Muon $g-2$ theory: beyond the SM

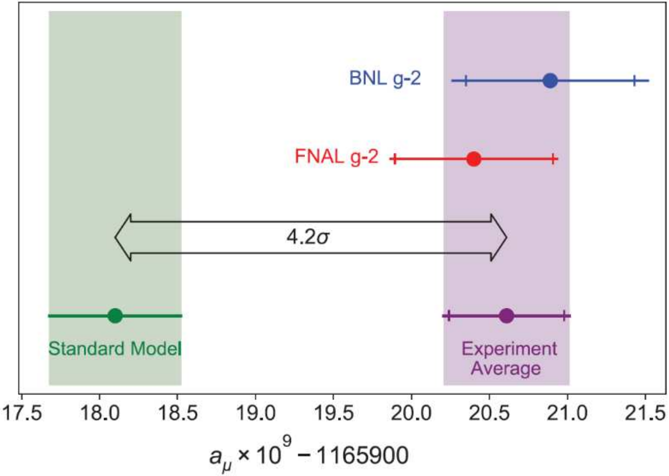
Dominik Stöckinger, TU Dresden

Paris GDR/IJCLab Virtual g-2 breakfast, 19th May 2021

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

Outline

Finally: Fermilab Run 1 versus Theory Initiative SM value



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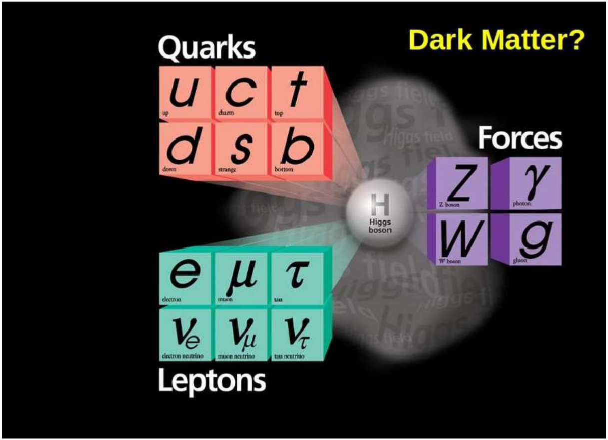
Open questions require Beyond the Standard Model (BSM) physics



Open questions!

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

  not easy to explain!

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

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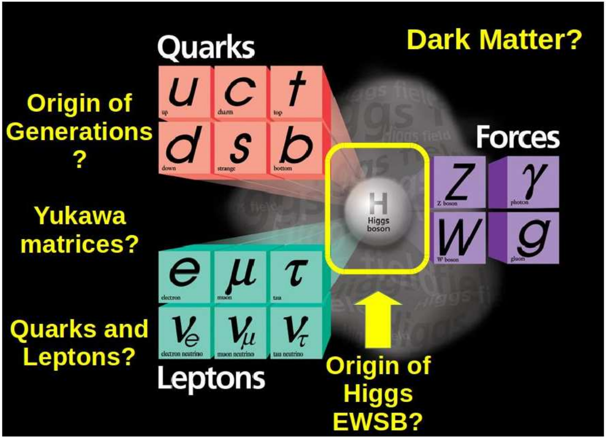

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Discrepancy

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

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Questions: Which models can(not) explain it?

Why is a single number so interesting?

"Why are you happy about a discrepancy?"

- Very active area (> 70 papers)
- Here: general remarks and examples from survey 2104.03691

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

Two important general points

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

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

Two important general points

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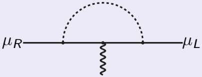
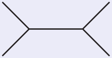
loop-induced, CP- and Flavor-conserving, chirality-flipping



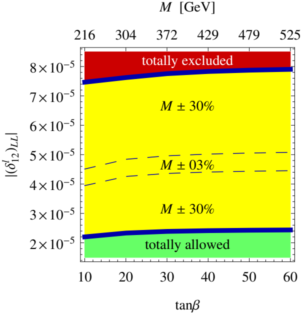
compare:

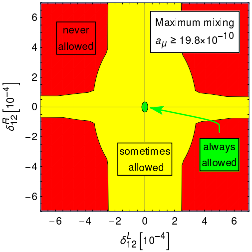


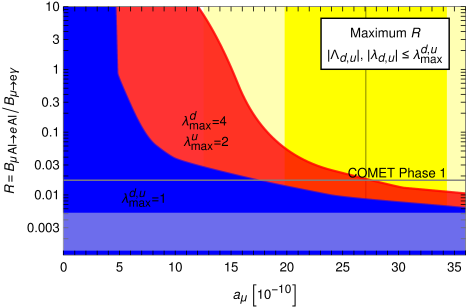
EDMs, $b \to s\gamma$, $B \to \tau\nu$, $\mu \to e\gamma$

EWPO

Connection to CP and flavor (example)





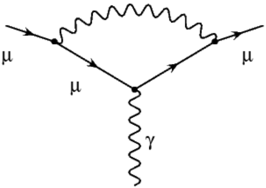


- given $g-2$, derive upper limits on LFV parameters from $\mu \to e\gamma$

  MSSM:
  [Kersten,Park,DS,Velasco-Sevilla '14]
  MRSSM:
  [Kotlarski,DS,Stöckinger-Kim'19]

- MRSSM: large $g-2$ enforces special parameter space with restricted $\mu \to e/\mu \to e\gamma$

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: $\bar{L}\sigma_{\mu\nu}\mu_R F^{\mu\nu}\langle H\rangle$

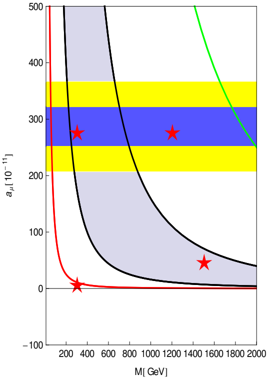
$$a_\mu \sim m_\mu \times \underbrace{(\text{some VEV}) \times (\mu_{L\leftrightarrow R}\text{-flipping param.})}_{\text{related to muon mass generation, potential enhancement!}} \times \frac{(\text{other couplings})}{M^2_{\text{typical}}}$$

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

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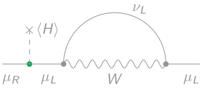
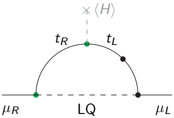
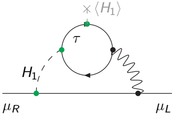
- EWSM: $\alpha \frac{m_\mu^2}{M_W^2}$

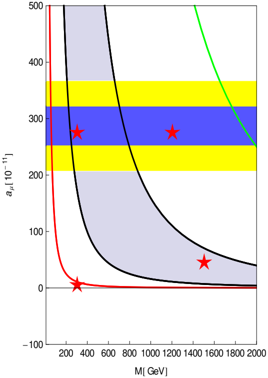


- LQ: $g_L g_R \frac{m_\mu m_t}{M^2_{\text{LQ}}}$



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





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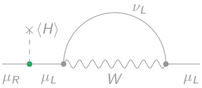

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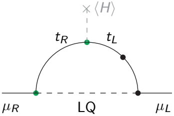
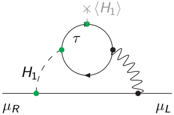


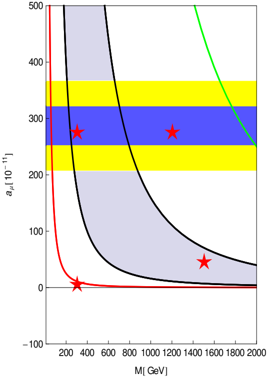
Can also involve Higgs couplings to b, c or new particles.

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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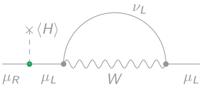
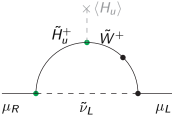
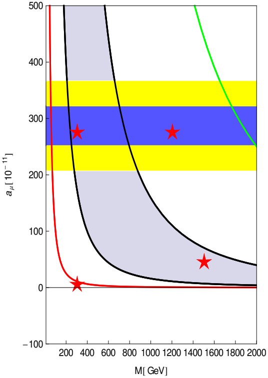


- SUSY: $\quad \alpha \frac{m_\mu^2 \tan\beta}{M^2_{\text{SUSY}}} \frac{\mu}{M_{\text{SUSY}}}$



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



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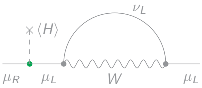
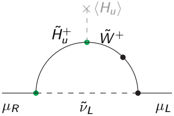


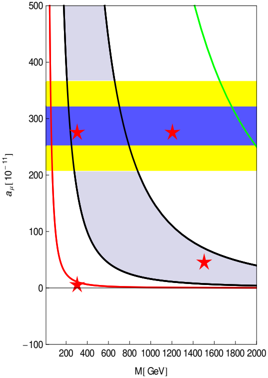
- SUSY: $\propto \frac{m_\mu^2 \tan\beta}{M^2_{\text{SUSY}}} \frac{\mu}{M_{\text{SUSY}}}$

  Well-motivated theory. Many other advantages



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

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

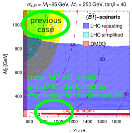


Outline

There are many more examples. . .

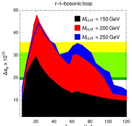
SUSY: MSSM, MRSSM

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



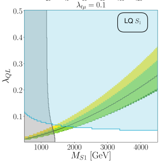
Two-Higgs doublet model

- 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]

Example BSM idea

- fundamental new QFT symmetry
- predicts Higgs potential/mass
- dark matter candidate
- chirality flip enhancement $\rightsquigarrow g-2$
- viable (LHC)?

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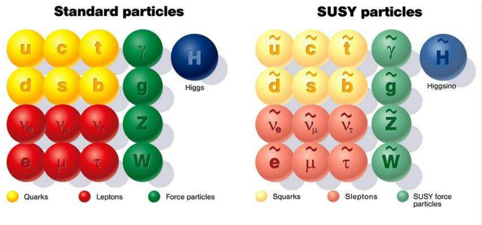
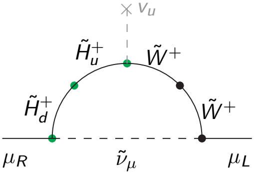


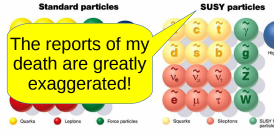
Superpartners and SUSY Higgs sector $\rightsquigarrow \tan\beta = \frac{v_u}{v_d}$, Higgsino mass μ

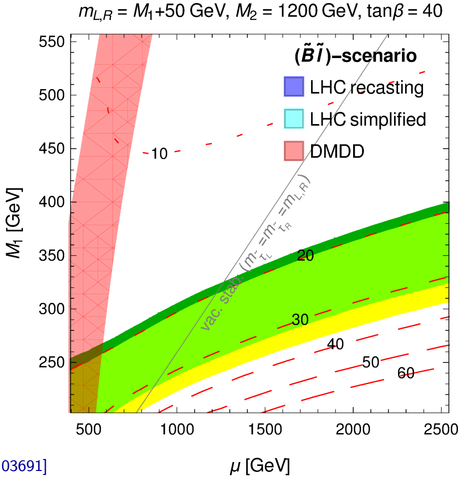
MSSM can explain $g-2$ and dark matter



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

- "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





[2104.03691]

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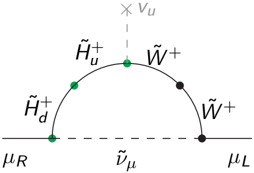

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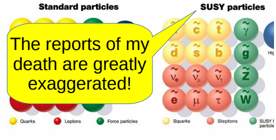
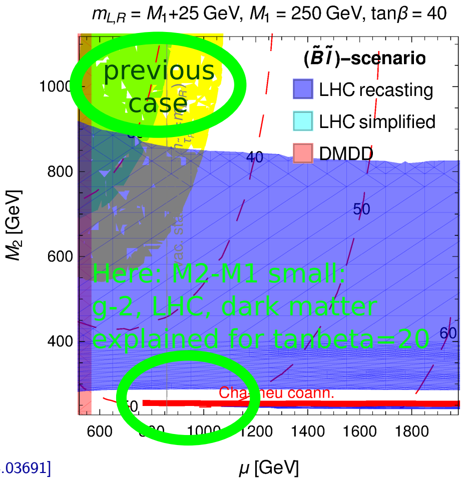
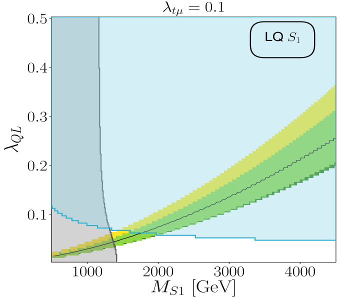
- Strong LHC limits on M_2
- DM also explained by Wino-coannihilation
- again evades (current) LHC limits

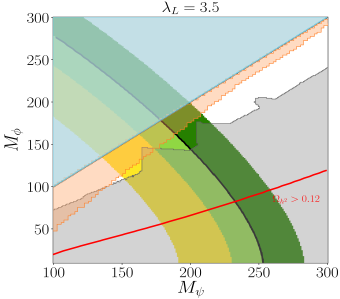




[2104.03691]

Leptoquarks and Model L with 2 fields





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

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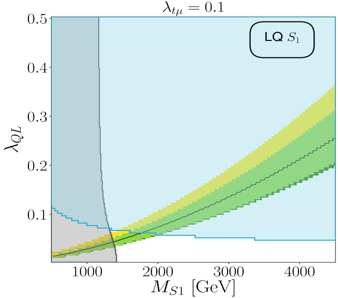

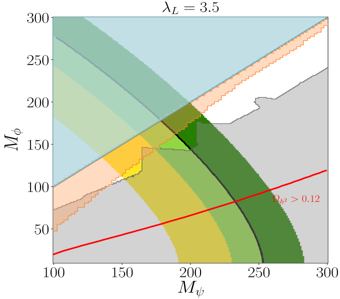

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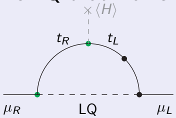
a_μ from LQ (or VLL) $\mathcal{L}_{S_1} = -\left(\lambda_{QL} Q_3 \cdot L_2 S_1 + \lambda_{t\mu} t \mu S_1^*\right)$

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)

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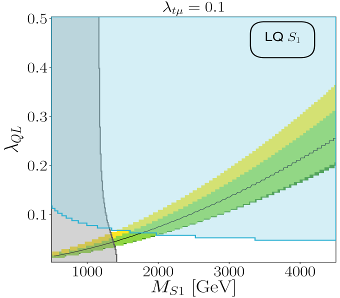

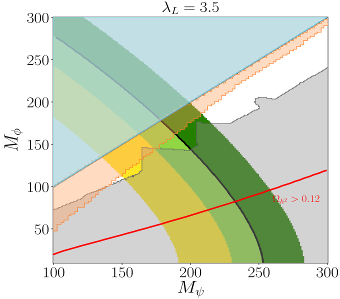

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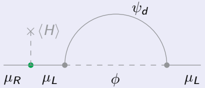
a_μ from 2-field model L

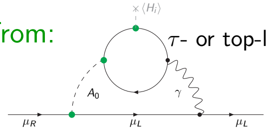


- No chiral enhancement, need very large couplings
- LHC: lower mass limits
- Dark matter candidate, but
  incompatible with large a_μ
  General result: a_μ and DM require at least three new fields!

BSM with smaller masses, hidden from colliders?

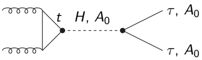
- Aligned 2-Higgs doublet model, rich new Higgs/Yukawa sectors

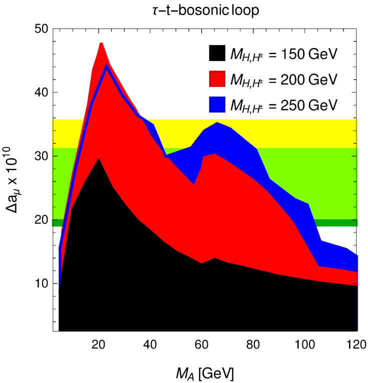
a_μ from:



τ- or top-loop

LHC constraints:

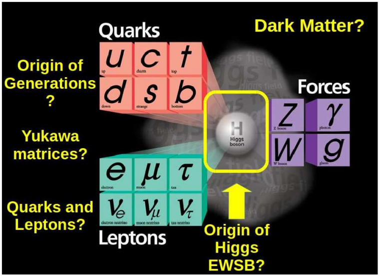




[2104.03691]

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

Outline



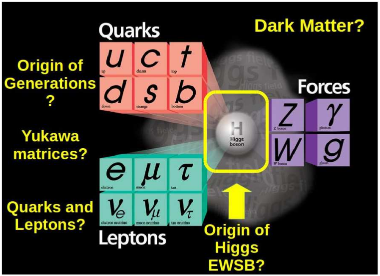
Window to muon mass generation mechanism?

Dark Matter? Hard to see in detectors

but could couple to muon ⇝ large effects possible!

many examples, but within simple models: need at least three new fields

generally: dark matter direct detection constraints important!



Window to muon mass generation mechanism?
allows significant chiral enhancements,

but such models are constrained by collider, flavour etc

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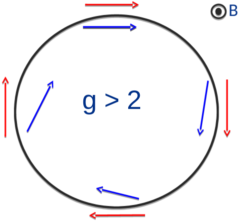
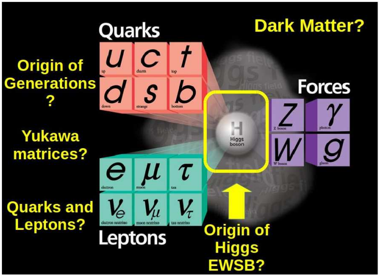
Window to the muon mass generation mechanism (Higgs/Yukawa sectors)

(continuous spin rotation requires rest mass!)





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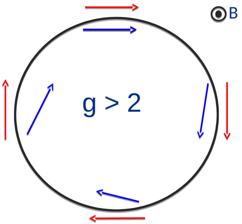
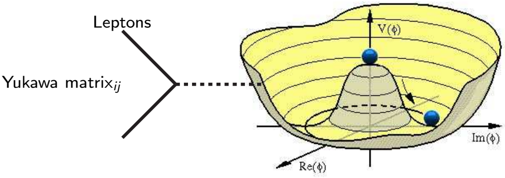




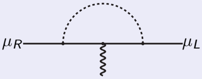
(changed by new physics?)

Two important general points

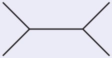
discrepancy $\approx 2 \times a_\mu^{\rm SM,weak}$

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

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



compare:



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

EWPO

Questions: Which models can(not) explain it?

Why is a single number so interesting?

"Why are you happy about a discrepancy?"

$\Rightarrow$ we might make significant progress!

Summary of main points

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

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

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

rather light, neutral (?) particles $\rightsquigarrow$ Connection to dark matter?

Chirality flip enhancement $\rightsquigarrow$ Window to muon mass generation? EWSB/generations?

Which models can still accommodate large deviation?

Many (but not all) models!

but always: experimental constraints!

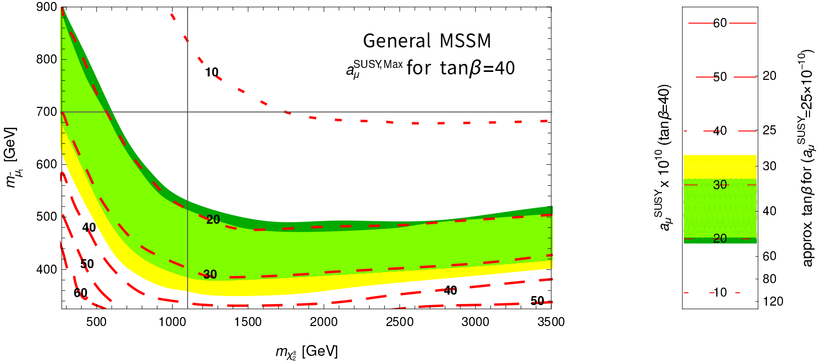
Outlook:

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

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

Full MSSM overview in 7 plots

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



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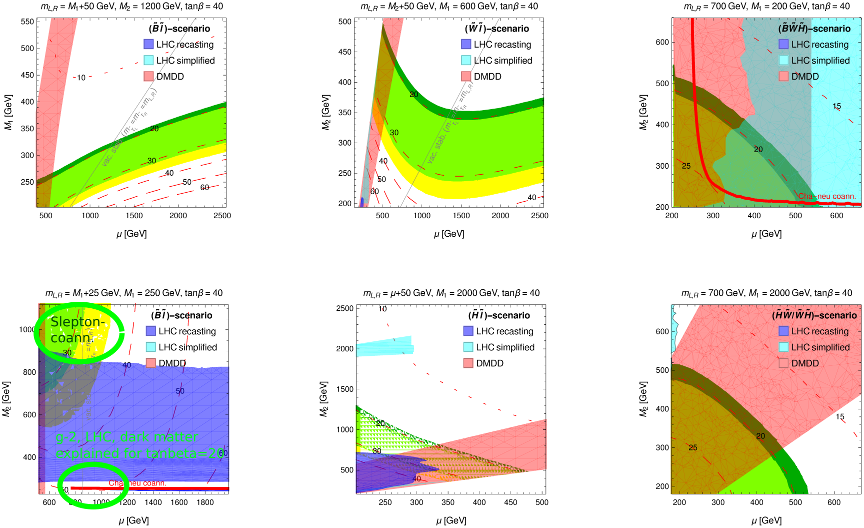
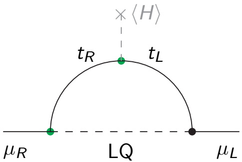
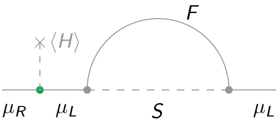


Summary: Bino-LSP: a_μ and DM. Wino-/Higgsino-LSP: a_μ. Both cha<slepton: ≈disfavoured.

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: $\Delta a_\mu < 0$
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	$(\overline{\mathbf{3}},\mathbf{1},4/3)$	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

- 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
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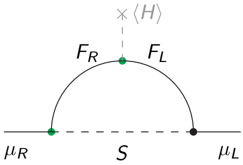
$(\mathbf{1},\mathbf{1},-1)_{1/2} - (\mathbf{1},\mathbf{1},0)_1$	No	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_{1/2} - (\mathbf{1},\mathbf{1},0)_1$	No	Excluded: $\Delta a_\mu < 0$
$(\mathbf{1},\mathbf{2},-1/2)_{1/2} - (\mathbf{1},\mathbf{3},0)_1$	No	Excluded: LHC searches + LEP contact 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

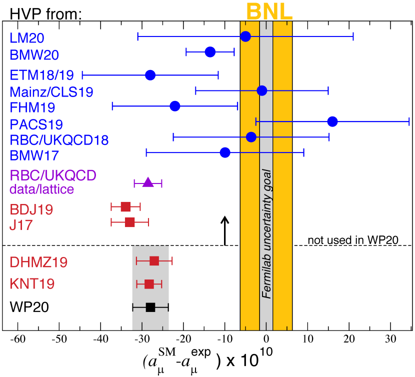
Three-field models



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

Details on hadronic vacuum polarization

a_μ^{HVP} : Status of Hadronic Vacuum Polarisation contributions



Lattice QCD + QED

- impressive progress, but…
- large spread between results
- tensions when looking at `Euclidean time window' comparisons
- large systematic uncertainties (e.g. from non-trivial extrapolation to continuum limit, finite size)

Dispersive/lattice hybrid (`window' method)

For WP20: Dispersive data-driven from DHMZ and KNT

TI White Paper 2020 value:

$\mathbf{a_\mu^{HVP} = 6845\ (40) \times 10^{-11}}$

- TI WP2020 prediction uses dispersive data-driven evaluations with **minimal model dependence**
- a_μ^{HVP} **value and error** obtained **by merging** procedure ➠ accounts for tensions in input data and differences in data treatment & combination (going beyond usual χ^2_{min} inflation)

Thomas Teubner 10