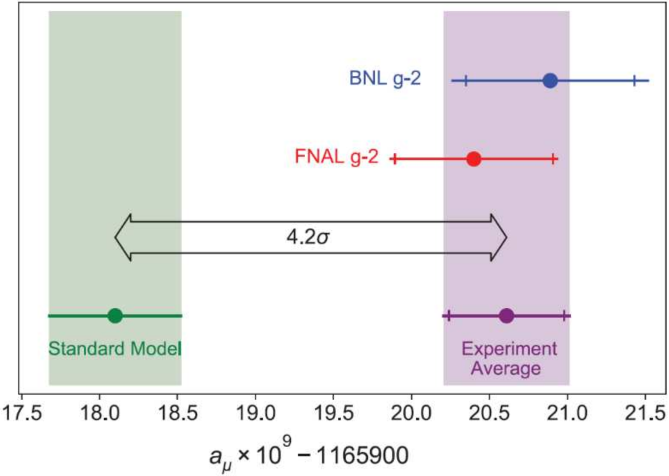
Muon $g-2$ theory: beyond the SM

Dominik Stöckinger, TU Dresden

Theory Initiative Workshop KEK (virtual), 28th June 2021

$(g_\mu - 2)/2 = a_\mu$ is among the most precise observables
sensitive to all known (and unknown?) interactions

Outline



Questions: Which models can(not) explain it?

- Here: general remarks and examples from survey 2104.03691

  [Peter Athron, Csaba Balasz, Douglas Jacob, Wojciech Kotlarski, DS, Hyejung Stöckinger-Kim]

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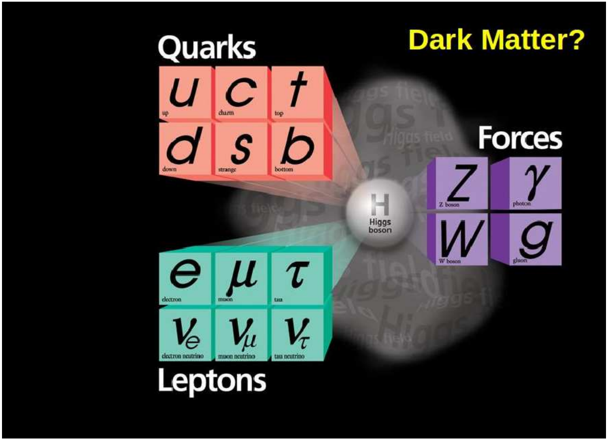
Open questions require Beyond the Standard Model (BSM) physics



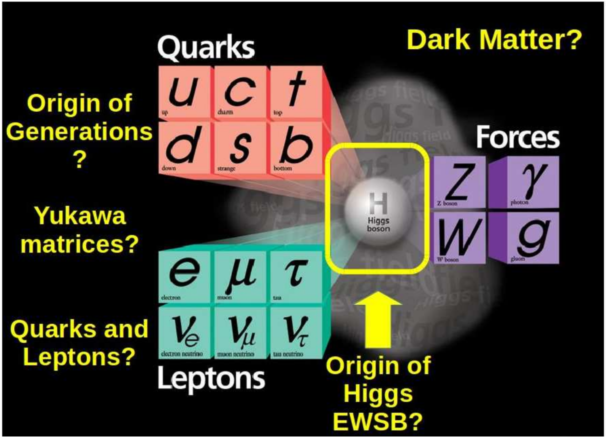
Open questions!

- experimental clues needed! $\rightsquigarrow g-2$!

  not easy to explain!

- relevant and deep questions may be related to $g-2$

Open questions require Beyond the Standard Model (BSM) physics



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Discrepancy

SM prediction too low by $\approx (25 \pm 6) \times 10^{-10}$

Two important general points

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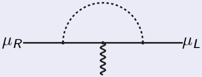
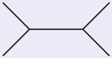
loop-induced, CP- and Flavor-conserving, chirality-flipping



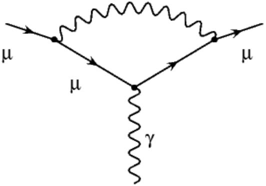
compare:



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

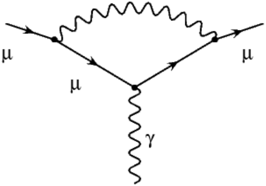
EWPO

Connection to chirality flip, and structure of BSM



$$\mathcal{L}_{\text{eff}} = -\frac{Qe}{4m_\mu} a_\mu \times \bar{\psi}_L \sigma_{\mu\nu} \psi_R F^{\mu\nu}$$

Connection to chirality flip, and structure of BSM



$$\mathcal{L}_{\text{eff}} = -\frac{Qe}{4m_\mu} a_\mu \times \bar{\psi}_L \sigma_{\mu\nu} \psi_R F^{\mu\nu}$$

In the SM QED and QCD: not crucial, trivial chirality flip via gauge invariant muon mass term appearing in propagator numerators

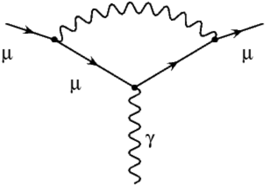
$$a_\mu^{\text{QED, } \tau\text{-loop}} = \frac{\alpha^2}{45\pi^2} \frac{m_\mu^2}{m_\tau^2} \qquad a_\mu^{\text{EFT-LbL (Knecht, Nyffeler, Perrotet, de Rafael)}} \sim \left(\frac{\alpha}{\pi}\right)^3 \frac{m_\mu^2}{F_\pi^2}$$

Even in the EW SM contributions, things don't change much, e.g.

$$a_\mu^{\text{W,Z-boson loops}} \sim \frac{\alpha}{4\pi} \frac{m_\mu^2}{M_{W,Z}^2} \approx 15 \times 10^{-10}$$

But the required chirality flip is key to understand BSM contributions!

Connection to chirality flip, and structure of BSM



$$\mathcal{L}_{\text{eff}} = -\frac{Qe}{4m_\mu} a_\mu \times \bar{\psi}_L \sigma_{\mu\nu} \psi_R F^{\mu\nu}$$

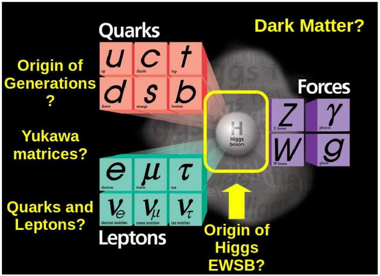
But:

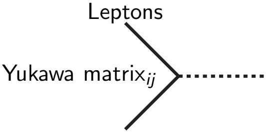
EW gauge invariant a_μ-operator: $\bar{L}\sigma_{\mu\nu}\mu_R F^{\mu\nu}\langle H\rangle$

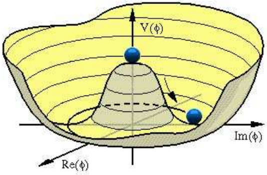
$$a_\mu \sim m_\mu \times \underbrace{(\text{some VEV}) \times (\mu_{L\leftrightarrow R}\text{-flipping param.})}_{\text{related to muon mass generation, potential enhancement!}} \times \frac{(\text{other couplings})}{M^2_{\text{typical}}}$$

$$m_\mu(\text{SM}) \sim (\text{SM Higgs-VEV}) \times (\text{muon Yukawa coupling})$$

Window to the muon mass generation mechanism (Higgs/Yukawa sectors)







(changed by new physics?)

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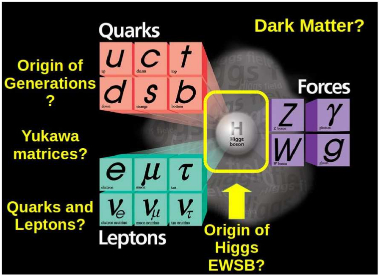
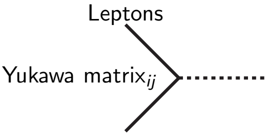
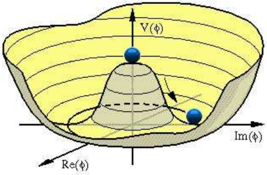






(changed by new physics?)

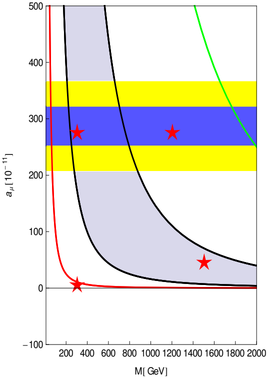
Second connection of a_μ: Dark Matter, (light?) dark sectors? Hard to see in detectors but could couple to muon $\rightsquigarrow$ large effects possible!

many concrete examples of both kinds of connections

Typical behaviour: $\sim$ chirality flip ($\rightsquigarrow$ Higgs!) and masses

$$a_\mu \sim \frac{m_\mu \times (\text{some VEV}) \times (\mu_{L\leftrightarrow R}\text{-flipping parameter})}{M^2_{\text{typical}}} \left[\lesssim \frac{m_\mu^2}{M^2_{\text{typical}}} \text{ (no finetuning)} \right]$$

$$\Delta m_\mu \sim (\text{some VEV}) \times (\mu_{L\leftrightarrow R}\text{-flipping parameter})$$



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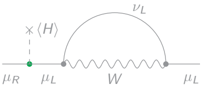
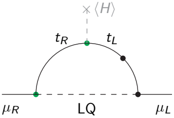
- EWSM: $\alpha \frac{m^2_\mu}{M^2_W}$

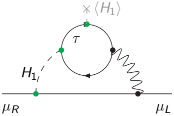
  Similar in Z', Dark Z_d models

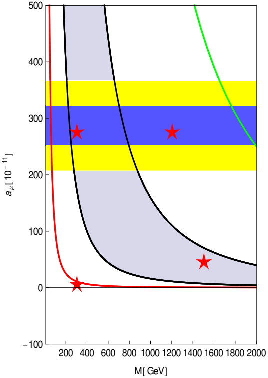


- LQ: $g_L g_R \frac{m_\mu m_t}{M^2_{\text{LQ}}}$



- 2HDM: $\alpha^2 \tan^2 \beta \frac{m^2_\mu}{M^2_H}$





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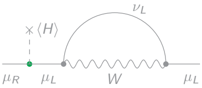

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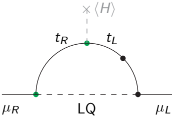
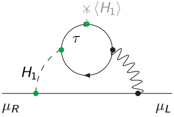


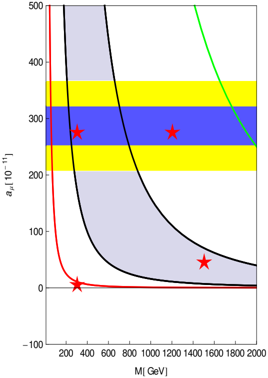
Can also involve Higgs couplings to b, c or new particles.

Beware: $\Delta m_\mu / m_\mu \sim g_L g_R m_t / m_\mu$ restricts couplings

- 2HDM: $\alpha^2 \tan^2 \beta \frac{m_\mu^2}{M_H^2}$



Well motivated; many variants; many constraints



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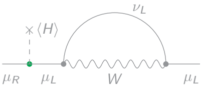
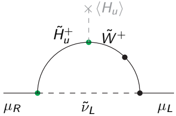
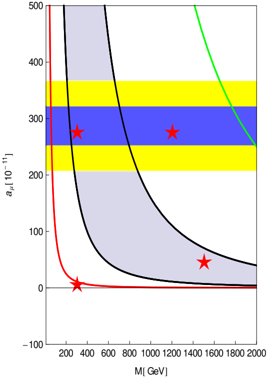
- EWSM: $\quad \propto \frac{m_\mu^2}{M_W^2}$



- SUSY: $\quad \propto \frac{m_\mu^2 \tan\beta}{M^2_{\text{SUSY}}} \frac{\mu}{M_{\text{SUSY}}}$



- rad. $m_\mu \quad \sim \frac{m_\mu^2}{M^2_{\text{NP}}}$



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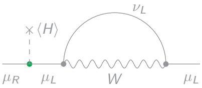
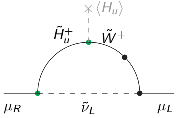


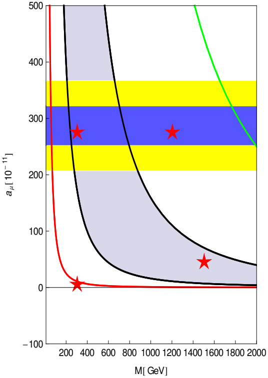


- SUSY: $\quad \alpha \dfrac{m_\mu^2 \tan\beta}{M^2_{\text{SUSY}}} \dfrac{\mu}{M_{\text{SUSY}}}$

  Well-motivated theory. Many other advantages

- rad. $m_\mu \quad \sim \dfrac{m_\mu^2}{M^2_{\text{NP}}}$

  E.g. MSSM for $\tan\beta \to \infty$ [Bach,Park,DS,Stöckinger-Kim'15]

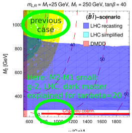


Outline

There are many more examples. . .

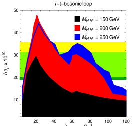
SUSY: MSSM, MRSSM

- MSugra. . . many other generic scenarios
- Bino-dark matter+some coannihil.+mass splittings
- Wino-LSP+specific mass patterns



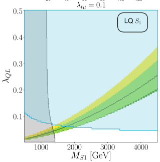
Two-Higgs doublet model

- Type I, II, Y, Type X(lepton-specific), flavour-aligned



Lepto-quarks, vector-like leptons

- scenarios with muon-specific couplings to μ_L and μ_R



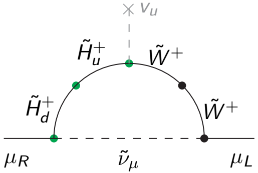
Simple models (one or two new fields)

- Mostly excluded
- light N.P. (ALPs, Dark Photon, Light $L_\mu - L_\tau$)

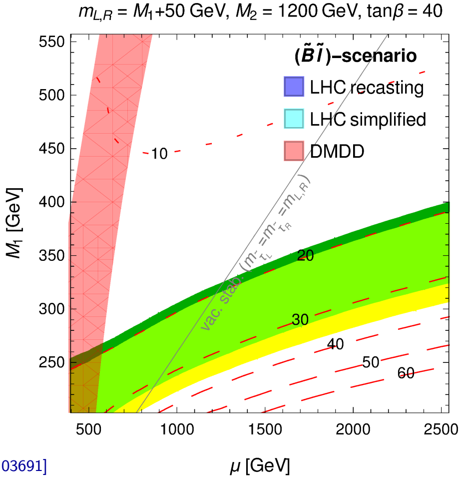
Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result
1	0	$(\mathbf{1},\mathbf{1},1)$	Ruled out: $\Delta a_\mu < 0$
2	0	$(\mathbf{1},\mathbf{1},2)$	Ruled out: $\Delta a_\mu < 0$
3	0	$(\mathbf{1},\mathbf{2},-\frac{1}{2})$	Special cases viable
4	0	$(\mathbf{1},\mathbf{3},-1)$	Ruled out: $\Delta a_\mu < 0$
5	0	$(\mathbf{3},\mathbf{1},1/3)$	Updated Sec. 3.2.
6	0	$(\bar{\mathbf{3}},\mathbf{1},4/3)$	Ruled out: $\Delta a_\mu < 0$
7	0	$(\bar{\mathbf{3}},\mathbf{3},1/3)$	Ruled out: $\Delta a_\mu < 0$
8	0	$(\mathbf{3},\mathbf{2},7/6)$	Updated Sec. 3.2.
9	0	$(\mathbf{3},\mathbf{2},2/3)$	Ruled out: $\Delta a_\mu < 0$
10	1/2	$(\mathbf{1},\mathbf{1},0)$	Ruled out: $\Delta a_\mu < 0$
11	1/2	$(\mathbf{1},\mathbf{1},-1)$	Ruled out: $\Delta a_\mu < 0$ or too small (disputed)
12	1/2	$(\mathbf{1},\mathbf{2},-\frac{1}{2})$	Ruled out: $\Delta a_\mu < 0$ or too small (disputed)
13	1/2	$(\mathbf{1},\mathbf{2},-\frac{3}{2})$	Ruled out: $\Delta a_\mu < 0$
14	1/2	$(\mathbf{1},\mathbf{3},0)$	Ruled out: $\Delta a_\mu < 0$
15	1/2	$(\mathbf{1},\mathbf{3},-1)$	Ruled out: $\Delta a_\mu < 0$
16	1	$(\mathbf{1},\mathbf{1},0)$	Special cases viable
17	1	$(\mathbf{1},\mathbf{2},-3/2)$	Ruled out: UV compl. $M_{Z'}$ limit

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

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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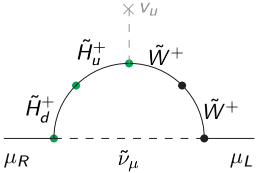

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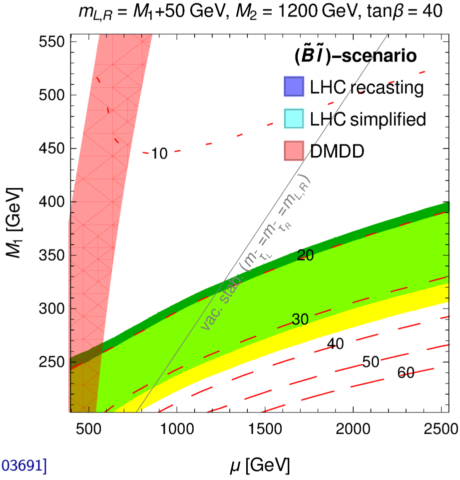
- "Dark matter mass" versus μ
- explains $g-2$ in large region (expands for $\tan\beta \neq 40$)
- DM explained by stau/slepton-coannihilation



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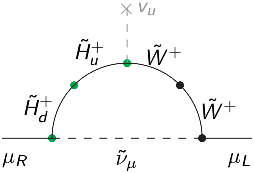

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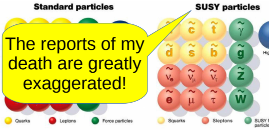
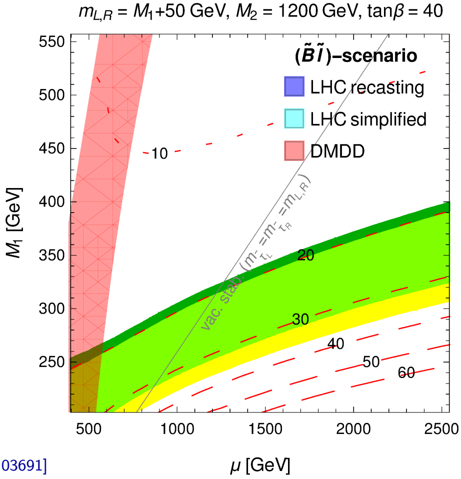
- "Dark matter mass" versus μ
- explains $g-2$ in large region (expands for $\tan\beta \neq 40$)
- DM explained by stau/slepton-coannihilation
- this automatically evades (current) LHC limits





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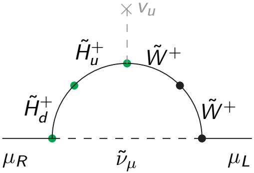

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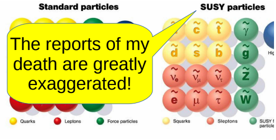
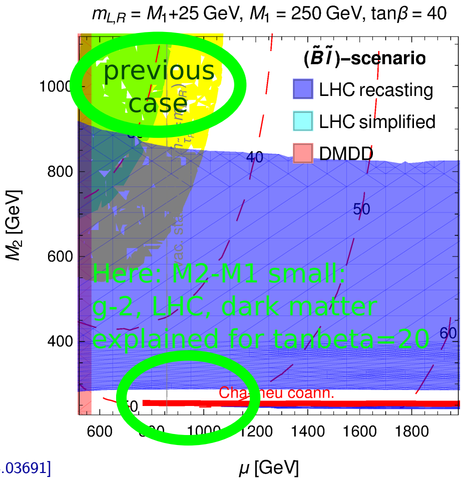
- Strong LHC limits on M_2
- DM also explained by Wino-coannihilation
- again evades (current) LHC limits





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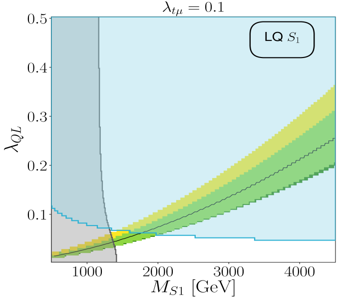
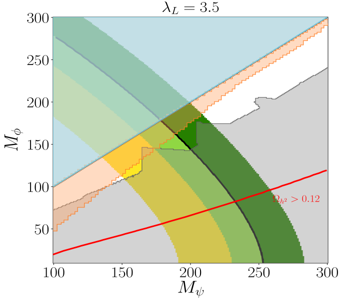
Leptoquarks: promising; 2-field models: less





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

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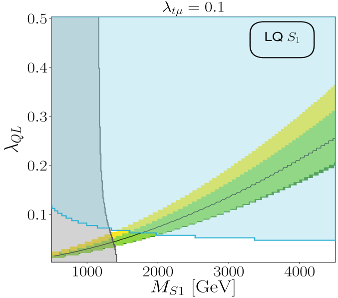
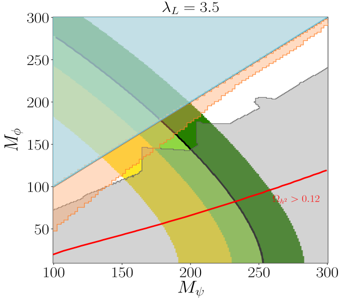
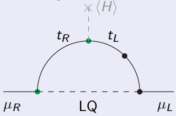




[Athron,Balazs,Jacob,Kotlarski,DS,Stöckinger-Kim, 2104.03691]

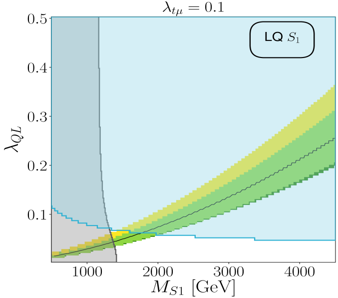
a_μ from LQ (or VLL) $\mathcal{L}_{S_1} = -\left(\lambda_{QL} Q_3 \cdot L_2 S_1 + \lambda_{t\mu} t \mu S_1^*\right)$

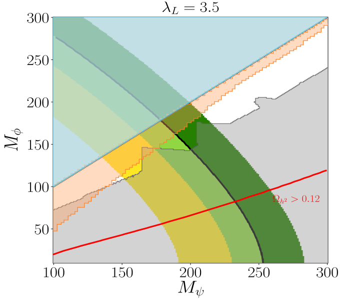
Specific LQ that works:



- Chiral enhancement $\sim y_{\text{top}}, y_{\text{VLL}}$ versus y_μ
- LHC: lower mass limits
- Flavour constraints $\rightsquigarrow$
  assume only couplings to muons
- Viable window above LHC (without m_μ-finetuning)

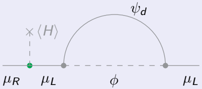
Leptoquarks: promising; 2-field models: less





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

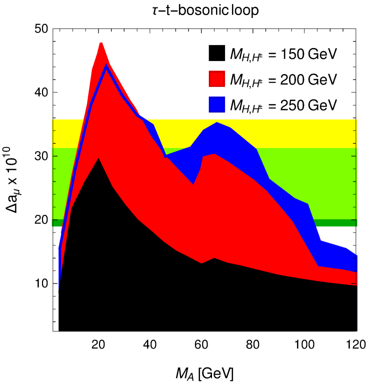
a_μ from 2-field model L



- No chiral enhancement, need very large couplings
- LHC: lower mass limits
- Dark matter candidate, but
  incompatible with large a_μ
  General result: a_μ and DM require at least three new fields! see also: [Arcadi,Calibbi,Fedele,Mescia] on B-physics

Two-Higgs doublet model: promising in specific versions

- Aligned 2-Higgs doublet model, rich new Higgs/Yukawa sectors



[2104.03691]

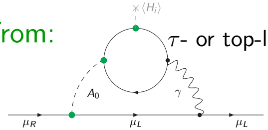
Details on Yukawa couplings:

Type X/lepton-specific: $Y_\ell \propto \tan\beta$ Type II: $Y_{\ell,d} \propto \tan\beta$ Aligned: $Y_\ell \propto \zeta_\ell$

Two-Higgs doublet model: promising in specific versions

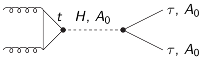
- Aligned 2-Higgs doublet model, rich new Higgs/Yukawa sectors

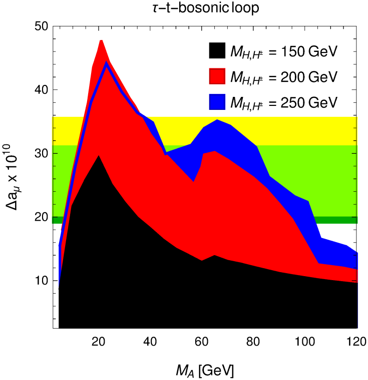
a_μ from:



τ- or top-loop

constraints (LHC, B-, τ-physics):





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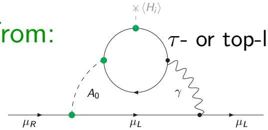
Two-Higgs doublet model: promising in specific versions

- Aligned 2-Higgs doublet model, rich new Higgs/Yukawa sectors

a_μ from:



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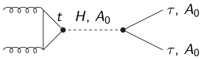
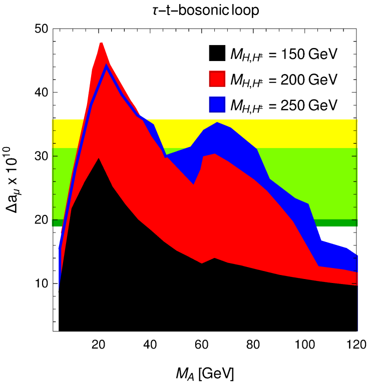




[2104.03691]

- can explain $g-2$
- need large new Yukawa couplings
- under pressure, testable at LHC, lepton colliders, B-physics

Light/dark sectors — compatible with large a_μ?

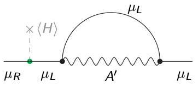
Very light, weakly interacting new particles

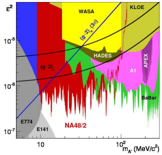
Light/dark sectors — compatible with large a_μ?

Very light, weakly interacting new particles

- "dark photon" NO

$$\mathcal{L} = -\frac{\epsilon}{2\cos\theta_W} F^{\mu\nu} B_{\mu\nu} \qquad a_\mu \sim \frac{\alpha}{2\pi}\epsilon^2$$





[NA48: 1504.00607]
excludes minimal dark photon for a_μ

- "dark Z_d" Better

$$a_\mu \sim \frac{\alpha}{2\pi}(\epsilon + \sim \delta' m_{Z_d}/m_Z)^2$$

Additional mass mixing δ, may assume invisible decays into dark sector, can evade limits (still nontrivial)

Davoudiasl,Lee,Marciano. . . Cadeddu,Cargioli,Dordei,Giunti,Picciau

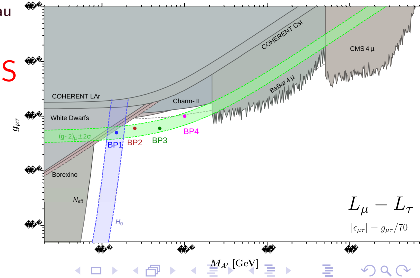
- Z' with quantum number $L_\mu - L_\tau$ YES

[Ma,Roy,Roy'01,Heeck,Rodejohann'11. . .]
(plot from [Amaral,Cerdeno,Cheek,Foldenauer'21])

Evades collider constraints,

subject to low-E constraints,

viable window 10 . . . 100 MeV

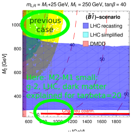


Outline

There are many more examples. . .

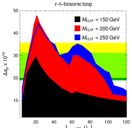
SUSY: MSSM, MRSSM

- MSugra. . . many other generic scenarios
- Bino-dark matter+some coannihil.+mass splittings
- Wino-LSP+specific mass patterns



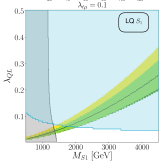
Two-Higgs doublet model

- Type I, II, Y, Type X(lepton-specific), flavour-aligned



Lepto-quarks, vector-like leptons

- scenarios with muon-specific couplings to μ_L and μ_R



Simple models (one or two new fields)

- Mostly excluded
- light N.P. (ALPs, Dark Photon, Light $L_\mu - L_\tau$)

Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result
1	0	$(\mathbf{1}, \mathbf{1}, 1)$	Ruled out: $\Delta a_\mu < 0$
2	0	$(\mathbf{1}, \mathbf{1}, 2)$	Ruled out: $\Delta a_\mu < 0$
3	0	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	Special cases viable
4	0	$(\mathbf{1}, \mathbf{3}, -1)$	Ruled out: $\Delta a_\mu < 0$
5	0	$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	Updated Sec. 3.2.
6	0	$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	Ruled out: $\Delta a_\mu < 0$
7	0	$(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	Ruled out: $\Delta a_\mu < 0$
8	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	Updated Sec. 3.2.
9	0	$(\mathbf{3}, \mathbf{2}, 2/3)$	Ruled out: $\Delta a_\mu < 0$
10	1/2	$(\mathbf{1}, \mathbf{1}, 0)$	Ruled out: $\Delta a_\mu < 0$
11	1/2	$(\mathbf{1}, \mathbf{1}, -1)$	Ruled out: $\Delta a_\mu < 0$ or too small (disputed)
12	1/2	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	Ruled out: $\Delta a_\mu < 0$ or too small (disputed)
13	1/2	$(\mathbf{1}, \mathbf{2}, -\frac{3}{2})$	Ruled out: $\Delta a_\mu < 0$
14	1/2	$(\mathbf{1}, \mathbf{3}, 0)$	Ruled out: $\Delta a_\mu < 0$
15	1/2	$(\mathbf{1}, \mathbf{3}, -1)$	Ruled out: $\Delta a_\mu < 0$
16	1	$(\mathbf{1}, \mathbf{1}, 0)$	Special cases viable
17	1	$(\mathbf{1}, \mathbf{2}, -3/2)$	Ruled out: UV compl. $M_{Z'}$ limit

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

Summary of main points

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

a_μ is loop-induced, CP- and flavor-conserving and chirality-flipping

rather light, neutral (?) particles ⇝ Connection to dark matter?

Chirality flip enhancement ⇝ Window to muon mass generation? EWSB/generations?

Which models can still accommodate large deviation?

Many (but not all) models!

but always: experimental constraints!

Outlook:

- $g-2$ + LHC, DM ⇝ constraints on BSM physics, great potential for future
- often chirality flips/new flavor structures/light particles ⇝ tests: Higgs couplings, B-physics, CLFV, EDM, light-particle searches, e^+e^-/muon collider

20 years after BNL. . . deviation confirmed . . . very promising future!

Dark matter and LHC constraints (rules of thumb)

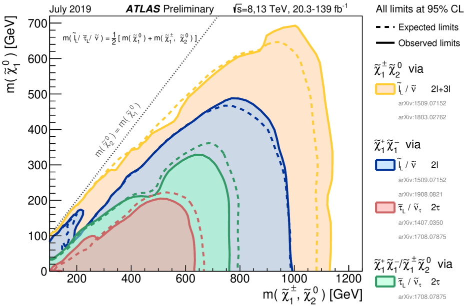
Dark matter (Wimps):

- Need to obtain $\Omega_{\text{DM}} = \Omega_{\text{obs}}$ or at least $\Omega_{\text{DM}} < \Omega_{\text{obs}}$, requires specific annihilation cross sections
- for Binos often too high, for scalars often too low
- Higgsinos or general fermion doublets: need masses around 1 TeV
- DM direct detection: limits on interactions with quarks: sometimes correlated with annihilation interactions

LHC:

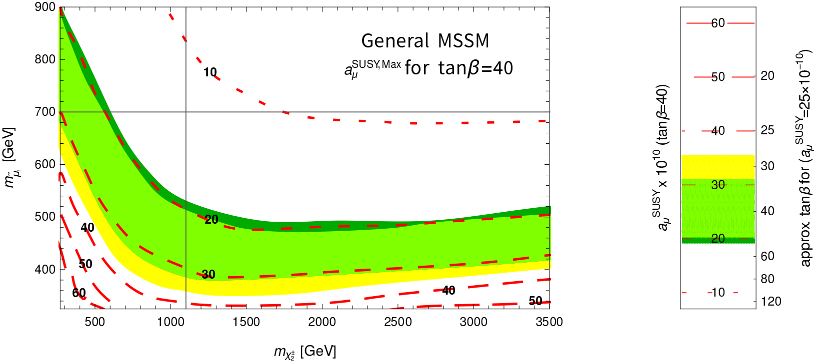
- "triangular limits", depending on assumptions/decay modes
- either Cha>1100, smuons>700 GeV
- or somewhat small mass splittings $\lesssim 100$ to LSP
- or more complicated decay modes
-

  E.g.: limits on Higgsinos are weak, limits on Winos weaker if sleptons>Winos



Full MSSM overview in 7 plots

[Peter Athron, Csaba Balasz, Douglas Jacob, Wojciech Kotlarski, DS, Hyejung Stöckinger-Kim, 2104.03691]



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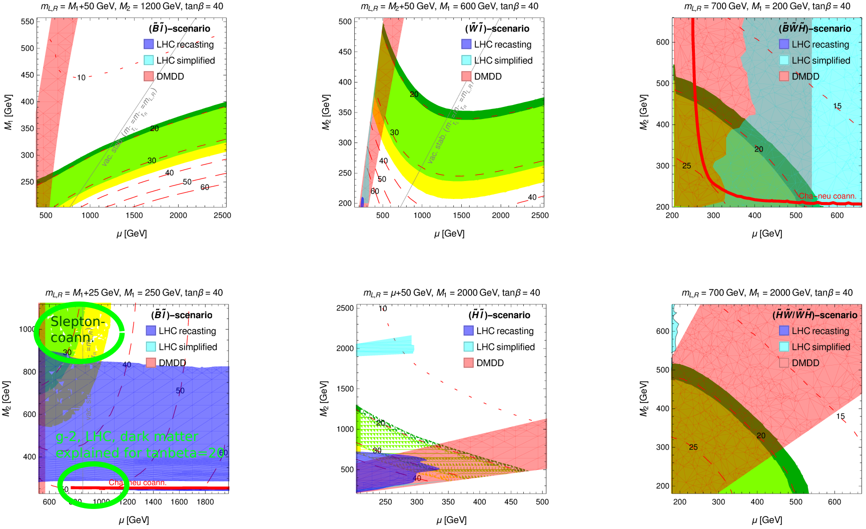
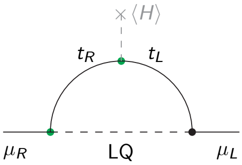
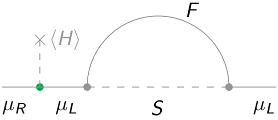


Summary: Bino-LSP: a_μ and DM. Wino-/Higgsino-LSP: a_μ. Both cha$<$slepton: ≈disfavoured.

DM+LHC⇒mass patterns! Coannihilation regions help! Specific cases excluded, e.g. Constrained MSSM

One-field, two-field models (renormalizable, spin $0, 1/2$)





- many models: excluded
- very special models: chiral enhancement specific leptoquarks, specific 2HDM versions
- however, no dark matter

Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result
1	0	$(\mathbf{1},\mathbf{1},1)$	Ruled out: $\Delta a_\mu < 0$
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5	0	$(\mathbf{3},\mathbf{1},1/3)$	Updated Sec. 3.2.
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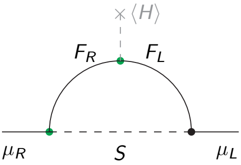
- even more models: excluded
- no chirality flip
- few models: either a_μ^{BNL} or dark matter

$(\mathbf{1},\mathbf{1},0)_0-(\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Projected LHC 14 TeV exclusion, not confirmed
	Yes	Updated Sec. 4.2
$(\mathbf{1},\mathbf{1},-1)_0-(\mathbf{1},\mathbf{1},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_0-(\mathbf{1},\mathbf{1},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{1},0)_0-(\mathbf{1},\mathbf{2},-1/2)_{1/2}$	No	Excluded: LHC searches
	Yes	Updated Sec. 4.2
$(\mathbf{1},\mathbf{1},0)_0-(\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LEP contact interactions
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{1},-1)_0-(\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_0-(\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: LEP search
$(\mathbf{1},\mathbf{1},0)_0-(\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LHC searches
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{1},0)_0-(\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LHC searches + LEP contact interactions
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{3},0)_0-(\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{1},0)_0-(\mathbf{1},\mathbf{1},-1)_{1/2}$	No	Excluded: LHC searches
	Yes	Viable with under abundant DM
$(\mathbf{1},\mathbf{3},-1)_0-(\mathbf{1},\mathbf{2},-1/2)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{3},-1)_0-(\mathbf{1},\mathbf{3},0)_{1/2}$	Both	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{1},-1)_{1/2}-(\mathbf{1},\mathbf{1},0)_1$	No	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_{1/2}-(\mathbf{1},\mathbf{1},0)_1$	No	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_{1/2}-(\mathbf{1},\mathbf{3},0)_1$	No	Excluded: LHC searches + LEP contact interactions
$(\mathbf{1},\mathbf{1},0)_{1/2}-(\mathbf{1},\mathbf{1},1)_1$	No	Excluded: LHC searches + LEP contact interactions
$(\mathbf{1},\mathbf{2},-1/2)_{1/2}-(\mathbf{1},\mathbf{1},-1)_1$	No	Excluded: LHC searches + LEP contact interactions

Three-field models



- many models: viable, large chirality enhancements
- can explain a_μ^{BNL} and LHC and dark matter