EFT approach for the electron EDM at two loops

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NPKI, May 2019

Based on **1810.09413**, with **Giuliano Panico** and **Alex Pomarol**

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

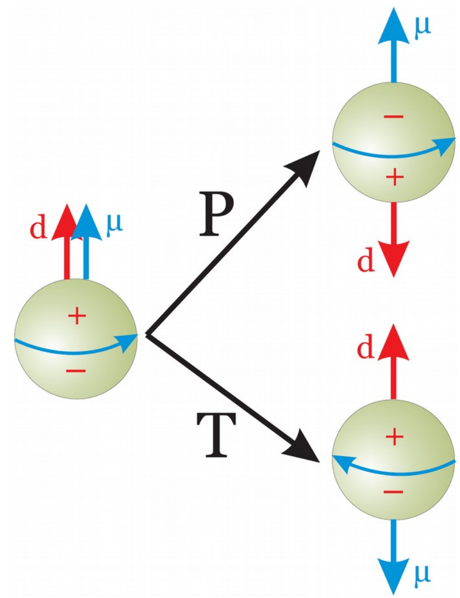
relativistic limit

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

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

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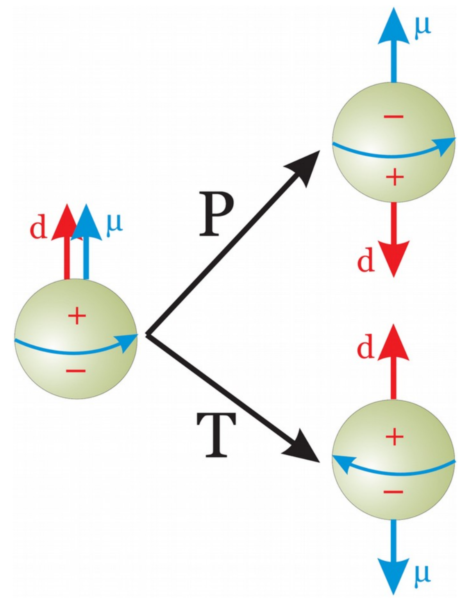
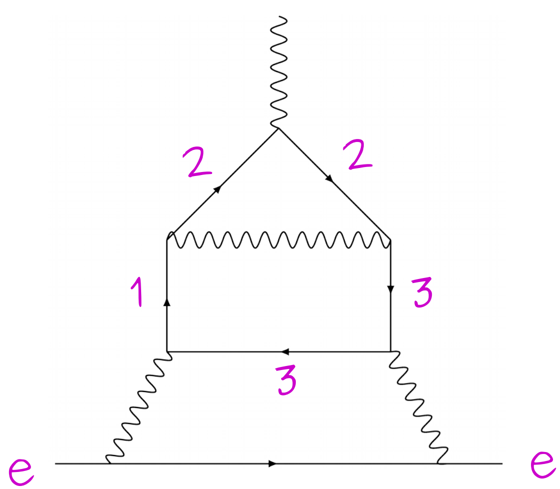


Nonvanishing d breaks CP

SM prediction:



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

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

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

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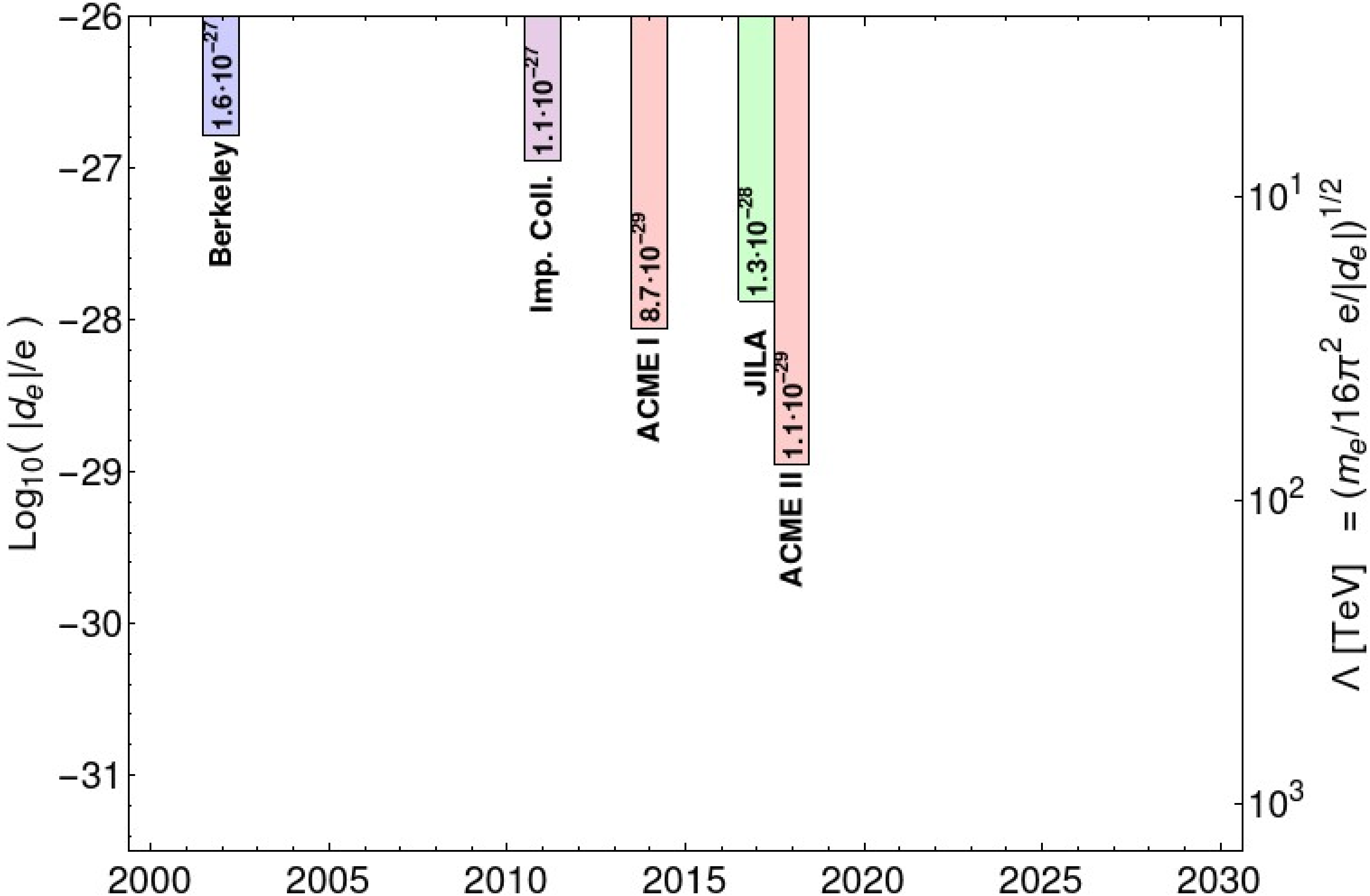
Theory Group, Department of Physics, University of Texas, Austin, Texas 78712
(Received 25 August 1989)

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: ACME II $|d_e| < 1.1 \cdot 10^{-29}$ e cm

Translation of ACME constraints to particle physics:

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

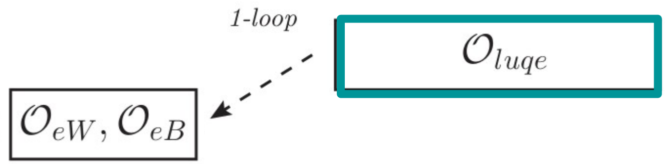
Relevant constraints even at two loops.

We want to characterize all effects that enter with

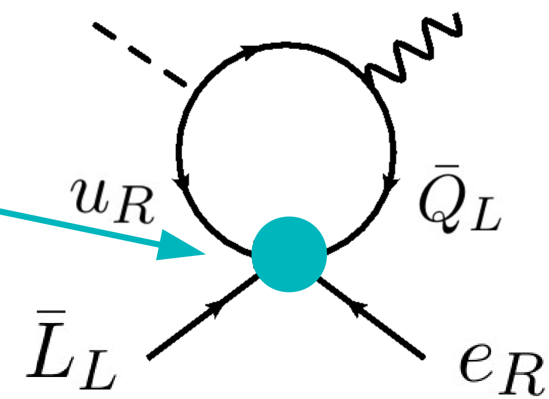
Two loops Chirality flip log enhanced

This is the key to help organize the contributions

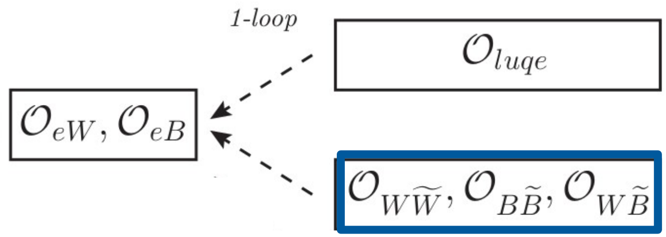
$$\boxed{\mathcal{O}_{eW}, \mathcal{O}_{eB}}$$



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



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

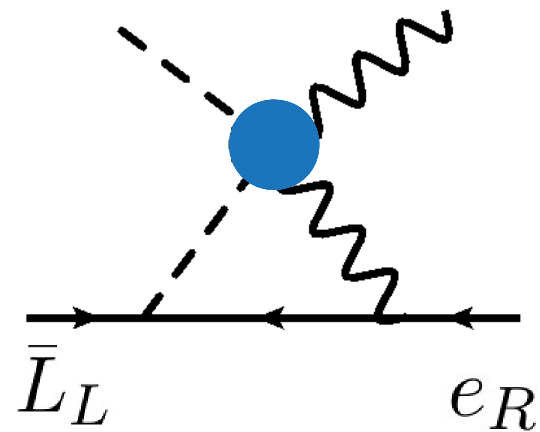


$$\frac{d}{d\ln\mu}\mathrm{Im}\begin{pmatrix} C_{eB} \\ C_{eW} \end{pmatrix} = -\frac{y_e g}{16\pi^2}\begin{pmatrix} 0 & 2t_{\theta_W}(Y_L+Y_e) & \frac{3}{2} \\ 1 & 0 & t_{\theta_W}(Y_L+Y_e) \end{pmatrix}\begin{pmatrix} C_{W\widetilde{W}} \\ C_{B\widetilde{B}} \\ C_{W\widetilde{B}} \end{pmatrix}$$

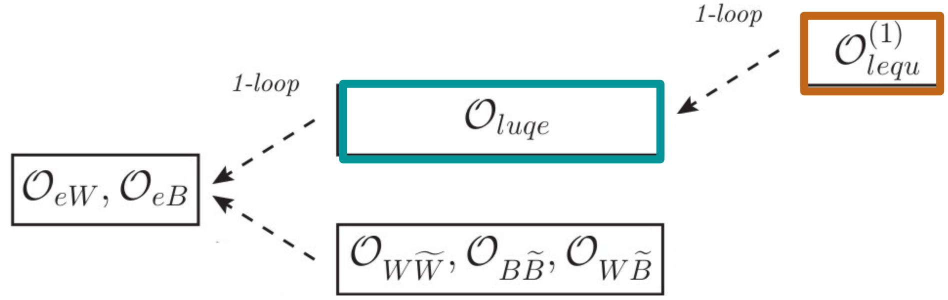
It is useful to write the parameters in a more physical way

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

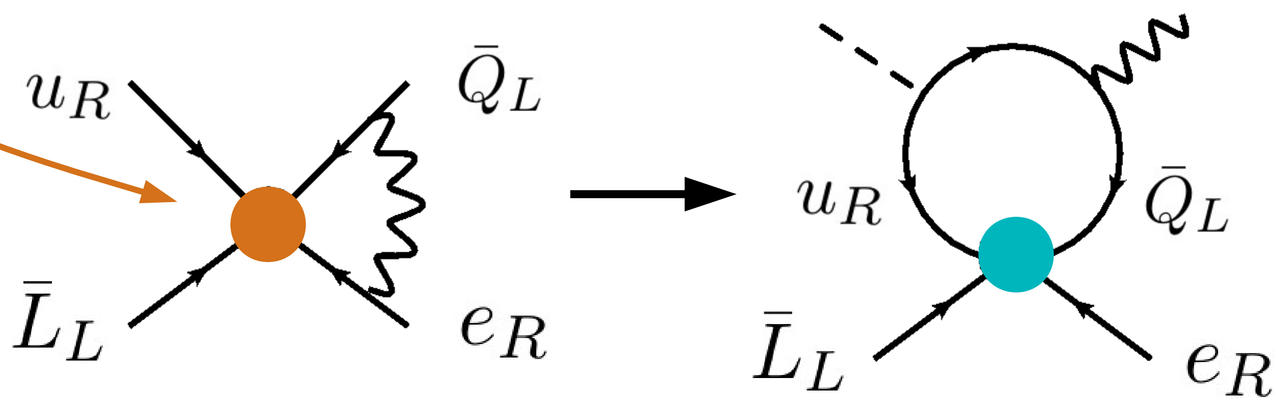
$$\frac{d}{d\ln\mu}d_e(\mu) = \frac{e}{8\pi^2}\frac{m_e}{\Lambda^2}\left[4Q_e\tilde{\kappa}_{\gamma\gamma} - \frac{4}{s_{2\theta_W}}\left(\frac{1}{2}+2Q_e s_{\theta_W}^2\right)\tilde{\kappa}_{\gamma Z} + \frac{\Lambda^2}{v^2}\delta\tilde{\kappa}_{\gamma}\right]$$

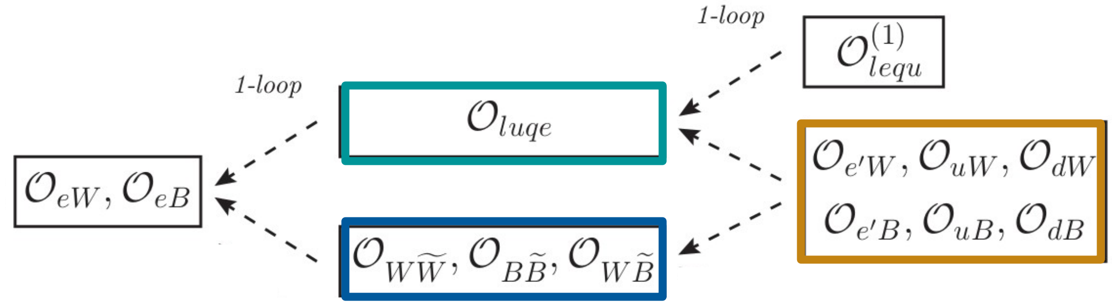


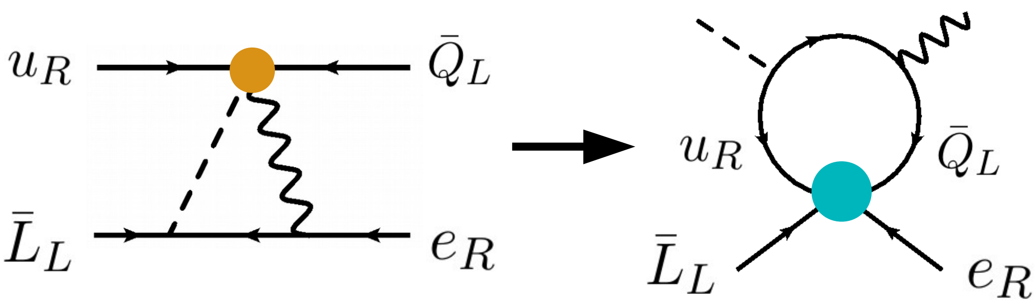
Due to approximate accidental cancellation, 1/2+2 Qe sin^2 ~ 0.04, Z boson contribution negligible.

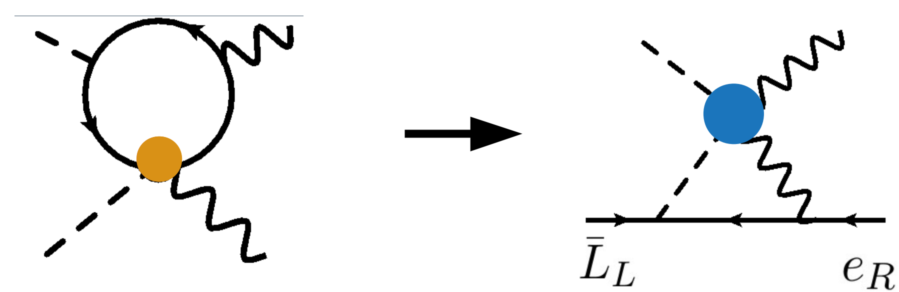


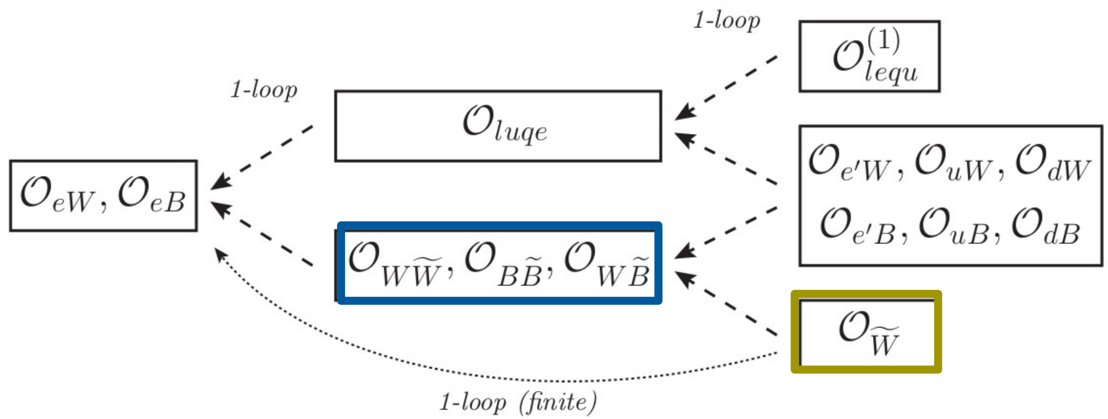
$\mathcal{O}^{(1)}_{lequ} = (\bar{L}_L e_R)(\bar{Q}_L u_R)$ enters through $\mathcal{O}_{luqe} = (\bar{L}_L u_R)(\bar{Q}_L e_R)$,
only 4−fermion that renormalizes it



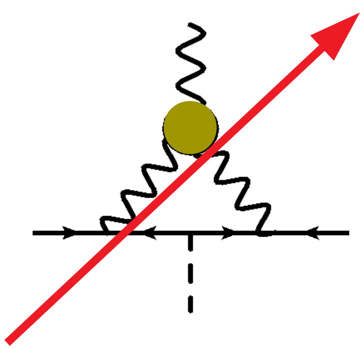

1-loop
$\mathcal{O}^{(1)}_{lequ}$
1-loop
$\mathcal{O}_{luqe}$
$\mathcal{O}_{eW}, \mathcal{O}_{eB}$
$\mathcal{O}_{e'W}, \mathcal{O}_{uW}, \mathcal{O}_{dW}$
$\mathcal{O}_{e'B}, \mathcal{O}_{uB}, \mathcal{O}_{dB}$
$\mathcal{O}_{W\widetilde{W}}, \mathcal{O}_{B\widetilde{B}}, \mathcal{O}_{W\widetilde{B}}$

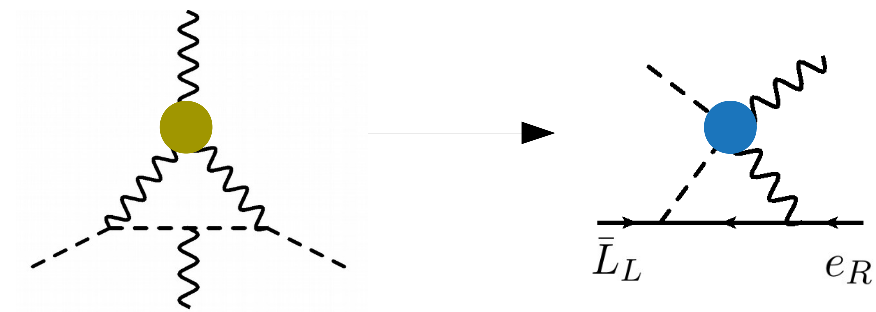

u_R
$\bar{Q}_L$
$\bar{L}_L$
e_R
u_R
$\bar{Q}_L$
$\bar{L}_L$
e_R


$\bar{L}_L$
e_R



This one is interesting, since a two loop, log^2 contribution competes with the single loop, no log contribution

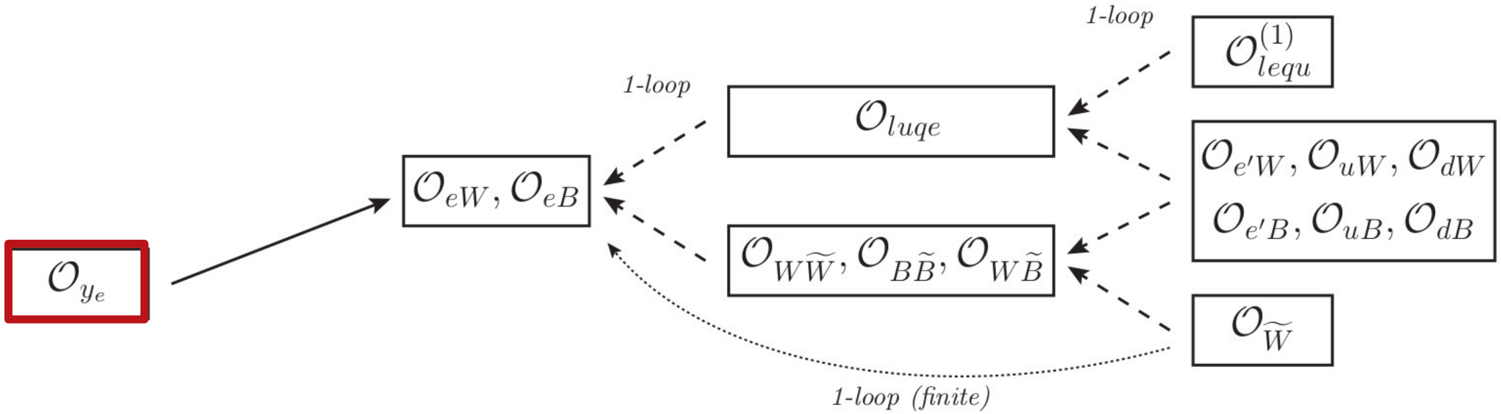




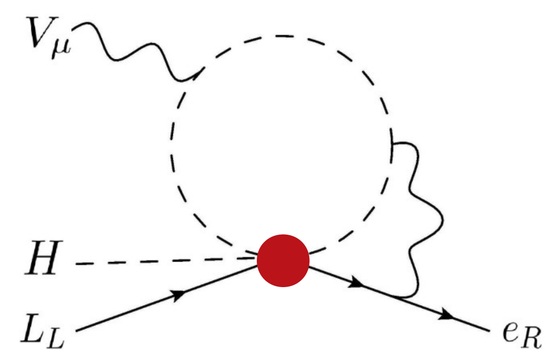
Compared with 1loop,

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

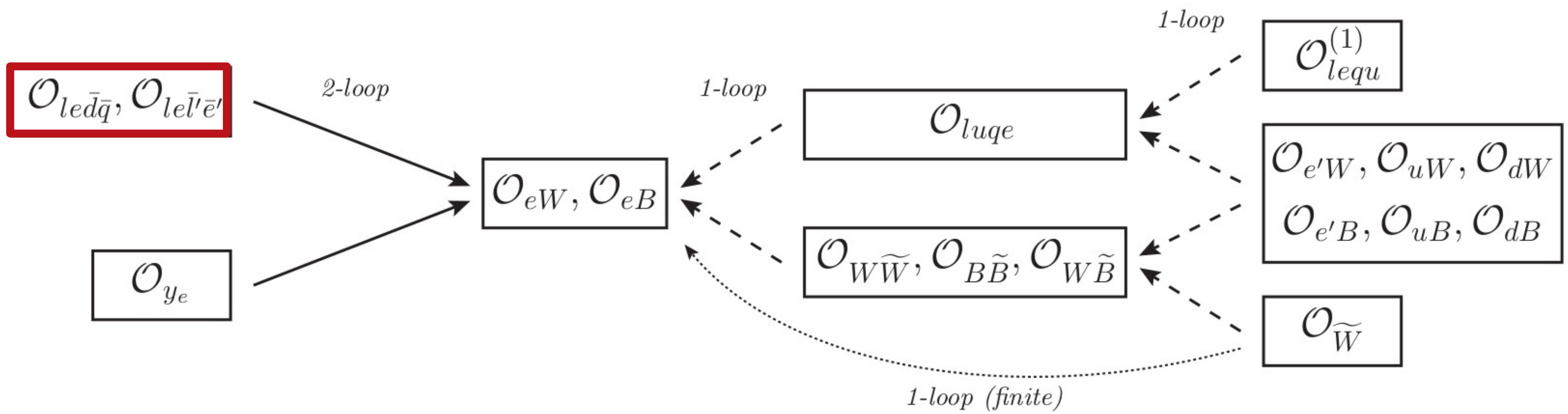
which is O(1) for $\Lambda \sim$ 5TeV



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

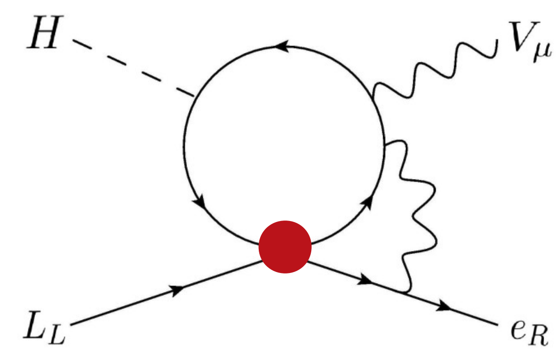


Accidental cancellation makes it smaller and only hypercharge contributes to EDM



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

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



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

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

Impact on BSM

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}	$47\, y_b g'$
$C_{led\bar{q}}$	$10\, y_e y_t (y_t/y_b)$
$C_{le\bar{e}'\bar{l}'}$	$0.63\, y_e y_t (y_t/y_\tau)$

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}	$3.1 \times 10^4\, y_\tau \lambda_h$

Leptoquarks

EDM sets strong constraints to leptoquarks that couple to both left and right leptons

$$(\mathbf{3},\mathbf{2},\mathbf{7/6})$$

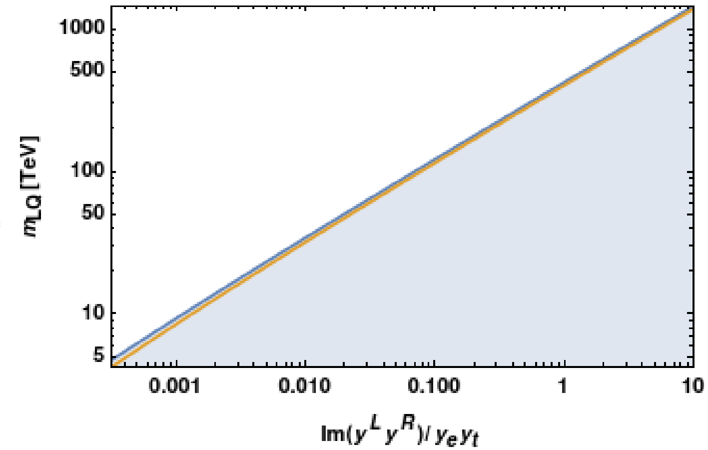
$$\mathcal{L} = -y_2^{RL}\bar{t}_R R^a \varepsilon^{ab} L_{L_1}^b + y_2^{LR}\bar{e}_R R^{a*} Q_{L_3}^a + \text{h.c.}\,,$$

$$\mathcal{L}_{eff}^{R_2} = \frac{y_2^{LR*}y_2^{RL*}}{m_{R_2}^2}\mathcal{O}_{luqe}$$

$$(\overline{\mathbf{3}},\mathbf{1},\mathbf{1/3})$$

$$\mathcal{L} = y_1^{LL}\overline{Q}_{L_3}^{C\,a} S_1 \varepsilon^{ab} L_{L_1}^b + y_1^{RR}\bar{t}_R S_1 e_R + \text{h.c.}$$

$$\mathcal{L}_{eff}^{S_1} = \frac{y_1^{LL*}y_1^{RR}}{m_{S_1}^2}\left[\mathcal{O}_{luqe} + \mathcal{O}_{lequ}^{(1)}\right]$$



$$(\overline{\mathbf{3}},\mathbf{2},\mathbf{5/6})$$

$$\mathcal{L} = x_2^{RL}\overline{b}_R^C \gamma^\mu V_{2,\mu}^a \varepsilon^{ab} L_{L_1}^b + x_2^{LR}\overline{Q}_{L_3}^{C\,a}\gamma^\mu \varepsilon^{ab} V_{2,\mu}^b e_R$$

$$m_{V_2} \gtrsim 5.5\,\text{TeV}\,\sqrt{\frac{\text{Im}(x_2^{LR}x_2^{RL\star})}{y_e y_b}}$$

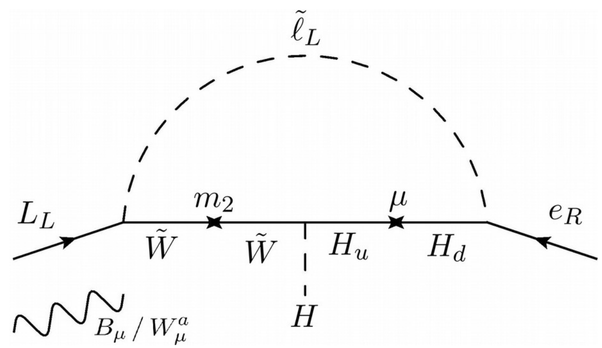
$$(\mathbf{3},\mathbf{1},\mathbf{2/3})$$

$$\mathcal{L} = x_1^{LL}\overline{Q}_{L_3}^a \gamma^\mu U_{1,\mu} L_{L_1}^a + x_1^{RR}\bar{b}_R \gamma^\mu U_{1,\mu} e_R$$

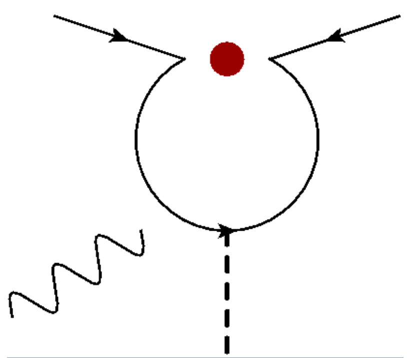
$$m_{U_1} \gtrsim 2.5\,\text{TeV}\,\sqrt{\frac{\text{Im}(x_2^{RR}x_2^{LL\star})}{y_e y_b}}$$

Supersymmetry: 1 loop + tree

One loop EDMs are very important in SUSY.
Exact expressions are very complicated, but now we know superpartners are heavy.



$$\mathcal{L} \supset \frac{y_e g}{m_{\widetilde{L}}^2} \bar{L}_L \widetilde{W} \bar{\widetilde{H}}_d e_R$$

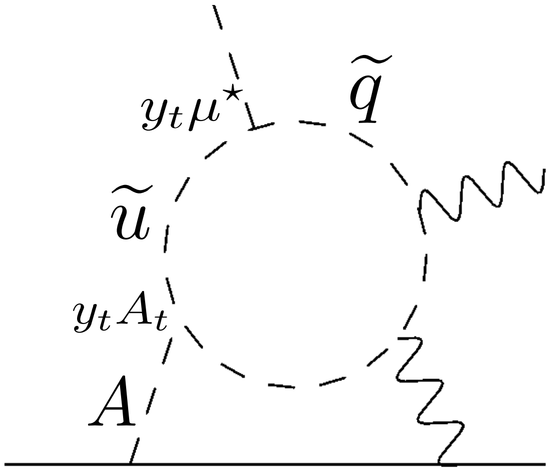


$$\frac{d_e}{e} \sim \frac{g^2}{16\pi^2} \frac{m_e}{m_{\widetilde{L}}^2} \tan\beta \frac{\mathrm{Im}(m_2 \mu)}{m_{\widetilde{L}}^2} \log \frac{|m_2 \mu|}{m_{\widetilde{L}}^2}$$

$$m_{\tilde{L}_L} \gtrsim 25\,(50)\ \mathrm{TeV} \quad \text{for } m_{\tilde{L}_L} = M_2 = \mu \ (m_{\tilde{L}_L} \gg \mu = M_2)$$

Supersymmetry: 2 loop + tree

At two loops, a Barr-Zee diagram gives sensitivity to stops.



Nakai, Reece, 1612.08090

$$\frac{d_e}{e} = \frac{e^2}{(16\pi^2)^2}\frac{m_e}{m_A^2}2N_c Q_t^2 y_t^2 \tan\beta \frac{|\mu A_t|}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2}\sin\arg(\mu A_t)\left[F\left(\frac{m_{\tilde{t}_1}^2}{m_A^2}\right) - F\left(\frac{m_{\tilde{t}_2}^2}{m_A^2}\right)\right]$$

$$F(z) = \int_0^1 dx \frac{x(1-x)}{z - x(1-x)}\log\frac{x(1-x)}{z}$$

Also understood via RGE of AFF to dipole. After integrating out the stops,

$$\mathcal{L} \sim y_u^2(H_u H_d A_u \mu^\star + H_u^\star H_d^\star A_u^\star \mu)F_{\mu\nu}F_{\mu\nu} \sim y_u^2(s_\beta v_u + c_\beta v_d)\mathrm{Im}(A_u\mu^\star)A^0 F_{\mu\nu}F_{\mu\nu}$$

$$\frac{d_e}{e} \sim \frac{e}{16\pi^2}\frac{4}{9}\frac{m_e}{m_A^2}\tan\beta\frac{|\mu A_t|}{m_{\tilde{t}}^2}\sin\arg(\mu A_t)\log\frac{m_{\tilde{t}}^2}{m_A^2}$$

➞ $m_{\tilde{t}} > 5\text{TeV} \;\text{for}\; \tan\beta \sim \sin\arg A_t\mu \sim 1, m_A \sim \mu \sim A_t \sim 1\text{TeV}$

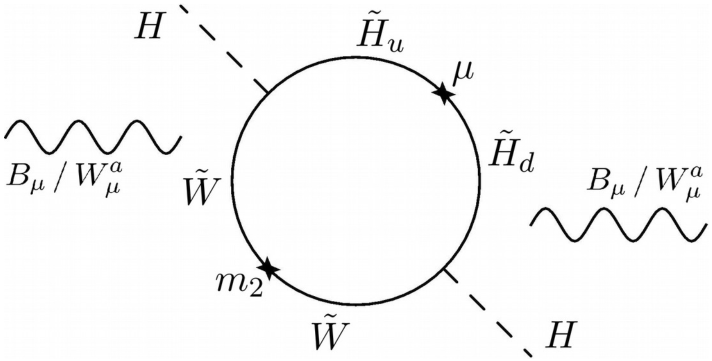
Supersymmetry: 1 loop + 1loop, HHFF

Since the decoupling 1/scalars^4, EDM via HHFF relevant in split SUSY

$$C_{W\widetilde{W}} = C_{loop}\,\frac{-8+27\rho-24\rho^2+5\rho^3+6\rho^2\ln\rho}{16(\rho-1)^3}\,,$$

$$C_{B\widetilde{B}} = t_{\theta_W}^2 C_{loop}\,\frac{\rho(11-16\rho+5\rho^2-2(\rho-4)\ln\rho)}{16(\rho-1)^3}\,,$$

$$C_{W\widetilde{B}} = t_{\theta_W} C_{loop}\,\frac{\rho(7-8\rho+\rho^2+2(\rho+2)\ln\rho)}{8(\rho-1)^3}\,,$$



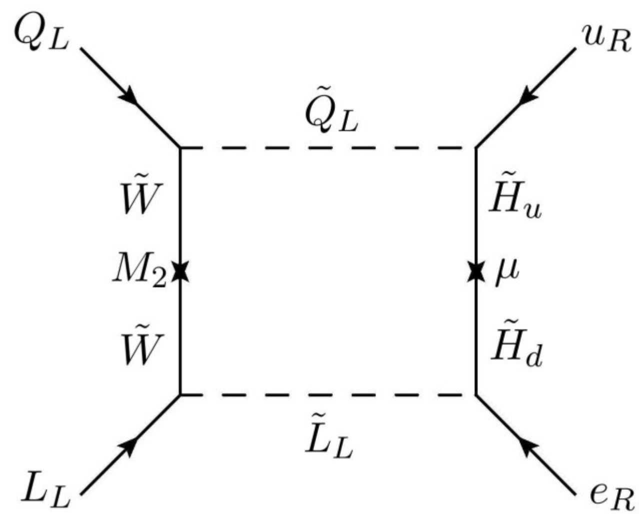
$$C_{loop} \equiv \frac{g^4 \sin 2\beta \sin\varphi}{16\pi^2|M_2\mu|}\,, \quad \varphi = \mathrm{Arg}[m_{12}^2\mu^* M_2^*] \qquad \rho \equiv |M_2/\mu|^2$$

For tan beta ~ CP phases ~ O(1)

$$\sqrt{|M_2\mu|} \gtrsim 4\,\mathrm{TeV}$$

Supersymmetry: 1 loop + 1loop, luqe

Contribution to luqe via squark–gauginos loop



$$\mathrm{Im}\, C_{luqe} = -y_e y_u \frac{3g^2\, \mathrm{Im}[\mu M_2]}{16\pi^2 \sin 2\beta} F(m_i^2)$$ with $$F(m_i^2) = -\sum_i \frac{m_i^2 \ln m_i^2}{\Pi_{i\neq j}(m_i^2 - m_j^2)}$$

For degenerate superpartner masses, $m_i \gtrsim 7.5\,\mathrm{TeV}$

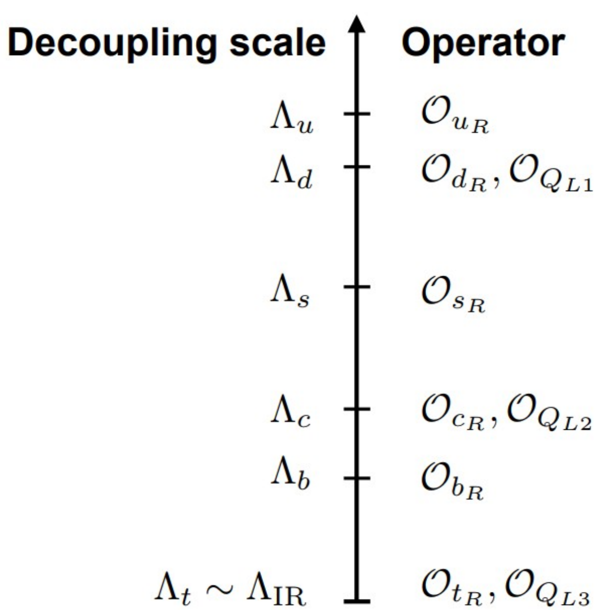
Consequences for Composite models

EDM sets very strong constraints to naive anarchic compositeness for leptons

$$\frac{d_e}{e} \sim \frac{1}{8\pi^2}\frac{m_e}{f^2} \quad \longrightarrow \quad f \gtrsim 107\ \text{TeV}$$

There are ways to avoid this, e.g. by O(2) symmetries or mass generation by bilinears

Panico, Pomarol, 1603.06609



$$\mathcal{L}_{\text{lin}} = \epsilon_{f_i}\, \bar{f}_i\, \mathcal{O}_{f_i}$$

↓ decouple at Λ_i

$$\mathcal{L}_{bil} = \frac{1}{\Lambda_i^{d_H-1}}(\epsilon_i f_i)\mathcal{O}_H(\epsilon_j f_j)$$

↓

$$\frac{d_e}{e} \sim \frac{g_\star^2}{16\pi^2}\frac{m_e}{\Lambda_e^2} \sim \frac{g_\star^2}{16\pi^2}\frac{y_e y_\tau}{g_\star^2}\frac{m_e}{\Lambda_{IR}^2}$$

We assume that somehow this is solved.

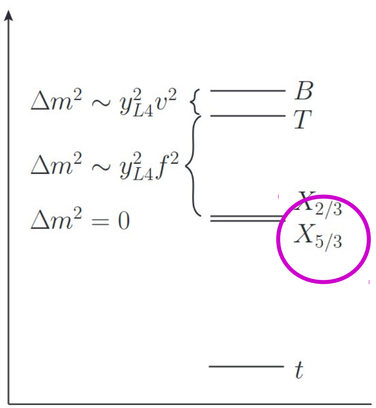
We focus on the EDM generated by **top partners**

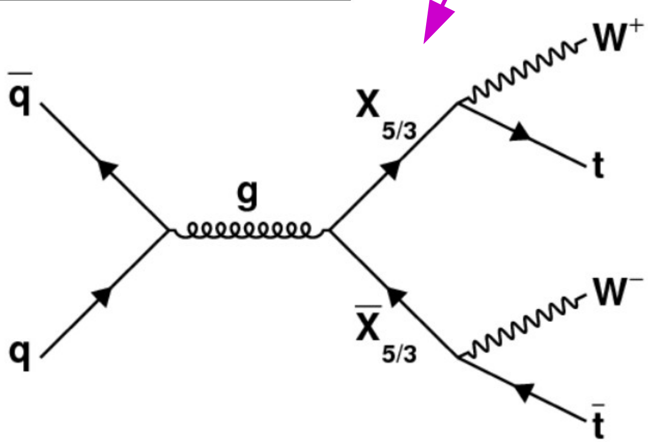
Consequences for Composite models

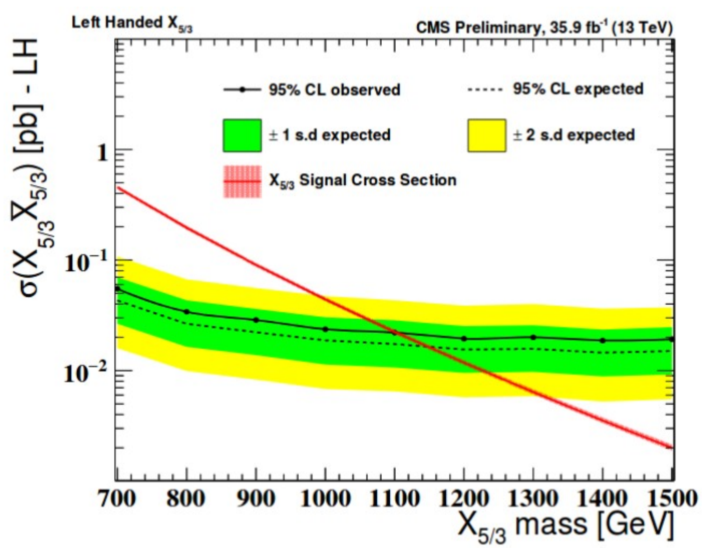
G.Panico, MR, T.Vantalon 1712.06337

Take SO(5)/SO(4):

$$\mathcal{L} = i\bar q_L \not{D} q_L + i\bar t_R \not{D} t_R + i\bar\psi_4(\not{D} - i\not{e})\psi_4 - (m_4 \bar\psi_{4L}\psi_{4R} + \text{h.c.})$$
$$+ \left(-i\, c_t \bar\psi^i_{4R}\gamma^\mu d^i_\mu t_R + \frac{y_{Lt}}{2} f (U^t \bar q^{\mathbf{14}}_L U)_{55} t_R + y_{L4} f (U^t \bar q^{\mathbf{14}}_L U)_{i5}\psi^i_{4R} + \text{h.c.}\right)$$







CMS B2G-16-019-pas

Consequences for Composite models

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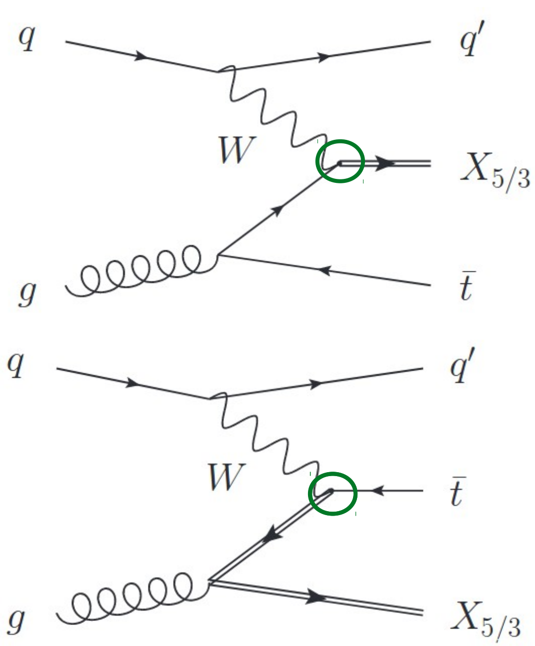

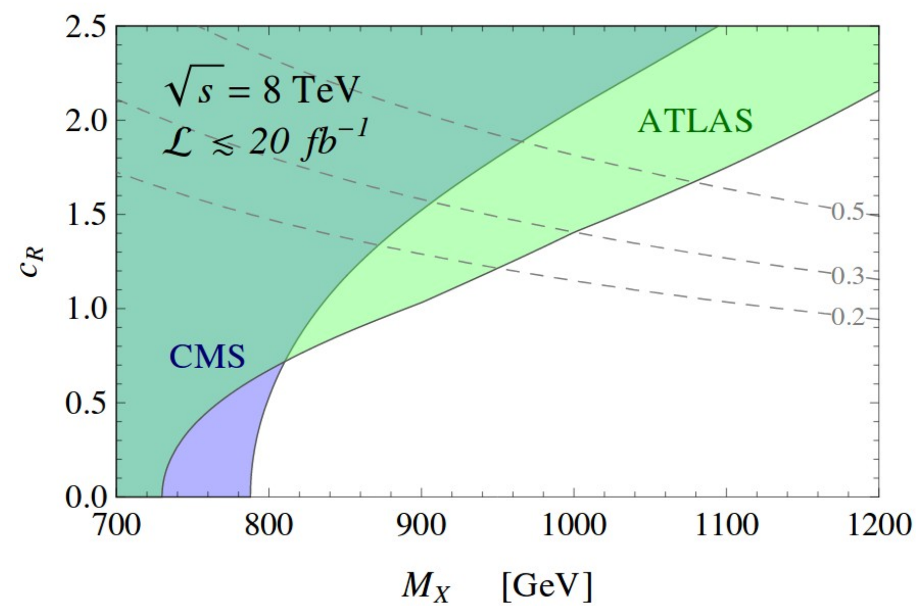

arXiv: 1409.0100

Consequences for Composite models

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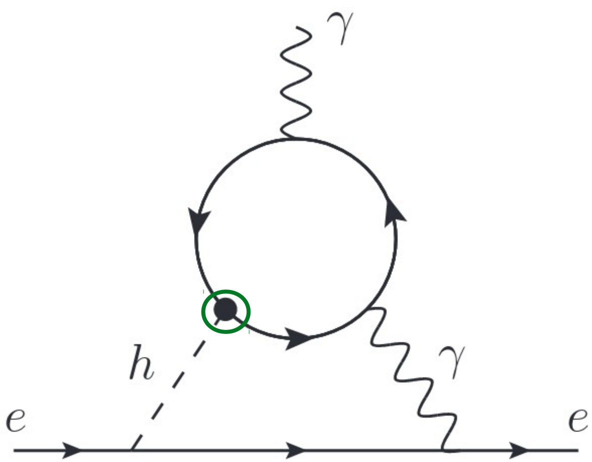
$$-\, i\, c_t \overline{\psi}^i_{4R}\gamma^\mu d^i_\mu t_R + \text{h.c.} \supset i\frac{c_t}{f}\partial_\mu h \left(\overline{\widehat{X}}_{2/3R}\gamma^\mu t_R - \overline{\widehat{T}}_R \gamma^\mu t_R\right) + \text{h.c.}$$



$$\frac{d_e}{e} = -\frac{e^2}{48\pi^4}\frac{y_e}{\sqrt{2}}\text{Im}\, c_t \frac{2 y_{L4}}{\sqrt{m_4^2 + y_{L4}^2 f^2}}\frac{m_{top}}{m_T}\log\frac{m_T^2}{m_{top}^2}$$

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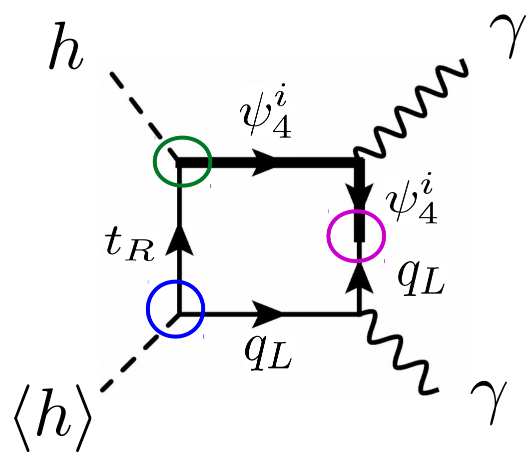
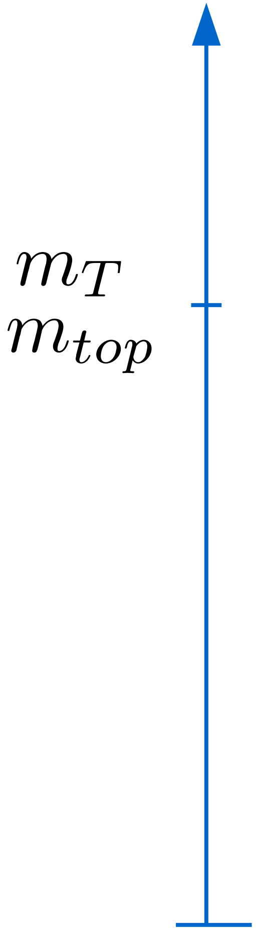


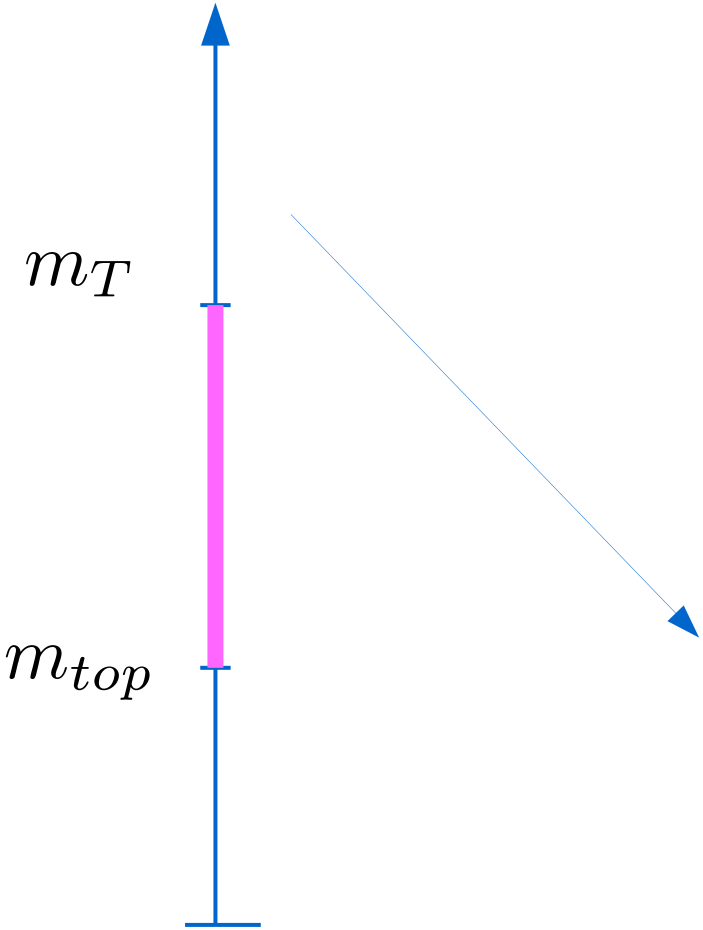
CPV controled by $c_t y^*_{Lt} y_{L4}$

For complete, degenerate multiplets the diagram is proportional to $tr\, c_t \sim tr\, T^a \sim 0$



$$H^\dagger H F_{\mu\nu} \tilde{F}_{\mu\nu} = 0$$

$$-\frac{d}{2} \bar{e} \sigma^{\mu\nu} i \gamma^5 F_{\mu\nu} e = 0$$



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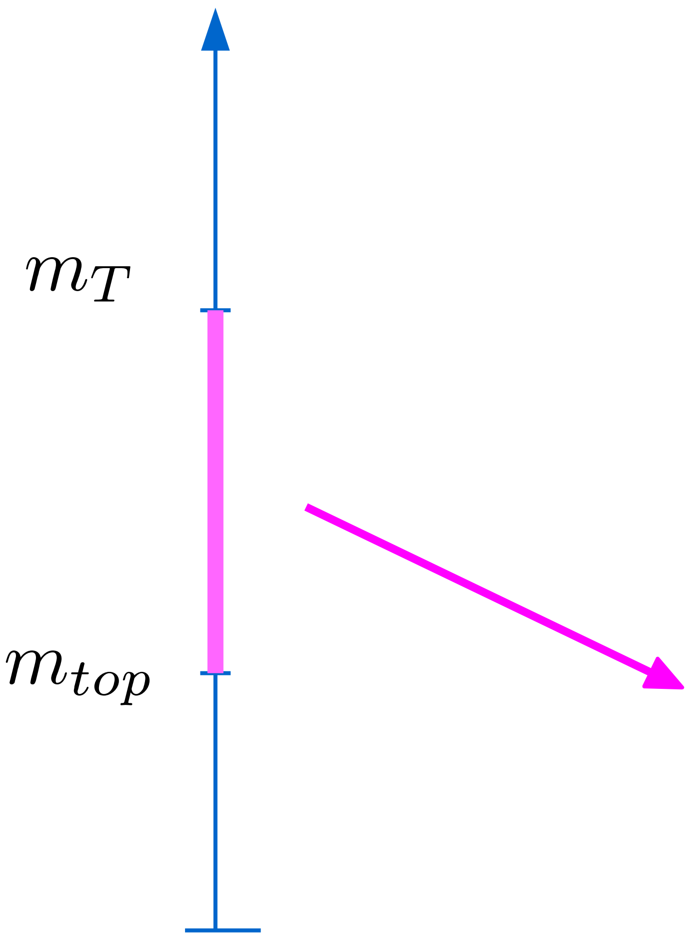

$$H^\dagger H F_{\mu\nu}\tilde{F}_{\mu\nu} \neq 0$$

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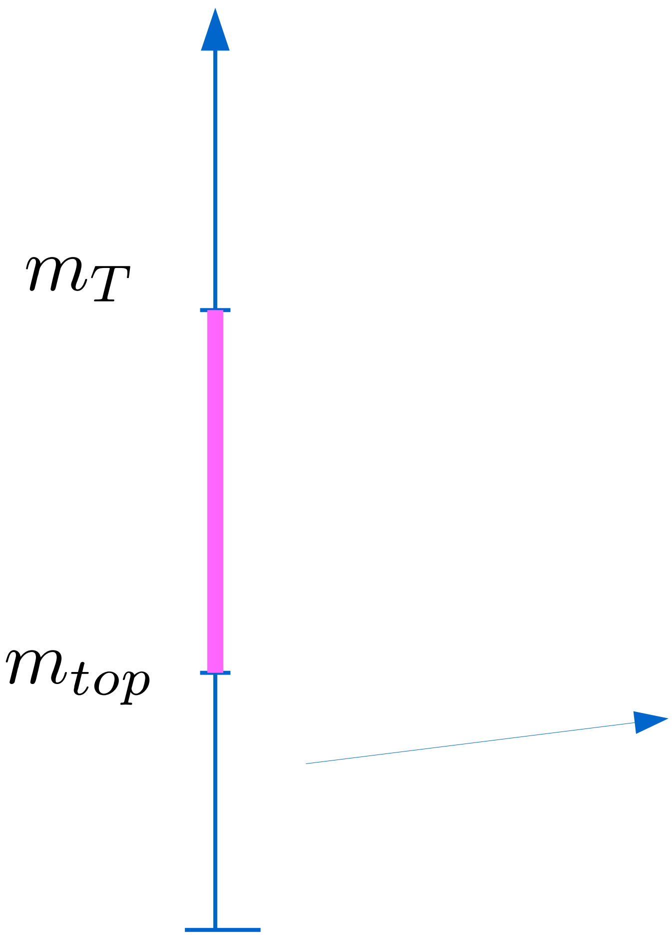

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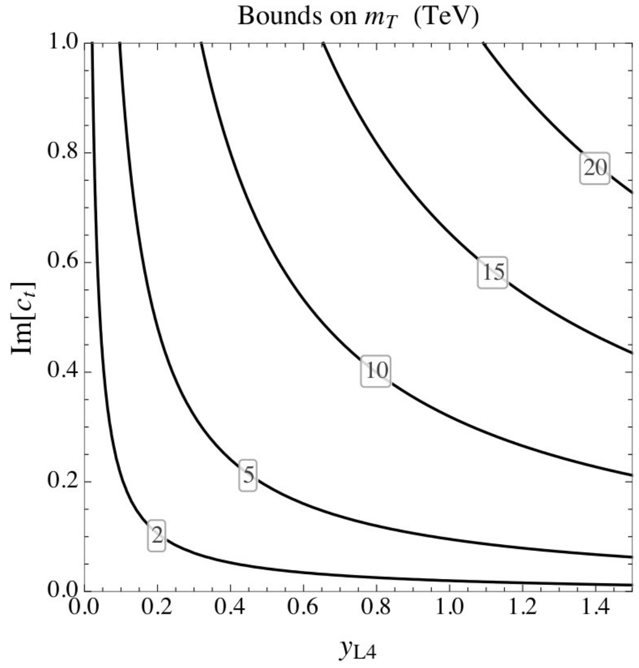
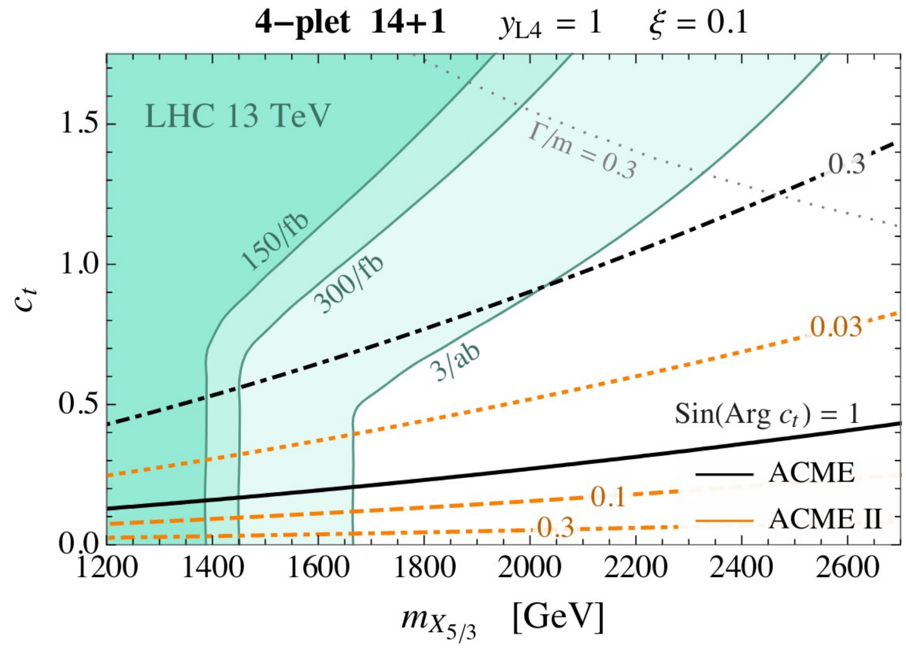
Electron EDM constraints and comparison with direct searches

Constraints from ACME II



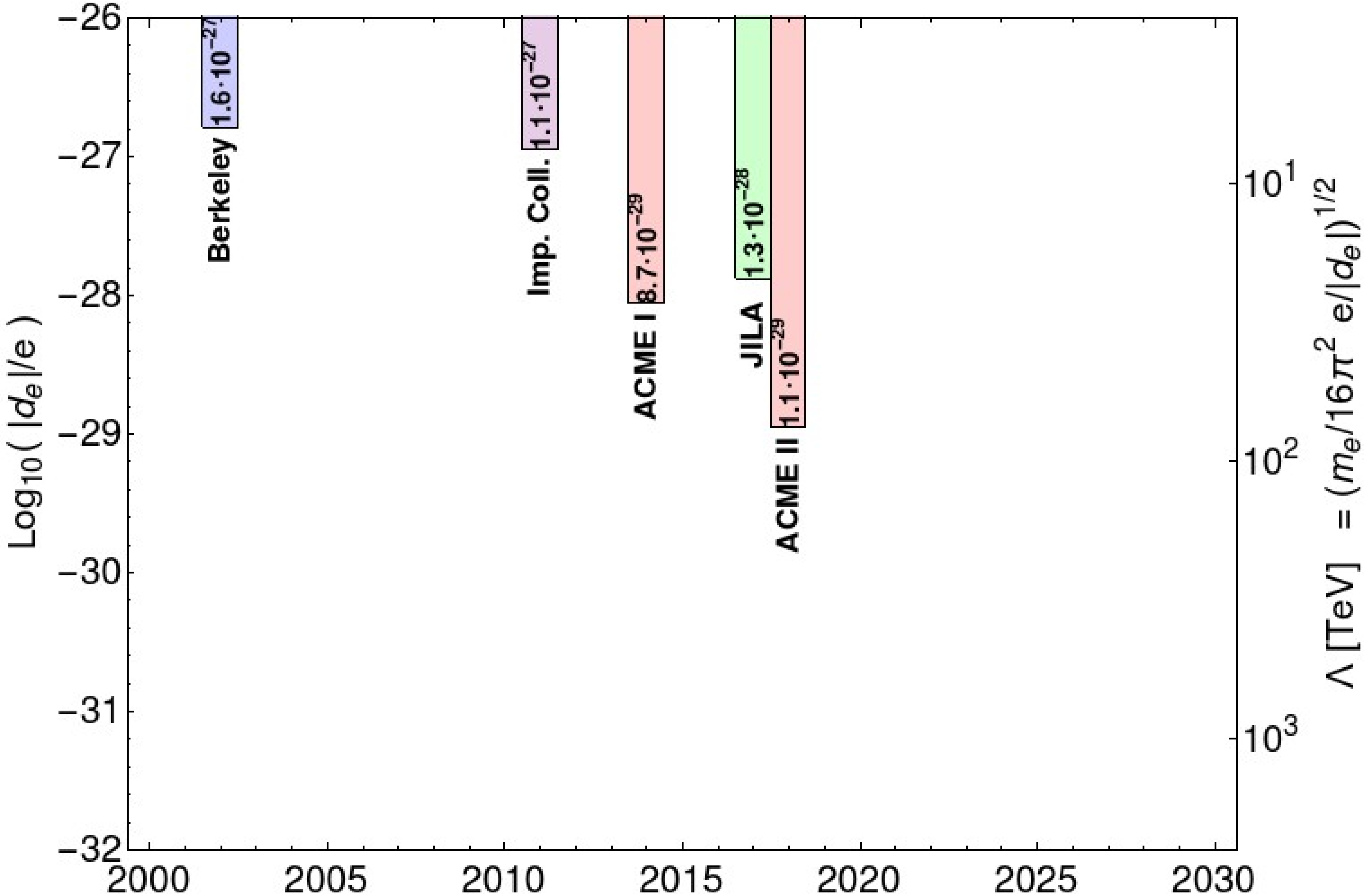
HL-LHC projections:



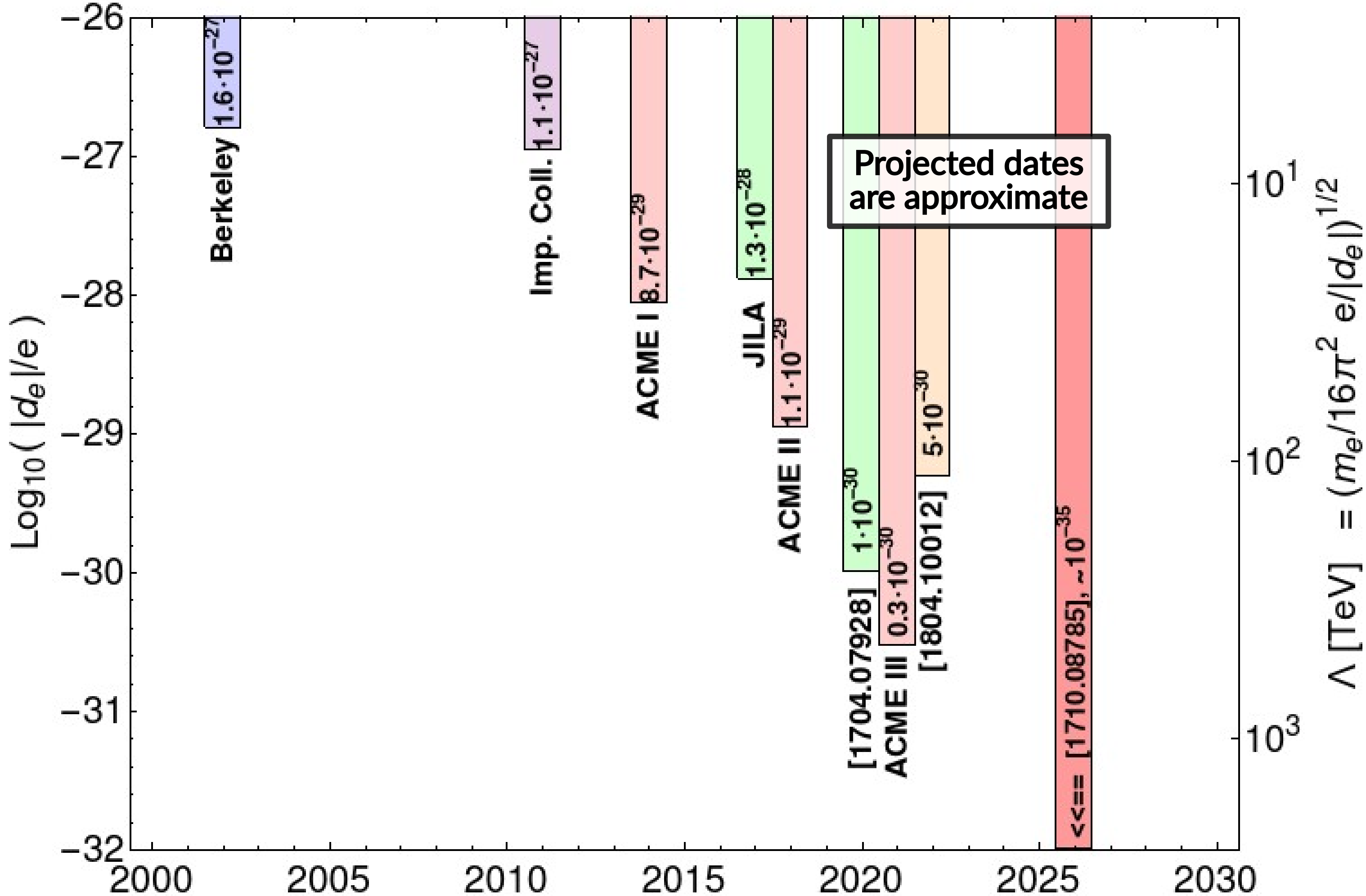
Im(ct) has to be of order 0.01 if we want to be within LHC reach

The future of the electron EDM

Evolution of electron EDM constraints



Evolution of electron EDM constraints

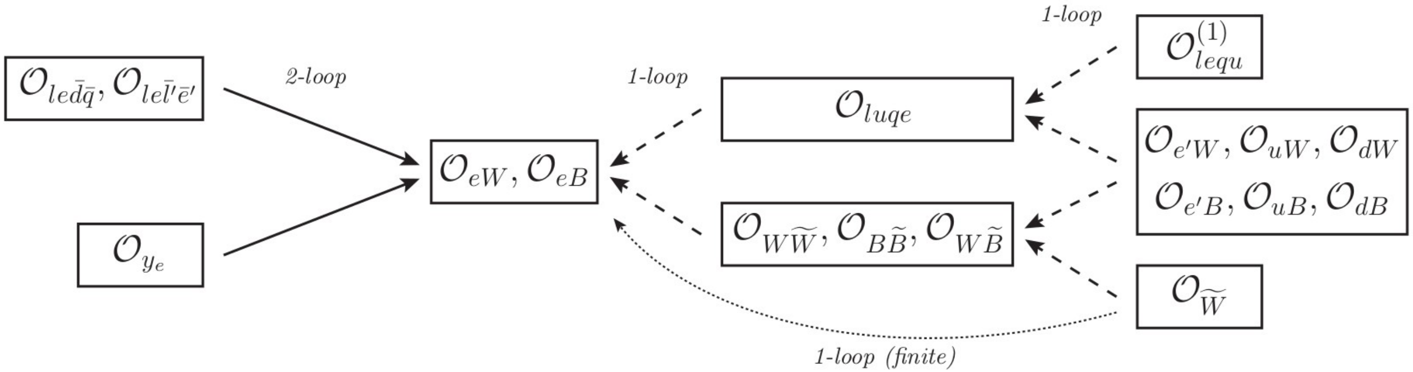


- After some time of promises of improvements with nothing happening, it seems that there will be further progress in a short time scale.
- If there is a positive signal, we'll have confirmation very quickly.
- There are some proposals for a total breakthrough.

Conclusions

Conclusions

- Map of the most relevant effects at two loops:



- CPV in Higgs sector pushed way outside any current or future collider reach

- Bounds of 1-100TeV for generic theories of leptoquarks

- Characterization of relevant constraints for the MSSM

- In composite models, CPV from top sector important. Top partners pushed outside LHC range, unless they have CP preserving couplings

- Unless there is a reason why, contrary to SM, BSM sector respects CP, ACME result makes these theories much less natural

Conclusions

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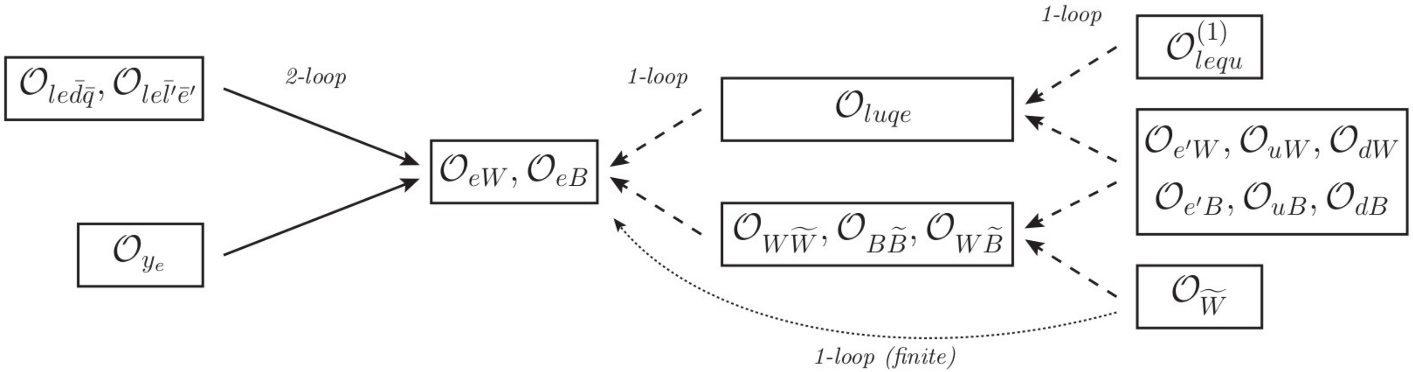

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Thanks!