Muon $g-2$ and Physics Beyond the SM

Dominik Stöckinger, TU Dresden

LoopFest, Fermilab, 12th August 2019

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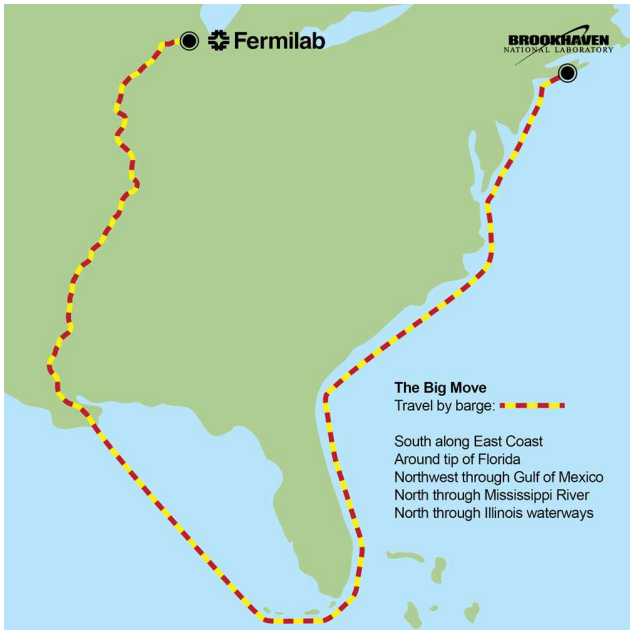
$(g_\mu - 2)/2 = a_\mu$ is among the most precise observables
many pioneering loop calculations done in the context of $(g-2)$

Motivation: measurement of a_μ at Fermilab

Brookhaven (1999–2006) $\longrightarrow$ Fermilab (2017–. . .)



Status and prospect (after significant SM theory progress)

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (27.06 \pm (6.3^{\rm Exp} \to 1.6^{\rm FUTURE}) \pm 3.6^{\rm Th(KNT)}) \times 10^{-10}$$

Motivation: measurement of a_μ at Fermilab

deviation $\approx (27 \pm 8) \times 10^{-10}$ tantalizing hint for BSM physics

Tasks:

- Prepare for new experiment
- Determine possible contributions in BSM scenarios

If deviation confirmed: proof of BSM! General: parameter constraints

Motivation: "Large" deviation

deviation $\approx (27 \pm 8) \times 10^{-10}$ is twice as large as $a_\mu^{\mathrm{SM,weak}} \approx 15 \times 10^{-10}$

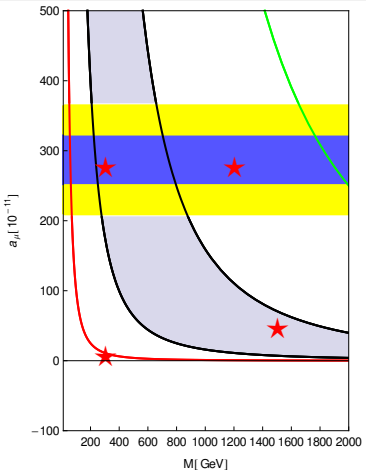
- but we expect: $a_\mu^{\mathrm{NP}} \sim a_\mu^{\mathrm{SM,weak}} \times \left(\frac{M_W}{M_{\mathrm{NP}}}\right)^2 \times$ couplings
- and we have not seen 200% effects anywhere else

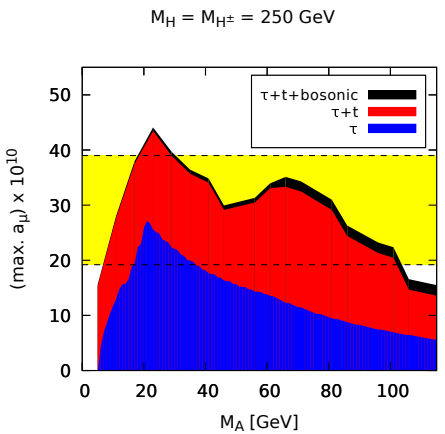
How can BSM physics manage to account for this deviation without conflict with other data?

Questions and outline

Questions/tasks:

- determine possible BSM contributions
- How can BSM accommodate this large deviation?



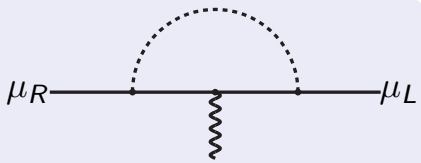


Overview:
– special properties of a_μ
– typical BSM contributions

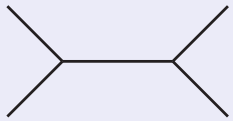
Specific models:
– e.g. THDM, SUSY
– interesting scenarios/tests

Special properties of a_μ

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



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



$$\mathcal{L}_{a_\mu, m_\mu} = \tilde{F}_M \, \overline{\mu_L} \sigma_{\mu\nu} \mu_R \, F^{\mu\nu} - m_\mu \, \overline{\mu_L} \mu_R + h.c.$$

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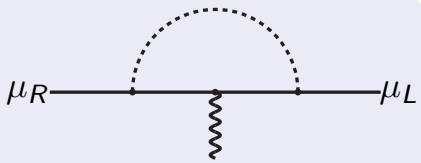

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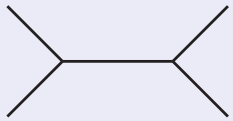

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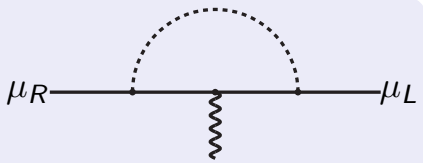
- break EW gauge invariance and chiral symmetry $\mu_{L,R}$:
- need some Higgs VEV(s) and some μ_L–μ_R flipping parameters

$$a_\mu, m_\mu \propto y_\mu^{\text{BSM}} v_\Phi^{\text{BSM}}$$

a_μ probes fermion mass generation — large room for BSM!

Special properties of a_μ

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



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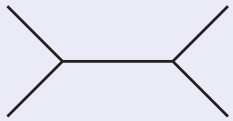

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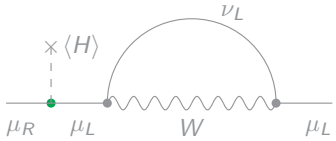
a_μ^{NP} related to Δm_μ^{NP}: $a_\mu = \mathcal{O}\left(\frac{\Delta m_\mu^{\text{NP}}}{m_\mu}\right) \times \frac{m_\mu^2}{M_{\text{NP}}^2} \Rightarrow M_{\text{NP}} <\sim 2$ TeV

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

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



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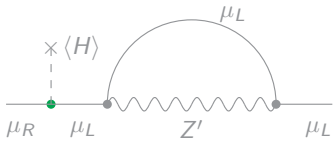

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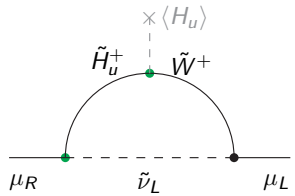

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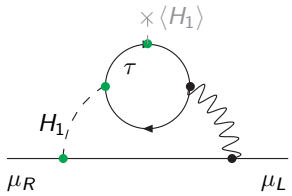
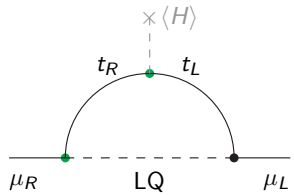
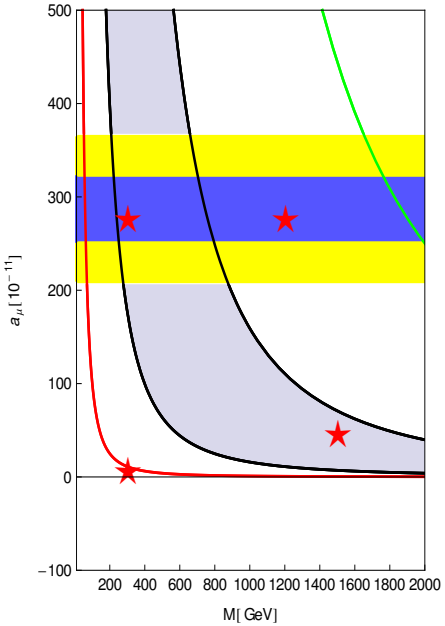


- LQ: $g_L g_R \frac{m_\mu m_t}{M_{\text{LQ}}^2}$





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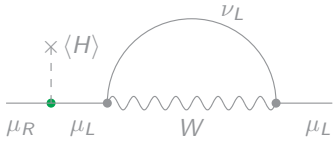

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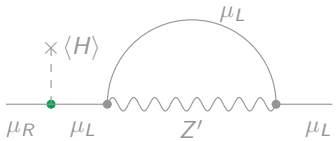
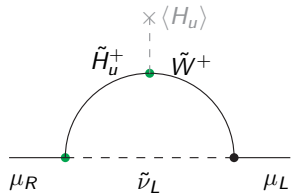


No chiral enhancement, possible if muon-specific

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

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



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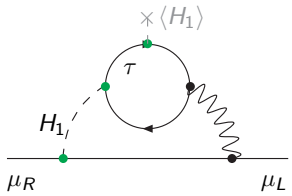

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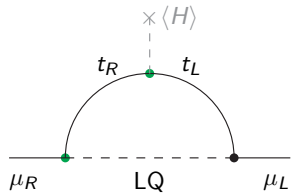

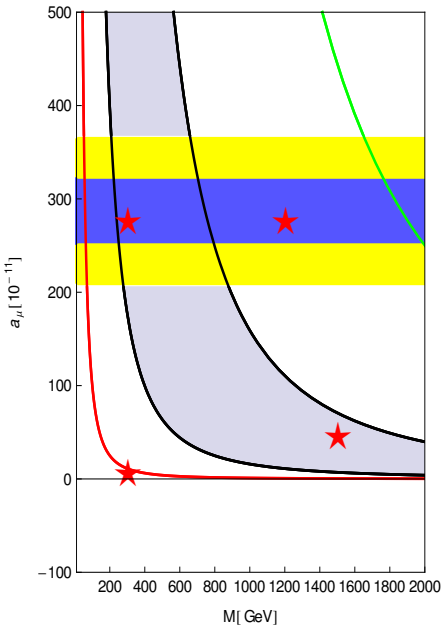

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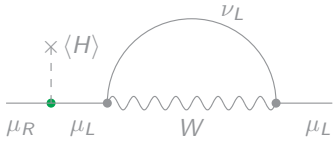

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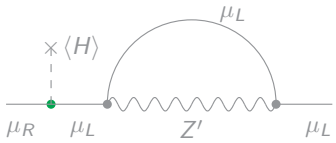
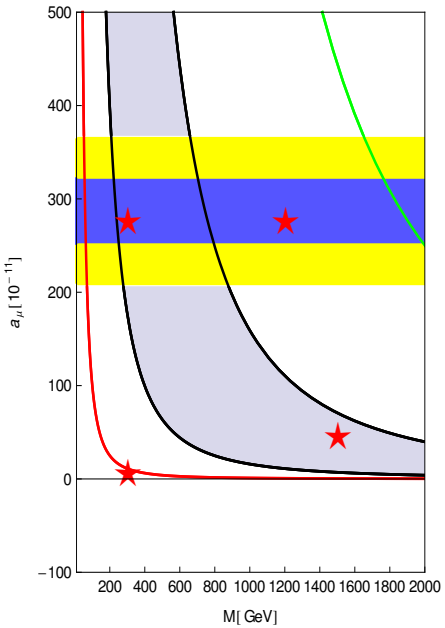


- rad. m_μ $\sim \frac{m_\mu^2}{M_{\text{NP}}^2}$

Theoretical maximum. Need $M_{\text{NP}} <\sim 2$ TeV



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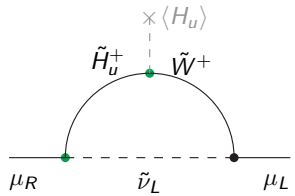

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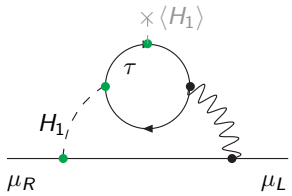

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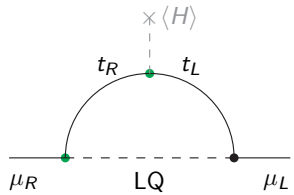

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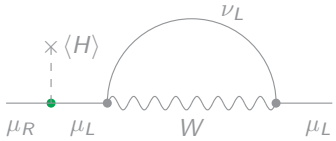

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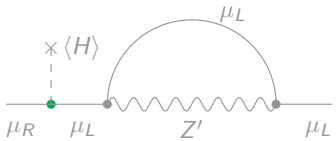

- rad. m_μ $\sim \frac{m_\mu^2}{M_{\text{NP}}^2}$

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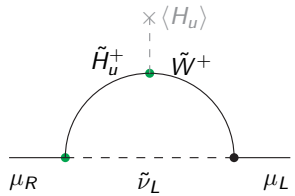
  Well-motivated. "Fits like a glove"



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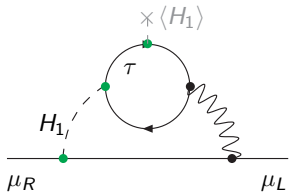

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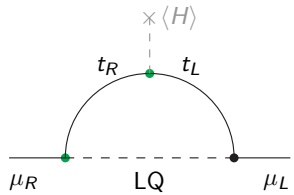

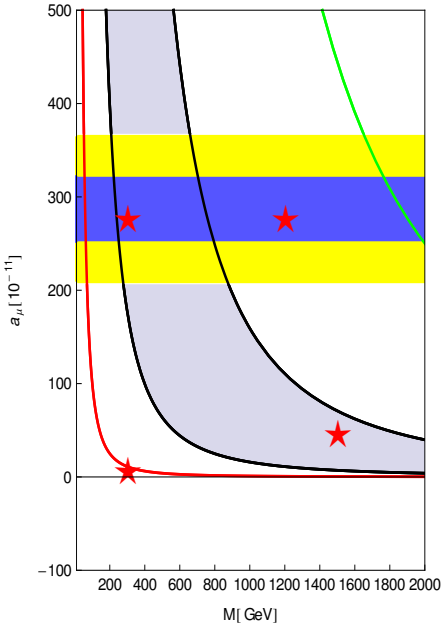

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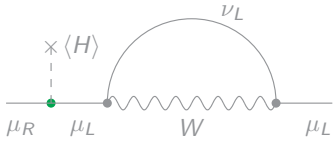

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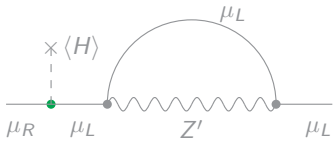

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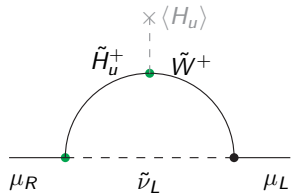

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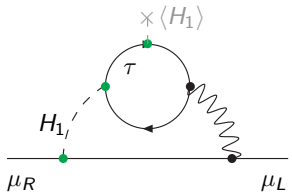

Well motivated; typically very small

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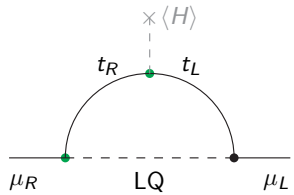

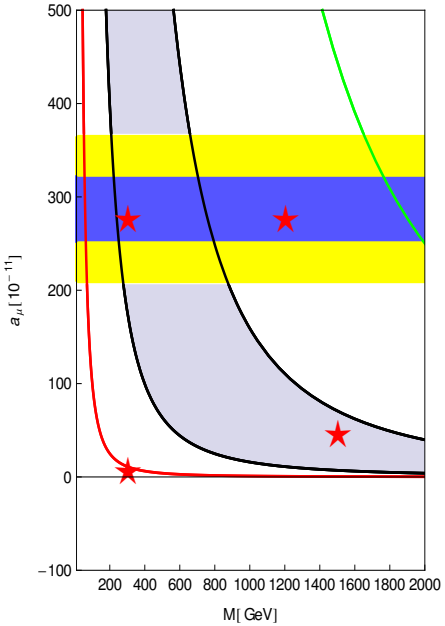

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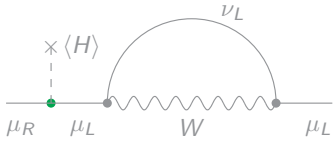

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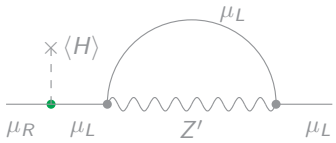

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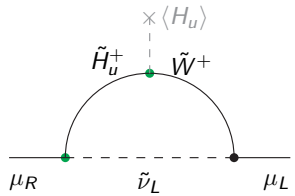

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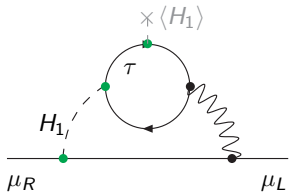

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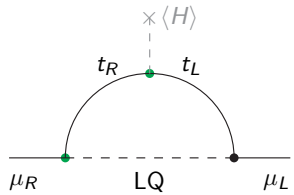
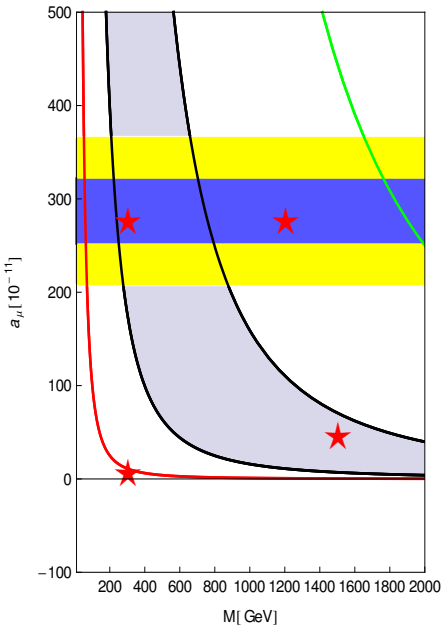


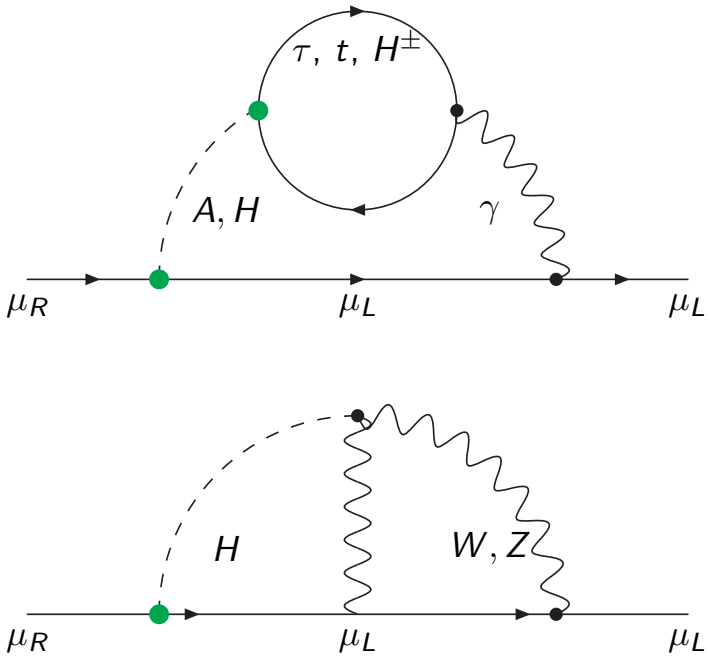
Beware: $\Delta m_\mu / m_\mu \sim g_L g_R m_t / m_\mu$ restricts couplings



Role of BSM loops — examples

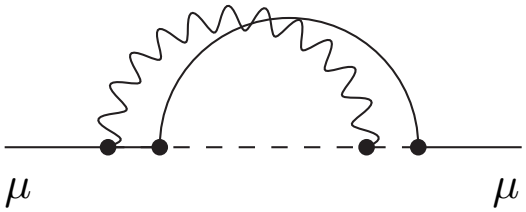
- EWSM: 2-loop = -20% of 1-loop — dominated by $\log(M_W/m_\mu)$
- 2HDM: 2-loop = leading order $\Rightarrow$ full 2-loop prediction motivated

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

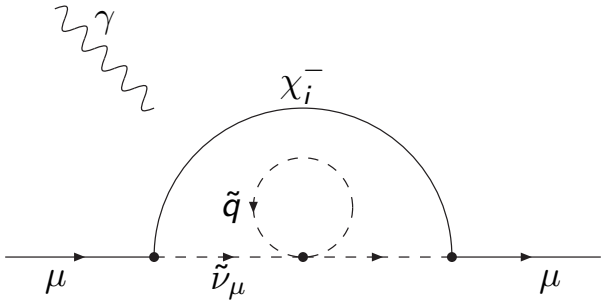


Role of BSM loops — examples

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



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

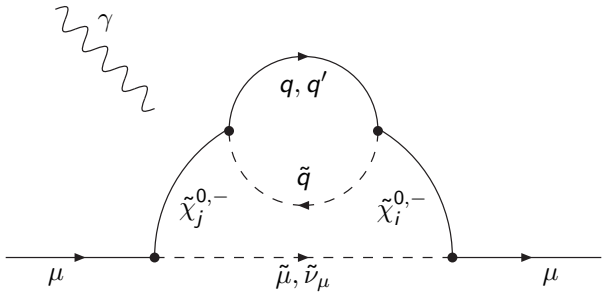


$$\to a_\mu^{\rm 1L} \times \frac{\alpha}{4\pi} \frac{M_{\tilde{q}}^2}{M_{\tilde{\mu}}^2}$$

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

* artifact of $\overline{\rm MS}$ scheme

not present in on-shell scheme!



$$\to a_\mu^{\rm 1L} \times \frac{\alpha}{4\pi} \log\left(\frac{M_{\tilde{q}}}{M_{\rm SUSY}}\right)$$

up to $\mathcal{O}(10\%)$

non-decoupling effect

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

Motivation:

- more than one Higgs well motivated $\rightsquigarrow$ simplest model
- two VEVs contribute differently to masses of W, Z, quarks, leptons

  (we assume flavour/generation-alignment)

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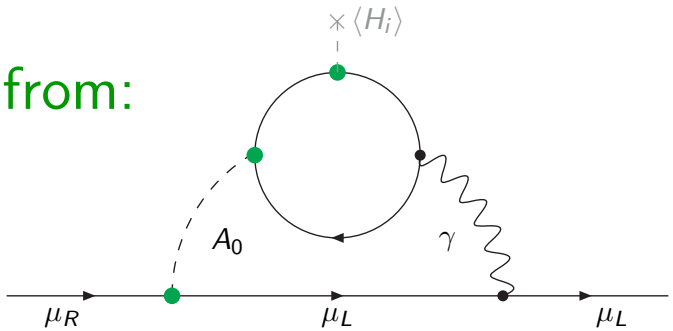
a_μ mainly from:

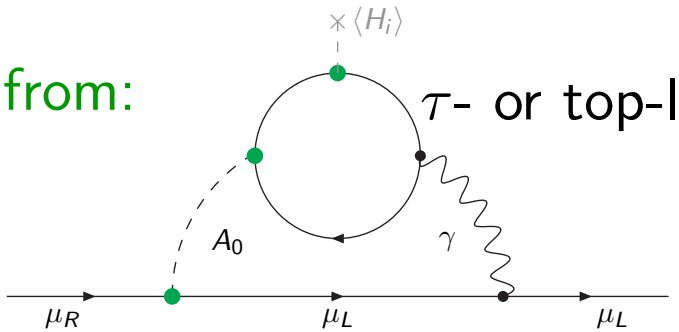


Question:

Can 2HDM accommodate large a_μ (and how large/for which M_A)?

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

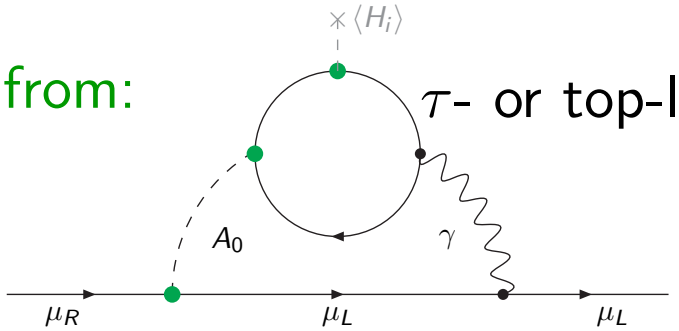
a_μ from:



τ- or top-loop need light A_0, large μ-, τ- and possibly top-Yukawa

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

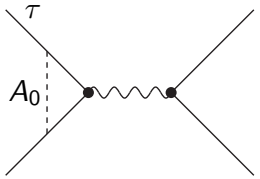
a_μ from:

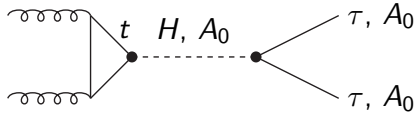


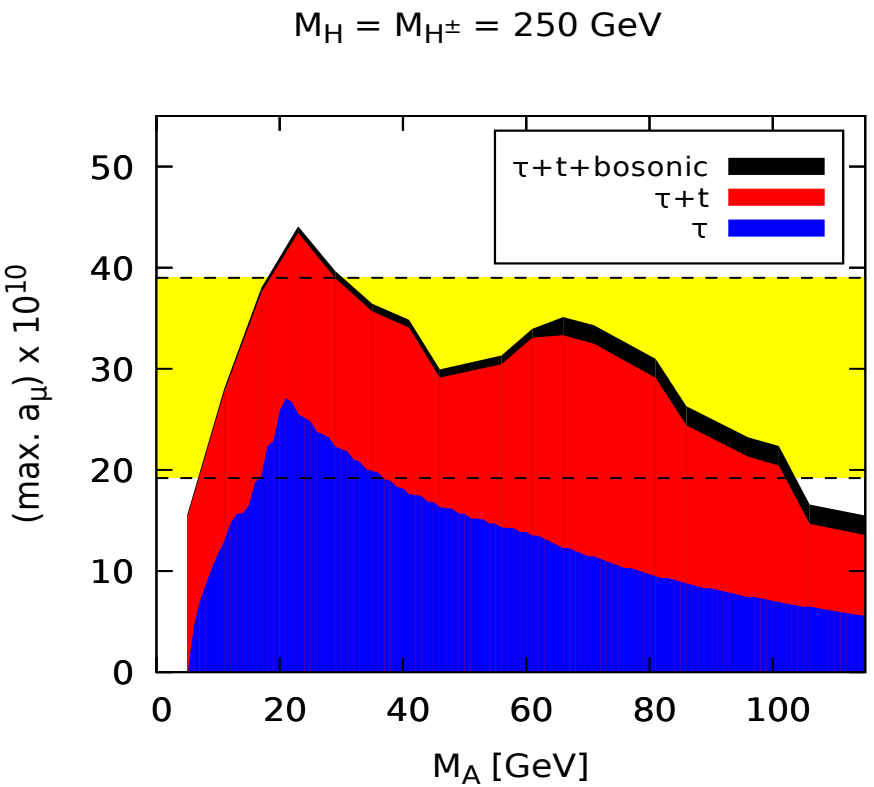
Constraints:

$Z \to \tau\tau$, τ-decay, LEP-4τ-search;

$b \to s\gamma$ and $B_s \to \mu\mu$, LHC $gg \to A, H \to \tau\tau$

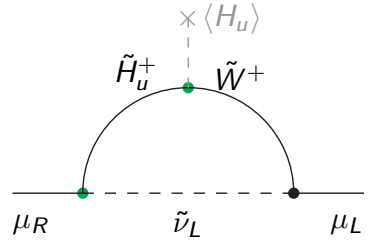






Results: a_μ explained in tightly constrained parameter space; testable by many observables: $Z \to \tau\tau$, τ- and b-decays, LHC $gg \to A, H \to \tau\tau$, future ILC?

Standard SUSY — MSSM



- Many complementary constraints: M_h, LHC-searches, a_μ
- theories of SUSY breaking/mediation $\Rightarrow$ mass relations
- "Constrained MSSM":
  excluded by $a_\mu \oplus M_H \oplus$ LHC-limits (if Δa_μ confirmed)
- viable possibility for a_μ and dark matter: [Cox, Han, Yanagida '18]
  $\tilde{B}\tilde{W}$ coannihilation $\Delta m = 15\text{GeV}$, $M_{\tilde{W}} = 300\text{GeV}$
- or non-minimal GMSB scenario [Bhattacharyya, Yanagida, Yokozaki '18]:
  $m_\chi^{\text{compressed}} < m_{\tilde{l}} \sim 600\text{GeV} \ll m_{\tilde{q}}$

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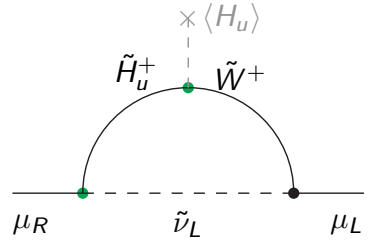

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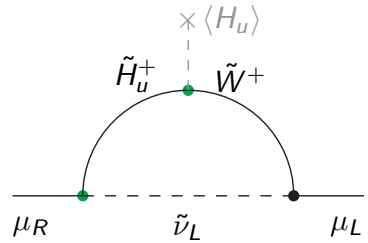
In the following: two unusual scenarios: $\tan\beta \to \infty$, SUSY+R-symmetry

a_μ and radiative muon mass: MSSM for $\tan\beta \to \infty$

[Bach,JH Park,DS,Stöckinger-Kim, '15]



$$v_d = 0 \rightsquigarrow \left\{ \begin{array}{lcl} a_\mu^{\rm SUSY} & \approx & y_\mu v_u \times \text{loop} \\ m_\mu^{\rm pole} & \approx & \underbrace{y_\mu v_d}_{\text{usual approx.}} + \underbrace{y_\mu v_u \times \text{loop}}_{\text{now important}} \end{array} \right\}$$

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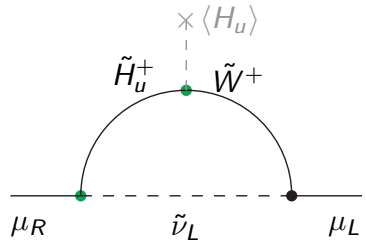

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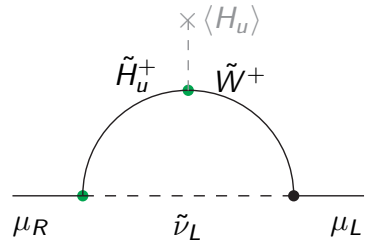

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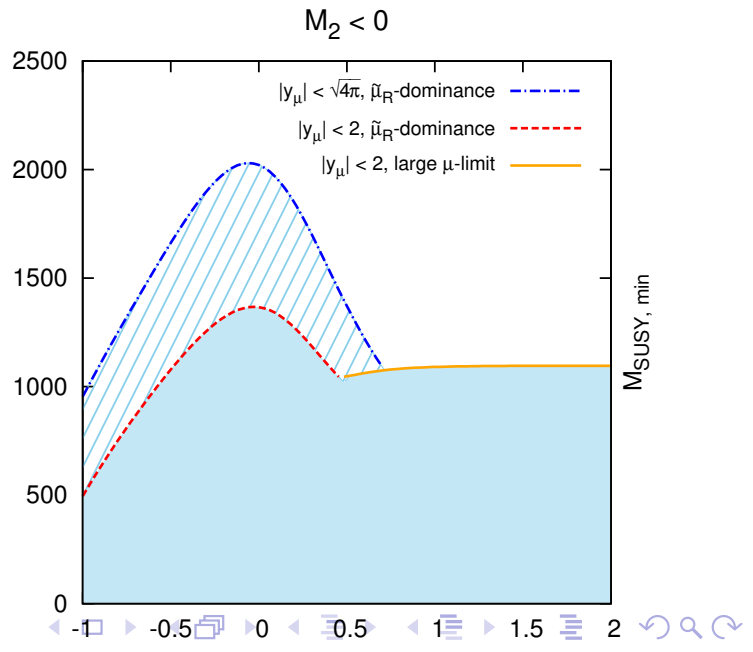
Results:

- radiatively generated m_μ
- a_μ explained for $M_{\rm LSP} > 1$ TeV

Sample TeV-scale masses:

μ	M_1	M_2	m_L	m_R	$a_\mu/10^{-9}$
15	1	-1	1	1	3.01
1.3	1.3	-1.3	26	1.3	2.90

"largest" possible SUSY masses ($:= a_\mu$ explained for $\tan\beta \to \infty$) $\longrightarrow$



a_μ in R-symmetric SUSY?

Motivation:

- SUSY+continuous R-symmetry: beautiful model [Kribs, Poppitz, Weiner]
- successful phenomenology (Higgs, dark matter, LHC, EWPO)
  [Diessner,Kalinowski,Kotlarski,DS'14-'19]
- However, a_μ and other dipoles NOT tan β-enhanced!

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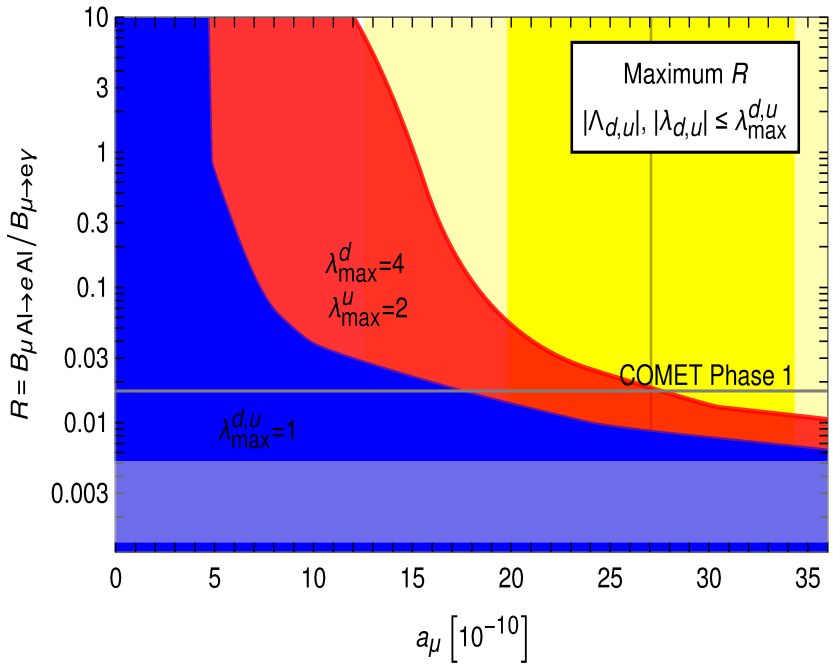
If a_μ large $\Rightarrow$

- $M_{\text{SUSY}} \sim 100$GeV, compressed spectra, testable by LHC/ILC
- strict LFV correlation
  MEG-result $\Rightarrow$ $\mu \to e$ very small

If $\mu \to e$ observed $\Rightarrow$

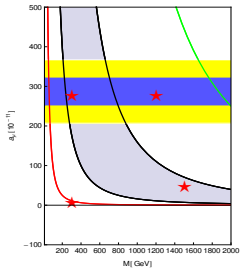
- a_μ must be small in MRSSM



[Kotlarski,DS,Stöckinger-Kim '19]

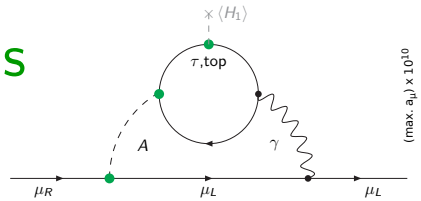
Conclusions

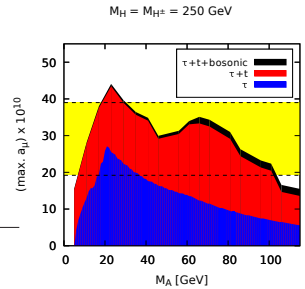
- a_μ longstanding hint for BSM



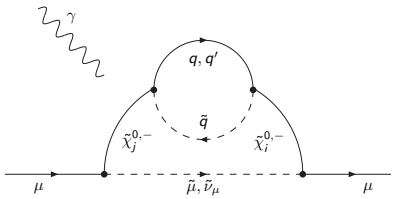
- How can BSM explain deviation in viable way?
  - $a_\mu \leftrightarrow$ Yukawa/SSB sector, large room for BSM
  - complementary to LHC, LEP, LFV, EDMs
  - Potential explanations with M_{NP} up to 2TeV

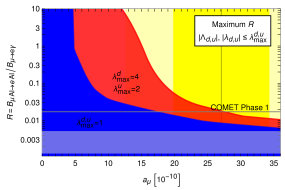
- 2HDM and a_μ: light A_0, large τ, t Yukawas
  - $a_\mu \leftrightarrow$ LHC/Higgs, B-, τ-physics





- SUSY: Standard MSSM, variations
  - a_μ/LHC/dark matter possible
  - $\tan\beta \to \infty$: radiative m_μ
    $\rightsquigarrow$ $M_{\text{LSP}} > 1$TeV possible
  - R-symmetry: no $\tan\beta$-enhancement
    $\rightsquigarrow$ interplay $a_\mu/\mu \to e\gamma/\mu \to e$





- Fermilab exp. running — first results expected this year — promising!