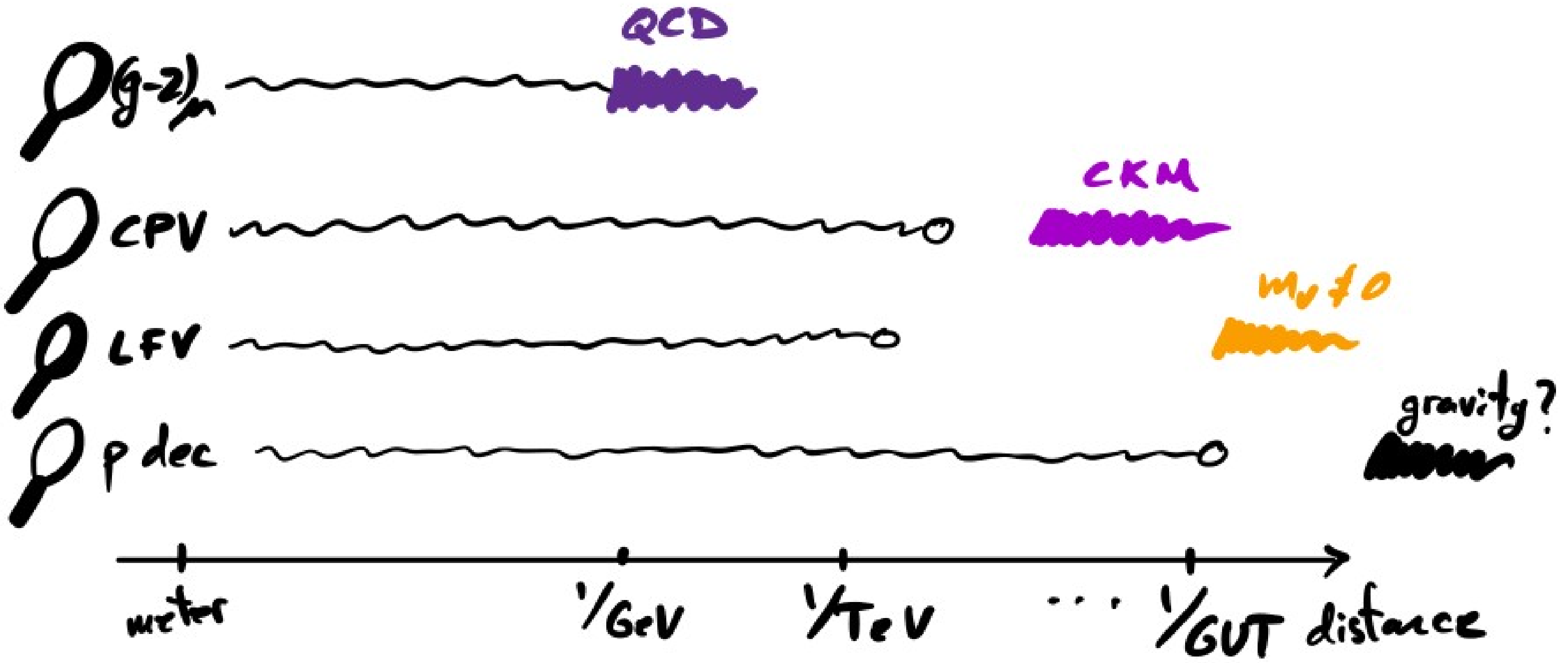
EFT interpretation of low scale CPV and LFV searches

Marc Riembau
CERN
6th October 2023



Experiments testing near-global SM symmetries can test dynamics at distances beyond TeV scale

$$H = -\mu\, \vec{B} \cdot \frac{\vec{S}}{S} - d\, \vec{E} \cdot \frac{\vec{S}}{S}$$

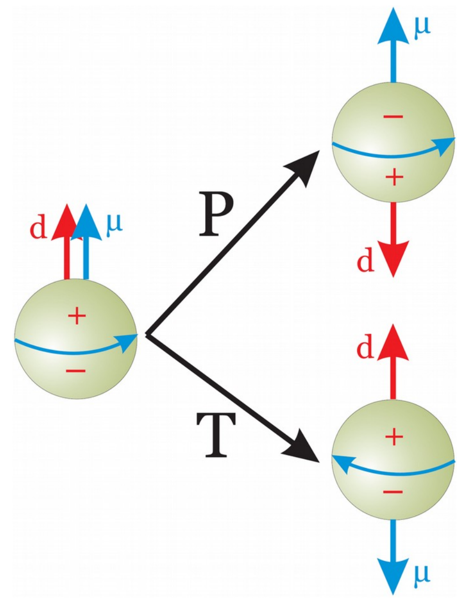
relativistic limit

$$\mathcal{L}_{dipole} = -\frac{\mu}{2} \bar{\Psi} \sigma^{\mu\nu} F_{\mu\nu} \Psi - \frac{d}{2} \bar{\Psi} \sigma^{\mu\nu} i\gamma^5 F_{\mu\nu} \Psi$$

SM

$$\mathcal{L} \supset \frac{c_W^e}{\Lambda^2} y_e g\, \bar{\ell}_L \sigma_{\mu\nu} e_R \sigma^a H W^a_{\mu\nu} + \frac{c_B^e}{\Lambda^2} y_e g'\, \bar{\ell}_L \sigma_{\mu\nu} e_R H B_{\mu\nu} + h.c.$$

$$d_e(\mu) = \frac{\sqrt{2}v}{\Lambda^2} \mathrm{Im}\left[s_{\theta_W}\, C_{eW}(\mu) - c_{\theta_W}\, C_{eB}(\mu) \right]$$



Nonvanishing d breaks CP

$$H = -\mu \, \vec{B} \cdot \frac{\vec{S}}{S} - d \, \vec{E} \cdot \frac{\vec{S}}{S}$$

↓ relativistic limit

$$\mathcal{L}_{dipole} = -\frac{\mu}{2} \bar{\Psi} \sigma^{\mu\nu} F_{\mu\nu} \Psi - \frac{d}{2} \bar{\Psi} \sigma^{\mu\nu} i \gamma^5 F_{\mu\nu} \Psi$$

↓ SM

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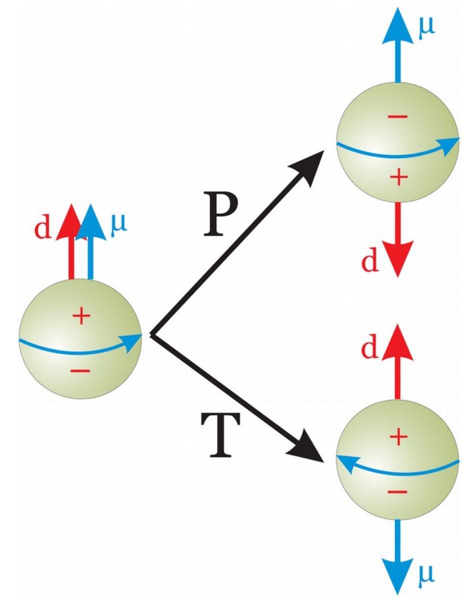
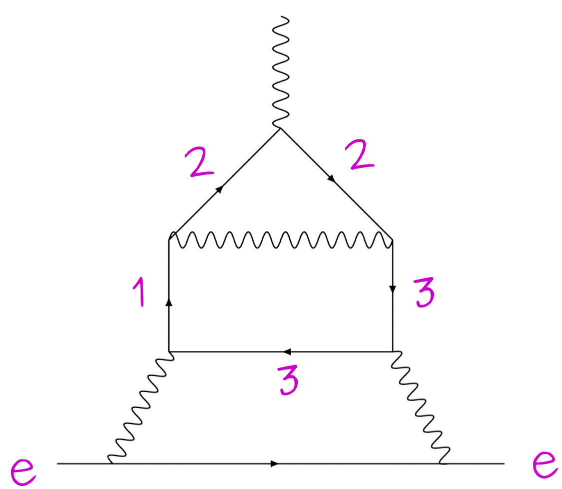


Nonvanishing d breaks CP

SM prediction:



$$\rightarrow d_e / e \sim 10^{-40} \;\; cm$$

SM contribution is ridiculously small,
EDM is a clear sign of New Phisics

Hints for this simplicity are old, coming from non-violations of accidental and approximate SM symmetries. In particular, CP:

Larger Higgs-Boson-Exchange Terms in the Neutron Electric Dipole Moment

Steven Weinberg

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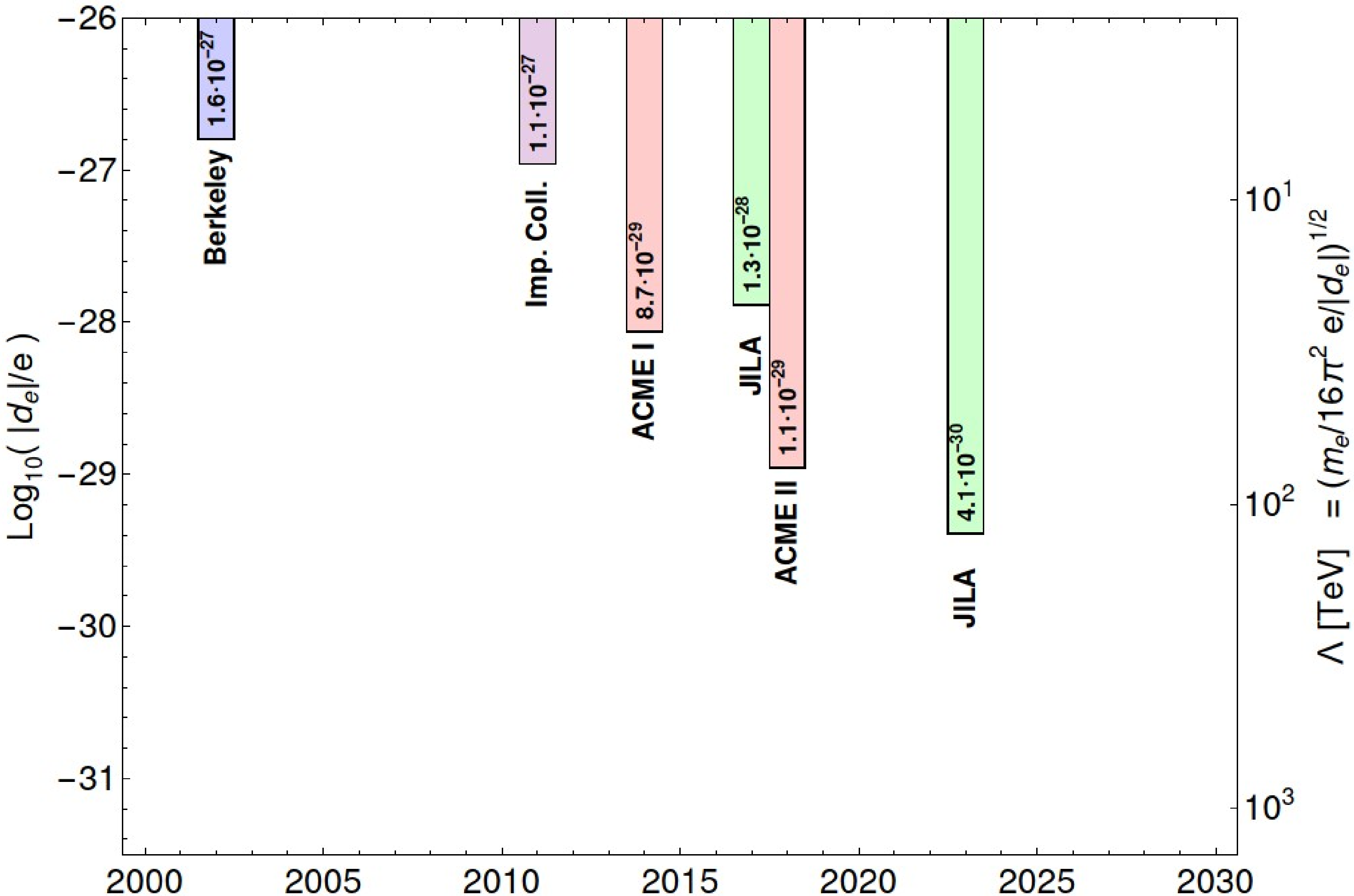
(Received 25 August 1989)

The neutron electric dipole moment (d_n) due to Higgs-boson exchange is reconsidered, now without assuming that Higgs-boson exchange is solely responsible for $K_L^0 \to 2\pi$. The dominant contribution to d_n arises from a three-gluon operator, produced in integrating out top quarks and neutral Higgs bosons. The estimated result together with current experimental bounds on d_n show, even for the largest plausible Higgs-boson masses, that *CP* is not maximally violated in neutral-Higgs-boson exchange.

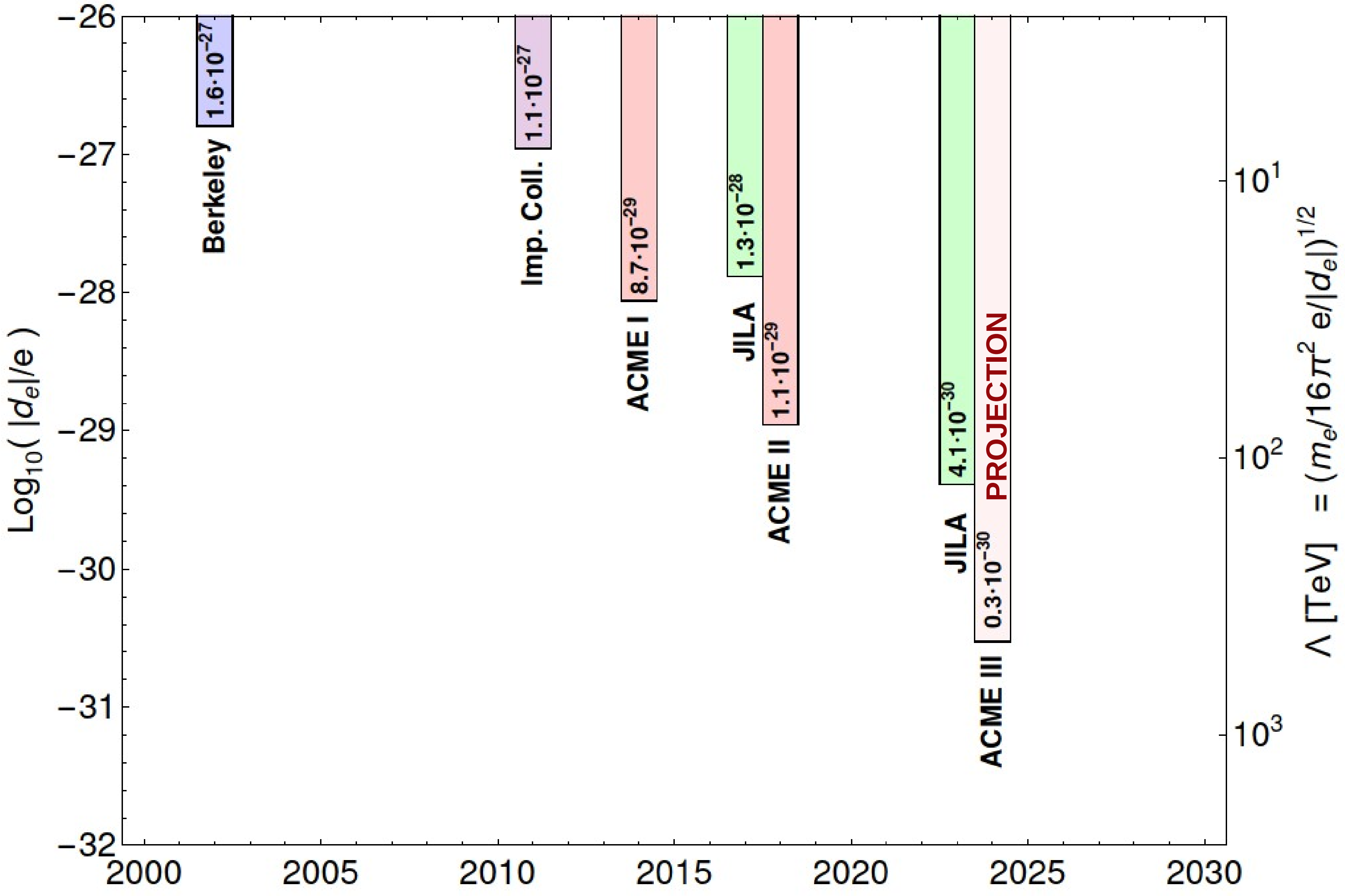
This is very large compared with other contributions, and potentially in conflict with the experimental results for d_n, $(-14 \pm 6) \times 10^{-26}$ e cm from Leningrad[20] and $(-3 \pm 5) \times 10^{-26}$ e cm from Grenoble.[21] We do not know m_H or m_t, but the experimental lower bound on m_t is rapidly increasing, and it is hard to imagine that m_H could be larger than $10 m_t$. This gives[15] $h > 0.015$. The experimental bound[21] $|d_n| < 1.2 \times 10^{-25}$ e cm thus requires that $|\mathrm{Im} Z_2| < 8 \times 10^{-5}$. Our conclusion is that *CP* is not maximally violated in the neutral Higgs sector.[14] The only way that I can see for this to be natural is for the Higgs sector to be very simple: no more than two doublets, and with two doublets, no mixing with any scalar singlets.

Evolution of electron EDM constraints



Current: JILA $|d_e| < 4.1 \cdot 10^{-30}$ e cm

Evolution of electron EDM constraints



Current: JILA $|d_e| < 4.1 \cdot 10^{-30}$ e cm

Translation of eEDM constraints to particle physics:

$$\frac{d_e}{e} \sim \frac{1}{(16\pi^2)^2} \frac{m_e}{\Lambda^2} \qquad \to \Lambda > 3\,\mathrm{TeV}$$

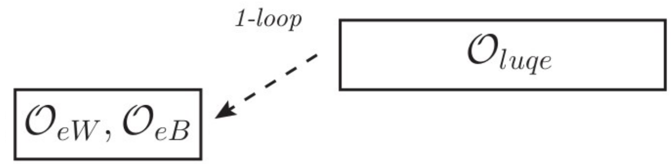
Relevant constraints even at two loops.

We want to characterize all effects that enter with

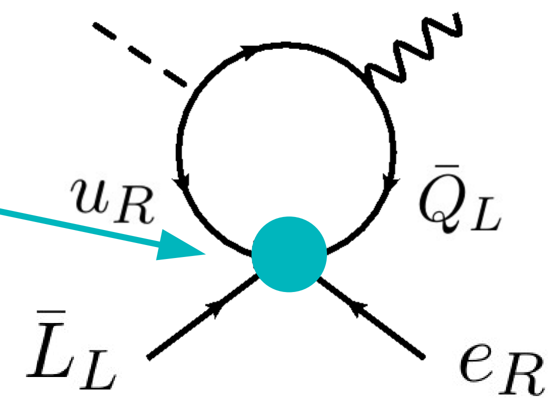
Two loops   Chirality flip   log enhanced

This is the key to help organize the contributions

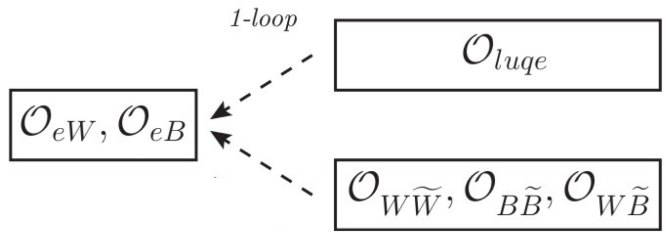
$$\boxed{\mathcal{O}_{eW}, \mathcal{O}_{eB}}$$



$$\mathcal{O}_{luqe} = (\bar{L}_L u_R)(\bar{Q}_L e_R)$$



Only 4-fermion to enter at one loop
The others do not have the correct structure

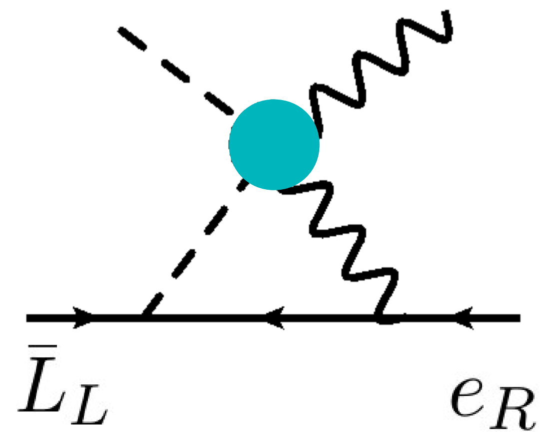


$$\frac{d}{d\ln\mu}\mathrm{Im}\begin{pmatrix} C_{eB} \\ C_{eW} \end{pmatrix} = -\frac{y_e g}{16\pi^2}\begin{pmatrix} 0 & 2t_{\theta_W}(Y_L+Y_e) & \frac{3}{2} \\ 1 & 0 & t_{\theta_W}(Y_L+Y_e) \end{pmatrix}\begin{pmatrix} C_{W\widetilde{W}} \\ C_{B\widetilde{B}} \\ C_{W\widetilde{B}} \end{pmatrix}$$

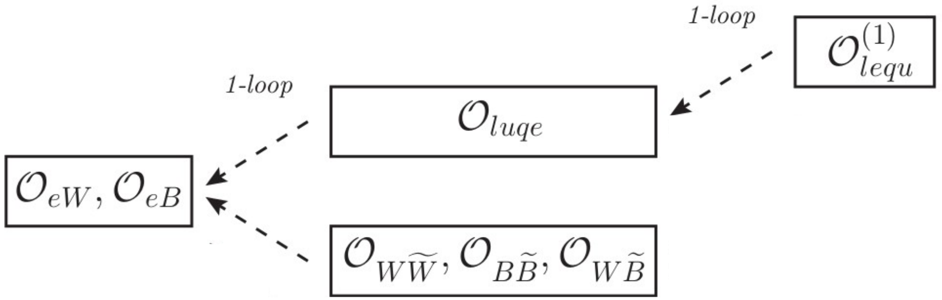
It is useful to write the parameters in a more physical way

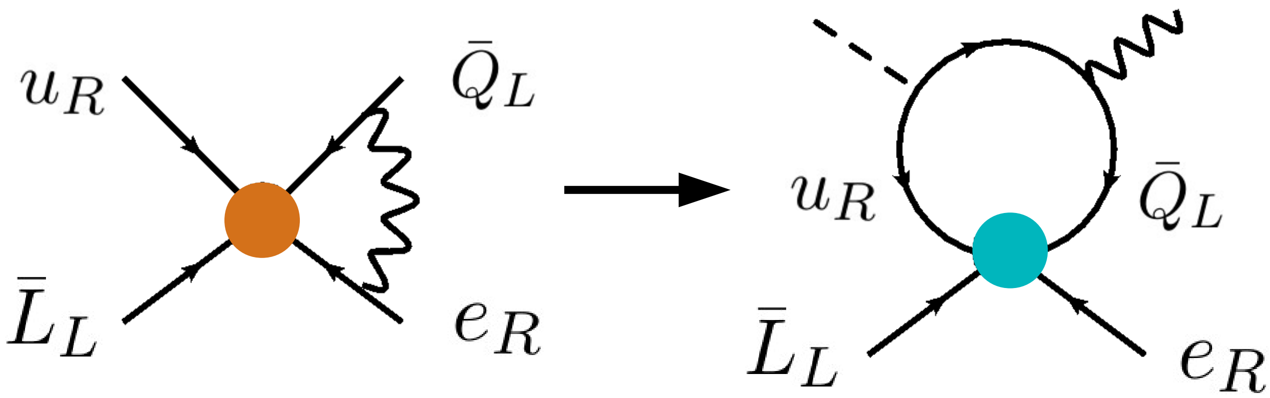
$$\frac{vh}{\Lambda^2}\left(\tilde{\kappa}_{\gamma\gamma}F_{\mu\nu}\widetilde{F}^{\mu\nu} + 2\tilde{\kappa}_{\gamma Z}F_{\mu\nu}\widetilde{Z}^{\mu\nu}\right) + ie\delta\tilde{\kappa}_{\gamma}W_{\mu}^{+}W_{\nu}^{-}\widetilde{F}^{\mu\nu}$$

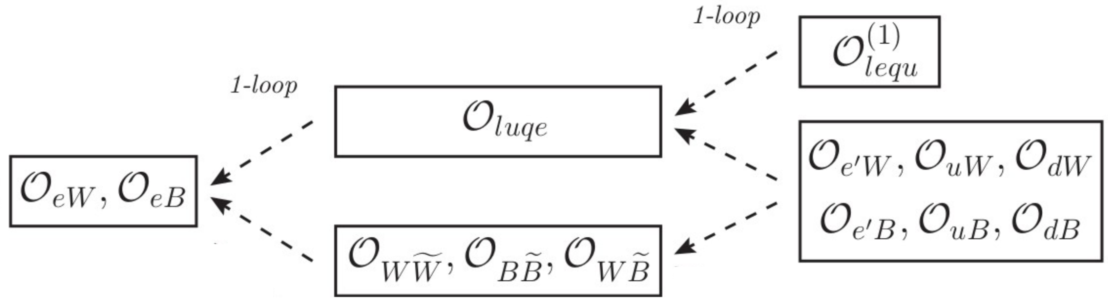
$$\frac{d}{d\ln\mu}d_e(\mu) = \frac{e}{8\pi^2}\frac{m_e}{\Lambda^2}\left[4Q_e\tilde{\kappa}_{\gamma\gamma} - \frac{4}{s_{2\theta_W}}\left(\frac{1}{2}+2Q_e s_{\theta_W}^2\right)\tilde{\kappa}_{\gamma Z} + \frac{\Lambda^2}{v^2}\delta\tilde{\kappa}_{\gamma}\right]$$

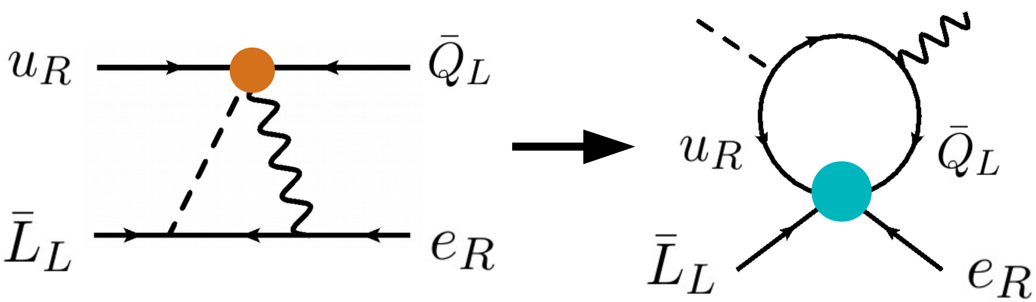


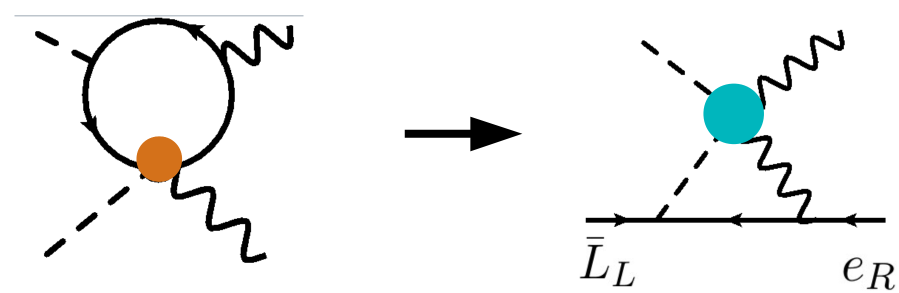
Due to approximate accidental cancellation, 1/2+2 Qe sin^2 ~ 0.04, Z boson contribution negligible.

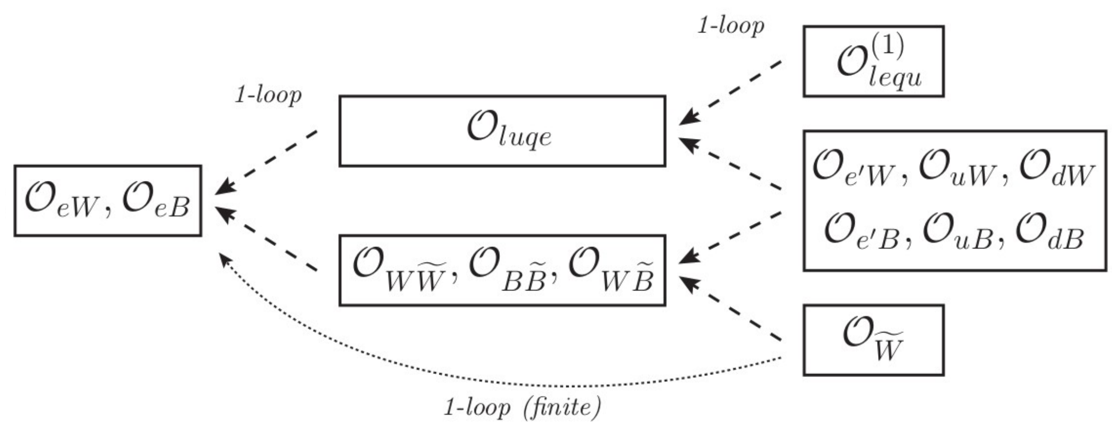

1-loop
$\mathcal{O}_{lequ}^{(1)}$
1-loop
$\mathcal{O}_{luqe}$
$\mathcal{O}_{eW}, \mathcal{O}_{eB}$
$\mathcal{O}_{W\widetilde{W}}, \mathcal{O}_{B\widetilde{B}}, \mathcal{O}_{W\widetilde{B}}$


u_R
$\bar{Q}_L$
$\bar{L}_L$
e_R
u_R
$\bar{Q}_L$
$\bar{L}_L$
e_R

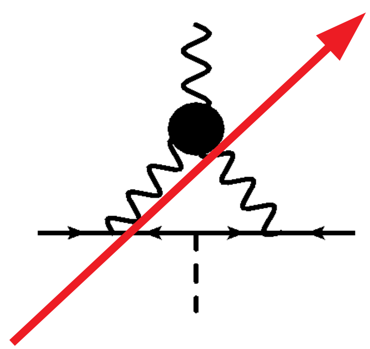

1-loop
$\mathcal{O}^{(1)}_{lequ}$
1-loop
$\mathcal{O}_{luqe}$
$\mathcal{O}_{eW}, \mathcal{O}_{eB}$
$\mathcal{O}_{e'W}, \mathcal{O}_{uW}, \mathcal{O}_{dW}$
$\mathcal{O}_{e'B}, \mathcal{O}_{uB}, \mathcal{O}_{dB}$
$\mathcal{O}_{W\widetilde{W}}, \mathcal{O}_{B\widetilde{B}}, \mathcal{O}_{W\widetilde{B}}$

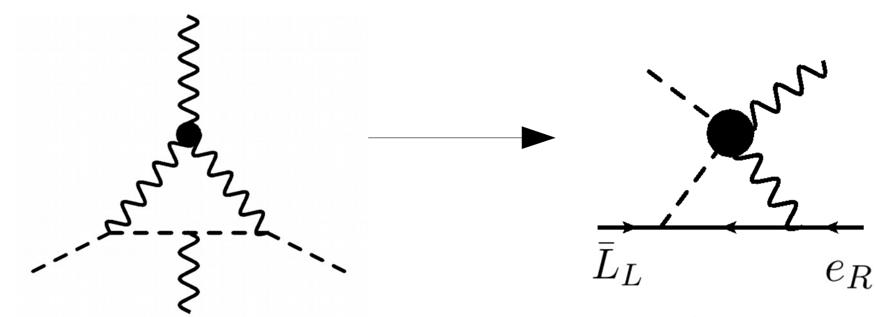

u_R
$\bar{Q}_L$
$\bar{L}_L$
e_R
u_R
$\bar{Q}_L$
$\bar{L}_L$
e_R


$\bar{L}_L$
e_R



Two loop, log^2 contribution competes with the single loop, no log contribution

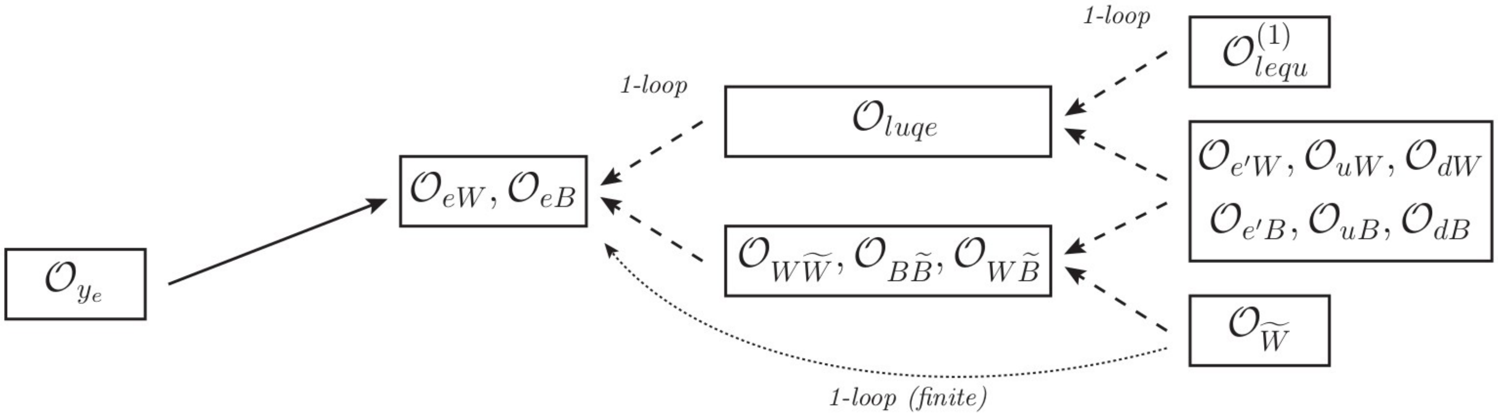




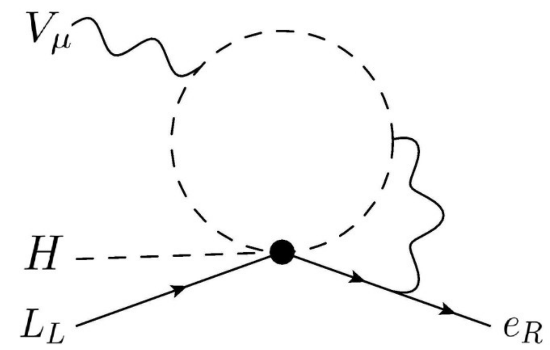
Compared with 1loop,

$$\frac{\frac{y_e e g^3}{(16\pi^2)^2}\,(13+3\tan\theta_W^2)\,\frac{1}{8}\left(\log\frac{\Lambda^2}{m_W^2}\right)^2 C_{3\tilde{W}}}{\sin\theta_W\,\frac{3}{4}\,\frac{1}{16\pi^2}\,y_e g^2 C_{3\tilde{W}}} = \frac{g^2}{16\pi^2}\,\frac{13+3t_W^2}{6}\left(\log\frac{\Lambda^2}{m_W^2}\right)^2$$

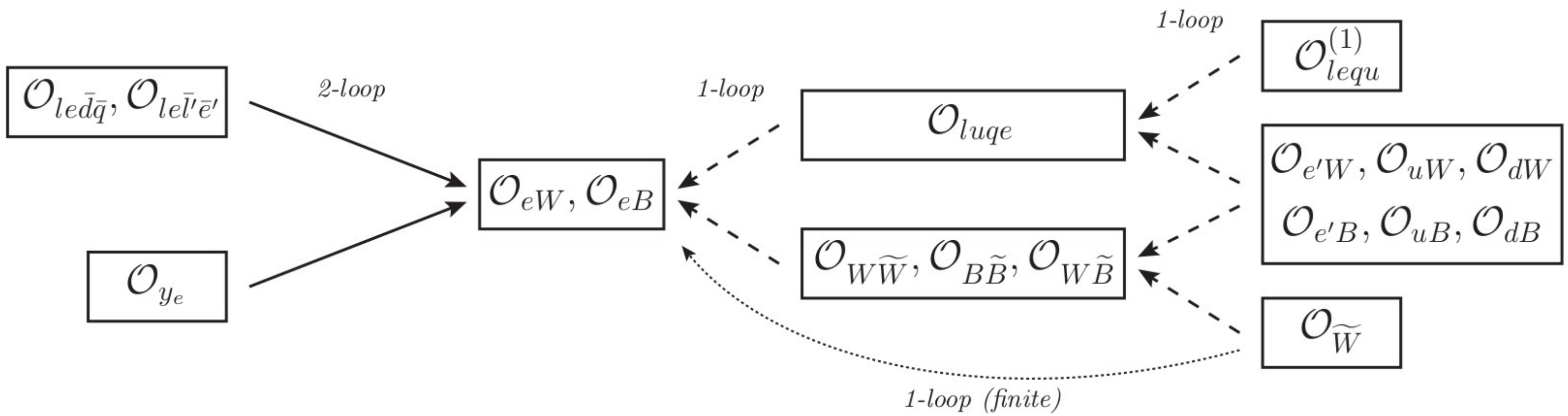
which is O(1) for $\Lambda \sim 5$TeV



$$\frac{d}{d\ln\mu}\begin{pmatrix} C_{eB} \\ C_{eW} \end{pmatrix} = \frac{g^3}{(16\pi^2)^2}\frac{3}{4}\begin{pmatrix} t_{\theta_W} Y_H + 4t_{\theta_W}^3 Y_H^2 (Y_L + Y_e) \\ \frac{1}{2} + \frac{2}{3} t_{\theta_W}^2 Y_H (Y_L + Y_e) \end{pmatrix} C_{y_e}$$

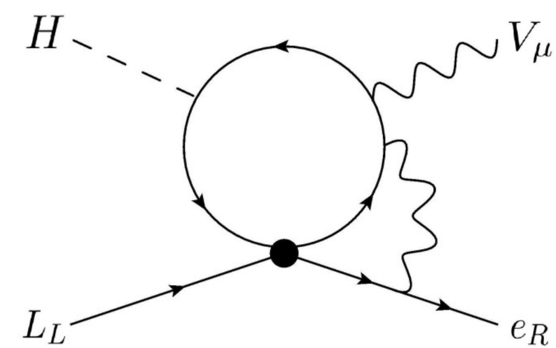


Accidental cancellation makes it smaller and only hypercharge contributes to EDM



$$\frac{d}{d\ln\mu}\mathrm{Im}\begin{pmatrix} C_{eB} \\ C_{eW} \end{pmatrix} = \frac{y_d g^3}{(16\pi^2)^2}\frac{N_c}{4}\begin{pmatrix} 3t_{\theta_W}Y_Q + 4t^3_{\theta_W}(Y_L+Y_e)(Y_Q^2+Y_d^2) \\ \frac{1}{2} + 2t^2_{\theta_W}(Y_L+Y_e)Y_Q \end{pmatrix} C_{led\bar{q}}$$

$$\frac{d}{d\ln\mu}\mathrm{Im}\begin{pmatrix} C_{eB} \\ C_{eW} \end{pmatrix} = \frac{y_{e'} g^3}{(16\pi^2)^2}\frac{1}{4}\begin{pmatrix} 3t_{\theta_W}Y_L + 4t^3_{\theta_W}(Y_L+Y_e)(Y_L^2+Y_e^2) \\ \frac{1}{2} + 2t^2_{\theta_W}(Y_L+Y_e)Y_L \end{pmatrix} C_{le\bar{e}'\bar{l}'}\,.$$



The other 4-fermions enter only at 2 loops, single log

Again, a cancellation for ledq: $\sim g^2 \to \frac{g'^2}{8}$

Impact on BSM

Power counting of the Wilson coefficients

Fix $\Lambda = 10\ TeV.$

tree-level

C_{eW}	$5.5 \times 10^{-5}\, y_e g$
C_{eB}	$5.5 \times 10^{-5}\, y_e g'$

one-loop

C_{luqe}	$1.0 \times 10^{-3}\, y_e y_t$
$C_{W\widetilde{W}}$	$4.7 \times 10^{-3}\, g^2$
$C_{B\widetilde{B}}$	$5.2 \times 10^{-3}\, g'^2$
$C_{W\widetilde{B}}$	$2.4 \times 10^{-3}\, gg'$
$C_{\widetilde{W}}$	$6.4 \times 10^{-2}\, g^3$

two-loops

C_{lequ}	$3.8 \times 10^{-2}\, y_e y_t$
$C_{\tau W}$	$260\, y_\tau g$
$C_{\tau B}$	$380\, y_\tau g'$
C_{tW}	$6.9 \times 10^{-3}\, y_t g$
C_{tB}	$1.2 \times 10^{-2}\, y_t g'$
C_{bW}	$64\, y_b g$
C_{bB}	$47\, y_b g'$
$C_{led\bar{d}\bar{q}}$	$10\, y_e y_t (y_t/y_b)$
$C_{le\bar{e}'\bar{l}'}$	$0.63\, y_e y_t (y_t/y_\tau)$

two-loops finite

C_{y_e}	$14\, y_e \lambda_h$
C_{y_t}	$14\, y_t \lambda_h$
C_{y_b}	$2.9 \times 10^3\, y_b \lambda_h$
C_{y_τ}	$3.1 \times 10^4\, y_\tau \lambda_h$

Table uses ACME-II bounds. Multiply by ~0.5 to get current constraints!

neutron EDM

Current constraints:

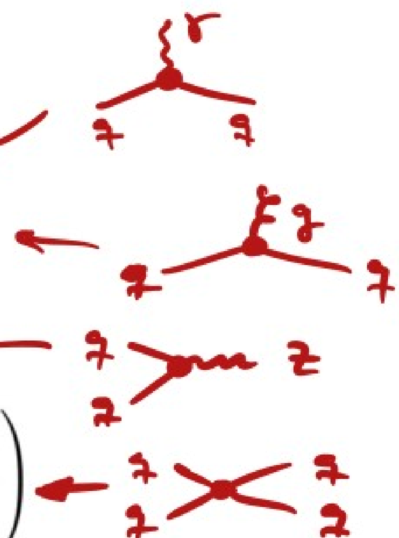
nEDM (PSI) : $d_n < 1.8 \cdot 10^{-26}\, e \cdot \mathrm{cm}$

Future constraints:

n2EDM (PSI) : $d_n < \cdot 10^{-27}\, e \cdot \mathrm{cm}$

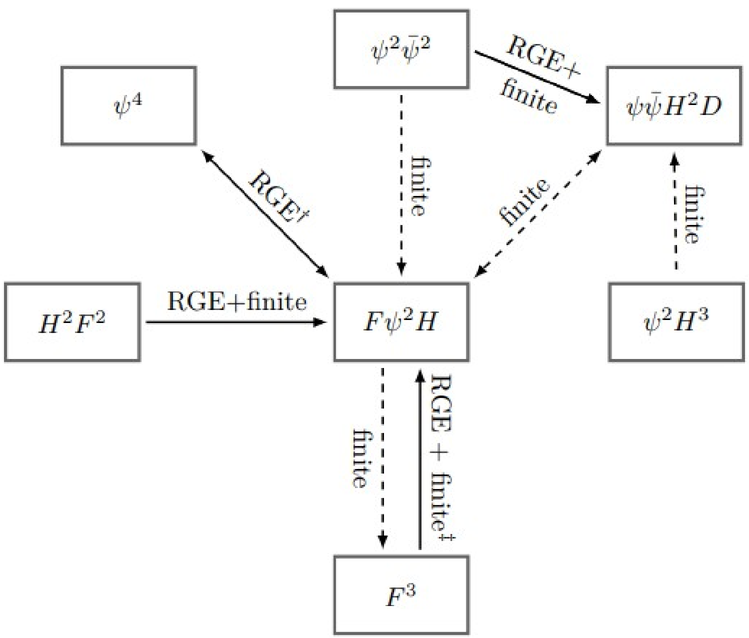
$$\mathcal{L} \supset \theta \frac{g_s^2}{32\pi^2} G\widetilde{G} + m_u \bar{u} u e^{i\theta_u} + m_d \bar{d} d e^{i\theta_d} \;\rightarrow\; \theta + \theta_u + \theta_d < 10^{-10}$$

$$\begin{aligned} d_n = &-(0.204 \pm 0.011)\, d_u + (0.784 \pm 0.028)\, d_d - (0.0027 \pm 0.0016)\, d_s + \\ &+ 0.055(1 \pm 0.5)\, \hat{d}_u + 0.111(1 \pm 0.5)\, \hat{d}_d - 51.2(1 \pm 0.5)\, e \cdot \mathrm{MeV}\, \frac{C_{\tilde{G}}}{\Lambda^2} + \\ &- 9.22(1^{+2.33}_{-0.67})\, e \cdot \mathrm{MeV}\, \frac{\mathrm{Im}[C_{\substack{Hud \\ 11}}]}{\Lambda^2} + \\ &- 0.615(1^{+1}_{-0.75})\, e \cdot \mathrm{GeV} \left(\frac{\mathrm{Im}[c^{(\mathrm{S1,RR})}_{\substack{ud \\ 1111}} - c^{(\mathrm{S1,RR})}_{\substack{duud \\ 1111}}]}{\Lambda^2} + \frac{\mathrm{Im}[c^{(\mathrm{S8,RR})}_{\substack{ud \\ 1111}} - c^{(\mathrm{S8,RR})}_{\substack{duud \\ 1111}}]}{\Lambda^2} \right) \end{aligned}$$



neutron EDM

Kley, Theil, Venturini, Weiler ‘22



$\Lambda = 5\text{TeV}$

Operator	RGE only	RGE + finite
$C_{H\widetilde{G}}$	$9.40 \cdot 10^{-3} g_s^2$	$7.81 \cdot 10^{-3} g_s^2$
$C_{H\widetilde{B}}$	$2.04 \cdot 10^{0} g'^2$	$1.53 \cdot 10^{0} g'^2$
$C_{H\widetilde{W}}$	$2.99 \cdot 10^{-1} g^2$	$2.62 \cdot 10^{-1} g^2$
$C_{HW\widetilde{B}}$	$1.76 \cdot 10^{-1} gg'$	$1.61 \cdot 10^{-1} gg'$
$C_{\widetilde{W}}$	—	$3.46 \cdot 10^{0} g^3$
$C_{\widetilde{G}}$	$4.74 \cdot 10^{-5} g_s^3$	$6.91 \cdot 10^{-5} g_s^3$

Operator	RGE only	RGE + finite
$\text{Im}\, C_{\underset{11}{Hud}}$	$1.87 \cdot 10^{-2} g'^2$	$2.03 \cdot 10^{-2} g'^2$
$\text{Im}\, C_{\underset{31}{Hud}}$	—	$1.03 \cdot 10^{-2} g'^2$
$\text{Re}\, C_{\underset{31}{Hud}}$	—	$3.53 \cdot 10^{-3} g'^2$
$\text{Im}\, C_{\underset{11}{uH}}$	—	$1.33 \cdot 10^{9} \lambda_u$
$\text{Im}\, C_{\underset{11}{dH}}$	—	$1.33 \cdot 10^{9} \lambda_d$

+ many 4-fermions...

proton EDM

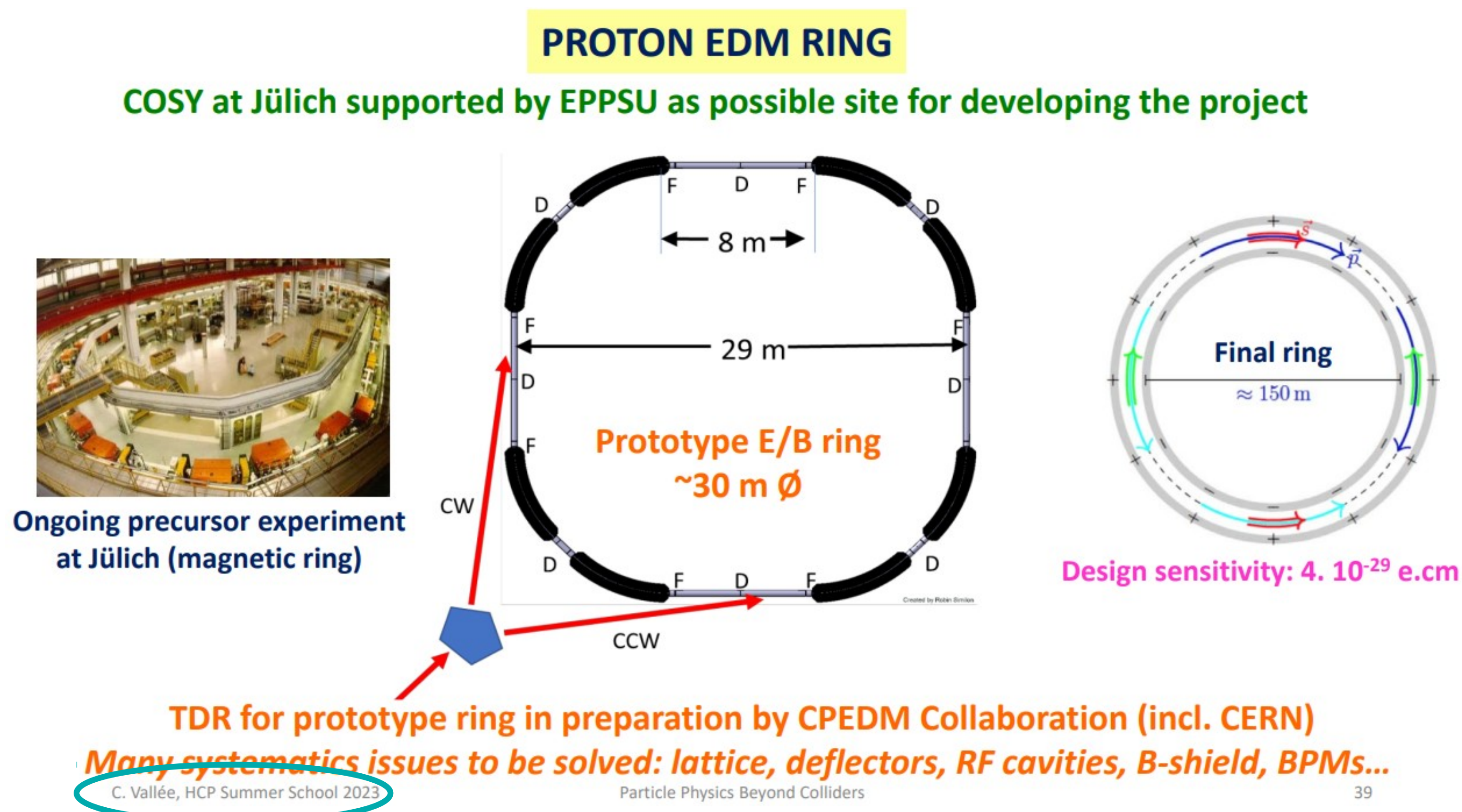
nEDM (PSI) : $d_n < 1.8 \cdot 10^{-26}\, e \cdot \mathrm{cm}$

Current constraints:

pEDM (199Hg) : $d_p <\sim 10^{-25}\, e \cdot \mathrm{cm}$

Future:

Storage ring (COSY, Julich, Germany): $d_p < 10^{-29}\, e \cdot \mathrm{cm}$



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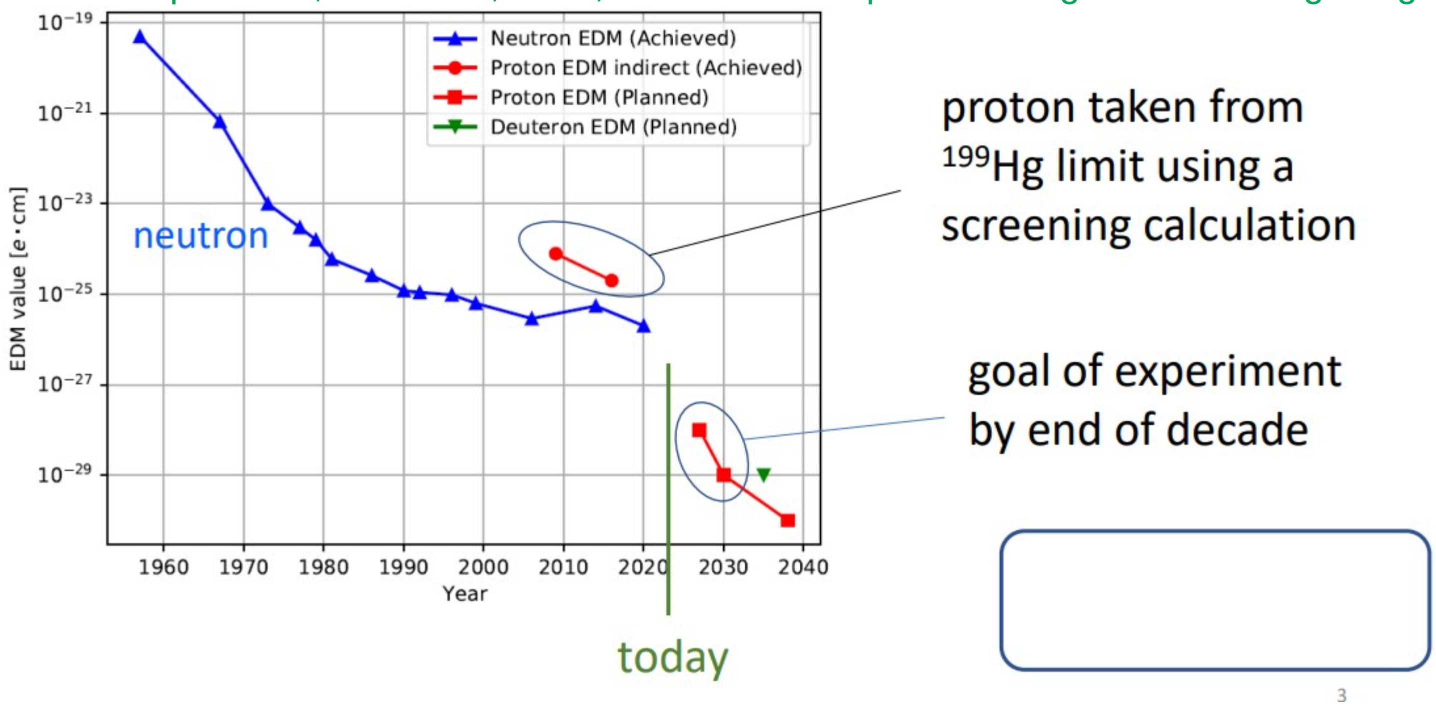
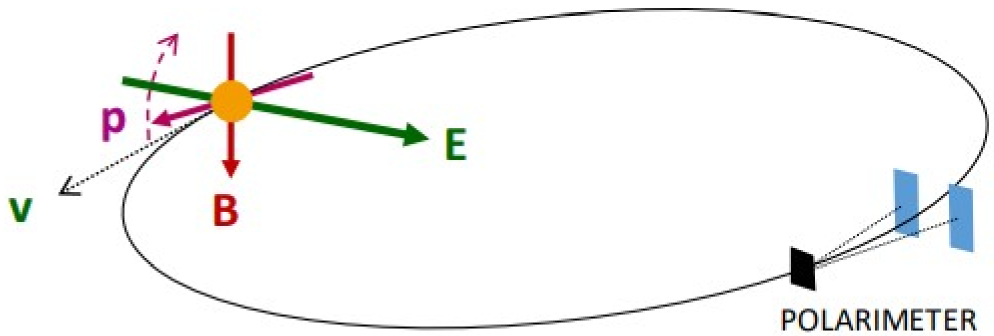
slide from E. Stephenson, March 23, 2023, The search for p EDM using electric storage ring



proton EDM

J. Pertz (JEDI and CPEDM collaborations)
DOI: 10.22323/1.412.0026



$$\frac{d\vec{S}}{dt} = (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}) \times \vec{S}$$

$$\vec{\Omega}_{MDM} = -\frac{q}{m}\left[G\vec{B} - \frac{\gamma G}{\gamma+1}\vec{\beta}\left(\vec{\beta}\cdot\vec{B}\right) - \left(G - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right],$$

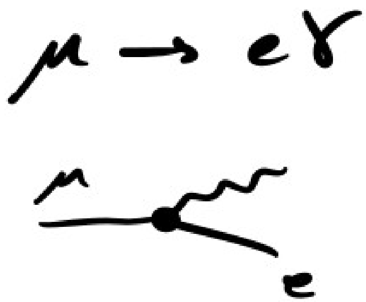
$$\vec{\Omega}_{EDM} = -\frac{\eta q}{2mc}\left[\vec{E} - \frac{\gamma}{\gamma+1}\vec{\beta}\left(\vec{\beta}\cdot\vec{E}\right) + c\vec{\beta}\times\vec{B}\right].$$

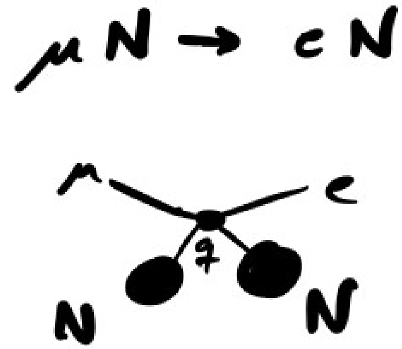
$$\vec{\mu} = g\frac{q\hbar}{2m}\vec{S} = (1+G)\frac{q\hbar}{m}\vec{S}, \qquad \vec{d} = \eta\frac{q\hbar}{2mc}\vec{S},$$

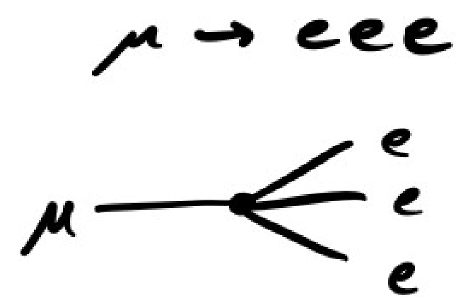
$$E_r = \frac{GBc\beta\gamma^2}{1 - GB\beta^2\gamma^2}$$ → Spin precession sensitive to p EDM

$$\sigma_{\text{stat}}(1\,\text{year}) = 2.4\times10^{-29}\,\text{e}\cdot\text{cm}$$

LFV







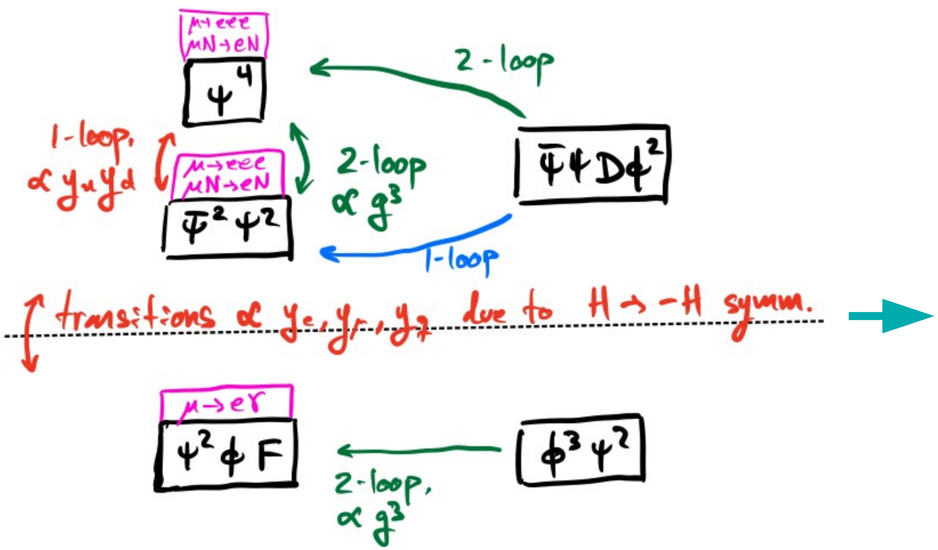
Current constraints:

MEG (PSI)	**SINDRUM-II (PSI)**	**SINDRUM (PSI)**
$\mathrm{Br}(\mu \to e\gamma) \leq 4.2 \cdot 10^{-13}$	$\mathrm{R}(\mu N \to eN) \leq 7 \cdot 10^{-13}$	$\mathrm{Br}(\mu \to eee) \leq 10^{-12}$

Future constraints:

MEG-II (PSI)	**Mu2e (Fermilab)**	**Mu3e (PSI)**
$\mathrm{Br}(\mu \to e\gamma) \leq 6.0 \cdot 10^{-14}$	$\mathrm{R}(\mu N \to eN) \leq 7 \cdot 10^{-17}$	$\mathrm{Br}(\mu \to eee) \leq 10^{-16}$

LFV



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	$\mu\to e\gamma$	$\mu\to eee$	$\mu N\to eN$	$h\to\mu e$
$C^{\mu e}_{DB}-C^{\mu e}_{DW}$	951 TeV (1547 TeV)	218 TeV (2183 TeV)	208 TeV (1812 TeV)	
$C^{\mu e}_{DB}+C^{\mu e}_{DW}$	127 TeV (214 TeV)	26 TeV (309 TeV)	24 TeV (253 TeV)	
$C^{\mu e}_{R}$	35 TeV (59 TeV)	160 TeV (1602 TeV)	225 TeV (1535 TeV)	
$C^{\mu e}_{L}+C^{\mu e}_{L3}$	4 TeV (7 TeV)	164 TeV (1642 TeV)	225 TeV (1535 TeV)	
$C^{\mu e}_{L}-C^{\mu e}_{L3}$	24 TeV (41 TeV)	35 TeV (421 TeV)	50 TeV (395 TeV)	
$C^{\mu ett}_{LuQe}$	304 TeV (510 TeV)	63 TeV (735 TeV)	59 TeV (604 TeV)	
$C^{\mu ett}_{LeQu}$	80 TeV (141 TeV)	14 TeV (209 TeV)	5 TeV (57 TeV)	
$C^{\mu eee}_{LL(RR),LR(RL)}$		207,174 TeV (2070,1740 TeV)		
$C^{\mu euu}_{LL,RR,LR}$			352 TeV (2693 TeV)	
$C^{\mu edd}_{LL,RR,LR}$			376 TeV (2725 TeV)	
$C^{\mu dde}_{LR}$			18 TeV (164 TeV)	
$C^{\mu e\tau\tau}_{LL,RR,LR,RL}$		14,16,14,16 TeV (174,194,174,194 TeV)	22 TeV (200 TeV)	
$C^{\mu e\tau\tau}_{LL3}$		20 TeV (247 TeV)	55 TeV (476 TeV)	
$C^{\mu ett}_{LL,RR,LR,RL}$	122 TeV (214 TeV)	21 TeV (317 TeV)	22,32,32,22 TeV (200,290,290,200 TeV)	
$C^{\mu ett}_{LL3}$	230 TeV (401 TeV)	41 TeV (592 TeV)	100 TeV (851 TeV)	
$C^{\mu ebb}_{LL,RR,LR,RL}$		14,16,14,16 TeV (174,194,174,194 TeV)	22 TeV (200 TeV)	
$C^{\mu e}_{y}$	4 TeV (6 TeV)	1 TeV (9 TeV)	1 TeV (7 TeV)	0.3 TeV

Present (future)

tree 1-loop (1-loop)^2 2-loop

Conclusions

In the near future, EDM and LFV searches are expected to improve from one to four orders of magnitude,

constraining generic microscopic sources even at the multi-TeV scale