Hints of new physics and EFT: a ν_R solution to $(g-2)$? [1]

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[1] Based on work w/ Cirigliano, Dekens, de Vries, Fuyuto, and Mereghetti [2105.11462]

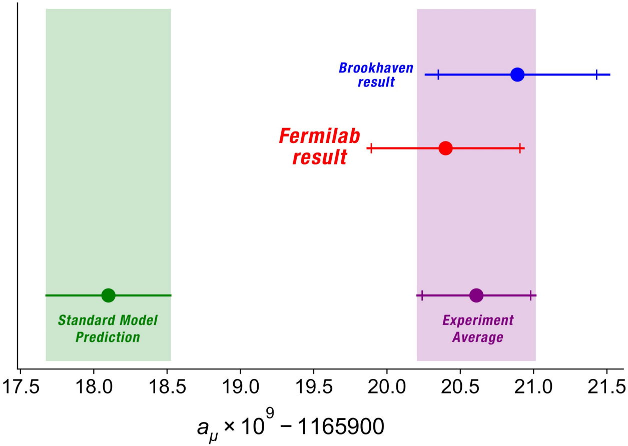
thank you for the invitation!

two experimental motivations for new physics

g-2

Anomalous magnetic moment of the μ at the LHC[2]

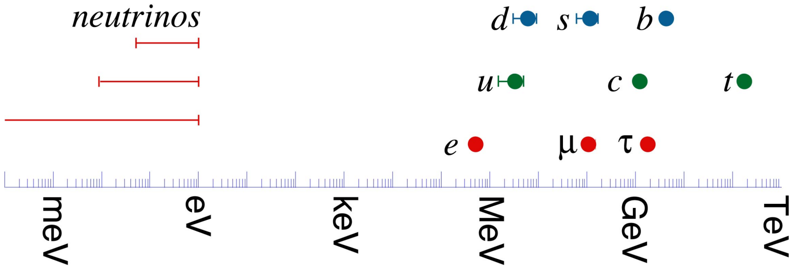
FNAL's $(g_\mu - 2)$ expt. *confirms* $a_\mu = (g_\mu - 2)/2$ is *a bit* large [2104.03281]



[2] Perhaps less compelling in light of recent updates from the lattice community: Bern, Mainz, et al [2206.06582], and Cyprus, Bonn, et al [2206.15084]

m_ν

Problem: according to the SM, $m_\nu = 0$. (The data disagree, obviously.)



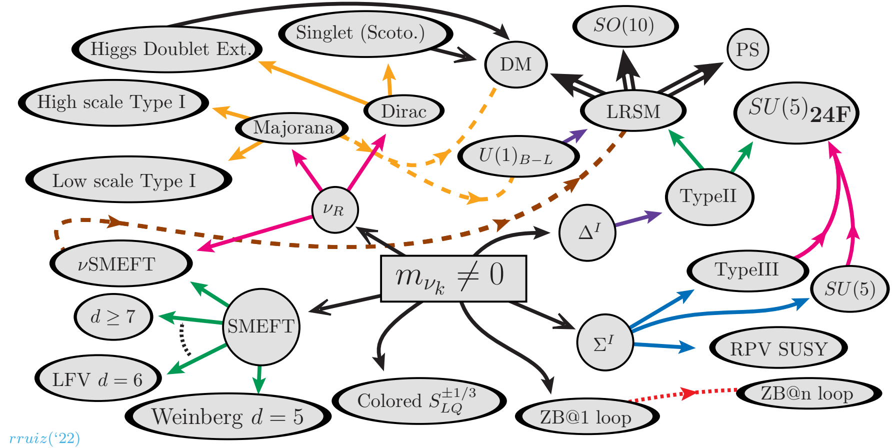
Neutrino masses ('15) $\Longrightarrow$ **many open questions:**

- ν have mass. What is generating m_ν?
- ν masses are *tiny*. What sets the scale of m_ν?
- m_ν are nearly degenerate. What sets the pattern of m_ν?
- ν carry no QCD/QED charge. Are $\nu, \overline{\nu}$ the same (Majorana)?

Neutrino mass models give some answers to these questions

Core ideas can be realized in ***many*** ways![3]

Minkowski ('77); Yanagida ('79); Glashow & Levy ('80); Gell-Mann et al., ('80); Mohapatra & Senjanović ('82); + *many* others



3 For a reviews, see Cai, et al [1706.08524]; Cai, RR, et al [1711.02180]

what is and why νSMEFT?

νSMEFT: the what

ν**SMEFT** (or sometimes Heavy N EFT) is the **S**tandard **M**odel **E**ffective **F**ield **T**heory extended by right-handed (RH) neutrinos ν_R

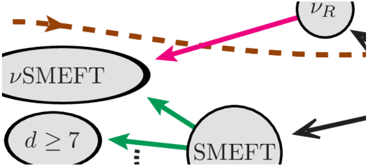
del Aguila, Bar-Shalom, Soni, Wudka [0806.0876]; Liao, et al [1612.04527]; + others + more recent activity

Start with Lagrangian for Type I Seesaw at $d = 4$:

$$\mathcal{L}_{\text{Type I}} = \mathcal{L}_{\text{SM}} + \frac{1}{2}\overline{\nu_R} i \not{\partial} \nu_R - \left[\frac{1}{2}\overline{\nu}_R^c \bar{\mu}_R \nu_R + y_\nu \overline{L}\tilde{\Phi}\nu_R + H.c.\right]$$

Following SMEFT rules for building $d > 4$:

$$\mathcal{L}_{\nu SMEFT} = \mathcal{L}_{\text{Type I}} + \sum_{i,n} \frac{c_i^{(n)}}{\Lambda^{(n-4)}} \mathcal{O}_i^{(n)}$$



νSMEFT: the why

– Absence of N_k (mass eigenstates!) in high- and low-energy searches may be suggesting picture is richer than low-scale Type I Seesaw model(s)

– Conceivable that mass hierarchies also exist in UV model (easy in some!)

– collider-scale LNV and LFV still accessible in semi-decoupled limits

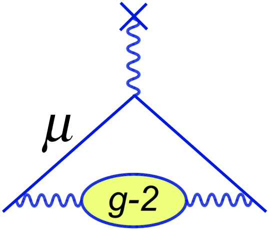
e.g., RR [1703.04669]

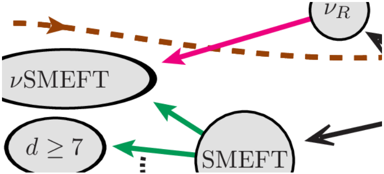
$\mathcal{L}_{\nu\text{SMEFT}} = \mathcal{L}_{\text{Type I}} + \sum_{i,n} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$, where at $d = 6$, the new $\mathcal{O}_i^{(n)}$ are:

$\psi^2 H^3$		$\psi^2 H^2 D$		$\psi^2 HX$(+H.c.)	
$\mathcal{O}_{L\nu H}$(+H.c.)	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{H\nu}$ $\mathcal{O}_{H\nu e}$(+H.c.)	$(\bar{\nu}_R\gamma^\mu\nu_R)(H^\dagger i\overleftrightarrow{D}_\mu H)$ $(\bar{\nu}_R\gamma^\mu e)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{\nu B}$ $\mathcal{O}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tilde{H}B^{\mu\nu}$ $(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I\tilde{H}W^{I\mu\nu}$
$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R)$(+H.c.)	
$\mathcal{O}_{\nu\nu}$ $\mathcal{O}_{e\nu}$ $\mathcal{O}_{u\nu}$ $\mathcal{O}_{d\nu}$ $\mathcal{O}_{du\nu e}$(+H.c.)	$(\bar{\nu}_R\gamma^\mu\nu_R)(\bar{\nu}_R\gamma_\mu\nu_R)$ $(\bar{e}\gamma^\mu e)(\bar{\nu}_R\gamma_\mu\nu_R)$ $(\bar{u}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu\nu_R)$ $(\bar{d}\gamma^\mu d)(\bar{\nu}_R\gamma_\mu\nu_R)$ $(\bar{d}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu e)$	$\mathcal{O}_{L\nu}$ $\mathcal{O}_{Q\nu}$	$(\bar{L}\gamma^\mu L)(\bar{\nu}_R\gamma_\mu\nu_R)$ $(\bar{Q}\gamma^\mu Q)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu Le}$ $\mathcal{O}_{L\nu Qd}$ $\mathcal{O}_{LdQ\nu}$	$(\bar{L}\nu_R)\epsilon(\bar{L}e)$ $(\bar{L}\nu_R)\epsilon(\bar{Q}d)$ $(\bar{L}d)\epsilon(\bar{Q}\nu_R)$
$(\bar{L}R)(\bar{R}L)$		$(\cancel{L}\cap B)$(+H.c.)		$(\cancel{L}\cap\cancel{B})$(+H.c.)	
$\mathcal{O}_{Qu\nu L}$(+H.c.)	$(\bar{Q}u)(\bar{\nu}_R L)$	$\mathcal{O}_{\nu\nu\nu\nu}$	$(\bar{\nu}_R^c\nu_R)(\bar{\nu}_R^c\nu_R)$	$\mathcal{O}_{QQd\nu}$ $\mathcal{O}_{udd\nu}$	$\epsilon_{ij}\epsilon_{\alpha\beta\sigma}(Q_\alpha^i CQ_\beta^j)(d_\sigma C\nu_R)$ $\epsilon_{\alpha\beta\sigma}(u_\alpha Cd_\beta)(d_\sigma C\nu_R)$

Table 1. The complete basis of dimension-six operators involving ν_R, taken from Ref. [47]. Operators are expressed in terms of a column vector of n gauge singlet fields, ν_R, and SM fields, i.e., the lepton and

connecting g-2 and neutrino masses





Active-sterile mixing for the non-experts (1 slide)

Generically paramerize active-sterile mixing via Atre, et al [0901.3589], Han, et al [1211.6447]

$$\underbrace{\nu_{\ell L}}_{\text{flavor basis}} \approx \underbrace{\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell 4} N_4}_{\text{mass basis}} \qquad \underbrace{\nu_{\ell R}}_{\text{flavor basis}} \approx \underbrace{\sum_{m=1}^{3} X_{\ell m}\nu_m + Y_{\ell 4} N_4}_{\text{mass basis}}$$

The SM W coupling to **leptons** in the **flavor basis** is

$$\mathcal{L}_{\text{Int.}} = -\frac{g_W}{\sqrt{2}} W_\mu^- \sum_{\ell=e}^{\tau} \left[\bar{\ell}\gamma^\mu P_L \nu_\ell\right] + \text{H.c.}, \qquad \text{where } P_L = \frac{1}{2}(1-\gamma^5)$$

$\implies$ W coupling to N in the **mass basis** is

$$\mathcal{L}_{\text{Int.}} = -\frac{g_W}{\sqrt{2}} W_\mu^- \sum_{\ell=e}^{\tau} \left[\bar{\ell}\gamma^\mu P_L \left(\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell N} N\right)\right] + \text{H.c.}$$

$\implies$ N is **accessible through** $W/Z/h$ bosons

$g-2$ in νSMEFT

Parameterize corrections to $g-2$ by $\Delta a_\ell = a_\ell^{\rm Expt.} - a_\ell^{\rm Thry.}$ and

$$\mathcal{L} =_{\rm dipole}= L^{\ell\gamma}_{pr}\ \overline{\ell}_{Lp}\ \sigma^{\mu\nu}\ \ell_{Rr}\ F_{\mu\nu} + \text{H.c.}$$

in this language, $\mathcal{C}_i = (v^2 C_i) = (c_i^{(6)} v^2/\Lambda^2)$ is the Wilson coeff., and

$$\Delta a_\ell = \frac{4m_\ell}{\sqrt{4\pi\alpha_{\rm EM}}}\ \Re\left[L^{\ell\gamma}_{pr}\right] = \frac{4m_\ell}{v}\ \Re\left[b_i\ v^2 C_i\right]$$

ψ^2H^3		ψ^2H^2D		ψ^2HX(+H.c.)	
$\mathcal{O}_{L\nu H}$(+H.c.)	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{H\nu}$ $\mathcal{O}_{H\nu e}$(+H.c.)	$(\bar{\nu}_R\gamma^\mu\nu_R)(H^\dagger i\overleftrightarrow{D}_\mu H)$ $(\bar{\nu}_R\gamma^\mu e)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{\nu B}$ $\mathcal{O}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tilde{H}B^{\mu\nu}$ $(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I\tilde{H}W^{I\mu\nu}$
$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R)$(+H.c.)	
$\mathcal{O}_{\nu\nu}$ $\mathcal{O}_{e\nu}$ $\mathcal{O}_{u\nu}$ $\mathcal{O}_{d\nu}$ $\mathcal{O}_{du\nu e}$(+H.c.)	$(\bar{\nu}_R\gamma^\mu\nu_R)(\bar{\nu}_R\gamma_\mu\nu_R)$ $(\bar{e}\gamma^\mu e)(\bar{\nu}_R\gamma_\mu\nu_R)$ $(\bar{u}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu\nu_R)$ $(\bar{d}\gamma^\mu d)(\bar{\nu}_R\gamma_\mu\nu_R)$ $(\bar{d}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu e)$	$\mathcal{O}_{L\nu}$ $\mathcal{O}_{Q\nu}$	$(\bar{L}\gamma^\mu L)(\bar{\nu}_R\gamma_\mu\nu_R)$ $(\bar{Q}\gamma^\mu Q)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu Le}$ $\mathcal{O}_{L\nu Qd}$ $\mathcal{O}_{LdQ\nu}$	$(\bar{L}\nu_R)\epsilon(\bar{L}e)$ $(\bar{L}\nu_R)\epsilon(\bar{Q}d)$ $(\bar{L}d)\epsilon(\bar{Q}\nu_R)$
$(\bar{L}R)(\bar{R}L)$		$(\not{L}\cap B)$(+H.c.)		$(\not{L}\cap \not{B})$(+H.c.)	
$\mathcal{O}_{Qu\nu L}$(+H.c.)	$(\bar{Q}u)(\bar{\nu}_R L)$	$\mathcal{O}_{\nu\nu\nu\nu}$	$(\bar{\nu}^c_R\nu_R)(\bar{\nu}^c_R\nu_R)$	$\mathcal{O}_{QQd\nu}$ $\mathcal{O}_{udd\nu}$	$\epsilon_{ij}\epsilon_{\alpha\beta\sigma}(Q^i_\alpha CQ^j_\beta)(d_\sigma C\nu_R)$ $\epsilon_{\alpha\beta\sigma}(u_\alpha Cd_\beta)(d_\sigma C\nu_R)$

Table 1. The complete basis of dimension-six operators involving ν_R, taken from Ref. [47]. Operators are expressed in terms of a column vector of n gauge singlet fields, ν_R, and SM fields, i.e., the lepton and Higgs doublets, L and H, left-handed quark doublet $Q = (u_L, d_L)^T$, and right-handed fields e, u, and d.

operators that fail

operators that do not immediately fail

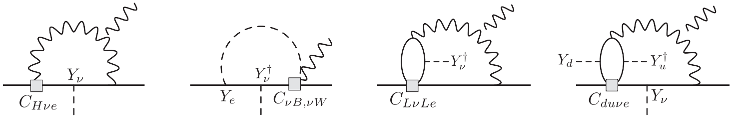
class	$\psi^2 H^3$	$\psi^2 H^2 D$		$(\bar{R}R)(\bar{R}R)$			
$\mathcal{C}_i = v^2 C_i$	$\mathcal{C}_{L\nu H}$	$\mathcal{C}_{H\nu}$	$^*\mathcal{C}_{H\nu e}$	$\mathcal{C}_{\nu\nu}$	$\mathcal{C}_{u\nu,d\nu}$	$\mathcal{C}_{e\nu}$	$^*\mathcal{C}_{du\nu e}$
b_i	$L^2 Y_\nu^\dagger Y_e$	$L^2 Y_e$	$L Y_\nu$	$L^3 Y_e Y_\nu^\dagger Y_\nu$	$L^2 Y_e \{Y_\nu Y_\nu^\dagger, L\}$	$L^2 Y_e$	$L^2 Y_u^\dagger Y_d Y_\nu$
$\Delta a_\mu / (\mathcal{C}_i \Delta a_\mu^{\text{expt.}})$	$10^{-2} Y_\nu$	10^{-2}	$3 \cdot 10^3\, Y_\nu$	$10^{-4} Y_\nu^\dagger Y_\nu$	$10^{-2}\{Y_\nu Y_\nu^\dagger, 10^{-2}\}$	10^{-2}	$0.4 Y_\nu^\dagger$
$\Delta a_e / (\mathcal{C}_i \Delta a_e^{\text{expt.}})$	$10^{-3} Y_\nu$	10^{-3}	$4 \cdot 10^4\, Y_\nu$	$10^{-5} Y_\nu^\dagger Y_\nu$	$10^{-3}\{Y_\nu Y_\nu^\dagger, 10^{-2}\}$	10^{-3}	$6 Y_\nu^\dagger$

class	$\psi^2 HX (+\text{H.c.})$	$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R)$			$(\bar{L}R)(\bar{R}L)$
$\mathcal{C}_i = v^2 C_i$	$^*\mathcal{C}_{\nu B,\nu W}$	$\mathcal{C}_{Q\nu}$	$\mathcal{C}_{L\nu}$	$^*\mathcal{C}_{L\nu Le}$	$\mathcal{C}_{L\nu Qd}$	$\mathcal{C}_{LdQ\nu}$	$\mathcal{C}_{Qu\nu L}$
b_i	$L Y_\nu^\dagger Y_e$	$L^2 Y_e \{Y_\nu Y_\nu^\dagger, L\}$	$L^2 Y_e$	$L^2 Y_\nu^\dagger$	$L^2 Y_d^\dagger Y_\nu^\dagger Y_e$	$L^2 Y_d^\dagger Y_\nu^\dagger Y_e$	$L^2 Y_u^\dagger Y_e^\dagger Y_\nu$
$\Delta a_\mu / (\mathcal{C}_i \Delta a_\mu^{\text{expt.}})$	$2 Y_\nu^\dagger$	$10^{-2}\{Y_\nu Y_\nu^\dagger, 10^{-2}\}$	10^{-2}	$20 Y_\nu^\dagger$	$10^{-4} Y_\nu$	$10^{-4} Y_\nu^\dagger$	$10^{-2} Y_\nu$
$\Delta a_e / (\mathcal{C}_i \Delta a_e^{\text{expt.}})$	$0.1 Y_\nu^\dagger$	$10^{-3}\{Y_\nu Y_\nu^\dagger, 10^{-2}\}$	10^{-3}	$300 Y_\nu^\dagger$	$10^{-5} Y_\nu$	$10^{-5} Y_\nu^\dagger$	$10^{-3} Y_\nu$

Table 2. Estimates of the contributions of the dimension-six Wilson coefficients to the coefficients b_i (defined in Eq. (3.3)), where $\Delta a_\ell = (4 m_\ell / v) b_i \mathcal{C}_i$. The third (fourth) row is the ratio $\Delta a_\ell / \Delta a_\ell^{\text{expt.}}$ for $\ell = \mu\ (e)$ in units of $\mathcal{C}_i = v^2 C_i$. L stands for a loop factor and Y_i are the different Yukawa couplings. The cases with $c_i,\ c_i' \geq 1$ are highlighted (in green) with an asterisk.

Many operators just do not work (tiny Yukawas, etc.) and some almost work

$$\mathcal{O}_{H\nu e}, \quad \mathcal{O}_{\nu B}, \quad \mathcal{O}_{\nu W}, \quad \mathcal{O}_{L\nu Le} \quad \text{and} \quad \mathcal{O}_{du\nu e}$$



but one operator seems to work

$\psi^2 H^3$		$\psi^2 H^2 D$		$\psi^2 HX(+\text{H.c.})$	
$\mathcal{O}_{L\nu H}(+\text{H.c.})$	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{H\nu}$ $\mathcal{O}_{H\nu e}(+\text{H.c.})$	$(\bar{\nu}_R\gamma^\mu\nu_R)(H^\dagger i\overleftrightarrow{D}_\mu H)$ $(\bar{\nu}_R\gamma^\mu e)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{\nu B}$ $\mathcal{O}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tilde{H}B^{\mu\nu}$ $(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I\tilde{H}W^{I\mu\nu}$
$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R)(+\text{H.c.})$	
$\mathcal{O}_{\nu\nu}$ $\mathcal{O}_{e\nu}$ $\mathcal{O}_{u\nu}$ $\mathcal{O}_{d\nu}$ $\mathcal{O}_{du\nu e}(+\text{H.c.})$	$(\bar{\nu}_R\gamma^\mu\nu_R)(\bar{\nu}_R\gamma_\mu\nu_R)$ $(\bar{e}\gamma^\mu e)(\bar{\nu}_R\gamma_\mu\nu_R)$ $(\bar{u}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu\nu_R)$ $(\bar{d}\gamma^\mu d)(\bar{\nu}_R\gamma_\mu\nu_R)$ $(\bar{d}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu e)$	$\mathcal{O}_{L\nu}$ $\mathcal{O}_{Q\nu}$	$(\bar{L}\gamma^\mu L)(\bar{\nu}_R\gamma_\mu\nu_R)$ $(\bar{Q}\gamma^\mu Q)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu Le}$ $\mathcal{O}_{L\nu Qd}$ $\mathcal{O}_{LdQ\nu}$	$(\bar{L}\nu_R)\epsilon(\bar{L}e)$ $(\bar{L}\nu_R)\epsilon(\bar{Q}d)$ $(\bar{L}d)\epsilon(\bar{Q}\nu_R)$
$(\bar{L}R)(\bar{R}L)$		$(\not{L}\cap B)(+\text{H.c.})$		$(\not{L}\cap \not{B})(+\text{H.c.})$	
$\mathcal{O}_{Qu\nu L}(+\text{H.c.})$	$(\bar{Q}u)(\bar{\nu}_R L)$	$\mathcal{O}_{\nu\nu\nu\nu}$	$(\bar{\nu}_R^c\nu_R)(\bar{\nu}_R^c\nu_R)$	$\mathcal{O}_{QQd\nu}$ $\mathcal{O}_{udd\nu}$	$\epsilon_{ij}\epsilon_{\alpha\beta\sigma}(Q^i_\alpha CQ^j_\beta)(d_\sigma C\nu_R)$ $\epsilon_{\alpha\beta\sigma}(u_\alpha Cd_\beta)(d_\sigma C\nu_R)$

Table 1: The complete basis of dimension-six operators involving ν_R taken from Ref. [24]. The operators are expressed in terms of a column vector of n gauge singlet fields, ν_R, and of SM fields, the lepton and Higgs doublets, L and H, the quark left-handed doublet $Q = (u_L, d_L)^T$, and the right-handed fields e, u, and d.

Unexpectedly, only one operator at $d = 6$ can generate "right" Δa_μ

$$\mathcal{L}_{H\nu e} \approx \frac{gv^2}{2\sqrt{2}\Lambda^2}\sum_{k=1}^{3}\left[\overline{C}_{H\nu e}\right]_{k\ell}\left(\overline{N_k}\gamma^\mu P_R\,\ell_R\right)W^+_\mu\left(1+\frac{h}{v}\right)^2 + \text{H.c.}$$

This generates Δa_μ of the form

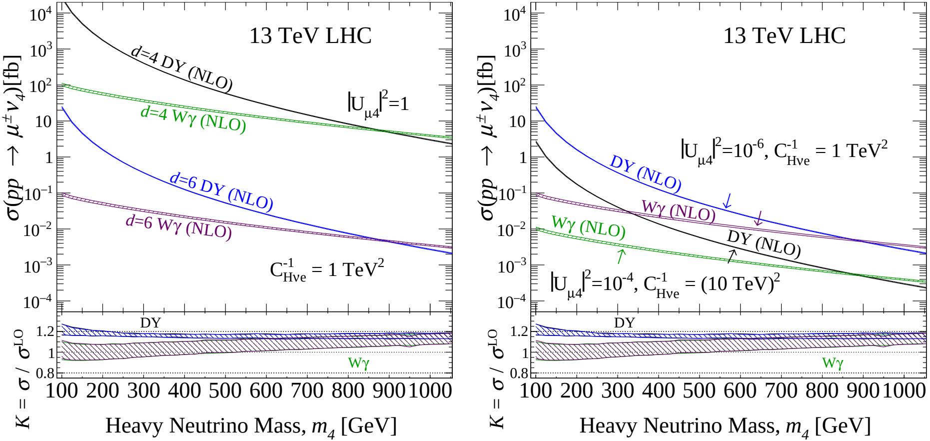
$$\Delta a_\mu \sim -\frac{2m_\mu m_N}{(4\pi)^2\Lambda^2}\text{Re}\left(V_{\mu N}\left[\overline{C}_{H\nu e}\right]_{N\mu}\right)$$

(see [2105.11462] for exact formula!)

can we have fun with this operator? yes!

Anomalous magnetic moment of the μ at the LHC

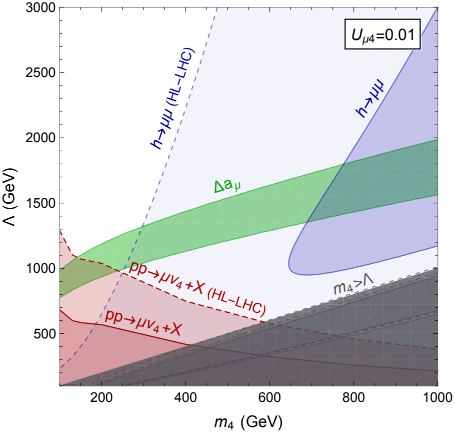
Plotted: $\sigma_{13\text{TeV}}$ vs mass for $d = 4, 6$ (L) separated and (R) combined

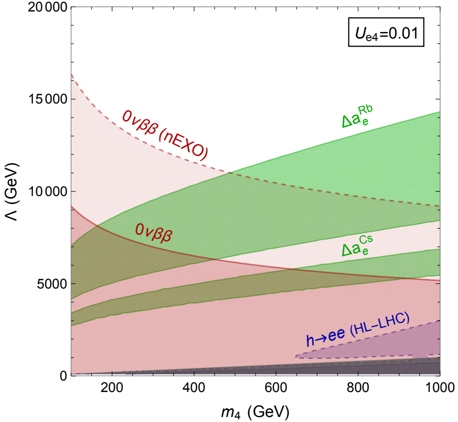


UFO with some $\mathcal{O}^{(6)}$ at NLO in QCD publicly available [feynrules.irmp.ucl.ac.be/wiki/HeavyN]

Take away: Even with realistic active-sterile mixing, $\sigma_{13\text{TeV}}$ not terrible

Anomalous magnetic moment of the μ at the LHC





Punchline: If N are involved in generating Δa_μ, then expect something in

$$pp \to N\mu^\pm + X \text{ and } H \to \mu^+\mu^-$$

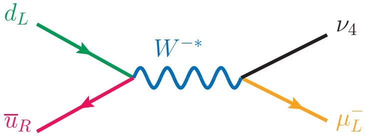
during Run III data and at the HL-LHC Cirigliano, de Vries, RR, et al (JHEP'21)

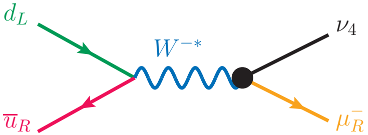
Thank you.

Backup

Validity of EFT at the LHC

Are N_4 light enough to justify using an EFT?





Yes, since for Drell-Yan $Q_{\max} \sim m_N\sqrt{1+\sqrt{3}} \approx m_N \times 1.65 \ll 1$ TeV