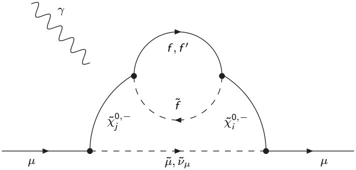
# Magnetic moment $(g-2)_\mu$ and Supersymmetry

Dominik Stöckinger

TU Dresden




Capri meeting "Flavour changing and conserving processes", September 2015

SM prediction too low by $\approx (30 \pm 8) \times 10^{-10}$

Can be due to new physics!

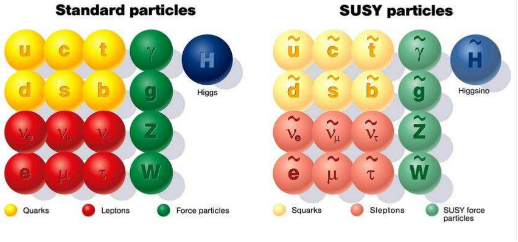
Plan:

- General overview
- Specific topics in SUSY phenomenology/precision calculations

# Outline

# SUSY well motivated

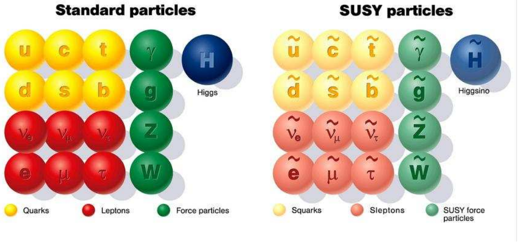
There must be new physics: Baryogenesis, $\nu$-masses, dark matter...



# SUSY well motivated

SUSY: maximal extension of Poincaré symmetry (Haag, Lopuszanski, Sohnius)

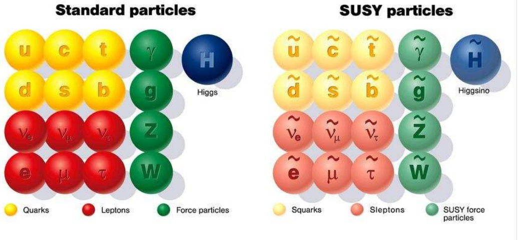
- improves quantum field theories
- connection to gravity
- explains existence of scalars



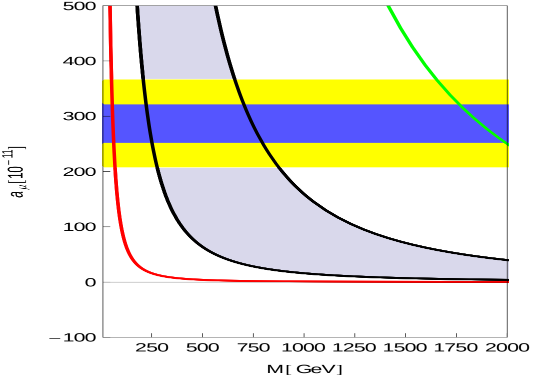
# SUSY well motivated

SUSY at TeV-scale motivated . . . and not excluded by LHC!

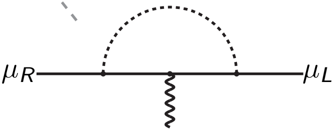
- can improve EW naturalness
- can generate/explain Mexican-hat potential and $M_h = 125$ GeV
- GUT
- dark matter



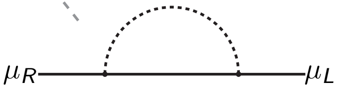
# Very different contributions to $a_\mu$: $C \sim \mathcal{O}(\alpha/4\pi)\ldots\mathcal{O}(1)$




$\times\langle H\rangle$ $\mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2$



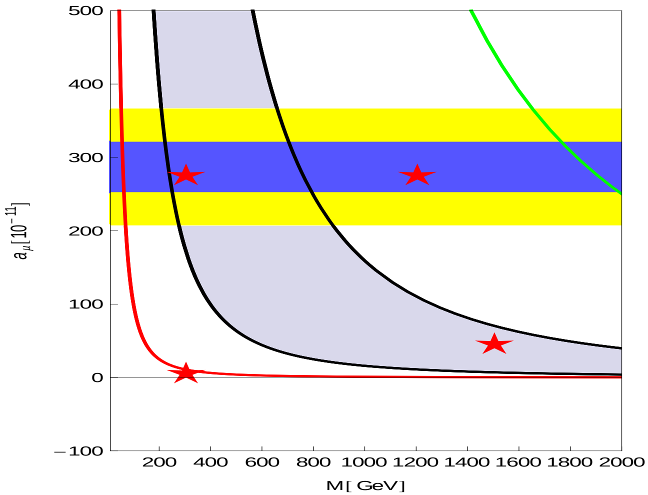

$\times\langle H\rangle$ $C = \frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}$



# Outline

2. SUSY: Phenomenology
   - Illustrate wide range of possibilities
   - Novel, special scenarios

# Plan: "Standard" and "Non-standard" scenarios



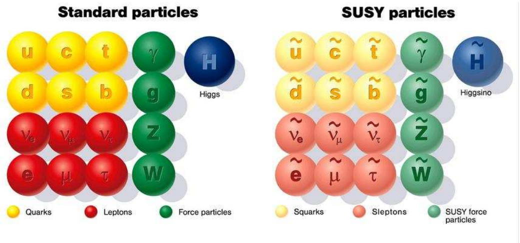

(SUSY is a framework not a concrete model! There is not "The SUSY prediction for $a_\mu$", but prediction depends on scenario)

# Standard SUSY and the MSSM

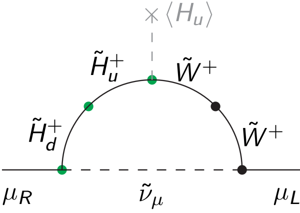
- MSSM: superpartners for all SM fields, two Higgs doublets
- free parameters: $\tilde{p}$ masses and mixings, $\mu$ and $\tan\beta$

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

SUSY could be the origin of the observed $(30 \pm 8) \times 10^{-10}$ deviation!



# Chirality flip and $\tan\beta$-enhancement




Two Higgs and Higgsino doublets:

$$\tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}, \quad \mu = H_u - H_d \text{ transition}$$

Large Yukawa as in 2HDM

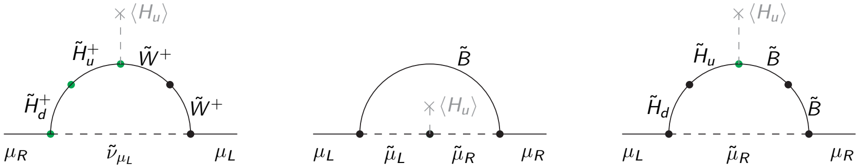
$$m_\mu^{\text{tree}} = y_\mu \langle H_d \rangle$$

Diagram enhanced by Yukawa and large "other" vev

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

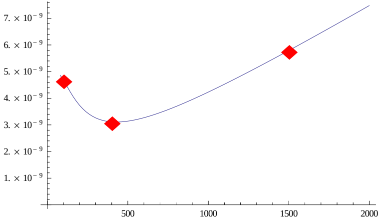
enhancement $\propto \tan\beta = 1 \ldots 50$ (and $\propto$sign($\mu$))

# Further diagrams can sometimes dominate

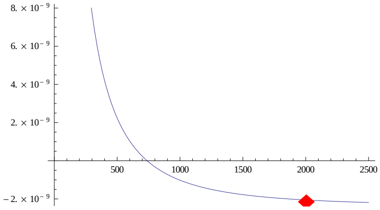



"standard" $\quad \propto \mu$ for $\mu \to \infty \quad \propto$ other sign!

small/large $\mu$

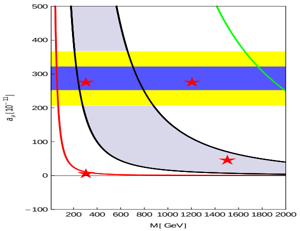



small/large $M_{\tilde{\mu}_L}$

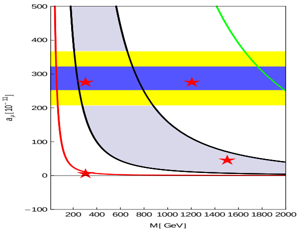



[Fargnoli,Gnendiger,Passehr,DS,Stöckinger-Kim '13]

# Hence: two examples within standard SUSY



# Hence: two examples within standard SUSY

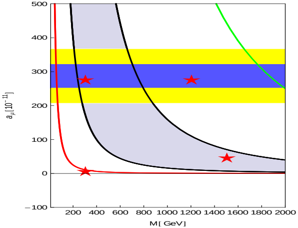



Obviously, the LHC rules out specific SUSY models as explanations of g-2.

e.g. "Constrained MSSM".
Universality ⇒ masses strongly correlated

- Observed Higgs mass
- no gluinos/squarks at LHC
  ⇒ all sparticles heavy
- hence, $a_\mu$ contributions negligible

# Hence: two examples within standard SUSY




## Many other scenarios exist

many model building studies

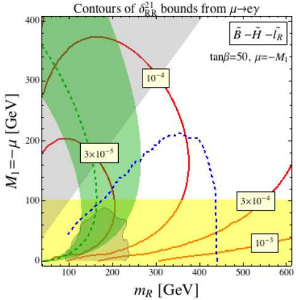
[Endo, Hamaguchi, Ibe, Yanagida, D.P. Roy, . . . ]

- large $a_\mu$ for $m_{\text{weak}} \sim 100 \ldots 400$ GeV

  [Fargnoli,Gnendiger,Passehr,DS,Stöckinger-Kim '13]

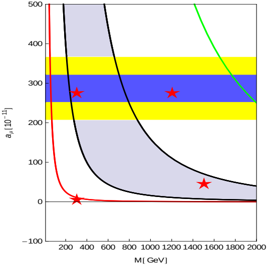
- evade LHC by $m_{\text{coloured}} \gg 1$ TeV
- or by compact spectra → talk by Patel
- can carry out dedicated LHC studies

  [Endo; Yanagida; Roy; Calibbi; Roszkowski. . . ] → talk by Paradisi




[Calibbi et al '15]

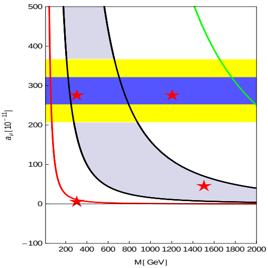
# 3rd Example: large $a_\mu$ for large masses




Is it possible to explain the $a_\mu$ deviation with TeV-scale SUSY?

What is the largest possible SUSY contribution to $a_\mu$?

# 3rd Example: large $a_\mu$ for large masses



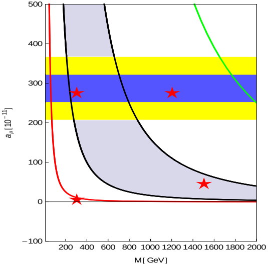

Idea: radiative muon mass in SUSY

$$m_\mu^{\text{tree}} = y_\mu v_d$$

set $v_d \to 0$, $\tan\beta \to \infty$

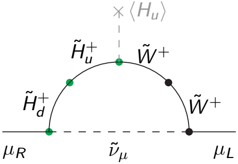
[Dobrescu, Fox '10][Altmannshofer, Straub '10] (see also [Davies,March-russell,Mccullough '11])

# 3rd Example: large $a_\mu$ for large masses




Idea: radiative muon mass in SUSY

$$m_\mu^{\text{full}} = y_\mu v_d +$$




$$+ \ldots$$

set $v_d \to 0$, $\tan\beta \to \infty$

[Dobrescu, Fox '10][Altmannshofer, Straub '10] (see also [Davies,March-russell,Mccullough '11])

# Large $a_\mu$ in MSSM for $\frac{v_u}{v_d} = \tan\beta \to \infty$

[Bach,Park,DS,Stöckinger-Kim, '15]

"standard case" (equal masses, 1-loop)

$$m_\mu = v_d y_\mu \Big(1 \underbrace{+\frac{v_u}{v_d}\Delta_\mu^{\text{red}}}_{\text{normally neglected}} \Big)$$

$$a_\mu^{\text{SUSY}} \approx \underbrace{12 \times 10^{-10} \tan\beta}_{y_\mu \ldots} \,\text{sign}(\mu) \left(\frac{100\text{GeV}}{M_{\text{SUSY}}}\right)^2$$

# Large $a_\mu$ in MSSM for $\frac{v_u}{v_d} = \tan\beta \to \infty$

[Bach,Park,DS,Stöckinger-Kim, '15]

actually, including higher order effects
[Marchetti,Mertens,Nierste,DS '08]

$$m_\mu = v_d y_\mu \Big(1 \underbrace{+\frac{v_u}{v_d}\Delta_\mu^{\text{red}}}_{\text{normally neglected}}\Big)$$

$$a_\mu^{\text{SUSY}} \approx \frac{12 \times 10^{-10} \tan\beta \,\text{sign}(\mu)}{1 - 0.0018 \tan\beta\,\text{sign}(\mu)} \left(\frac{100\text{GeV}}{M_{\text{SUSY}}}\right)^2$$

# Large $a_\mu$ in MSSM for $\frac{v_u}{v_d} = \tan\beta \to \infty$

limit $\tan\beta \to \infty$

$$m_\mu = v_d y_\mu \Big( 1 \quad \underbrace{+ \frac{v_u}{v_d} \Delta_\mu^{\text{red}}}_{\text{normally neglected}} \quad \Big)$$

$$a_\mu^{\rm SUSY} \approx -70 \times 10^{-10} \left( \frac{1000 \rm GeV}{M_{\rm SUSY}} \right)^2$$

$\tan\beta$ and sign($\mu$) drop out, large contributions for $M_{\rm SUSY} \sim$ TeV!

# Large $a_\mu$ in MSSM for $\frac{v_u}{v_d} = \tan\beta \to \infty$

limit $\tan\beta \to \infty$

$$m_\mu = v_d y_\mu \Big(1 \quad \underbrace{+\frac{v_u}{v_d}\Delta_\mu^{\text{red}}}_{\text{normally neglected}} \quad \Big)$$

$$a_\mu^{\mathrm{SUSY}} \approx -70 \times 10^{-10} \left(\frac{1000\mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^2$$

"standard" case: sign wrong! But note: all masses were set equal!

# Large $a_\mu$ in MSSM for $\tan\beta \to \infty$, different masses

[Bach,Park,DS,Stöckinger-Kim, '15]

Generally: $a_\mu^{\rm SUSY} \to \frac{a_\mu^{\rm red}}{\Delta_\mu^{\rm red}}$

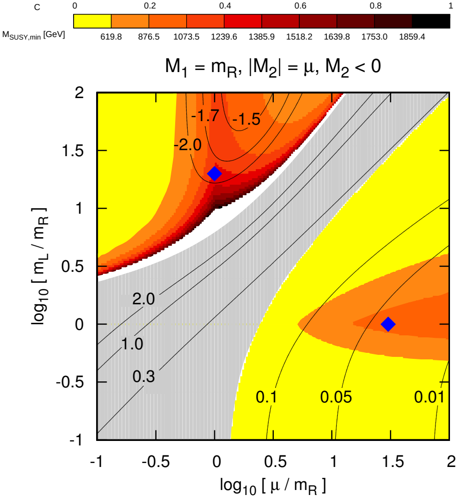
coloured: $a_\mu$ positive

Sample TeV-scale masses:

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

Experimental constraints ok: B-physics,

Higgs-physics, vacuum stability

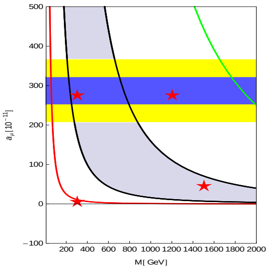


# 4th Example: small $a_\mu$, small masses

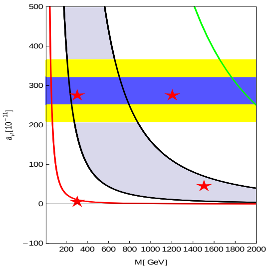
Questions:

Can all SUSY scenarios give large contributions?

Try opposite reaction to LHC: not less, but
more SUSY, more symmetry, more light sparticles!



# 4th Example: small $a_\mu$, small masses




Questions:

Can all SUSY scenarios give large contributions?

Try opposite reaction to LHC: not less, but
more SUSY, more symmetry, more light sparticles!
R-symmetry, MRSSM [Kribs, Poppitz, Weiner '08]

- sparticles charged under conserved R-charge
- gauge bosons have two gauginos ($R = \pm 1$) and one scalar superpartner
- R-symmetry suppresses LHC cross sections, lighter sparticles viable [Kribs, Martin '10]
- compatible with Higgs and LEP constraints [Diessner, Kalinowski, Kotlarski, DS '14]

# 4th Example: small $a_\mu$, small masses

Questions:

Can all SUSY scenarios give large contributions?

Try opposite reaction to LHC: not less, but
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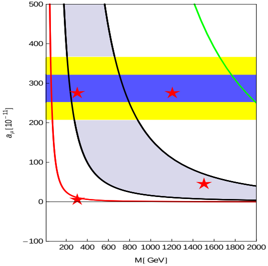
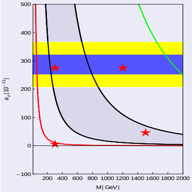



- kills $g-2$ (no $\tan\beta$ enhancement)
- all $\tan\beta$-enhanced contributions: $\propto \mu M_{1,2}$
- both $\mu$ and Majorana gaugino masses forbidden by R-symmetry

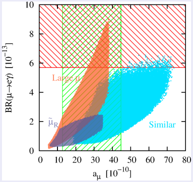
predictive!

# Complementarity/correlations

Strong correlations between observables are interesting
But they typically depend strongly on the scenario
all observables needed to uncover model details



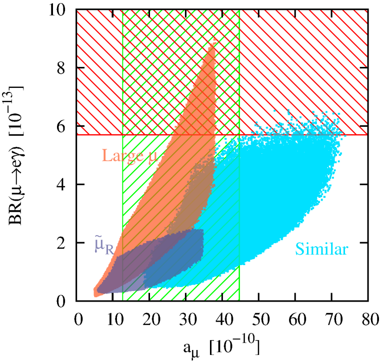

LHC$\oplus a_\mu$: masses



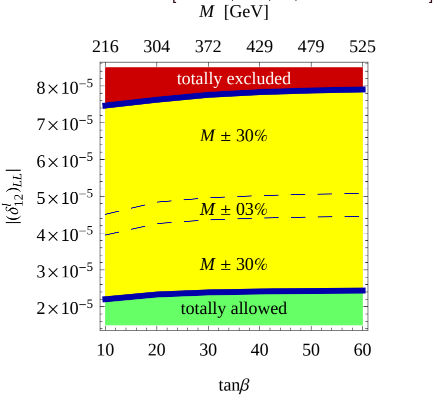

LFV$\oplus a_\mu$: LFV parameters

# $\mu \to e\gamma$: correlation with $g-2$ depends on scenario

[Kersten,Park,DS,Velasco-Sevilla '14]




parameter regions where single diagrams dominate




bounds on $\delta_{LL}$ assuming $M$ is fixed to accommodate $a_\mu$

- study correlation for fixed $\delta_{LL} = m^2_{\tilde{L}_{12}} / \sqrt{m^2_{\tilde{L}_{11}} m^2_{\tilde{L}_{22}}} = 2 \times 10^{-5}$
  - correlation often studied [Chacko,Kribs'01; Isidori, Mescia, Paradisi, Temes '07]
  - but depends on mass pattern [Kersten,Park,DS,Velasco-Sevilla '14]
- still, can constrain $\delta_{LL}$ assuming $a_\mu$ and mass pattern

# Outline

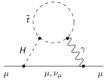
3 SUSY: Precision

# Some Numbers

| | | |
|---|---|---|
| $M_W^{\rm exp} = 80.385(15)$ GeV | | $0.02\%$ |
| MSSM | 1Loop | $\mathcal{O}(0\ldots 10\sigma)$ |
| $M_h^{\rm exp} = 125.09(0.24)$ GeV | | $0.2\%$ |
| MSSM | 1Loop | $> 30\sigma$ |
| $a_\mu^{\rm exp} = 11\,659\,208.9(6.3) \times 10^{-10}$ | | 0.5ppm |
| MSSM | loop effects | $\mathcal{O}(0\ldots \pm 10\sigma)$ |

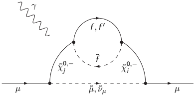
Current SUSY theory uncertainty: $3 \times 10^{-10}$

# Status of 2-loop computations $a_\mu^{\text{BSM}}$




- SUSY corrections to SM-like 1-loop complete
- QED-corrections to SUSY-like 1-loop complete
- $\tan^2\beta$ corrections known
- $f\tilde{f}$-corrections to SUSY-like 1-loop complete
- remaining SUSY 2-loop in progress

  [65000 diagrams computed, 1 class of counterterms missing]

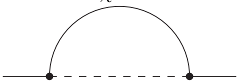


- 2HDM: leading two-loop contributions known [Krawczyk; Chun et al; Ilisie], rest in progress

# Status of SUSY prediction

## 1-Loop

$\propto \tan\beta$




[Fayet '80],...

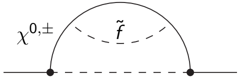
[Kosower et al '83],[Yuan et al '84],...

[Lopez et al '94],[Moroi '96]

complete

## 2-Loop (SUSY 1L)

e.g. $\propto \log \frac{M_{\text{SUSY}}}{m_\mu}$




[Degrassi,Giudice '98]

[Marchetti, Mertens, Nierste, DS '08]

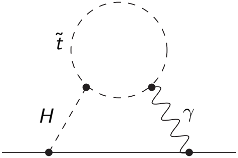
[Schäfer, Stöckinger-Kim, v. Weitershausen, DS '10]

[Fargnoli,Gnendiger,Passehr,DS, Stöckinger-Kim '13]

QED,$\tan^2\beta$
$f, \tilde{f}$-loops

## 2-Loop (SM 1L)

e.g. $\propto \tan\beta\,\mu\,m_t$



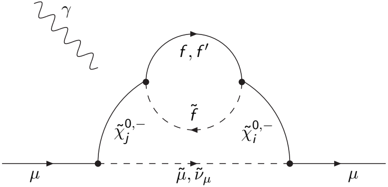

[Chen,Geng'01][Arhib,Baek '02]

[Heinemeyer,DS,Weiglein '03]

[Heinemeyer,DS,Weiglein '04]

complete

# The new contributions with $f\tilde{f}$ loops




Motivation:

- Split spectra / Big step towards full 2-loop calculation
- remaining class with dependence on squarks
- maximum complexity: 5 heavy + 2 light scales
- computed exactly, including renormalization
- contains large logs, $\Delta\rho$

# Contributions involving $\Delta\rho$

One-loop ambiguity

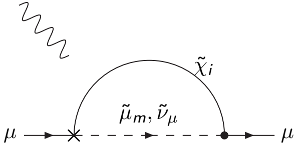
$$\left.\begin{aligned} a_\mu^{1L} &= \alpha(0)\ldots &&= 29.4 \\ a_\mu^{1L} &= \alpha(M_Z)\ldots &&= 31.6 \\ a_\mu^{1L} &= \alpha(G_F)\ldots &&= 30.5 \end{aligned}\right\}$$

differ by $\Delta\alpha$, $\Delta\rho$: 2L$f\tilde{f}$-terms

Fixed by full $2Lf\tilde{f}$ calculation

(for SPS1a, unit: $10^{-10}$)

# Contributions involving $\Delta\rho$




$$= a_\mu^{1L} \times \left( \ldots + \frac{\delta\left(e^2/s_W^2\right)}{e^2/s_W^2} \right)$$
$$= a_\mu^{1L} \times \left( \Delta\alpha - \frac{c_W^2}{s_W^2} \Delta\rho + \ldots \right)_{f,\tilde{f}\text{-loops}}$$

One-loop ambiguity

$$\left.\begin{array}{lll} a_\mu^{1L} & = \alpha(0)\ldots & = 29.4 \\ a_\mu^{1L} & = \alpha(M_Z)\ldots & = 31.6 \\ a_\mu^{1L} & = \alpha(G_F)\ldots & = 30.5 \end{array}\right\}$$

differ by $\Delta\alpha$, $\Delta\rho$: 2L$f\tilde{f}$-terms

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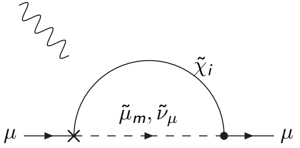
# Contributions involving $\Delta\rho$




$$= a_\mu^{\mathrm{1L}} \times \left( \ldots + \frac{\delta\left(e^2/s_W^2\right)}{e^2/s_W^2} \right)$$
$$= a_\mu^{\mathrm{1L}} \times \left( \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \ldots \right)_{f,\tilde{f}\text{-loops}}$$

One-loop ambiguity

$$\left.\begin{array}{lll} a_\mu^{\mathrm{1L}} & = \alpha(0)\ldots & = 29.4 \\ a_\mu^{\mathrm{1L}} & = \alpha(M_Z)\ldots & = 31.6 \\ a_\mu^{\mathrm{1L}} & = \alpha(G_F)\ldots & = 30.5 \end{array}\right\}$$

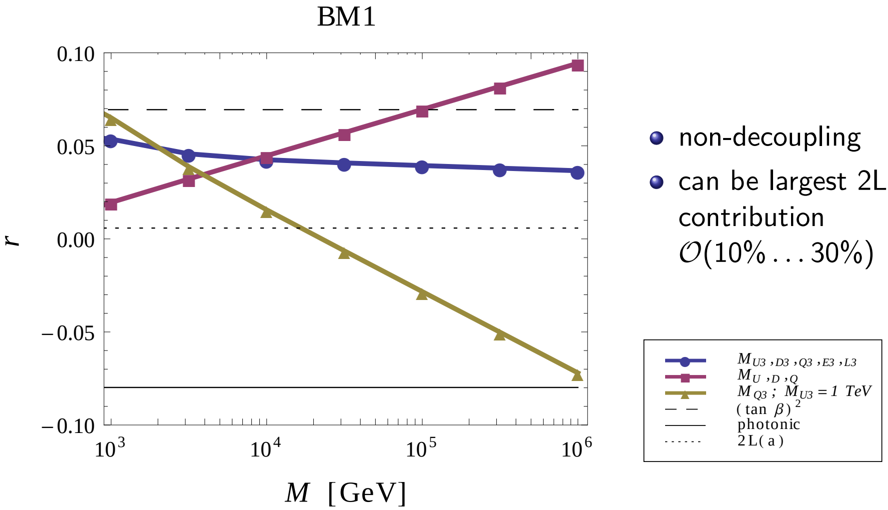
differ by $\Delta\alpha$, $\Delta\rho$: $2\mathrm{L}f\tilde{f}$-terms

Fixed by full $2Lf\tilde{f}$ calculation

$$a_\mu^{\mathrm{1L+2L}f\tilde{f}} = 32.2$$

(for SPS1a, unit: $10^{-10}$)

# Results for $f\tilde{f}$-loops: Large contributions from heavy squarks [Fargnoli, Gnendiger, Passehr, DS, Stöckinger-Kim '13]



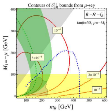

- non-decoupling
- can be largest 2L contribution $\mathcal{O}(10\% \ldots 30\%)$

$\mu = 350$, $M_2 = 2M_1 = 300$, $m_{\tilde{\mu}_{R,L}} = 400$ GeV, $\tan\beta = 40$

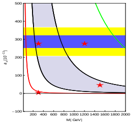
# Outline

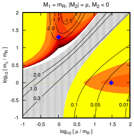
# Summary: $a_\mu$ and SUSY

- New physics/SUSY not excluded and still well motivated



- $a_\mu^{\rm SUSY}$ very model-dependent
  - can be $\mathcal{O}(\pm 1 \ldots 50) \times 10^{-10}$
  - special SUSY scenarios
    $\tan\beta \to \infty$, R-symmetry





- New measurement will have strong impact
  - constraints, model discriminator
  - precise (2-loop) predictions important