Magnetic moment $(g-2)_\mu$ and beyond the Standard Model

Dominik Stöckinger

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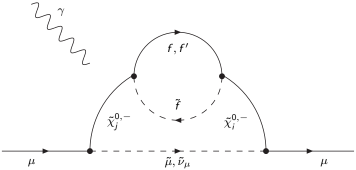
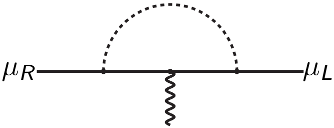


Collaboration Meeting, Seattle, July 2015

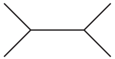
Why is a_μ special?



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

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

EWPO



Outline

1. Isn't New Physics ruled out by LHC? Still motivated?
2. Overview: New Physics in General
3. Representative Examples
4. Conclusions

Outline

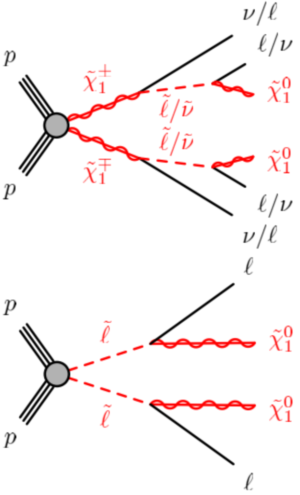
1. Isn't New Physics ruled out by LHC? Still motivated?

Beware of "propaganda plots"

Exclusion by LHC-data/EDMs/LFV
depends on assumptions!

Why isn't new physics ruled out by LHC?

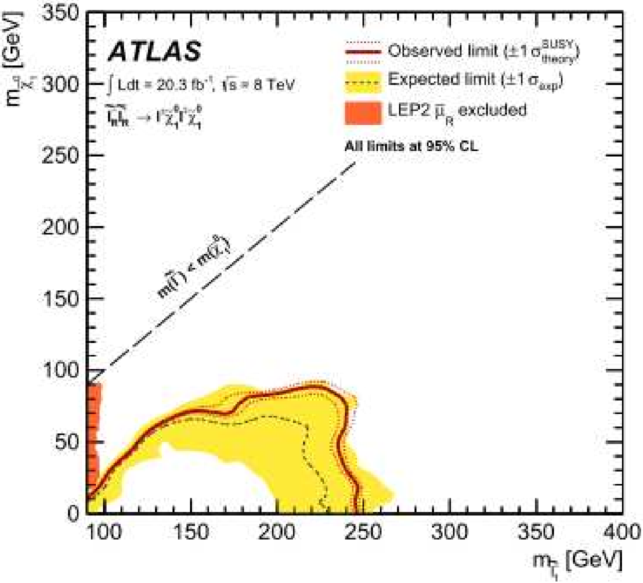
Indeed, robust bounds on new coloured particles with simple decays, also on Z' with SM-like couplings



- But consider e.g. sleptons, charginos, neutralinos
- very low $\sigma \Rightarrow$ low mass reach

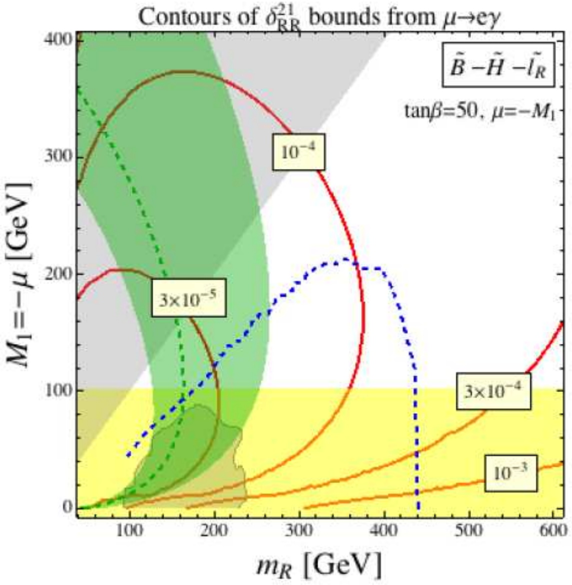
$$\sigma_{\text{LHC8}}(m_{\tilde{l}_R} = 370\text{GeV}) = 0.2\text{fb}$$
$$\sigma_{\text{LHC8}}(m_{\tilde{\chi}^\pm} = 450\text{GeV}) = 10\text{fb}$$

- analysis needs visible, hard leptons $\Rightarrow$ simple decays and large mass splittings
- bad but possible in reality: $\chi_2^0 \to \chi_1^0 + H$, $H \to b\bar{b}$ essentially invisible



- ATLAS $\tilde{l}_R$ search, assuming only two new particles,
- decay $\tilde{l}_R \to l\chi_1^0$
- σ is very low
- no exclusion above 250 GeV
- no exclusion if mass gap $\tilde{l}_R - \chi_1^0 < 80$ GeV

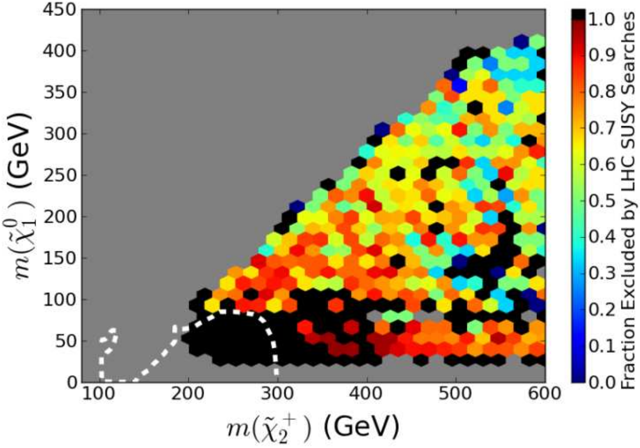
[arxiv:1403.5294]



- now three particles, $\tilde{l}_R, \tilde{B}, \tilde{H}$
- current LHC exclusion covers only masses below 250 GeV and mass gaps above 80 GeV
- even future LHC exclusion only twice as high
- Compare: [Fargnoli, Gnendiger, Passehr, DS, Stöckinger-Kim '13] motivated BM4: $\mu = -160$, $M_1 = 140$, $m_{\tilde{\mu}_R} = 200$, $M_2 = m_{\tilde{\mu}_L} = 2000 GeV$, $\tan\beta = 50$

  this will remain allowed

[Calibbi, Galon, Masiero, Paradisi, Shadmi, arxiv:1502.07753]



- SUSY models with "low fine tuning" $\tilde{t} > \tilde{l} > \chi^{\tilde{0},\pm}$
- only small region is completely excluded
- all neutralinos and charginos can be light

[Cahill-Rowley, Hewett, Ismail, Rizzo, arxiv:1407.4130]

Hence new physics is still possible!

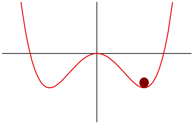
- in particular, new particles can still give large a_μ
- however, it is true that some scenarios are excluded, and specific (sometimes non-traditional) scenarios are now better motivated (e.g. very large or very small mass splittings)

similar for other observables:

- $B_s \to \mu\mu$ rules out SUSY with very large $\tan\beta$ and small CP-odd Higgs mass
- EDMs rule out new physics with small masses and large complex phases

Why new physics?

Big questions. . . point to (TeV scale) new physics

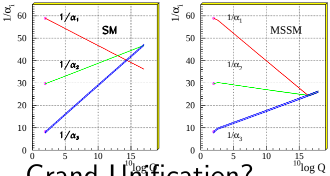


EWSB, Higgs, scalar particle?

hierarchy $M_{\rm Pl}/M_W$? Naturalness?

Dark Matter?

Baryon Asymmetry?



Grand Unification?
Flavor Structure?

Many ideas for new fundamental theories, principles, interactions
Need complementary experiments to discover and scrutinize new physics

Outline

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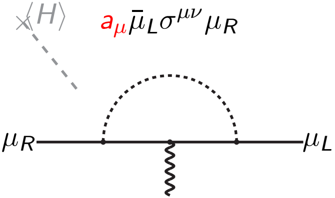
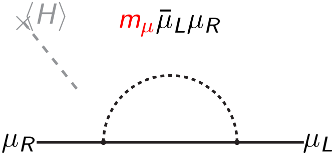
Explain new physics contributions to a_μ

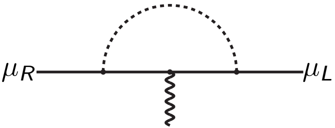
Loop contributions to a_μ, m_μ related to source of chirality flips





Very different contributions to a_μ: classify $\propto C$

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



$C = \frac{\delta m_\mu(\text{N.P.})}{m_\mu}$

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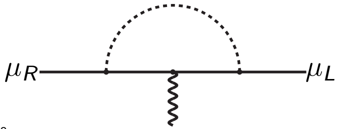

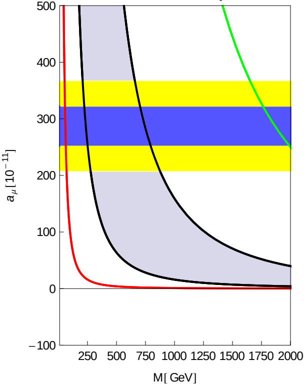

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$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	
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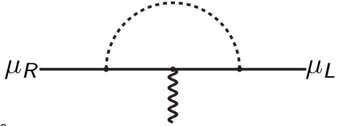

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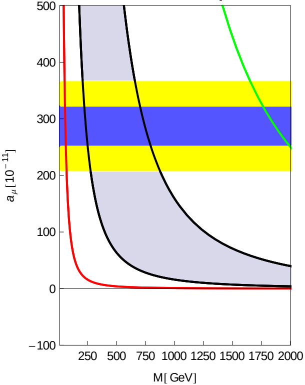

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$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	supersymmetry ($\tan\beta$), unparticles [Cheung, Keung, Yuan '07] extra dim. (ADD/RS) (n_c)... [Davioudasl, Hewett, Rizzo '00] [Graesser,'00][Park et al '01][Kim et al '01]
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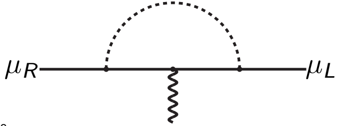

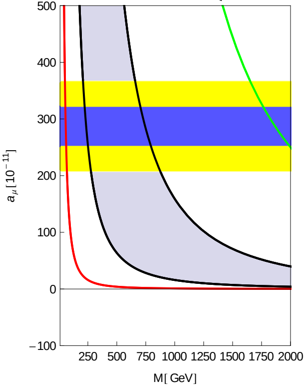

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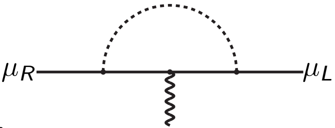

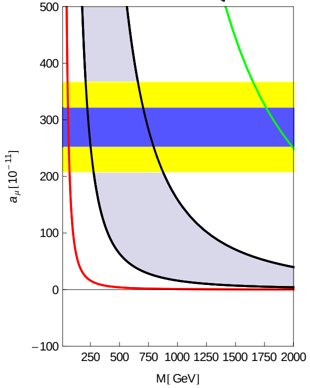

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$\mathcal{O}(\frac{\alpha}{4\pi})$	Z', W', UED, Littlest Higgs (LHT). . .
$\ll \frac{\alpha}{4\pi}$	dark photon . . .

Outline

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1. Isn't New Physics ruled out by LHC? Still motivated?

2. Overview: New Physics in General
   - Simple classification of models
   - Wide range of possibilities, complementarity

3. Representative Examples
   - Illustrate wide range of possibilities
   - Different chirality flipping mechanisms
   - Different numbers/types of particles
   - Complementarity to LHC, LFV

4. Conclusions

Outline

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Navigate through examples

- SM weak
- $\leq$ two new particles (structure as for SM weak, easy to estimate)
- $\geq$ three new particles

Navigate through examples

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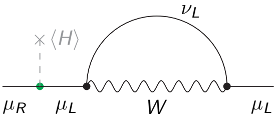

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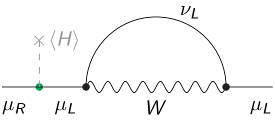

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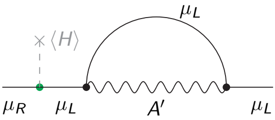
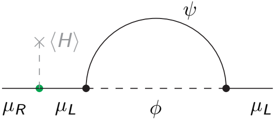
  model-"independent" study [Freitas, Kell, Lykken, Westhoff '14] and other models





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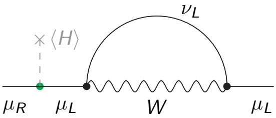

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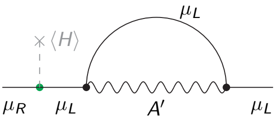
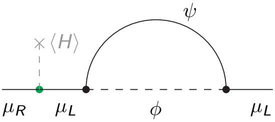
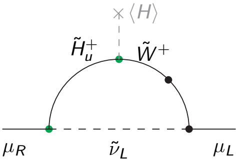
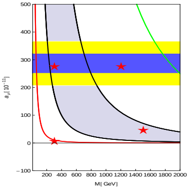




- $\geq$ three new particles $\Rightarrow$ (ab)use SUSY-scenarios as simplified models



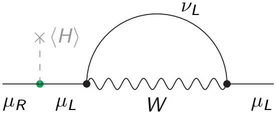


Model-"independent" analysis of $\leq$ two new fields

[Freitas, Kell, Lykken, Westhoff '14]

- SM: doublet $L = \begin{pmatrix} \nu_L \\ \mu_L \end{pmatrix}$, singlet μ_R, doublet H

Chirality flip: $\bar{L}H\mu_R \to \langle H\rangle\bar{\mu}_L\mu_R$



Model-"independent" analysis of $\leq$ two new fields

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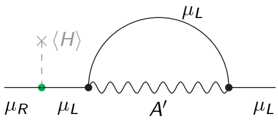
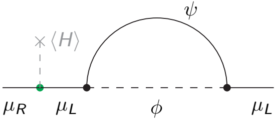
- New fields: either doublets, singlets or triplets, no flavour violation





$\Rightarrow$ no additional chirality flip! Behaviour like $a_\mu^{\text{SM, weak}}$

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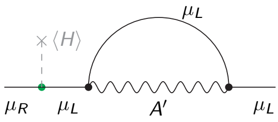

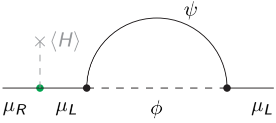

$\Rightarrow$ no additional chirality flip! Behaviour like $a_\mu^{\text{SM, weak}}$

- large contributions need $M < \mathcal{O}(500)$ GeV and $g_{\text{New}} = \mathcal{O}(1)$
- Constrained by LHC and LEP

Model-"independent" analysis of ≤ two new fields

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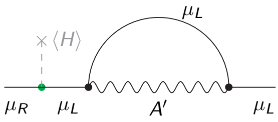
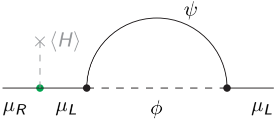
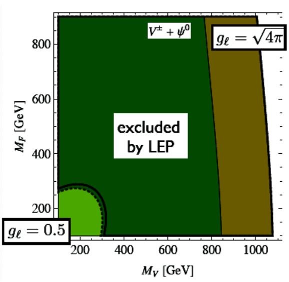
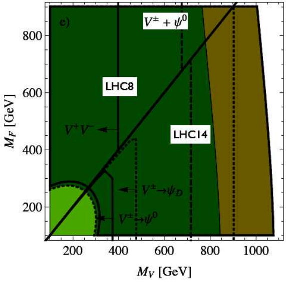
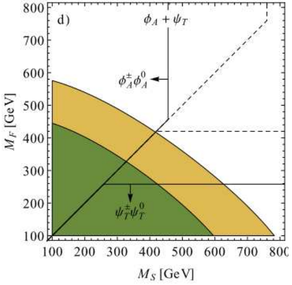










Some scenarios still viable, will be tested at LHC14

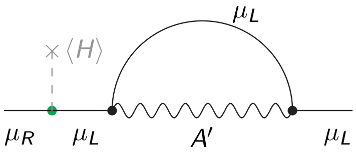
Beware of "model-independent" statements

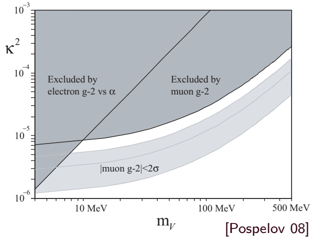
What about dark photons?

What about two-Higgs doublet model?

Dark photon: "second most promising scenario" [Marciano]

- very light/weakly interacting ⇒ not covered by previous analysis

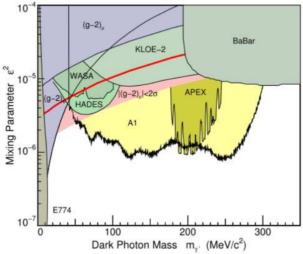




[Pospelov 08]

- theory motivation:
  new U(1) gauge group (from GUTs, ...)
- could explain: dark matter, $(g-2)_\mu$
  (for very specific coupling/mass range)
- a_μ-explanation now almost completely excluded!!
- generalization: "dark Z"
  with more general couplings,
  also strongly constrained

[Davoudiasl,Lee,Marciano'14][Izaguirre et al '13]



[A1/Mainz '14]

Two-Higgs Doublet Model: one field but tricky behaviour

- Second Higgs doublet well motivated in theory
- Promising case: H_1 couples to leptons, $H_2 \approx H_{\text{SM}}$ to quarks (type X)

  recent analyses: [Broggio, Chun, Passera, Patel, Vempati '14, Ilisie '15]
- Not covered in previous analysis for two reasons:
  1. no fields with vacuum expectation value
  2. only one-loop contributions to a_μ

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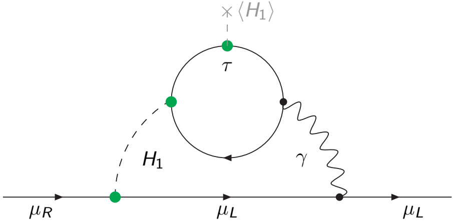
  2. and appears as CP-odd scalar $M_A \approx M_{H_1}$



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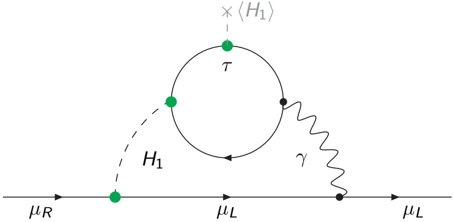

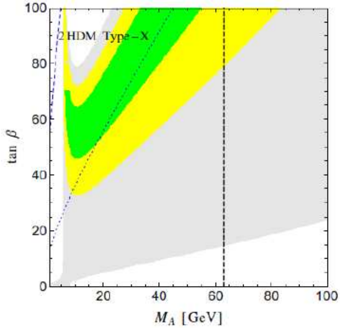

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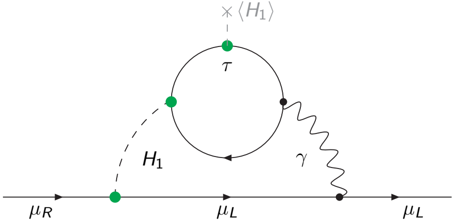


$$\propto \frac{y_\mu y_\tau m_\tau}{M_{H_1}^2} \approx \frac{\tan^2\beta\, y_{\mu,\text{SM}}^2 m_\tau}{M_{H_1}^2}$$

explanation:

$$\tan\beta = \frac{\langle H_2\rangle}{\langle H_1\rangle} \approx \frac{\langle H_{\text{SM}}\rangle}{\langle H_1\rangle} \gg 1$$

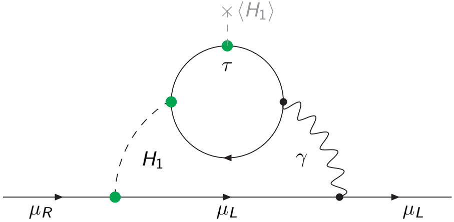
$$y_{\mu,\tau} = \frac{m_{\mu,\tau}}{\langle H_1\rangle} \approx \tan\beta\, y_{\mu,\tau,\text{SM}}$$

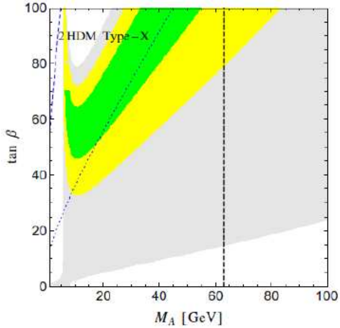
Two-Higgs Doublet Model: one field but tricky behaviour

- Second Higgs doublet well motivated in theory
- Promising case: H_1 couples to leptons, $H_2 \approx H_{SM}$ to quarks (type X)

recent analyses: [Broggio, Chun, Passera, Patel, Vempati '14, Ilisie '15]

1. H_1 gives mass to leptons $m_{\mu,\tau} = y_{\mu,\tau} \langle H_1 \rangle$
2. and appears as CP-odd scalar $M_A \approx M_{H_1}$





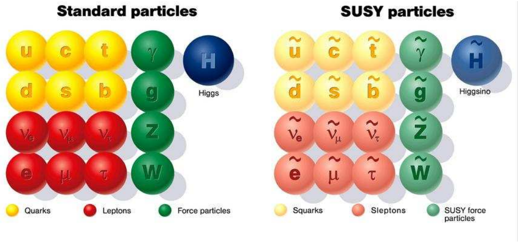
Viable region $M_A \sim 50$ GeV, $\tan\beta \sim 100$ not excluded by anything

Models with $\leq$ two new fields already rich:
light or heavy new particles, constrained/testable by LHC and/or low-energy data

further models: Z' with $L_\mu - L_\tau$, dark Z (mass mixing), non-MFV models

SUSY and the MSSM — four examples

- MSSM:



- free parameters: $\tilde{p}$ masses and mixings, μ and $\tan\beta$

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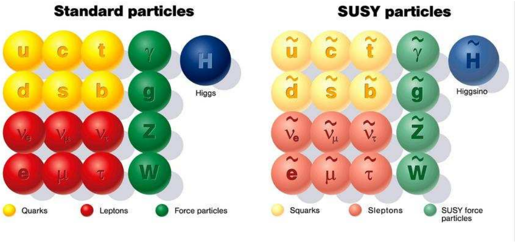
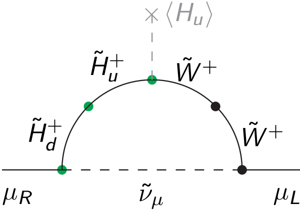


- free parameters: $\tilde{p}$ masses and mixings, μ and $\tan\beta$

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

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

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

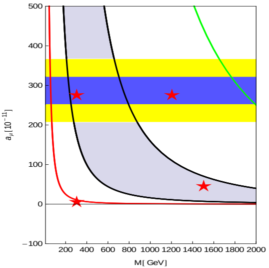
Diagram enhanced by Yukawa and large "other" vev

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

enhancement $\propto \tan\beta = 1 \dots 50$ (and $\propto$sign(μ))

1st example: large masses, small a_μ

Obviously, the LHC rules out specific SUSY models as explanations of g-2. Consider one of them, the "Constrained MSSM".



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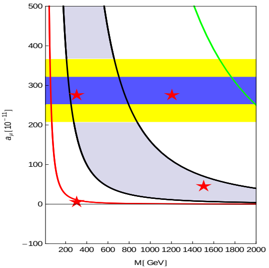
Assumption at GUT scale:

$$m_0 = \text{universal scalar mass}$$
$$m_{1/2} = \text{universal fermion mass}$$
$$\alpha = \text{universal gauge coupling}$$

$\Rightarrow$ physical masses strongly correlated



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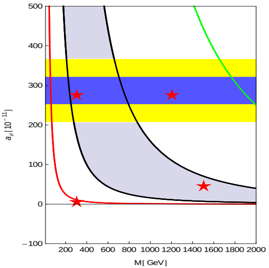

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- LHC requires heavy gluinos
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- hence, a_μ contributions negligible

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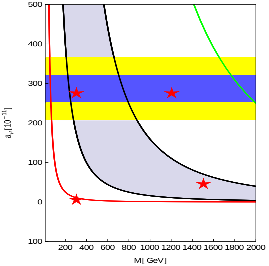

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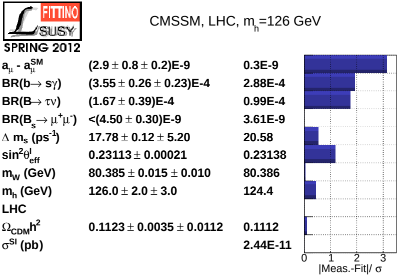
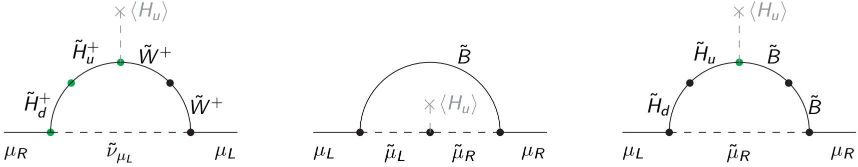


2nd example: small masses, large a_μ

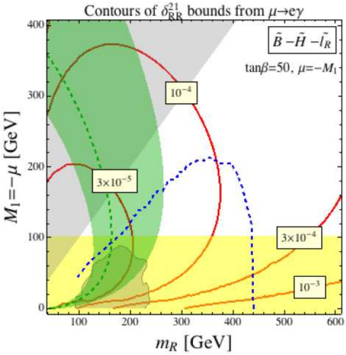


"standard" $\propto \mu$ for $\mu \to \infty$ $\propto$ other sign!

- large a_μ 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
- can carry out dedicated LHC studies and top-down motivation

  [Endo; Yanagida; Roy; Calibbi; Roszkowski. . .]
- such scenarios are viable, some might even survive LHC14

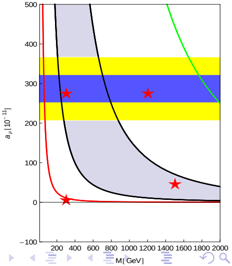


Comments:

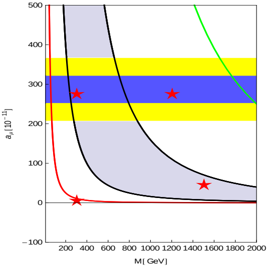
- CMSSM assumptions are simple but theoretically not preferred
- CMSSM (and other models) cannot explain large a_μ any more
- Now: theory as well as experiment motivates to construct models with more complicated mass relations, e.g. higher mass splittings

  many model building studies [Endo, Hamaguchi, Ibe, Yanagida, D.P. Roy, et al]

- Light particles are (and will remain) possible but specific models will be tested at LHC14, particular if they should also explain dark matter
  [Kowalska, Roszkowski, Sessolo, Williams '15]



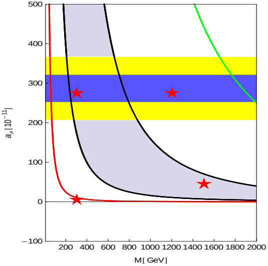
3rd Example: large a_μ for large masses



Is it possible to explain the a_μ deviation with TeV-scale SUSY?

What is the largest possible SUSY contribution to a_μ?

3rd Example: large a_μ 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])

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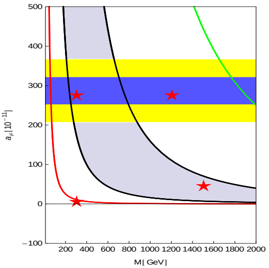

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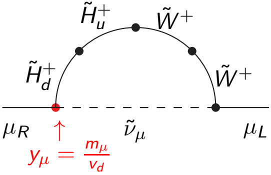
[Dobrescu, Fox '10][Altmannshofer, Straub '10] (see also [Davies,March-russell,Mccullough '11])

- MSSM-scenarios for $\tan\beta \to \infty$ can be regarded as genuinely interesting parameter regions or as simplified models which realize radiative muon mass generation

Large a_μ in MSSM for $\tan\beta \to \infty$

[Bach,Park,DS,Stöckinger-Kim, '15]

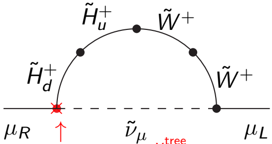


"standard case" (equal masses, 1-loop)

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

Large a_μ in MSSM for $\tan\beta \to \infty$

[Bach,Park,DS,Stöckinger-Kim, '15]



actually, including higher order effects

[Marchetti,Mertens,Nierste,DS '08]

$$y_\mu \approx \frac{m_\mu}{v_d + v_u(\text{1-loop})} = \frac{y_\mu^{\text{tree}}}{(1+\Delta_\mu)}$$

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

Large a_μ in MSSM for $\tan\beta \to \infty$

limit $\tan\beta \to \infty$

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

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

Large a_μ in MSSM for $\tan\beta \to \infty$

limit $\tan\beta \to \infty$

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

"standard" case: sign wrong!

Large a_μ in MSSM for $\tan\beta \to \infty$

limit $\tan\beta \to \infty$

$$a_\mu^{\rm SUSY} \approx +37 \times 10^{-10} \left(\frac{1000 {\rm GeV}}{M_{\rm SUSY}}\right)^2$$

sign positive e.g. if $|\mu| \gg M_{\rm SUSY}$ (then only $\tilde{B}\tilde{\mu}_L\tilde{\mu}_R$ important)

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

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$\exists$ models with large a_μ in spite of TeV-scale masses

[also other models with radiative muon mass [Crivellin et al, Straub et al...]]

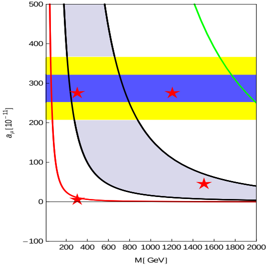
not easy to detect at LHC, but large couplings$\Rightarrow$other effects

4th Example: small a_μ, small masses

Questions:

Can all SUSY scenarios give large contributions?

What is the SUSY contribution with R-symmetry?



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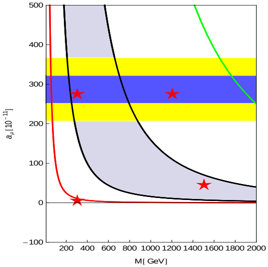


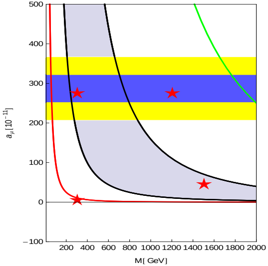
Questions:

Can all SUSY scenarios give large contributions?

What is the SUSY contribution with R-symmetry?

- Opposite reaction to LHC: not less, but more SUSY, more symmetry, more light sparticles!
- possible with 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_μ, small masses



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- all $\tan\beta$-enhanced contributions: $\propto \mu M_{1,2}$
- both μ and Majorana gaugino masses forbidden by R-symmetry

predictive!

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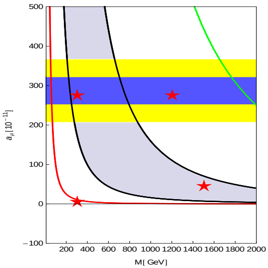

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predictive!

$\exists$ well-motivated models which predict $\approx$ zero a_μ

[other models: LHT, UED, Z'...]

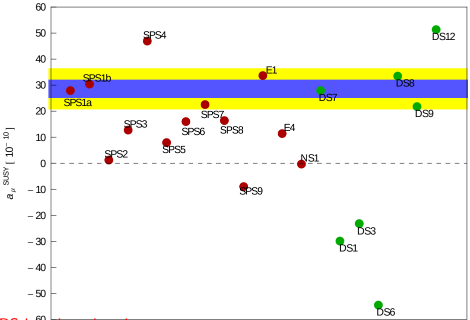
will be under pressure if non-zero a_μ is confirmed

Using a_μ: complementarity to LHC

Many different models with different contributions to a_μ

$\Downarrow$

New measurement will be very important

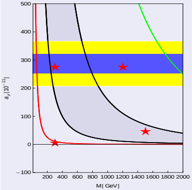


SPS benchmark points
[v.Weitershausen,Schäfer, Stöckinger-Kim,DS '10]

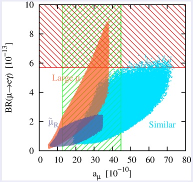
LHC Inverse Problem (300fb^{-1}) can't be distinguished at LHC
[Sfitter: Adam, Kneur, Lafaye, Plehn, Rauch, Zerwas '10]

- a_μ distinguishes models
- helps measure parameters

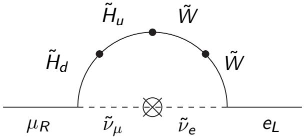
Complementarity/correlation with $\mu \to e\gamma$



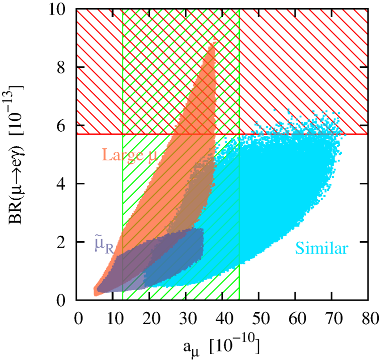
LHC$\oplus a_\mu$: masses and model details



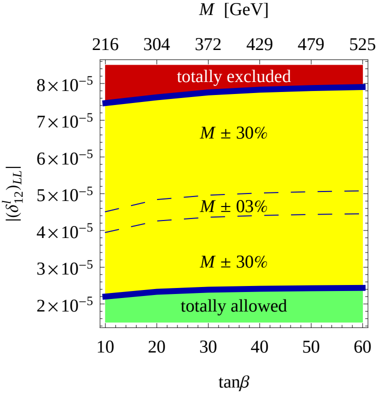
LFV$\oplus a_\mu$: LFV parameters



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



parameter regions where single diagrams dominate



bounds on δ_{LL} assuming M is fixed to accommodate a_μ

- 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 δ_{LL} assuming a_μ and mass pattern

Precision computations (our work and plans)

Precision computations in new physics models motivated

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Precision computations in new physics models motivated

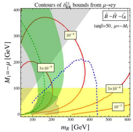
- e.g. two-loop contributions qualitatively different
- reduce theory uncertainty (e.g. from $\alpha = 1/137$ or $\alpha = 1/128$)
- SUSY uncertainty $\sim 3 \times 10^{-10}$ [DS '06]

Status:

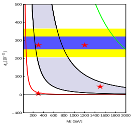
- SUSY: 8 of 9 classes of two-loop contributions known, rest in progress [65000 diagrams computed, 1 class of counterterms missing]
- 2HDM: leading two-loop contributions known, rest in progress

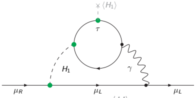
Outline

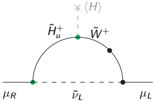
Summary: a_μ as a probe of new physics



- New physics not excluded and still well motivated
- $a_\mu^{\mathrm{N.P.,SUSY}}$ very model-dependent
  - can be $\mathcal{O}(\pm 1 \ldots 50) \times 10^{-10}$
  - different mechanisms
  - special SUSY scenarios
    $\tan\beta \to \infty$, R-symmetry







- New measurement will have strong impact
  - constraints, model discriminator
  - unique properties
  - precise predictions (will be) available