Muon $g-2$ — Three BSM scenarios, lepton flavour violation and a_e

Dominik Stöckinger, TU Dresden

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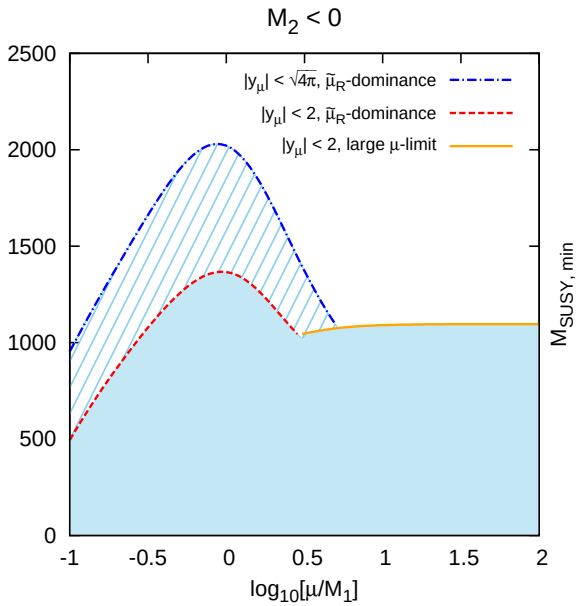
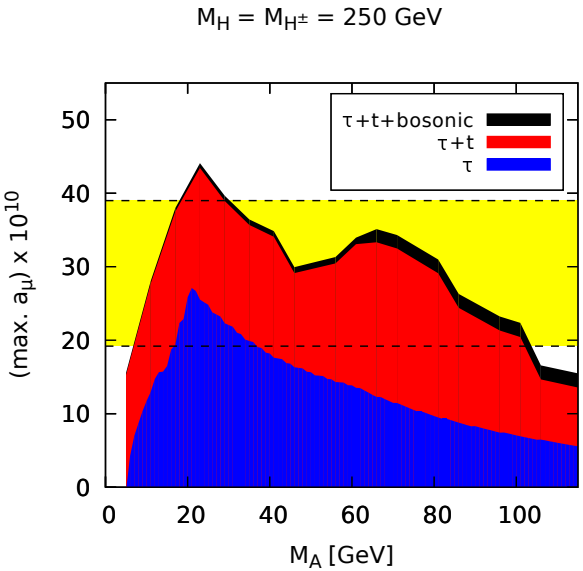
Motivation 1

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (28.1 \pm (6.3^{\rm Exp} \to 1.6^{\rm FUTURE}) \pm 3.6^{\rm Th(KNT)}) \times 10^{-10}$$



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

[Bach,Park,DS,Stöckinger-Kim '15]

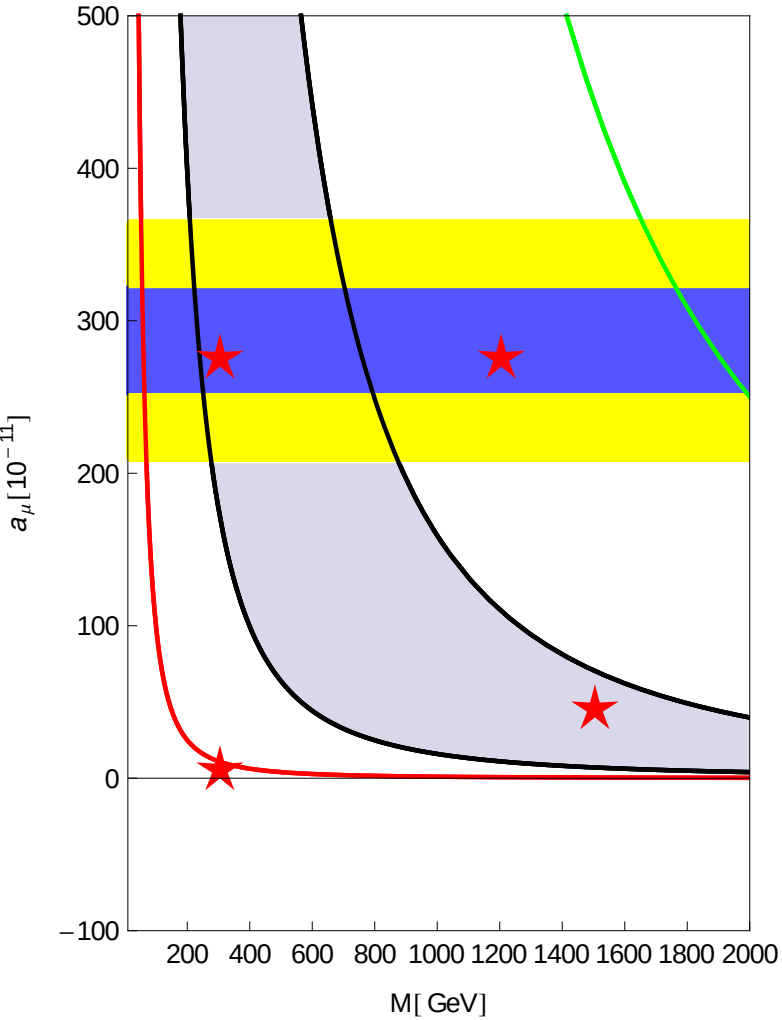


Largest THDM

[Cherchiglia,DS,Stöckinger-Kim '17]

Motivation 2: $g-2$ New Physics overview

Need $a_\mu^{\text{BSM}} \sim 30 \times 10^{-10}$. BUT: $a_\mu^{\text{SM weak}} \sim 15 \times 10^{-10}$ only!



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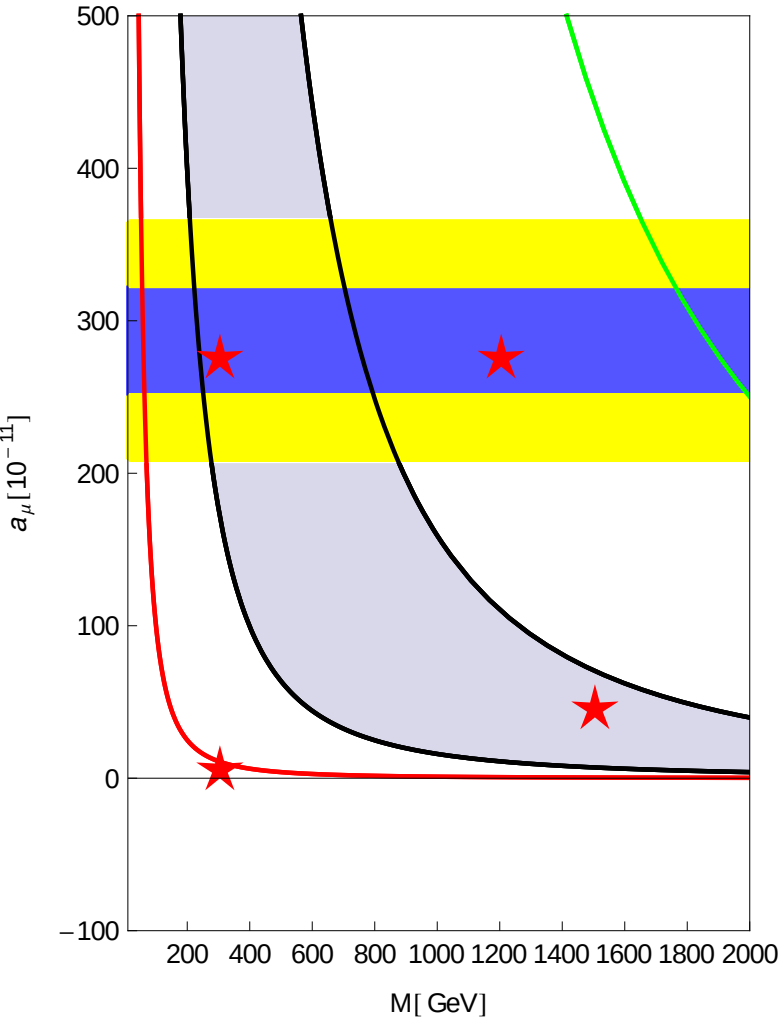

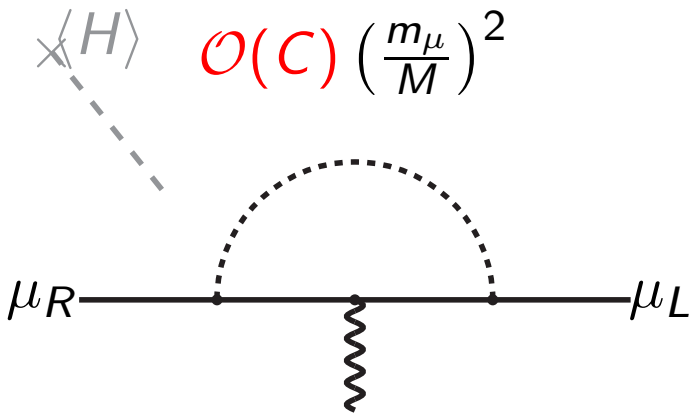

$$a_\mu^{\text{SUSY}} \sim 12 \times 10^{-10} \tan\beta \left(\frac{100\text{GeV}}{M_{\text{SUSY}}}\right)^2$$

$$\sim \frac{\alpha}{4\pi} \tan\beta \left(\frac{m_\mu}{M_{\text{SUSY}}}\right)^2$$

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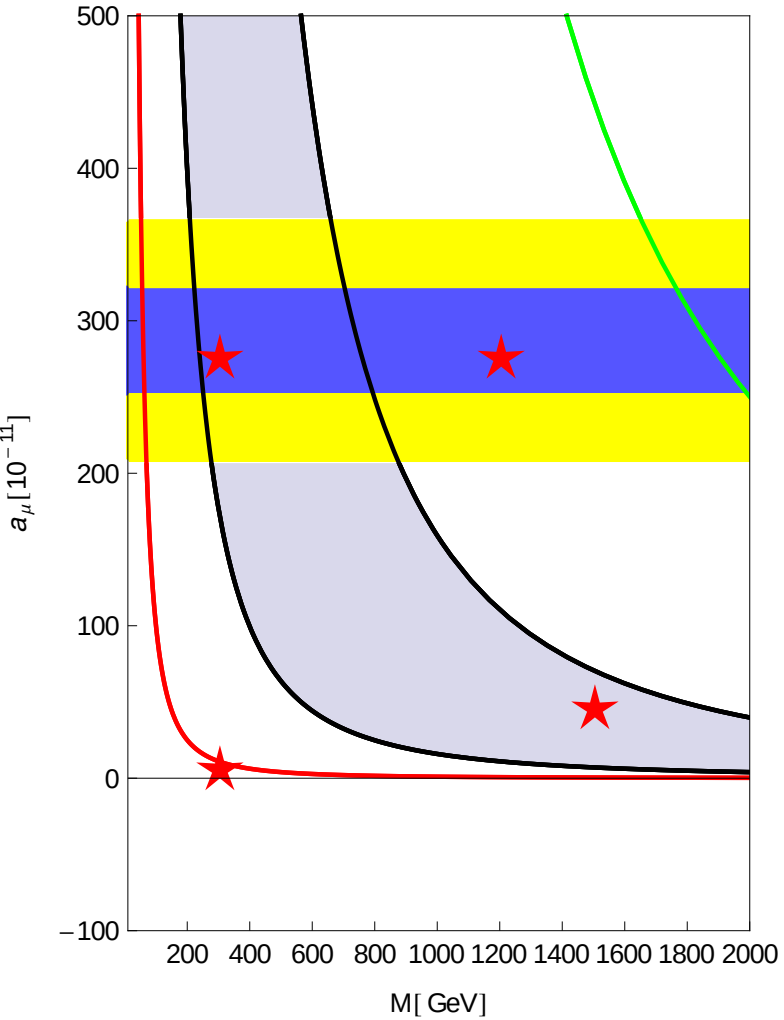

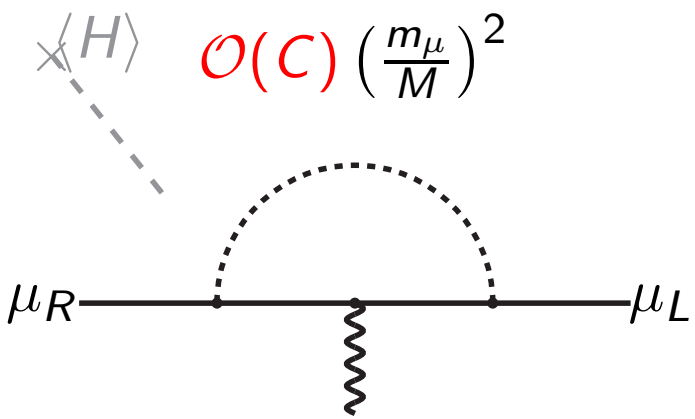

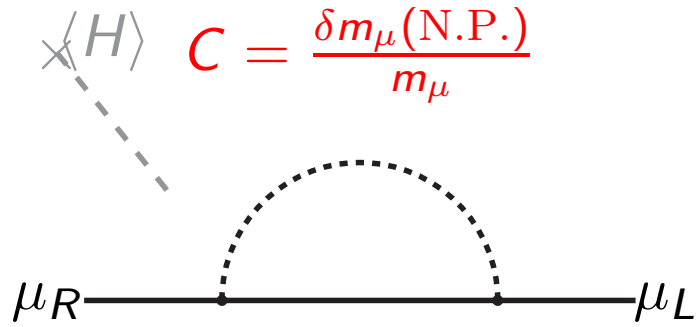

$\Rightarrow$largest reasonable value: $C \approx 1$

Questions and scenarios

- Question 1: Which models/scenarios can explain $a_\mu^{\mathrm{Exp}-\mathrm{SM}}$?
- Question 2: How can these be tested/excluded?

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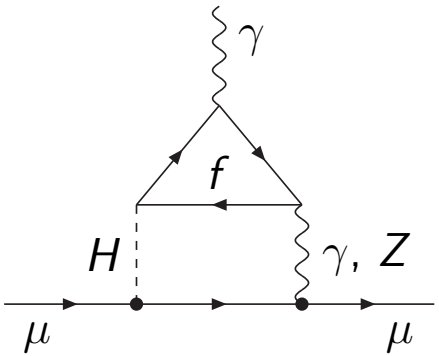
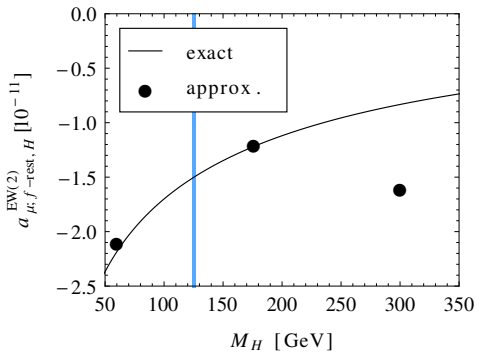
- Question 2: How can these be tested/excluded?
  Outcome: interesting scenarios, correlated observables, tests

Outline

Two-Higgs Doublet Model

- Why only one fundamental scalar doublet in nature?
- Two Higgs doublets H_1, H_2 well motivated! $\Rightarrow h, H, H^{\pm}, A^0$
  [Broggio, Chun, Passera, Patel, Vempati '14, Ilisie '15...]
- However, THDM not very promising for a_μ!





[Gnendiger, DS, Stöckinger-Kim '13]

Tiny SM-Higgs contributions!
THDM typically also small

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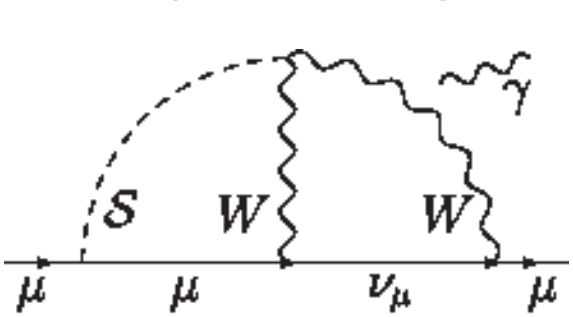
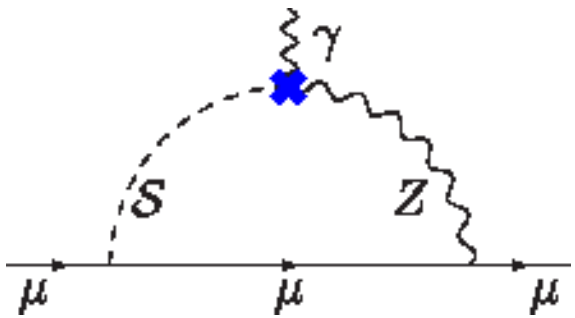
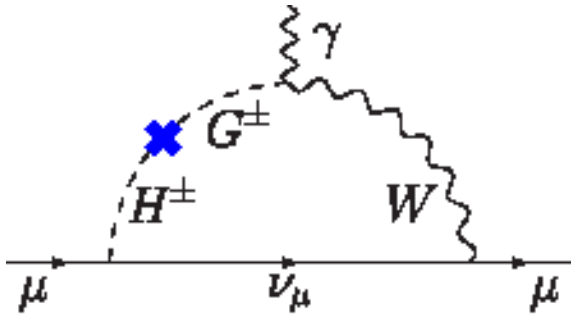
2-loop=leading order, previously not all diagrams known

$\rightsquigarrow$ complete 2-loop calculation motivated [Cherchiglia,Kneschke,DS,Stöckinger-Kim'16]





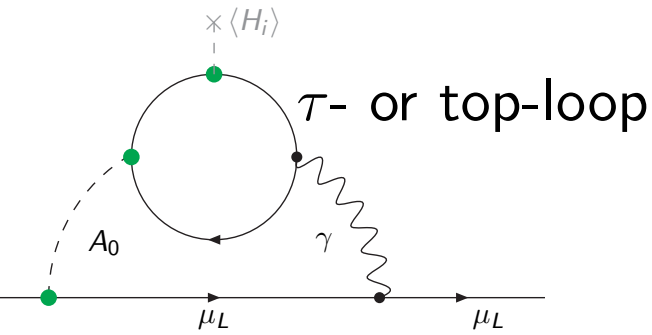


bosonic loops small, if constraints from Higgs/EWPO/unitarity used:

$$|a_\mu^B| \simeq \rho |C_{HH^+H^-}/\text{GeV}|\,|\zeta_I| \times 10^{-15}$$

fermionic Barr-Zee diagrams (previously known) dominant

THDM: Dominant behaviour



$\hat{x} = m/100\,GeV$

$$a_\mu^{F\tau} \simeq \left(\frac{\zeta_l}{100}\right)^2 \left\{\frac{8 + 4\hat{x}_A^2 + 2\ln(\hat{x}_A)}{\hat{x}_A^2}\right\}$$

$$a_\mu^{Ft} \simeq \left(\frac{-\zeta_l \zeta_u}{100}\right) \left\{54 - 14\ln(\hat{x}_A) - 15\ln(\hat{x}_H)\right\}$$

Yukawa couplings: $Y_i^{A_0} = \zeta_i\, Y_i^{SM}$ $(i = l, u, d)$ flavour-aligned [Pich,Tuzon(Jung)]

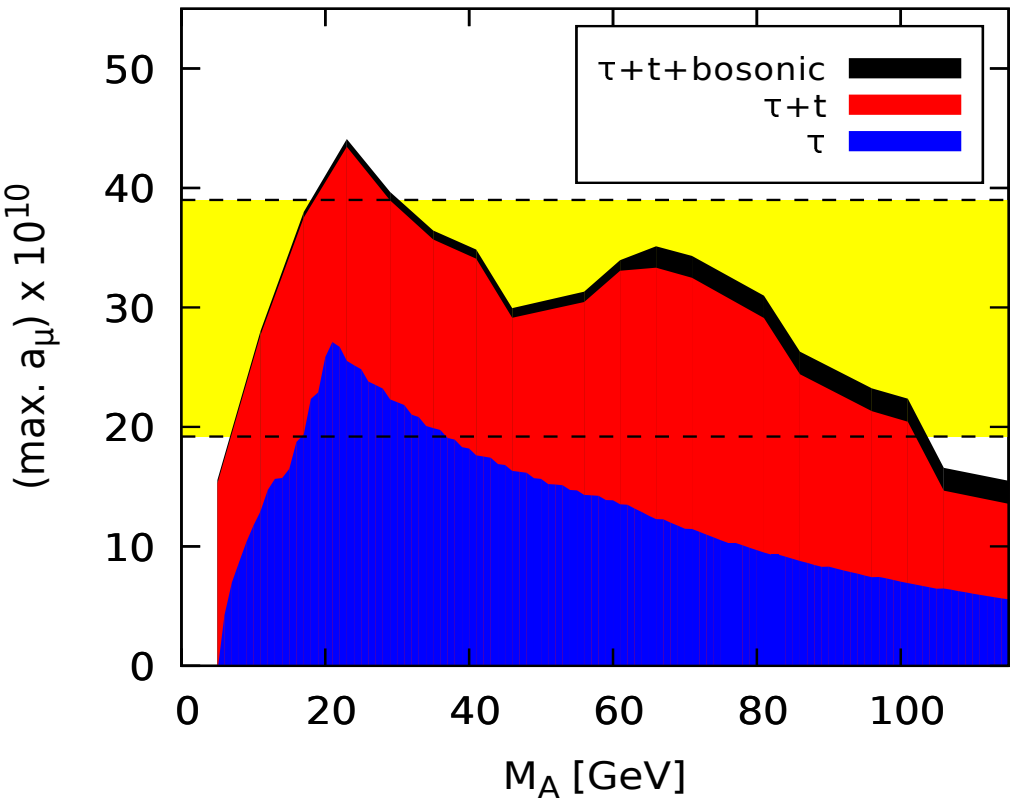
MSSM/Type 2:	$\zeta_{d,l} = -\tan\beta,$	$\zeta_u = 1/\tan\beta$	
Type X (lepton-specific):	$\zeta_l = -\tan\beta,$	$\zeta_{d,u} = 1/\tan\beta$	
General: expect	$\zeta_l \sim 50,$	$\zeta_{d,u} \sim 1,$	$M_A < M_h$

Question: need light M_A and large ζ_l; large ζ_u helps — allowed?

What is the maximum possible a_μ in the 2HDM?

[Cherchiglia,DS,Stöckinger-Kim '17]

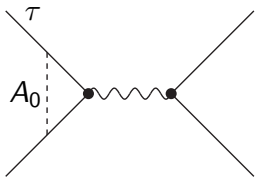
$M_H = M_{H^\pm} = 250$ GeV



Constraints:

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

  Remark: generally $\zeta_l <\sim 100$, $\tan\beta^{\text{type X,II}} <\sim 100$



Type X: 1σ explanation only up to $M_A = 40$
beyond type X: top-loop, bosonic not suppressed for high M_A, 1σ explanation possible up to $M_A = 100$.

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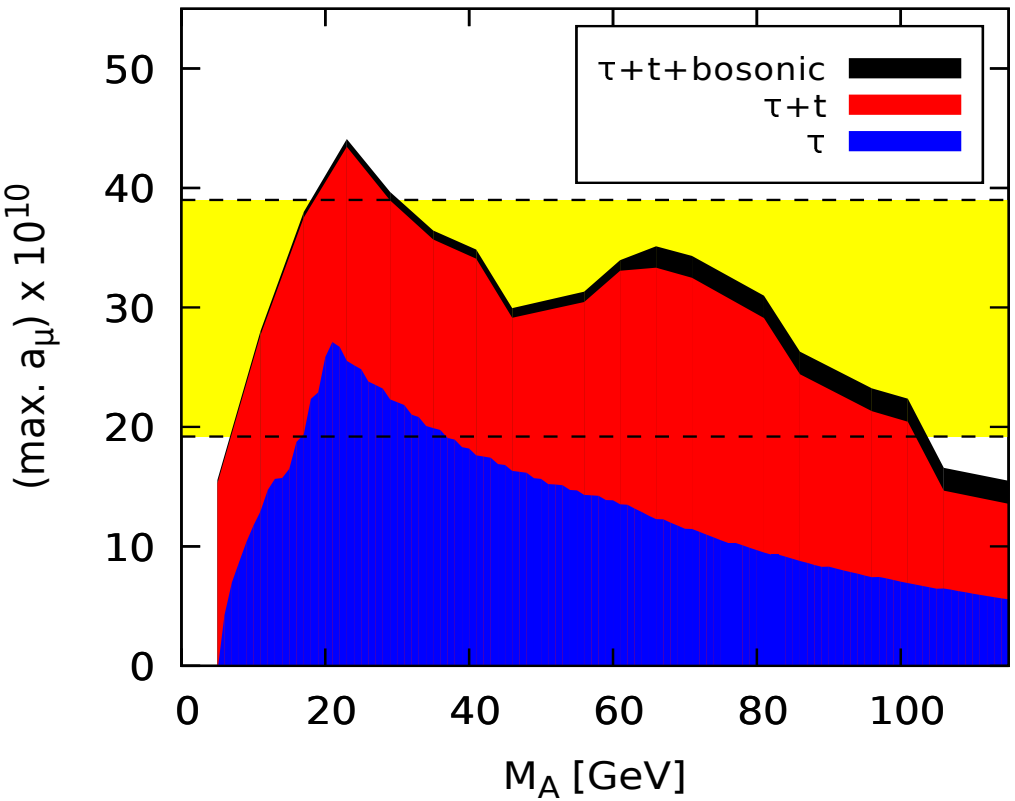
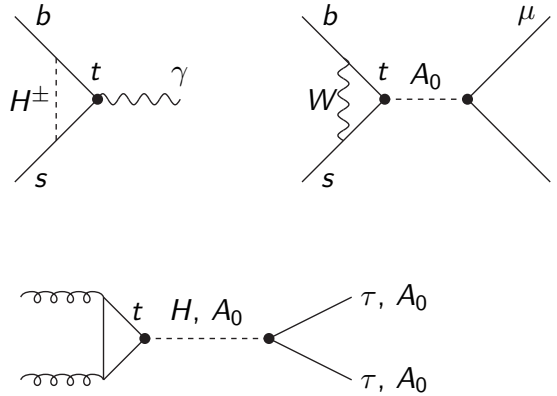


Constraints:

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

Remark: $\zeta_u <\sim 0.5$



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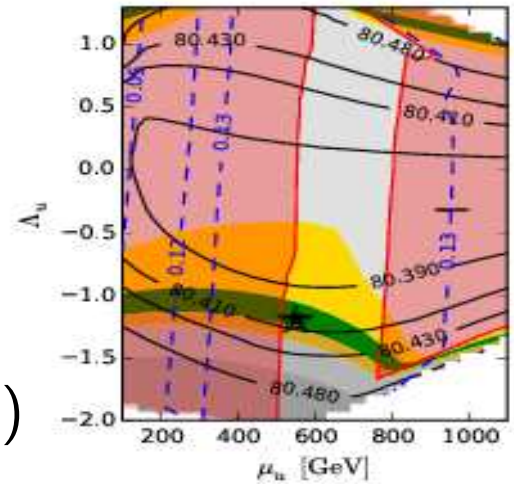
Outline

R-symmetric model MRSSM [Kribs, Poppitz, Weiner]

New fundamental U(1) symmetry, MRSSM related to $N = 2$ SUSY

- surprisingly promising:
  LHC, EWPO, dark matter
  many light states possible
  $S, \chi_1^0, \tilde{H}_d, \tilde{\tau}_R < 150\text{GeV}$,
  $\tilde{W} \approx 400\text{GeV}$
- beautiful/rigid: conserved R-charges
- Gauginos/Higgsinos must be Dirac (not Majorana!)

[Diessner,Kalinowski,Kotlarski,DS,(Liebschner)'14–'16]



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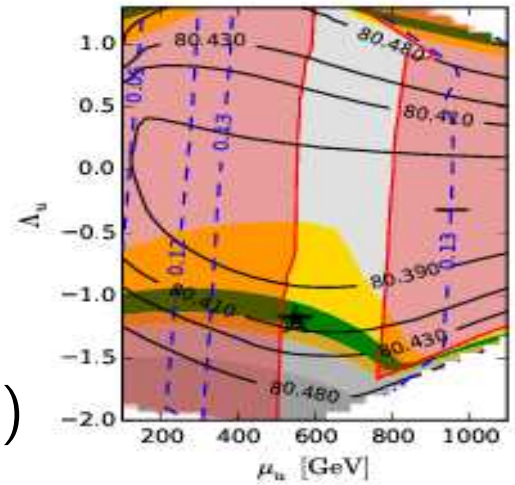

new Yukawa-like terms for Dirac partners $\hat{R}_{u,d}$, $\hat{T}$, $\hat{S}$

$$W_{\text{MRSSM}} = \ldots + \mu \hat{H}_u \hat{H}_d + \mu_u \hat{R}_u \hat{H}_u + \Lambda_u \hat{H}_u \hat{T} \hat{R}_u + y_u \hat{Q} \hat{H}_u \hat{U}$$

$g-2$: compare standard/R-symmetric SUSY

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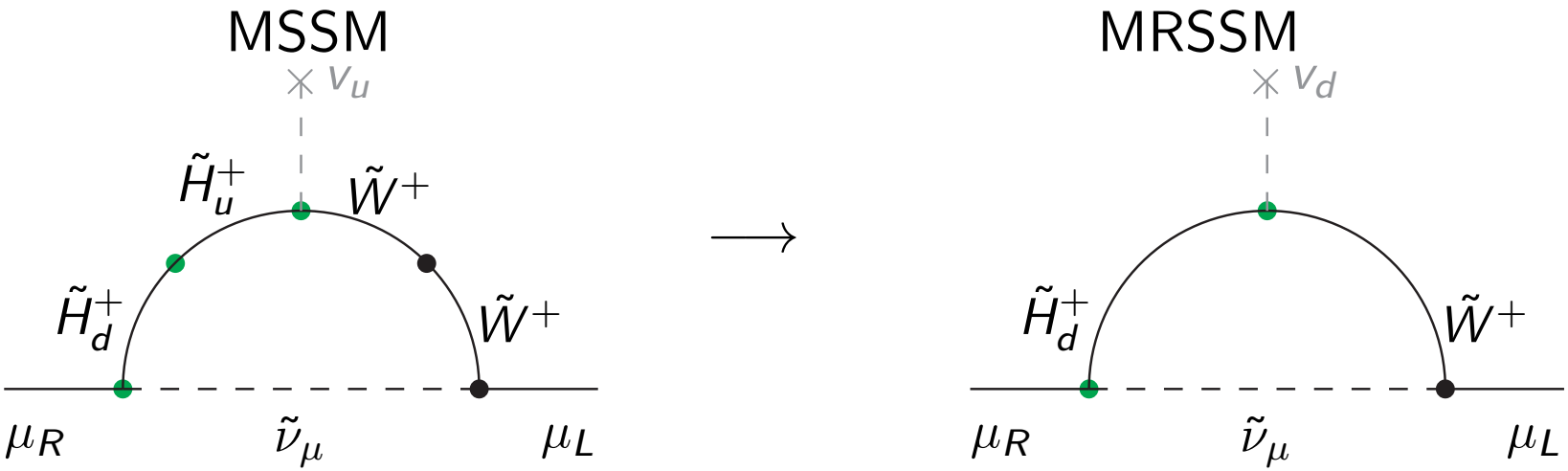

MSSM$\propto v_u y_\mu \propto \tan\beta$

MRSSM$\propto v_d y_\mu = m_\mu$

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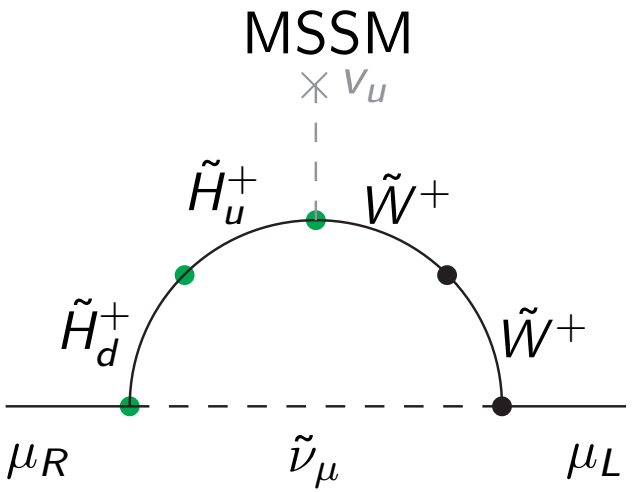
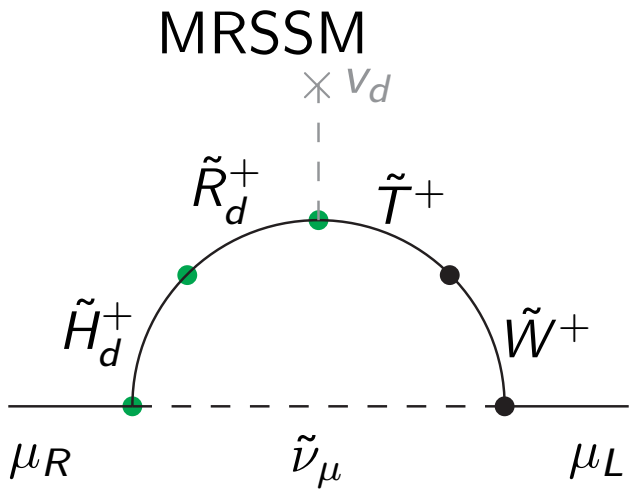


$\longrightarrow$



MSSM$\propto v_u y_\mu \propto \tan\beta$

MRSSM$\propto \Lambda_d / g_2$

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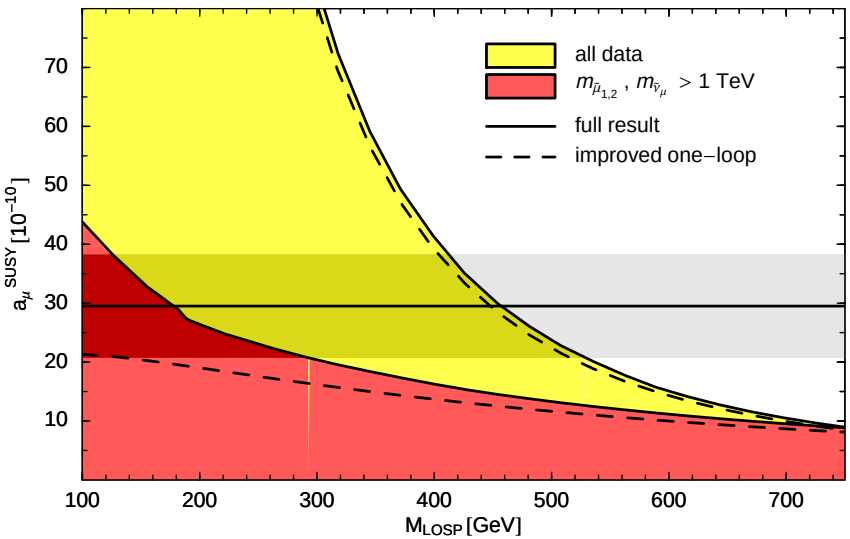
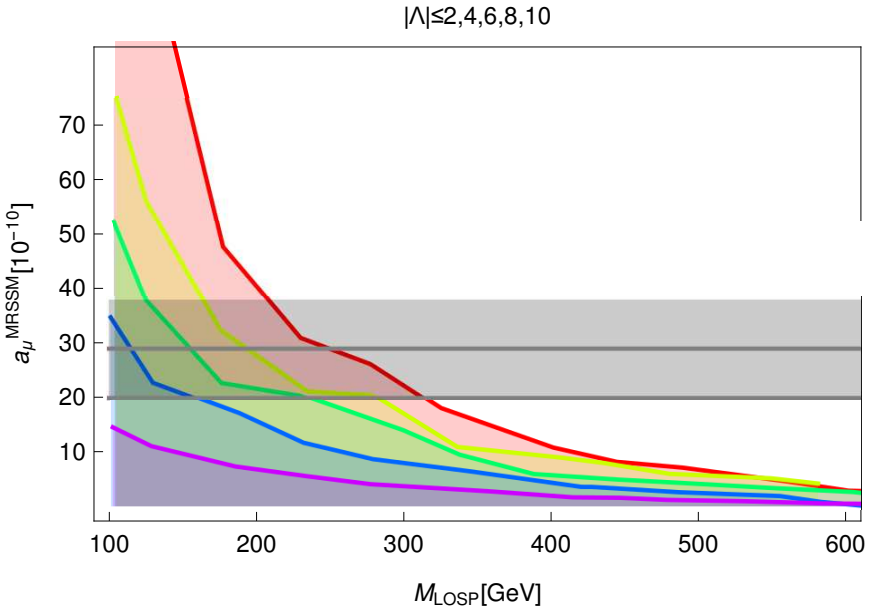
MSSM



[DS '07]

MRSSM



[Kotlarski,Park,DS,Stöckinger-Kim]

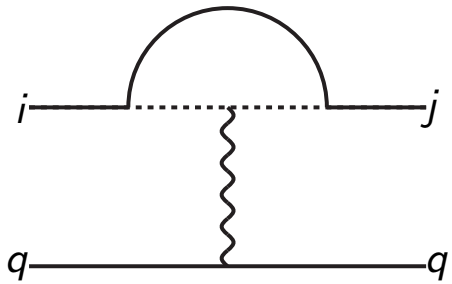
Large a_μ only for very small M_{SUSY} and $\Lambda_i \gg g_i$ (non-$N=2$ SUSY)

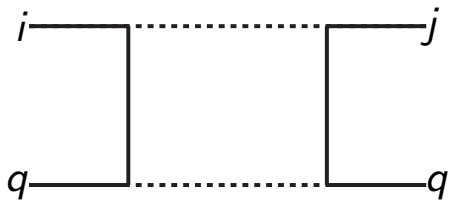
(Non-)correlation with lepton flavour violation

dipole dominance $\Rightarrow$ correlation $\mu \to e$, $\mu \to e\gamma$, $(g-2)_\mu$

- Dipole dominance holds in many BSM scenarios → talk by P. Paradisi
- MRSSM: only for $\Lambda_i \gg g$ (problematic), otherwise not!

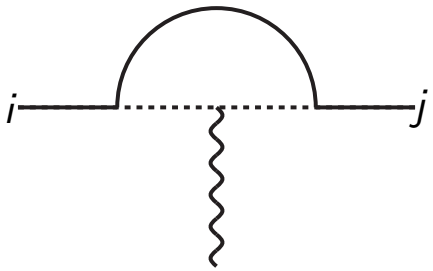
$\mu \to e$





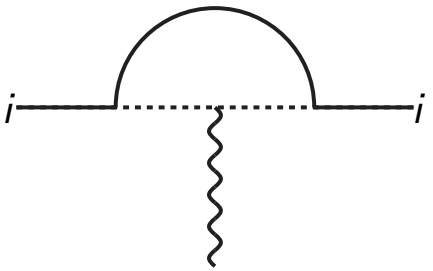
D, A_1^{21}, A_2^{21}

$\mu \to e\gamma$



A_2^{21}

$(g-2)_\mu$



A_2^{22}

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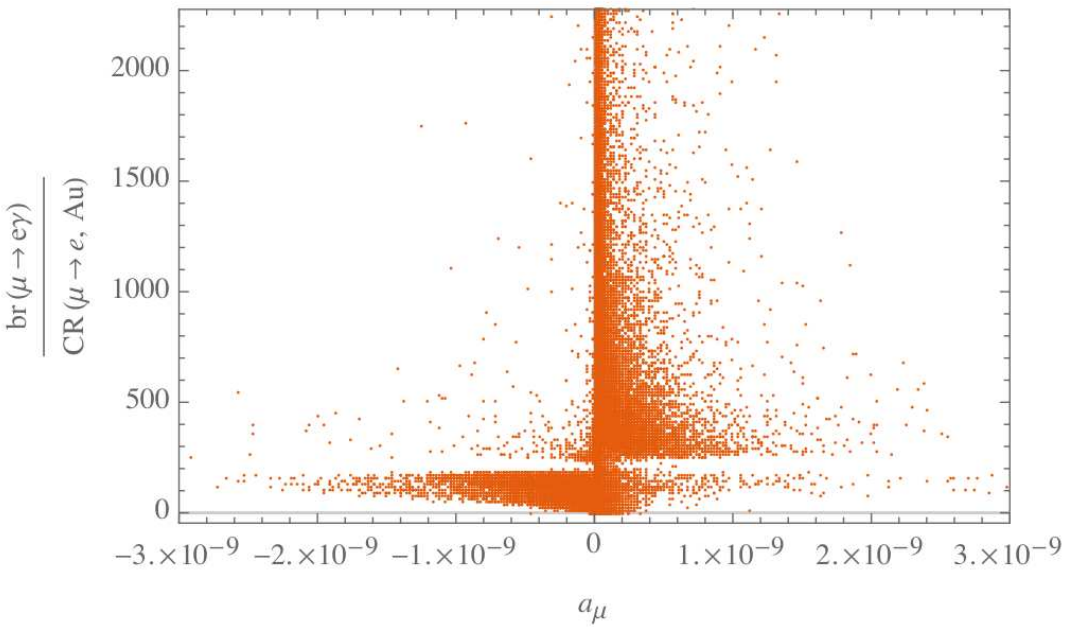


$$\frac{\mu \to e\gamma}{\mu \to e} \text{ vs. } a_\mu$$

from Wojtek Kotlarski

- $\mu \to e\gamma$: MEG-result
- $\mu \to e$: future COMET/Mu2E

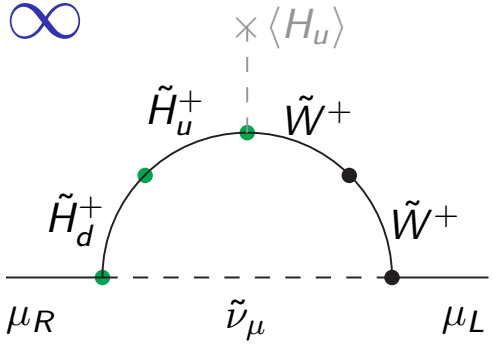
If a_μ large $\Rightarrow$ strict correlation $\overset{\text{MEG-result}}{\Rightarrow}$ $\mu \to e$ unobservable

If $\mu \to e$ observed $\Rightarrow$ a_μ must be small in MRSSM

Outline

Radiative muon mass: MSSM for $\tan\beta \to \infty$

[Bach,JH Park,DS,Stöckinger-Kim, '15]



Idea: $v_d = 0 \rightsquigarrow m_\mu^{\text{tree}} = 0$

$$a_\mu^{\text{SUSY}} = \frac{y_\mu v_u \; a_\mu^{\text{red}}}{m_\mu^{\text{pole}}} + \dots$$

$$m_\mu^{\text{pole}} = \underbrace{y_\mu v_d}_{\text{usual approx.}} + \underbrace{y_\mu v_u \Delta_\mu^{\text{red}}}_{\text{now important}} + \dots$$

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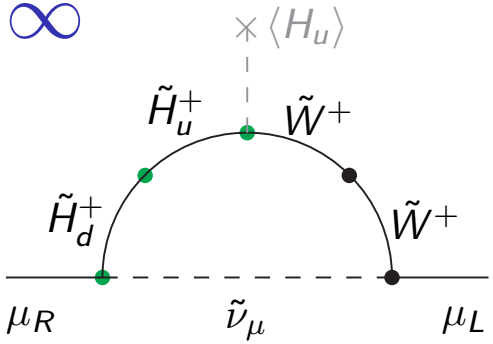

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$$a_\mu^{\text{SUSY}} \longrightarrow \frac{a_\mu^{\text{red}}}{\Delta_\mu^{\text{red}}}$$

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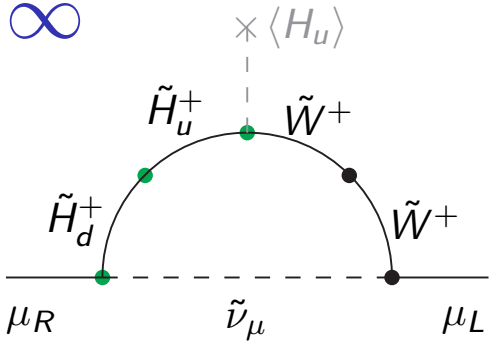

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New features for $\tan\beta \to \infty$:

- a_μ = ratio of loops — no loop suppression!
- many details cancel in ratio — important: mass ratios

Large a_μ in MSSM for $\tan\beta \to \infty$ (or $v_d \to 0$)

[Bach,JH Park,DS,Stöckinger-Kim, '15]

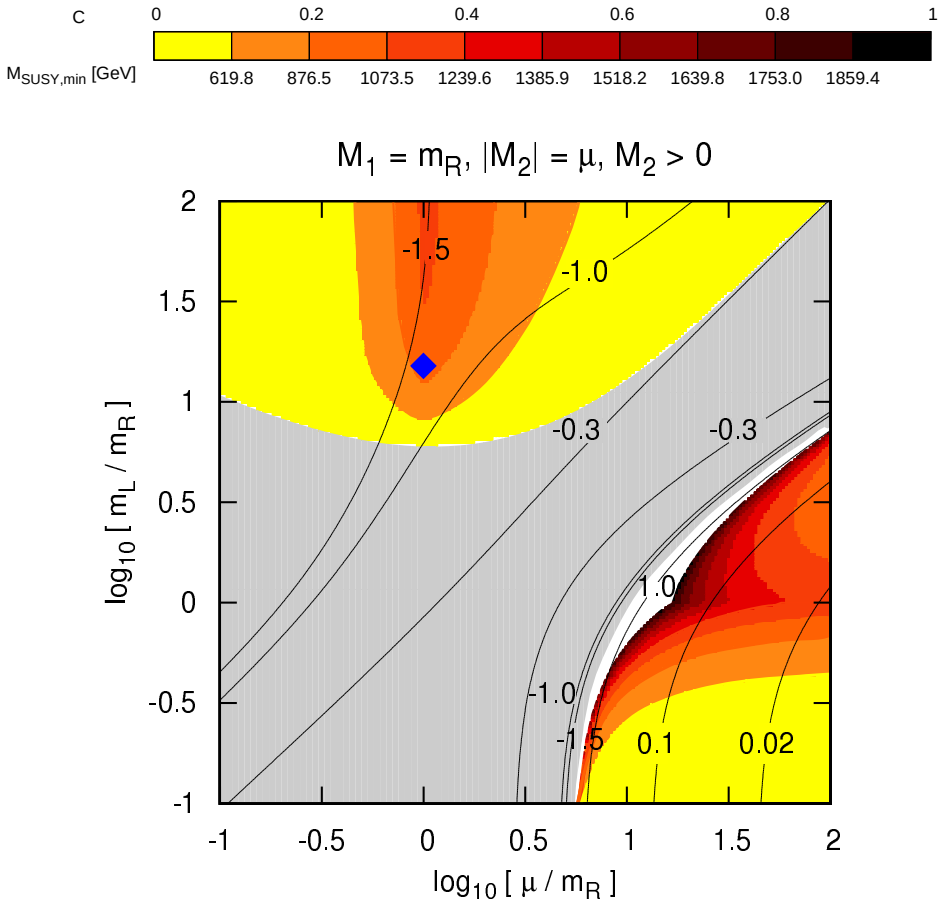
Generally:

$$a_\mu^{\rm SUSY} \equiv C \left(\frac{m_\mu}{M_{\rm SUSY}}\right)^2$$

here

$$C = \mathcal{O}(1)$$

coloured: a_μ positive



Can explain a_μ even if $M_{\rm LSP} > 1$ TeV, large mass hierarchies needed
Experimental constraints ok: B-physics, Higgs-physics, vacuum stability

Thoughts on a_μ vs a_e

Take seriously:

$$a_\mu^{\text{Exp-SM}} = 30 \times 10^{-10}$$
$$a_e^{\text{Exp-SM}} = -9 \times 10^{-13}$$
$$\text{ratio} = -3 \times 10^3$$

Expected:

$$a_\mu^{\text{BSM}} \sim C\,(m_\mu/M_{\text{BSM}})^2$$
$$a_e^{\text{BSM}} \sim C\,(m_e/M_{\text{BSM}})^2$$
$$\text{ratio} \sim 40 \times 10^3$$

Thoughts on a_μ vs a_e

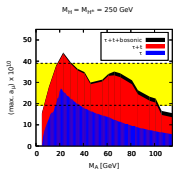
Take seriously:

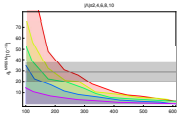
$$a_\mu^{\text{Exp-SM}} = 30 \times 10^{-10}$$
$$a_e^{\text{Exp-SM}} = -9 \times 10^{-13}$$
$$\text{ratio} = -3 \times 10^3$$

Expected:

$$a_\mu^{\text{BSM}} \sim C\,(m_\mu/M_{\text{BSM}})^2$$
$$a_e^{\text{BSM}} \sim C\,(m_e/M_{\text{BSM}})^2$$
$$\text{ratio} \sim 40 \times 10^3$$

$a_e^{\text{Exp-SM}}$ "too large" by factor 12, sign opposite





Try THDM $\Rightarrow$ overall maximum $|a_e^{\text{A-THDM}}| \leq 1 \times 10^{-13}$

Try MRSSM $\Rightarrow$ a_e explained for $M_{\text{LOSP}} < 50$ GeV

Try vanilla MSSM $\Rightarrow$ a_e explained for $\tan\beta = 50$ and $M_{\text{LOSP}} < 150$ GeV

a_e cannot (almost not) be explained in these models (even ignoring a_μ)

Thoughts on a_μ vs a_e

Take seriously:

$$a_\mu^{\text{Exp-SM}} = 30 \times 10^{-10}$$
$$a_e^{\text{Exp-SM}} = -9 \times 10^{-13}$$
$$\text{ratio} = -3 \times 10^3$$

Expected:

$$a_\mu^{\text{BSM}} \sim C\,(m_\mu / M_{\text{BSM}})^2$$
$$a_e^{\text{BSM}} \sim C\,(m_e / M_{\text{BSM}})^2$$
$$\text{ratio} \sim 40 \times 10^3$$

Radiative m_e, m_μ, $\tan\beta \to \infty$:

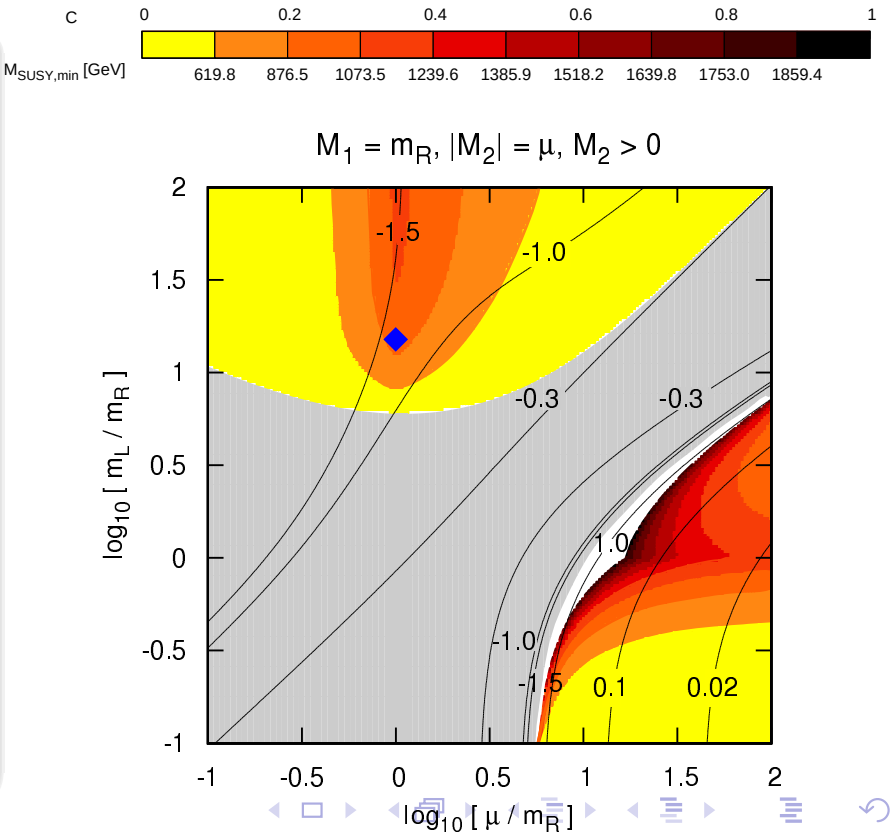
$$M_{\text{SUSY}} = \ldots = m_{\tilde{e}_R} = 500 \text{ GeV}$$

$$\Rightarrow \quad a_e = -7 \times 10^{-13}$$

$$m_{\tilde{\mu}_R} = (7 \ldots 10) \times M_{\text{SUSY}}$$

$$\Rightarrow \quad a_\mu \sim 30 \times 10^{-10}$$

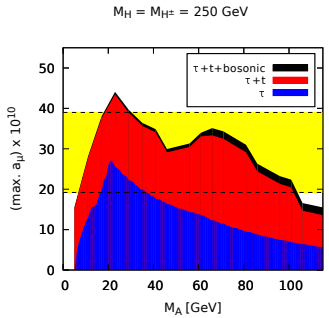
$\tan\beta \to \infty$: perfect fit to a_μ and a_e!



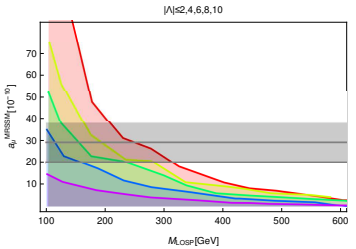
Outline

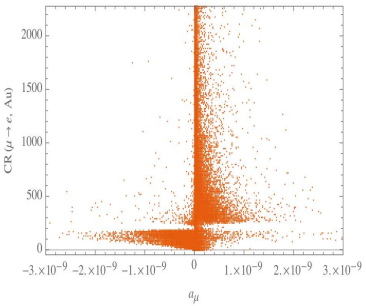
Conclusions

- $(g-2)_\mu$: Intriguing hint for new physics
  - $a_\mu^{\text{Exp}} - a_\mu^{\text{SM}} \approx (30 \pm 8) \times 10^{-10}$
  - Exp and TH progress
- Two-Higgs doublet model
  - $g-2 \rightsquigarrow$ light A_0, large τ, t Yukawas
  - LEP,LHC,B-physics $\Rightarrow |\zeta_l| <\sim 50$, $\zeta_u <\sim 0.5$



- R-symmetric SUSY MRSSM
  - motivated by fundamental symmetry
  - successful phenomenology
  - interplay $g-2/\mu \to e\gamma/\mu \to e$





- MSSM $\tan\beta \to \infty$
  - largest a_μ in SUSY
  - could fit well even to a_e