Interplay of New Physics Effects in $(g-2)_\ell$ and $h \to \ell^+\ell^-$ Lessons from SMEFT

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Based on 2103.10859 with J.F. Kamenik and S. Fajfer

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Spoilers

- Small set of operators in SMEFT describes the observables

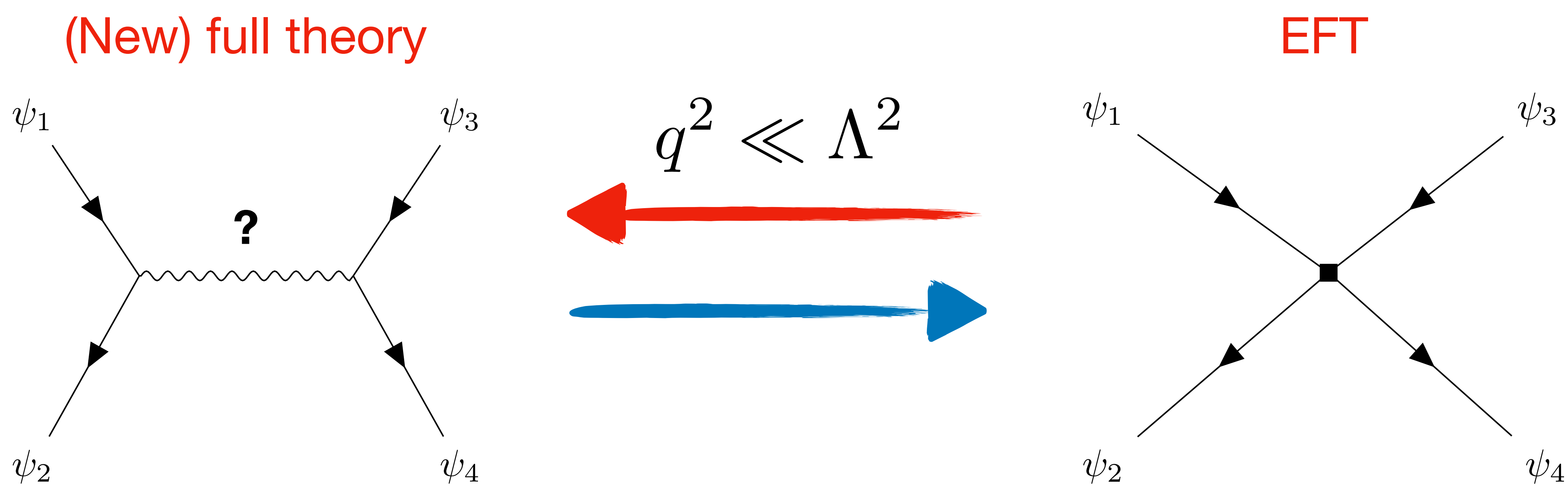
- Correlations via one-loop RGE

- Chirally enhanced matching conditions at one-loop

- Pheno analysis can give hints on model building

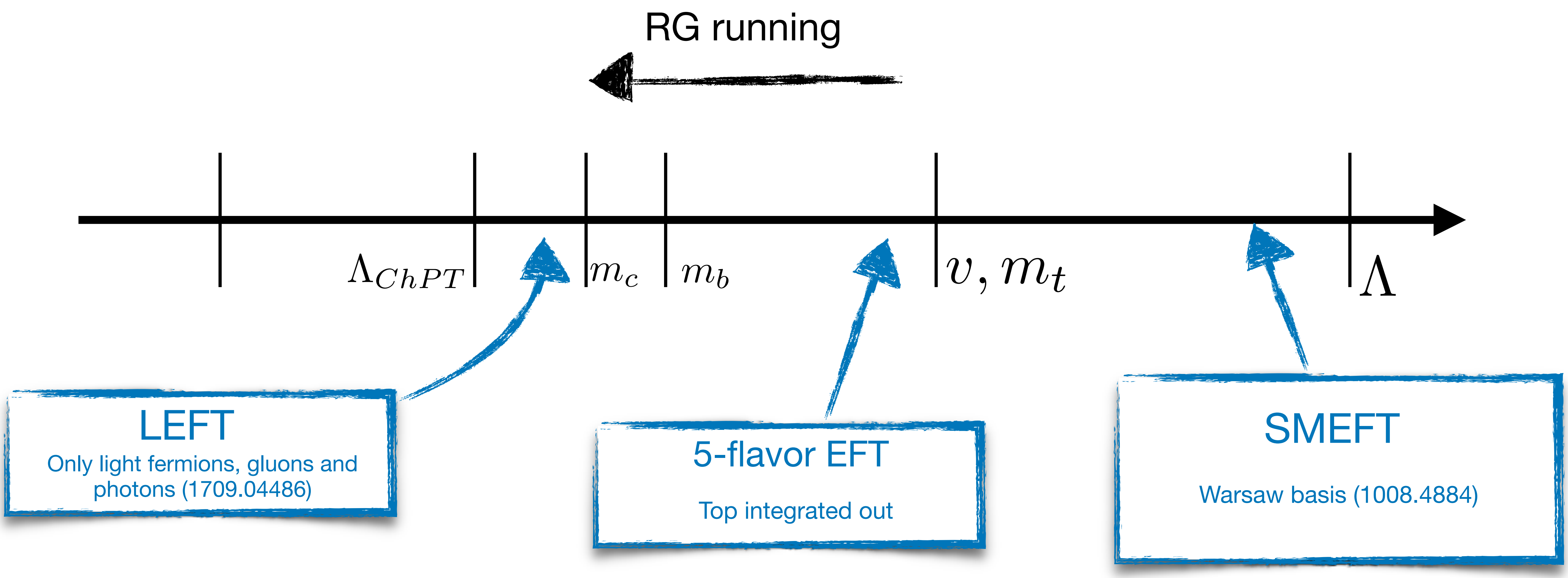
- Tree-level matching + running can capture the dominant effects of NP

$$\mathcal{L}_{EFT} = \sum_{d,i} \frac{\mathcal{C}_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

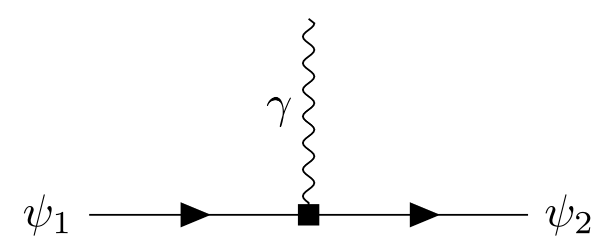


Top-down (model-dependent): define new theory, match with EFT, enjoy

Bottom-up (model-independent) approach: build complete basis with light d.o.f. (?), fit all coefficients with experiments

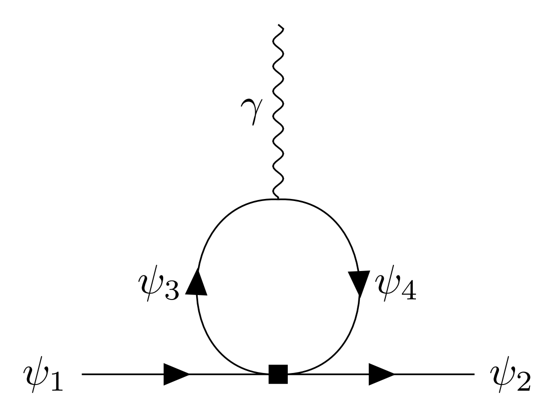


SMEFT $\left(\bar{\ell}_p \sigma^{\mu\nu} e_r\right) \varphi B_{\mu\nu}$

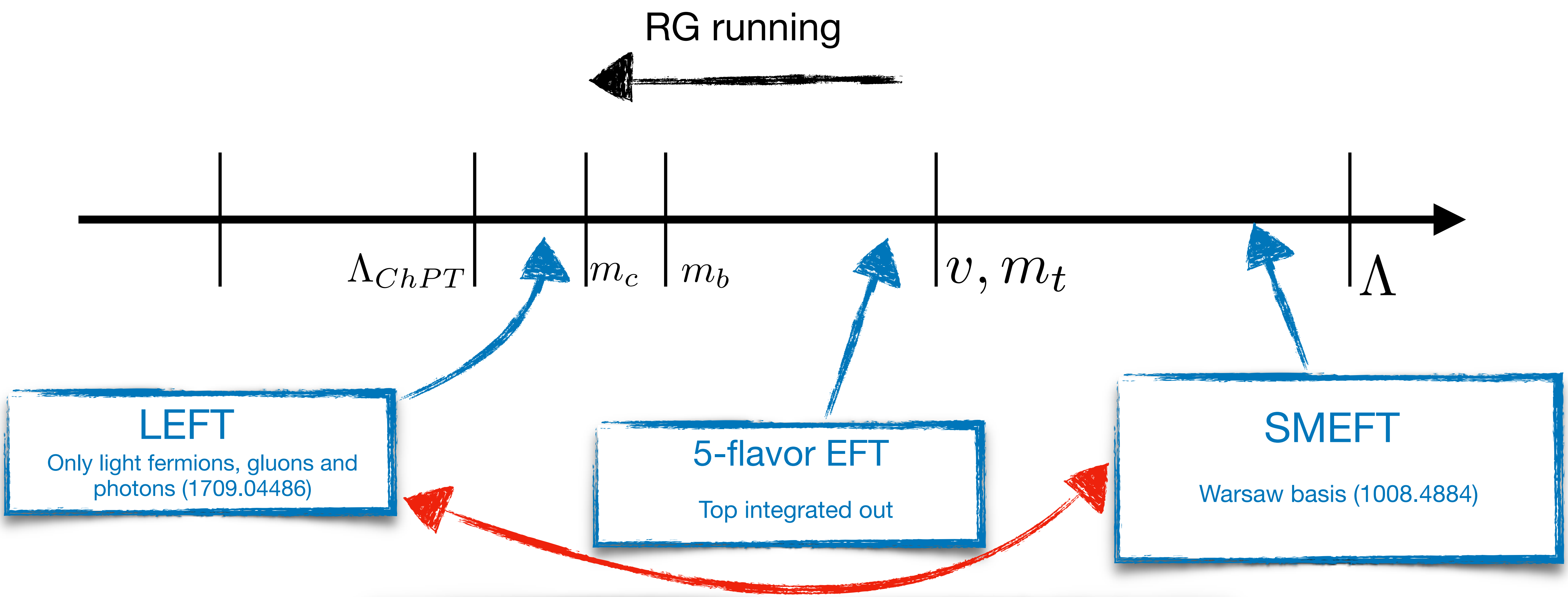


Operator mixing

LEFT $\left(\bar{l} \sigma^{\mu\nu} l\right) F_{\mu\nu}$



Threshold matching



SMEFT $(\bar{\ell}_p \sigma^{\mu\nu} e_r)$ ... erator mixing

LEFT $(\bar{l}\sigma^{\mu\nu} l)\, F$ ... shold matching

Complete one-loop RGE in SMEFT

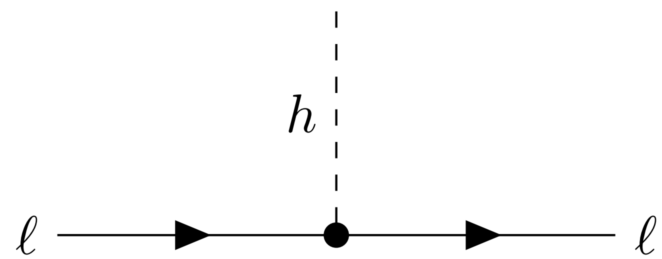
(Jenkins et al.: 1312.2014, 1310.4838, 1312.2014)

One-loop SMEFT matching into LEFT

(Dekens, Stoffer: 1908.05295)

$h \to \ell^+ \ell^-$

Standard Model



$$\mathcal{L}^{SM} \supset \frac{y_\ell^{SM}}{\sqrt{2}} \left(\bar{\ell} \varphi e\right)$$

$$\varphi^T = \left(0,\ \frac{h+v}{\sqrt{2}}\right)$$

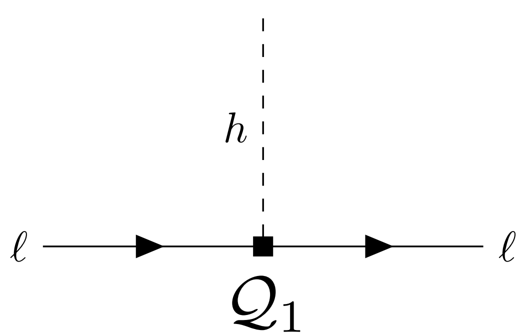
$$y_\ell^{SM} = \frac{\sqrt{2} m_\ell}{v}$$

LEFT

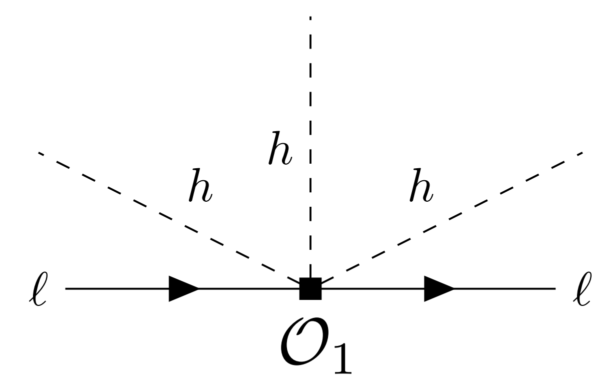
$$\mathcal{Q}_{1,\ell} = c_{1,\ell} h \left(\bar{l}_\ell l_\ell\right)$$

SMEFT

$$\mathcal{O}_{1,pr} = \left(\varphi^\dagger \varphi\right) \left(\bar{\ell}_p e_r \varphi\right)$$



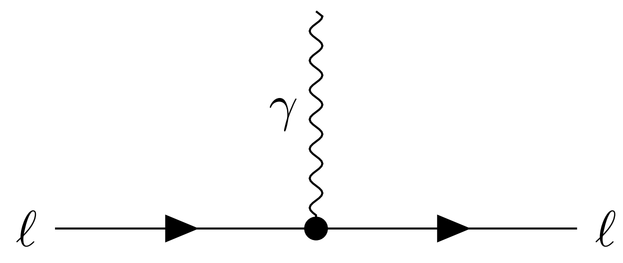
$$c_{1,\ell}(\mu_w)|_{tree} = \hat{\mathcal{C}}_{1,\ell}(\mu_w) \frac{v^2}{\sqrt{2}}$$



$$\kappa_\ell^2 = \frac{\Gamma(h \to \ell^+ \ell^-)}{\Gamma_{SM}(h \to \ell^+ \ell^-)} = \left(1 + \frac{c_{1,\ell} v}{m_\ell}\right)^2$$

$(g-2)_\ell$

Standard Model



$$i\mathcal{M} = -ie\bar{u}_\ell(p')\left[F_1(q^2)\gamma^\mu + \frac{i\sigma^{\mu\nu}q_\nu}{2m_\ell}F_2(q^2)\right]u_\ell(p)\epsilon^*_\nu(q)$$

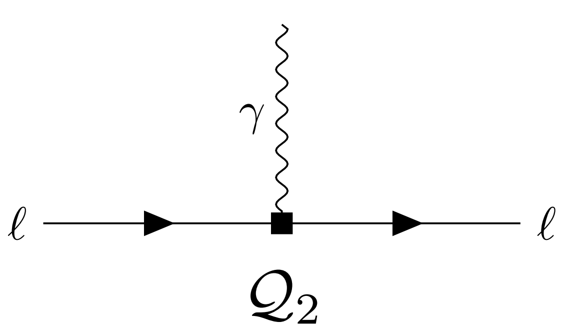
$$a_\ell = \frac{(g-2)_\ell}{2} = F_2(0)$$

LEFT

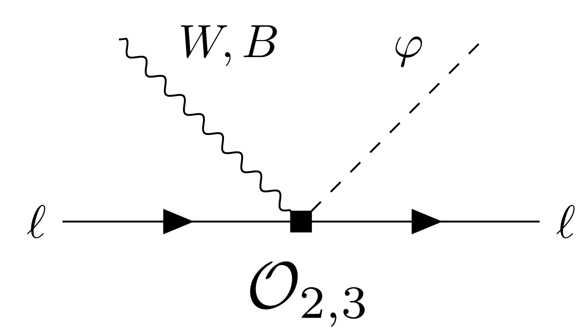
$$\mathcal{Q}_{2,\ell} = e\frac{c_{2,\ell}}{m_\ell}\left(\bar{l}_\ell\sigma_{\mu\nu}l_\ell\right)F^{\mu\nu}$$

SMEFT

$$\mathcal{O}_{2,pr} = (\bar{\ell}_p\sigma^{\mu\nu}e_r)\tau^a\varphi W^a_{\mu\nu}$$
$$\mathcal{O}_{3,pr} = (\bar{\ell}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$$



$$c_{2,\ell}(\mu_w)|_{tree} = \frac{v\,m_\ell}{\sqrt{2}e}\left(c_w\hat{\mathcal{C}}_{3,\ell}(\mu_w) - s_w\hat{\mathcal{C}}_{2,\ell}(\mu_w)\right)$$



$$\delta a_\ell = 4c_{2,\ell}(m_\ell)$$

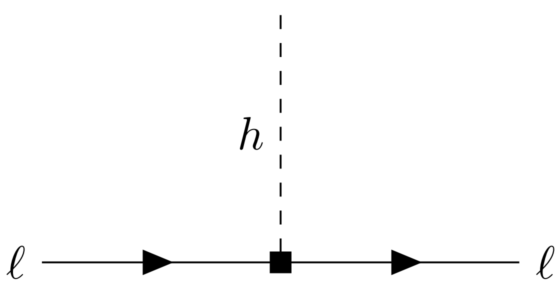
Assume all fermions massless except the top —> need two more to form a closed set under RGE

$$\mathcal{O}_{4,prst} = \left(\bar{\ell}^j_p e_r\right) \epsilon_{jk} \left(\bar{q}^k_s u_t\right) \qquad \mathcal{O}_{5,prst} = \left(\bar{\ell}^j_p \sigma_{\mu\nu} e_r\right) \epsilon_{jk} \left(\bar{q}^k_s \sigma^{\mu\nu} u_t\right)$$

LEFT

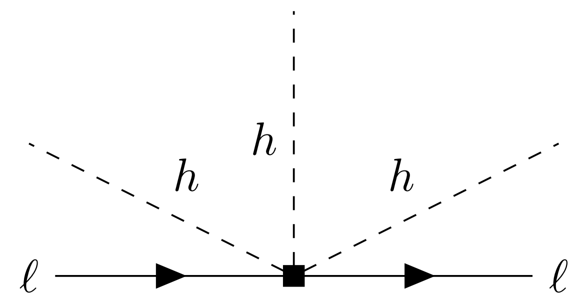
$$h \to \ell^+ \ell^-$$

SMEFT

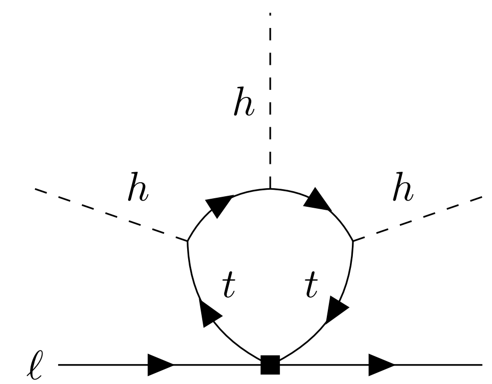


$\mathcal{Q}_1$

$$\dot{C}_1 \propto y_t^3 \cdot C_4$$

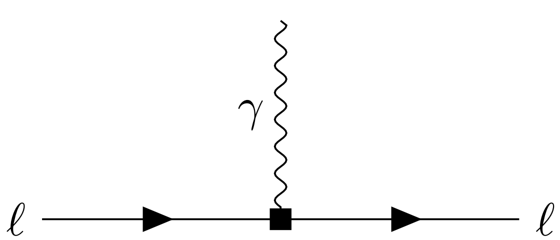


$\mathcal{O}_1$



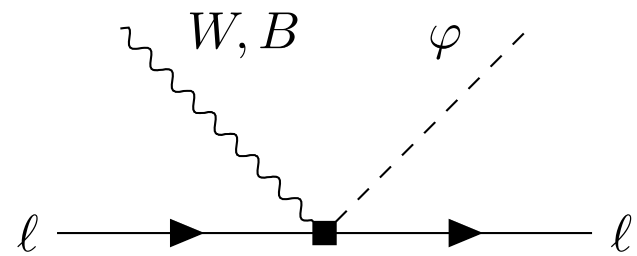
$\mathcal{O}_4$

$$(g-2)_\ell$$

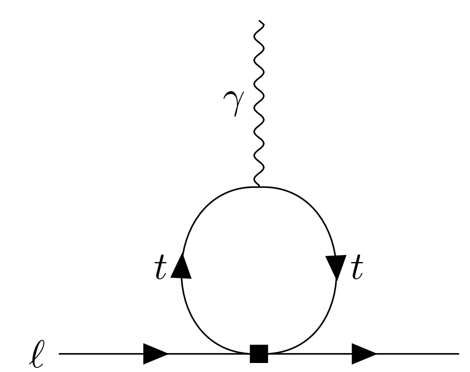


$\mathcal{Q}_2$

$$\dot{C}_{2,3} \propto y_t C_5$$



$\mathcal{O}_{2,3}$



$\mathcal{O}_5$

Pheno guidelines

LEFT

$$\mathcal{Q}_{1,\ell} = c_{1,\ell} h \left(\bar{l}_\ell l_\ell\right)$$

$$\mathcal{Q}_{2,\ell} = e \frac{c_{2,\ell}}{m_\ell} \left(\bar{l}_\ell \sigma_{\mu\nu} l_\ell\right) F^{\mu\nu}$$

SMEFT

$$\mathcal{O}_{1,pr} = \left(\varphi^\dagger \varphi\right) \left(\bar{\ell}_p e_r \varphi\right)$$

$$\mathcal{O}_{2,pr} = (\bar{\ell}_p \sigma^{\mu\nu} e_r) \tau^a \varphi W^a_{\mu\nu}$$

$$\mathcal{O}_{3,pr} = (\bar{\ell}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$$

$$\mathcal{O}_{4,prst} = \left(\bar{\ell}^j_p e_r\right) \epsilon_{jk} \left(\bar{q}^k_s u_t\right)$$

$$\mathcal{O}_{5,prst} = \left(\bar{\ell}^j_p \sigma_{\mu\nu} e_r\right) \epsilon_{jk} \left(\bar{q}^k_s \sigma^{\mu\nu} u_t\right)$$

1 - Assume initial condition for each Λ: $\mathcal{C}_i(\Lambda) = 1\,, \quad \mathcal{C}_{j\neq i}(\Lambda) = 0$

2 - RGE running from heavy scale to weak scale

3 - Match SMEFT with LEFT including one-loop

4 - Compute NP effects in observables as function of Λ

$$\kappa_\ell^2 = \frac{\Gamma(h \to \ell^+\ell^-)}{\Gamma_{SM}(h \to \ell^+\ell^-)} = \left(1 + \frac{c_{1,\ell} v}{m_\ell}\right)^2$$

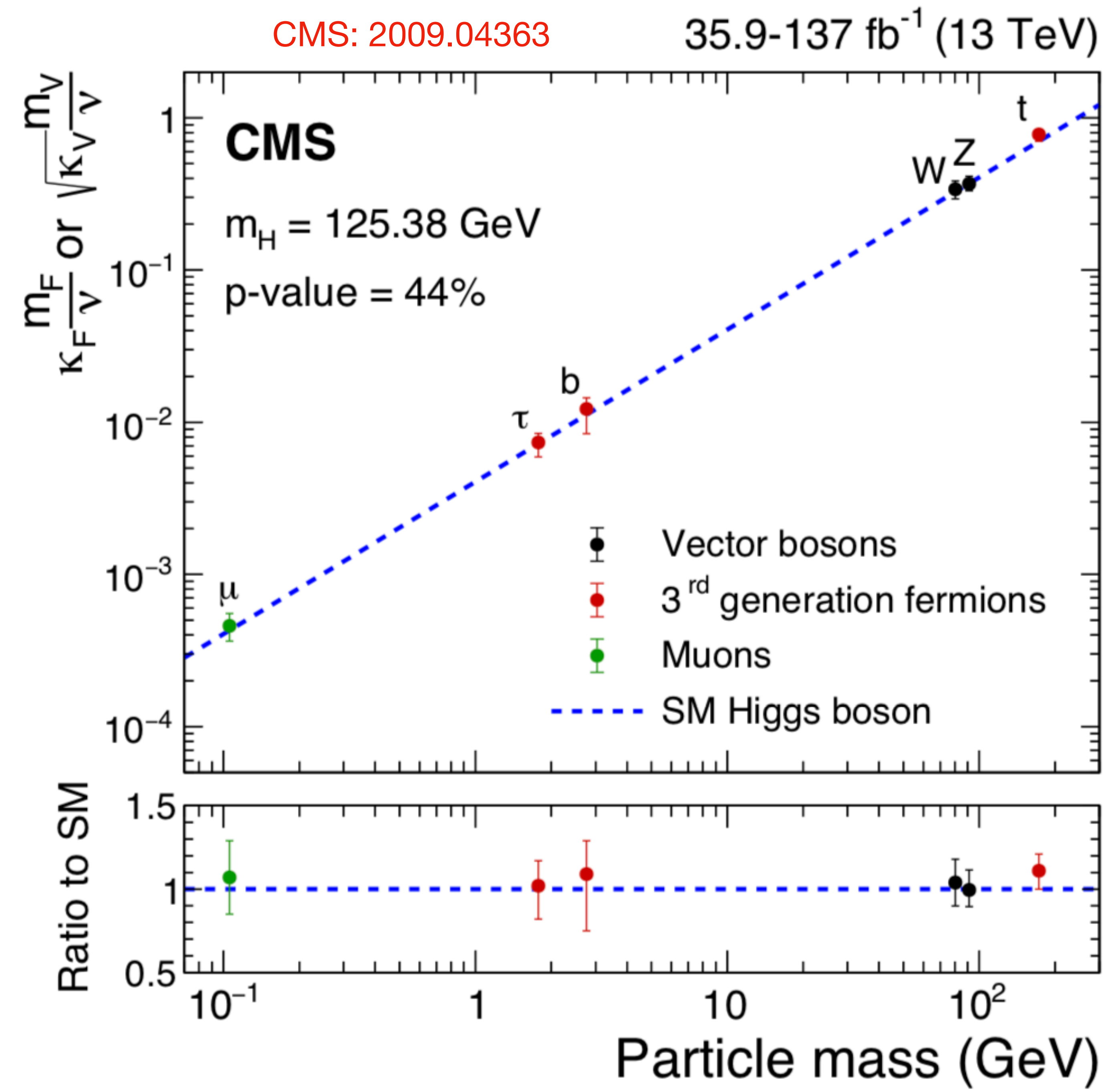
$$\delta a_\ell = 4 c_{2,\ell}(m_\ell)$$

Muon

LHC (CMS) $\kappa_\mu^2 = 1.19 \pm 0.55$

HL-LHC $|\kappa_\mu^2 - 1| < 0.053$

FCC $|\kappa_\mu^2 - 1| < 0.0042$



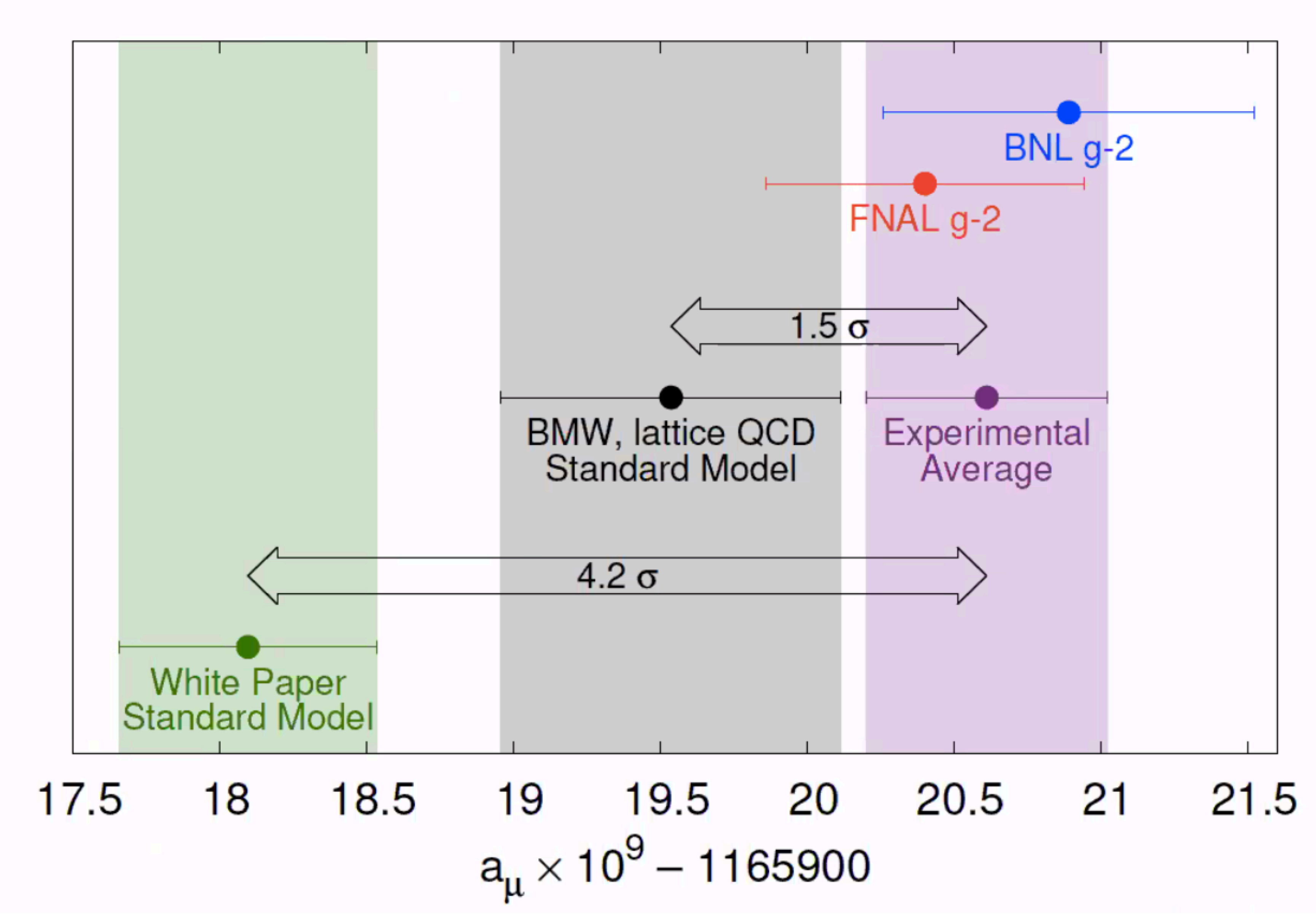
Theory Initiative

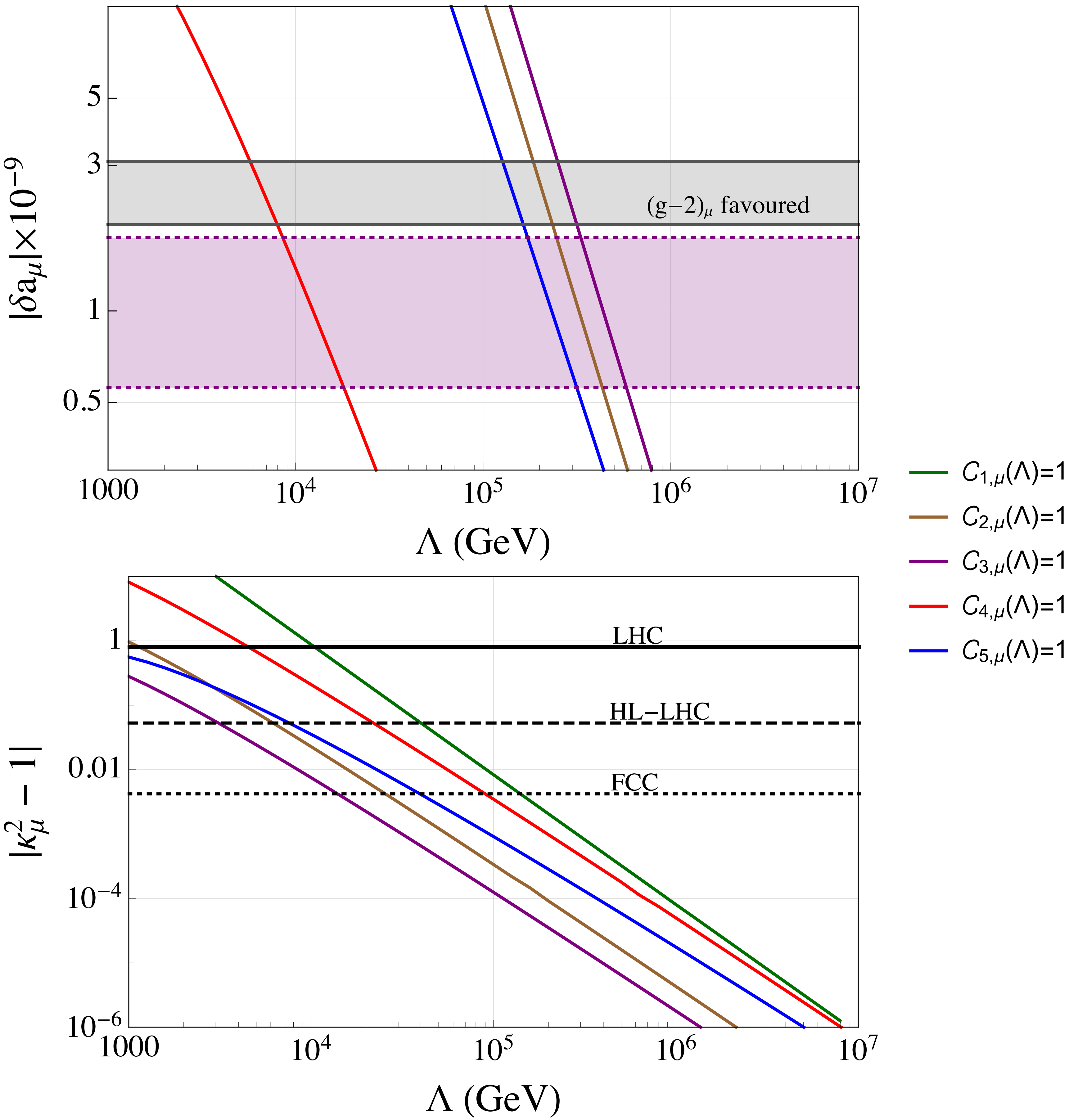
$$\delta a_\mu = (251 \pm 59) \times 10^{-11}$$

BMW lattice

$$\delta a_\mu = (113 \pm 68) \times 10^{-11}$$

Picture from Fodor's talk





5
3
1
0.5
$|\delta a_\mu| \times 10^{-9}$
$(g-2)_\mu$ favoured
1000
10^4
10^5
10^6
10^7
Λ (GeV)
$C_{1,\mu}(\Lambda)=1$
$C_{2,\mu}(\Lambda)=1$
$C_{3,\mu}(\Lambda)=1$
$C_{4,\mu}(\Lambda)=1$
$C_{5,\mu}(\Lambda)=1$
1
0.01
10^{-4}
10^{-6}
$|\kappa_\mu^2 - 1|$
LHC
HL−LHC
FCC
1000
10^4
10^5
10^6
10^7
Λ (GeV)

Top-down approach

or

How effective is EFT?

1 - Two-Higgs Doublet Model

2 - Scalar LeptoQuarks

2HDM

Two scalar doublets with hypercharge +1

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = R_\beta \begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix} \qquad \Phi_1 = \begin{pmatrix} G^+ \\ \frac{v+\rho_1+iG_0}{\sqrt{2}} \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{\rho_2+i\eta}{\sqrt{2}} \end{pmatrix}$$

$$\begin{pmatrix} h \\ H^0 \end{pmatrix} = R_\alpha \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} \qquad v = \sqrt{v_1^2 + v_2^2}$$

Decoupling limit

$$\alpha,\ \beta \to 0$$
$$v_2 \to 0$$
$$g_{HW} = g_{HB} = g_{Hh} = 0$$

No mixing, only mass terms

$$m_H^2 \Phi_2^\dagger \Phi_2 = m_H^2 \left(|H^+|^2 + \frac{1}{2}|\eta|^2 + \frac{1}{2}|H^0|^2 \right)$$

Only diagonal coupling to up-quarks and leptons

$$\mathcal{L}_Y = Y_{st}^u \bar{q}_s \tilde{\Phi}_1 u_t + Y_{st}^d \bar{q}_s \Phi_1 d_t + Y_{pr}^\ell \bar{\ell}_p \Phi_1 e_r + Y_{pr}^{\prime,\ell} \bar{\ell}_p \Phi_2 e_r + Y_{st}^{\prime,u} \bar{q}_s \tilde{\Phi}_2 u_t + \text{h.c.}$$

2HDM

Two scalar doublets with hypercharge +1

$$\begin{pmatrix}\Phi_1\\ \Phi_2\end{pmatrix} = R_\beta \begin{pmatrix}\varphi_1\\ \varphi_2\end{pmatrix} \qquad \Phi_1 = \begin{pmatrix} G^+ \\ \frac{v+\rho_1+iG_0}{\sqrt{2}}\end{pmatrix} \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{\rho_2+i\eta}{\sqrt{2}}\end{pmatrix}$$

$$\begin{pmatrix}h\\ H^0\end{pmatrix} = R_\alpha \begin{pmatrix}\rho_1\\ \rho_2\end{pmatrix} \qquad v = \sqrt{v_1^2 + v_2^2}$$

Decoupling limit

$\alpha,\ \beta \to 0$

$v_2 \to 0$

$g_{HW} = g_{HB} =$

No mixing, only mass terms

$\frac{1}{2}|\eta|^2 + \frac{1}{2}|H^0|^2\Big)$

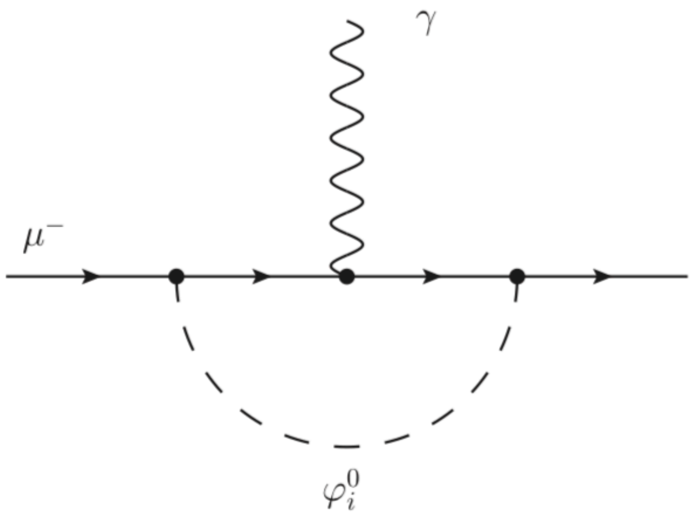
Tree-level matching to SMEFT

$$\hat{C}_{4,\ell} = \frac{y'_t y'_\ell}{m_H^2}$$

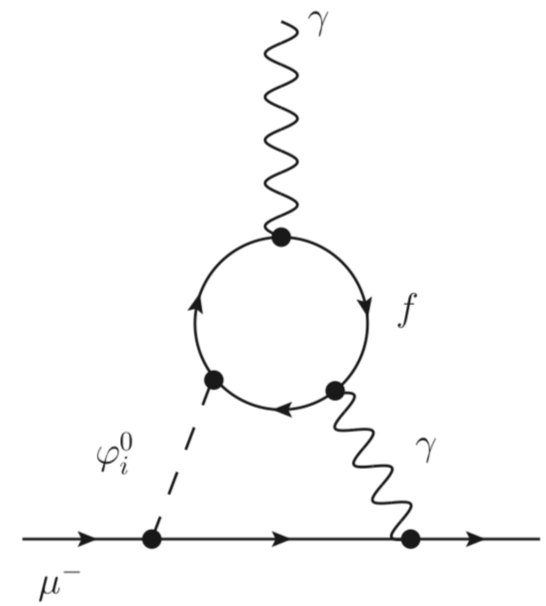
$\mathcal{L}_Y = Y^u_{st}\bar{q}_s\tilde{\Phi}_1 u$ … ${}_s\tilde{\Phi}_2 u_t + \text{h.c.}$

2HDM

(g-2) dominated by two-loop Barr-Zee diagrams (Ilisie: 1502.04199)



$$\varphi^0 = \{h, H^0, \eta\}$$



One-loop: chirally suppressed

Two-loop enhanced by heavy mass

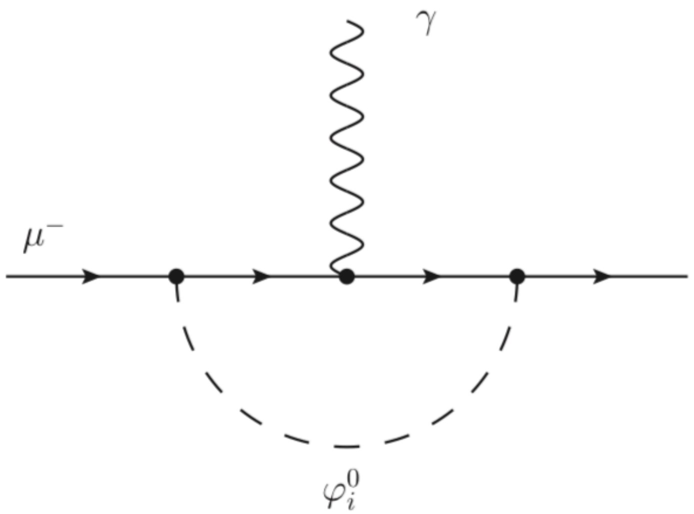
Dominated by leading logs

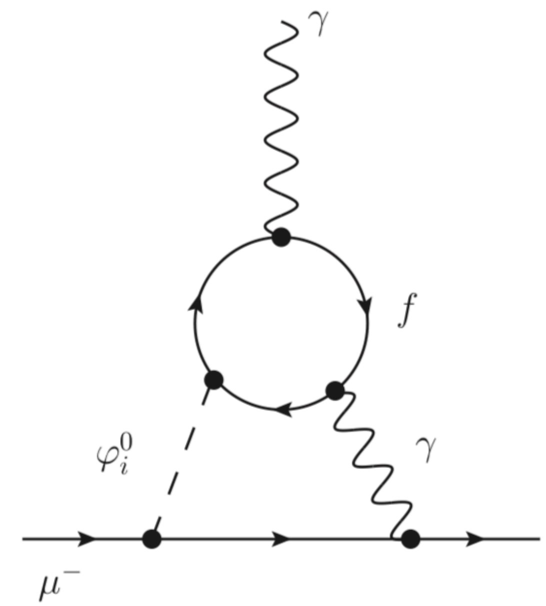
$$\ln\left(\frac{m_t^2}{m_H^2}\right)$$

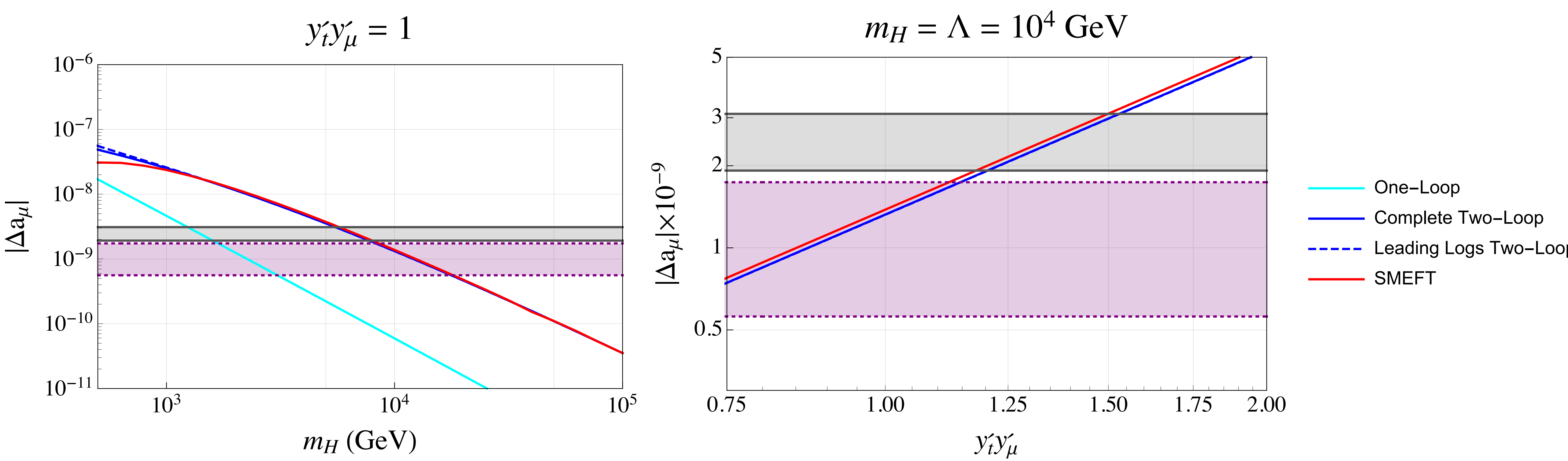
2HDM

(g-2) dominated by two-loop Barr-Zee diagrams (Ilisie: 1502.04199)

$$\varphi^0 = \{h, H^0, \eta\}$$

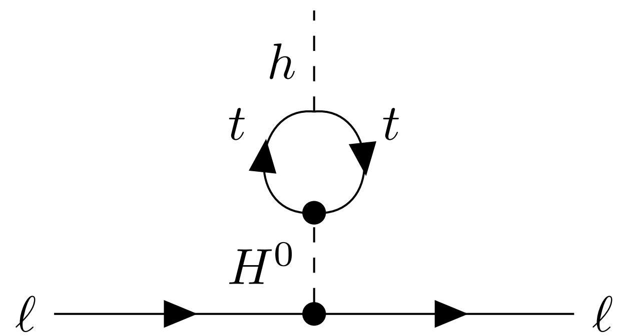


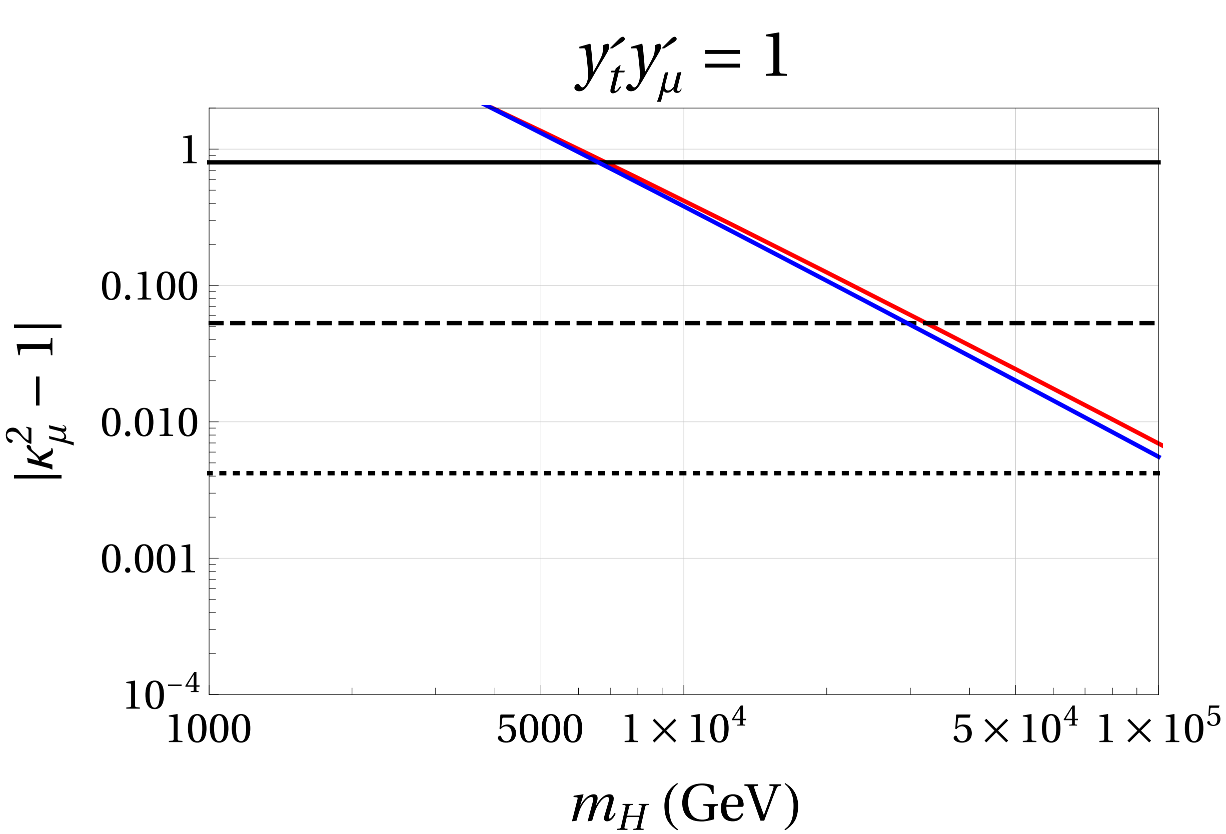


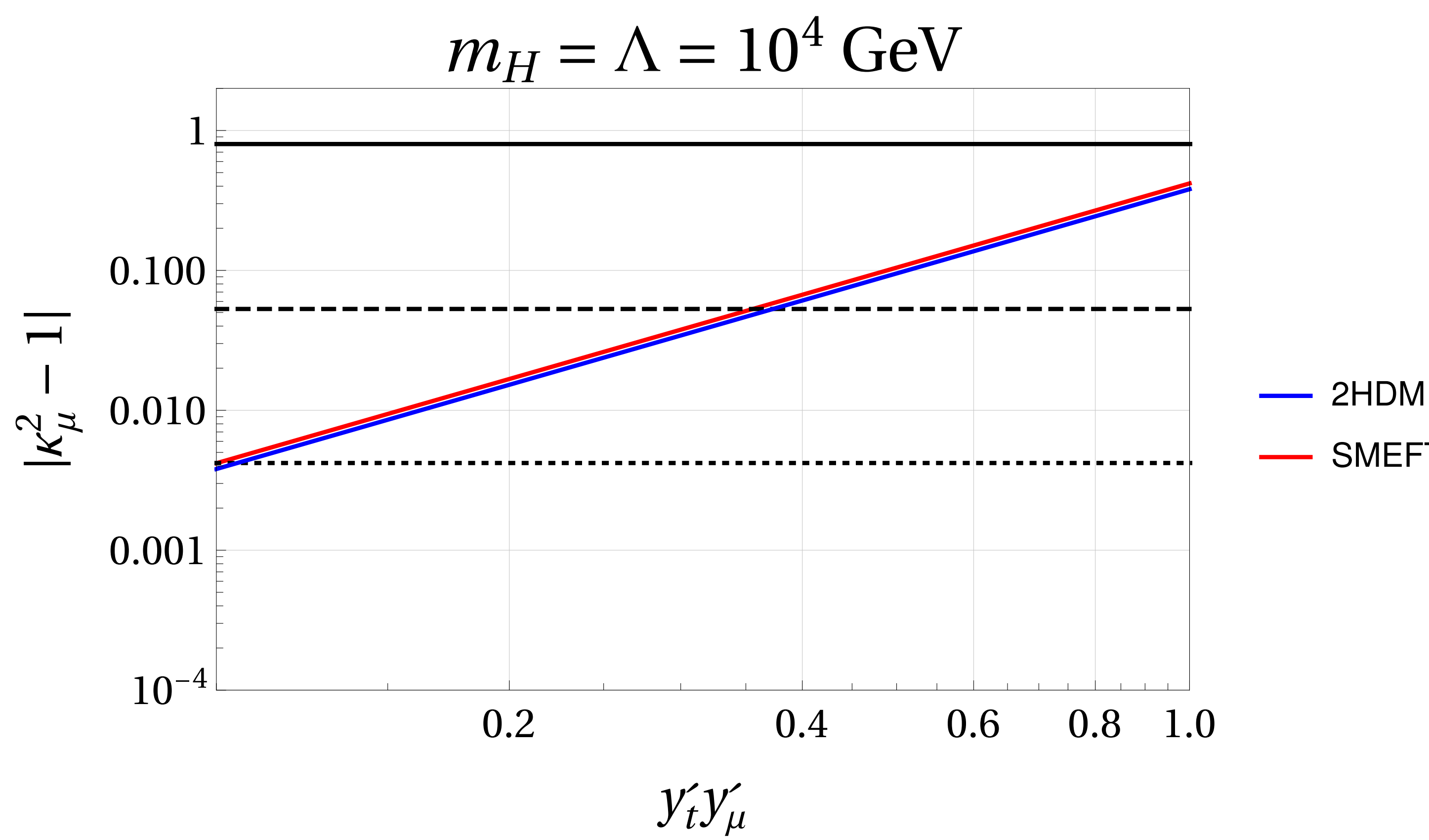


2HDM

Higgs decay at one-loop from neutral heavy scalar







Scalar LQ

A complete review: 1603.04993

$$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$$

$$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$$

$$\mathcal{L}_{S_1} \supset y_{1,ij}^{LL} \bar{q}^{C,ia} S_1 \epsilon^{ab} \ell^{j,b} + y_{1,ij}^{RR} \bar{u}^{C,i} S_1 \epsilon^{ab} e^j + \text{h.c.}$$

$$\mathcal{L}_{R_2} \supset -y_{2,ij}^{RL} \bar{u}^i R_2^a \epsilon^{ab} \ell^{j,b} + y_{2,ij}^{LR} \bar{e}^i R_2^{a\ *} q^{j,a} + \text{h.c.}$$

By Fierz transformation, will generate

$$\mathcal{L} \supset -\frac{4G_F}{\sqrt{2}} \left[g_{ij,ks}^{LL} \left(\bar{q}_L^i q_R^j \right) \left(\bar{\ell}_L^k \ell_R^s \right) + h_{ij,ks}^{LL} \left(\bar{q}_L^i \sigma_{\mu\nu} q_R^j \right) \left(\bar{\ell}_L^k \sigma^{\mu\nu} \ell_R^s \right) \right]$$

$$S_1 : g_{ij,ks}^{LL} = -4h_{ij,ks}^{LL} = \frac{v^2}{4m_{LQ}^2} y_{1,js}^{RR} \left(y_1^{LL} \right)_{ik}^*$$

$$R_2 : g_{ij,ks}^{LL} = 4h_{ij,ks}^{LL} = -\frac{v^2}{4m_{LQ}^2} y_{2,jk}^{RL} \left(y_2^{LR} \right)_{si}^*$$

Scalar LQ

A complete review: 1603.04993

$$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3) \qquad R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$$

$$\mathcal{L}_{S_1} \supset y^{LL}_{1,ij} \bar{q}^{C,ia} S_1 \epsilon^{ab} \ell^{j,b} + y^{RR}_{1,ij} \bar{u}^{C,i} S_1 \epsilon^{ab} e^j + \text{h.c.}$$

$$\mathcal{L}_{R_2} \supset -y^{RL}_{2,ij} \bar{u}^i R_2^a \epsilon^{ab} \ell^{j,b} + y^{LR}_{2,ij} \bar{e}^i R_2^{a\,*} q^{j,a} + \text{h.c.}$$

By Fierz transformation, will generate

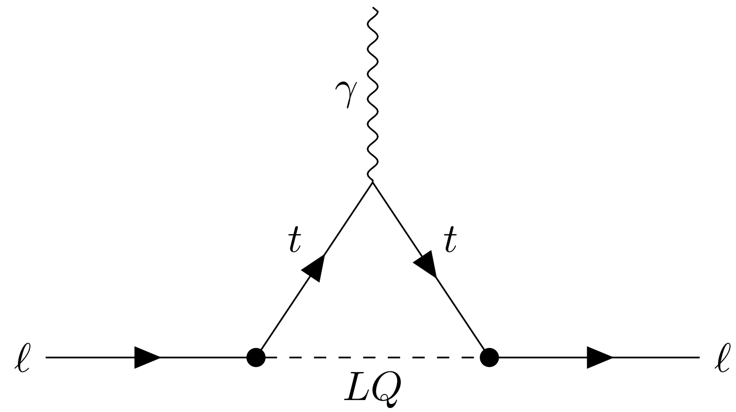
$$\mathcal{L} \supset -\frac{4G_F}{\cdots} \Big[\cdots \Big) \Big]$$

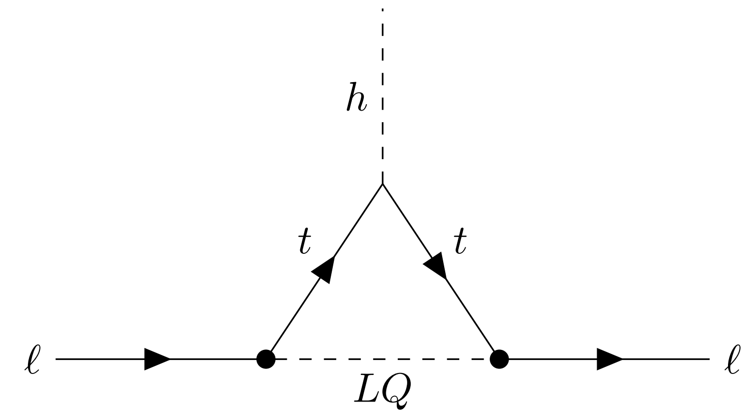
Tree-level matching to SMEFT

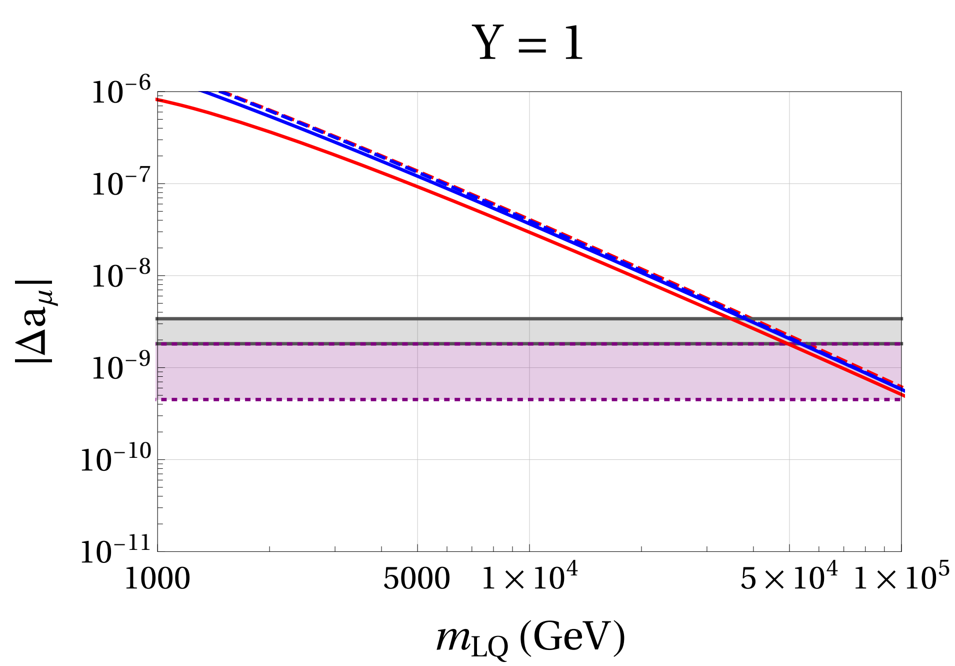
$$\hat{\mathcal{C}}_{4,\mu} = \mp 4 \hat{\mathcal{C}}_{5,\mu} = -\frac{4G_F}{\sqrt{2}} g^{LL} = \frac{v^2 G_F}{\sqrt{2} m^2_{LQ}} Y$$

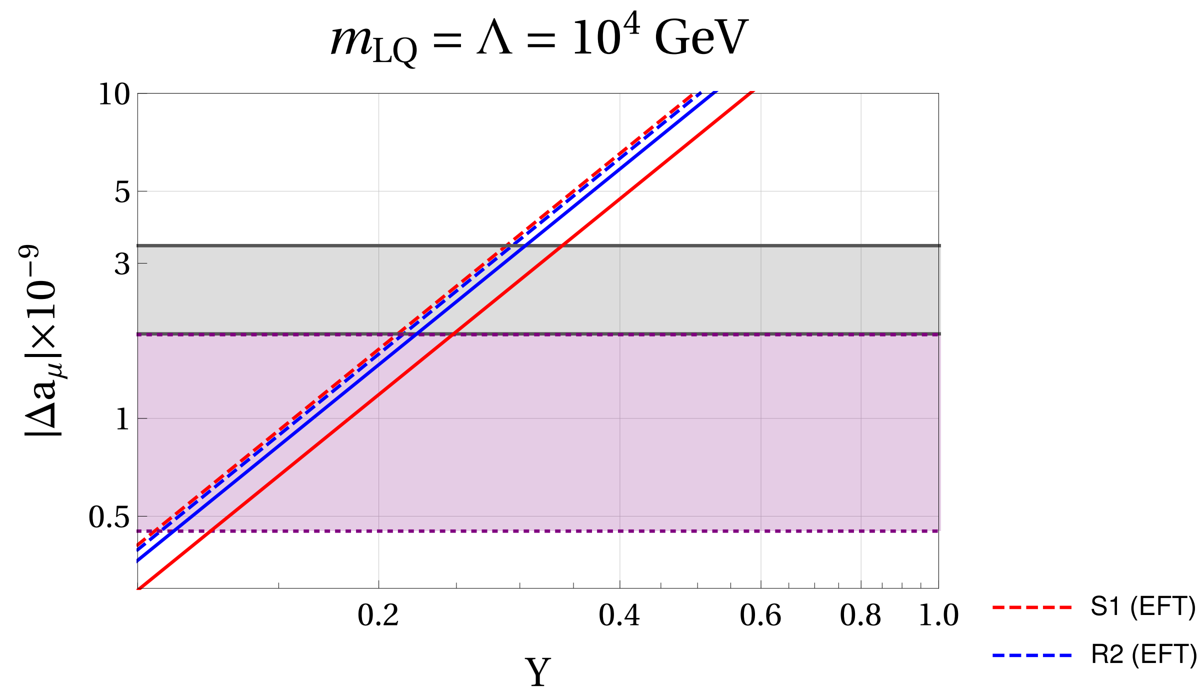
Scalar LQ

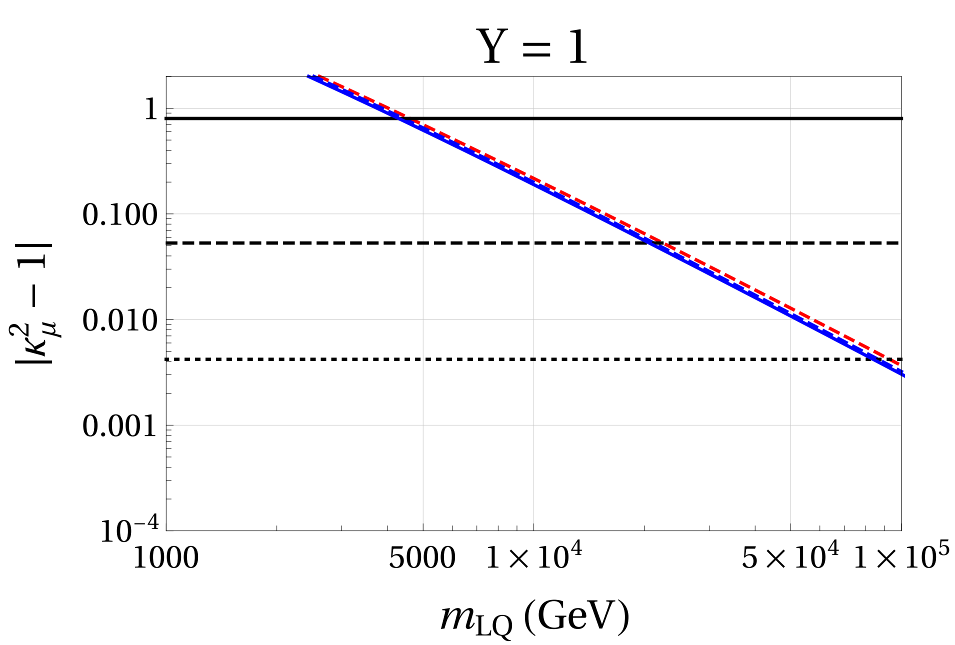
Calculated in: 2008.02643

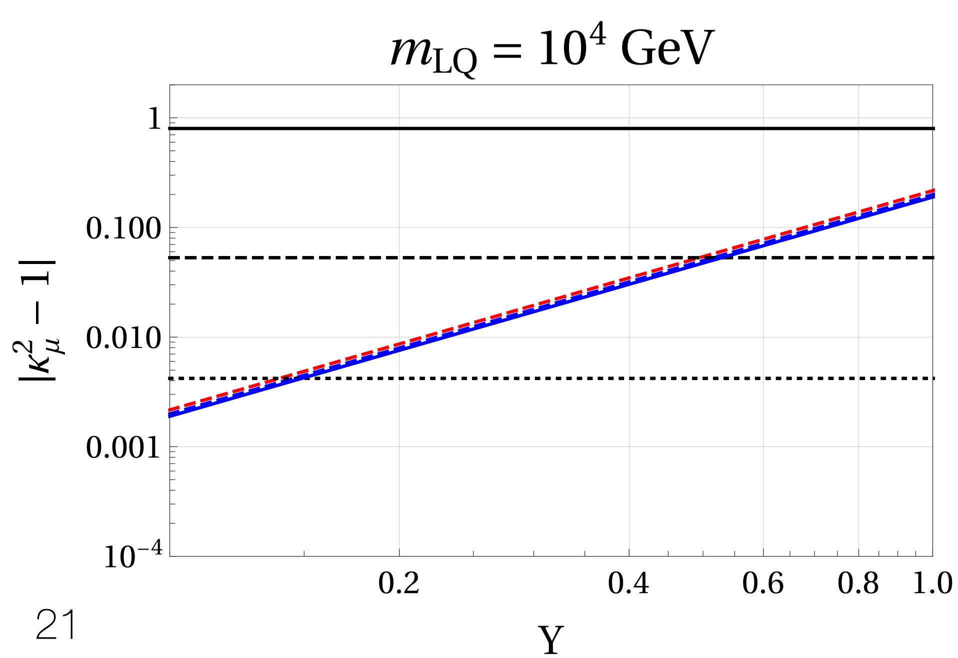










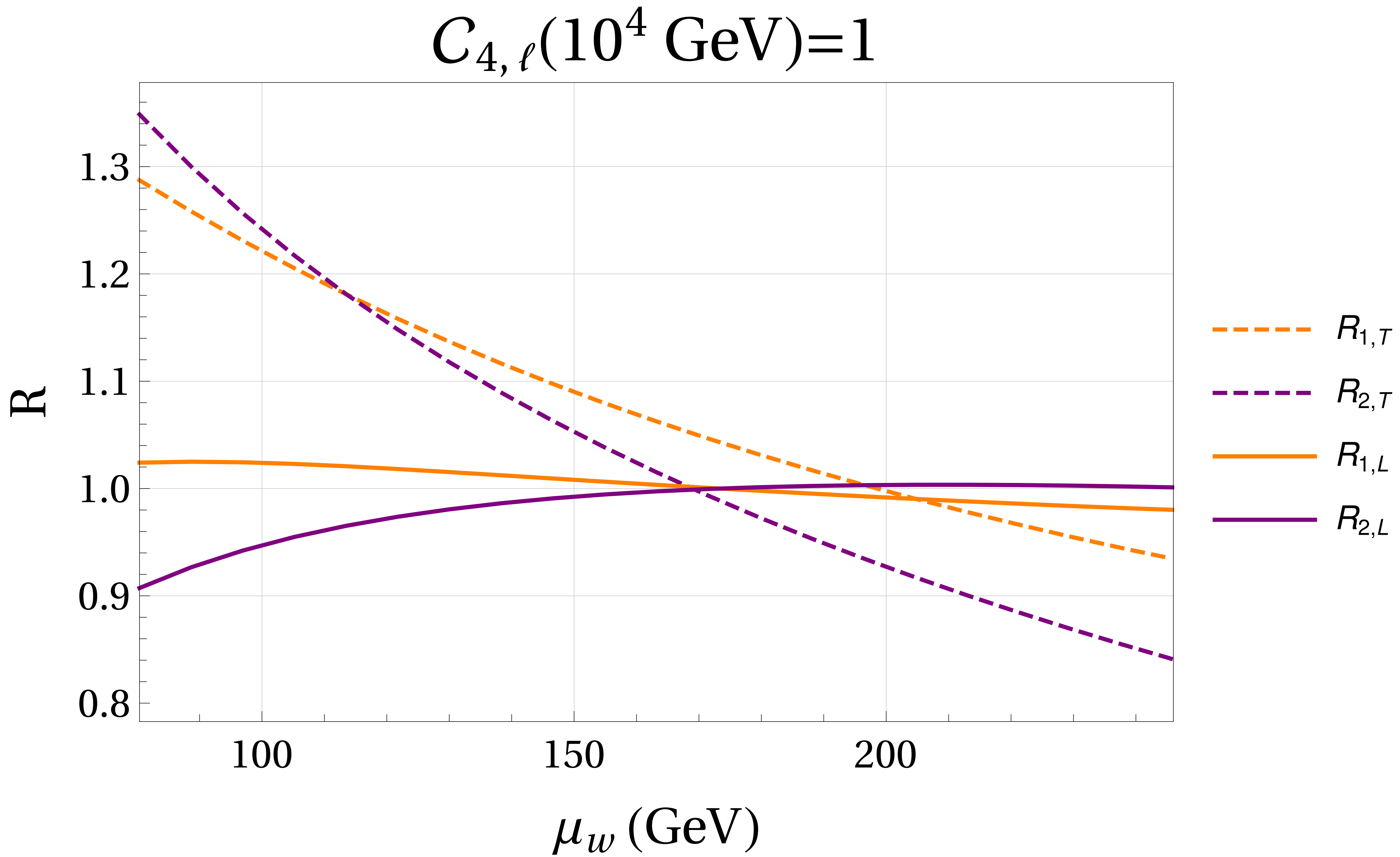


Summary

- Small set of operators in SMEFT describes the observables
- Correlations via one-loop RGE
- Chirally enhanced matching conditions at one-loop
- Pheno analysis can give hints on model building
- Tree-level matching + running can capture the dominant effects of NP

Backup

$$R_{i,j}(\mu_w) = \frac{c_{i,\ell}(\mu_w)|_j}{c_{i,\ell}(m_t)|_L}\,, \quad i = 1, 2$$

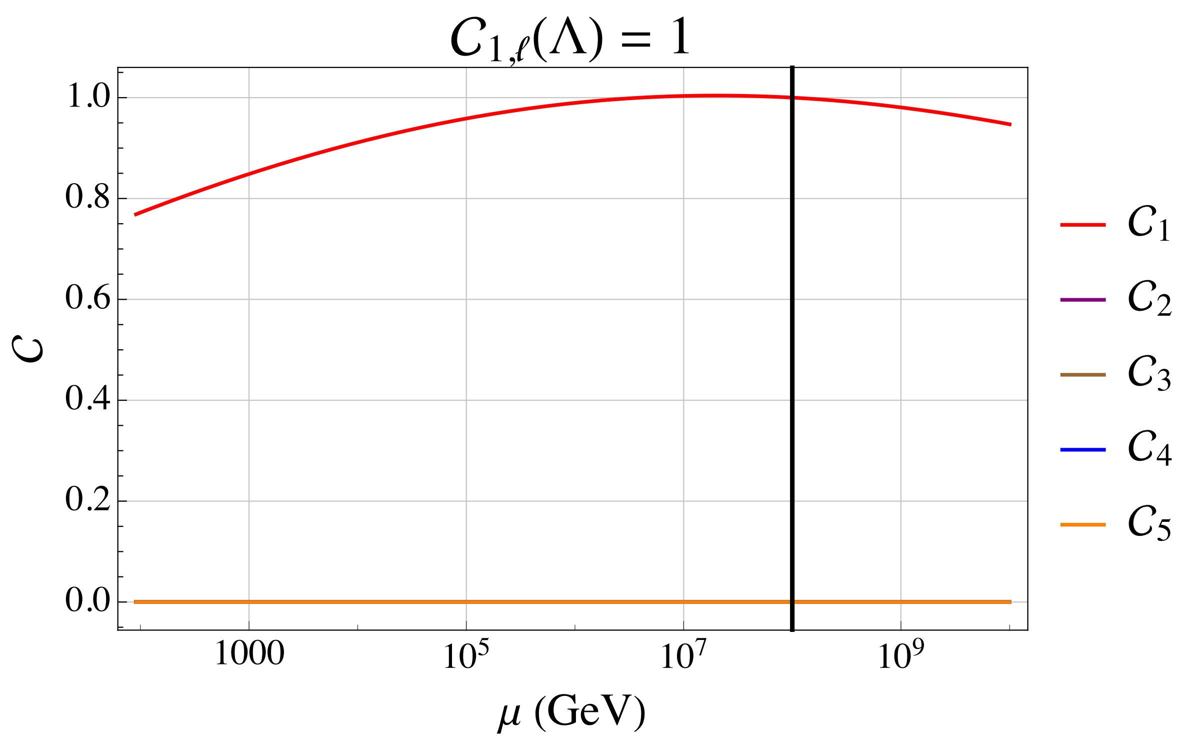


Assume all fermions massless except the top —> need two more to form a closed set under RGE

$$\mathcal{O}_{4,prst} = \left(\bar{\ell}_p^j e_r\right) \epsilon_{jk} \left(\bar{q}_s^k u_t\right) \qquad \mathcal{O}_{5,prst} = \left(\bar{\ell}_p^j \sigma_{\mu\nu} e_r\right) \epsilon_{jk} \left(\bar{q}_s^k \sigma^{\mu\nu} u_t\right)$$

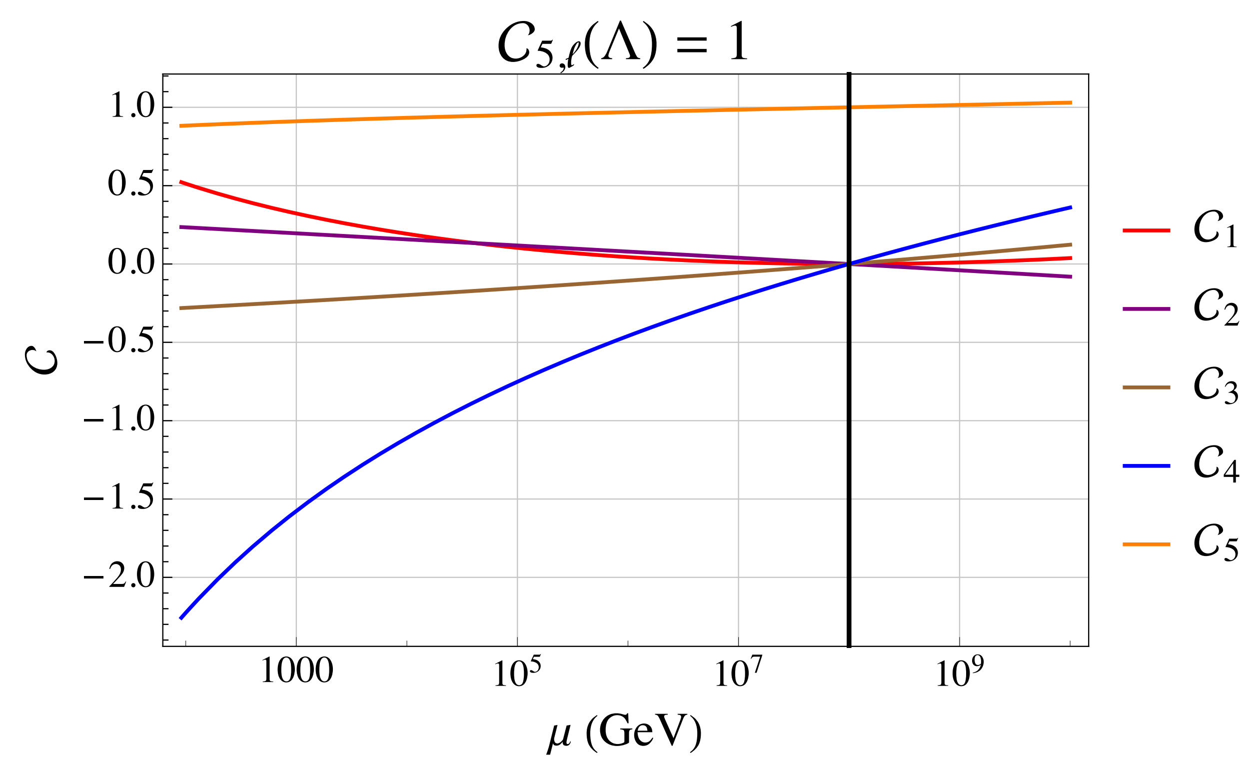
1 - Four-fermion operators have chiral enhancement at one-loop

2 - RGE mixing will generate both observables



$$\dot{\mathcal{C}}_1 \propto y_t^3 \mathcal{C}_4$$

$$\dot{\mathcal{C}}_{2,3} \propto y_t \mathcal{C}_5$$



No mixing at one loop with $\mathcal{C}_1$

$$
\begin{aligned}
\dot{\mathcal{C}}_{1,\ell} &= \left[-\frac{27}{4}g_2^2 - 3\left(3Y_\ell^2 + 3Y_e^2 - 4Y_\ell Y_e\right)g_1^2 + 3N_c y_t^2 + 24\lambda\right]\mathcal{C}_{1,\ell} + 4N_c y_t\left(y_t^2 - \lambda\right)\mathcal{C}_{4,\ell} \\
&\quad - 3\left(4g_1^2 g_2 Y_h\left(Y_e + Y_\ell\right) + 3g_2^3\right)\mathcal{C}_{2,\ell} - 6\left(4g_1^3 Y_h^2\left(Y_e + Y_\ell\right) + g_2^2 g_1 Y_h\right)\mathcal{C}_{3,\ell}\,, \\
\dot{\mathcal{C}}_{2,\ell} &= \left[\left(3c_{F,2} - b_{0,2}\right)g_2^2 + \left(-3Y_e^2 + 8Y_e Y_\ell - 3Y_\ell^2\right)g_1^2 + N_c y_t^2\right]\mathcal{C}_{2,\ell} \\
&\quad + g_1 g_2\left(3Y_\ell - Y_e\right)\mathcal{C}_{3,\ell} - 2g_2 N_c y_t \mathcal{C}_{5,\ell}\,, \\
\dot{\mathcal{C}}_{3,\ell} &= \left[-3c_{F,2}g_2^2 + \left(3Y_e^2 + 4Y_e Y_\ell + 3Y_\ell^2 - b_{0,1}\right)g_1^2 + N_c y_t^2\right]\mathcal{C}_{3,\ell} \\
&\quad + 4c_{F,2}g_1 g_2\left(3Y_\ell - Y_e\right)\mathcal{C}_{2,\ell} + 4g_1 N_c y_t\left(Y_u + Y_q\right)\mathcal{C}_{5,\ell}\,, \\
\dot{\mathcal{C}}_{4,\ell} &= -\left[6\left(Y_e^2 + Y_e\left(Y_u - Y_q\right) + Y_q Y_u\right)g_1^2 + 3\left(N_c - \frac{1}{N_c}\right)g_3^2 + y_t^2\left(2N_c + 1\right)\right]\mathcal{C}_{4,\ell} \\
&\quad - \left[24\left(Y_q + Y_u\right)\left(2Y_e - Y_q + Y_u\right)g_1^2 - 18g_2^2\right]\mathcal{C}_{5,\ell}\,, \\
\dot{\mathcal{C}}_{5,\ell} &= g_1\left(Y_q + Y_u\right)y_t\mathcal{C}_{3,\ell} - \frac{3}{2}g_2 y_t \mathcal{C}_{2,\ell} + \left[2\left(Y_e^2 - Y_e Y_q + Y_e Y_u - 2Y_q^2 + 5Y_q Y_u - 2Y_u^2\right)g_1^2\right. \\
&\quad \left. - 3g_2^2 + \left(N_c - \frac{1}{N_c}\right)g_3^2 + y_t^2\right]\mathcal{C}_{5,\ell} + \frac{1}{8}\left[-4\left(Y_q + Y_u\right)\left(2Y_e - Y_q + Y_u\right)g_1^2 + 3g_2^2\right]\mathcal{C}_{4,\ell}\,.
\end{aligned}
$$