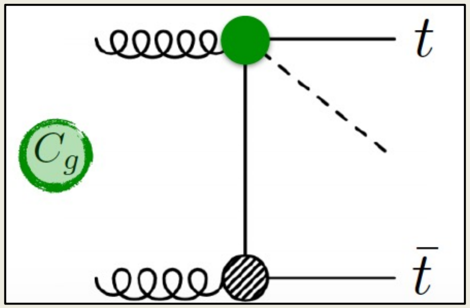
$$L_{eff} = \sum C_\alpha O_\alpha + h.c. \qquad C_\alpha = c_\alpha + i\,\tilde{c}_\alpha \qquad C_\alpha \sim \frac{1}{\Lambda^2}$$

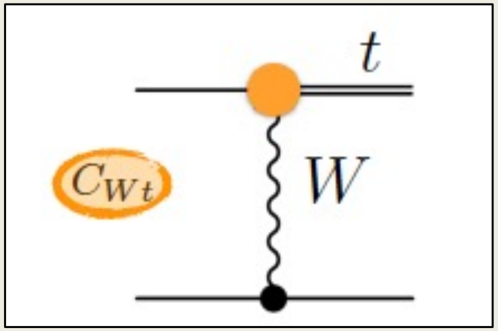
Some additional interactions without direct SM analogues

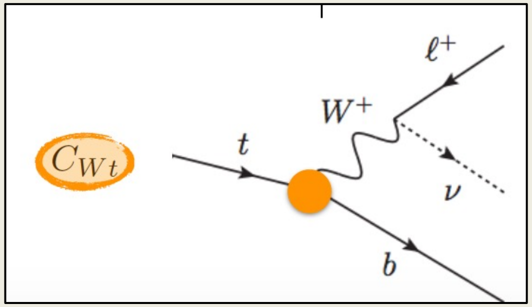


Collider searches

- These operators modify all kinds of LHC processes



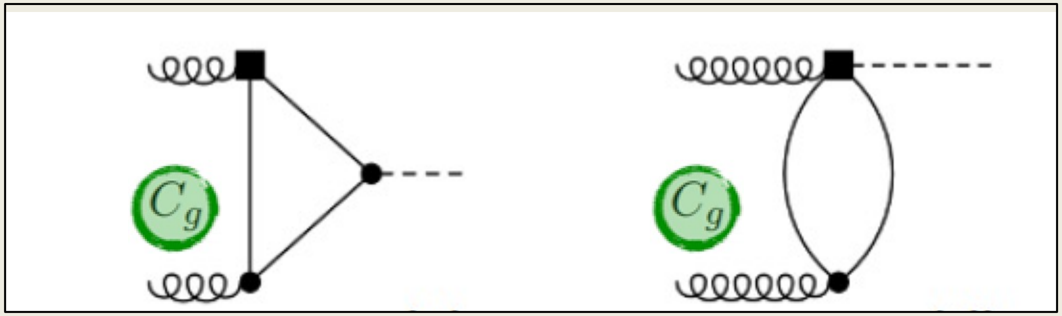


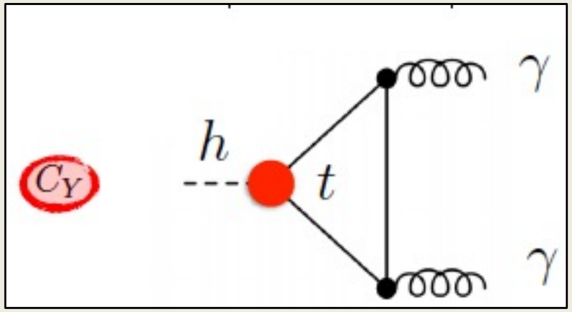


Top-Antitop-Higgs production

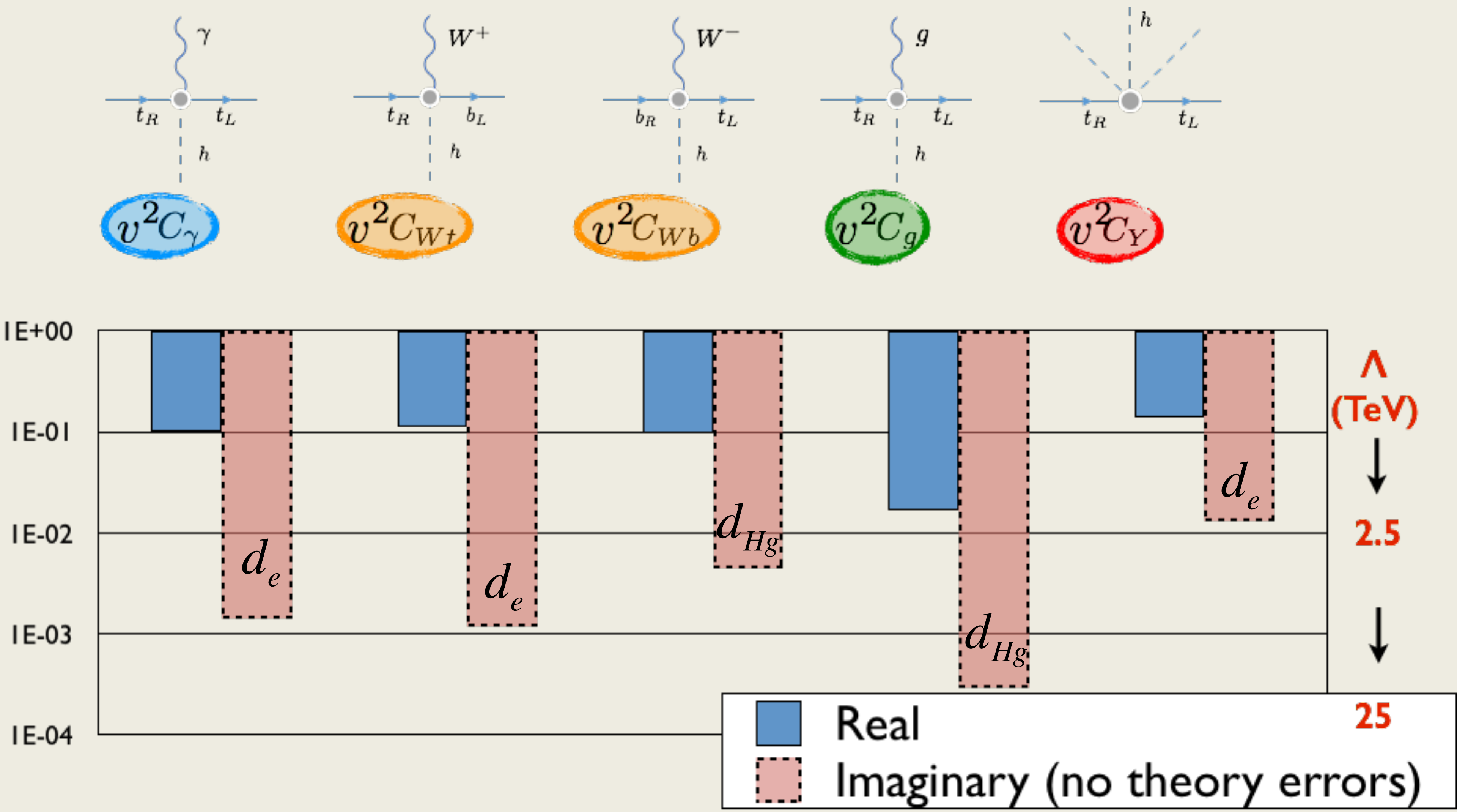
Single-top production and top decay

- But also just higgs production/decay via **loop processes**



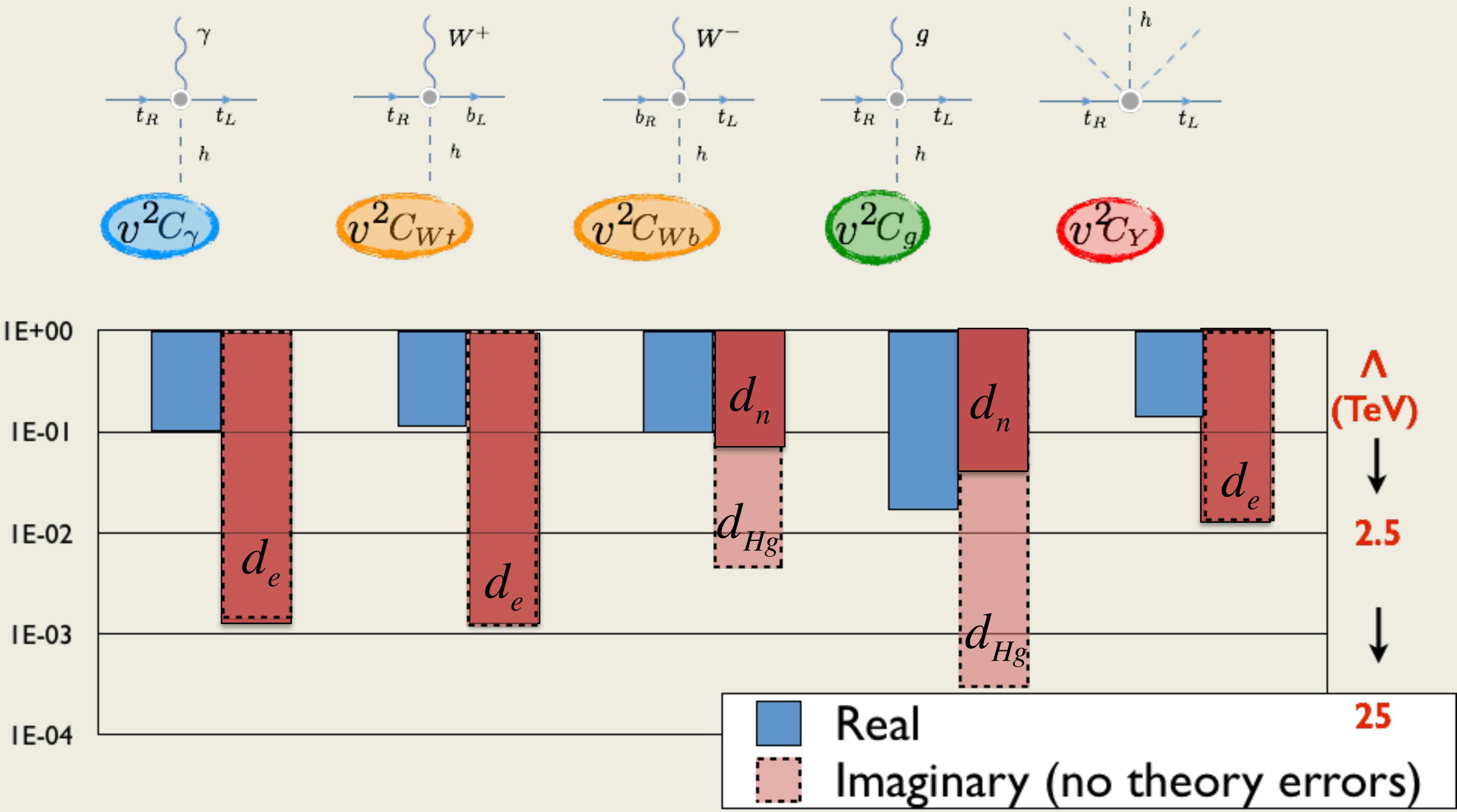


How much room for CPV is left ?



- EDMs are very constraining. Bounds dominated by Hg and ThO/HfF

How much room for CPV is left ?

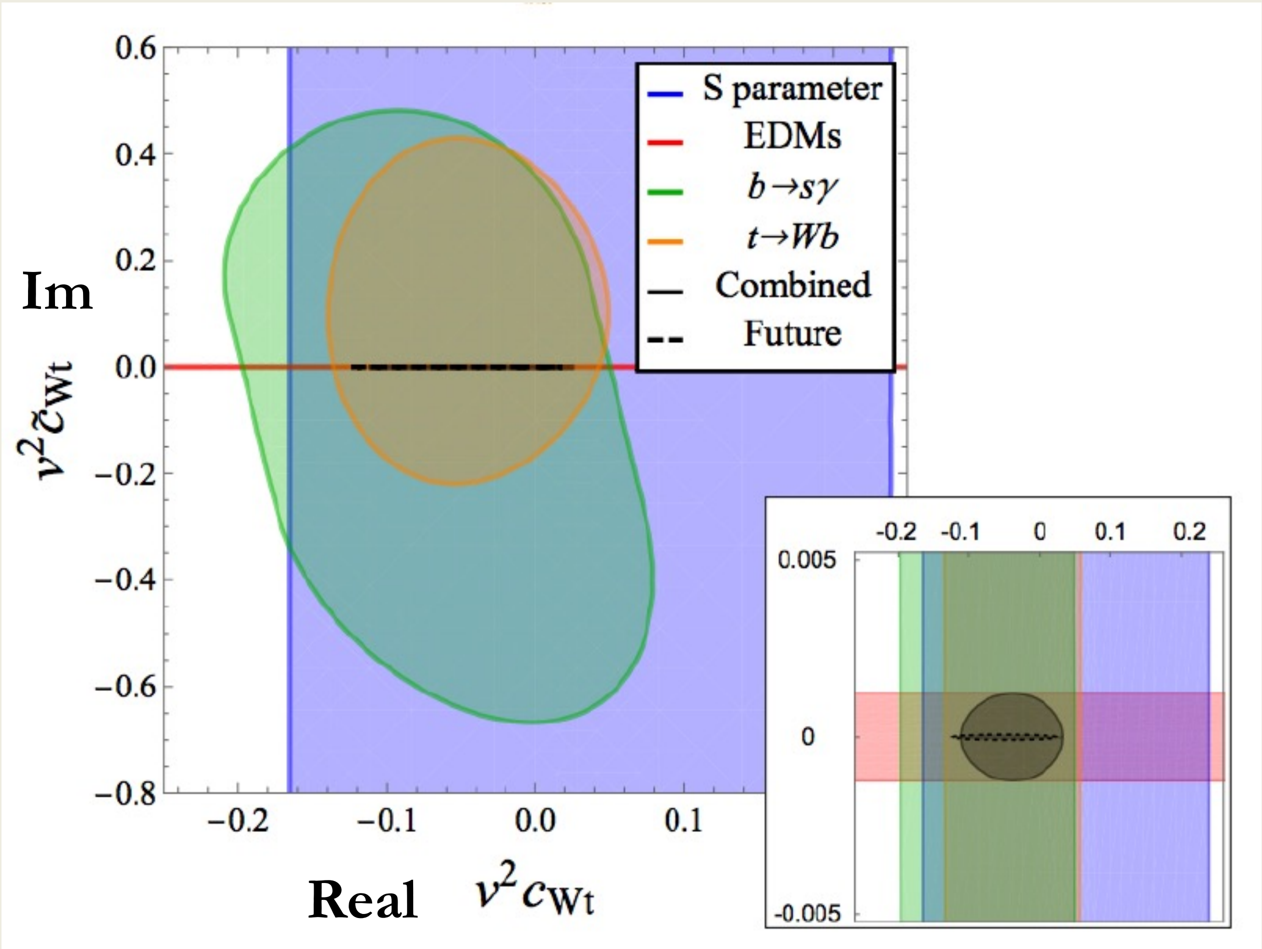


- Nuclear and hadronic theory needs to improve

CP-even versus CP-odd

JdV et al ’16

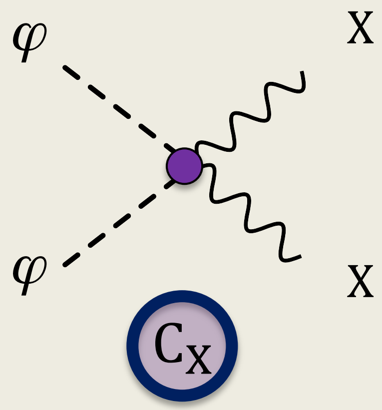
C_{Wt}



- **CP-even** Higgs couplings dominated by **LHC** measurements
- **CP-odd** Higgs couplings dominated by **low-energy** measurements
- **Very complementary experiments**

An explicit example: CPV in Higgs sector

$\varphi^{+}\varphi \, X\tilde{X}$



$\xrightarrow{\quad}$

After EW symmetry breaking

- **h-gluon-gluon**
- **h-gamma-gamma**
- **h-gamma-Z**
- **W-W-gamma**
- **h-Z-Z (not independent)**

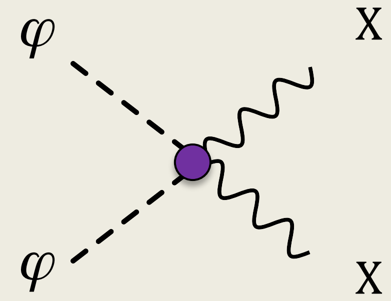
- Evades flavor constraints (MFV automatic). Scale can be relatively low

- Motivated by universal theories (BSM couples to SM bosons/fermions through SM currents)

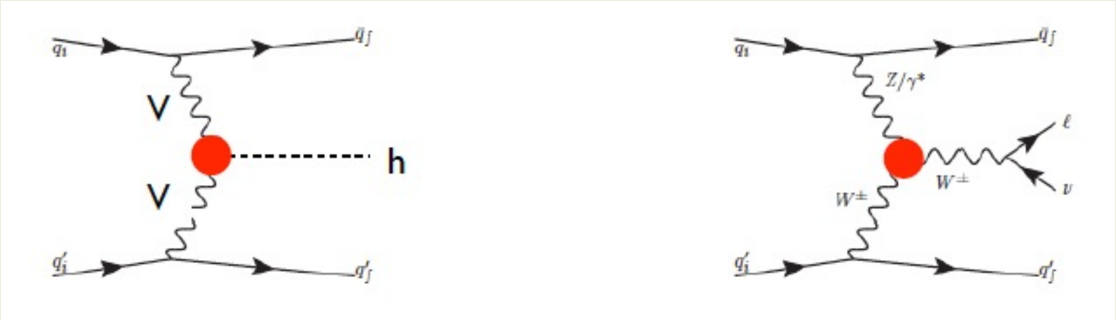
Peskin, Takeuchi ‘90
Barbieri et al ’04
Ferreira et al ‘17

Collider and low-energy probes

$\varphi^{+}\varphi \, X\tilde{X}$



- Induce CPV angular distribution in pp → h/V + 2 jets

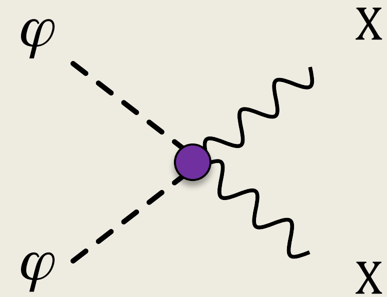


e.g. ATLAS 2006.15458 $\quad 0.23 < \tilde{C}_{HWB}/\Lambda^2 < 2.34 \ (TeV^{-2})$

Bernlochner et al '19 $\quad -0.19 < \tilde{C}_{HGG}/\Lambda^2 < 0.03 \ (TeV^{-2})$

Collider and low-energy probes

$\varphi^+\varphi\, X\tilde{X}$



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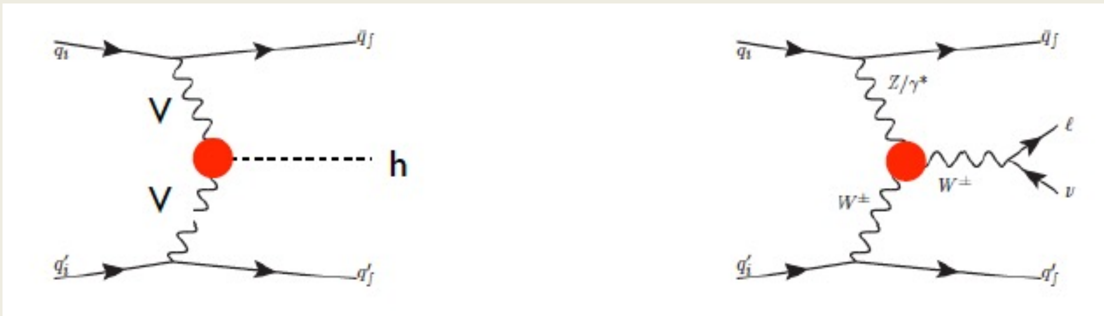

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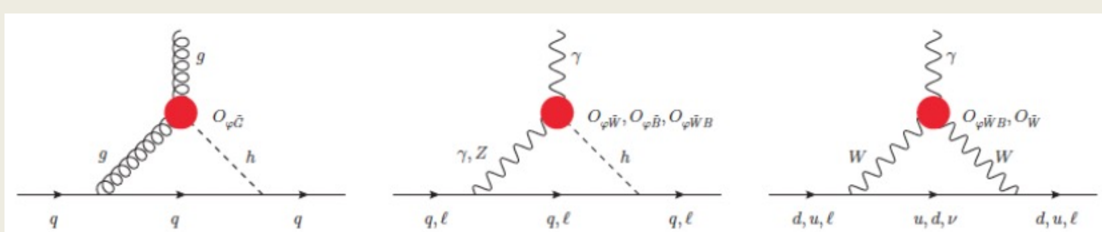
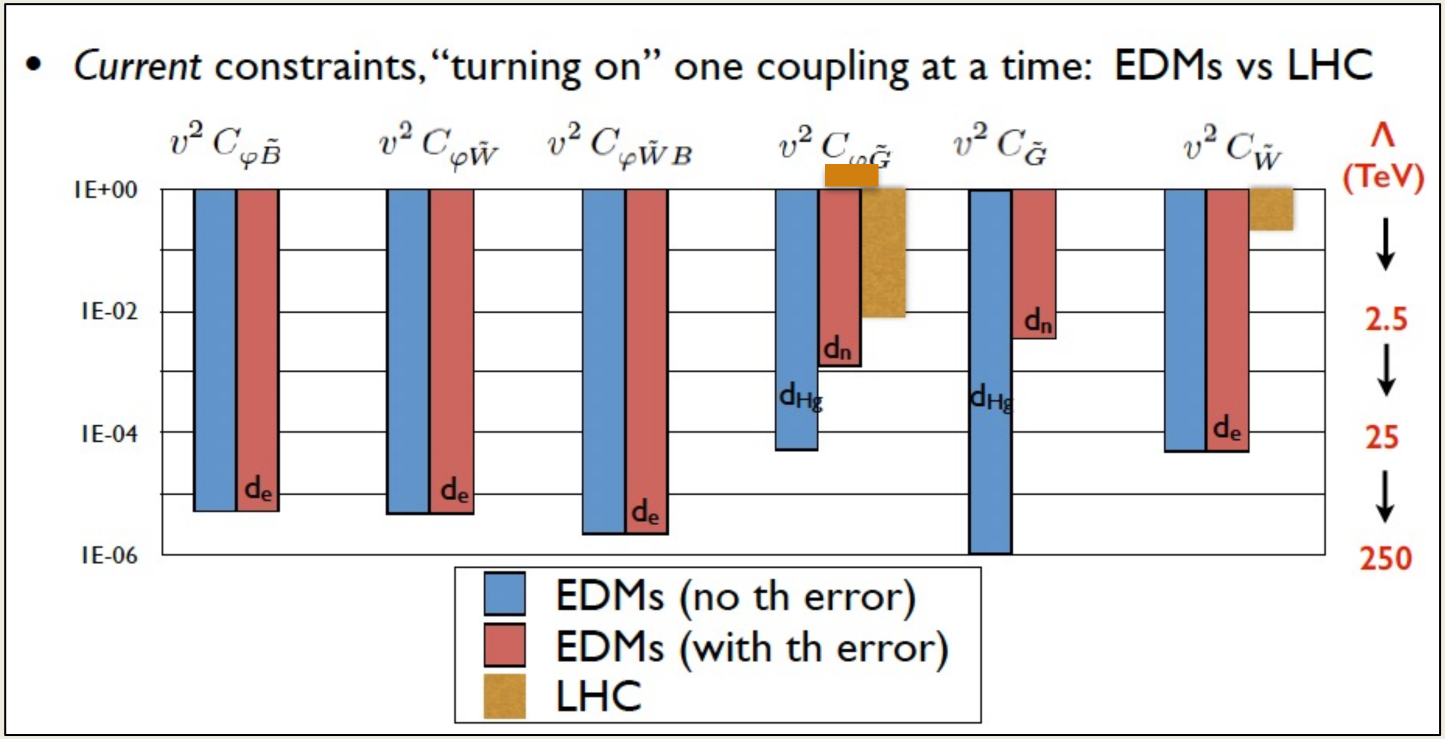
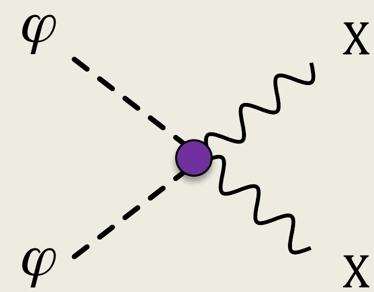
Bernlochner et al '19 $\quad -0.19 < \tilde{C}_{HGG}/\Lambda^2 < 0.03\ (TeV^{-2})$

- Same couplings induce contributions to EDMs at loop level
- Also induce CPV in B → s gamma transitions



Low-energy constraints are stringent

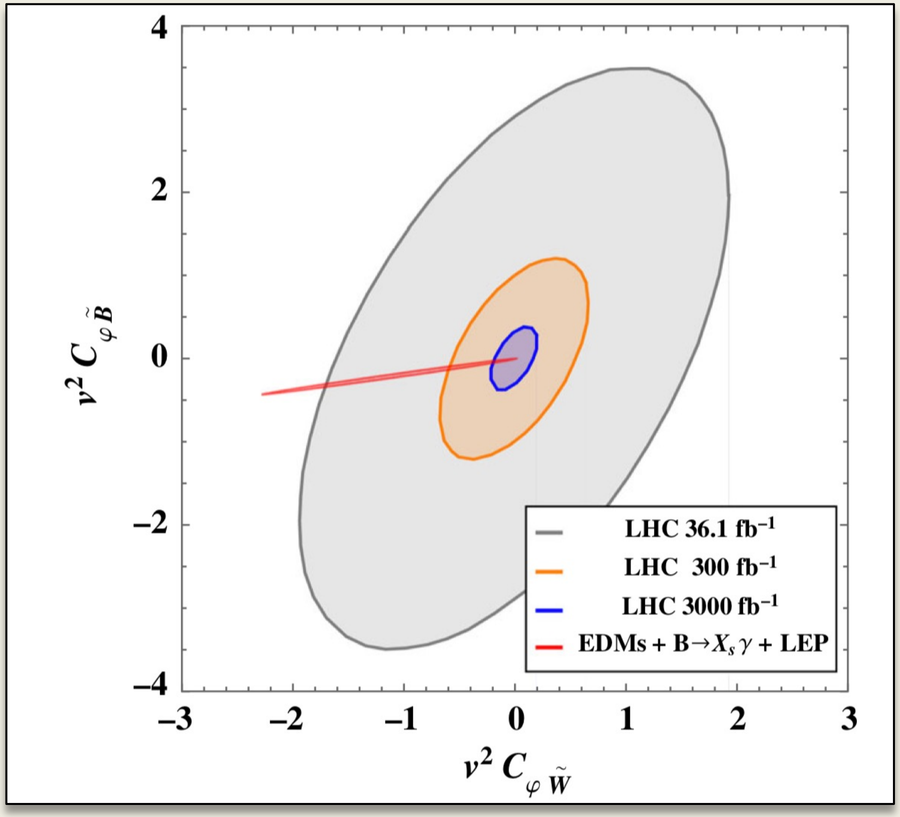




- EDM constraints are very stringent for single couplings
- **But EDMs only probe several direction in parameter space**

Free direction : $0.17\, C_{\varphi\tilde{B}} + 0.86\, C_{\varphi\tilde{W}} + 0.48\, C_{\varphi\tilde{W}B}$

CP violation in 'universal theories'

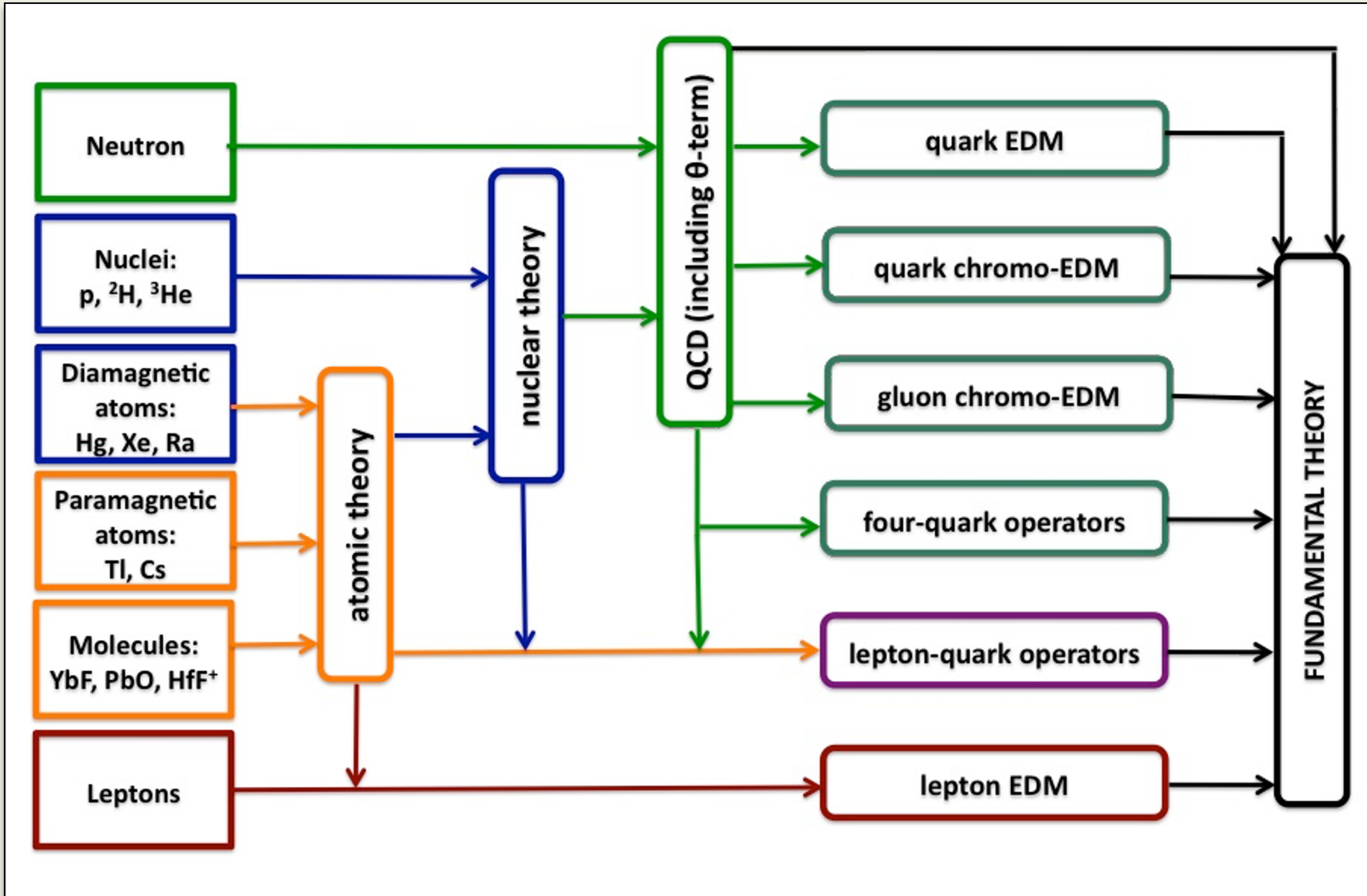


Cirigliano, JdV et al PRL '19

HL-LHC projections from Bernlochner et al '18

- Low-energy limits avoided in global fits (free directions)
- **Future of BSM searches: inclusive low- and high-energy probes**

The EDM metromap



Conclusion/Summary/Outlook

EDMs

- ✓ Very powerful search for BSM physics (probe high scales)
- ✓ Heroic experimental effort and **great outlook**
- ✓ **Theory improvements** needed to get the most out of the measurements

EFT framework

- ✓ Framework exists for CP-violation (EDMs) from 1st principles
- ✓ Keep track of **symmetries** (gauge/CP/chiral) from multi-Tev to molecular scales
- ✓ **Need young people working on CP violation of 'large' systems.**

EDMs in era of the LHC

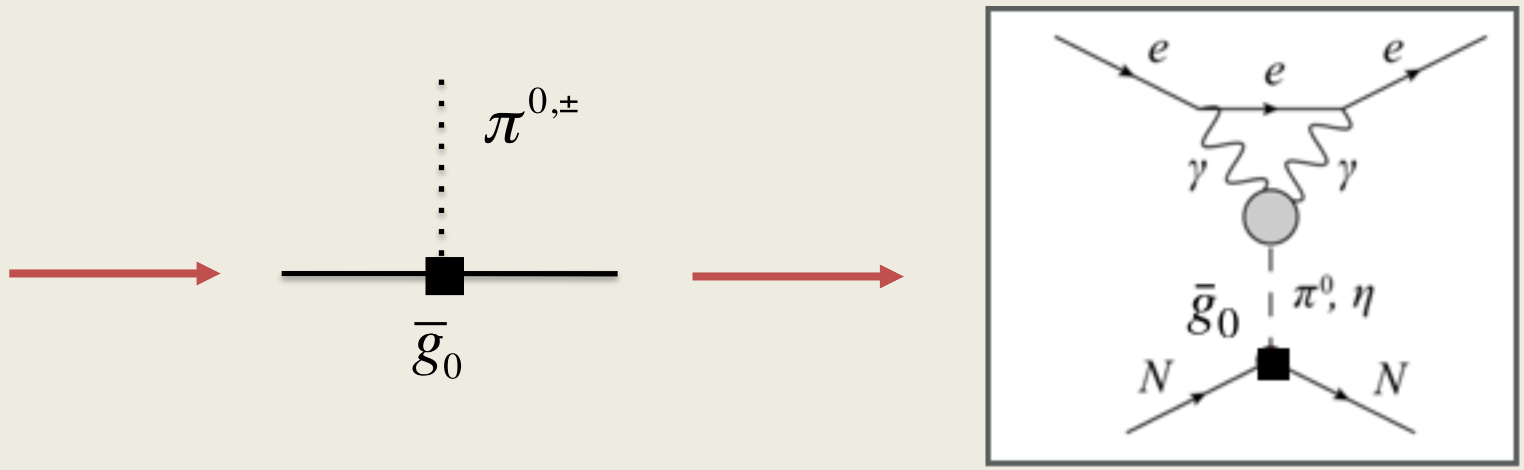
- ✓ EDMs play important role in global searches for BSM physics
- ✓ Complementary to many high-energy searches
- ✓ Constraining for electroweak baryogenesis (not today)

Progress with molecules

Pospelov et al PRD' 20

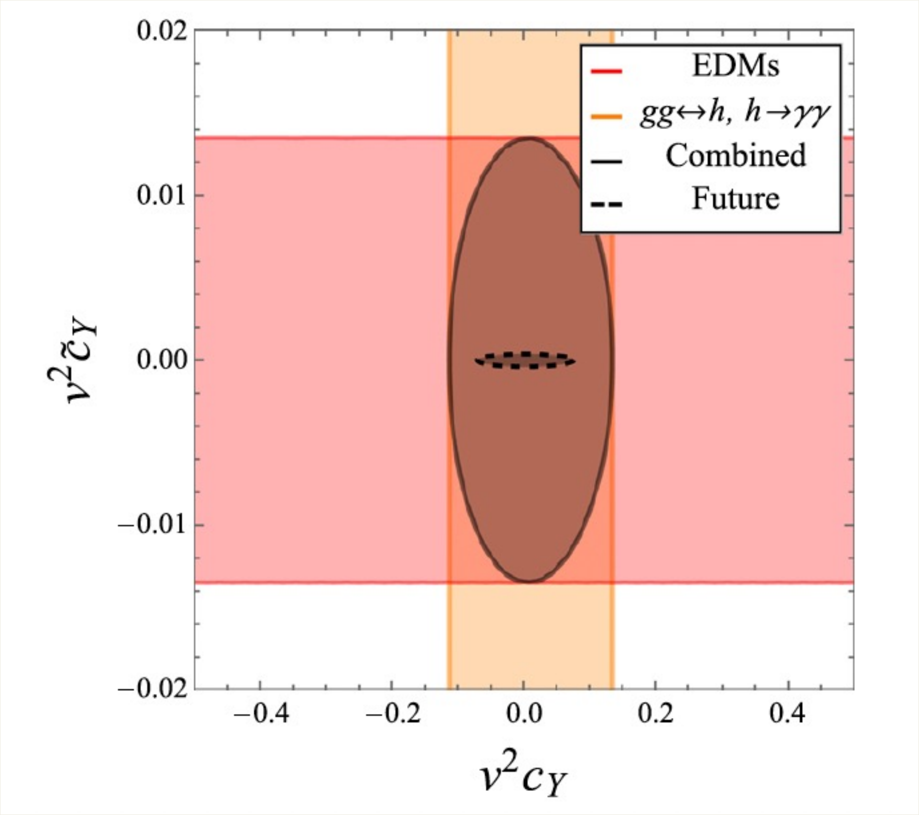
- Division in para- and diamagnetic systems is artifical

QCD
(θ-term)



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

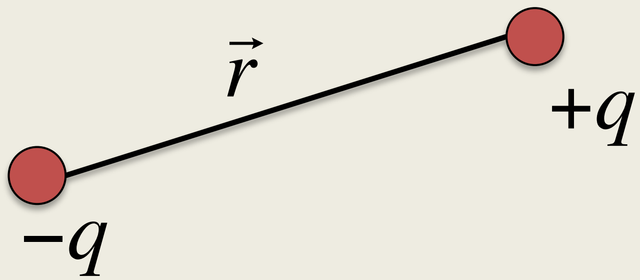
CP-even versus CP-odd



- EDMs allow roughly 1% of CP-violation in top Yukawa coupling
- **Rules out several models of electroweak baryogenesis**

Jorinde van de Vis et al '17, '18

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**.

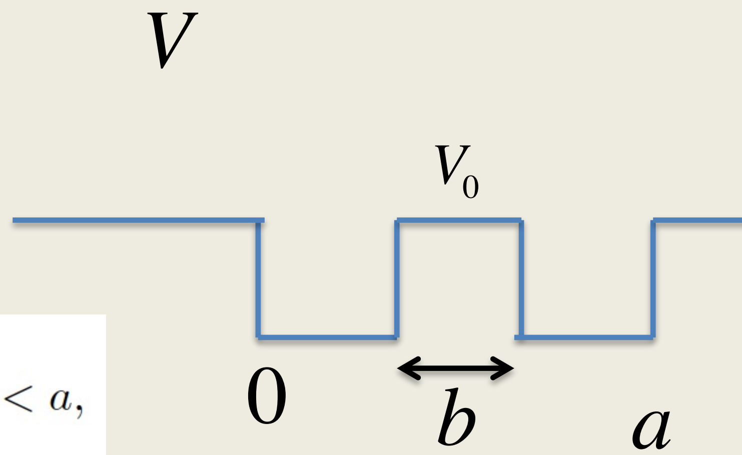
- For electron, neutron, atom, the only quantity available is the spin.
  So there is no 'r' around

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

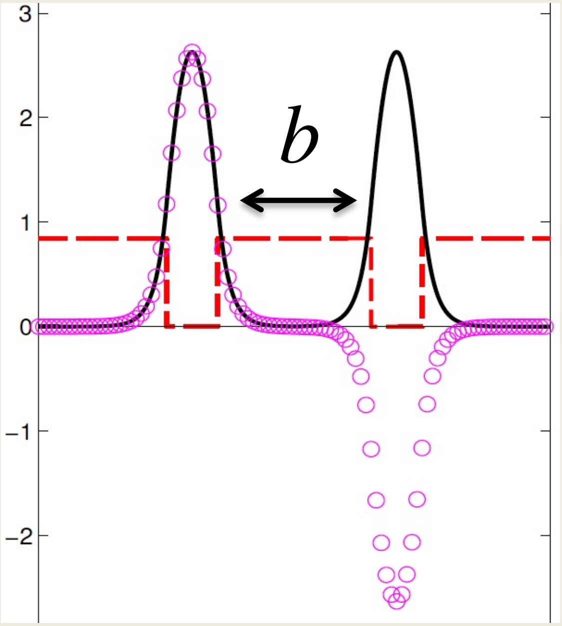
Double-well potential

- 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

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

- 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 $|\pm\rangle$
- 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

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

Fake EDMs

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- If the E field is smaller than the energy gap

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

- 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 ?

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

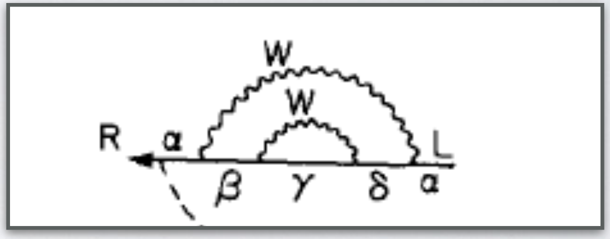
- Not really. **It is just a parameter**. No inconsistencies.
- **Could it have been larger?**
- Seems yes, nothing really changes in the universe if θ **~ 0.1** **No anthropic argument.**

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

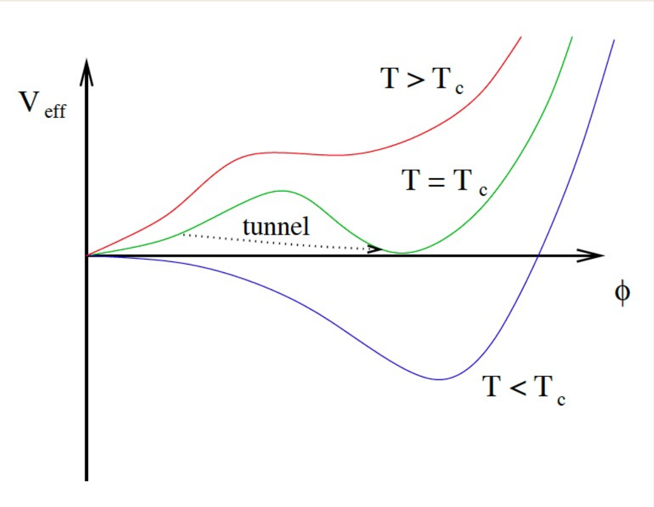
Electroweak baryogenesis in a nut-shell

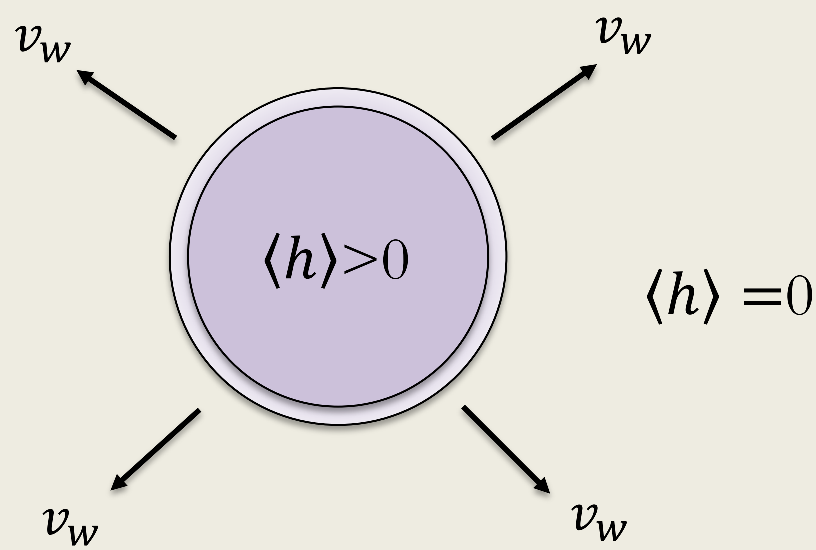
- Many BSM models for electroweak baryogenesis

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





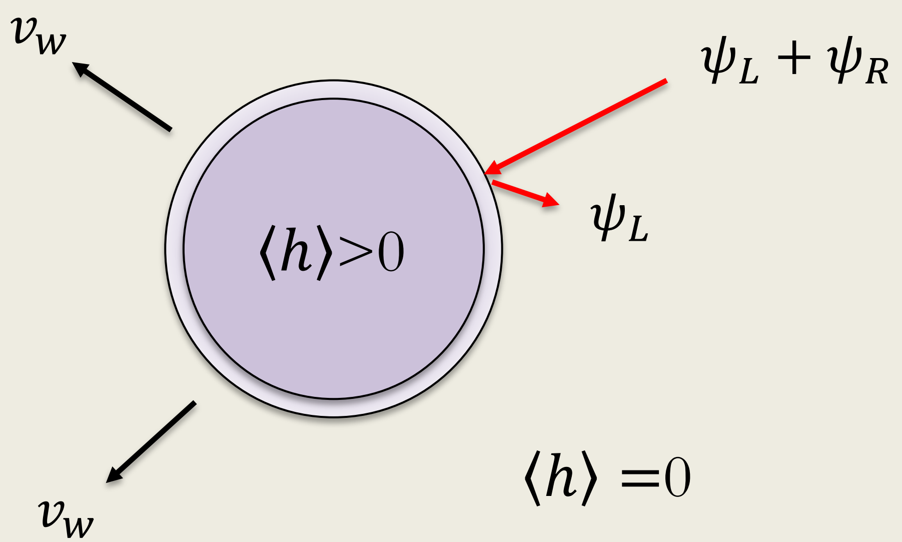
Experimental probes: di-Higgs production, new scalars, Higgs couplings, Gravitational waves

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

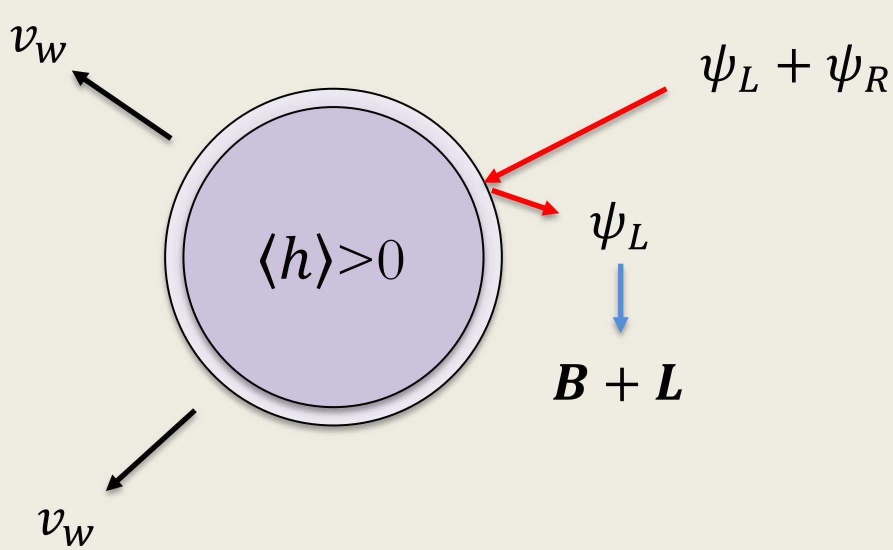


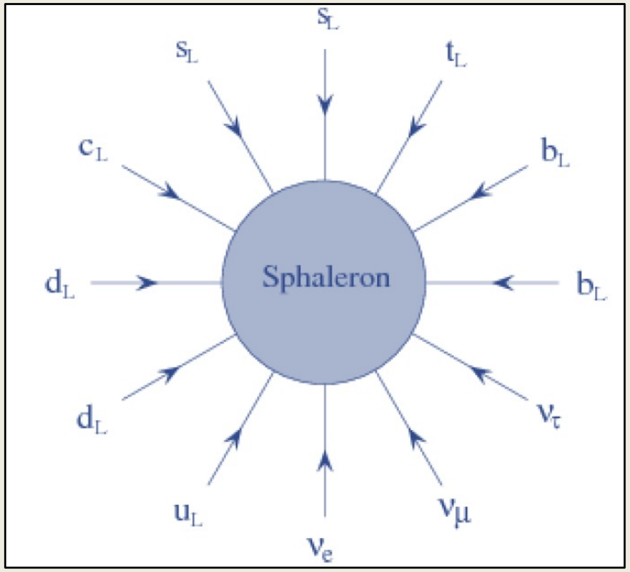
Electroweak baryogenesis in a nut-shell

- 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 $T > M_W$)



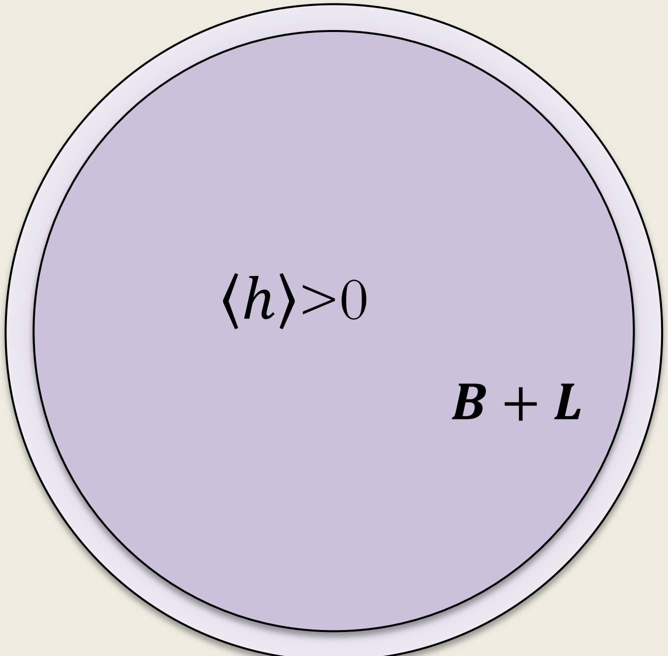


Electroweak baryogenesis in a nut-shell

- Generation of matter happens during EW phase transition

  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**

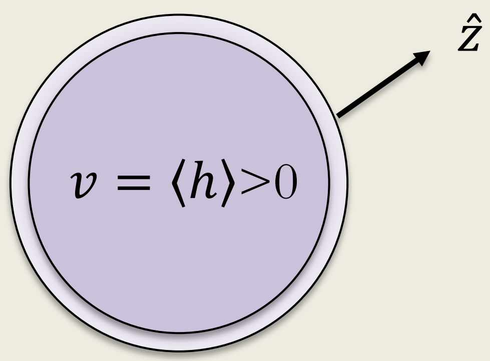
JdV, Postma, van de Vis, White '17

- 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

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



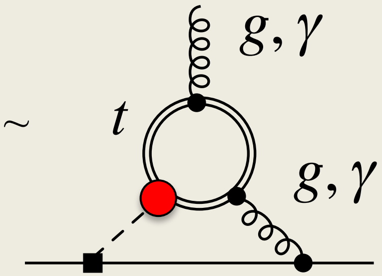
- Main focus in literature on top quark

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 $\sim$



$\Lambda_t \geq 7$ TeV

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

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
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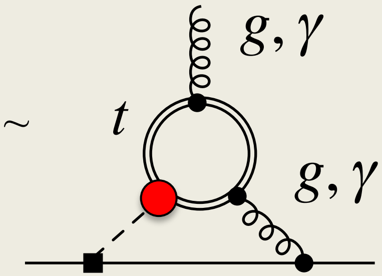
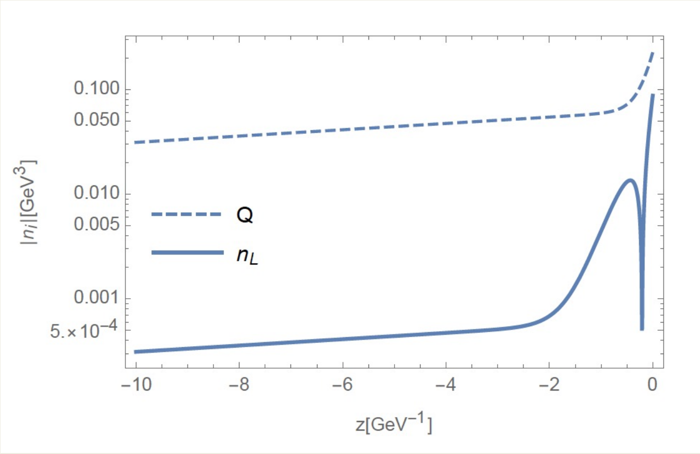
Electron EDM ~

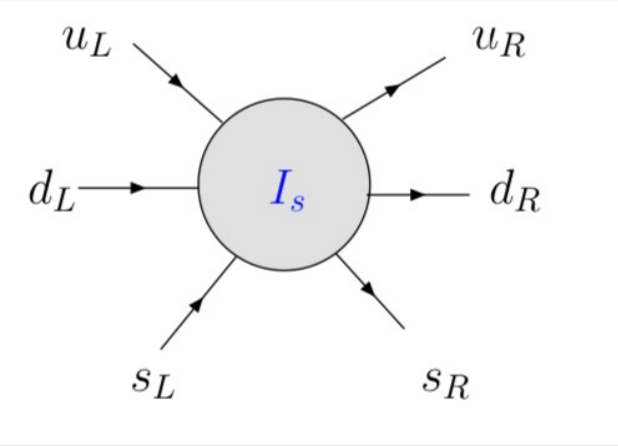


$\Lambda_t \geq 7$ TeV

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

Giudice, Shaposhnikov '94



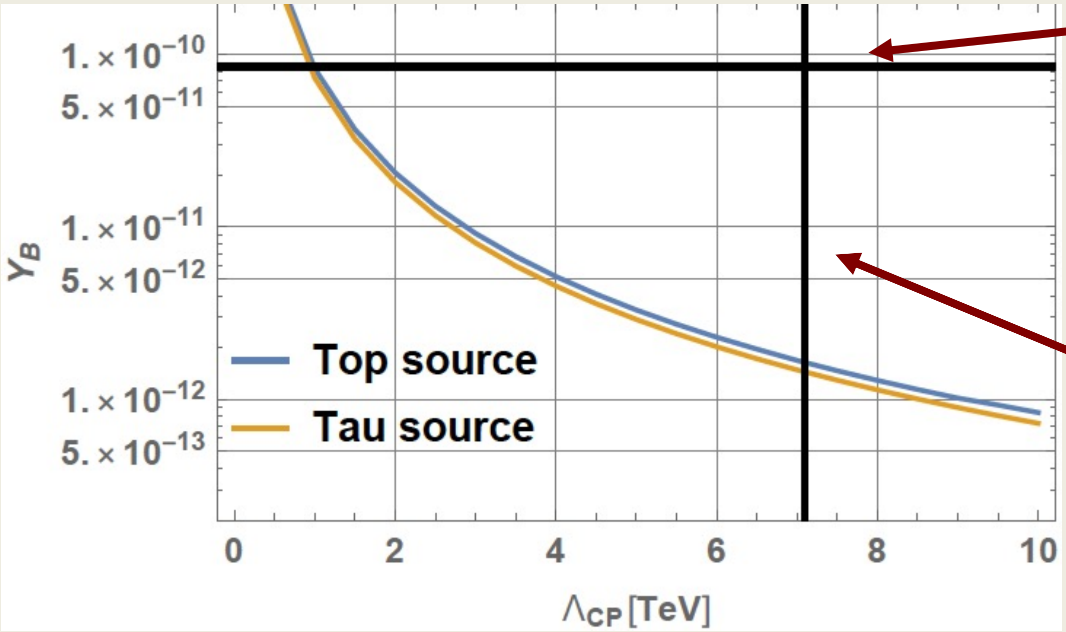


Does it work ?

- 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 $\Lambda_\tau \lesssim 1$ 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}	$\mathrm{FCC\text{-}ee}_{365}$
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]
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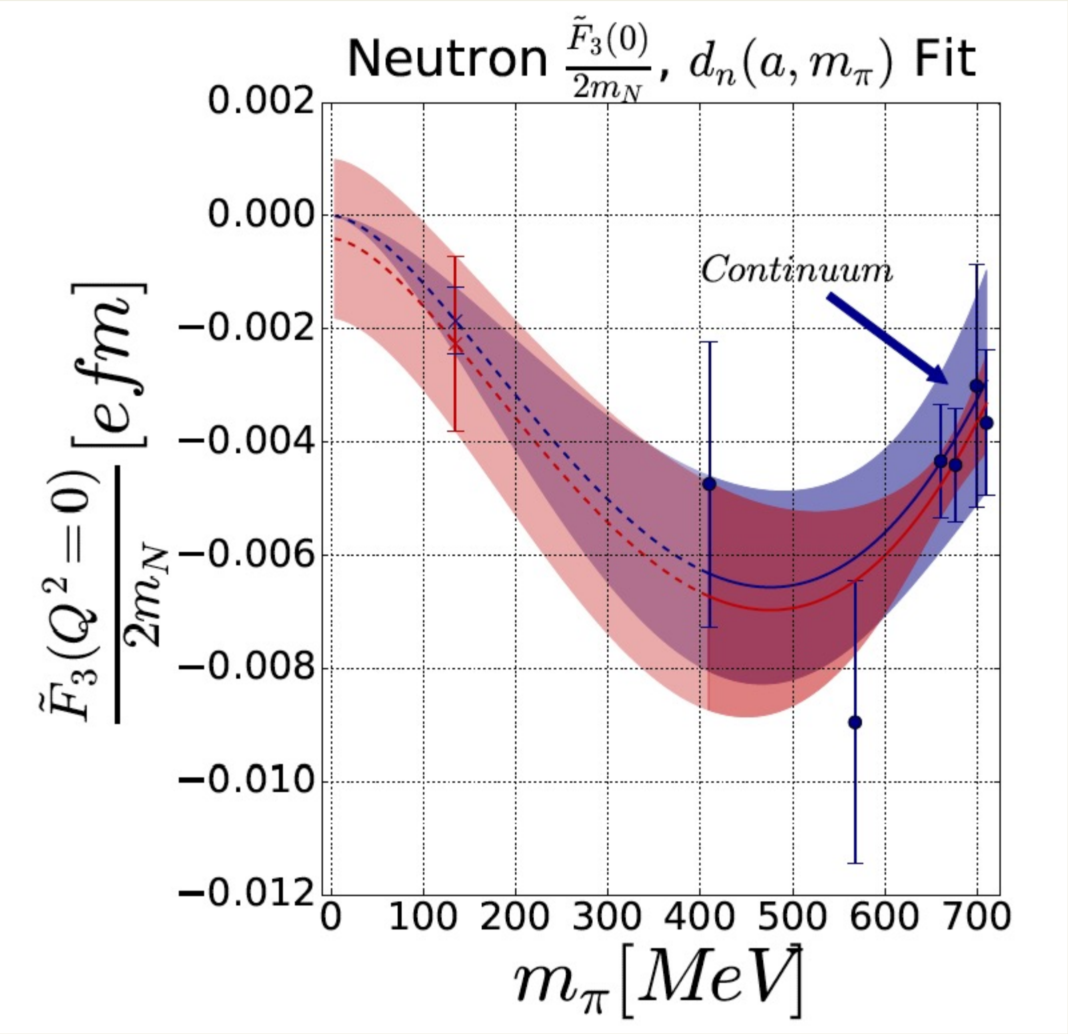
Charting the European Course to the High-Energy Frontier 1912:13466

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