$(g-2)_\mu$ and the Status of Physics Beyond the Standard Model

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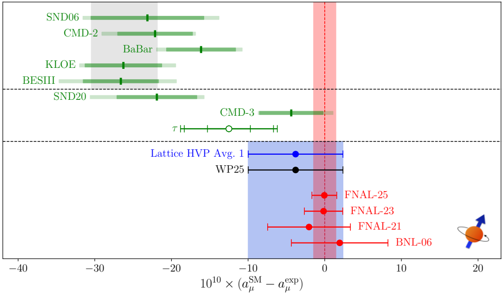

Outline

1. Chiral enhancement and connection to lepton masses
   - 2HDM and Leptoquarks
   - Collider constraints
   - Neutrino masses
2. Correlation with the Muon–Higgs coupling
   - Vector-like leptons
3. Correlation with Dark matter / Dark sectors
   - SUSY models
   - Light new gauge-bosons, HVP problem

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muon mass and the role of chirality flips

$$\mathcal{L}_{\text{eff}} \supset \underbrace{-m_\mu \, \overline{\psi_L}\psi_R}_{\text{dim-4 mass term}} + \underbrace{\frac{a_\mu e}{4m_\mu} \, \overline{\psi_L}\sigma^{\mu\nu}\psi_R \, F_{\mu\nu}}_{\text{dim-5 dipole term}} + h.c.$$

connection: both break chiral symmetry $\psi_R \to e^{i\alpha}\psi_R$ and EW gauge-invariance

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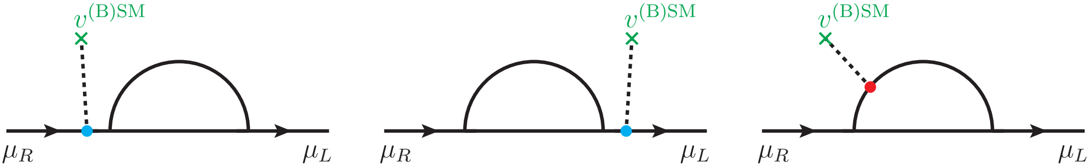


$$\Delta a_\mu \sim m_\mu \times \psi_{L\leftrightarrow R}\text{-flip param.} \times v^{\rm (B)SM} \times \frac{\text{other couplings}}{16\pi^2 M_{\rm BSM}^2}$$

muon mass and the role of chirality flips

without **chiral enhancement**

chirality flip only from $y_\mu \times v^{\text{SM}}$

$$\Delta a_\mu \sim m_\mu \times m_\mu \times \frac{|c_{L/R}|^2}{16\pi^2 M^2}$$

$\mathcal{O}(10^{-9})$ for $c \sim 1$, $M \sim 100$ GeV

e.g. Dark Photon, Z', ALPs, ...

with **chiral enhancement**

new chiral symm. breaking: $c_{LR} \times v^{\text{(B)SM}}$

$$\Delta a_\mu \sim m_\mu \times c_{LR} \times v^{\text{(B)SM}} \times \frac{c_L c_R}{16\pi^2 M^2}$$

$\Longrightarrow$ *chiral enhancement* $R_\chi \equiv \frac{c_{LR} v^{\text{(B)SM}}}{m_\mu}$

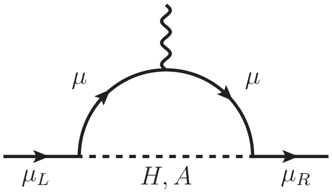
e.g. 2HDM: $R_\chi \sim \frac{v_1}{v_2}$, LQ: $R_\chi \sim \frac{y_t}{y_\mu}$, ...

$$\Delta a_\mu \quad \sim \quad m_\mu \times \psi_{L\leftrightarrow R}\text{-flip param.} \times v^{\text{(B)SM}} \times \frac{\text{other couplings}}{16\pi^2 M_{\text{BSM}}^2}$$

Example 1: Two-Higgs-Doublet Model

SM $+$ second scalar doublet Φ_2
motivation: ρ-parameter, strong CP/ PQ, baryogenesis, EW phase transitions/ GW, SUSY, ...

$\Longrightarrow$ 3 new scalars $H, A, H^{\pm}$ with $y_\mu = \zeta_l \times y_\mu^{\text{SM}}$

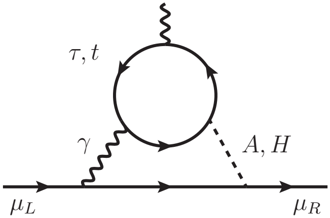


@ one-loop

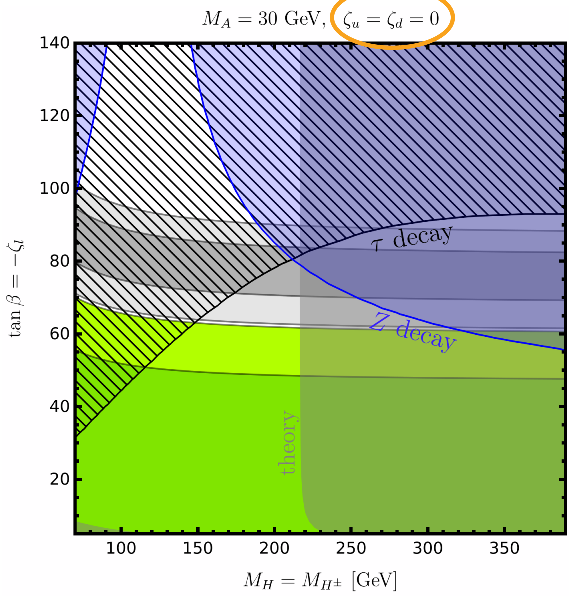
$$\Delta a_\mu^{1\ell} \sim \frac{\zeta_l^2}{8\pi^2} \frac{m_\mu^4}{v^2 M_S^2} \times \begin{cases} +1 & S = H, H^{\pm} \\ -1 & S = A \end{cases}$$

@ two-loop

$$\Delta a_\mu^{2\ell,\tau} \sim \mp \frac{\zeta_l^2}{8\pi^2} \frac{\alpha}{\pi} \frac{m_\tau^2 m_\mu^2}{v^2 M_S^2}, \qquad \Delta a_\mu^{2\ell,t} \sim -\frac{\zeta_l \zeta_u}{6\pi^2} \frac{\alpha}{\pi} \frac{m_t^2 m_\mu^2}{v^2 M_S^2}$$



2HDM: allowed and excluded regions



- **previously:** $\Delta a_\mu^{\mathrm{WP20}} \approx 2.5 \times 10^{-9}$

  $M_A \sim \mathcal{O}(10\ \mathrm{GeV}), \quad \zeta_l \sim \mathcal{O}(10)$

  $\hookrightarrow$ constraints τ/Z decay, theory, B-physics

  $\Rightarrow$ only possible in type-X / FA2HDM

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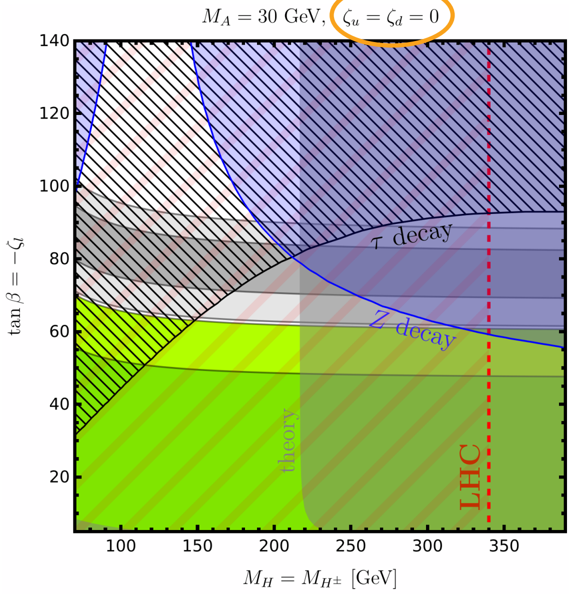

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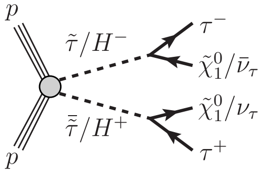
- **new:** LHC exclusion limits (2022)



$\Longrightarrow \quad M_{H^\pm} \gtrsim 340$ GeV, $\quad (M_A \simeq M_{H^\pm})$

- **now:** $M_S \sim$ TeV, $\zeta_u \lesssim 1 \;\Rightarrow\; \Delta a_\mu \lesssim 10^{-9}$

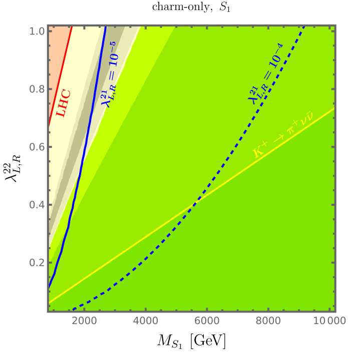
Example 2: Leptoquarks

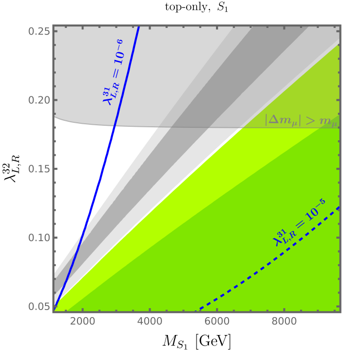
new scalar/ vectors coupling to lepton + quark

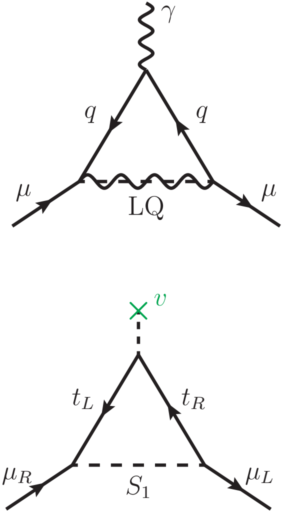
motivation: GUTs, flavour structure, B-physics and Δa_μ

$\Rightarrow$ *chiral enhancement:* $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$, $R_2 \sim (\mathbf{3}, \mathbf{2}, \frac{7}{6})$, $U_1^\mu \sim (\mathbf{3}, \mathbf{1}, \frac{2}{3})$

$$\mathcal{L} \supset -\left[\lambda_L\, \overline{q_L^c}\ell_L^{c*} + \lambda_R\, \overline{u_R^c}\mu_R\right] S_1 \quad \Longrightarrow \quad \boxed{\Delta a_\mu \propto \lambda_L \lambda_R y_u}$$

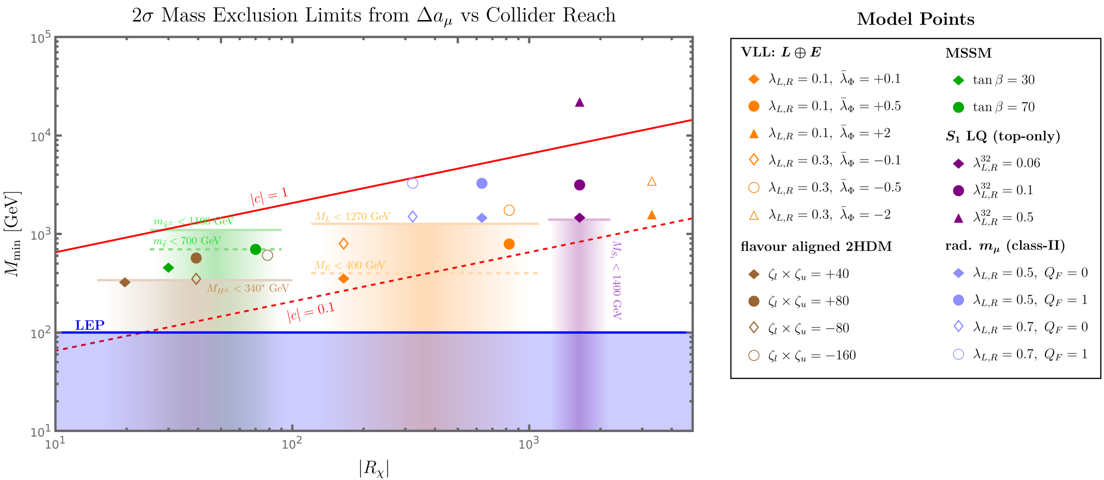






Chiral enhancement vs collider constraints

$$\Delta a_\mu = R_\chi \times \frac{c_L c_R}{16\pi^2} \frac{m_\mu^2}{M^2} \quad \overset{\text{WP25}}{\Longrightarrow} \quad M \gtrsim |R_\chi c_L c_R|^{\frac{1}{2}} \times 250\ \text{GeV}$$



Aside: correlation to neutrino masses

Neutrinos are have **tiny** masses $m_\nu \lesssim \mathcal{O}(\text{eV})$! ... why?

$\Longrightarrow$ *correlation:* interaction with ν_μ $\leftrightarrow$ interaction with muon

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Two options for small m_ν: $\begin{cases} \text{mass suppression } \Lambda_\nu \sim 10^{12}\ \text{TeV} & \Longrightarrow \Delta a_\mu = 0 \\ \text{suppressed L-violation, } \Lambda_\nu \sim \text{TeV} & \Longrightarrow \Delta a_\mu \sim 10^{-9} \text{ possible} \end{cases}$

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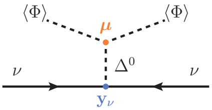
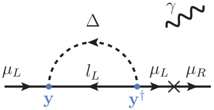
E.g. type II: $m_\nu \sim$ 

$\Delta a_\mu \sim$ 

$\Longrightarrow \frac{c_{\mu\gamma}}{c_{\nu\nu}} \propto -\frac{y_\nu}{16\pi^2}\frac{M_\Delta}{\mu}$

… some models with TeV-scale origin (scotogenic, Zee, LQs, VLFs, …) are constrained!

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Muon–Higgs coupling

SMEFT: dim-6

$$\begin{cases} C_{\mu\gamma}\left[\overline{\ell_L}\sigma^{\mu\nu}\mu_R\Phi\right]F_{\mu\nu} & \Longrightarrow \quad \Delta a_\mu \propto C_{\mu\gamma}v \\ C_{\mu\Phi}\left[\overline{\ell_L}\mu_R\Phi\right]\Phi^\dagger\Phi & \Longrightarrow \quad \Delta m_\mu \propto C_{\mu\Phi}v^3, \quad \Delta y_\mu \propto 3\times C_{\mu\Phi}v^2 \end{cases}$$

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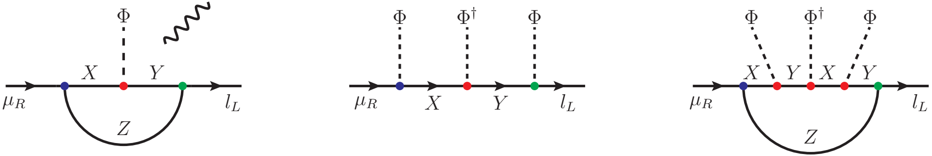
Coefficients connected via chirality flips! $C_{\mu\Phi} = \boldsymbol{\kappa} \times C_{\mu\gamma}$



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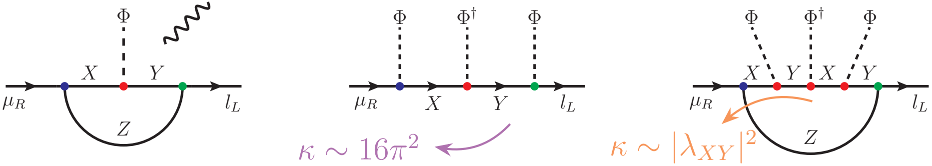

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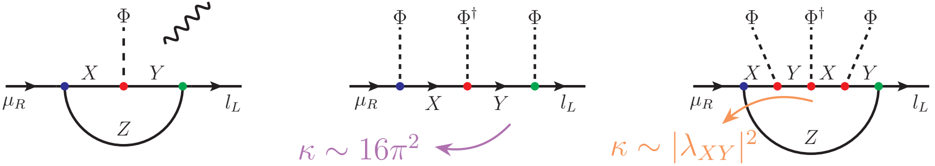
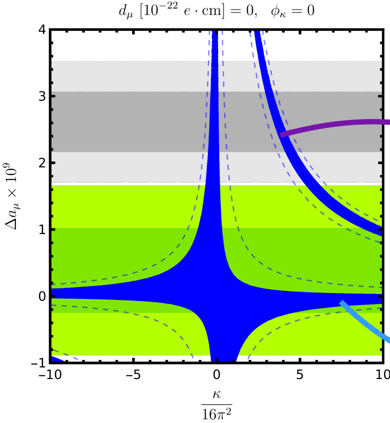


$$\frac{y_\mu}{y_\mu^{\text{SM}}} = 1 - \frac{|\kappa|}{728}\left(\frac{\Delta a_\mu}{10^{-9}}\right)$$

- **tree-models:** $\kappa \sim \mathcal{O}(100)$, $\Delta y_\mu \sim 100\%$
- **loop-models:** $\kappa \sim \mathcal{O}(1)$, $\quad \Delta y_\mu \sim 1\%$

$\Rightarrow$ needs future colliders (HL-LHC, FCC-ee, ...)

Muon–Higgs coupling



LHC: $\left|\dfrac{y_\mu}{y_\mu^{\text{SM}}}\right|^2 \simeq \mu(H\to\mu\mu) = 1.21 \pm 0.35$

$y_\mu \simeq -y_\mu^{\text{SM}}$

$y_\mu \simeq +y_\mu^{\text{SM}}$

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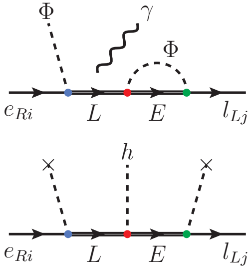
Example: vector-like leptons

new fermions (with Dirac mass) coupling to lepton + Higgs

motivation: (extra dimensions), GUT, flavour structure, DM
asymptotic safety, $H \to \mu\mu$ and Δa_μ, ...

$\Rightarrow$ *chiral enhancement:* at least 2 VLL with Yukawa coupling

$$\mathcal{L} \supset -\left[\lambda_L\, \overline{\ell_L} E + \lambda_R\, \overline{L} \mu_R + \bar{\lambda}\, \overline{L} E\right] \Phi \qquad \Longrightarrow \qquad \boxed{\Delta a_\mu \propto \lambda_L \lambda_R \bar{\lambda}}$$



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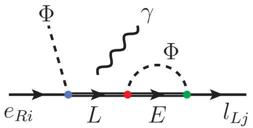

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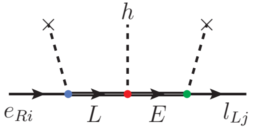

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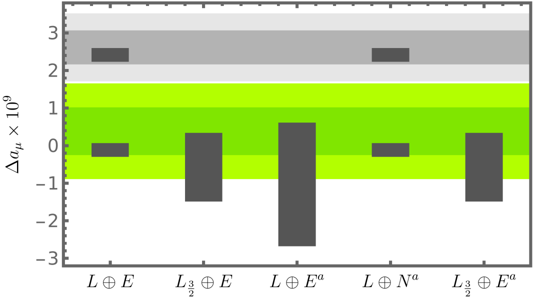
- strong correlation with $H \to \mu\mu$

$$\left|\frac{y_\mu}{y_\mu^{\text{SM}}}\right|^2 \approx \left(1 - \frac{\Delta a_\mu}{Q\, 10^{-9}}\right)^2$$



$\Longrightarrow$ "opposite sign" case excluded by $\Delta a_\mu^{\text{WP25}}$

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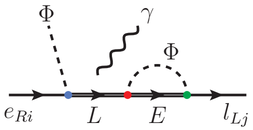

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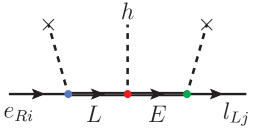

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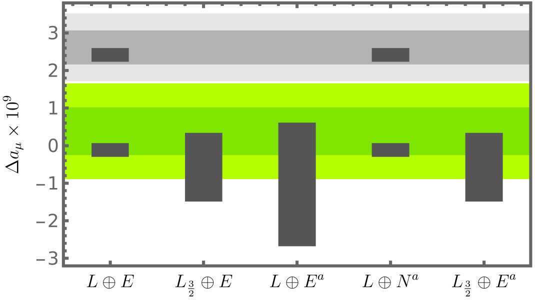

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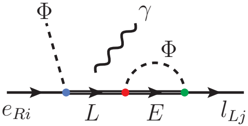

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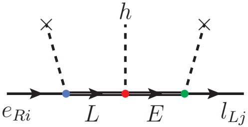

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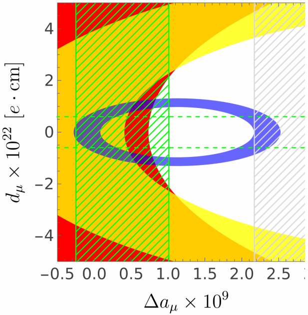

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$\Longrightarrow$ Δa_μ complementary with future measurements of d_μ

Outline

1. Chiral enhancement and connection to lepton masses
   - 2HDM and Leptoquarks
   - Collider constraints
   - Neutrino masses
2. Correlation with the Muon–Higgs coupling
   - Vector-like leptons
3. Correlation with Dark matter / Dark sectors
   - SUSY models
   - Light new gauge-bosons, HVP problem

Dark Matter

DM exists! ...but what is it $m = 10^{-21} \dots 10^{73}$ eV?

$\Longrightarrow$ *correlation:* thermal production $\Omega_{\text{DM}} \propto \frac{1}{\langle \sigma v \rangle}$ $\leftrightarrow$ interaction with muon

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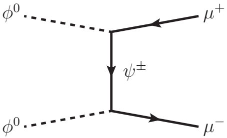
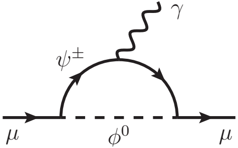
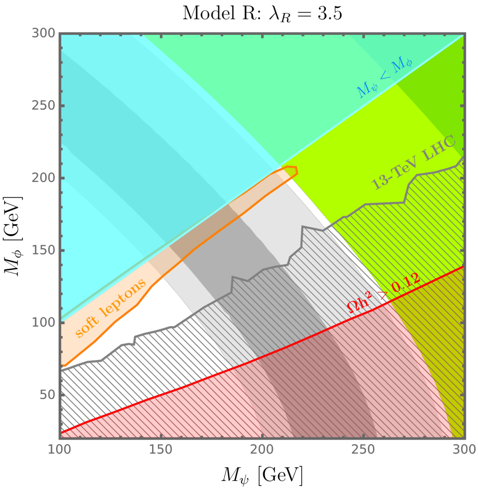




$\Longrightarrow$ large Δa_μ $\overset{\rm LHC}{\sim}$ incompatible with correct $\Omega_{\rm DM}$



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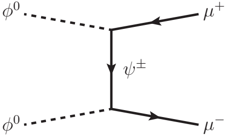
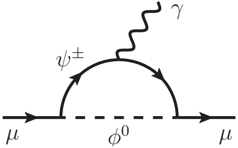
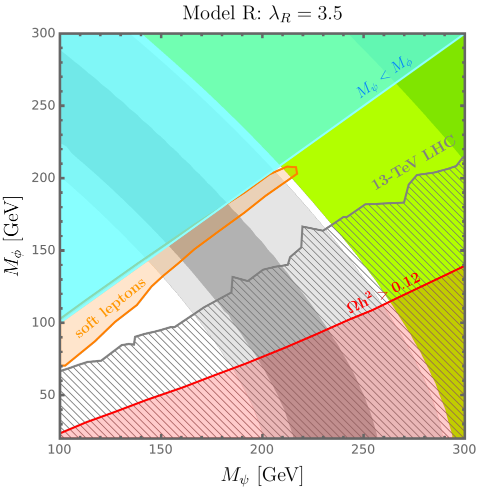






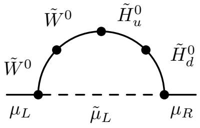
$\Longrightarrow$ large $\Delta a_\mu \overset{\text{LHC}}{\sim}$ incompatible with correct Ω_{DM}

complicated models: both possible (e.g. SUSY, ...)

SUSY models

many realisations $\longrightarrow$ (N/R/C)MSSM, mGMSB, AMSB, ...

motivation: hierarchy problem, DM, Coleman – Mandula, String theory/ QG, GUTs , ...



$$\Delta a_\mu \approx 5 \times 10^{-10} \left(\frac{1\text{ TeV}}{M_{\text{SUSY}}}\right)^2 \frac{\tan\beta}{40}$$

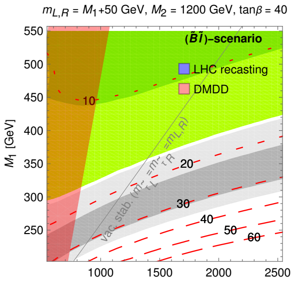
LHC bounds $\Longrightarrow$ either $M_{\text{SUSY}} \gtrsim$ TeV or small ΔM_{SUSY}

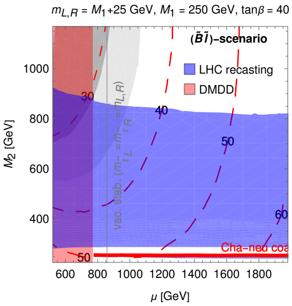
e.g. Higgsino DM

$\Delta a_\mu \lesssim 10^{-10}$

e.g. Bino DM

$\tan\beta \lesssim \mathcal{O}(1)$





Dark Photon and Z'

broken $U(1)_X \rightsquigarrow$ light gauge-boson $+$ coupling to muon

motivation: accidental symmetries, cosmology, DM mediator, HVP problem (?), ...

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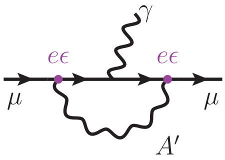
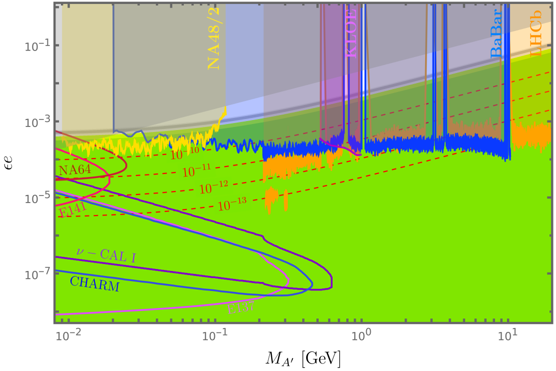


$\Rightarrow$ kinetic mixing and gauge coupling to muon

$$\mathcal{L} \supset \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} - g_{Z'} (\bar{\mu}\gamma^{\nu}\mu) Z'_{\nu}$$

1 $$\Delta a_{\mu} \simeq \epsilon^2 \times \frac{\alpha}{2\pi} \lesssim 10^{-10}$$



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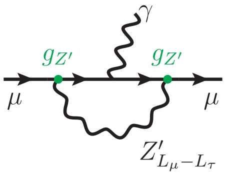

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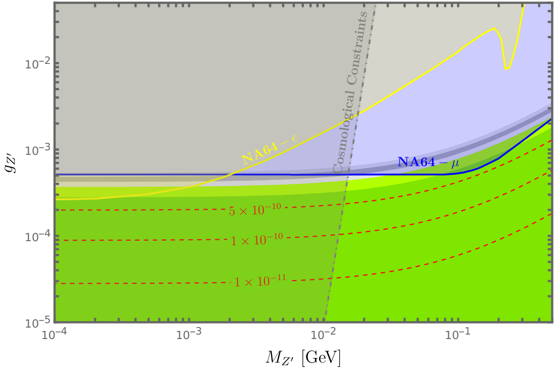
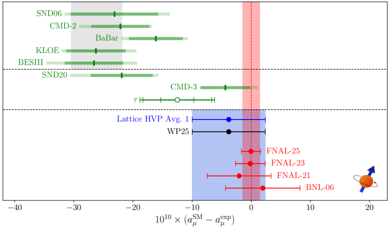
1 $\quad \Delta a_\mu \simeq \epsilon^2 \times \frac{\alpha}{2\pi} \lesssim 10^{-10}$

2 $\quad \Delta a_\mu \simeq \frac{g_{Z'}^2}{12\pi^2} \frac{m_\mu^2}{M_{Z'}^2} \lesssim 10^{-9}$

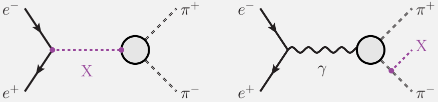


Light new physics as solution to the HVP problem?



$$\frac{d\sigma_{\text{had}}}{ds} = \frac{N_{\text{had}} - N_{\text{bg}}}{\epsilon(s) L(s)}$$

1 BSM in $e^+e^- \to$ had

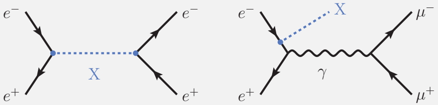


$\Longrightarrow$ mostly excluded (also: CMD3?)

[Di Luzio, Masiero, Paradisi, Passera '22;

Coyle, Wagner '23]

2 indirect BSM effect



$\Longrightarrow$ DP/$Z' \sim 1$ GeV can work for WP20 (even KLOE/BaBar), but not CMD2/3

[Darmè, di Cortana, Nardi '22]

Conclusion

- Fermilab exp. finished + updated SM value! $\implies$ $\Delta a_\mu = (3.8 \pm 6.3) \times 10^{-10}$

  $\sim 5\sigma$ discrepancy $\rightsquigarrow$ now consistent with Experiment! (but: Data vs Lattice, theory uncertainty)

- Models with **small** $\Delta a_\mu \to$ again viable

  e.g. (CM/MR/mGM)SSM, $\mathbb{Z}_2$-2HDM, see-saw models, two-field DM, anarchic flavour/CP violation, ...

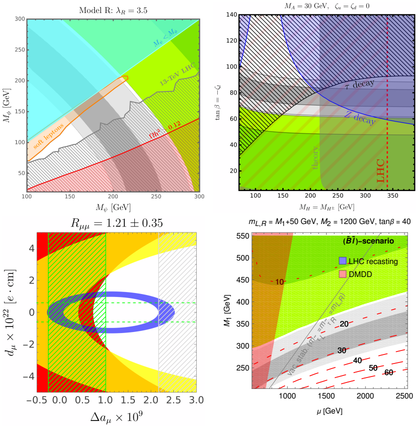
- Models with **large** $\Delta a_\mu \to$ now constrained

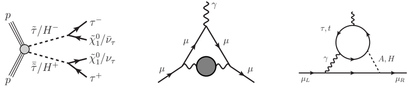
  e.g. vector-like leptons, lepto-quarks, rad. m_μ, ALPs, ...

  $\hookrightarrow$ but: still relevant if $\Delta a_\mu \gtrsim 10^{-12}$ re-emerges

- Complementary observables

  strong correlations with: m_μ, $H \to \mu\mu$, $\mu \to e\gamma$, EDM





Final remarks:

- no deviation, no more need for "contrived" models!
- typically $\Delta a_\mu \lesssim 10^{-13} \implies$ long term goal or give up??
- at what point should we take e^+e^- as signal for BSM?

Backup

Details on BSM effect in HVP

- **energy scan**: SND, CMD-2, CMD-3 $\Longrightarrow$ $\sqrt{s} \sim 0.1 \dots 1$ GeV
- **radiative return**: BaBar ($\sqrt{s} \sim 10.6$ GeV), KLOE ($\sqrt{s} \sim 1$ GeV), BES III ($\sqrt{s} \sim 3.8$ GeV)

$$a_\mu^{\text{HVP,LO}} = \frac{1}{4\pi^3} \int_{s_0}^{\infty} K(s) \Big(\sigma_{\text{had}}^{\text{SM}}(s) + \Delta\sigma_{\text{had}}^{\text{BSM}}(s) \Big) \quad \Longrightarrow \quad \Delta\sigma_{\text{had}}^{\text{BSM}}(s) \overset{!}{\approx} -5\%$$

① $\underline{Z' \text{ coupling to } e \text{ and } q\text{:}}$ $\quad \Delta\sigma_{\pi\pi}^{\text{BSM}}(s) = \sigma_{\pi\pi}^{\text{SM}}(s) \dfrac{2s(s - M_{Z'}^2)\epsilon + s^2\epsilon^2}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}}, \qquad \epsilon = g_e(g_u - g_d)/e^2$

requires $M_{Z'} \sim$ few $\times\, 0.1$ GeV and $|\epsilon| \approx 0.01$

constraints: $m_{\pi^\pm}^2 - m_{\pi^0}^2 \propto (g_u - g_d)^2 \Longrightarrow |g_u - g_d| \lesssim 0.06 \dots 0.1$ LEP: $g_e \lesssim 10^{-4} \dots 10^{-2}$

caveats: resonant feature $\curvearrowright$ either $M_{Z'} \sim m_{\rho,\omega}$ or $\Gamma_{Z'} \neq 0$ ($\rightsquigarrow$ DM)

② $\underline{\text{ISR measurements:}}$ $\quad \sigma_{\pi\pi} = \sigma_{\mu\mu} \times N_{\pi\pi\gamma_{\text{ISR}}} / N_{\mu\mu\gamma_{\text{ISR}} / X} \Longrightarrow \Delta\sigma_{\pi\pi} \approx \sigma_{\pi\pi} \frac{\sigma_{\mu\mu X}}{\sigma_{\mu\mu}} \frac{\epsilon^{\text{NP}}}{\epsilon^{\text{SM}}}$

caveats: some experiments calibrate to Bhabha scattering instead / measure $\sigma_{\pi\pi}$ directly

$\Longrightarrow$ in general very specific (highly coincidental) scenarios required...
$\Longrightarrow$ old energy scan experiments (SND/ CMD2) unaffected

Dipole observables and flavour violation

- general dipole term $\mathcal{L} \supset C_{ij}\,\overline{\psi_{Li}}\sigma^{\mu\nu}\psi_{Rj}F_{\mu\nu} \quad \curvearrowright \quad d_i \propto \operatorname{Im} C_{ii}, \quad \mathcal{B}_{i\to j\gamma} \propto |C_{ij}|^2$

SM: tiny CP and flavour violation $\begin{cases} \text{EDM} \sim 10^{-40}\, e\cdot\text{cm} \\ \text{BR}(\mu \to e\gamma) \sim 10^{-50} \end{cases} \implies$ clean signal for BSM!

$$d_\mu \approx \left(\frac{\Delta a_\mu}{10^{-9}}\right)\left(\frac{\tan\theta_\mu}{2000}\right)1.9\times 10^{-19} e\cdot\text{cm}, \qquad \mathcal{B}_{\mu\to e\gamma} \approx \left(\frac{\Delta a_\mu}{10^{-9}}\right)^2\left(\frac{\theta_{12}}{3\times 10^{-5}}\right)^2 3.1\times 10^{-13}$$

naive scaling $\theta_{ij} \propto m_i/m_j$

$|d_\mu| \lesssim 10^{-27} e\cdot\text{cm}$

flavour anarchy $\theta_{ij} \sim 1$

$\Delta a_\mu \lesssim 10^{-14}$

large μ-CPV still possible, LFV already strongly constrained

$\implies$ *either* specific flavour/CP structure or $\Delta a_{e,\mu} \approx 0$

small $\Delta a_{e,\mu} \curvearrowright$ often **no "dipole dominance"**

$\implies$ independent bounds from $\mu \to e\gamma$, $\mu \to 3e$ and $\mu \to e$

$\Delta a_\mu^{\mathrm{HVP}}$ vs $\Delta\alpha_{\mathrm{had}}$

$$a_\mu^{\mathrm{HVP}} = \frac{\alpha}{\pi^2}\int_{s_0}^{\infty} ds K(s)\,\mathrm{Im}\{\Pi(s)\}$$

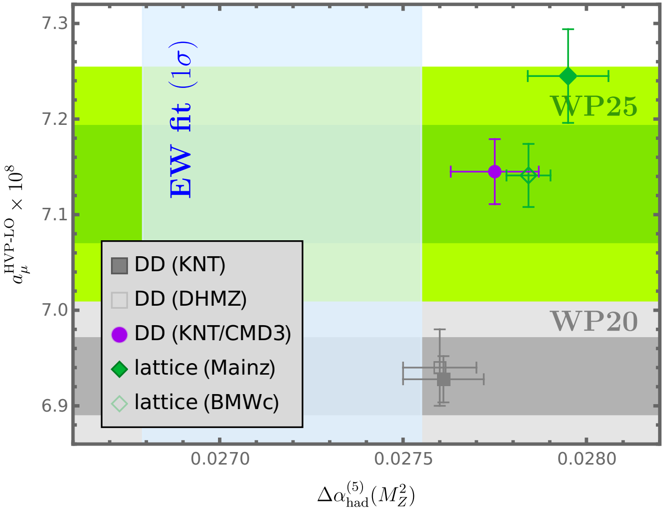
$$\Delta\alpha_{\mathrm{had}} = \frac{M_Z^2}{\pi}\int_{s_0}^{\infty} ds\frac{\mathrm{Im}\{\Pi(s)\}}{s[M_Z^2 - s]}$$

Shift in σ_{had} increases both. But $K(s)$ is more strongly peaked at low energies

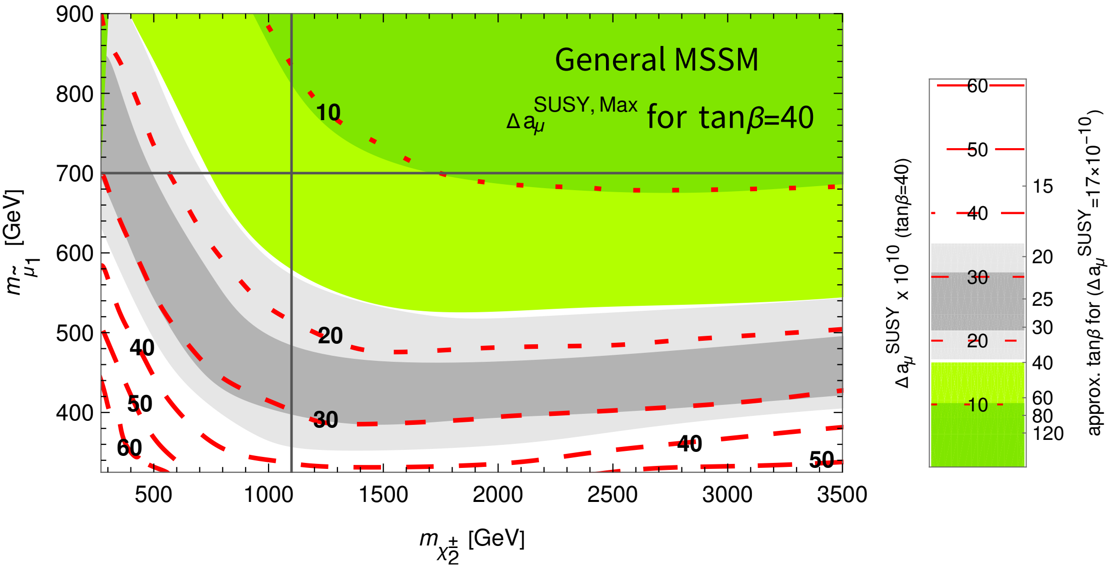
$\Longrightarrow$ tension in $\Delta\alpha$ slightly increases, but the overall EWPO fit becomes better.

also: small decrease of M_W

$$\Delta M_W^2 \sim \frac{M_W^2 s_W^2}{s_W^2 - c_W^2}\Delta\alpha_{\mathrm{had}} < 0$$



MSSM: maximum Δa_μ



Axion-like Particles

pseudo-scalar, shift-invariant (effective) couplings

motivation: strong CP problem, DM, cosmology, string theory
like WIMP but different, ...

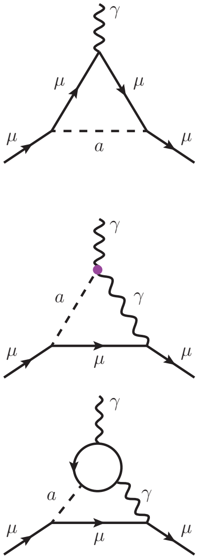
$\Rightarrow$ **ALP:** *dim-5* coupling to ~~gluon~~ $\rightsquigarrow$ photon and muon

$$\mathcal{L} \supset \frac{c_{\gamma\gamma}}{f_a}\frac{\alpha}{4\pi}\, a\widetilde{F}_{\mu\nu}F^{\mu\nu} - \frac{c_{\mu\mu}}{2f_a}(\overline{\mu}\gamma^{\nu}\gamma^{5}\mu)\partial_{\nu}a$$

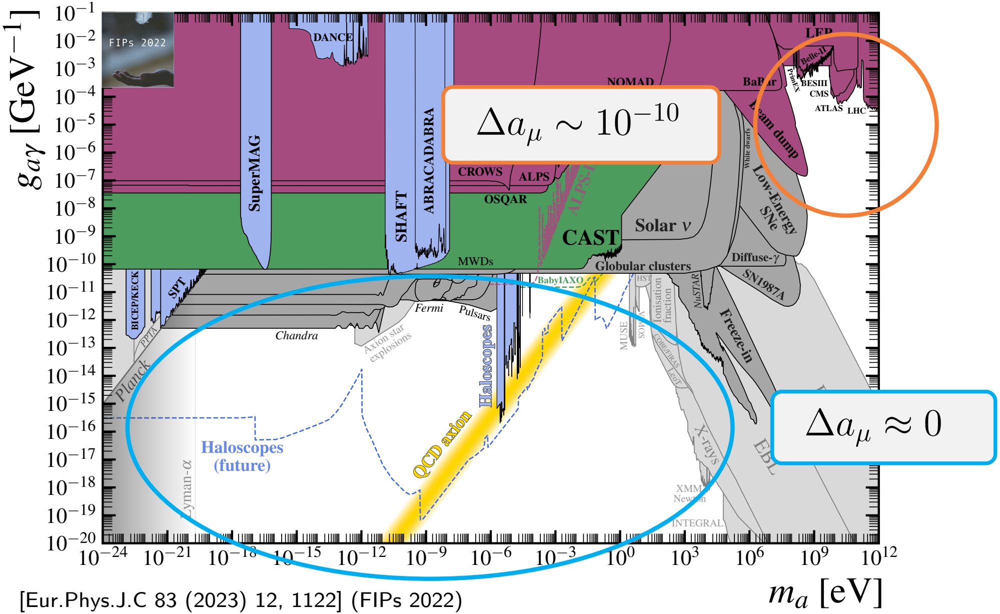
two competing contributions (similar to 2HDM):

@ one – loop $\quad \Delta a_\mu \sim -\frac{c_{\mu\mu}^2}{16\pi^2}\frac{m_\mu^2}{f_a^2}$

@ "two" – loop $\quad \Delta a_\mu \sim -\frac{c_{\mu\mu}c_{\gamma\gamma}^{\text{eff}}}{2\pi^2}\frac{\alpha}{4\pi}\frac{m_\mu^2}{f_a^2}$



Axion-like Particles: constraints



[Eur.Phys.J.C 83 (2023) 12, 1122] (FIPs 2022)

Axion-like Particles: constraints