EFT approach to the electron EDM at the two-loop level

Giuliano Panico

Università di Firenze and INFN Firenze

DESY Zeuthen — 2/7/2020

based on GP, A. Pomarol, M. Riembau 1810.09413

GP, M. Riembau, T. Vantalon 1712.06337

The precision frontier

Precision measurements provide fundamental tests of the **SM**

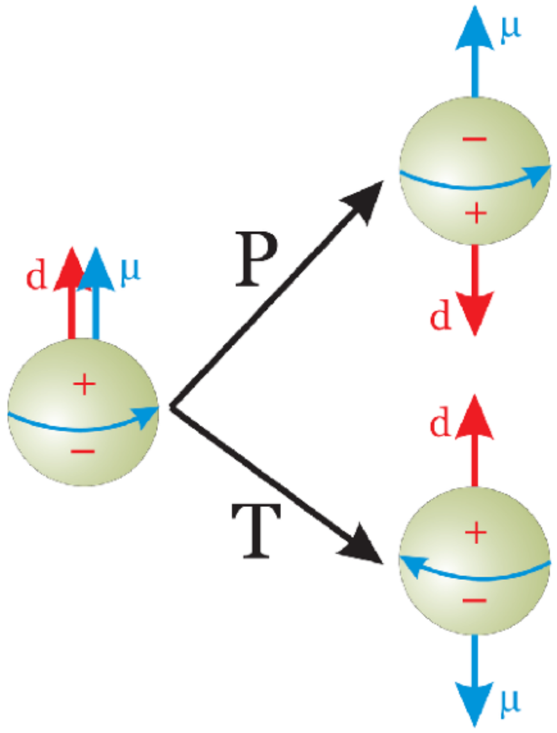
… which means they can probe **new physics**

- ✦ They can significantly extend the reach of direct searches
  - access hard-to-test parameter space points
  - extend reach to new physics at higher energy scales
- ✦ Particularly relevant since no convincing direct signal of new physics has been seen at the LHC

The electron EDM

Excellent probes of new physics are provided
by the **Electric Dipole Moment** (EDM) of the electron

1. predicted to be very small in the SM
2. usually enhanced in the presence of new physics
3. very well tested experimentally



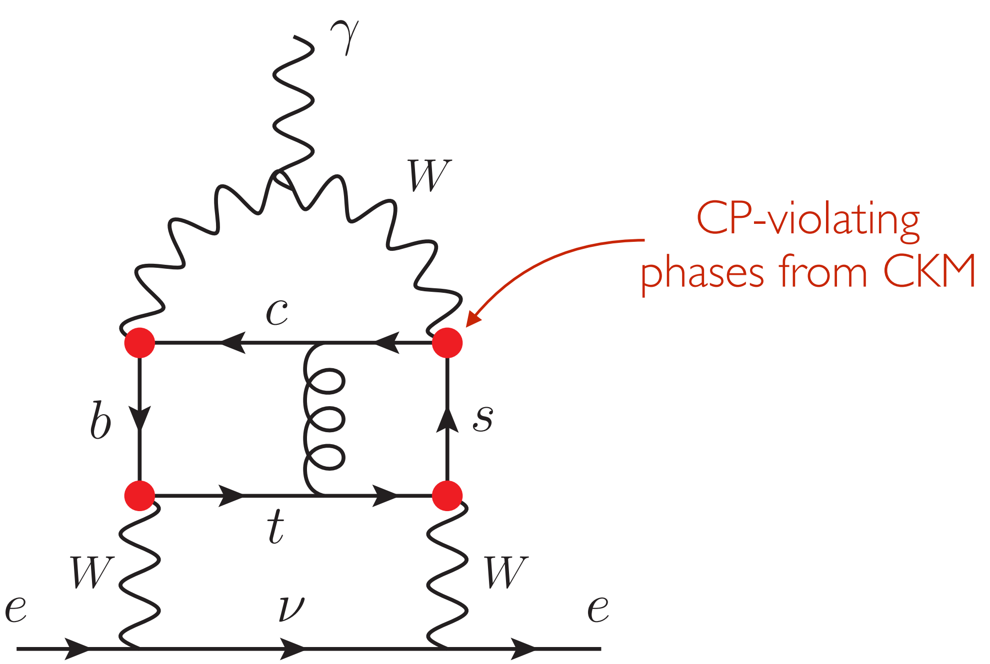
The electron EDM in the SM

EDM generated from radiative corrections with CP-violating interactions

In the **SM** the electron EDM is **extremely small**

$$d_e < 10^{-38}\, e\ \text{cm}$$

- vanishing up to 3 loops
  [Khriplovich, Pospelov '91]
- severe cancellations due to GIM mechanism

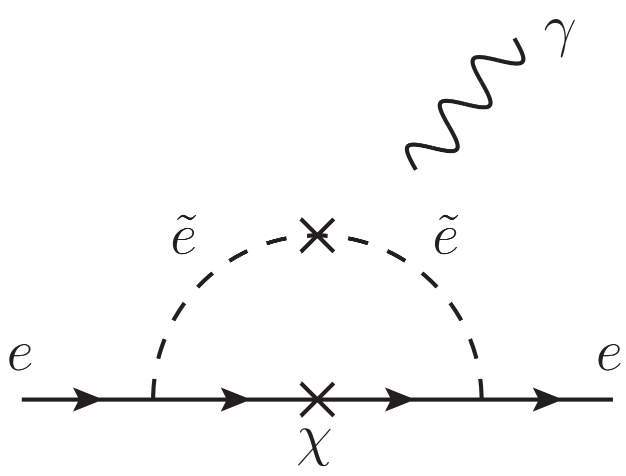


The electron EDM beyond the SM

BSM physics typically gives rise to additional contributions to EDMs

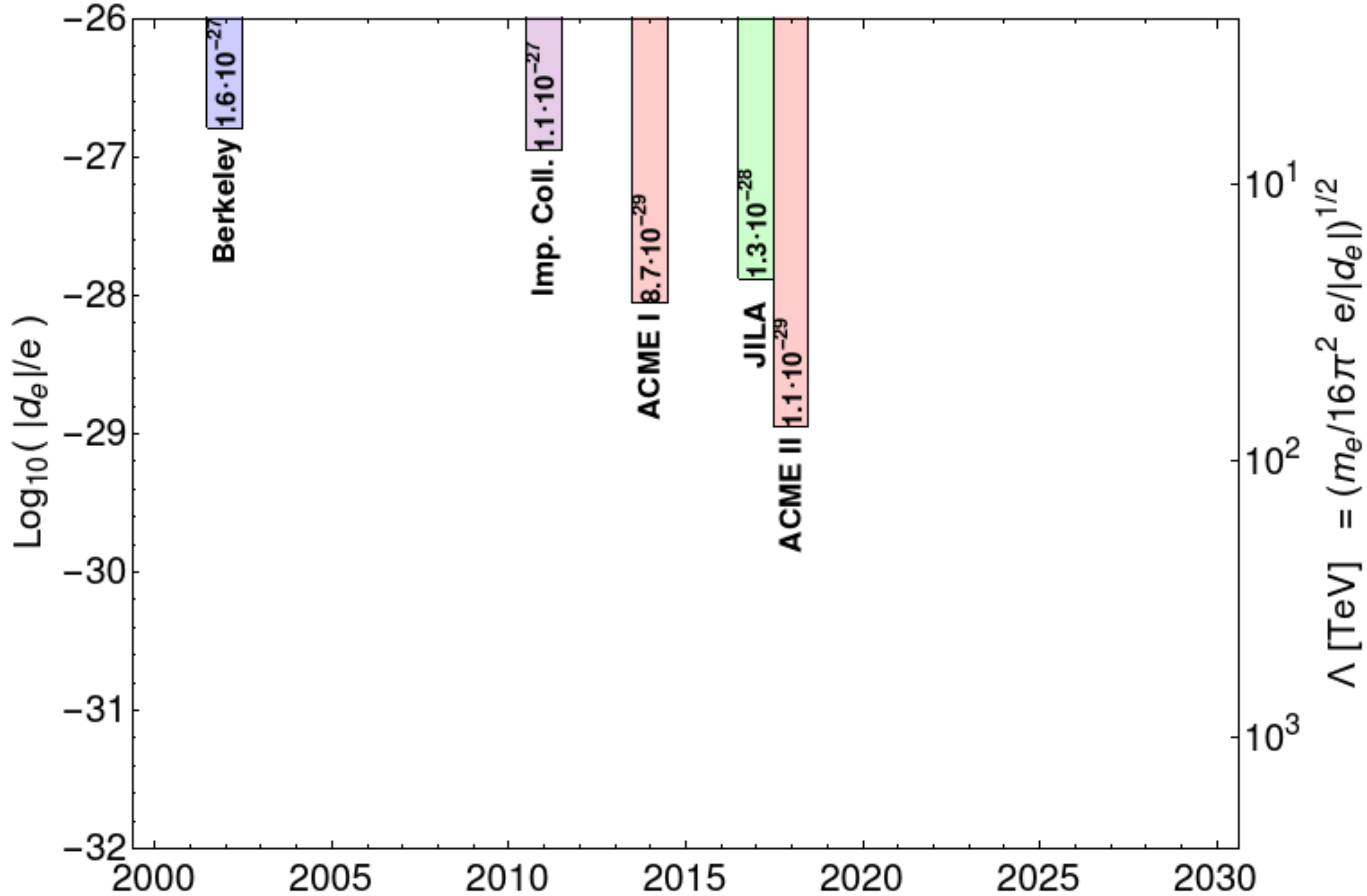
- additional sources of CP-violation
- cancellations are typically not present
- contributions can arise at low loop level
  (eg. 1-loop or 2-loop)

typical contribution to the electron EDM in the MSSM



→ BSM corrections much larger than SM prediction

The experimental bounds



ACME II bounds

1-loop : $$\frac{d_e}{e} \sim \frac{1}{16\pi^2}\frac{m_e}{\Lambda^2} \longrightarrow \Lambda > 40\,\mathrm{TeV}$$

2-loop : $$\frac{d_e}{e} \sim \frac{1}{(16\pi^2)^2}\frac{m_e}{\Lambda^2} \longrightarrow \Lambda > 3\,\mathrm{TeV}$$

relevant bound even at 2-loop

The EFT approach

LHC results provide a strong hint that new physics scale should be well above the EW scale

If new physics is heavy, we can adopt the **Effective Field Theory** (EFT) language

- model independent
- bounds easy to be recast in explicit theories

New-physics effects encoded in deformations of the SM Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

leading corrections from dimension-6 operators $\mathcal{O}_i^{(6)}$

EDMs in the EFT language

EDMs can be reinterpreted in terms of high-energy effective operators

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

↓ relativistic limit

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

↓ SM : SU(2)$_L$×U(1)$_Y$

$$\mathcal{L} = \frac{c_{eW}}{\Lambda^2}\left(\bar{\ell}_L\sigma^{\mu\nu}\sigma^a e_R\right)HW^a_{\mu\nu} + \frac{c_{eB}}{\Lambda^2}\left(\bar{\ell}_L\sigma^{\mu\nu}e_R\right)HB_{\mu\nu}$$

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

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

Classifying EFT effects

A preliminary step to apply the EFT approach is to **identify and organize** the most relevant new-physics effects

Classification criteria:

- loop order (we will consider affects up to 2 loops)
- additional enhancement from running (large log if there is a significant mass gap)
- power counting

Selection rules for RGEs

Running effects are controlled by several **selection rules**

[Elias-Miro, Espinosa, Pomarol '14;
Cheung, Shen '15]

F^3

$H^2 F^2$

$H\psi'^2 F$

e EDM
$(H\psi^2 F)$

ψ^4

$\psi^2 \bar{\psi}^2$

$H^3 \psi^2$

Note: four-fermion operators in Weyl notation

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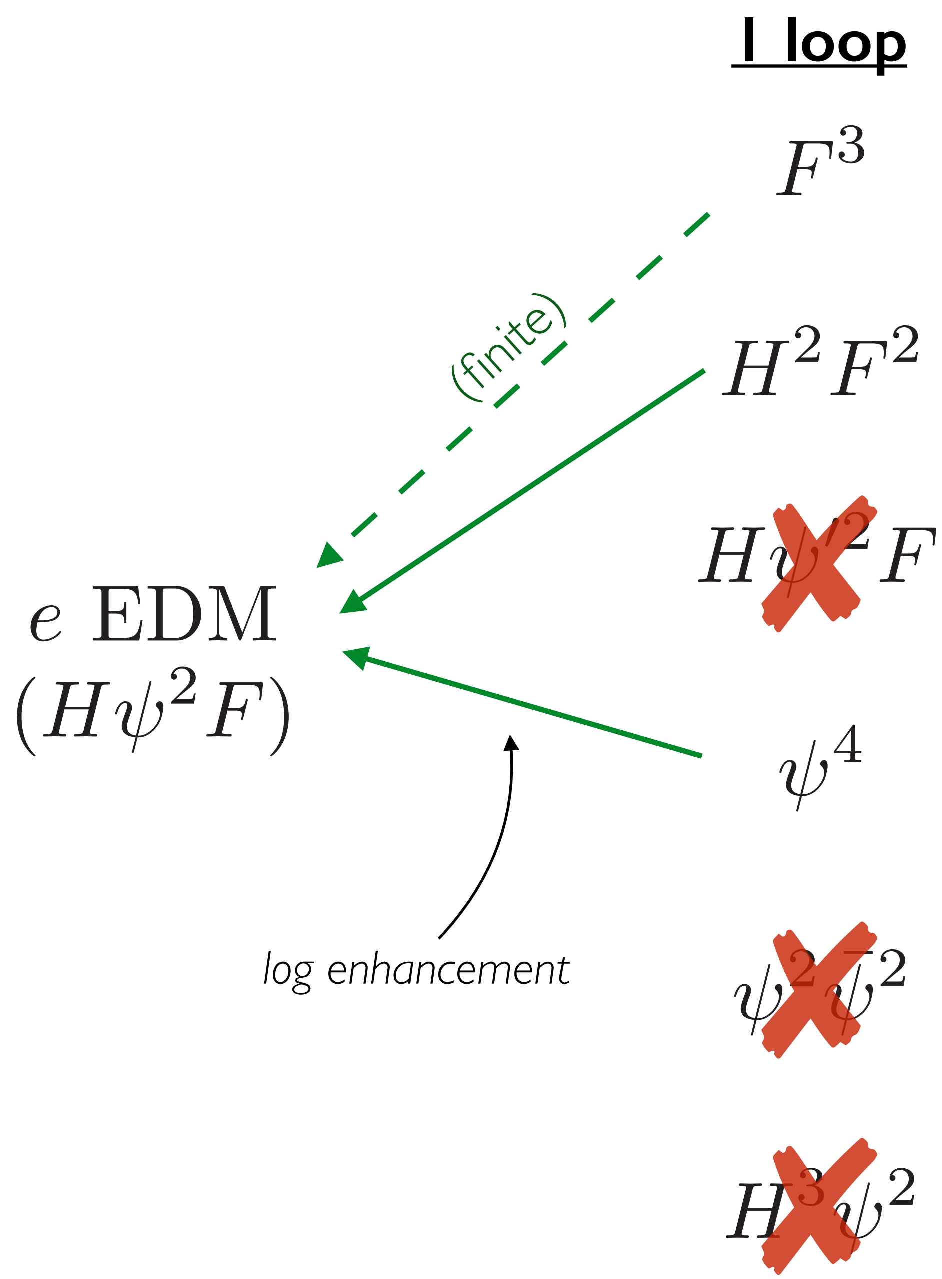

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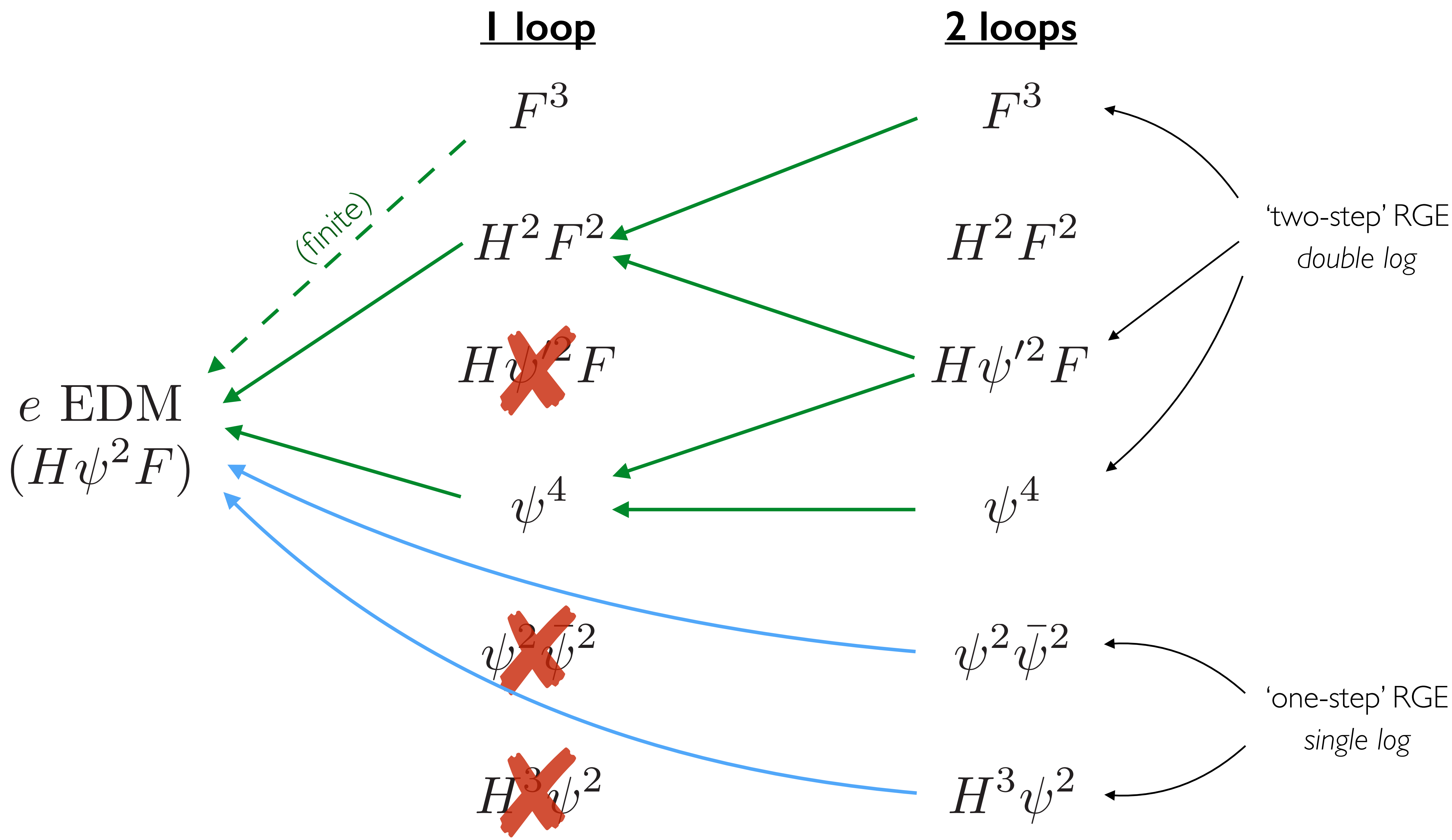
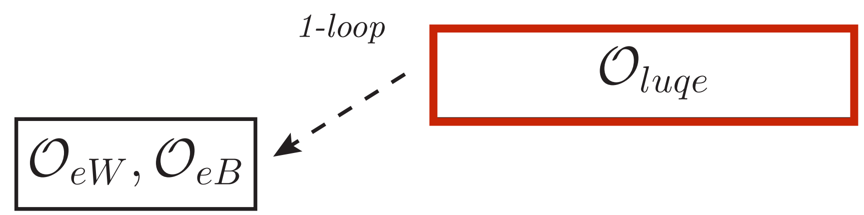


Note: four-fermion operators in Weyl notation

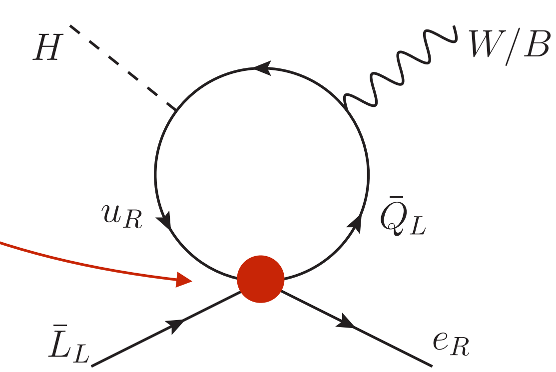
Classifying RGE contribution

1-loop RGE



Only one 4-fermion operator ψ^4 contributes at 1-loop

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

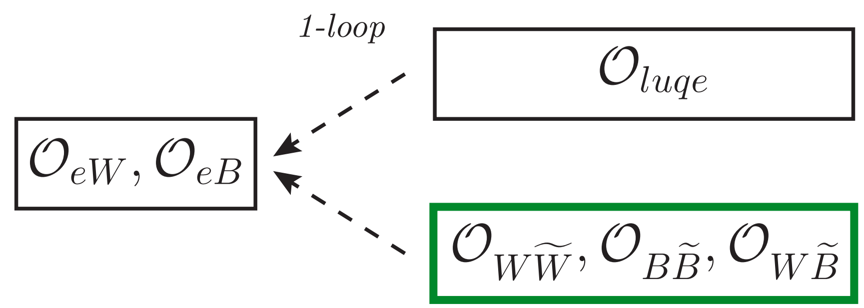


proportional to quark Yukawa

$$\frac{d}{d\ln\mu}\begin{pmatrix} C_{eB} \\ C_{eW} \end{pmatrix} = \frac{y_u g}{16\pi^2}\begin{pmatrix} -\frac{1}{2}t_{\theta_W} N_c(Y_Q + Y_u) \\ \frac{1}{4}N_c \end{pmatrix} C_{luqe}$$

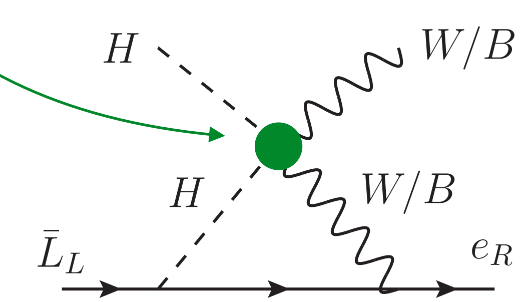
- The structure of the other four-fermion operators does not allow for 1-loop diagrams

1-loop RGE



Operators involving the Higgs and gauge bosons

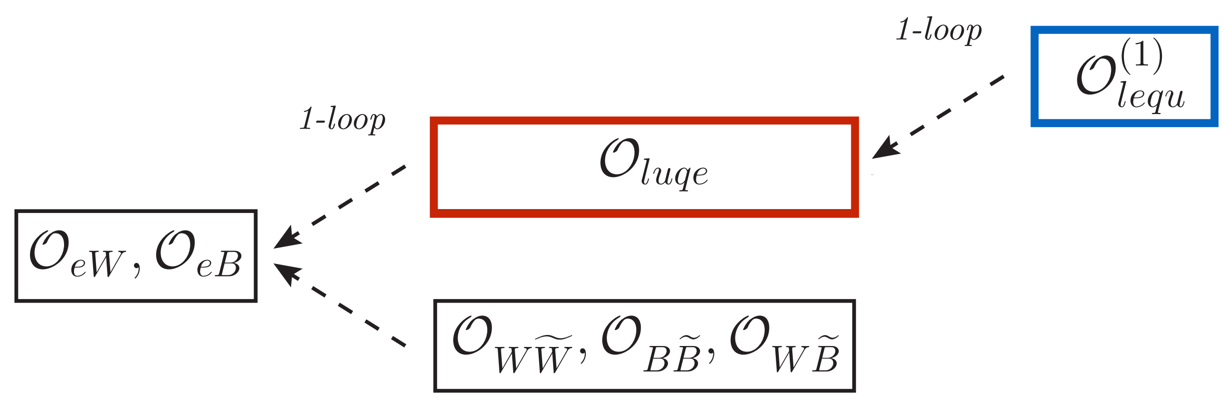
$$\mathcal{O}_{W\widetilde{W}} = |H|^2 W^{a\,\mu\nu}\widetilde{W}^a_{\mu\nu} \qquad \mathcal{O}_{B\widetilde{B}} = |H|^2 B^{\mu\nu}\widetilde{B}_{\mu\nu} \qquad \mathcal{O}_{W\widetilde{B}} = (H^\dagger \sigma^a H) W^{a\,\mu\nu}\widetilde{B}_{\mu\nu}$$



proportional to electron Yukawa

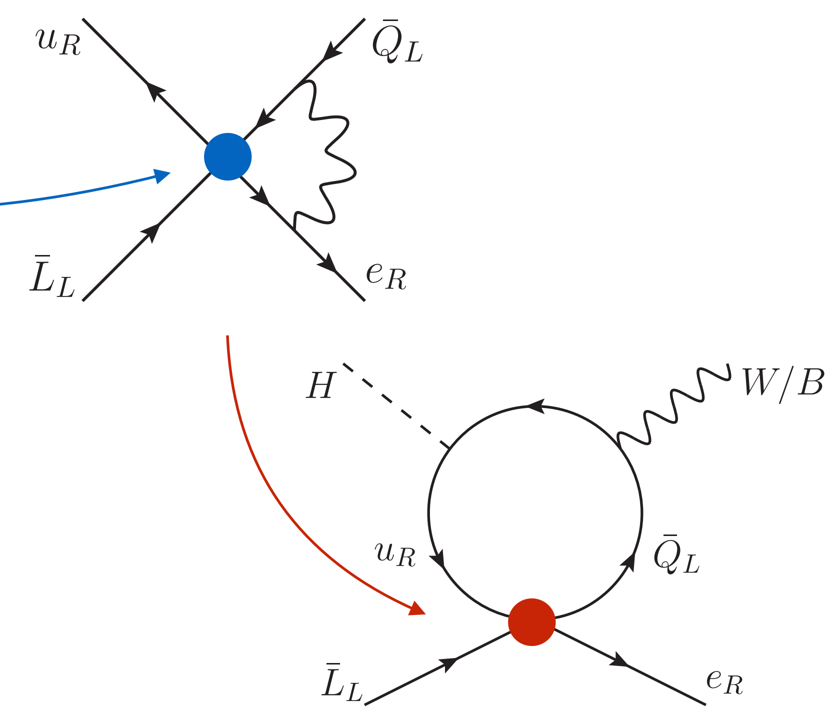
$$\frac{d}{d\ln\mu}\mathrm{Im}\begin{pmatrix} C_{eB} \\ C_{eW} \end{pmatrix} = -\frac{y_e g}{16\pi^2}\begin{pmatrix} 0 & 2t_{\theta_W}(Y_L + Y_e) & \frac{3}{2} \\ 1 & 0 & t_{\theta_W}(Y_L + Y_e) \end{pmatrix}\begin{pmatrix} C_{W\widetilde{W}} \\ C_{B\widetilde{B}} \\ C_{W\widetilde{B}} \end{pmatrix}$$

2-loop double-log RGE



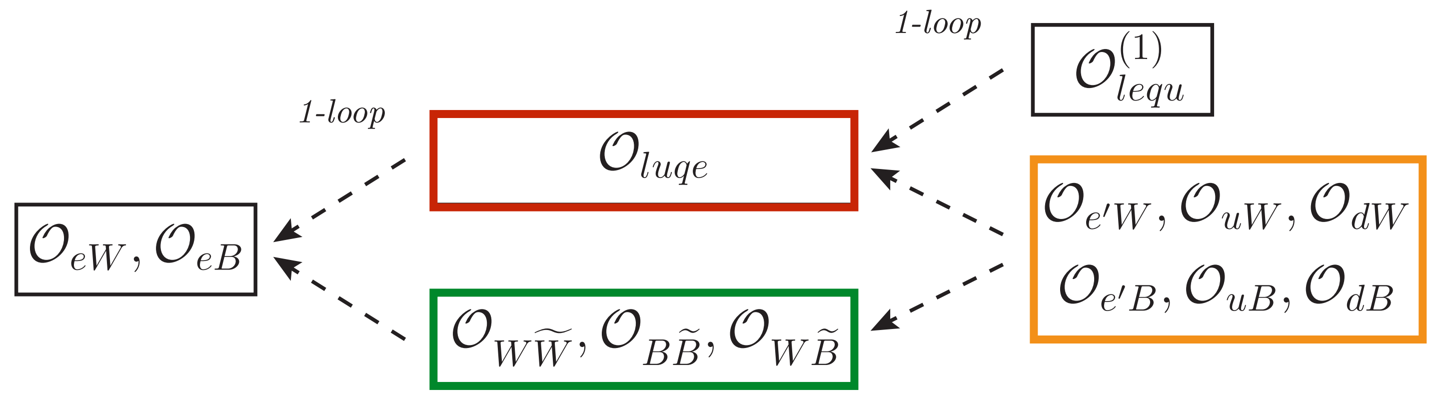
Additional 4-fermion operator ψ^4 contributes at 2-loop double log

$$\mathcal{O}^{(1)}_{lequ} = (\bar{L}_L\, e_R)(\bar{Q}_L\, u_R)$$



$$\frac{d}{d\ln\mu} C_{luqe} = \frac{g^2}{16\pi^2}\left[4(Y_L+Y_e)(Y_Q+Y_u)t^2_{\theta_W} - 3\right] C^{(1)}_{lequ}$$

2-loop double-log RGE



Dipole operators $H\psi'^2 F$ contribute at 2-loop double log

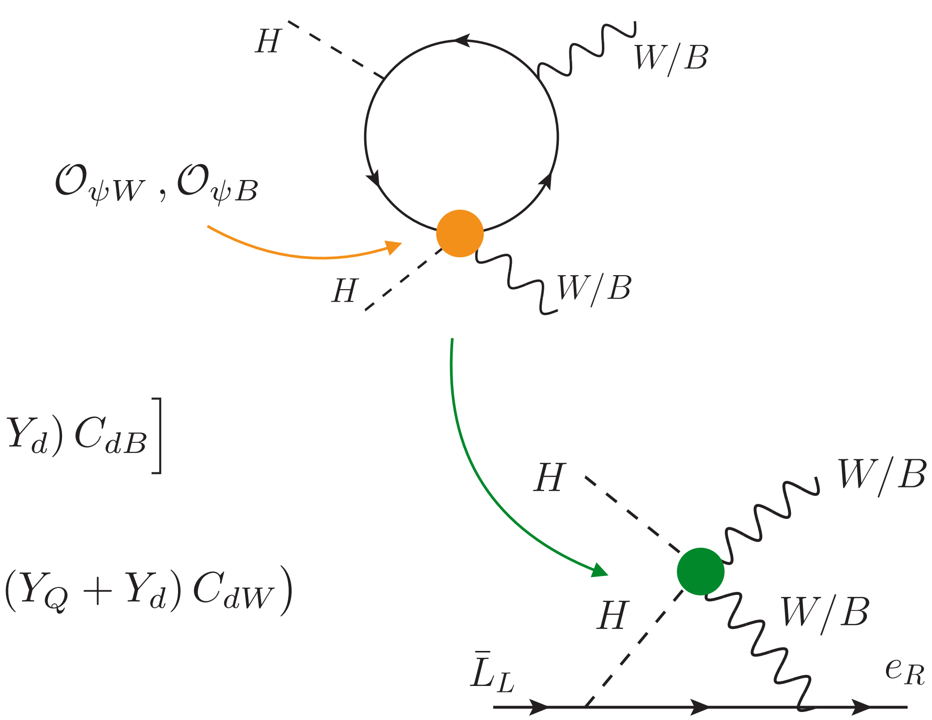
Two RGE patterns:

- through the H^2F^2 operators

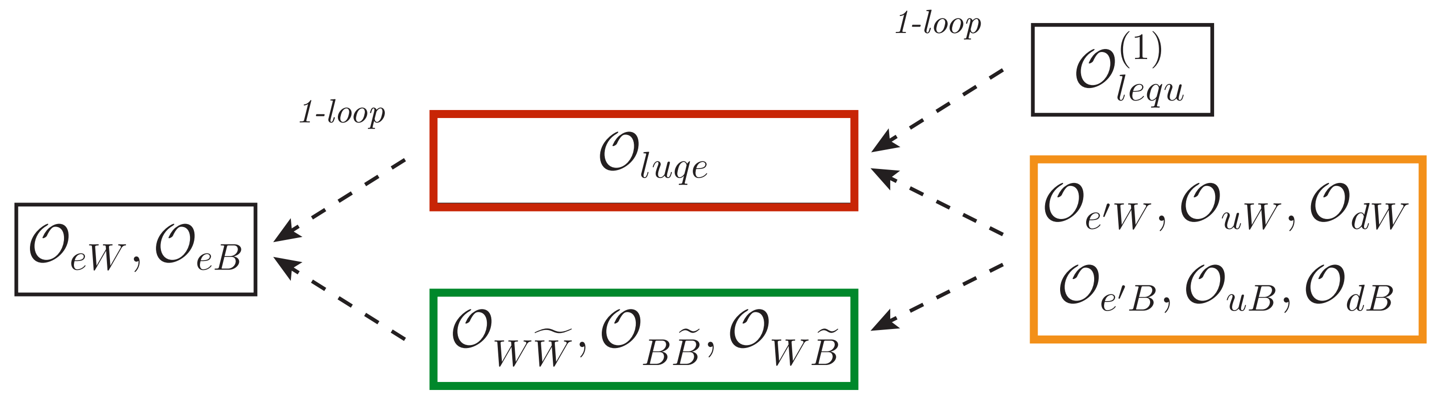
$$\frac{d}{d\ln\mu} C_{W\widetilde{W}} = -\frac{2g}{16\pi^2}\mathrm{Im}\Big[y_{e'}\, C_{e'W} + y_u N_c\, C_{uW} + y_d N_c\, C_{dW}\Big]$$

$$\frac{d}{d\ln\mu} C_{B\widetilde{B}} = -\frac{4g'}{16\pi^2}\mathrm{Im}\Big[y_{e'}(Y_L+Y_e)\, C_{e'B} + y_u N_c (Y_Q+Y_u)\, C_{uB} + y_d N_c (Y_Q+Y_d)\, C_{dB}\Big]$$

$$\frac{d}{d\ln\mu} C_{W\widetilde{B}} = -\frac{2g}{16\pi^2}\mathrm{Im}\Big[2t_{\theta_W}\left(y_{e'}(Y_L+Y_e)\, C_{e'W} - y_u N_c (Y_Q+Y_u)\, C_{uW} + y_d N_c (Y_Q+Y_d)\, C_{dW}\right) + y_{e'}\, C_{e'B} - y_u N_c\, C_{uB} + y_d N_c\, C_{dB}\Big]$$



2-loop double-log RGE

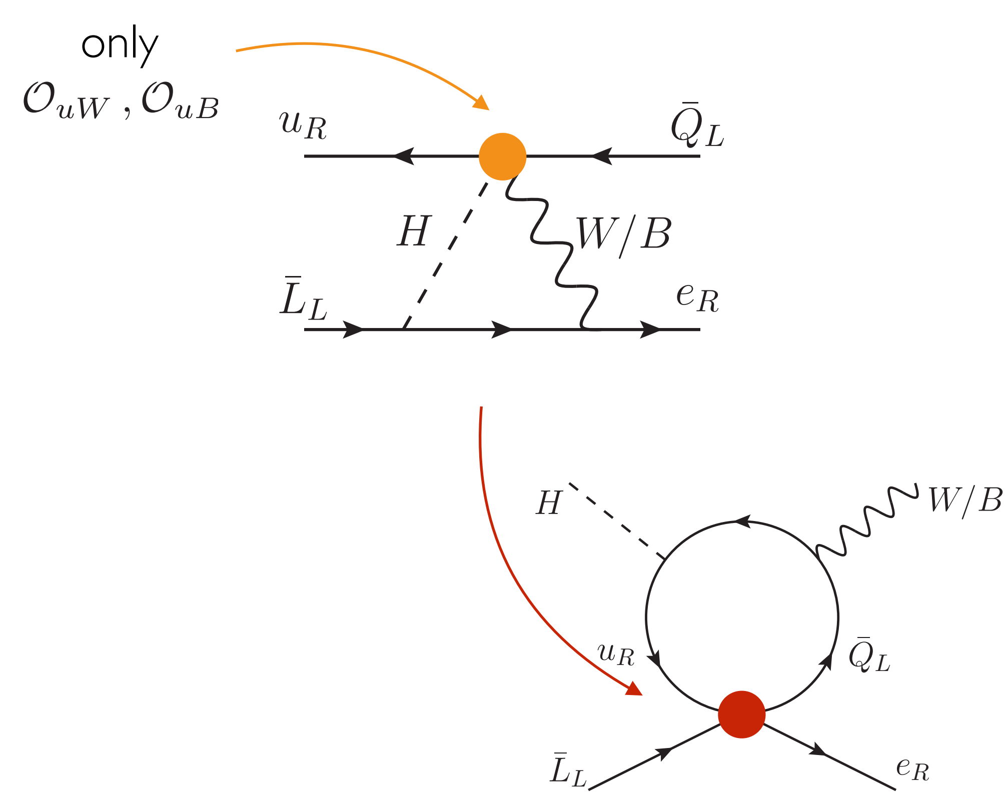


Dipole operators $H\psi'^2 F$ contribute at 2-loop double log

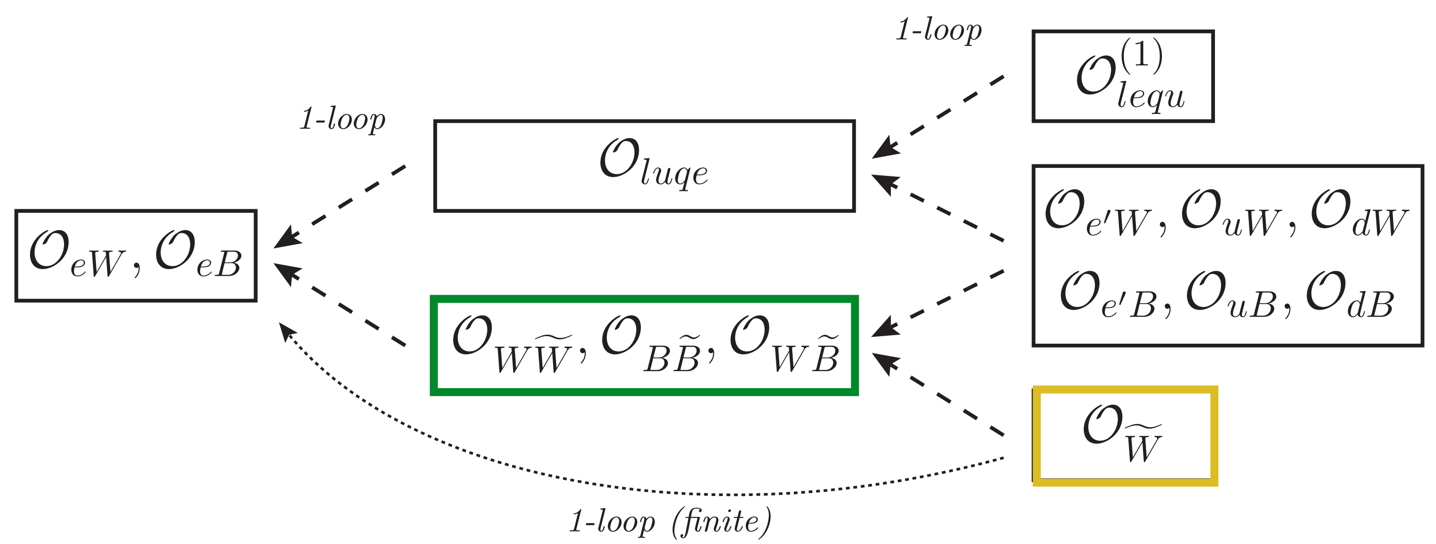
Two RGE patterns:

- through the H^2F^2 operators
- through the $\mathcal{O}_{luqe}$ operator

$$\frac{d}{d\ln\mu}C_{luqe} = \frac{g\,y_e}{16\pi^2}\Big[-8t_{\theta_W}(Y_L+Y_e)C_{uB}+12C_{uW}\Big]$$



2-loop double-log RGE

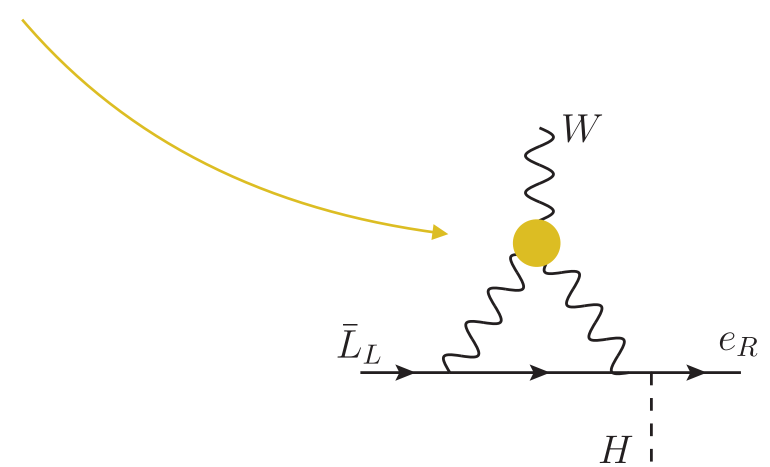


F^3 operator

$$\mathcal{O}_{\widetilde{W}} = \varepsilon_{abc} \widetilde{W}^{a\,\nu}_{\mu} W^{b\,\rho}_{\nu} W^{c\,\mu}_{\rho}$$

- finite 1-loop contributions

$$\mathrm{Im}[C_{eW}] = \frac{3}{64\pi^2} y_e g^2 C_{\widetilde{W}}$$



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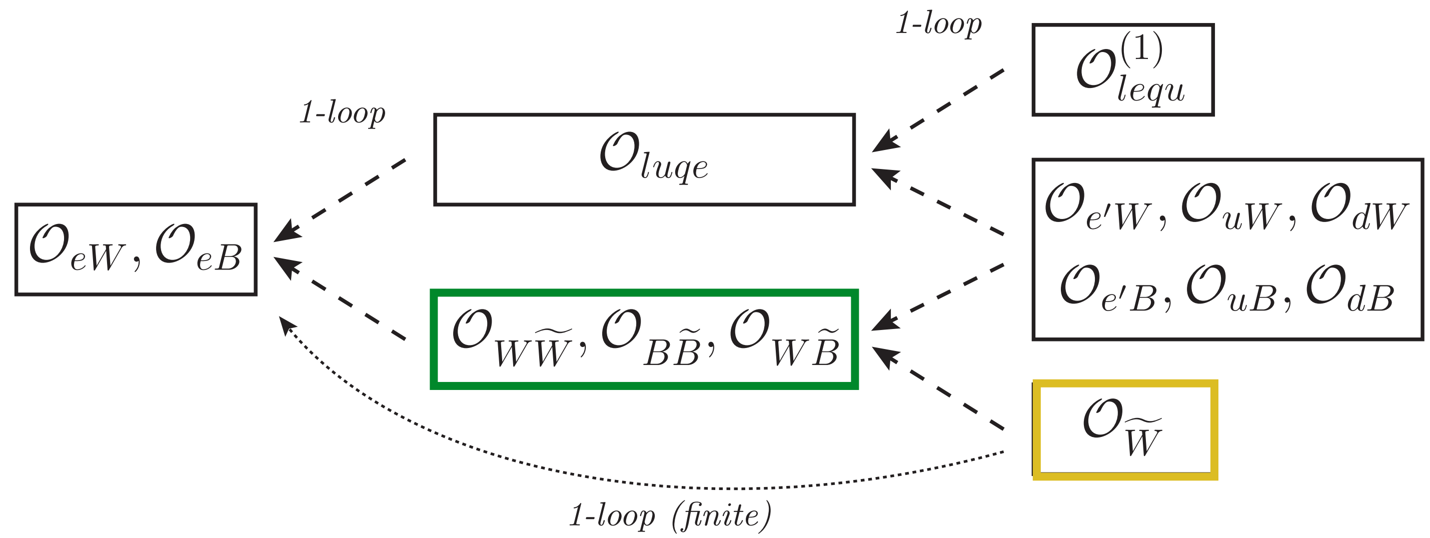

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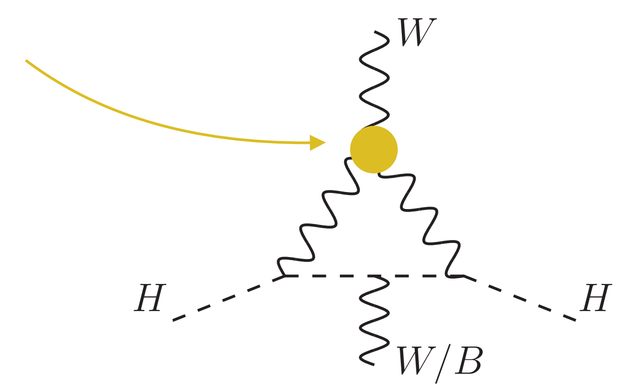
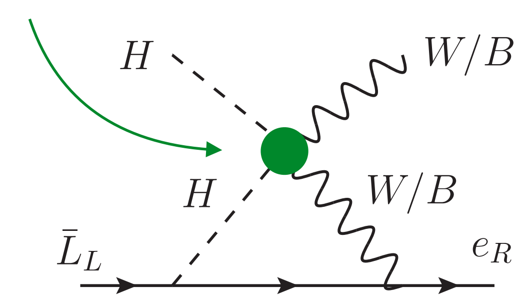


- finite 1-loop contributions

$$\mathrm{Im}[C_{eW}] = \frac{3}{64\pi^2} y_e g^2 C_{\widetilde{W}}$$

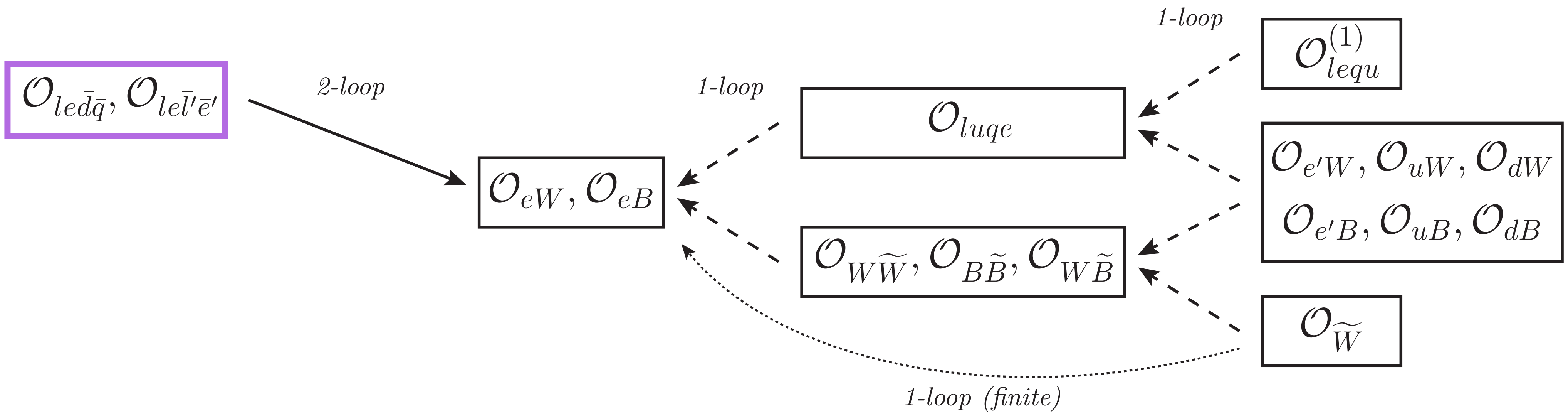
- 2-loop double log contributions



$$\frac{d}{d\ln\mu} C_{W\widetilde{W}} = -\frac{1}{16\pi^2} 15 g^3 C_{\widetilde{W}}\,, \qquad \frac{d}{d\ln\mu} C_{W\widetilde{B}} = +\frac{1}{16\pi^2} 6 g' g^2 Y_H C_{\widetilde{W}}$$

- 2-loop contributions dominant for $\Lambda > 5\,\mathrm{TeV}$

2-loop single-log RGE

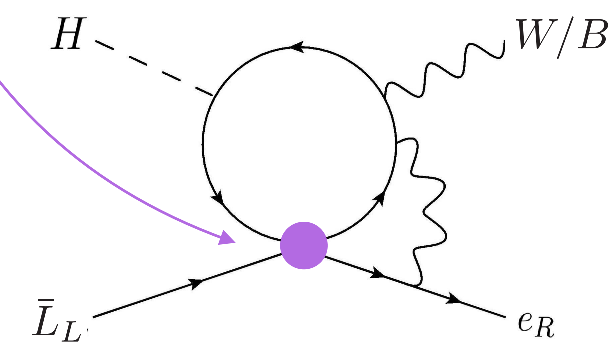


4-fermion operators $\psi^2\bar{\psi}^2$ contribute at 2-loop single log

$$\mathcal{O}_{led\bar{q}} = (\bar{L}_L\, e_R)(\bar{d}_R\, Q_L) \qquad \mathcal{O}_{le\bar{e}'\bar{l}'} = (\bar{L}_L\, e_R)(\bar{e}'_R\, L'_L)$$

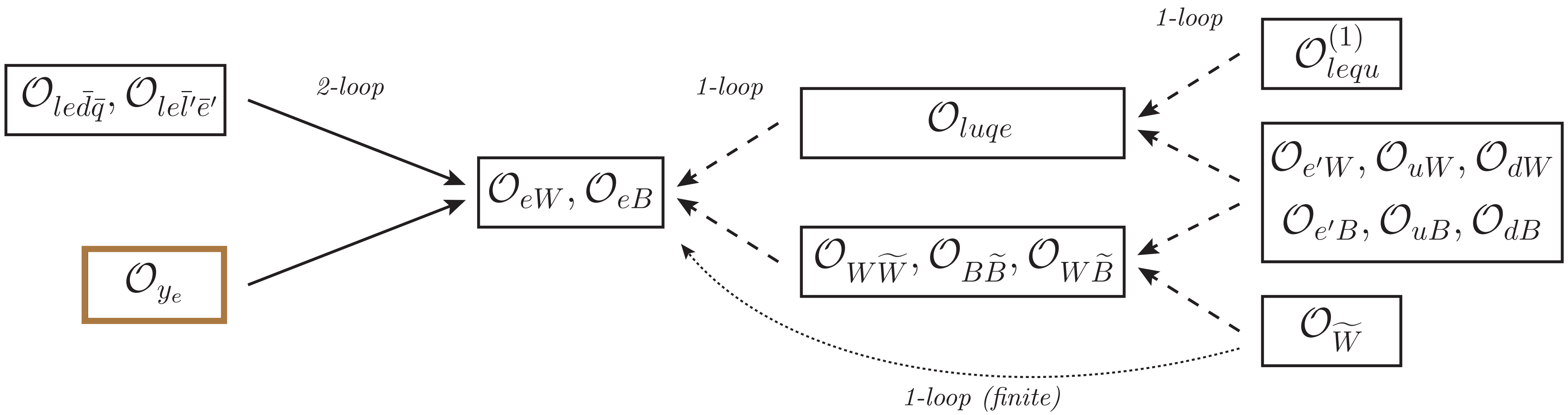
$$\frac{d}{d\ln\mu}\mathrm{Im}\begin{pmatrix} C_{eB} \\ C_{eW}\end{pmatrix} = \frac{y_{e'}g^3}{(16\pi^2)^2}\frac{1}{4}\begin{pmatrix} 3t_{\theta_W}Y_L + 4t^3_{\theta_W}(Y_L+Y_e)(Y_L^2+Y_e^2) \\ \frac{1}{2} + 2t^2_{\theta_W}(Y_L+Y_e)Y_L \end{pmatrix} C_{le\bar{e}'\bar{l}'}$$

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



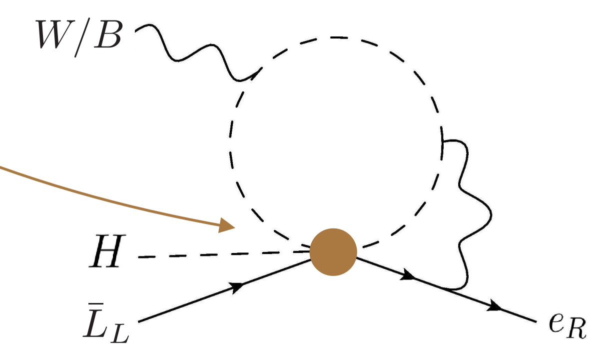
cancellation suppresses leading contributions to electron EDM,
only hypercharge terms survive
$g^2 \to g'^2/8$

2-loop single-log RGE



Electron Yukawa corrections contribute at 2-loop single log

$$\mathcal{O}_{y_e} = |H|^2 \bar{L}_L e_R H$$



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

cancellation suppresses leading contributions to electron EDM,
only hypercharge terms survive
$g^2 \to g'^2$

EW scale threshold corrections

Additional contribution generated at the EW scale can be relevant

Example: threshold effects from Yukawa couplings
(from finite Barr-Zee-type diagrams)

- **Electron Yukawa**

$$\frac{d_e}{e} \simeq -\frac{16}{3}\frac{e^2}{(16\pi^2)^2} v \left(2 + \ln\frac{m_t^2}{m_h^2}\right)\frac{\mathrm{Im}\, C_{y_e}}{\Lambda^2}$$

larger than log-enhanced contributions for $\Lambda \lesssim 10^3\ \mathrm{TeV}$

- **Top Yukawa**

$$\frac{d_e}{e} \simeq -\frac{e^2}{(16\pi^2)^2} 4N_c Q_t^2 \frac{m_e}{m_t} v \left(2 + \ln\frac{m_t^2}{m_h^2}\right)\frac{\mathrm{Im}\, C_{y_t}}{\Lambda^2}$$

no contribution from running

Implications for BSM

Model-independent constraints

Constraints from ACME II

ACME II results translate to very strong constraints on CP-violating effective operators

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

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}	$3.4 \times 10^3\, y_\tau \lambda_h$

Obtained by fixing $\Lambda = 10\,\mathrm{TeV}$ and considering 3-rd generation fermions

Estimating BSM effects

Classification in weakly-coupled renormalizable BSM theories

Generated at **tree-level**:

typical BSM coupling

$$C_{y_e}, C_{luqe}, C_{lequ}, C_{led\bar{q}}, C_{le\bar{e}'\bar{l}'} \sim g_*^2$$

$\mathcal{O}_{y_e}$	Fermion $(\mathbf{1},\mathbf{2},-\mathbf{1/2}) \oplus (\mathbf{1},\mathbf{1(3)},-\mathbf{1})$
	Fermion $(\mathbf{1},\mathbf{2},-\mathbf{1/2}) \oplus (\mathbf{1},\mathbf{1(3)},\mathbf{0})$
	Fermion $(\mathbf{1},\mathbf{2},-\mathbf{3/2}) \oplus (\mathbf{1},\mathbf{1(3)},\mathbf{0})$
	Scalar $(\mathbf{1},\mathbf{2},\mathbf{1/2})$

$\mathcal{O}_{luqe}$	Scalar $(\mathbf{3},\mathbf{2},\mathbf{7/6})$
	Scalar $(\bar{\mathbf{3}},\mathbf{1},\mathbf{1/3})$
$\mathcal{O}_{lequ}^{(1)}$	Scalar $(\mathbf{1},\mathbf{2},\mathbf{1/2})$
	Scalar $(\bar{\mathbf{3}},\mathbf{1},\mathbf{1/3})$
$\mathcal{O}_{led\bar{q}}$	Vector $(\bar{\mathbf{3}},\mathbf{2},\mathbf{5/6})$
	Vector $(\mathbf{3},\mathbf{1},\mathbf{2/3})$
	Scalar $(\mathbf{1},\mathbf{2},\mathbf{1/2})$
$\mathcal{O}_{le\bar{e}'\bar{l}'}$	Vector $(\mathbf{1},\mathbf{1},\mathbf{0})$
	Vector $(\mathbf{1},\mathbf{2},\mathbf{1/2})$
	Scalar $(\mathbf{1},\mathbf{2},\mathbf{1/2})$

Generated at **loop**:

$$C_{fV} \sim \frac{g_*^3 g}{16\pi^2}\ , \quad C_{V\widetilde{V}} \sim \frac{g_*^2 g^2}{16\pi^2}$$

1-loop

$$C_{\widetilde{W}} \sim \frac{g_*^2 g^3}{(16\pi^2)^2}$$

2-loops

Constraints from electron mass

To keep under control 1-loop corrections to the electron mass

$$\left\{ \frac{C_{eV}\, v}{16\pi^2} \,,\; \frac{C_{y_e}\, v^3}{\Lambda^2} \,,\; \frac{C_{lequ}\, m_u}{16\pi^2} \,,\; \frac{C_{luqe}\, m_u}{16\pi^2} \,,\; \frac{C_{le\bar{d}\bar{q}}\, m_d}{16\pi^2} \,,\; \frac{C_{le\bar{e}\bar{l}}\, m_{e'}}{16\pi^2} \right\} \lesssim m_e$$

Automatically satisfied in MFV-like theories

$$C_{fV} \propto y_f \;,\; C_{y_e} \propto y_e \;,\; C_{lequ} \propto y_e y_u \;,\; C_{luqe} \propto y_e y_u \;,\; C_{le\bar{d}\bar{q}} \propto y_e y_d \;,\; C_{le\bar{e}'\bar{l}'} \propto y_e y_{e'}$$

- chirality-flipping operators are proportional to Yukawa couplings

Contributions to the electron EDM

Hierarchy of effects taking into account power-counting

1 loop log : $\mathcal{O}_{luqe}$

1 loop : $\mathcal{O}_{eV}$

2 loop double-log : $\mathcal{O}^{(1)}_{lequ}$

suppressed by Yukawa ($\mathcal{O}_{led\bar{d}\bar{q}}$, $\mathcal{O}_{le\bar{e}'\bar{l}'}$)

2 loop single-log : $\mathcal{O}_{V\widetilde{V}}$ $\mathcal{O}_{led\bar{d}\bar{q}}$ $\mathcal{O}_{le\bar{e}'\bar{l}'}$

2 loop : $\mathcal{O}_{y_u}$ $\mathcal{O}_{y_e}$ $\mathcal{O}_{y_{e'}}$ $\mathcal{O}_{y_d}$

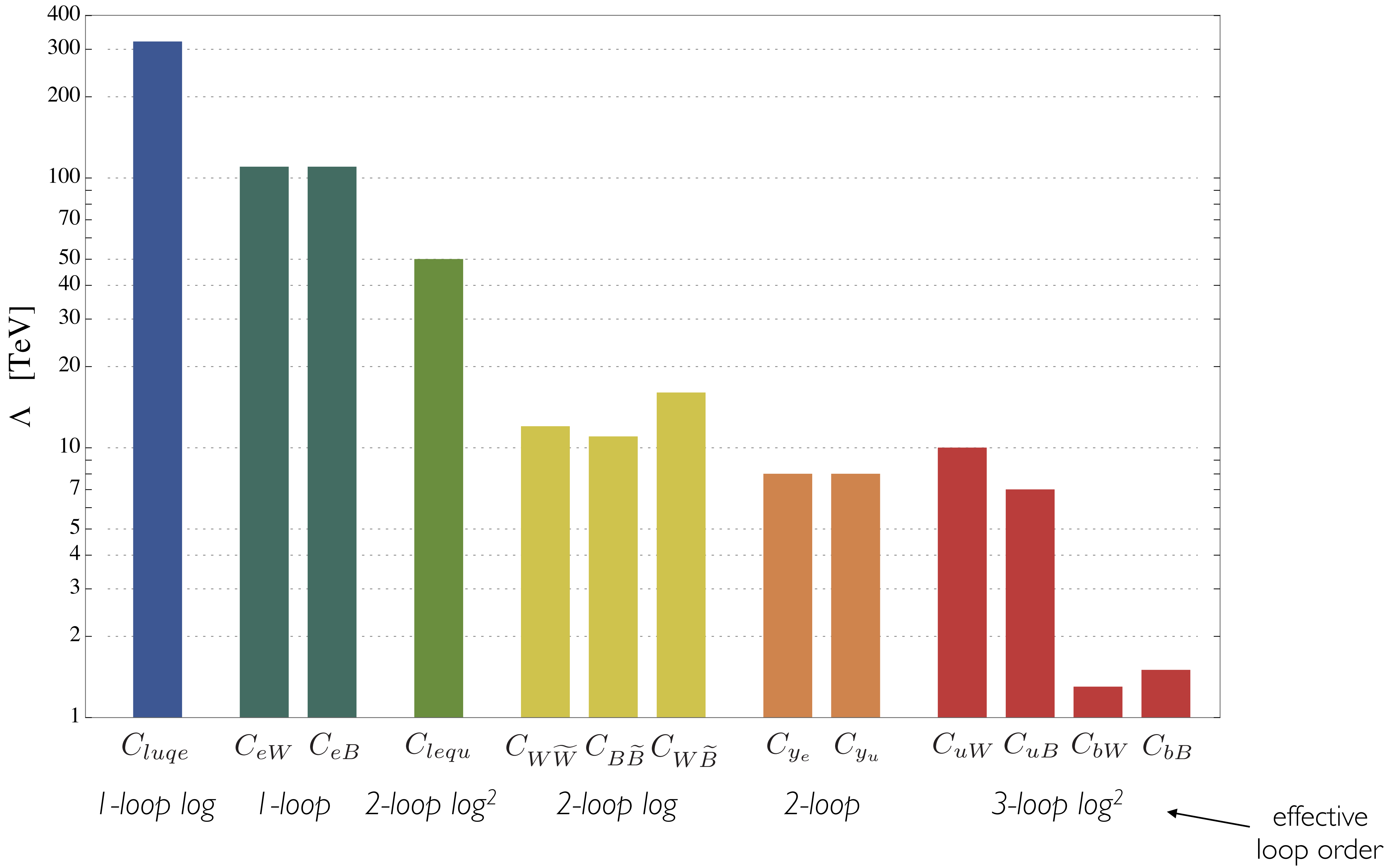
suppressed by Yukawa ($\mathcal{O}_{y_{e'}}$, $\mathcal{O}_{y_d}$, $\mathcal{O}_{dV}$, $\mathcal{O}_{l'V}$)

3 loop double-log : $\mathcal{O}_{uV}$ $\mathcal{O}_{dV}$ $\mathcal{O}_{l'V}$

3 loop : $\mathcal{O}_{\widetilde{W}}$

Constraints from ACME II

Constraints taking into account power-counting



(obtained by fixing $g_* = 1$)

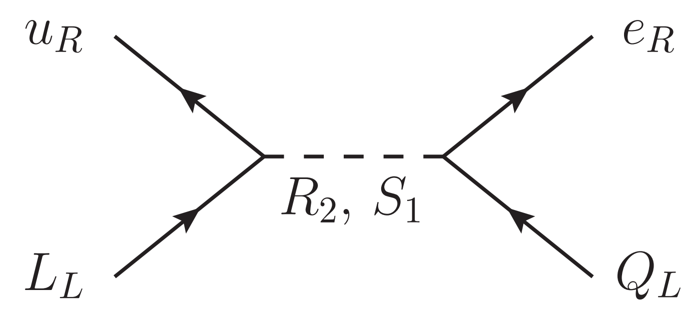
Implications for BSM

Constraints on specific BSM theories

Leptoquarks

Scalar leptoquarks

Contribute to 4-fermion operators



- The R_2 leptoquark (3, 2, 7/6)

$$\mathcal{L} = -y_2^{RL}\bar{t}_R R^a \varepsilon^{ab} L^b_{L_1} + y_2^{LR}\bar{e}_R R^{a*} Q^a_{L_3} + \text{h.c.} \longrightarrow \frac{y_2^{LR*} y_2^{RL*}}{m^2_{R_2}} \mathcal{O}_{luqe}$$

$$m_{R_2} \gtrsim \mathbf{420\ TeV} \sqrt{\frac{|\text{Im}(y_2^{LR} y_2^{RL})|}{y_e y_t}}$$

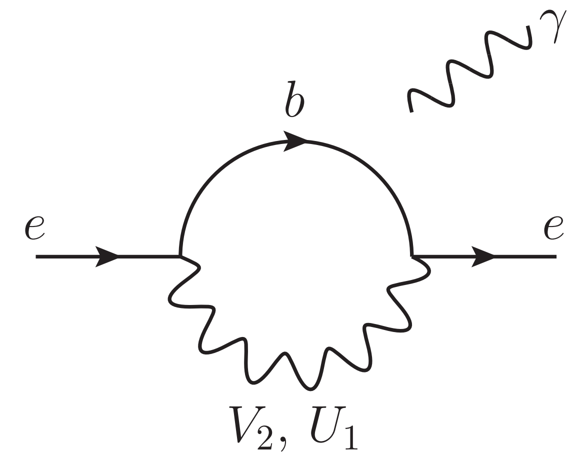
- The S_1 leptoquark ($\bar{3}$, 1, 1/3)

$$\mathcal{L} = y_1^{LL}\overline{Q}^{C\,a}_{L_3} S_1 \varepsilon^{ab} L^b_{L_1} + y_1^{RR}\bar{t}_R S_1 e_R + \text{h.c.} \longrightarrow \frac{y_1^{LL*} y_1^{RR}}{m^2_{S_1}} \left[\mathcal{O}_{luqe} + \mathcal{O}^{(1)}_{lequ}\right]$$

$$m_{S_1} \gtrsim \mathbf{400\ TeV} \sqrt{\frac{|\text{Im}(y_1^{LL} y_1^{RR*})|}{y_e y_t}}$$

Vector leptoquarks

Directly contribute to $\mathcal{O}_{eW}\,,\ \mathcal{O}_{eB}$



- The V_2 leptoquark $(\bar{3}, 2, 5/6)$

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

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

- The U_1 leptoquark $(3, 1, 2/3)$

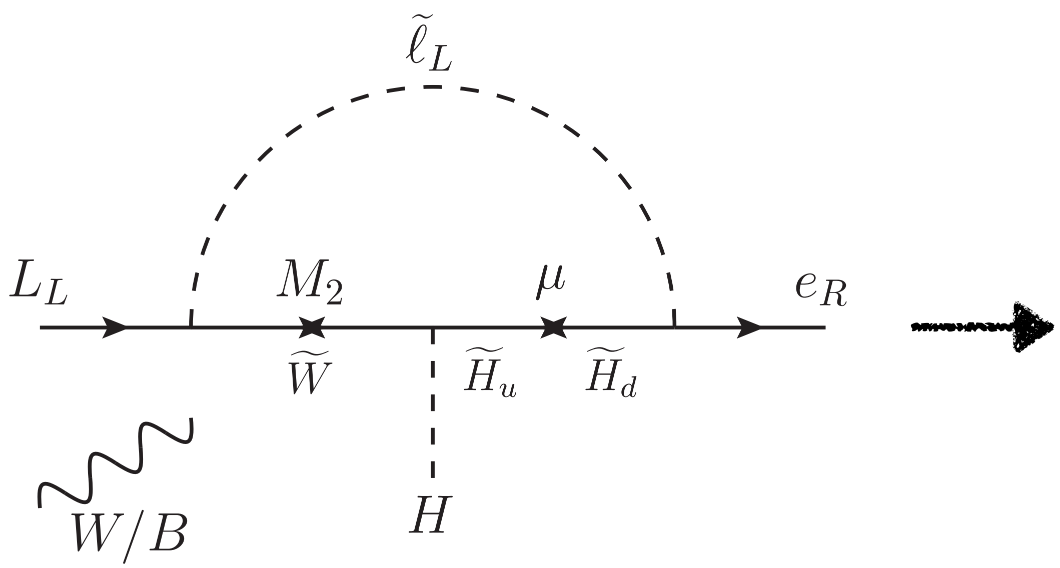
$$\mathcal{L} = x_1^{LL}\overline{Q}_{L_3}^a\gamma^\mu U_{1,\mu}L_{L_1}^a + x_1^{RR}\overline{b}_R\gamma^\mu U_{1,\mu}e_R + \text{h.c.}$$

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

SUSY

Constraints on electron partners

Large effects at 1-loop



$$\frac{d_e}{e} \sim \frac{g^2}{16\pi^2} \frac{m_e}{m_{\widetilde{\ell}}^2} \tan\beta \frac{\mathrm{Im}(M_2\mu)}{m_{\widetilde{\ell}}^2} \log \frac{|M_2\mu|}{m_{\widetilde{\ell}}^2}$$

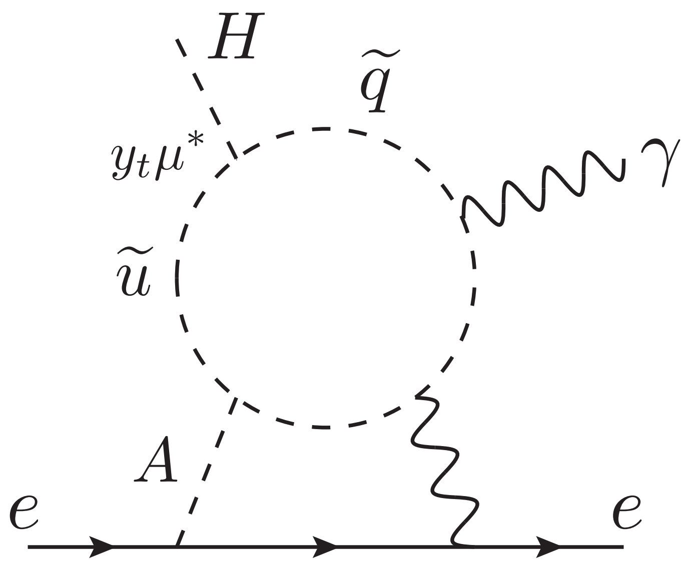
- Simple results in the limit of heavy partners

Strong constraint on mass of electron superpartners

$m_{\widetilde{\ell}} \gtrsim 25\ (50)\ \mathrm{TeV}$ for $m_{\widetilde{\ell}} = M_2 = \mu \ \ (m_{\widetilde{\ell}} \gg M_2 = \mu)$

Constraints on the stop

2-loop effects through Barr-Zee diagrams



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

- Can also be interpreted as running induced by AFF operator

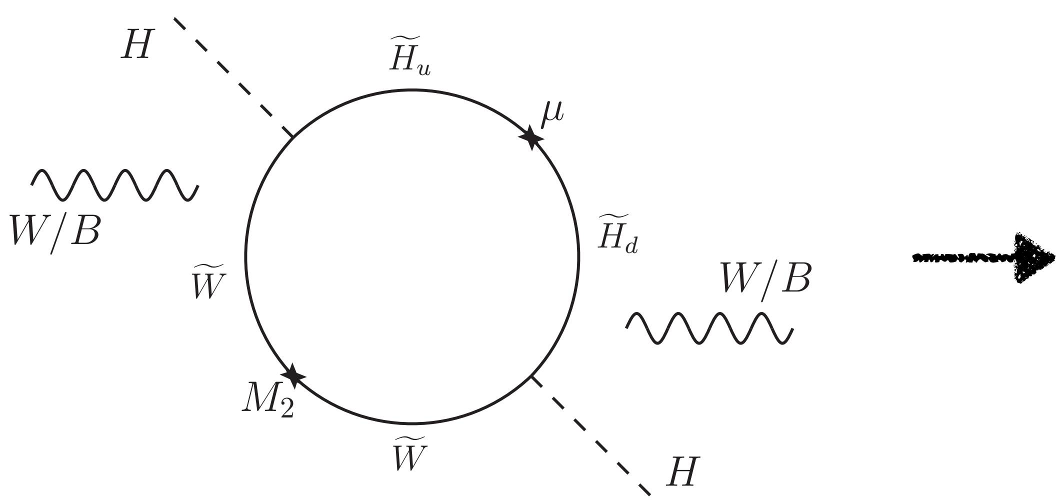
Strong constraint on stop mass

$$m_{\widetilde{t}} \gtrsim 5 \text{ TeV}$$

for $\tan\beta \sim \sin\arg(\mu A_t) \sim 1\,, \qquad m_A \sim \mu \sin A_t \sim 1\,\text{TeV}$

Constraints from heavy EW-inos

Heavy electroweak-inos contribute to HHFF operators



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

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

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

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

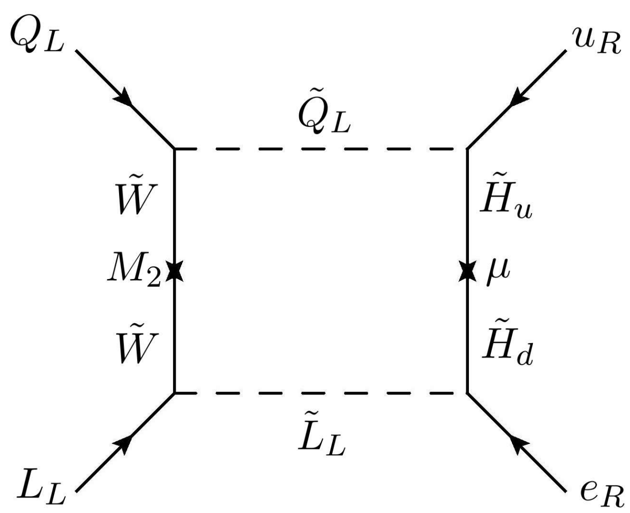
ACME II bounds

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

for $\tan\beta \sim 1$ and $O(1)$ CP-violating phases

Squark-selectron-gauginos loop

Contribution to $\mathcal{O}_{luqe}$ via squark-selectron-gauginos loop



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

sum over Wino, Higgsinos and sfermion masses

Strong bounds on superpartner mass scale

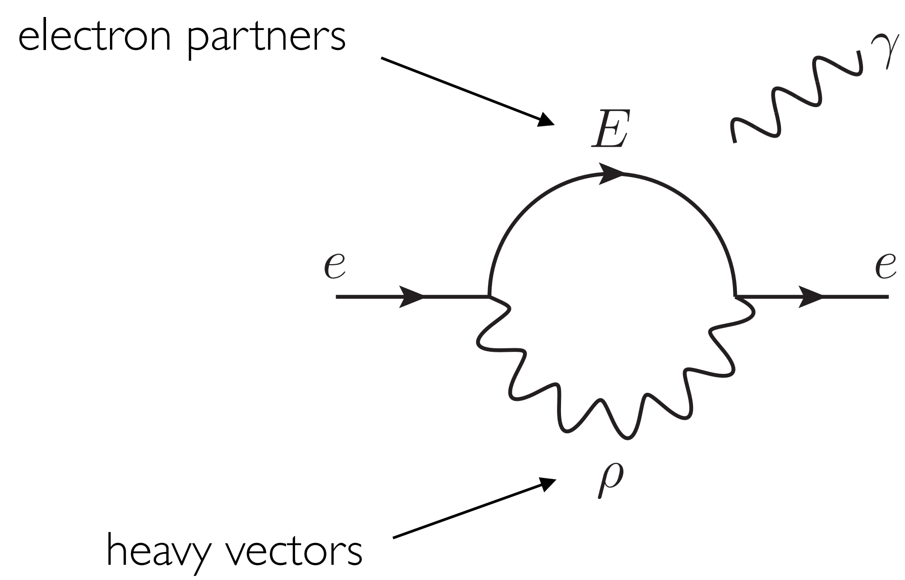
$$m_i \gtrsim 7.5\,\mathrm{TeV}$$

for degenerate superpartner masses and $\sin\arg(\mu M_2)/\sin 2\beta \sim 1$

Composite Higgs

Anarchic composite Higgs

Anarchic flavor models generate lepton EDMs at 1-loop level
(through the exchange of heavy vectors and electron partners)



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

compositeness scale
connected to **tuning**!

Multi-scale composite Higgs

CP-violating effects can be drastically reduced in **multi-scale models**

[G.P., Pomarol '16]

energy scale	decoupling operators
Λ_u	$\mathcal{O}_{u_R}$
Λ_d	$\mathcal{O}_{d_R}$, $\mathcal{O}_{Q_{L1}}$
Λ_s	$\mathcal{O}_{s_R}$
Λ_c	$\mathcal{O}_{c_R}$, $\mathcal{O}_{Q_{L2}}$
Λ_b	$\mathcal{O}_{b_R}$
$\Lambda_t \sim \Lambda_{\rm IR}$	$\mathcal{O}_{t_R}$, $\mathcal{O}_{Q_{L3}}$

Yukawa's for each family generated at different energy scales

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

$$\Downarrow$$

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

Multi-scale composite Higgs

CP-violating effects can be drastically reduced in **multi-scale models**

[G.P., Pomarol '16]

energy scale	decoupling operators
Λ_u	$\mathcal{O}_{u_R}$
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Λ_s	$\mathcal{O}_{s_R}$
Λ_c	$\mathcal{O}_{c_R}\,,\ \mathcal{O}_{Q_{L2}}$
Λ_b	$\mathcal{O}_{b_R}$
$\Lambda_t \sim \Lambda_{\rm IR}$	$\mathcal{O}_{t_R}\,,\ \mathcal{O}_{Q_{L3}}$

High energy scale suppresses flavour effects

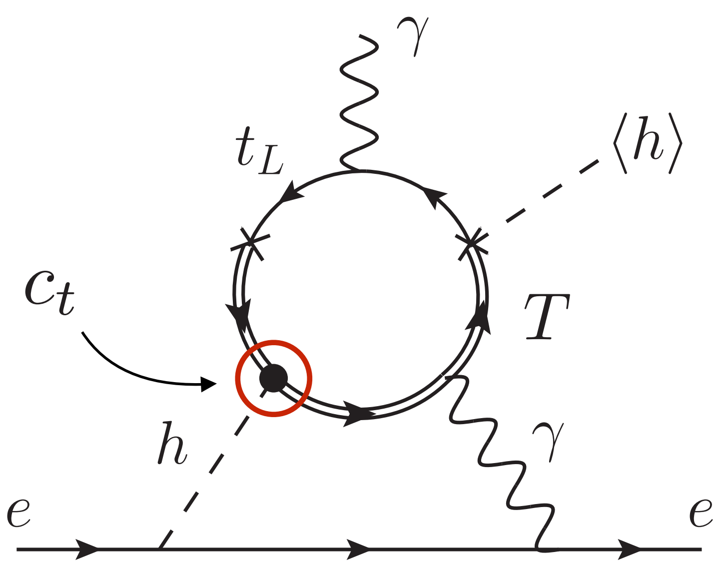
- negligible EDMs

Main flavor effects from top

Bounds on top partners

Main contribution to the electron EDM from top parters

2-loop Barr-Zee diagrams



$$\frac{d_e}{e} \sim \frac{e^2}{48\pi^2} y_e (\mathrm{Im}\ c_t) \sin\theta \frac{m_{top}}{m_T^2} \log \frac{m_{top}^2}{m_T^2}$$

mixing between top and top partners

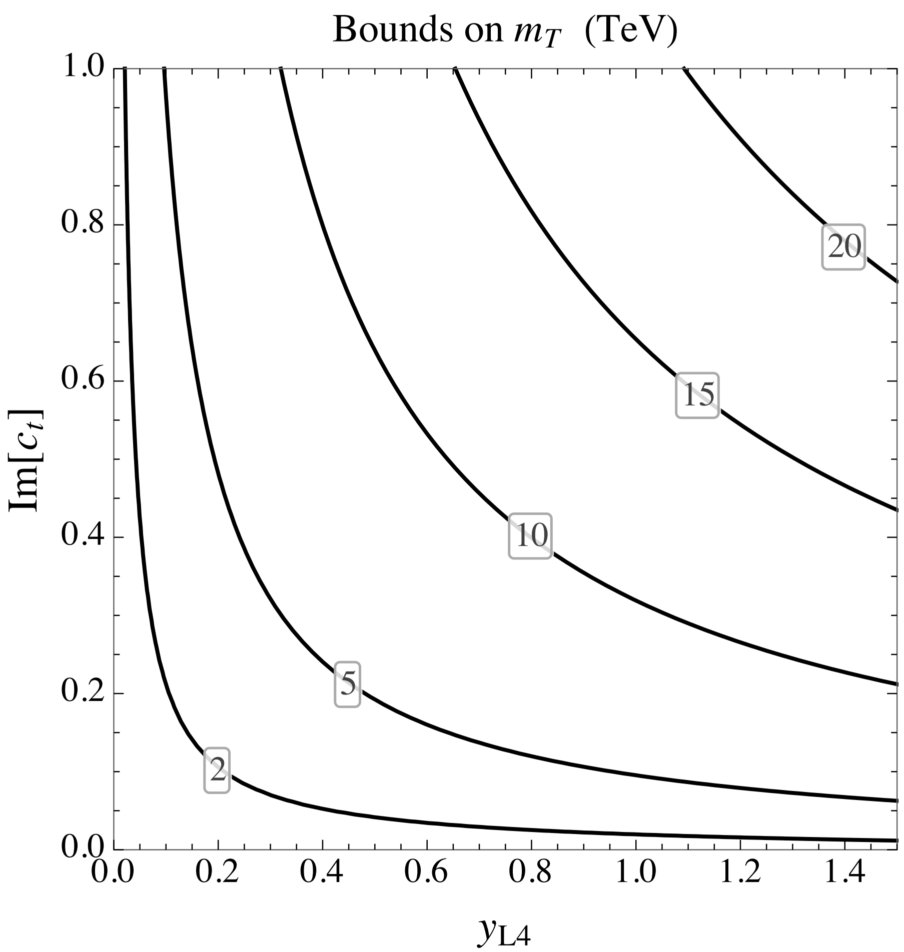
Strong bounds on top partners mass scale

$$m_T \gtrsim 20\ \mathrm{TeV}$$

for $\mathrm{Im}\ c_t \sim 1$ and $\sin\theta \sim O(1)$

Comparison with direct searches

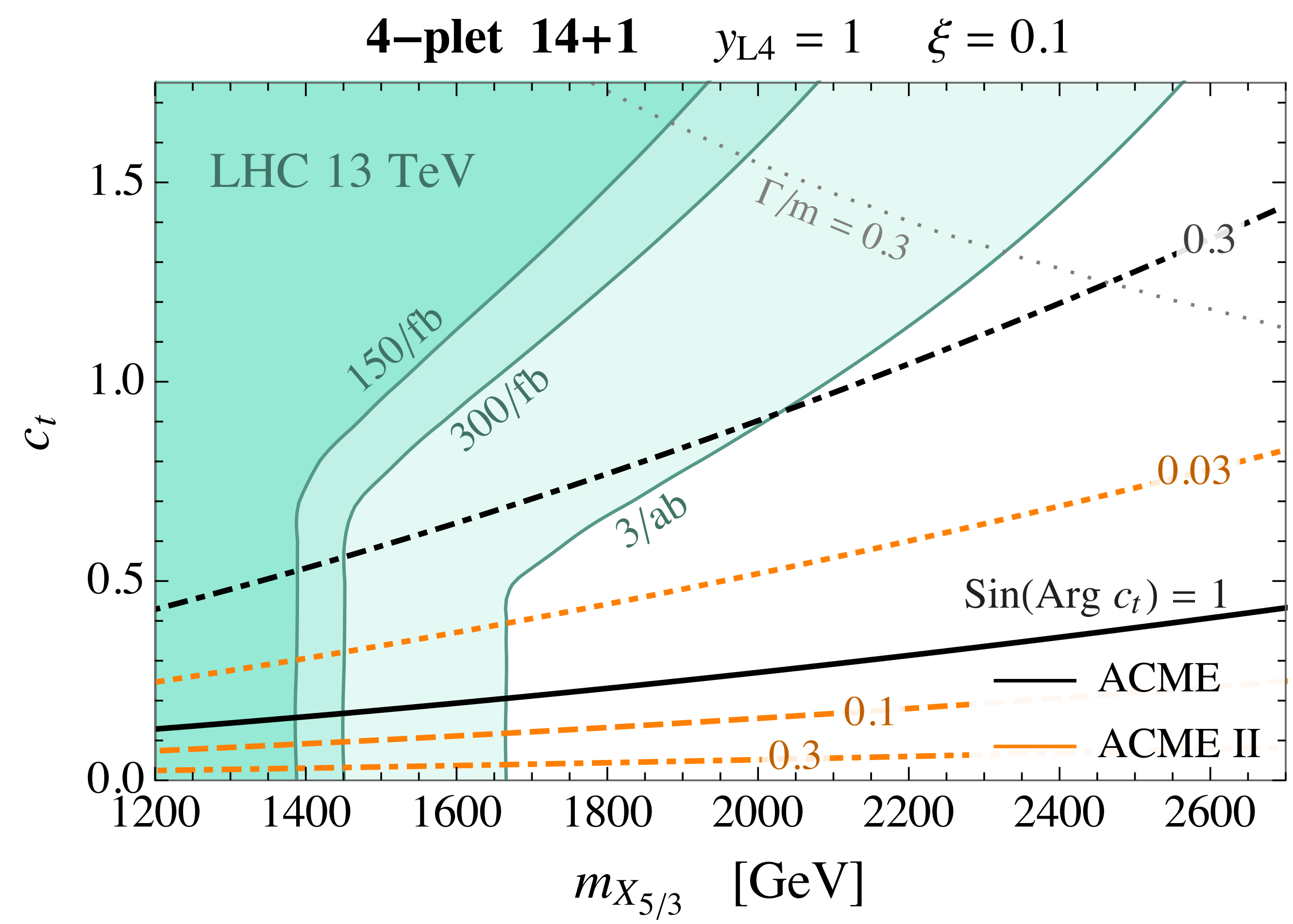
Constraints from ACME II



mixing parameter

$$\tan\theta = \frac{y_{L4}}{m_T}$$

HL-LHC projections



→ electron EDM bounds stronger than HL-LHC ones if $\mathrm{Im}\, c_t \gtrsim 0.01$

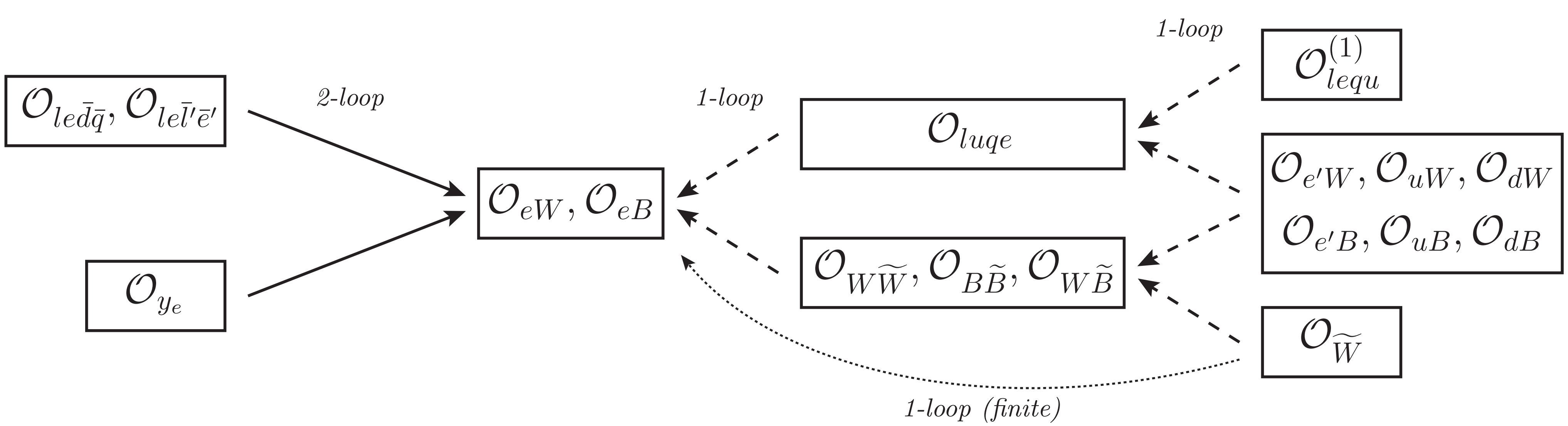
Conclusions

Conclusions

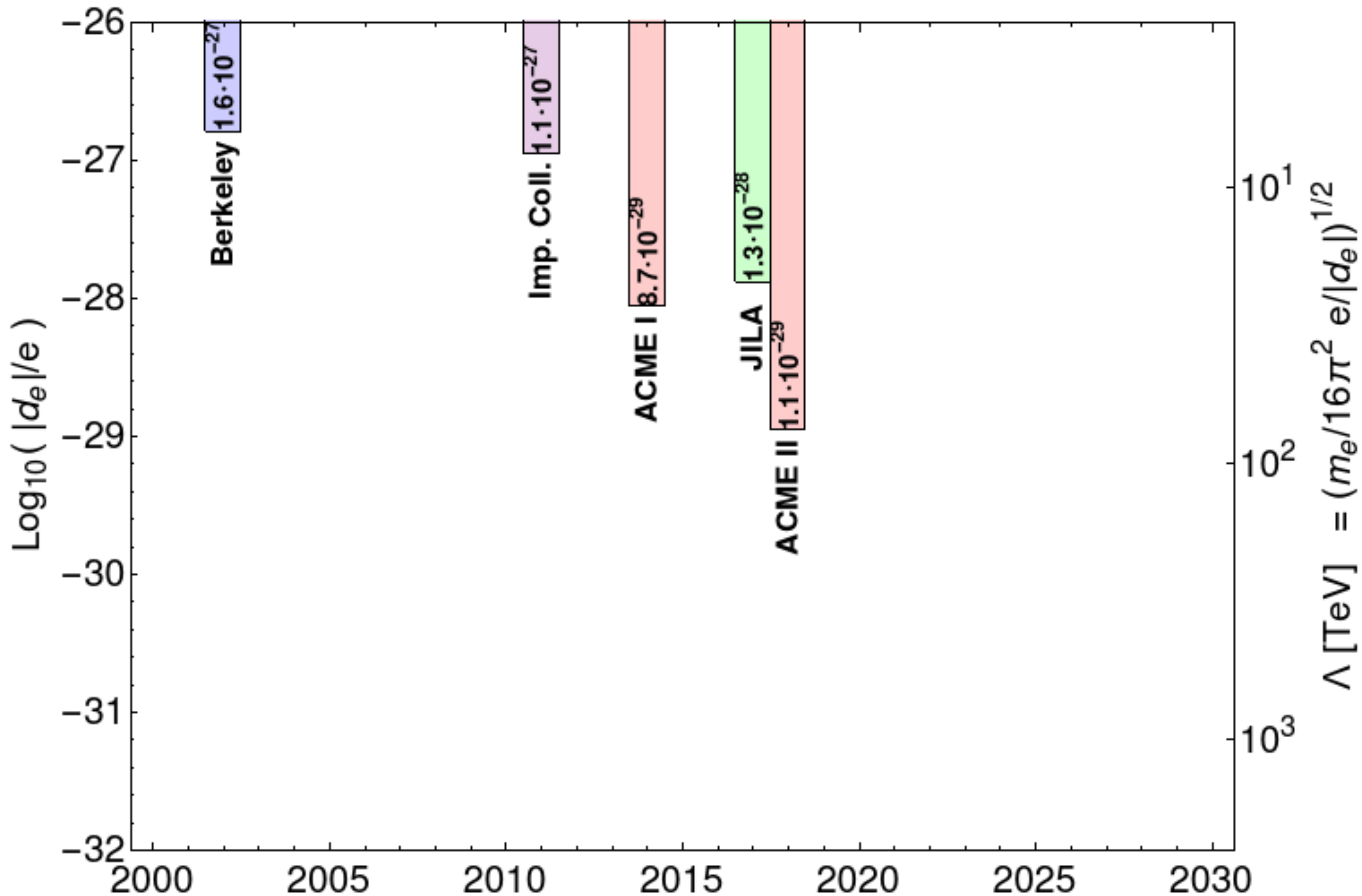
The **electron EDM** provides an excellent way to probe new physics

- clean observable, with strong sensitivity to new CP-violating sources
- can test new-physics at the 10 TeV scale even with 2-loop effects

New-physics effects can be cleanly classified within an EFT framework

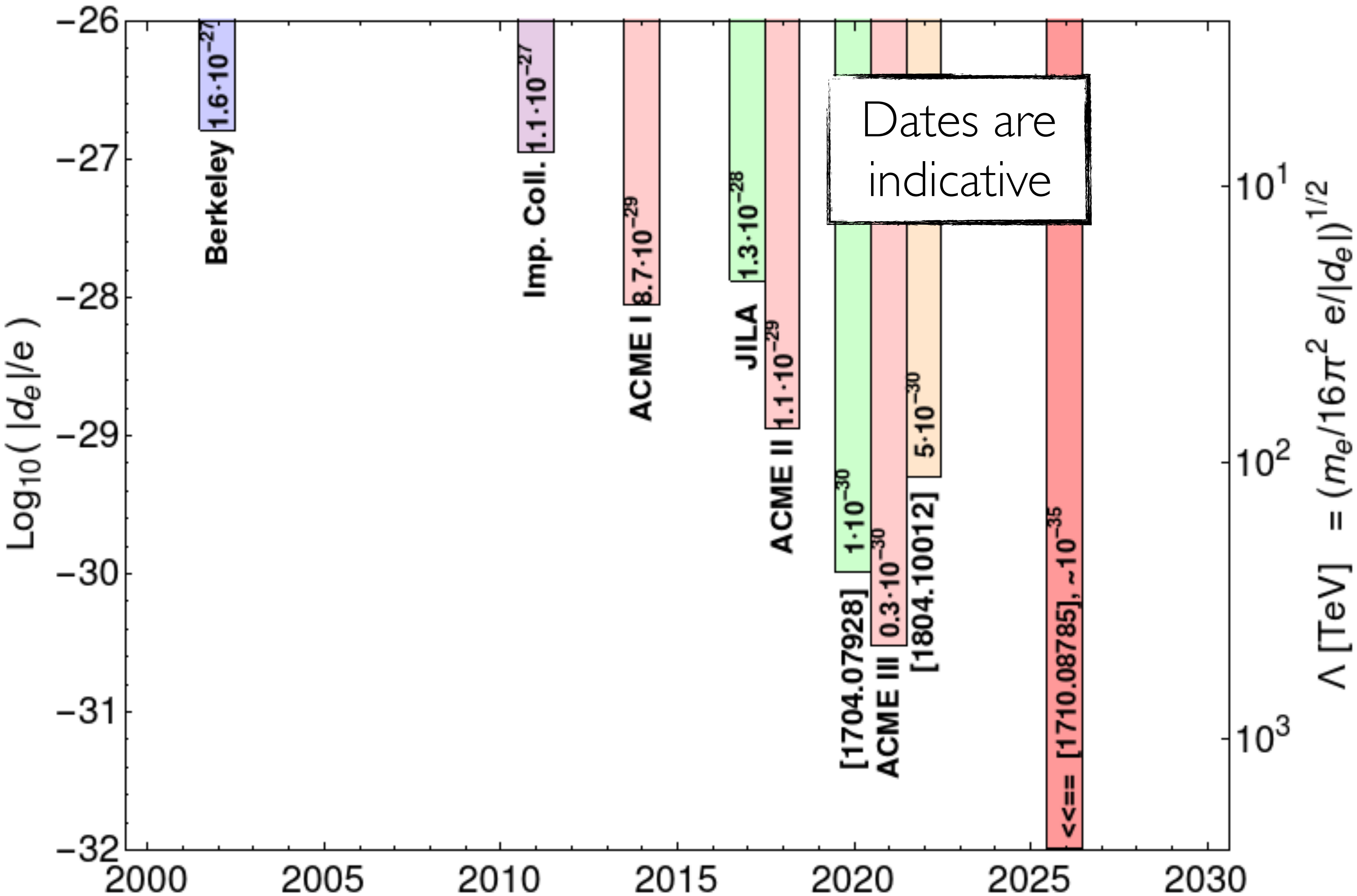


Outlook



- Experimental bounds steadily improved in the past years

Outlook



- Experimental bounds steadily improved in the past years
- Significant boost is expected in the near future

→ probe most BSM models well beyond the 10^2 TeV scale