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

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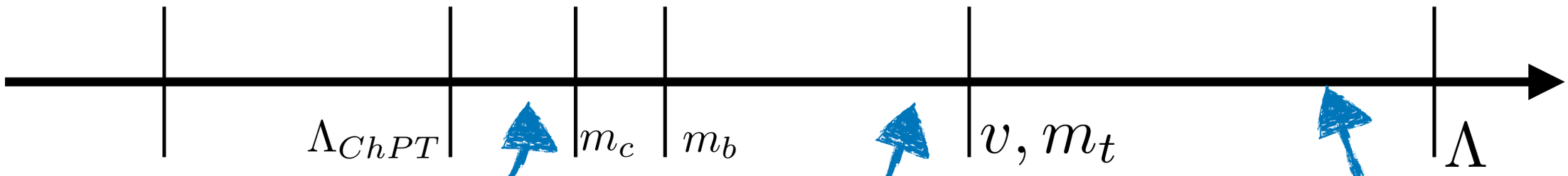
@ Portoroz, 21/09/2021

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

RG running

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



LEFT

Only light fermions, gluons and photons (1709.04486)

5-flavor EFT

Top integrated out

SMEFT

Warsaw basis (1008.4884)

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)

Spoilers

- Small set of operators in SMEFT describes the observables

- Correlations via one-loop RGE

- Chirally enhanced matching conditions at one-loop

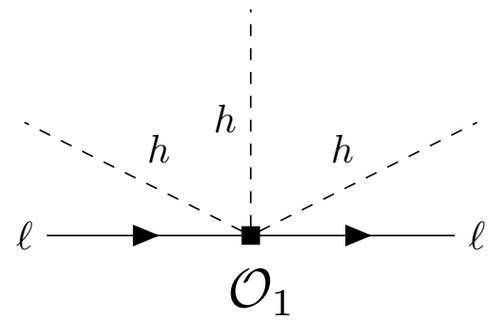
- Pheno analysis can give hints on model building

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

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

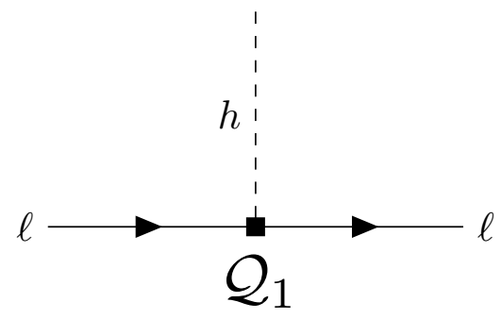
SMEFT

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



LEFT

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



Exp

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

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

SMEFT

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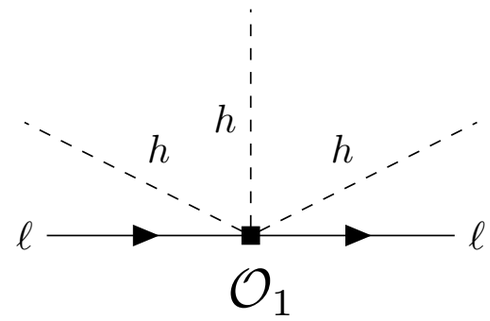
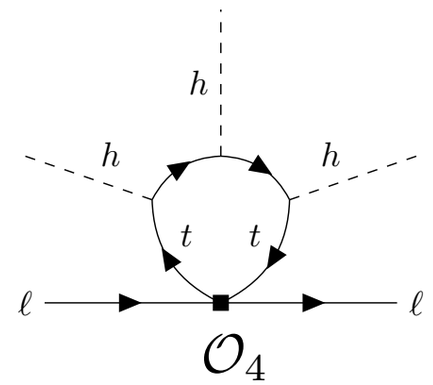


$$\mathcal{O}_{4,prst} = \left(\bar{\ell}_p^j e_r\right) \epsilon_{jk} \left(\bar{q}_s^k u_t\right)$$



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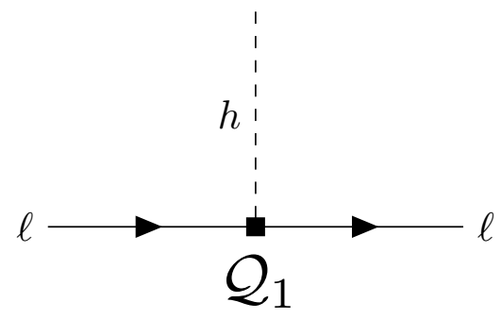

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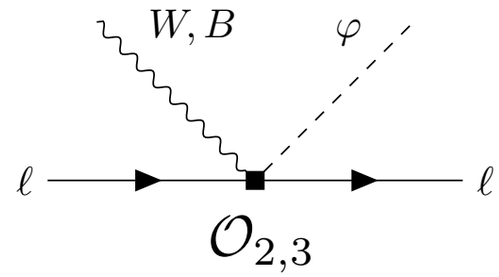
$$\kappa_\ell^2 = \frac{\Gamma(h \to \ell^+\ell^-)}{\Gamma_{SM}(h \to \ell^+\ell^-)} = \left(1 + \frac{c_{1,\ell} v}{m_\ell}\right)^2$$

$(g-2)_\ell$

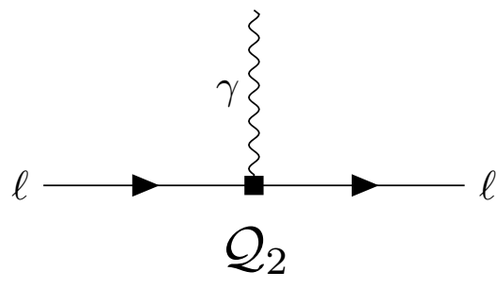
SMEFT

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



LEFT

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



Exp

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

$(g-2)_\ell$

SMEFT

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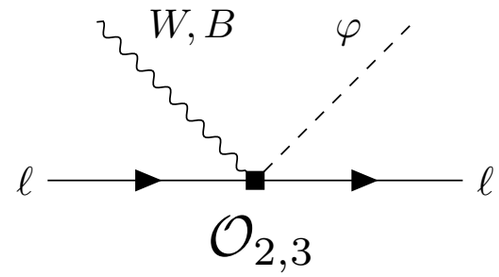
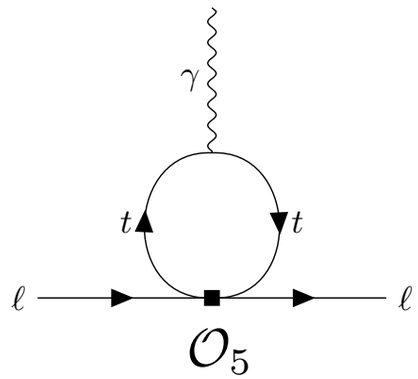
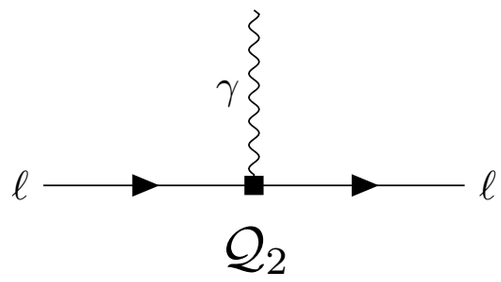


$$\mathcal{O}_{5,prst} = \left(\bar{\ell}^j_p \sigma_{\mu\nu} e_r\right) \epsilon_{jk} \left(\bar{q}^k_s \sigma^{\mu\nu} u_t\right)$$



LEFT

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



Exp

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

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

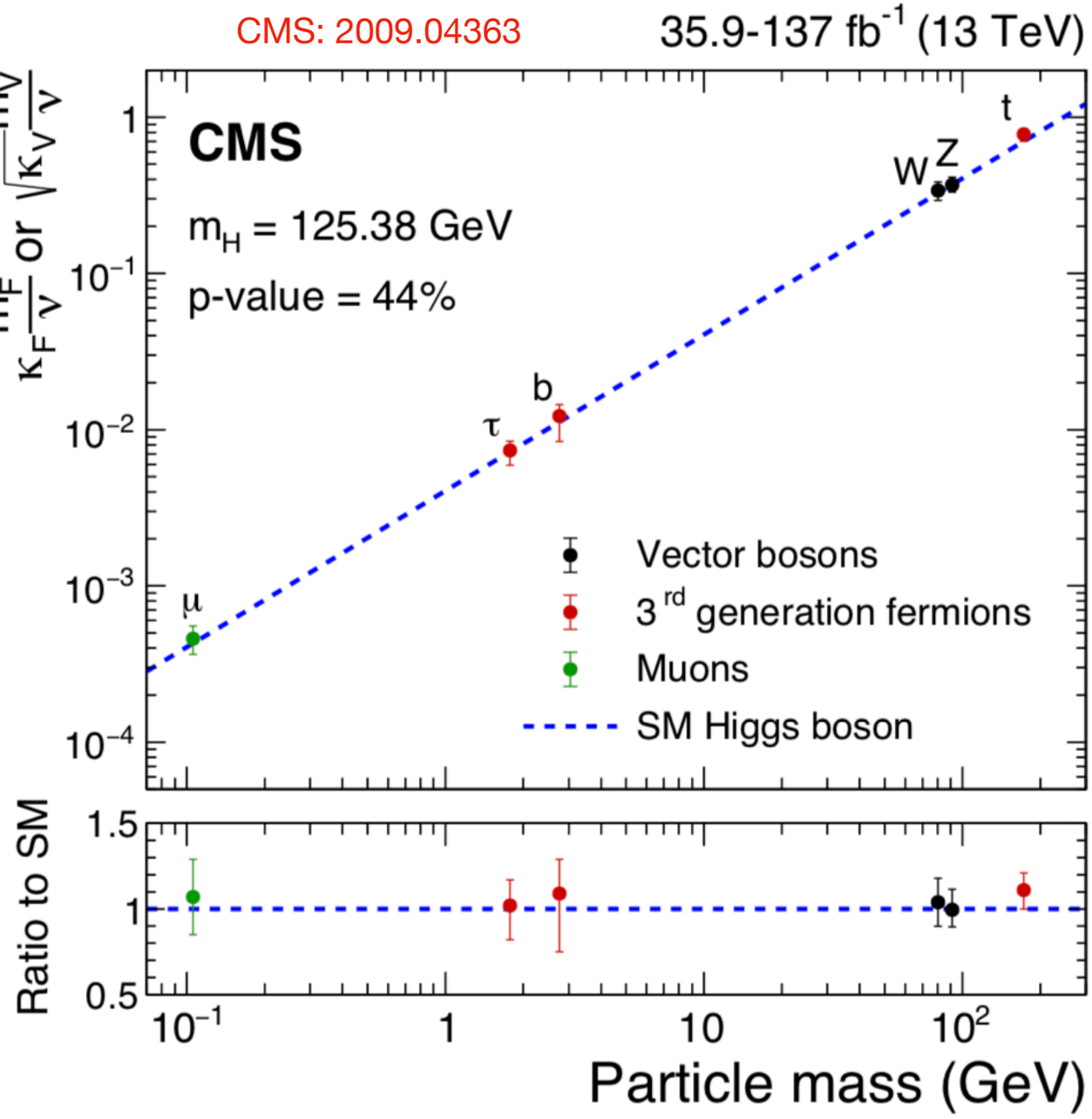
$$\kappa^2_\ell = \frac{\Gamma(h\to\ell^+\ell^-)}{\Gamma_{SM}(h\to\ell^+\ell^-)} = \left(1+\frac{c_{1,\ell}v}{m_\ell}\right)^2 \qquad \delta a_\ell = 4c_{2,\ell}(m_\ell)$$

Muon

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

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

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



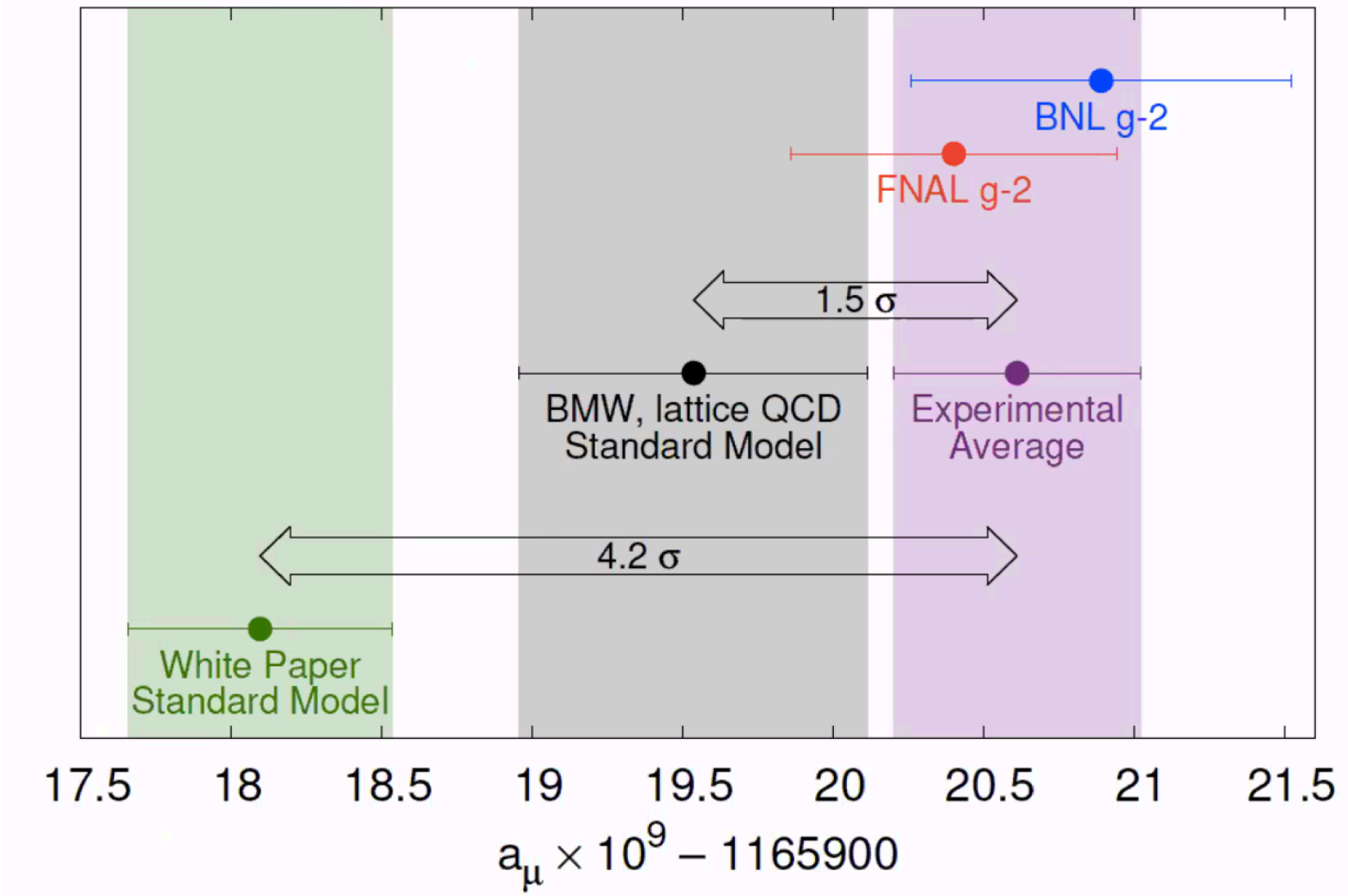
Theory Initiative

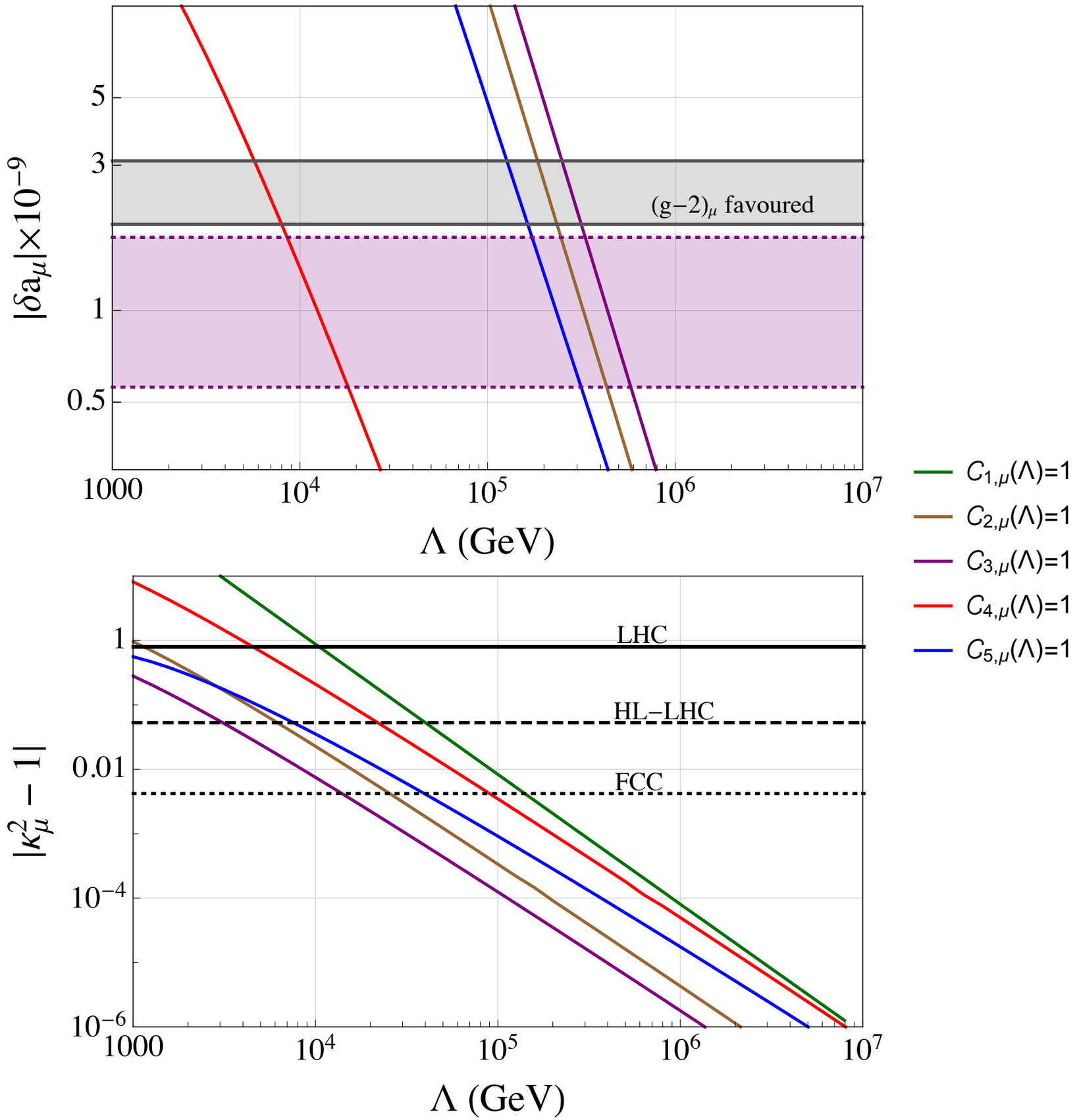
$$\delta a_\mu = (251 \pm 59) \times 10^{-11}$$

BMW lattice

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

Picture from Fodor's talk




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

Top-down approach

or

How effective is EFT?

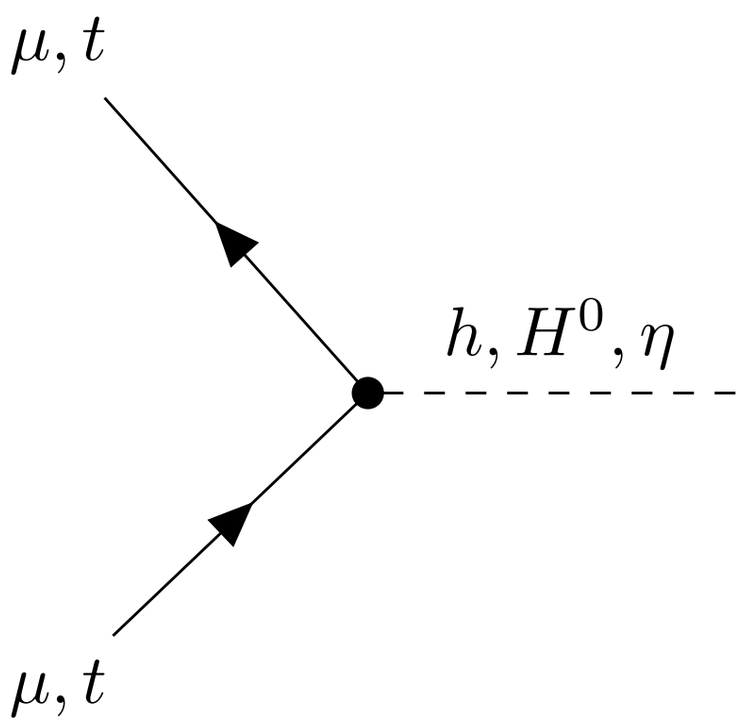
1 - Two-Higgs Doublet Model

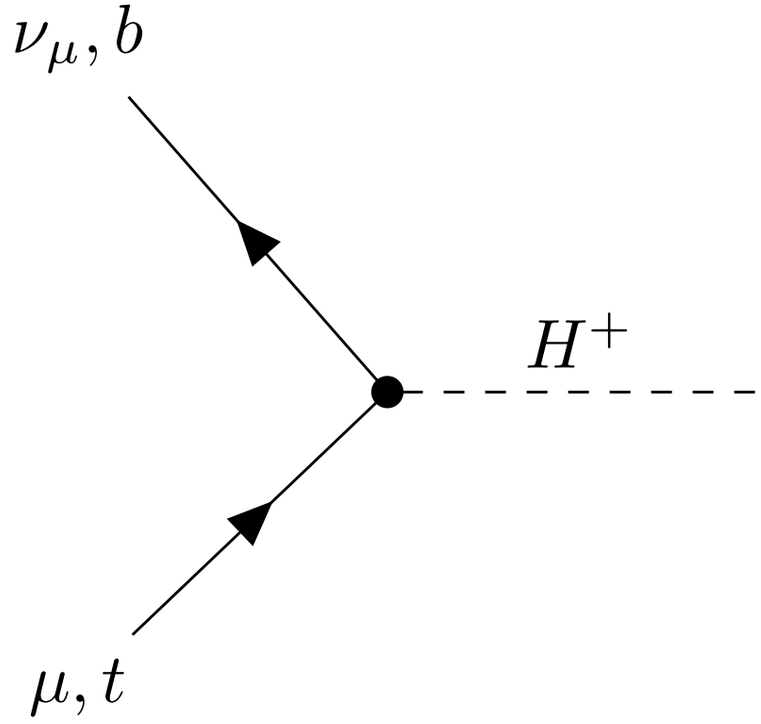
2 - Scalar LeptoQuarks

2HDM

Two scalar doublets with hypercharge +1

$$\mathcal{L}_Y \supset \left(\frac{\eta + H^0}{\sqrt{2}}\right)\left[y'_t \bar{t} P_R t + y'_\mu \bar{\mu} P_R \mu\right] + H^+\left[y'_t V_{ti} \bar{t} P_L d_i + y'_\mu \bar{\nu}_\mu P_R \mu\right] + \text{h.c.}\,,$$

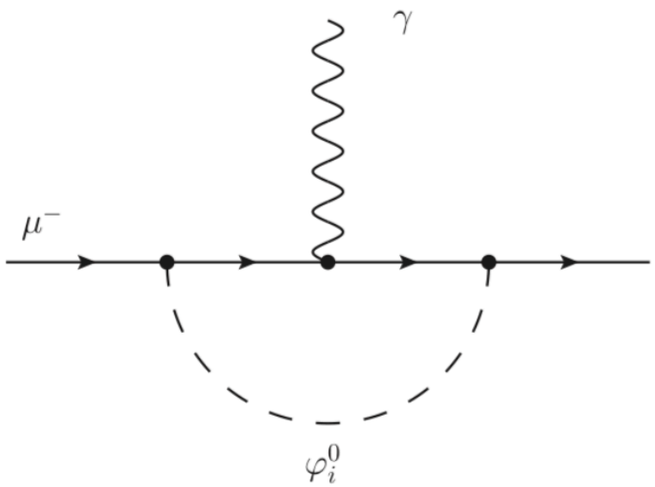


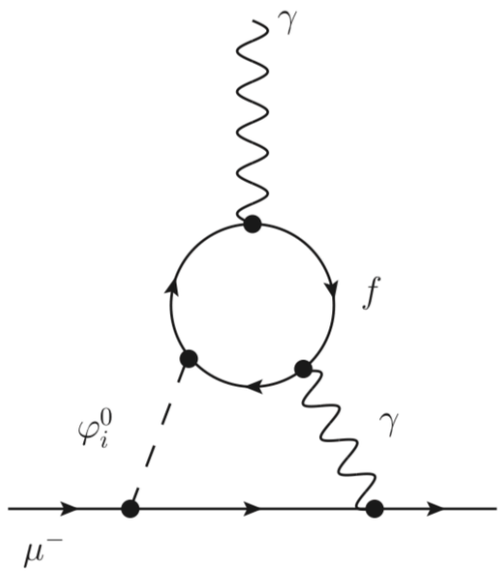


2HDM

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

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





Tree-level matching to SMEFT

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

2HDM

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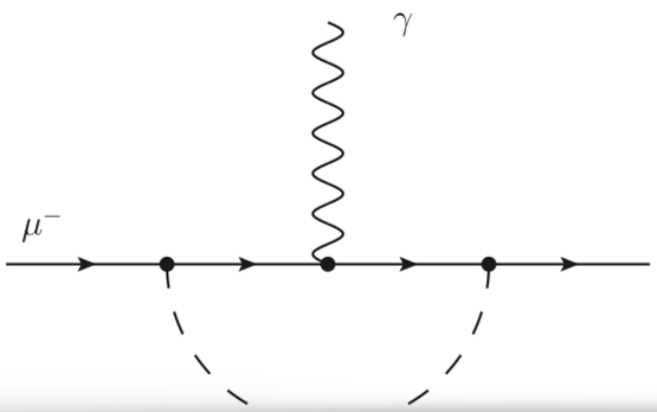

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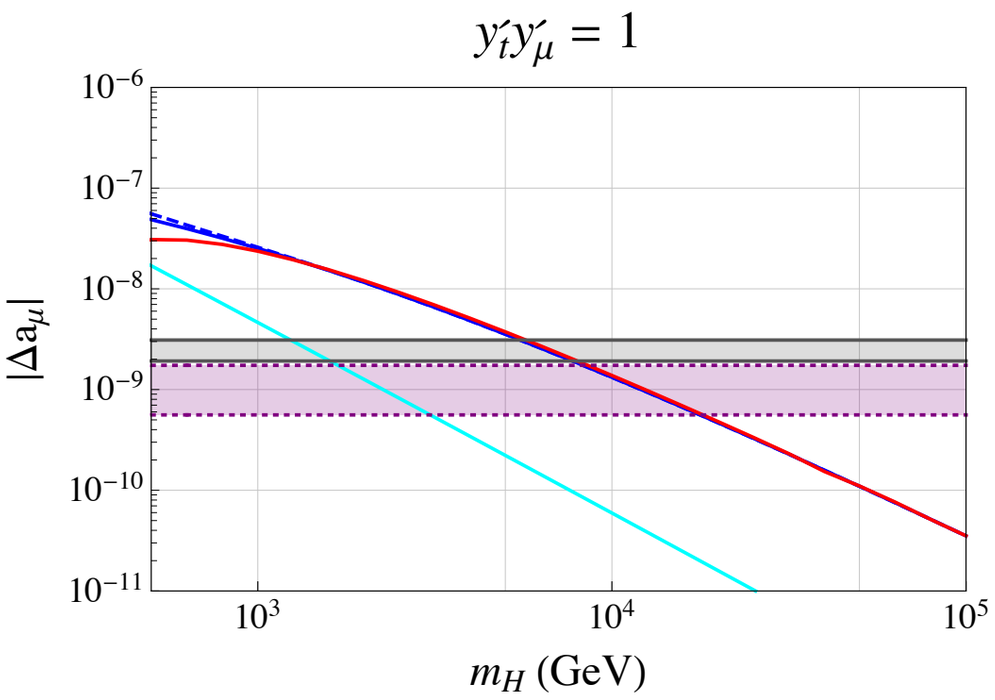
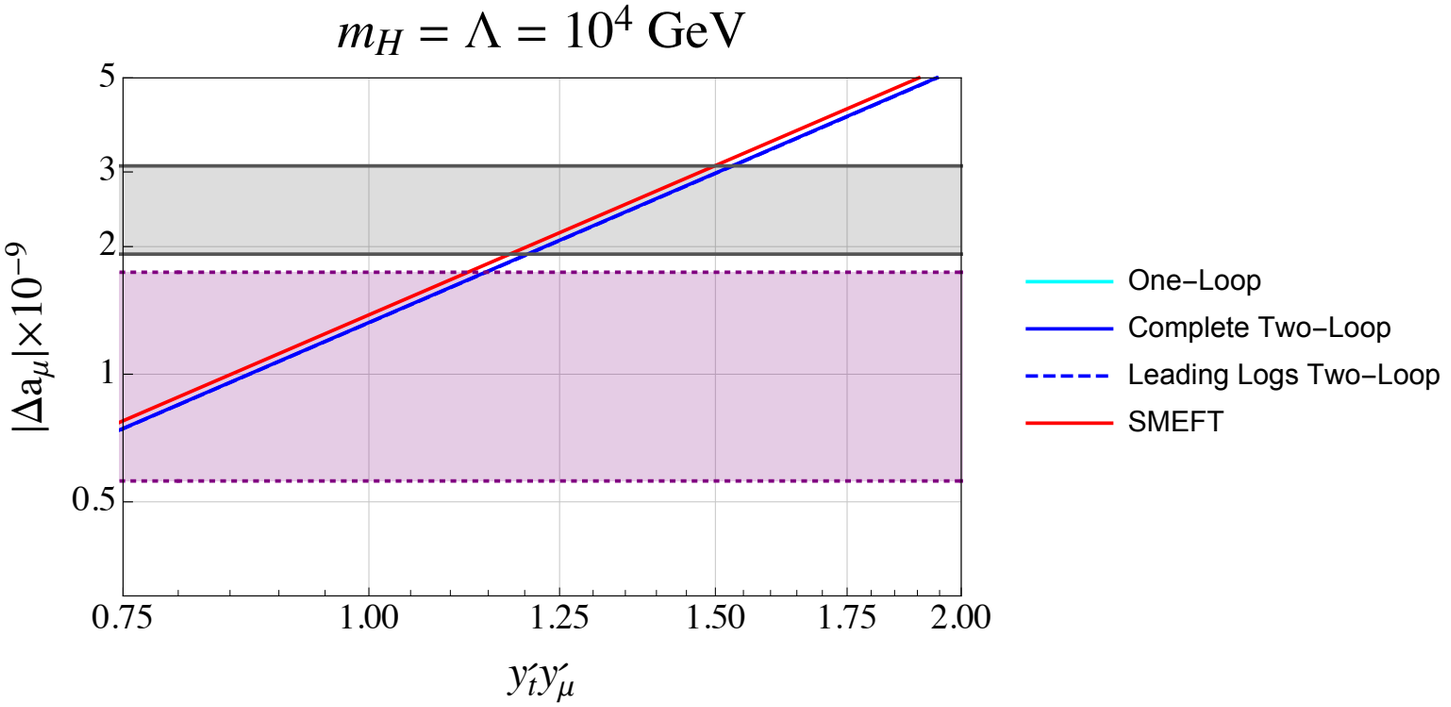
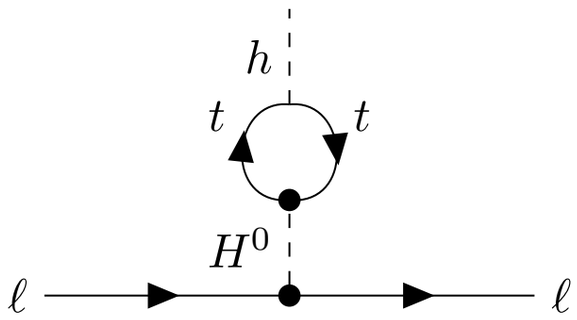




2HDM

Higgs decay at one-loop from neutral heavy scalar



Tree-level matching to SMEFT

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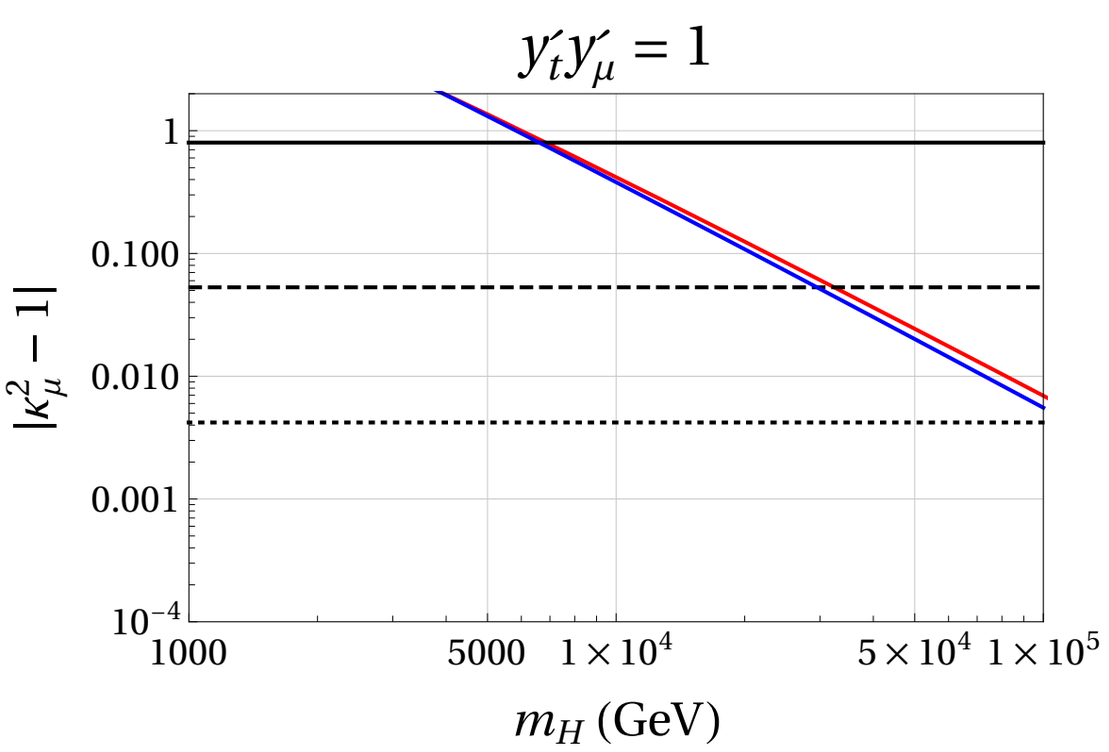
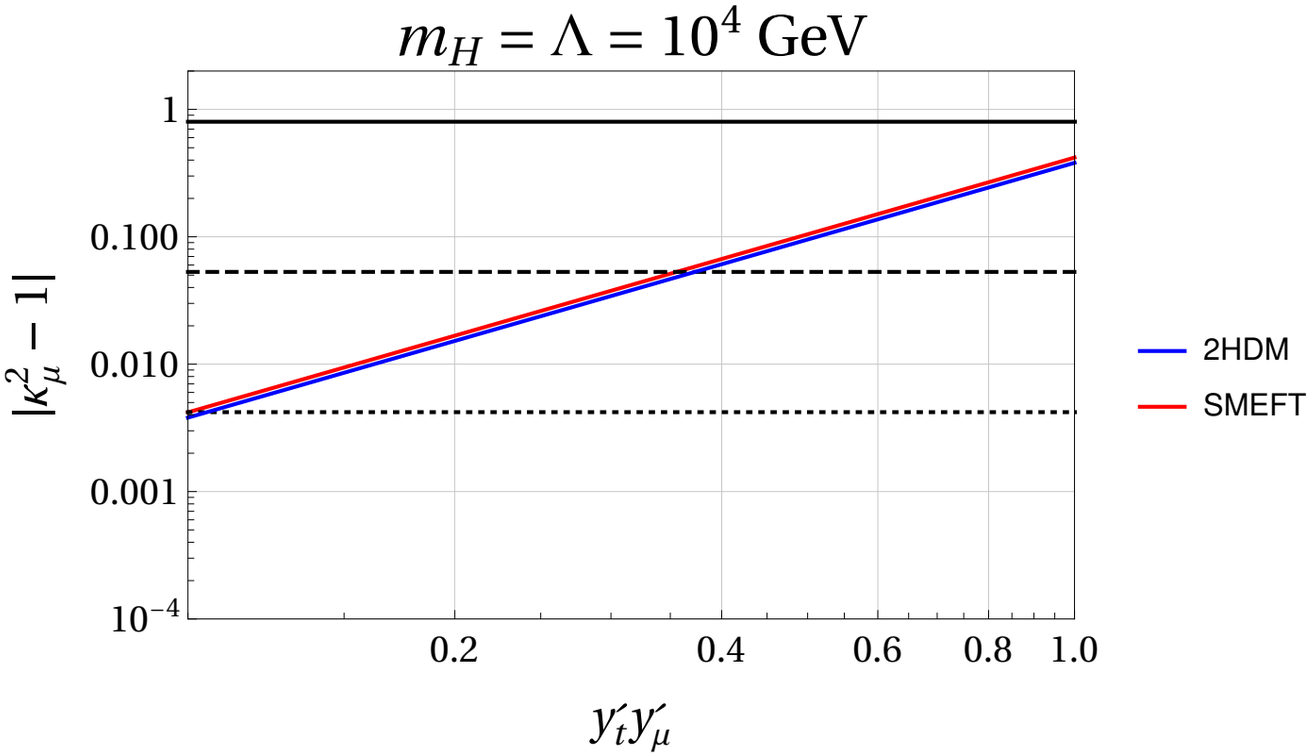


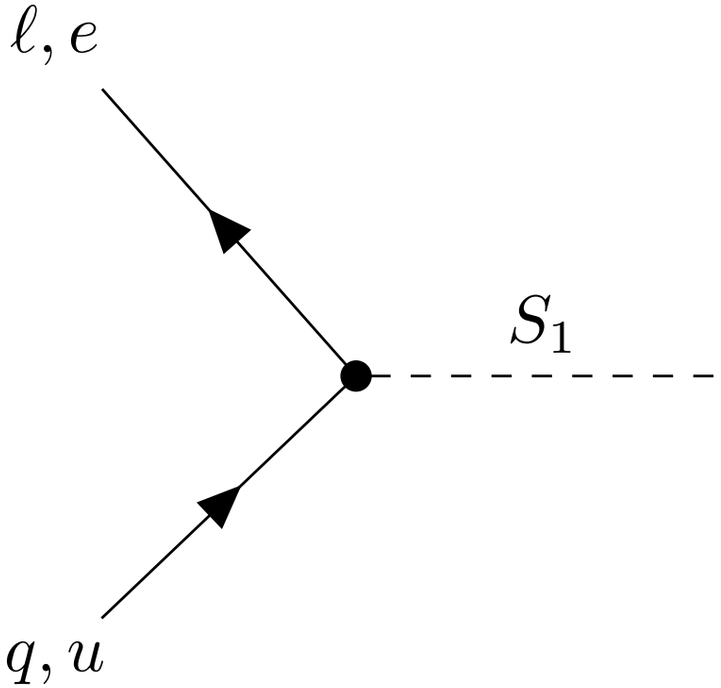


Scalar LQ

A complete review: 1603.04993

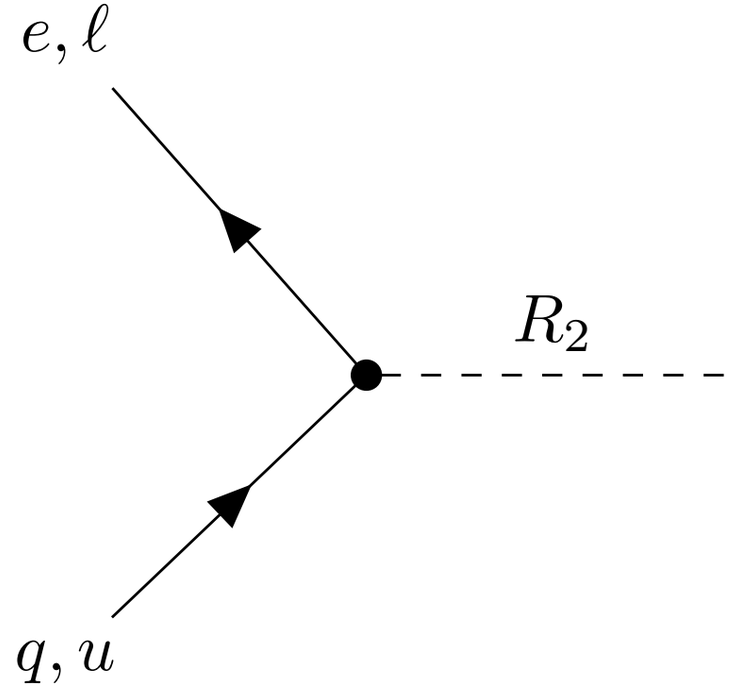
$$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$$

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



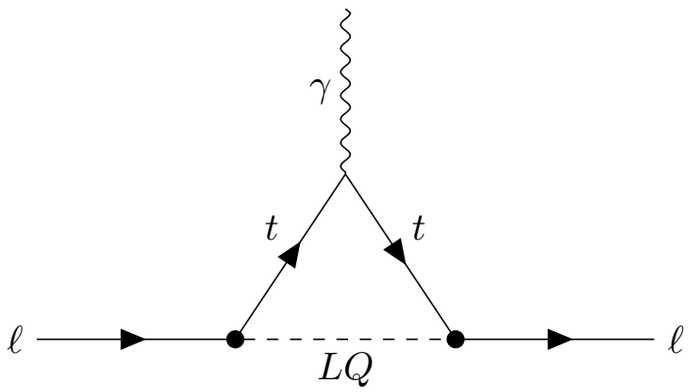
$$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$$

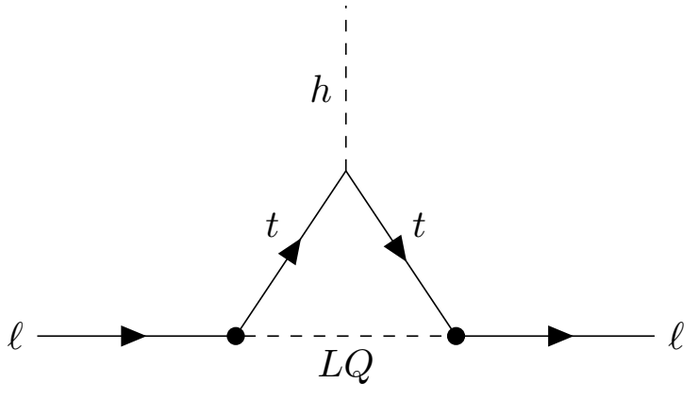
$$\mathcal{L}_{R_2} \supset -y^{RL}_{2,ij} \bar{u}^i R^a_2 \epsilon^{ab} \ell^{j,b} + y^{LR}_{2,ij} \bar{e}^i R^a_2 \, {}^* q^{j,a} + \text{h.c.}$$



Scalar LQ

Calculated in: 2008.02643





By Fierz transformation, will generate

$$\mathcal{L} \supset -\frac{4G_F}{\sqrt{2}}\left[g^{LL}_{ij,ks}\left(\bar{q}^i_L q^j_R\right)\left(\bar{\ell}^k_L \ell^s_R\right) + h^{LL}_{ij,ks}\left(\bar{q}^i_L \sigma_{\mu\nu} q^j_R\right)\left(\bar{\ell}^k_L \sigma^{\mu\nu} \ell^s_R\right)\right]$$

$$S_1 : g^{LL}_{ij,ks} = -4h^{LL}_{ij,ks} = \frac{v^2}{4m^2_{LQ}} y^{RR}_{1,js}\left(y^{LL}_1\right)^*_{ik}$$

$$R_2 : g^{LL}_{ij,ks} = 4h^{LL}_{ij,ks} = -\frac{v^2}{4m^2_{LQ}} y^{RL}_{2,jk}\left(y^{LR}_2\right)^*_{si}$$

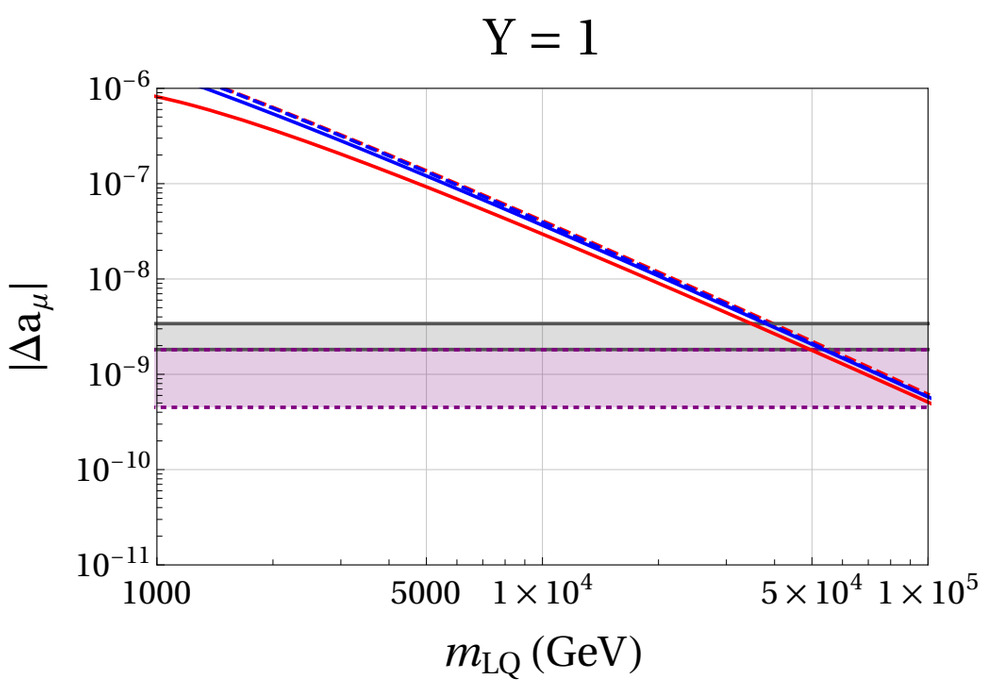
Tree-level matching to SMEFT

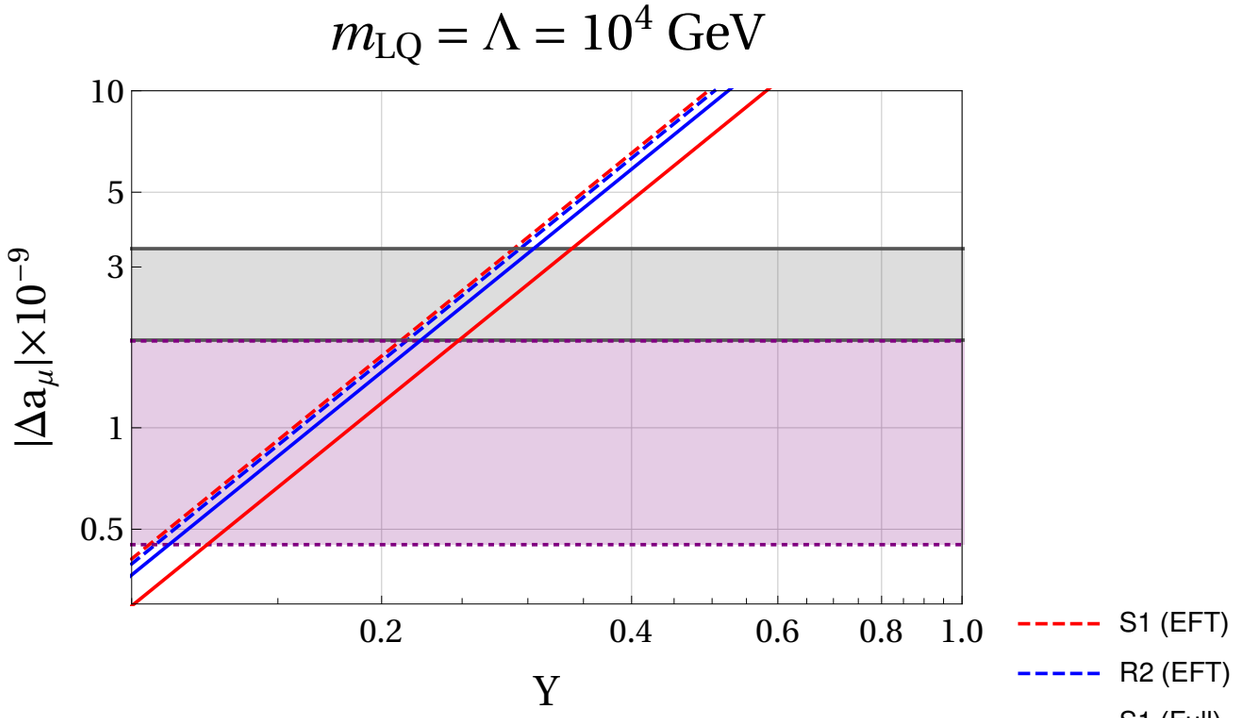
$$\hat{\mathcal{C}}_{4,\mu} = \mp 4\hat{\mathcal{C}}_{5,\mu} = -\frac{4G_F}{\sqrt{2}} g^{LL} = \frac{v^2 G_F}{\sqrt{2} m^2_{LQ}} Y$$

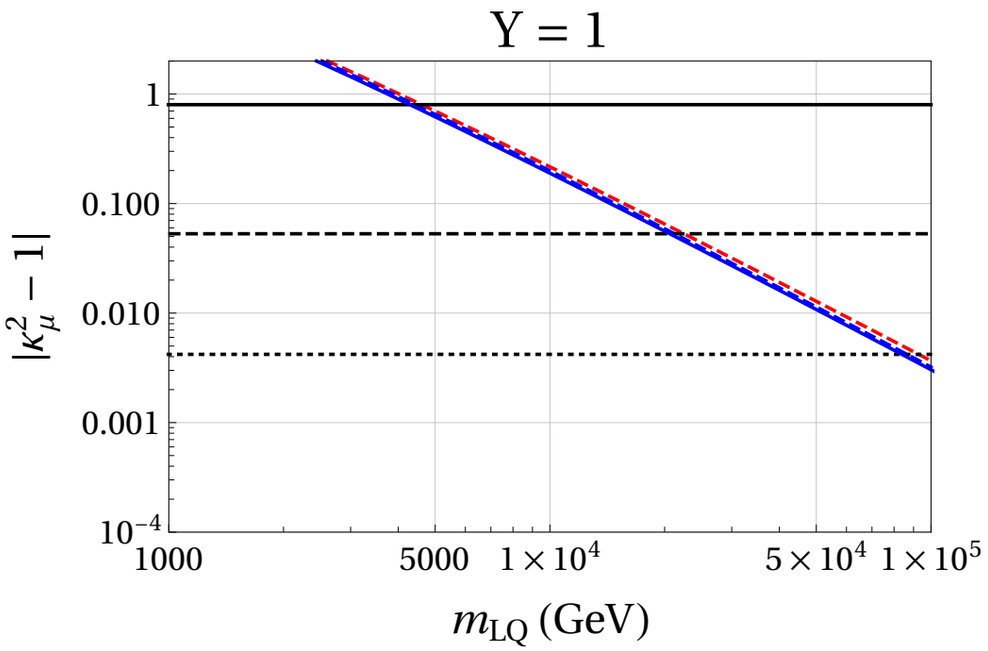
Scalar LQ

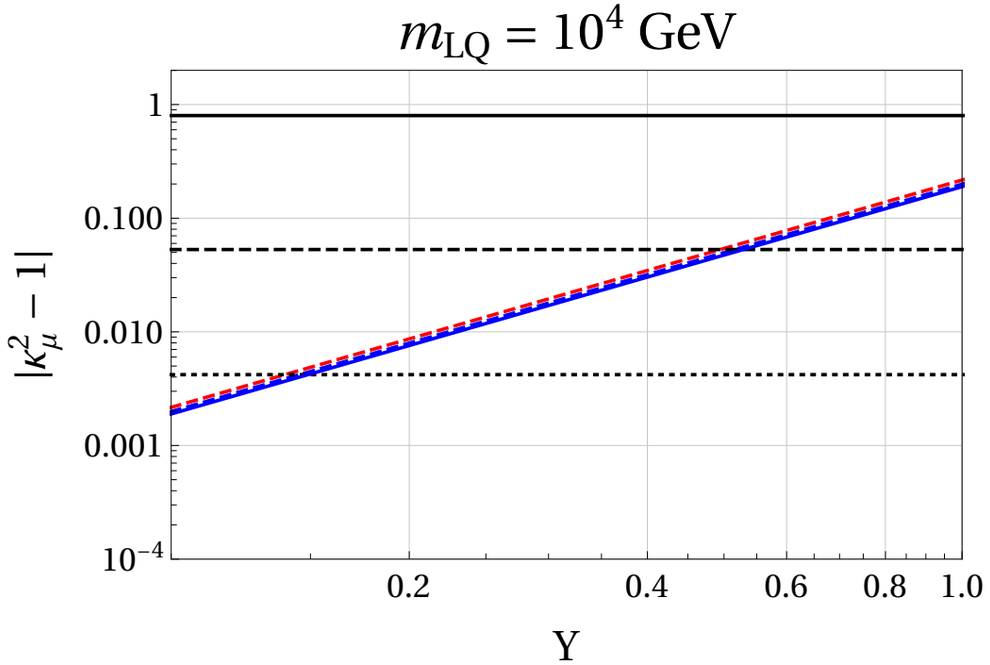
Calculated in: 2008.02643

By Fierz transformation, will generate









Summary

- Small set of operators in SMEFT describes the observables

- Correlations via one-loop RGE

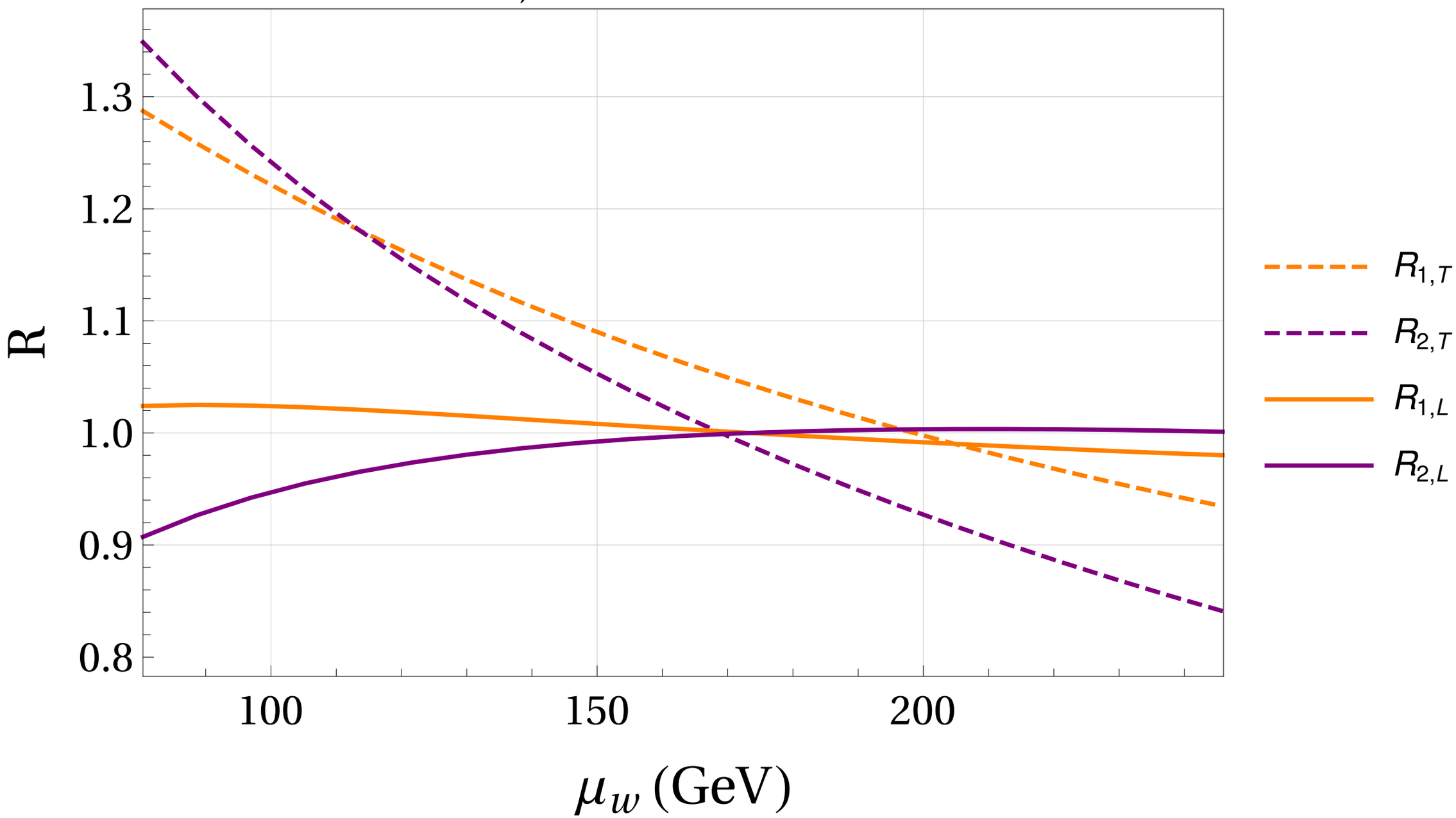
- Chirally enhanced matching conditions at one-loop

- Pheno analysis can give hints on model building

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

Backup

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



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

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

2HDM

Two scalar doublets with hypercharge +1

$$\begin{pmatrix}\Phi_1\\ \Phi_2\end{pmatrix} = R_\beta \begin{pmatrix}\varphi_1\\ \varphi_2\end{pmatrix}$$

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

$$\begin{pmatrix}h\\ H^0\end{pmatrix} = R_\alpha \begin{pmatrix}\rho_1\\ \rho_2\end{pmatrix}$$

$$v = \sqrt{v_1^2 + v_2^2}$$

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

$$\mathcal{L}_Y = Y^u_{st}\bar{q}_s\tilde{\Phi}_1 u_t + Y^d_{st}\bar{q}_s\Phi_1 d_t + Y^\ell_{pr}\bar{\ell}_p\Phi_1 e_r + Y^{'\ell}_{pr}\bar{\ell}_p\Phi_2 e_r + Y^{'u}_{st}\bar{q}_s\tilde{\Phi}_2 u_t + \text{h.c.}$$

2HDM

Two scalar doublets with hypercharge +1

$$\begin{pmatrix}\Phi_1\\ \Phi_2\end{pmatrix} = R_\beta \begin{pmatrix}\varphi_1\\ \varphi_2\end{pmatrix}$$

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

$$\begin{pmatrix}h\\ H^0\end{pmatrix} = R_\alpha \begin{pmatrix}\rho_1\\ \rho_2\end{pmatrix}$$

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Decoupling limit

No mixing, only mass terms

$\alpha,\ \beta \to 0$

$v_2 \to 0$

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

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

Tree-level matching to SMEFT

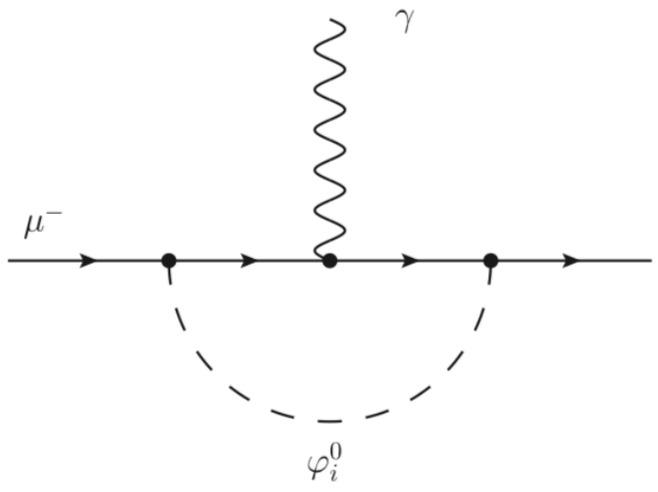
$$\hat{C}_{4,\ell} = \frac{y'_t y'_\ell}{m_H^2}$$

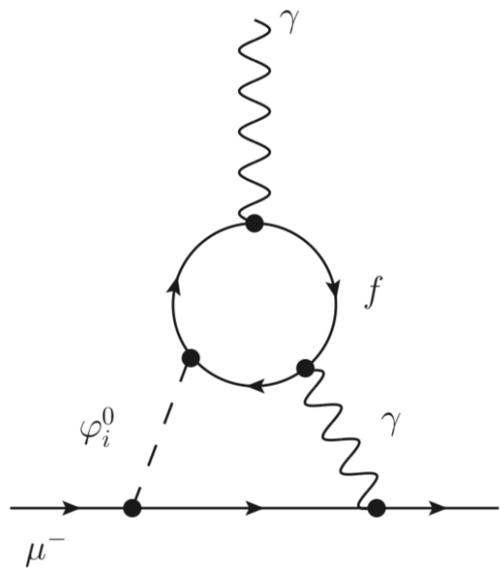
$\mathcal{L}_Y = Y^u_{st}\bar{q}_s\tilde{\Phi}_1 u$ $\quad$ $_s\tilde{\Phi}_2 u_t + \text{h.c.}$

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

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