TECHNISCHE UNIVERSITÄT DRESDEN

INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

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

Kilian Möhling

[Prog.Part.Nucl.Phys. 148 (2026)] in Collaboration with:

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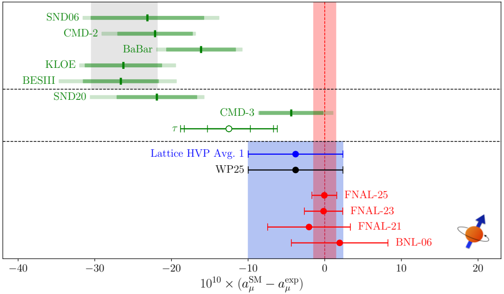
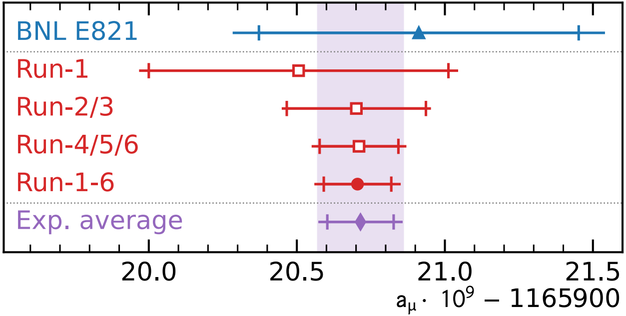
and Peter Athron

TU Dresden, Institut für Kern- und Teilchenphysik

BNL Seminar, 30.07.2026



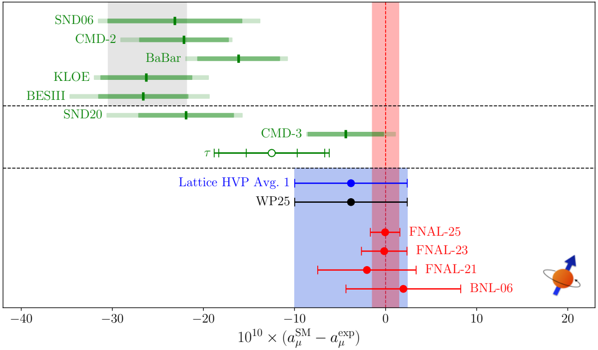
FNAL final measurement



Experiment:

$$a_\mu^{\text{Exp}} = 11\,659\,207.15(1.45) \times 10^{-10}$$

FNAL final measurement and Standard Model update



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$$a_\mu^{\mathrm{SM20}} = 11\,659\,181.0\ (4.3)\ \times 10^{-10}$$

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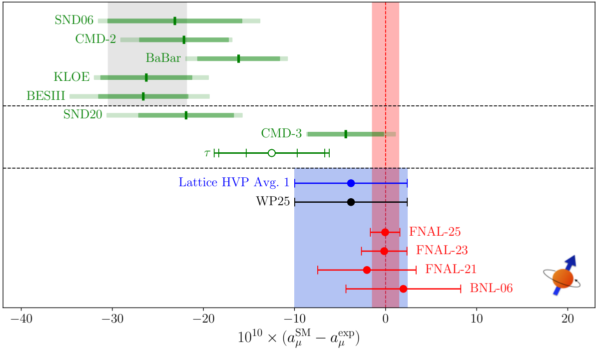

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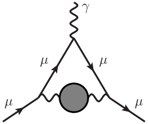
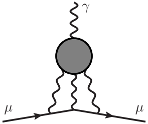
$a_\mu^{\mathrm{HVP,LO}} \times 10^{10}$



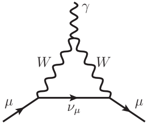
$$\begin{cases} 693.1(4.0) \\ 713.2(6.1) \end{cases}$$

$a_\mu^{\mathrm{HLbL}} \times 10^{10}$



$$\begin{cases} 9.20(1.8) \\ 11.55(0.9) \end{cases}$$

$a_\mu^{\mathrm{EW}} \times 10^{10}$



$$\begin{cases} 15.36(0.1) \\ 15.44(0.04) \end{cases}$$

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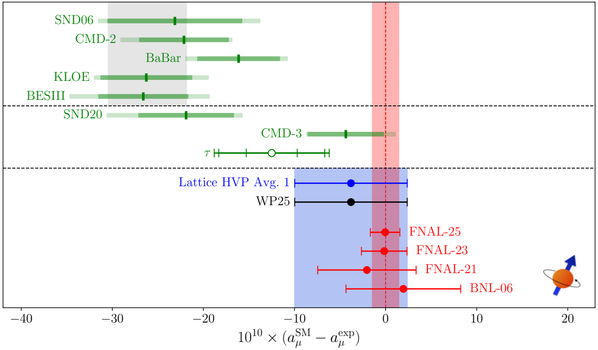

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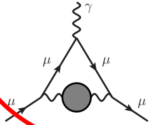

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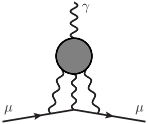

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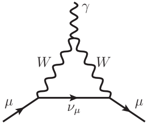

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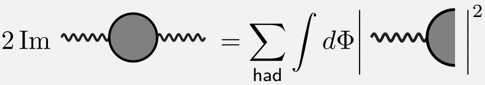
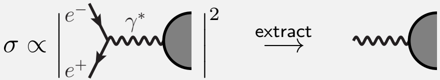
HVP: two competing methods

Data-driven

1. unitarity + causality



2. measure $e^+e^- \to$ hadrons



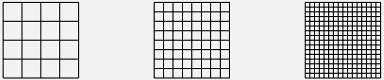
and correct for ISR, virtual correction, efficiencies, backgrounds, ...

3. dispersion integral

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

lattice QCD

1. generate gauge configurations



2. *euclidean* correlator $(Q^2 = -s)$

$$\Pi(Q^2) \sim \int d^4x \, \langle j_\mu(x) j_\nu(0) \rangle \, e^{-iQx}$$

and correct for iso-spin breaking, fermion doublers, finite volume, ...

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$$a_\mu^{\text{HVP}} = \frac{\alpha}{\pi^2} \int_0^{\infty} dQ^2\, f(Q^2)\, \Pi(Q^2)$$

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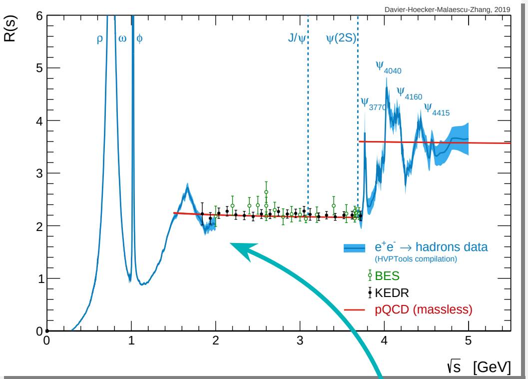

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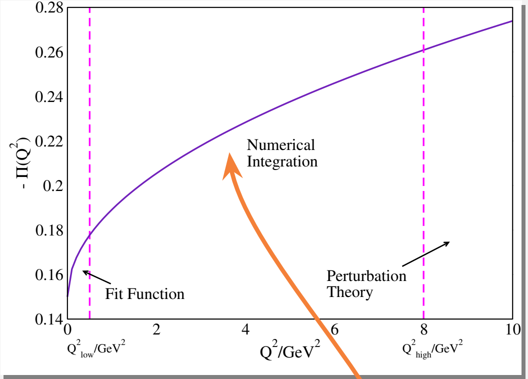

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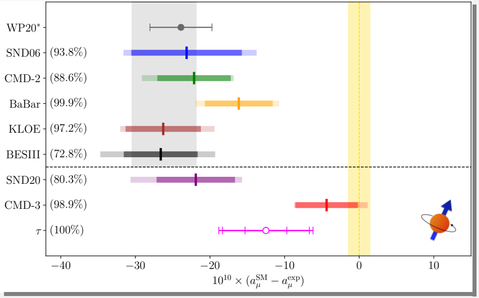
Data-driven

- multiple experiments (WP20 average):

SND06, CMD-2, BaBar, KLOE, BESIII

$\Longrightarrow$ all consistently below lattice

- since 2024: **CMD-3**

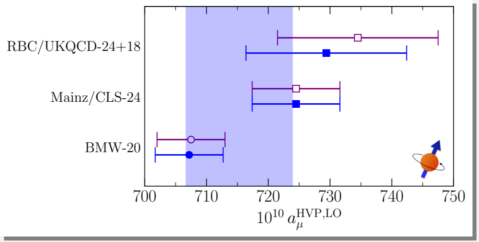


- ongoing efforts: re-analyses, MC, ...

lattice QCD

- first complete result from BMW $\rightsquigarrow$ 2020, but not included in WP20 average
- WP25: many additional results from 8 independent collaborations

$\Longrightarrow$ average consistent with a_μ^{exp}, but also some tensions between groups



- ongoing efforts: comparisons, IB, LD, ...

Is BSM dead?

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BSM papers 2021 vs 2025

P. Athron et al. [**21**04.03691]	P. Athron et al. [**25**07.09289]
$\Delta a_\mu \sim 25 \times 10^{-10}$, ${\color{blue} N_{2021} \sim 100}$	$\Delta a_\mu \sim 4 \times 10^{-10}$, ${\color{red} N_{2025} \sim 30}$

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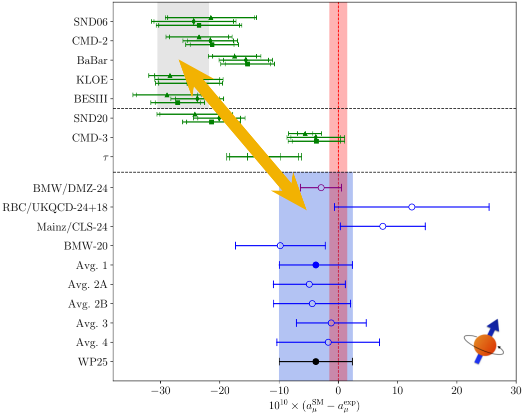

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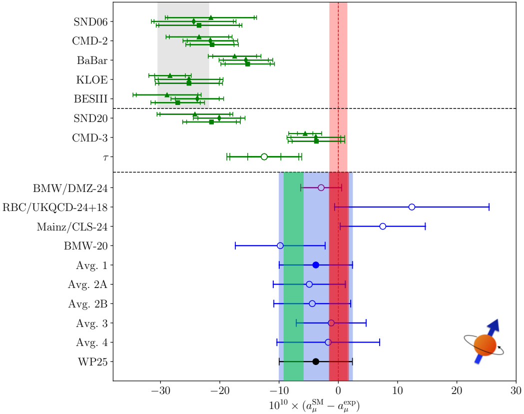

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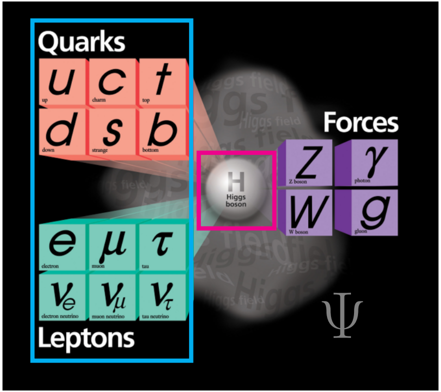

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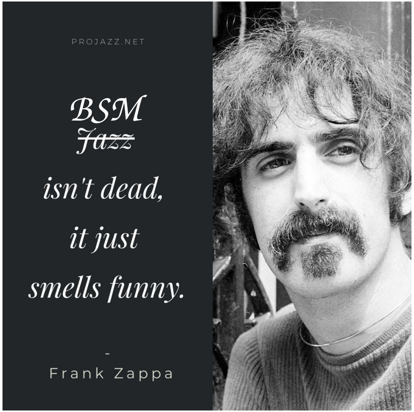

Outline

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   - muon mass and chiral enhancement
   - Dipole observables
   - $H \to \mu\mu$
   - Neutrino masses and Dark matter

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   - 2HDM and Supersymmetry
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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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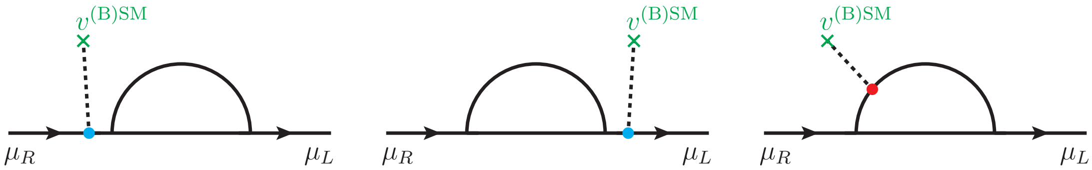

$$\Delta a_\mu \sim m_\mu \times \left[v^{(B)SM} \times \psi_{L\leftrightarrow R}\text{-flip param.}\right] \times \frac{\text{other couplings}}{16\pi^2 M_{\text{BSM}}^2}$$

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: $v^{\text{(B)SM}} \times c_{LR}$

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

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

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

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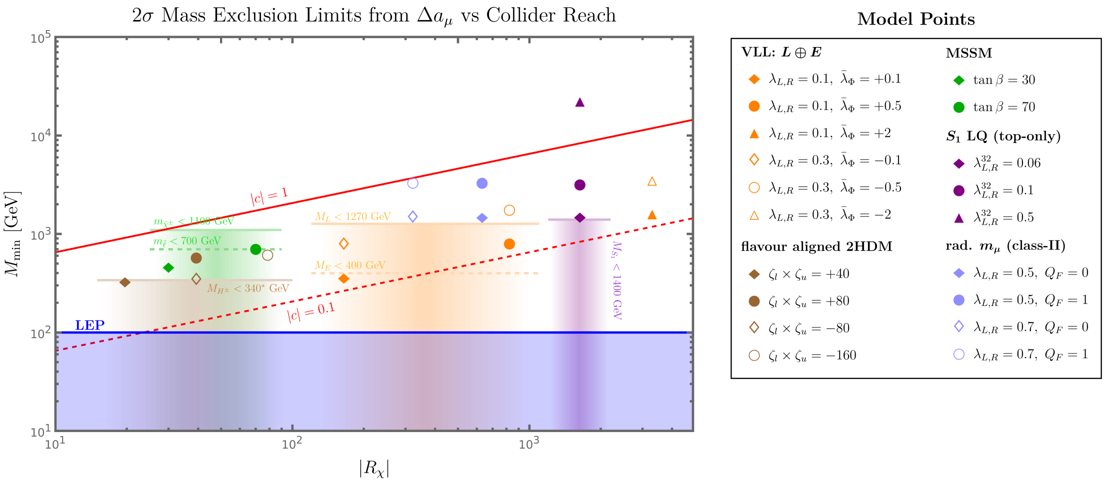
Chiral enhancement vs collider constraints

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



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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 $\begin{cases} \text{EDM} \sim 10^{-40}\, e \cdot \text{cm} \\ \text{BR}(\mu \to e\gamma) \sim 10^{-50} \end{cases} \Longrightarrow$ clean signal for BSM!

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

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 $\mu \to e$

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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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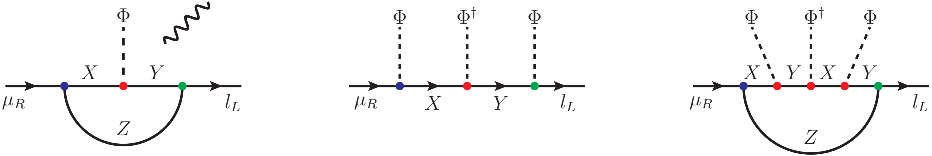

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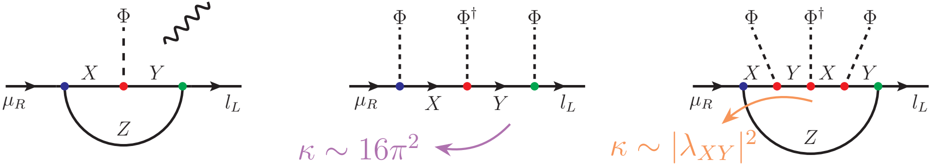

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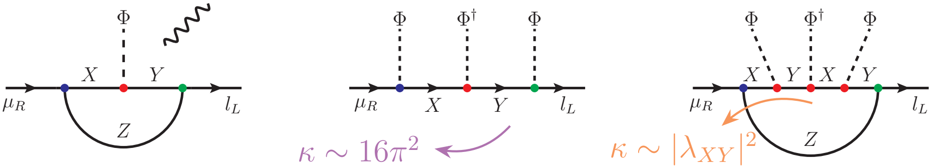

$$\frac{y_\mu}{y_\mu^{\text{SM}}} = 1 - \frac{|\kappa|}{728}\left(\frac{\Delta a_\mu}{10^{-9}}\right)$$

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

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

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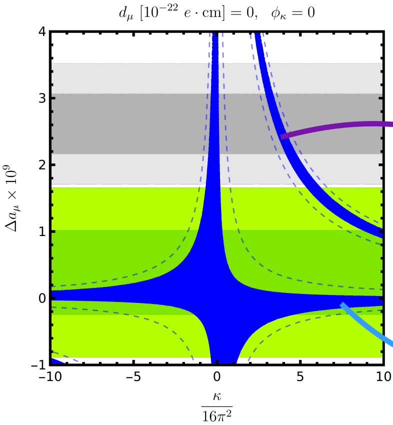

LHC: $\left|\frac{y_\mu}{y_\mu^{\text{SM}}}\right|^2 \simeq \mu(H\to\mu\mu) = 1.21 \pm 0.35$

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

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

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

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

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

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Neutrino masses

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

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$$\boxed{\Longrightarrow \qquad \Delta a_\mu \sim 10^{-9} \times \left(\frac{1\ \text{TeV}}{\Lambda_\nu}\right) \times \left(\frac{c_{\mu\gamma}}{c_{\nu\nu}} \cdot 10^{-8}\right)}$$

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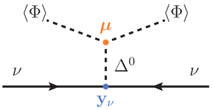
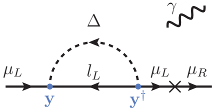
E.g. type II: $m_\nu \sim$ 

$\Delta a_\mu \sim$ 

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

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

Dark Matter

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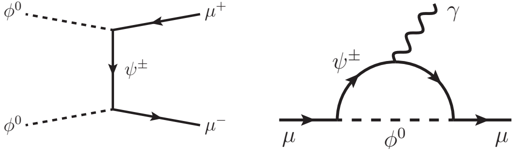

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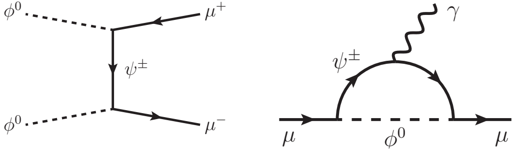

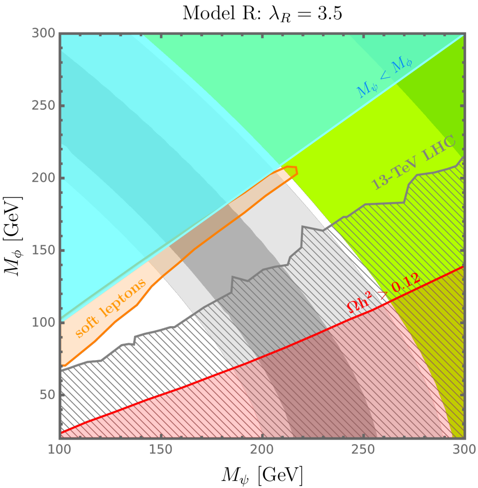

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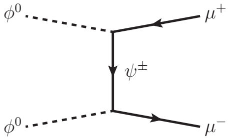

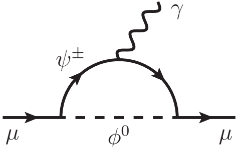

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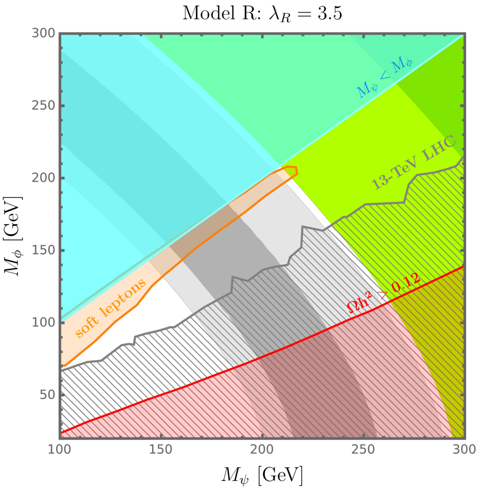
complicated models: both possible (e.g. SUSY, ...)



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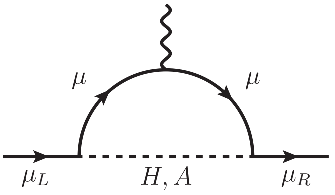
Two-Higgs-Doublet Model

SM $+$ second scalar doublet Φ_2
motivation: ρ-parameter, strong CP/ PQ, baryogenesis, EW phase transitions/ GW, SUSY, $g-2$, ...

$\Longrightarrow$ 3 heavy states $H, A, H^\pm$ with $y_\mu \propto \zeta_l\, m_\mu$

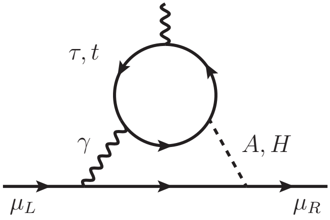
@ one-loop

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

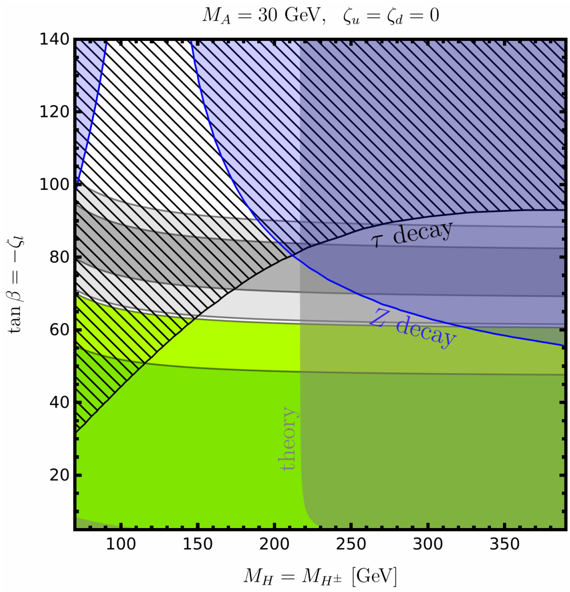


@ two-loop

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



2HDM: allowed and excluded regions

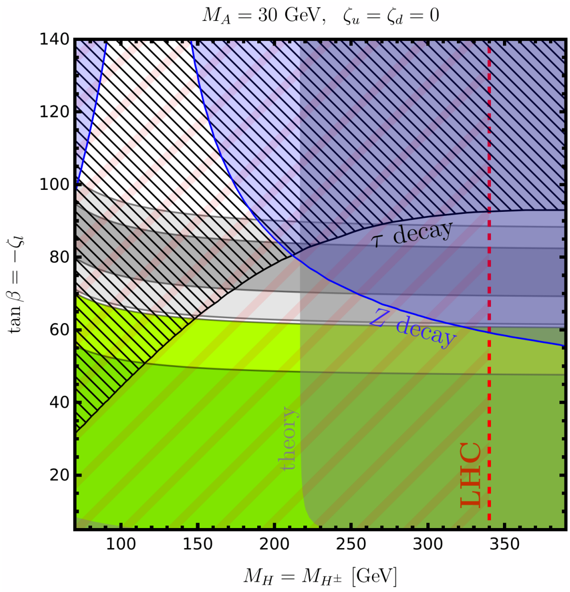


- **previously:** $\Delta a_\mu^{\text{WP20}}$

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

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

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



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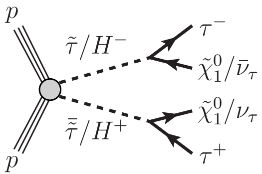

$\Longrightarrow$ $M_{H^\pm} \gtrsim 340$ GeV, $\quad (M_A \simeq M_{H^\pm})$

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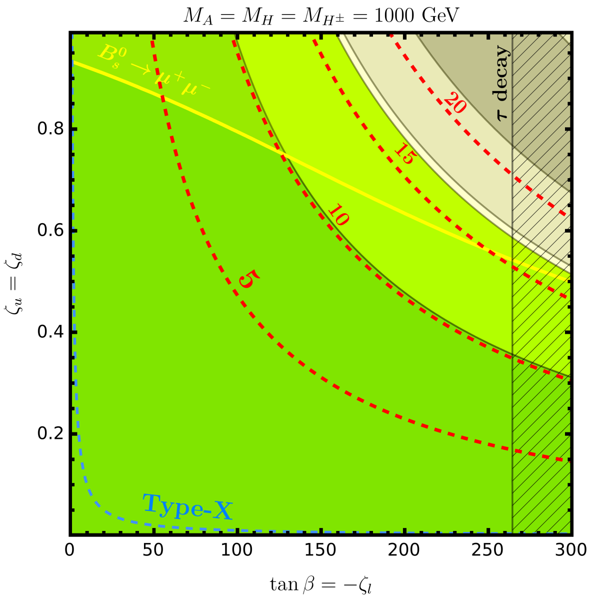

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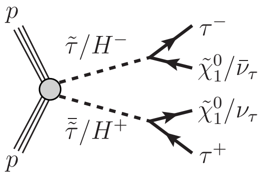

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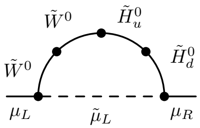
- **now:** complementary bounds from $\Delta a_\mu^{\text{WP25}}$

Supersymmetry

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

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



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

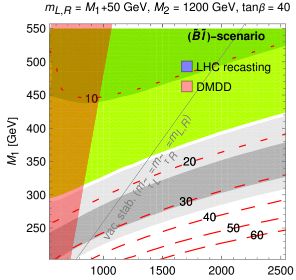
LHC bounds $\Longrightarrow$ either $M_{\text{SUSY}} \gtrsim$ TeV or small ΔM_{SUSY}

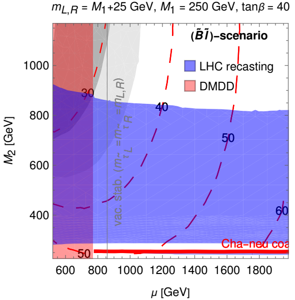
e.g. Higgsino DM

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

e.g. Bino DM

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





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new scalar/ vectors coupling to lepton + quark

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

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

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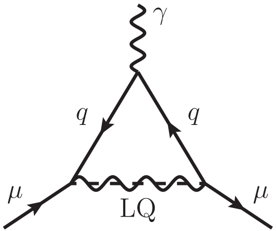

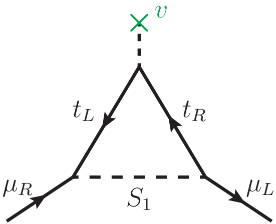

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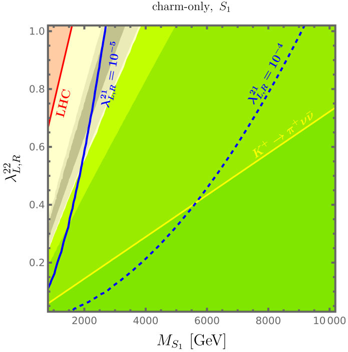

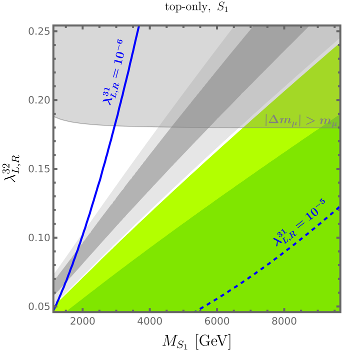

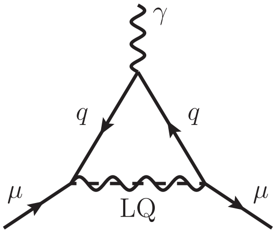

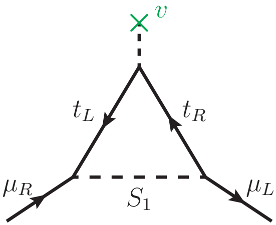

Vector-like leptons

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, ...

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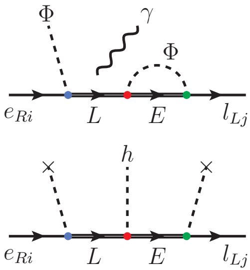

$\Rightarrow$ *chiral enhancement:* at least 2 VLL with Yukawa coupling

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

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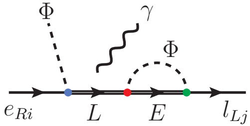

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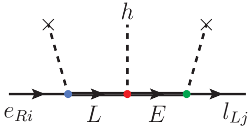

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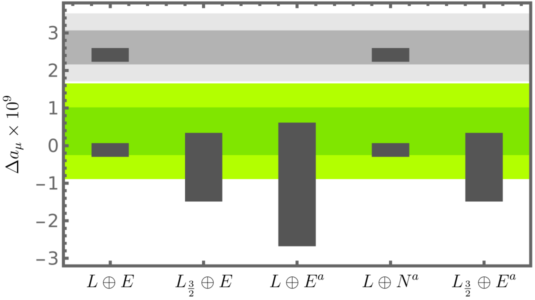

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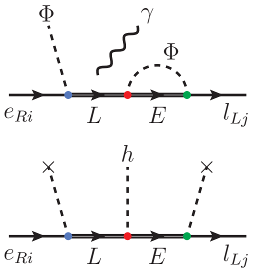

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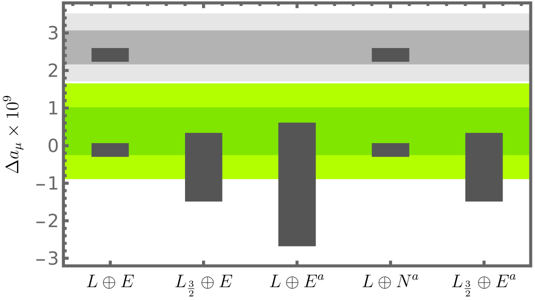

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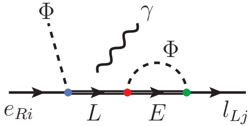

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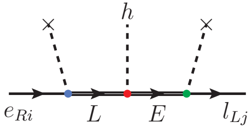

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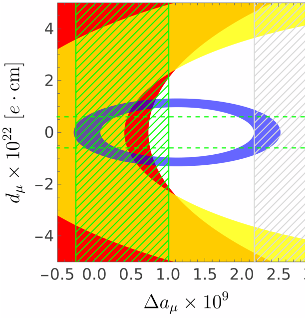

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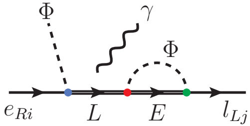

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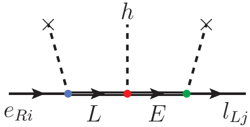
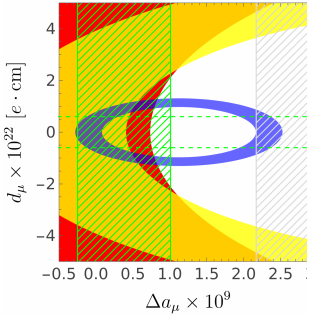


$$\mathcal{L} \supset -\left[\lambda_L \overline{\ell_L} E + \lambda_R \overline{L} \mu_R + \bar{\lambda} \overline{L} E\right] \Phi \quad \Longrightarrow \quad \boxed{\Delta a_\mu \propto \lambda_L \lambda_R \bar{\lambda}}$$

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

$$\left|\frac{y_\mu}{y_\mu^{\mathrm{SM}}}\right|^2 \approx \left(1 - \frac{\Delta a_\mu}{\mathcal{Q}\, 10^{-9}}\right)^2 + \left(\frac{d_\mu\, [e\,\mathrm{cm}]}{2\mathcal{Q} \times 10^{-22}}\right)^2$$



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

$\Longrightarrow$ Δa_μ complementary with future measurements of d_μ

Outline

1. Complementary observables
   - muon mass and chiral enhancement
   - Dipole observables
   - $H \to \mu\mu$
   - Neutrino masses and Dark matter
2. Specific BSM scenarios
   - 2HDM and Supersymmetry
   - Leptoquarks and Vector-like leptons
   - Light-dark sectors, HVP problem

Axion-like Particles

pseudo-scalar, shift-invariant (effective) couplings

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

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

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

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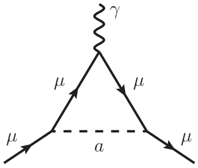
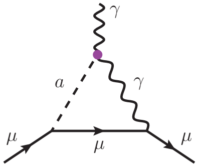
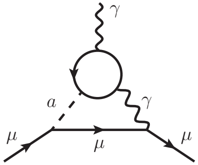
two competing contributions (similar to 2HDM):

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

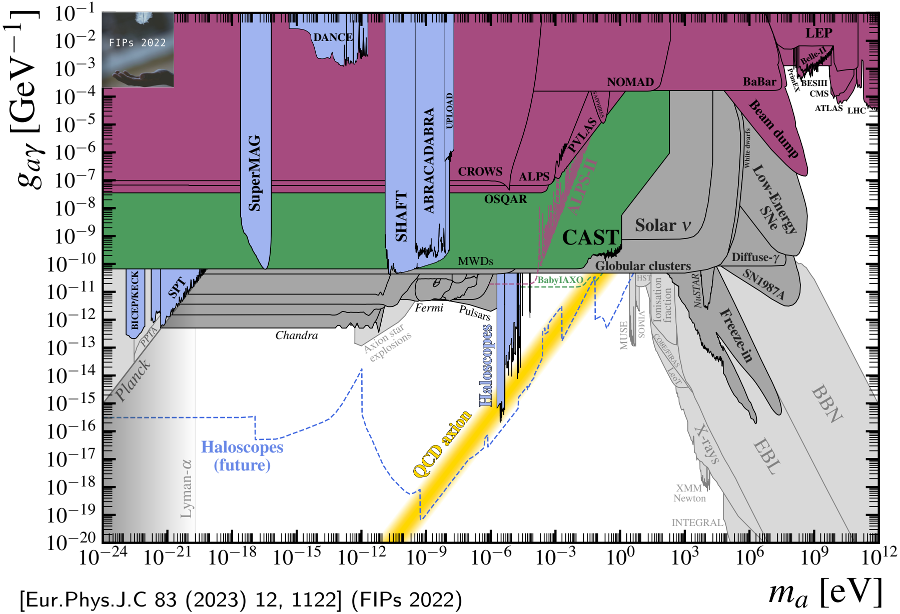
@ "two" – loop $\quad \Delta a_\mu \sim -\frac{c_{\mu\mu}c_{\gamma\gamma}^{\text{eff}}}{2\pi^2}\frac{\alpha}{4\pi}\frac{m_\mu^2}{f_a^2}$







Axion-like Particles: constraints



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

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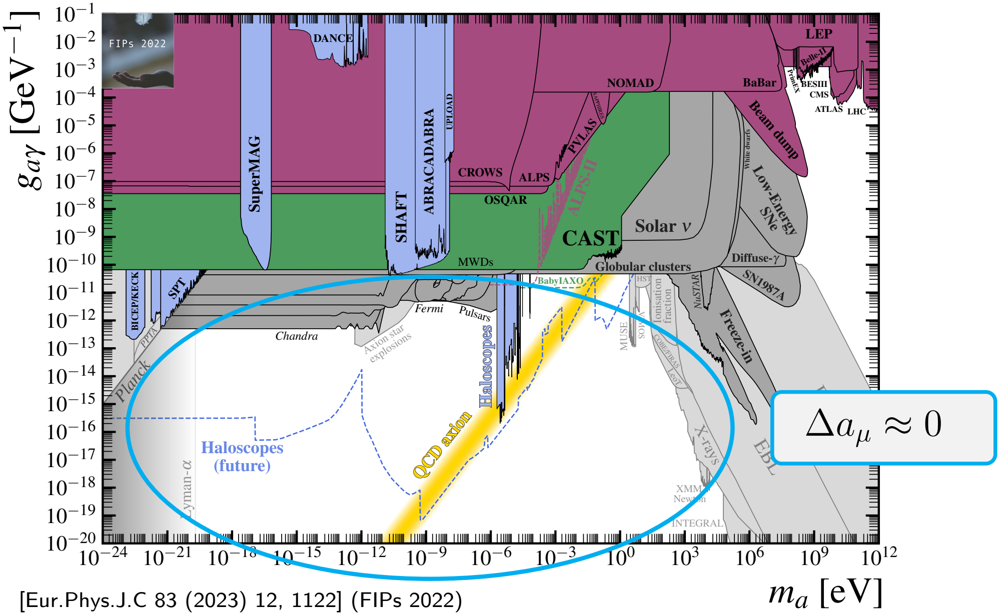

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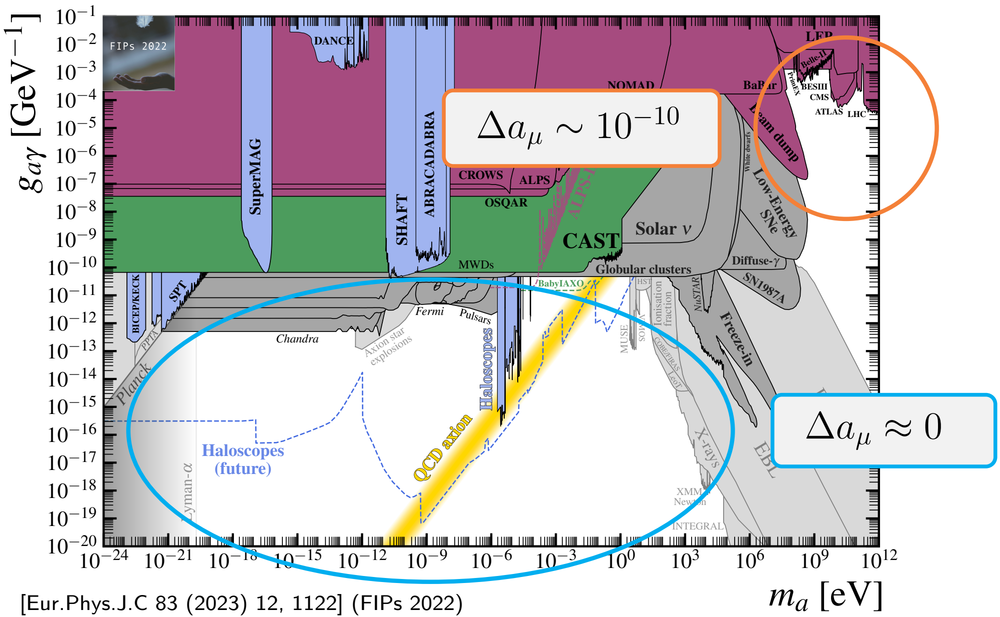

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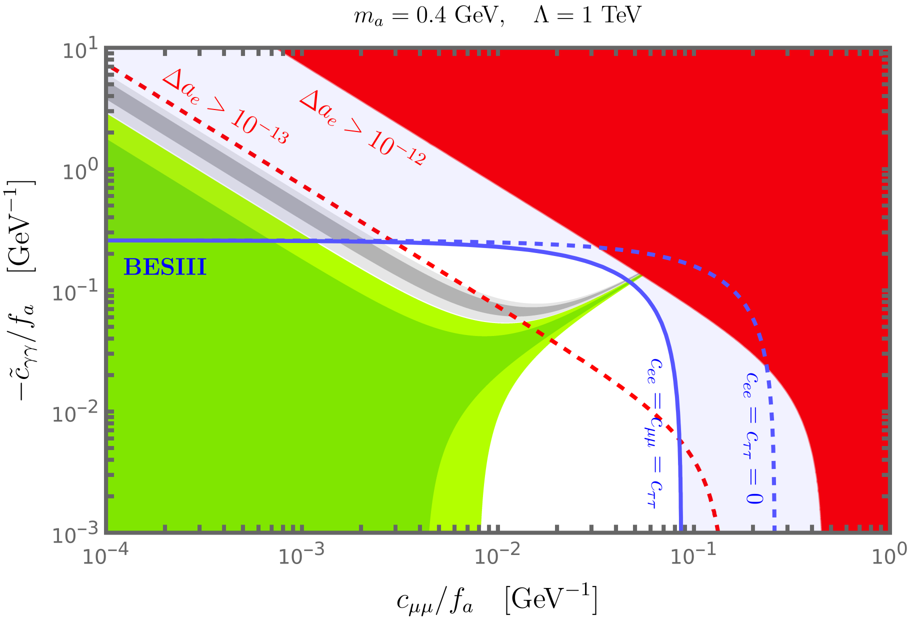

Dark Photon and Z'

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

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

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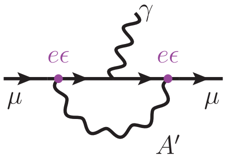
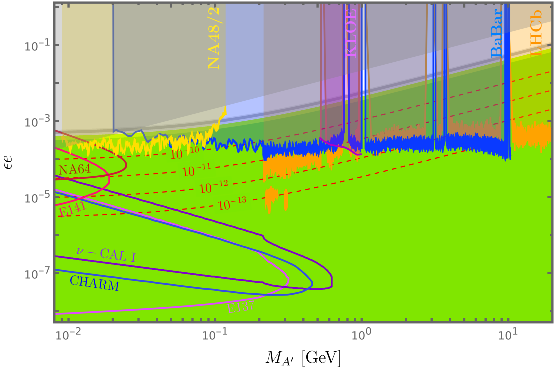


$\Rightarrow Z'$: kinetic mixing and gauge coupling to muon

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

1 $U(1)_{B-L, L_e - L_\mu}, \ldots \curvearrowright$ couplings to $e^\pm$:

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



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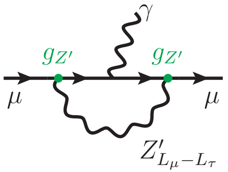

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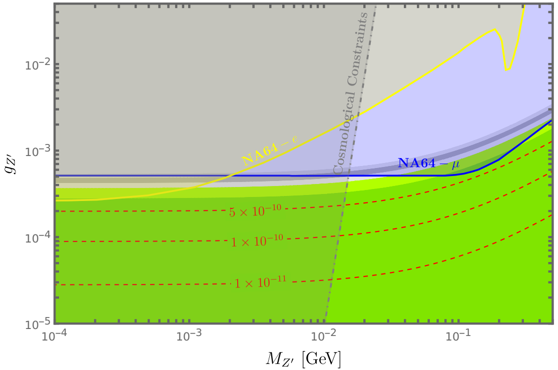
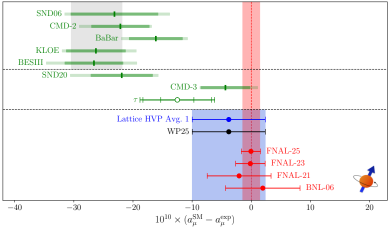
2 $U(1)_{\mu-\tau}$ with $M_{Z'} \sim \mathcal{O}(10\text{ MeV})$

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

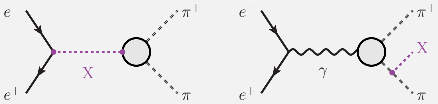


BSM solutions to the HVP problem?



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

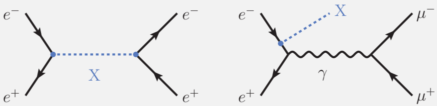
1 BSM effect in $e^+e^- \to$ had



$\Longrightarrow$ mostly excluded

[Di Luzio, Masiero, Paradisi, Passera '22; Coyle, Wagner '23]

2 BSM effect in luminosity



$\Longrightarrow$ 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 SM (but: Data vs Lattice, theory uncertainty)

- Models with **small** Δa_μ $\to$ again viable

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

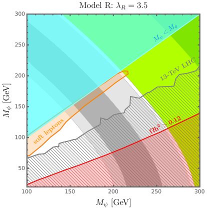
- Models with **large** Δa_μ $\to$ now constrained

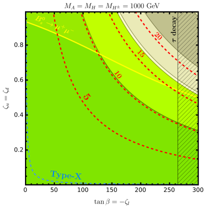
  e.g. vector-like leptons, lepto-quarks, ALPs, Z', ...

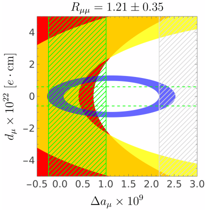
  $\hookrightarrow$ relevant if $\Delta a_\mu \sim \mathcal{O}(10^{-10})$ re-emerges

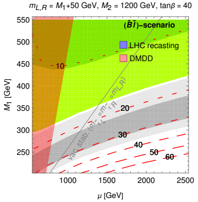
- Complementary observables

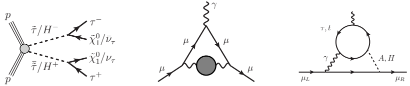
  strong correlations with: m_μ, $H \to \mu\mu$, $\mu \to e\gamma$, EDM











Outlook:

- improvements in computational methods, experiments, cosmological obs. $\to$ more complete picture of BSM
- Δa_μ will remain useful to understand BSM in the future

Backup

Details on BSM effect in HVP

- **energy scan**: SND, CMD-2, CMD-3 $\Longrightarrow$ $\sqrt{s} \sim 0.1 \ldots 1$ 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 Z' coupling to e and q: $\quad \Delta\sigma_{\pi\pi}^{\text{BSM}}(s) = \sigma_{\pi\pi}^{\text{SM}}(s) \dfrac{2s(s - M_{Z'}^2)\epsilon + s^2\epsilon^2}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}}, \qquad \epsilon = g_e(g_u - g_d)/e^2$

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

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

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

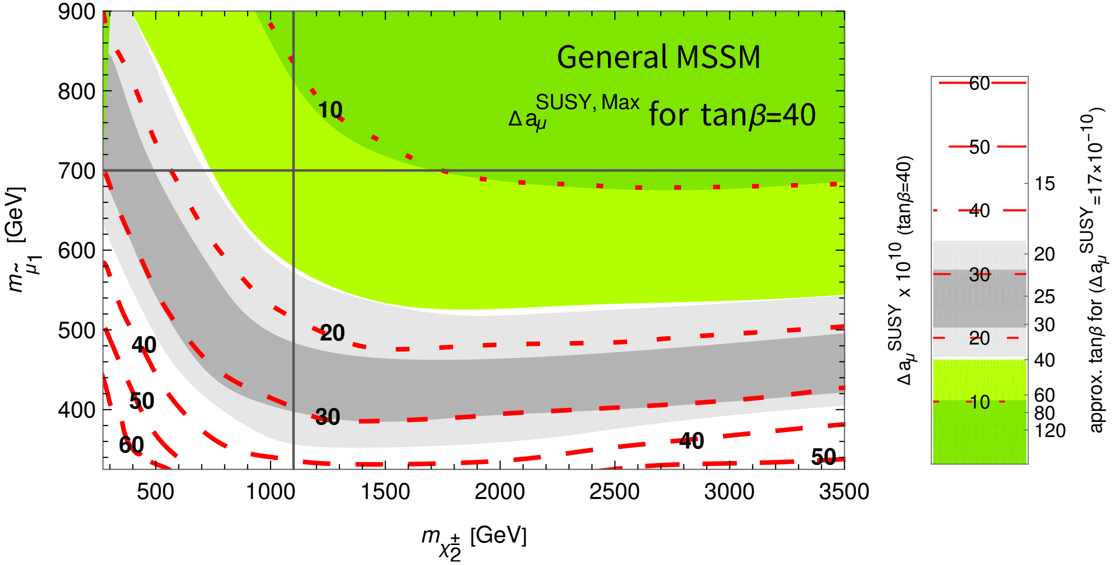
2 ISR measurements: $\quad \sigma_{\pi\pi} = \sigma_{\mu\mu} \times N_{\pi\pi\gamma_{\text{ISR}}} / N_{\mu\mu\gamma_{\text{ISR}}/X} \Longrightarrow \Delta\sigma_{\pi\pi} \approx \sigma_{\pi\pi} \frac{\sigma_{\mu\mu X}}{\sigma_{\mu\mu}} \frac{\epsilon^{\text{NP}}}{\epsilon^{\text{SM}}}$

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 (i.e. must be wrong for this to work.)

MSSM: maximum Δa_μ



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

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

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

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

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