Muon $g-2$ theory: SM and beyond the SM

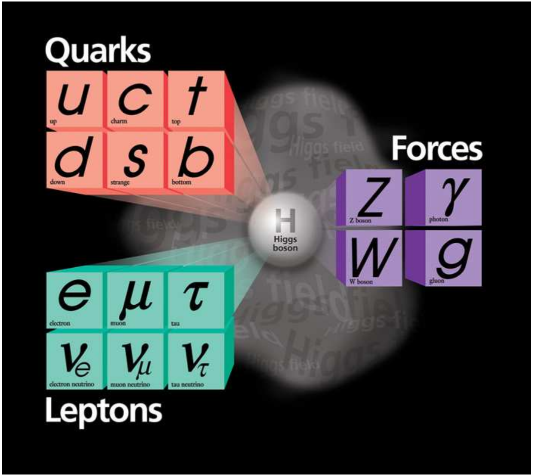
Dominik Stöckinger, TU Dresden

Warsaw Physics Colloquium, 26th April 2021

Collaborations:

Muon $g-2$ collaboration
SM Theory Initiative
BSM collaborators: Peter Athron, Csaba Balasz, Douglas Jacob, Wojciech Kotlarski, Hyejung Stöckinger-Kim

Standard Model of particle physics (est. 1967...1973))

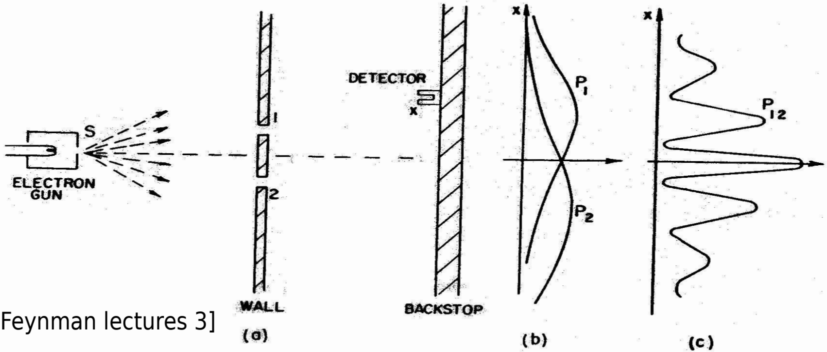


SM very well confirmed!

- All known interactions ($\neq$ gravity)
- relativistic QFT $\rightsquigarrow$ renormalizable
- gauge invariance $\rightsquigarrow$ specific interactions
- spontaneous EWSB $\rightsquigarrow$ Higgs

a_μ sensitive to all particles and forces via quantum fluctuations!

Quantum fluctuations: double slit experiment



[Feynman lectures 3]

- essence of quantum mechanics
- All possible paths contribute, probability amplitudes interfere

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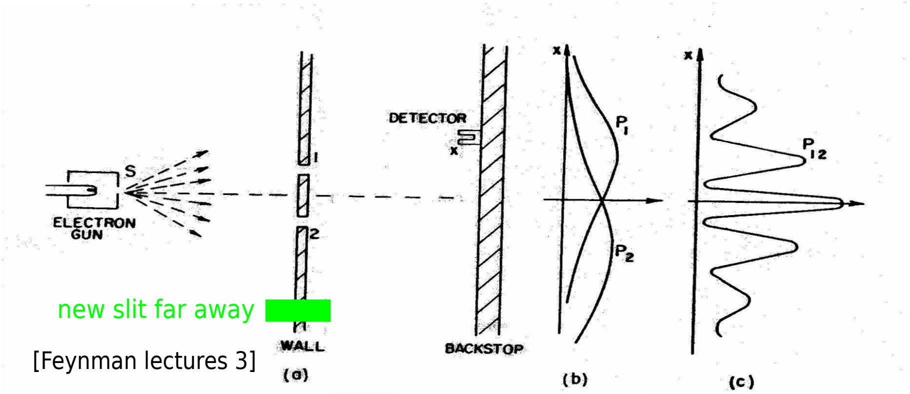

[Feynman lectures 3]

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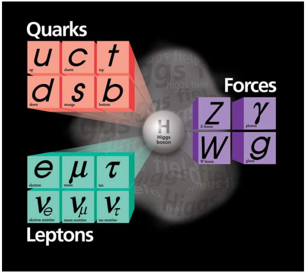
Our “paths” for $g-2$: Feynman diagrams

μ couples to B-field directly or via virtual particles



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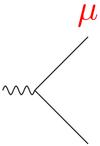
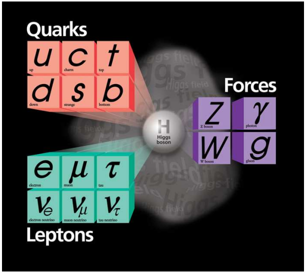


Dirac equation/direct $\rightsquigarrow$"pointlike"

$$g = 2$$



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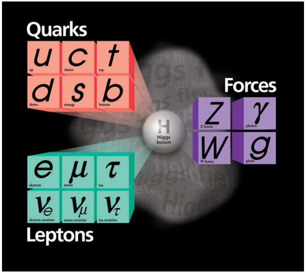

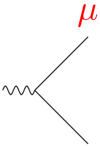

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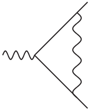

Schwinger (1948): quantum fluctuations ⇝ "non-pointlike"

$$g = 2\left(1 + \frac{\alpha}{2\pi}\right)$$

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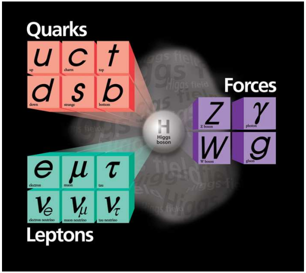

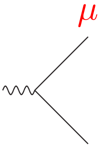

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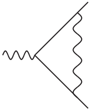

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Technically: effective Lagrangian/Hamiltonian

$$\mathcal{L}_{\text{eff}} = -\frac{Qe}{4m_\mu} a_\mu \times \bar{\psi}_L \sigma_{\mu\nu} \psi_R F^{\mu\nu} \qquad H_{\text{eff}} = -2(1+a_\mu)\frac{e}{2m_\mu}\vec{B}\cdot\vec{S}$$

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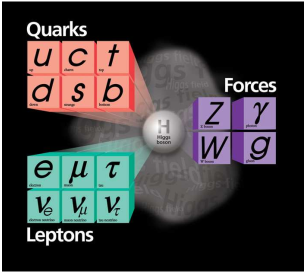

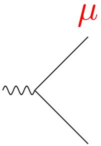

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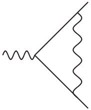

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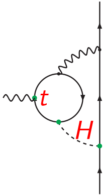
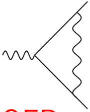


All SM particles contribute, even Higgs and top!

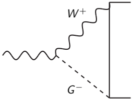
$$g = 2\left(1 + \ldots - 1.5 \times 10^{-11}\right)$$

Theory Initiative prediction $a_\mu^{\mathrm{SM}} = (11\,659\,181.0 \;\; (4.3)\;)\;[10^{-10}]$

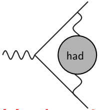
since 2017, 6 workshops, White Paper (2020), 132 authors, ongoing effort



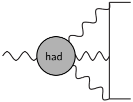
QED: 11 658 471.9 (0.0)



Weak: 15.36 (0.1)



Hadronic vac.pol.: 684.5 (4.0)



Hadr. light-by-light: 9.0 (1.7)

number = conservative combination of approaches

very precise particle theory prediction

evaluation uses all conceivable

QFT methods & tricks

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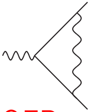

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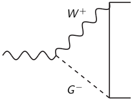

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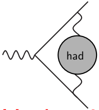
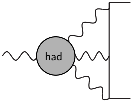


Hadronic vac.pol.: $684.5 \;\; (4.0)$



Hadr. light-by-light: $9.0 \;\; (1.7)$

QED:

- 4-/5-loop Feynman integrals analytical & numerical
- most precise QED test: $(g-2)_e$!

Weak:

- first EW 2-loop calculation, also use renormalization group methods

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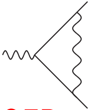

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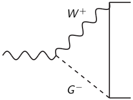

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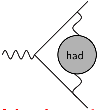

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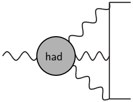

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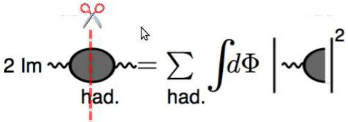
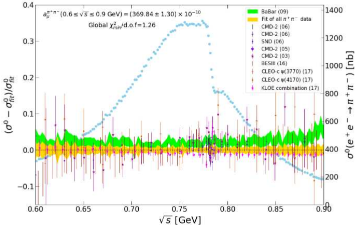
Hadronic vacuum polarization:

- unitarity+causality $\rightsquigarrow$ exact dispersion relation





- lattice QCD impressive progress (not yet used in TI value)

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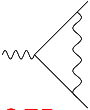

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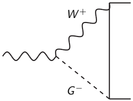

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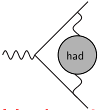

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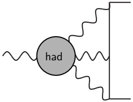

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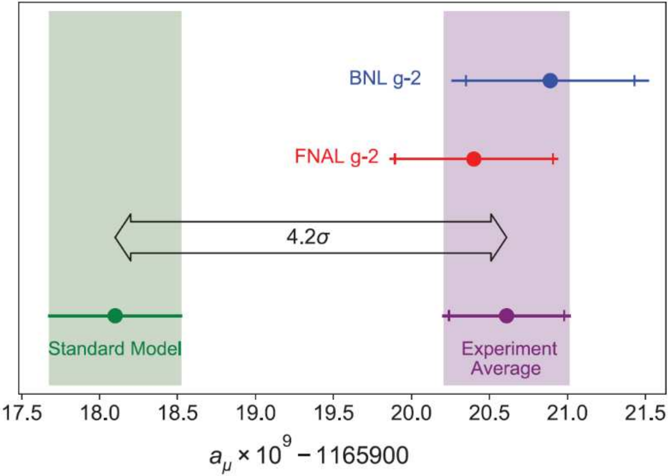
Hadronic light-by-light:

- difficult QFT problem
- Traditionally: low-energy models
- Recently: data-driven (dispersion relations) & lattice QCD results
- consistent results
- uncertainty better under control

Finally: Fermilab Run 1 versus Theory Initiative SM value



Discrepancy

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

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Large!

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

how to explain without conflict to LHC etc?

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

how to explain without conflict to LHC etc?

Questions: Which models can(not) explain it?

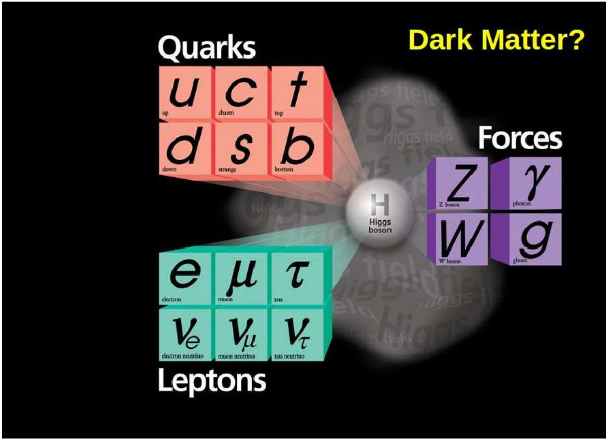
Why is a single number so interesting?

"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]

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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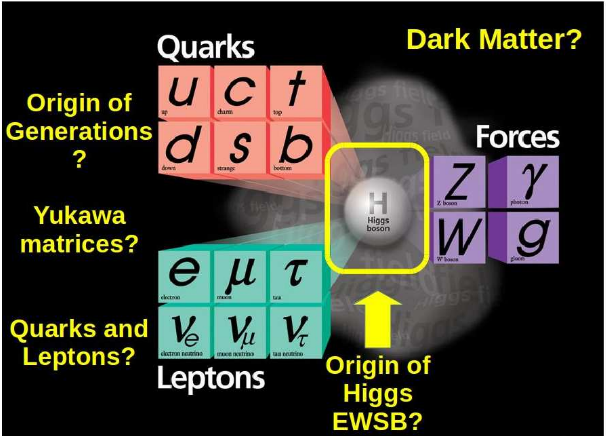

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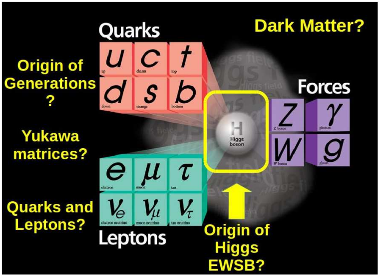
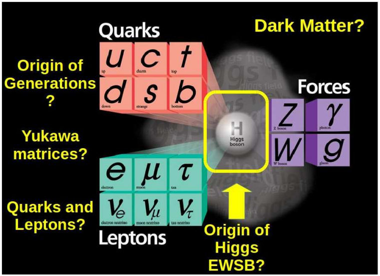


Window to muon mass generation mechanism?

Dark Matter? Hard to see in detectors

but could couple to muon ⇝ large effects possible!

$\geq$ 15 explanations of $g-2$ via dark matter



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papers: 16 SUSY, 7 2HDM, 3 mass-generation, 4 leptoquark (+B-anomalies), 4-field model (+B-anomalies and DM), 1 vector-like lepton, 1 GUT(331)

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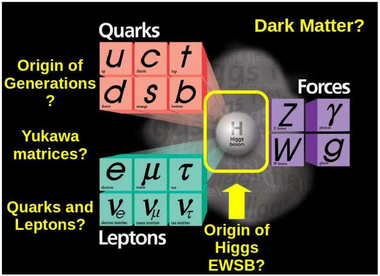
Window to the muon mass generation mechanism (Higgs/Yukawa sectors)

Technically: QFT operators for m_μ and a_μ are chirality flipping and break gauge invariance:

$$m_\mu \bar{\psi}_L \psi_R$$
$$\frac{a_\mu}{m_\mu} \bar{\psi}_L \sigma_{\mu\nu} \psi_R F^{\mu\nu}$$



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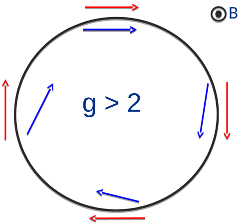

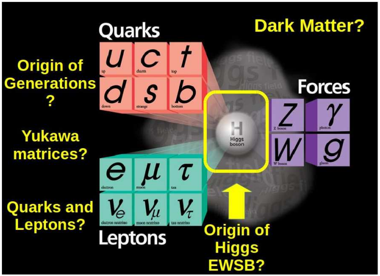

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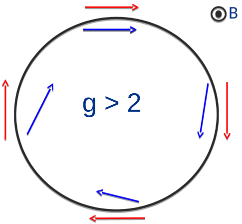
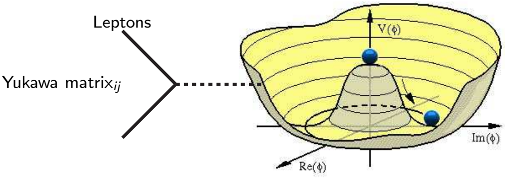
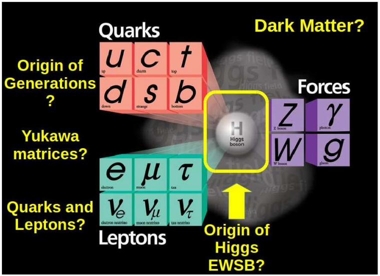




(changed by new physics?)



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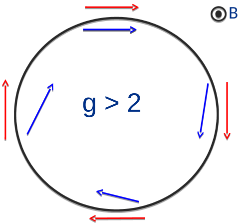

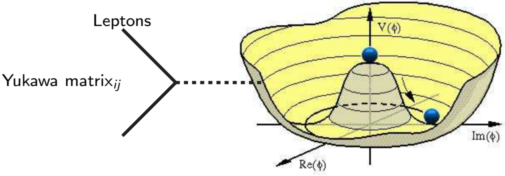

(changed by new physics?)

Example BSM idea

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

Example BSM idea Minimal SUSY Standard Model

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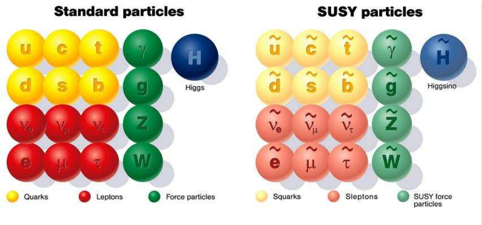
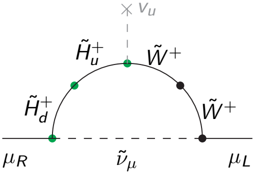


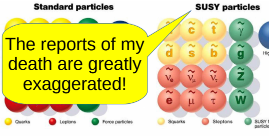
Superpartners and SUSY Higgs sector $\rightsquigarrow \tan\beta = \frac{v_u}{v_d}$, Higgsino mass μ

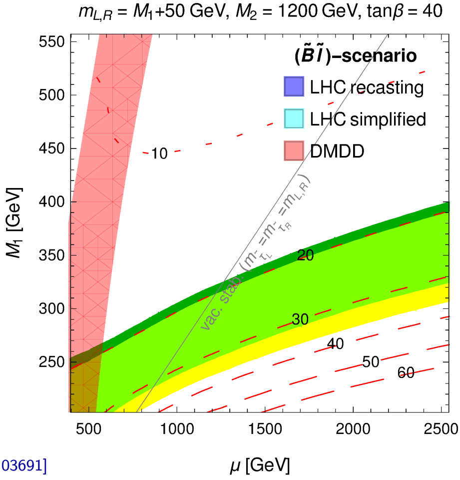
MSSM can explain $g-2$ and dark matter



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

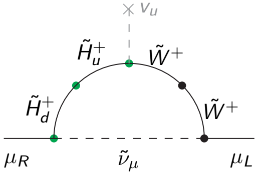
- "Dark matter mass" versus μ
- explains $g-2$ in large region (expands for $\tan\beta \neq 40$)
- DM explained by stau/slepton-coannihilation
- this automatically evades (current) LHC limits





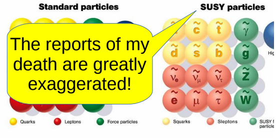
[2104.03691]

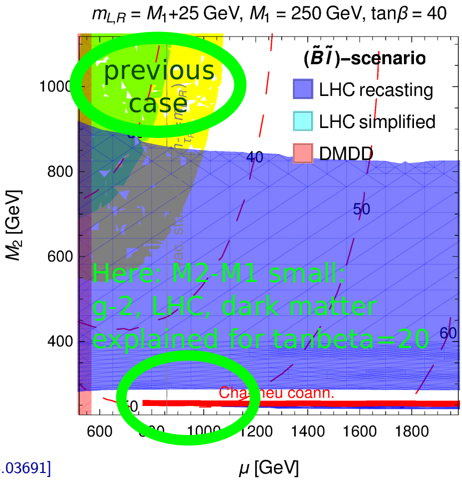
MSSM can explain $g-2$ and dark matter



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

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





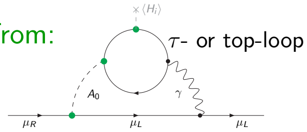
[2104.03691]

BSM with smaller masses, hidden from colliders?

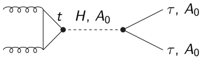
- Aligned 2-Higgs doublet model, rich new Higgs/Yukawa sectors

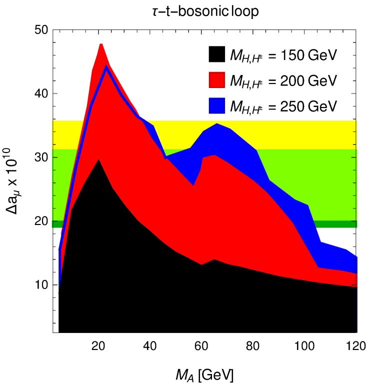
[compare: Type 2 pioneered by Maria Krawczyk, excluded for $g-2$ e.g. by Mikolaj Misiak et al]

a_μ from:



LHC constraints:





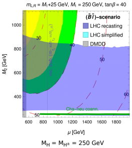
[2104.03691]

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

There are many more examples. . .

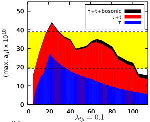
SUSY: MSSM, MRSSM

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



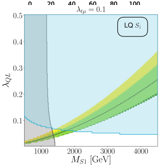
Two-Higgs doublet model

- 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)

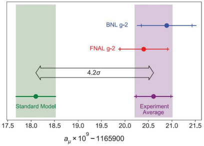
- Mostly excluded
- light N.P. (ALPs, Dark Photon, Light $L_\mu - L_\tau$)

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

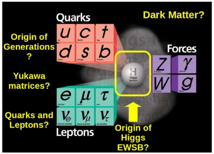
[Athron,Balazs,Jacob,Kotlarski,DS,Stöckinger-Kim, preliminary]

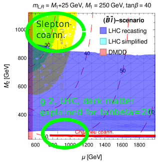
Conclusions

- SM prediction for $g-2$:
  - All known particles relevant (and all QFT tricks)
  - Theory Initiative: worldwide (ongoing!) effort, agreed & conservative value

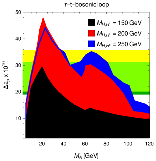


- BSM contributions to $g-2$:
  - large effect needed
  - Connections to deep questions
  - many viable models . . . but
  - constraints from LHC, DM . . .





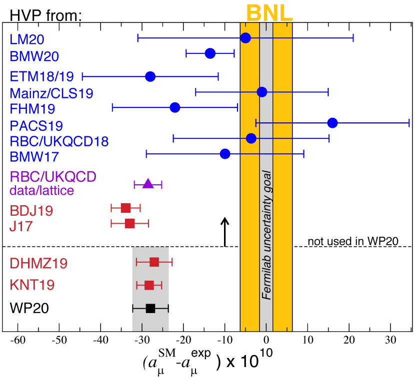
- Outlook
  - Fermilab Run-2,3,. . .
  - SM: scrutinize lattice, more e^+e^--data, MUonE
  - Exp. tests of BSM models:
    Higgs couplings, B-physics, CLFV,
    EDM, light-particle searches, e^+e^-/muon collider



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

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:

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

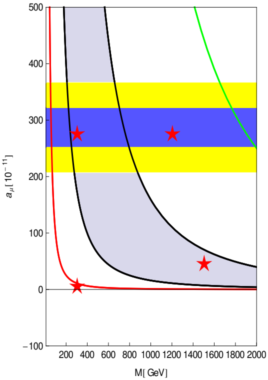
- TI WP2020 prediction uses dispersive data-driven evaluations with **minimal model dependence**
- $\mathbf{a_\mu^{HVP}}$ **value and error** obtained **by merging** procedure ➠ accounts for tensions in input data and differences in data treatment & combination (going beyond usual χ^2_{min} inflation)

Thomas Teubner 10

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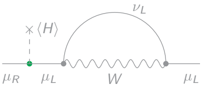
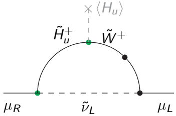
- EWSM: $\alpha \frac{m_\mu^2}{M_W^2}$

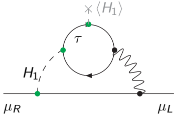


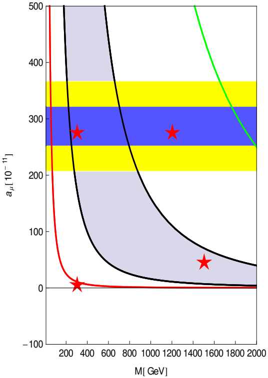
- SUSY: $\alpha \frac{m_\mu^2 \tan\beta}{M^2_{\text{SUSY}}}$

  Well-motivated theory. Many other advantages



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





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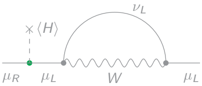

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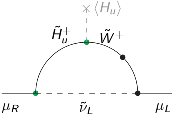

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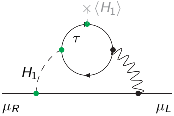
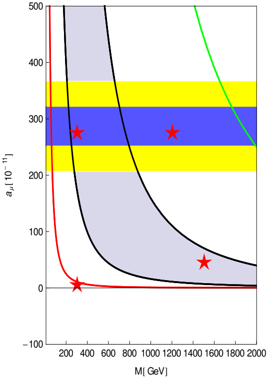


Well motivated; many variants; many constraints



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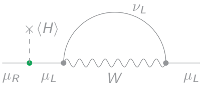
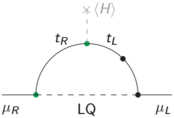
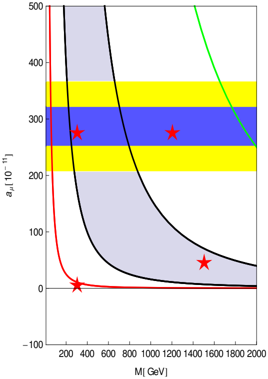


- LQ: $g_L g_R \frac{m_\mu m_t}{M^2_{\text{LQ}}}$



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



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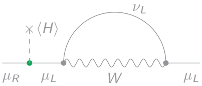
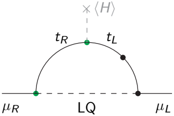
- EWSM: $\quad \alpha \frac{m_\mu^2}{M_W^2}$



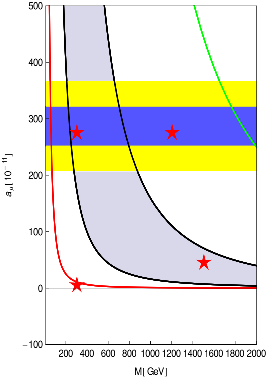
- LQ: $\quad g_L g_R \frac{m_\mu m_t}{M^2_{\text{LQ}}}$



  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

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



Take-home message 2:

Many models involve enhancement mechanisms

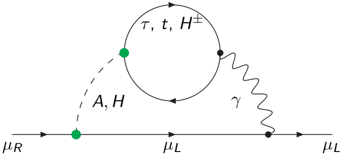
but: experimental constraints!

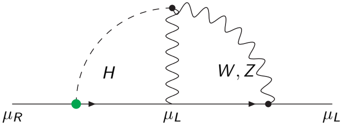
- LHC, LEP (particle mass limits; Higgs-data; EW-precision)
- Dark matter (direct detection limits!)
- Quark and lepton flavour, EDMs

Interlude — Role of BSM loops — examples

- EWSM: 2-loop $= -20\%$ of 1-loop — dominated by $\log(M_W/m_\mu)$
- 2HDM: 2-loop $=$ leading order $\Rightarrow$ full 2-loop prediction motivated

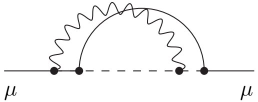
[Cherchiglia,Kneschke,DS,Stöckinger-Kim '16,'17]



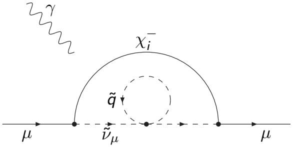


Role of BSM loops — examples

- SUSY: several 2-loop effects $\mathcal{O}(10\%)$ or more



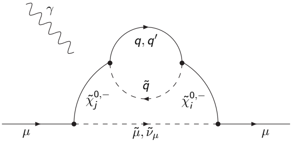
$\rightarrow a_\mu^{1L} \times \frac{\alpha}{4\pi} \log\left(\frac{M_{SUSY}}{m_\mu}\right)$ $\approx -9\%$



$\rightarrow a_\mu^{1L} \times \frac{\alpha}{4\pi} \frac{M_{\tilde{q}}^2}{M_{\tilde{\mu}}^2}$

can* be $\mathcal{O}(100\%)$

* artifact of $\overline{\text{MS}}$ scheme
not present in on-shell scheme!



$\rightarrow a_\mu^{1L} \times \frac{\alpha}{4\pi} \log\left(\frac{M_{\tilde{q}}}{M_{SUSY}}\right)$ up to $\mathcal{O}(10\%)$

non-decoupling effect

Outline

Outline

1. Concrete models
   - SUSY/MSSM, Two-Higgs doublet model, Leptoquarks, Vector-like leptons ...
   - Overview of old results + [Athron,Balazs,Jacob,Kotlarski,DS,Stöckinger-Kim, preliminary]
2. Conclusions

Outline

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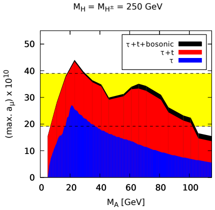
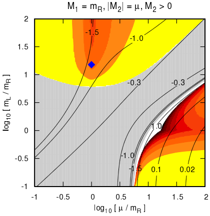
2. Conclusions

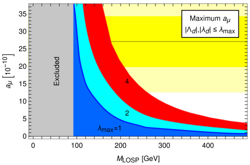
Example models and a_μ: "Largest results"



Largest THDM

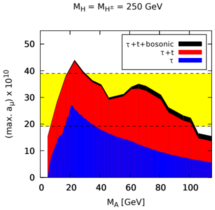


Largest SUSY ($\tan\beta \to \infty$)



Largest MRSSM

Example models and a_μ: "Largest results"



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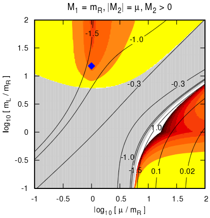

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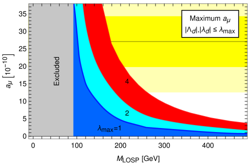
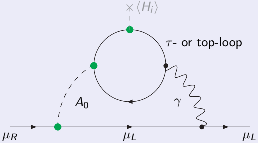


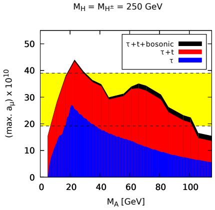
Largest MRSSM

a_μ in the 2-Higgs doublet model? [Cherchiglia,DS,Stöckinger-Kim '17]

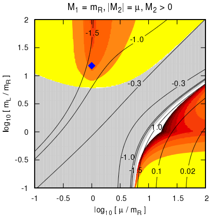


Results: a_μ explained in tightly constrained parameter space;
testable by many observables: $Z \to \tau\tau$, τ- and b-decays, LHC $gg \to A, H \to \tau\tau$, future ILC?

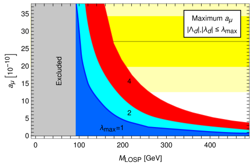
Example models and a_μ: "Largest results"



Largest THDM



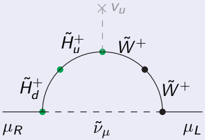
Largest SUSY ($\tan\beta \to \infty$)



Largest MRSSM

a_μ in special SUSY: $\tan\beta \to \infty$, MRSSM

[Bach,Park,DS,Stöckinger-Kim '15]
[Kotlarski,DS,Stöckinger-Kim '19]

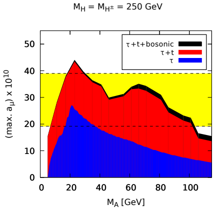


MSSM $\neq$ SUSY! SUSY can be realized differently!

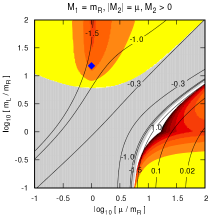
$\tan\beta \to \infty$: radiative m_μ

Result: a_μ explained even if $M_{LSP} > 1$ TeV

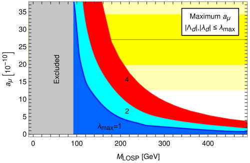
Example models and a_μ: "Largest results"



Largest THDM



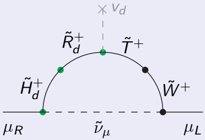
Largest SUSY ($\tan\beta \to \infty$)



Largest MRSSM

a_μ in special SUSY: $\tan\beta \to \infty$, MRSSM

[Bach,Park,DS,Stöckinger-Kim '15]
[Kotlarski,DS,Stöckinger-Kim '19]



MRSSM has more symmetry but no $\tan\beta$-enhancement!

Result: a_μ explained for $M_{\rm SUSY} \sim 100$GeV, compressed spectra;

testable by LHC/ILC, $\mu \to e/\mu \to e\gamma$

Which models are now promising in view of a_μ^{BNL}, LHC and dark matter?

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

Which models can still accommodate large deviation?

SUSY: MSSM, MRSSM

- MSugra. . . many other generic scenarios
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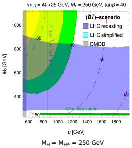

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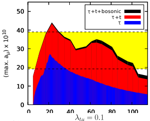

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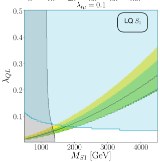

Simple models (one or two new fields)

- Mostly excluded
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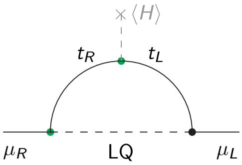
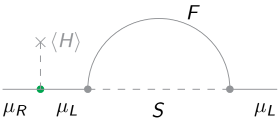
[Athron,Balazs,Jacob,Kotlarski,DS,Stöckinger-Kim, preliminary]

One-field, two-field models





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

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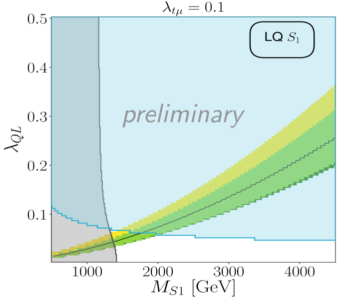
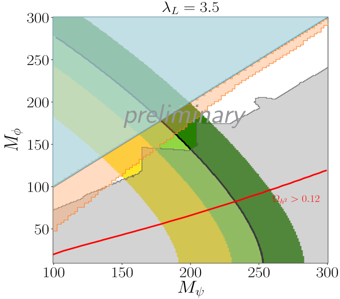
$(\mathbf{1},\mathbf{1},0)_{1/2} - (\mathbf{1},\mathbf{1},1)_1$	No	Excluded: LHC searches + LEP contact interactions
$(\mathbf{1},\mathbf{2},-1/2)_{1/2} - (\mathbf{1},\mathbf{1},-1)_1$	No	Excluded: LHC searches + LEP contact interactions

Leptoquarks and Model L with 2 fields





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

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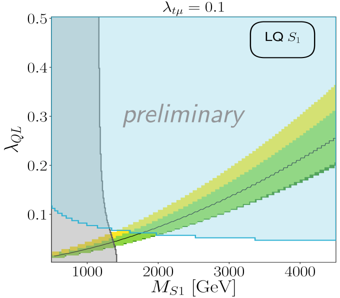
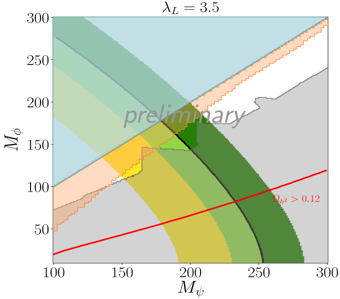
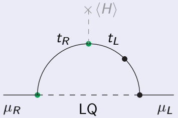




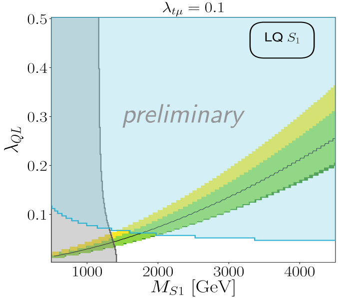
[Athron,Balazs,Jacob,Kotlarski,DS,Stöckinger-Kim, preliminary]

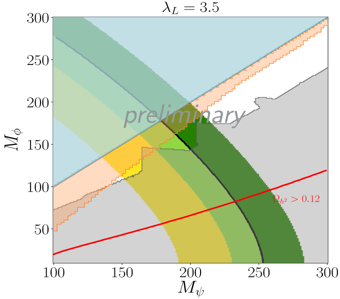
a_μ from LQ (or VLL) (motivation: simple/by GUTs, extra dim, . . .)



- 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)

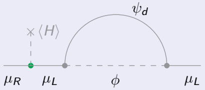
Leptoquarks and Model L with 2 fields





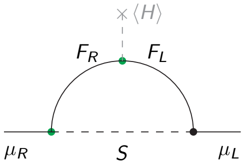
[Athron,Balazs,Jacob,Kotlarski,DS,Stöckinger-Kim, preliminary]

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

Three-field models



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

MSSM fits very well: Chirality flip and $\tan\beta$-enhancement

Charginos=mixtures $\tilde{H}$–$\tilde{B}$–$\tilde{W}$:

couplings to μ_L and to μ_R

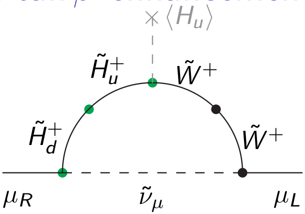


Diagram enhanced by Yukawa and large "other" vev, $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$

$\propto y_\mu \langle H_u \rangle \; \mu = m_\mu \tan\beta \; \mu \qquad \to a_\mu^{\rm SUSY} \propto \tan\beta \, \mathrm{sign}(\mu) \, \frac{m_\mu^2}{M_{\rm SUSY}^2}$

numerically: fits well if $\tan\beta = 10 \ldots 50$ and $M_{\rm SUSY} <\sim 500$ GeV

$$a_\mu^{\rm SUSY} \sim 12 \times 10^{-10} \times \tan\beta \left(\frac{100\mathrm{GeV}}{M_{\rm SUSY}} \right)^2 \mathrm{sign}(\mu)$$

Status of SUSY and a_μ

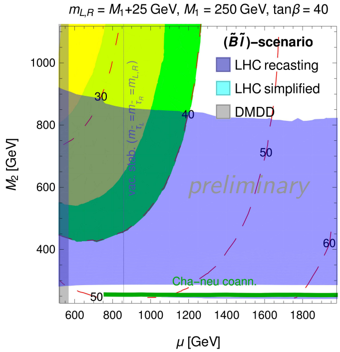
- SUSY and MSSM well-motivated!
- In general: large a_μ possible, precision computations available [GM2Calc]
- scenarios with large a_μ require only 3 light sparticles $\lesssim$ 500 GeV
- constraints pull in different directions:

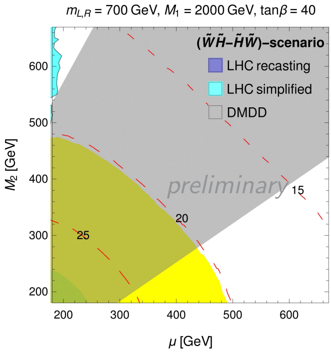
$$\text{LHC} \leftrightarrow M_h \leftrightarrow \text{dark matter} \leftrightarrow \text{finetuning} \leftrightarrow a_\mu$$

- "Constrained MSSM": Higgs+LHC $\Rightarrow$ stops, squarks very heavy $\Rightarrow$ sleptons heavy $\Rightarrow$ a_μ tiny!

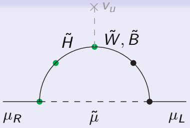
Standard MSSM

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





MSSM: well motivated, can explain large deviation (but...)



- LHC + Dark Matter ⇒ mass patterns!
- Co-annihil. regions; large $\mu \equiv m_{\tilde{H}}$; Wino-LSP; ...
- Excludes many simple scenarios (MSugra, ...)

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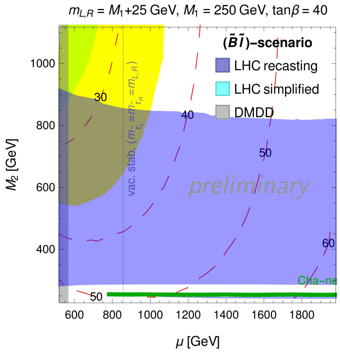

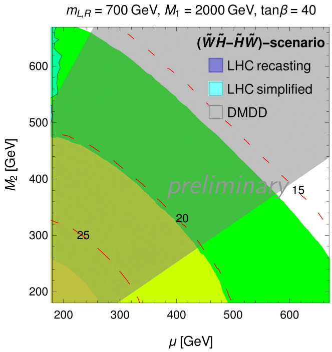

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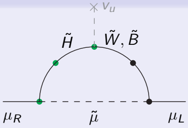

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Outline

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

Many models involve enhancement mechanisms

but: experimental constraints!

Take-home message 3:

Which models can still accommodate large deviation?

Many models! General ideas still viable (SUSY, THDM, LQ, VLL, . . .)

but: restricted parameter space! Specific scenarios excluded!

What can now happen? Deviation confirmed? Back to SM?

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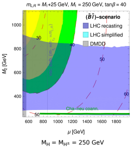

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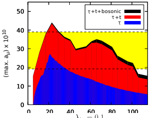

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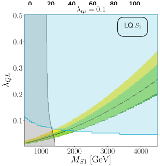

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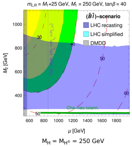

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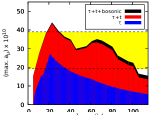

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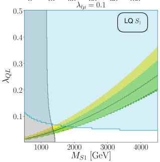

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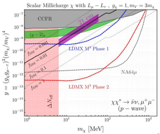


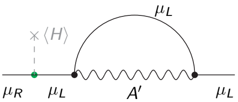
[Berlin, Blinov, Krnjaic, Schuster, Toro '18]

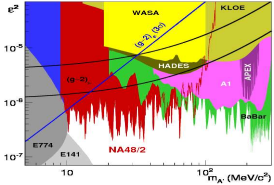
Light/dark sectors — compatible with large a_μ?

Very light, very weakly interacting new particles

- "dark photon" NO

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

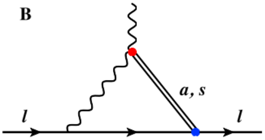


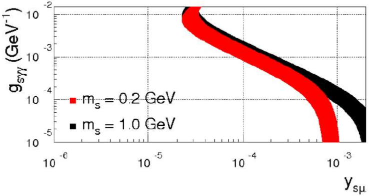


[NA48: 1504.00607]
excludes minimal dark photon for a_μ

- "ALPs" YES

$$\mathcal{L} = \frac{1}{4} g_{s\gamma\gamma} s F^{\mu\nu} F_{\mu\nu} + y_s s \bar{\mu}\mu \qquad a_\mu^{\mathrm{BZ}} \sim \frac{m_\mu}{4\pi^2} g_{s\gamma\gamma} y_s \ln(\Lambda/m_s)$$





o

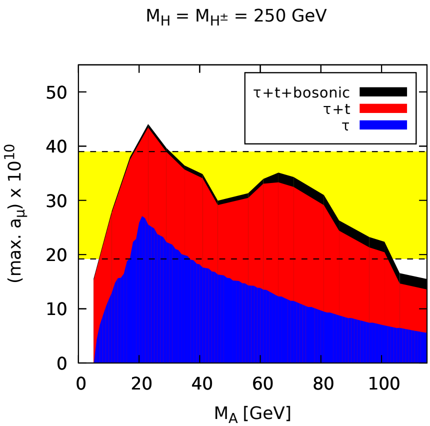
[Marciano, Masiero, Paradisi, Passera '16]

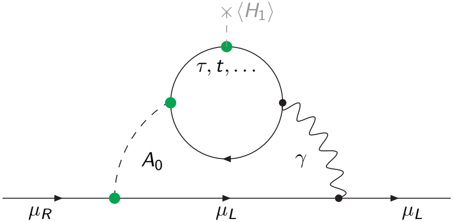
Two-Higgs doublet model — can it explain Δa_μ?

[Cherchiglia, DS, Stöckinger-Kim '17]

Answer: YES (in small par. space)!

- light A_0-boson, large couplings to leptons (and top-quarks)





- full computation

[Cherchiglia,Kneschke,DS,Stöckinger-Kim'16]

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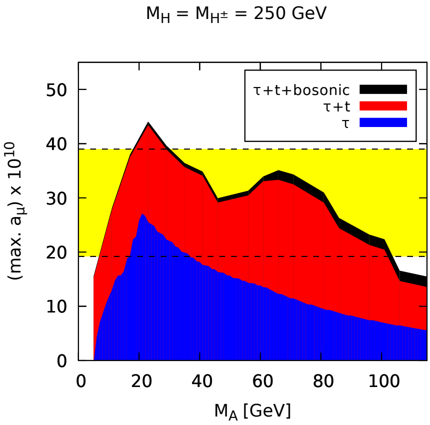

constrained/testable by

- τ-, Z-decays, LEP
- b-decays, LHC

$\Rightarrow$ maximum Yukawa couplings

- lepton Yukawa $<\sim 100$
- quark Yukawas $<\sim 0.5$
- (for $M_A = 20 \ldots 100$ GeV, else even stronger)

More on bounds on dark photons, ALPs

- beam dump: dark bremsstrahlung (works for specific coupling range)
- electron fixed target (APEX,A1)
- Babar, KLOE, WASA: meson decays
- often assumed: $A' \to e^+e^-$ dominant
- if not: $K \to \pi A'$, $A' \to$invisible and $e^+e^- \to \gamma+$invisible lead to bounds

  [Davoudiasl,Lee,Marciano'14][Izaguirre et al '13]
- generalization: also mass mixing "dark Z" with more general couplings, also strongly constrained
- for ALPs: [Marciano et al '16]
  $e^+e^- \to \gamma a, e^+e^-a$ at future low-E experiments