Low-energy lepton physics and SCALARS

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SCALARS, 13th September 2023

muon $(g-2)$

muon $g-2$ BSM survey: [Athron,Balazs,Jacob,Kotlarski,DS,Stöckinger-Kim, '21]

leptoquark LFV: [Khasianevich,DS,Stöckinger-Kim,Wünsche '23]

neutrino mass (Grimus-Neufeld) LFV: [Dudenas,Gajdosik,Khasianevich,Kotlarski,DS '22]

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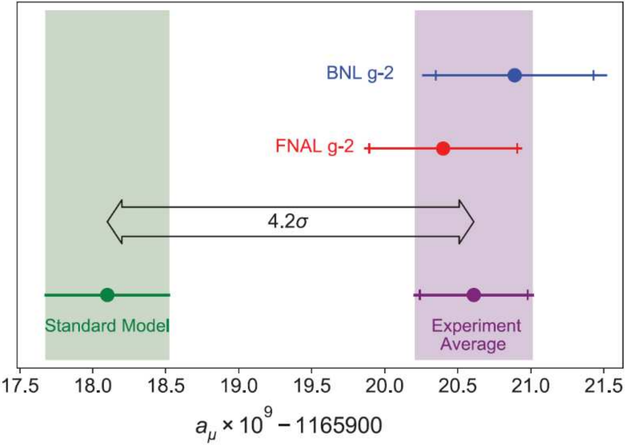
Outline

Difficult situation for muon $g-2$



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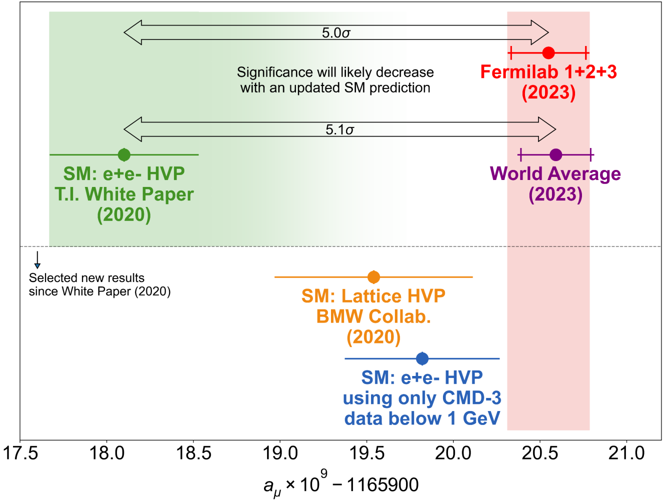


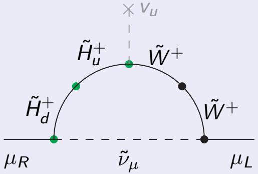
Question for Δa_μ:

Which new physics model(s) could explain $\Delta a_\mu = 25 \times 10^{-10}$?

$\rightsquigarrow$ here: focus on MSSM and leptoquarks

Note: conclusions qualitatively unchanged for $\Delta a_\mu \approx 10 \times 10^{-10}$

SUSY (MSSM): can explain $g-2$ and dark matter



$$a_\mu^{\mathrm{SUSY}} \approx 25 \times 10^{-10} \, \frac{\tan\beta}{50} \, \frac{\mu}{M_{\mathrm{SUSY}}} \left(\frac{500\mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^2$$

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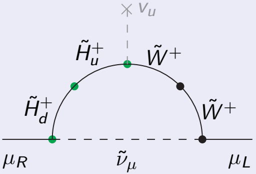

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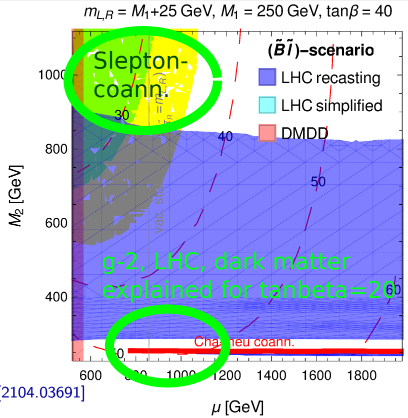

[2104.03691]

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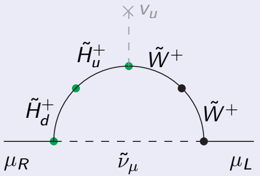

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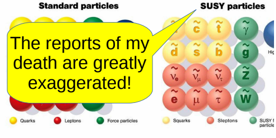
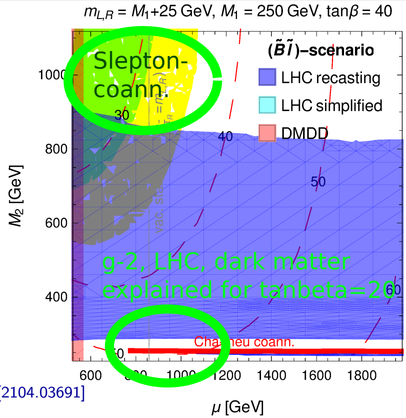
- Bino-LSP, nearby sleptons
- DM via Slepton- or Wino-coannihilation
- LHC limits easily evanded
- can easily accommodate Δa_μ





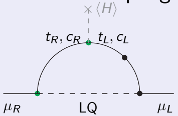
[2104.03691]

Leptoquark S_1 model with couplings μ–top or μ–charm

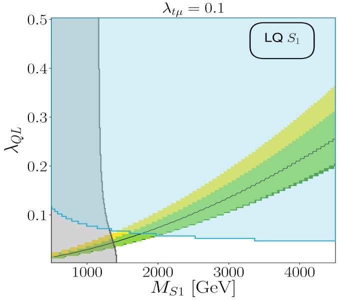
a_μ from LQ $\mathcal{L}_{S_1} = -\left(\lambda_{QL} Q_3 \cdot L_2 S_1 + \lambda_{t\mu} t \mu S_1^*\right)$

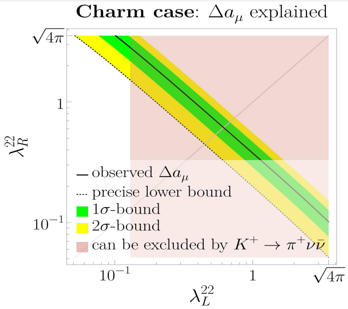
Specific LQ type

with L- and R-couplings



- Chiral enhancement $\sim y_{\text{top}}$ versus y_μ
- LHC: lower mass limits
- Kaon constraints on charm [Kowalska, Sessolo, Yamamoto '19]
- Charm case more favorable for smaller Δa_μ





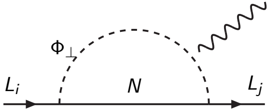
[Athron, Balazs, Jacob, Kotlarski, DS, Stöckinger-Kim, 2104.03691]

[Khasianevich, DS, Stöckinger-Kim, Wünsche '23]

Outline

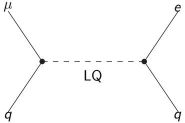
Lepton flavour violation: experimental constraints

- $\mu \to e\gamma$ decay



MEG: $< 4.2 \times 10^{-13} \longrightarrow$ planned MEG-II: $< 6 \times 10^{-14}$

- $\mu \to e$ conversion in presence of nucleus



SINDRUM-II: $< 7 \times 10^{-13} \longrightarrow$ planned COMET-I: $< 7 \times 10^{-15}$

Two important general points on $g-2$

discrepancy $\approx 2 \times a_\mu^{\mathrm{SM,weak}}$

but: expect $a_\mu^{\mathrm{NP}} \sim a_\mu^{\mathrm{SM,weak}} \times \left(\frac{M_W}{M_{\mathrm{NP}}}\right)^2 \times$ couplings

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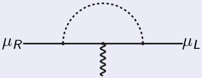
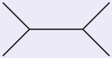
loop-induced, CP- and Flavor-conserving, chirality-flipping



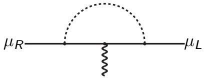
compare:



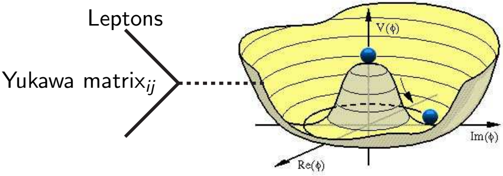
EDMs, $b \to s\gamma$, $B \to \tau\nu$, $\mu \to e\gamma$

EWPO

Connection to chirality flip, and structure of BSM



$$a_\mu \sim m_\mu \times \underbrace{(\text{some VEV}) \times (\mu_{L\leftrightarrow R}\text{-flipping param.})}_{\text{related to muon mass generation, potential enhancement!}} \times \frac{(\text{other couplings})}{M^2_{\text{typical}}}$$



changed by new physics?
⇝ strong effects on flavour?
(see MSSM, LQ examples)
⇝ strong LFV constraints?

Danger: lepton flavour violation — explore for LQ

Question for LQ model:

Given a_μ: how non-universal does the flavour structure have to be?

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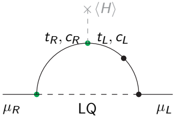
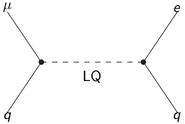
LQ a_μ diagram:



$\propto \lambda^{q2}$ $(q = 2, 3)$

LQ couplings to e, τ lead to $\mu \to e\gamma$, $\tau \to \mu\gamma$, ... $\propto \lambda^{q1}$, λ^{q3}

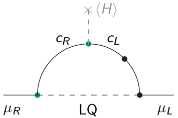
$\mu \to e$ conversion possible at tree-level



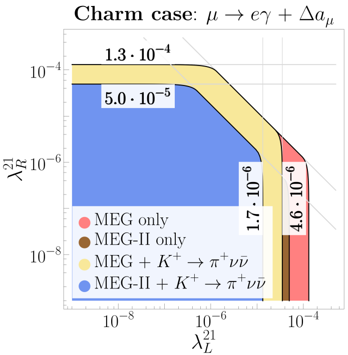
$\propto \lambda^{q1}, \lambda^{q2} (q = 1)$

Example for LQ with muon–charm explanation of a_μ

Assume Δa_μ is explained by muon–charm couplings



and derive upper limits on electron–charm couplings



[Khasianevich,DS,Stöckinger-Kim,Wünsche '23]

Explore flavour constraints for LQ

$q\backslash\ell$	e	μ	τ	valid
u	$\lambda_L^{11}\lambda_R^{11}\lambda_L^{12}\lambda_R^{12} < 6.5\cdot10^{-12} \to 3.7\cdot10^{-14}$ (spans e and μ)		—	all
	$\lambda_L^{11}(\lambda_R^{12}-0.65) < 2.9\cdot10^{-6} \to$ $\lambda_L^{11}(\lambda_R^{12}-0.40) < 2.4\cdot10^{-7}$	$\lambda_L^{12} < 0.82$		
c	$\lambda_L^{21}\lambda_R^{21} < 1.2\cdot10^{-10} \to 1.8\cdot10^{-11}$ $\lambda_{L,R}^{21} < 1.3\cdot10^{-4} \to 5.0\cdot10^{-5}$ $\lambda_L^{21} < 4.6\cdot10^{-6} \to 1.7\cdot10^{-6}$	$0.18 < \lambda_L^{22}\lambda_R^{22} < 0.56$ $5.1\cdot10^{-2} < \lambda_{L,R}^{22} < \sqrt{4\pi}$ $\lambda_L^{22} < 0.13\,,\ 1.5 < \lambda_R^{22}$	$\lambda_L^{23}\lambda_R^{23} < 2.1\cdot10^{-2} \to 4.7\cdot10^{-4}$ $\lambda_{L,R}^{23} < 1.7 \to 0.23$ $\lambda_L^{23} < 6.0\cdot10^{-2} \to 8.9\cdot10^{-3}$	sc. 2
t	$\lambda_L^{31}\lambda_R^{31} < 2.1\cdot10^{-12} \to 2.9\cdot10^{-13}$ $\lambda_{L,R}^{31} < 1.3\cdot10^{-4} \to 4.9\cdot10^{-5}$	$3.1\cdot10^{-3} < \lambda_L^{32}\lambda_R^{32} < 9.3\cdot10^{-3}$ $8.7\cdot10^{-4} < \lambda_{L,R}^{22} < \sqrt{4\pi}$	$\lambda_L^{33}\lambda_R^{33} < 3.5\cdot10^{-4} \to 7.8\cdot10^{-6}$ $\lambda_{L,R}^{33} < 1.7 \to 0.25$	sc. 1

[Khasianevich,DS,Stöckinger-Kim,Wünsche '23]

[see also Felipe, Goncalves, Morais et al '22, Hiller et al '16]

muon $g-2$ explained by top-loop

constraint from $\mu \to e\gamma$ (MEG and future MEG-II)

constraint from $\mu \to e$ conversion (SINDRUM and future COMET-I)

LQ couplings must be strongly non-universal!

($\mu \to e\gamma$ constraint would relax by factor 2 if Δa_μ goes down)

Outline

Grimus-Neufeld model — explain neutrino mass via 2HDM

2HDM plus single RH neutrino

$$\mathcal{L} \ni M_N \bar{N} N \qquad + y_i \bar{L}_i \Phi_v N \qquad + d_i \bar{L}_i \Phi_\perp N$$

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seesaw

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rank 1
tree-level: 1 massive ν

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loop-level: 2nd massive ν

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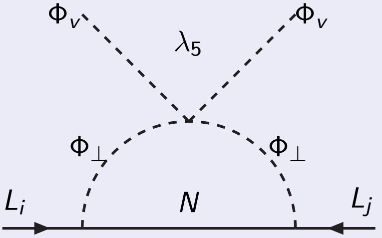

- $m_\nu \sim \lambda_5$ (Z_2-violating!) $\rightsquigarrow$ small $\lambda_5 \Leftrightarrow$ large Yukawas

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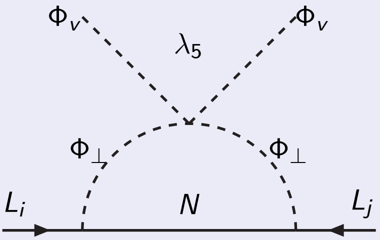

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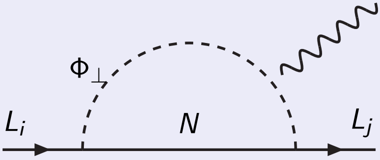
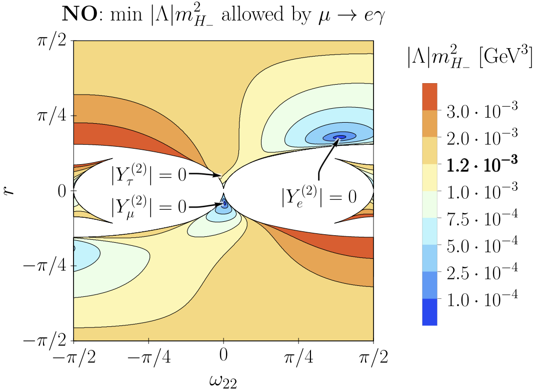


- danger: $\mu \to e\gamma$, $\tau \to e\gamma \ldots \rightsquigarrow$ interplay Higgs – m_{ν_2} – LFV

Question for GN model:

Given m_{ν_i}: what does LFV imply for the Higgs sector/Z_2-symmetry?

Answer:



[Dudenas,Gajdosik,Khasianevich,Kotlarski,DS '22]

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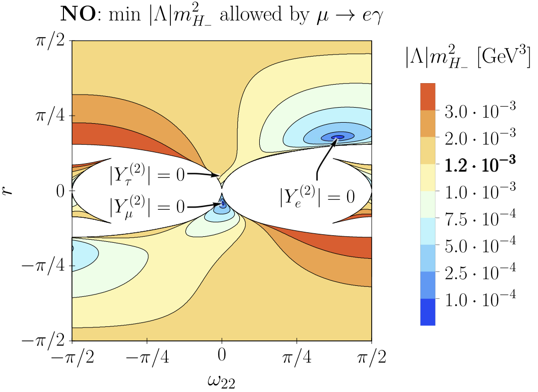
Answer:

- Parametrization— at each point in the ω_{22}–r-plane: m_{ν_i} are explained and Yukawas scale only with $\Lambda m^2_{H_-} \propto \lambda_5$



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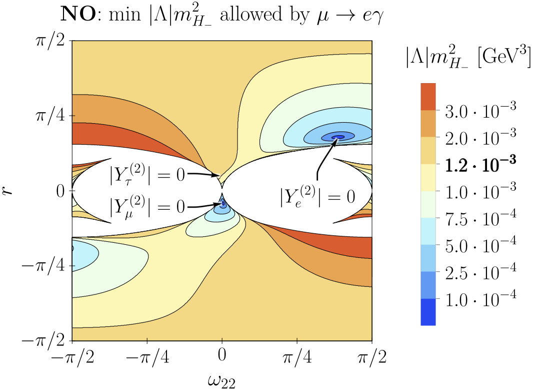

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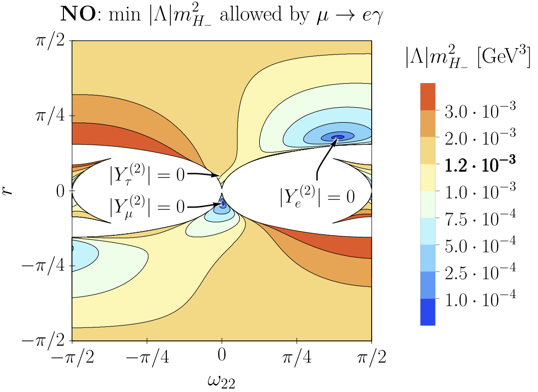

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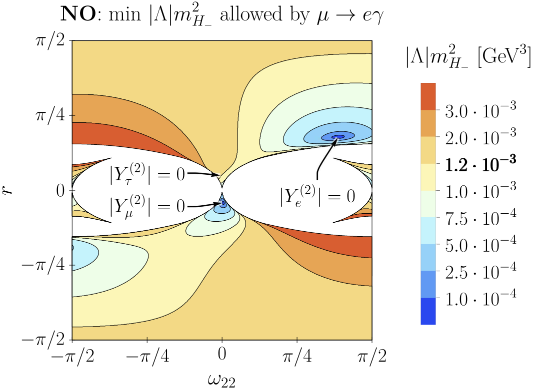

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absolute bound: $|\lambda_5| > 1 \cdot 10^{-2} \frac{\text{keV}}{m_4}$,

typical bound: (no $\tau \to e\gamma/\mu\gamma$ expected): $|\lambda_5| \gtrsim \frac{\text{keV}}{m_4}$.

Conclusions

- muon $g-2$ after FNAL Run-2/3: $\Delta a_\mu = (?10\ldots25??)\times10^{-10}$
  - MSSM, leptoquark $\sim$ chiral enhancements $\rightsquigarrow$ viable explanations
  - chiral enhancements $\Rightarrow$ new flavour structure, constrained by LFV
- leptoquarks: large Δa_μ $\Rightarrow$ strongly non-universal couplings
- neutrino mass via 2HDM+loops: GNM
  - LFV implies specific Higgs sector, outlook: LFV τ-decays
- technical tool for LFV: FlexibleSUSY + NPointFunctions [Khasianevich '22]