Motivation, New g-2 Experiments

Dominik Stöckinger, TU Dresden

MITP g-2 Workshop, Mainz, April 2014

Outline

1. Motivation to study g-factors, a_μ
2. Motivation to improve theory prediction
   - SM status
   - New Experiments
   - Impact on New Physics
3. Conclusions and Outlook to Workshop
4. Backup
   - History & SM
   - SUSY
   - Alternatives to SUSY

Three Fermions

Electron: $g = 2.002\,319\,304\,361\,46(56)$

Muon: $g =$

Proton: $g = 5.585\,694\,713(46)$

$$g_\mu = 2(1 + a_\mu)$$

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$$g_\mu = 2(1 + a_\mu)$$

a_μ probes quantum structure of all interactions (SM and beyond!)

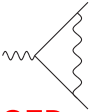
Muon $g-2$ experiment at Brookhaven

$$a_\mu^{\rm exp} = (11\,659\,208.9(5.4)_{\rm stat}(3.3)_{\rm syst}(6.3)_{\rm tot}) \times 10^{-10}$$

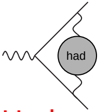
(error statistics dominated! agreement μ^+, μ^-)

Outline

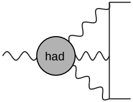
SM prediction a_μ^{SM} $[10^{-10}]$ [Gnendiger, Stöckinger, Stöckinger-Kim '13]



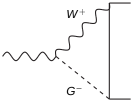
QED: $11\,658\,471.8$ (0.0) [Aoyama, Hayakawa, Kinoshita, Nio '12]



Had vp: 685.1 (4.3) [Hagiwara, Liao, Martin, Nomura, Teubner '11]



Had lbl: 10.5 (2.6) [de Rafael, Prades, Vainshtein '09]



Weak: 15.36 (0.1) [Gnendiger, Stöckinger, Stöckinger-Kim '13]

Discrepancy

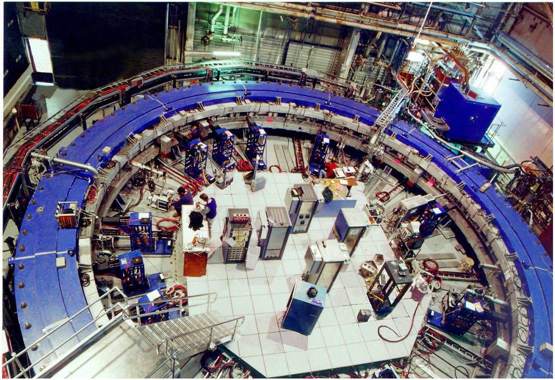
SM prediction too low by $(26.1 \pm 8.0) \times 10^{-10}$

Note: discrepancy twice as large as $a_\mu^{\mathrm{SM,weak}}$

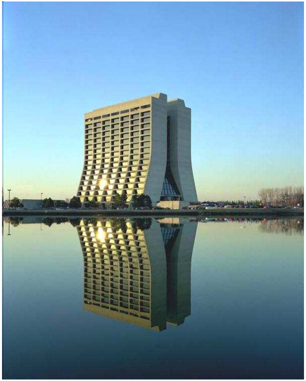
but we expect: $a_\mu^{\mathrm{NP}} \sim a_\mu^{\mathrm{SM,weak}} \times \left(\frac{M_W}{M_{\mathrm{NP}}}\right)^2 \times$ couplings

Outline

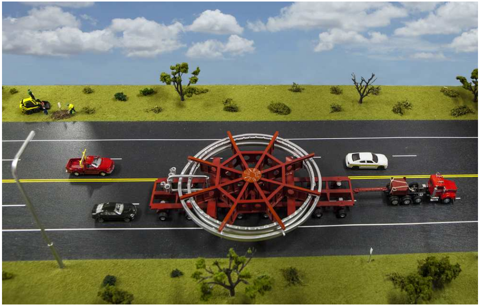
The Opportunity

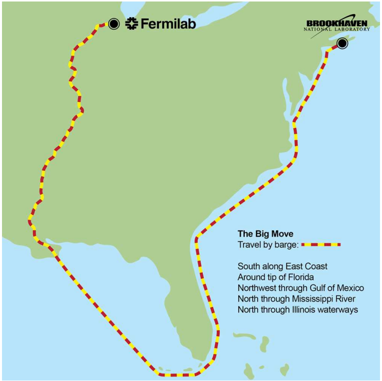


$\Rightarrow$



becomes reality





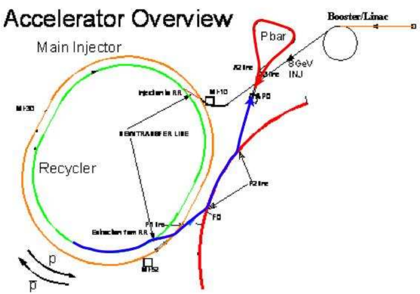
24/06/13 Get started!

24/06/13 On deck

19/07/13 Past St. Louis

29/07/13 Arrived!

Advantages of Fermilab



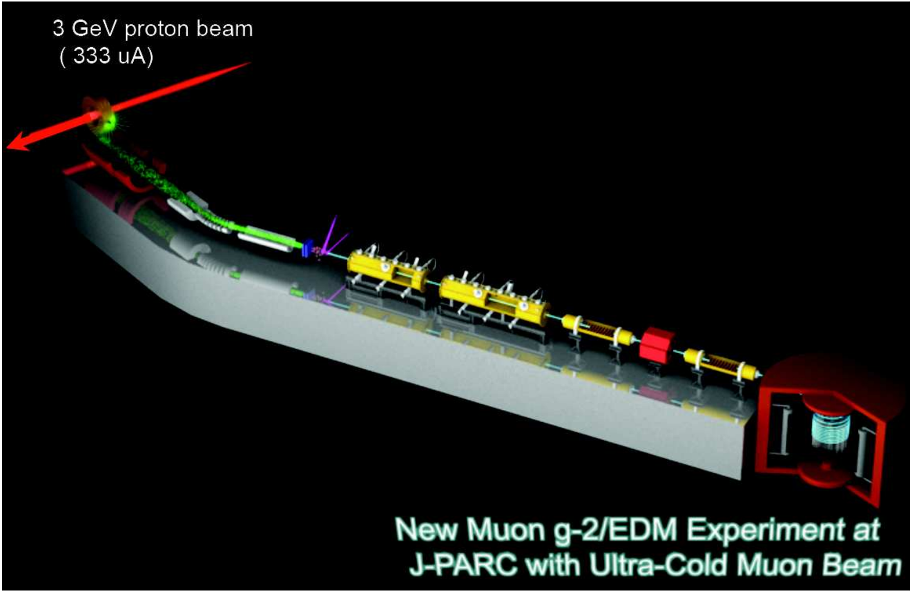
π decay length 900m vs 88m

- 6–12 times more stored muons per initial proton
- 4 times fill frequency
- 20 times reduced hadronic-induced background at injection

Timeline

- CDR: 2013
- TDR: mid 2014
- Magnet construction, cooldown, shimming: 2014–2015
- Install vacuum, detector, electronics: 2016
- Datataking: 2017

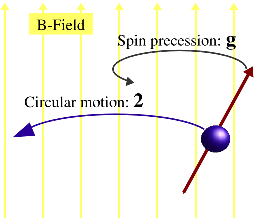
Complementary experiment at JParc (N. Saito)



Complementary experiment at JParc (N. Saito)

	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		None
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.1 ppm

Complementarity

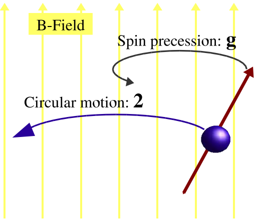


$$\vec{\omega}_a = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

either magic γ or $\vec{E} = 0$

Task: Even reconsider the basics

Working group "other topics"



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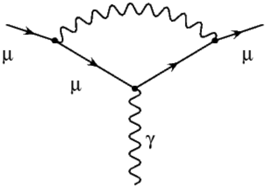
Quantum field theory:



$$\tilde{=} \bar{u}(p')\left[\gamma_\mu F_1 + \frac{i}{2m_\mu}\sigma_{\mu\nu} q^\nu F_2(q^2)\right] u(p)$$

$\rightarrow$ Form factor: $a_\mu = F_2(0)$

QFT-corrections needed?

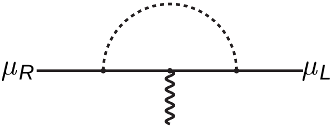
Goal of both new $(g-2)$ experiments

$$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (30?? \pm 1.6^{\mathrm{Exp}} \pm 3.4^{\mathrm{Th}}??) \times 10^{-10}$$

- Useful complement of LHC (and flavour physics experiments), independent of final value [Hertzog, Miller, de Rafael, Roberts, DS '07]

Outline

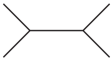
Why is a_μ special?



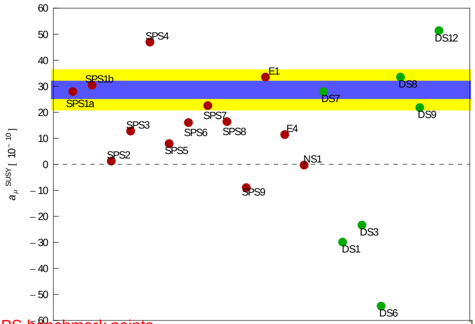
CP- and Flavour-conserving, chirality-flipping, loop-induced

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

EWPO

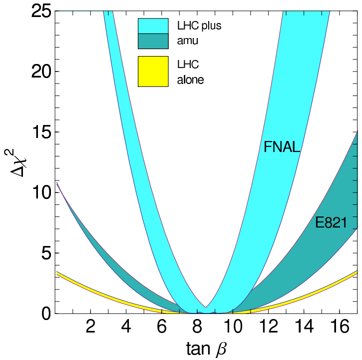


a_μ central complement for SUSY parameter analyses



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]

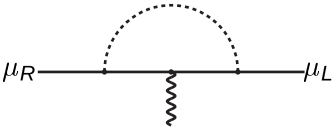


[Hertzog, Miller, de Rafael, Roberts, DS '07]
[Miller, de Rafael, Roberts, DS '12]

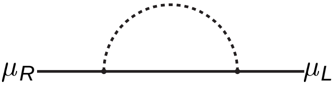
- a_μ sharply distinguishes SUSY models (model dependent)
- (complementary to other experiments)

Explain new physics contributions to a_μ

$a_\mu \bar{\mu}_L \sigma^{\mu\nu} \mu_R$



$m_\mu \bar{\mu}_L \mu_R$



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

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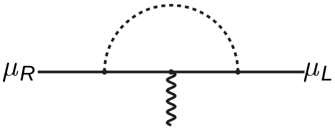

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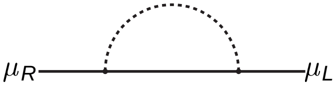


Loop contributions to a_μ, m_μ related to source of chirality flips

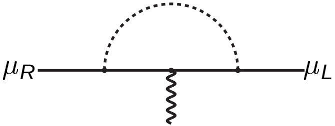
- SM: only one source of chirality flips: Yukawa coupling $y_\mu H \bar{\mu}_L \mu_R$

$$m_\mu = y_\mu \langle H \rangle, \qquad a_\mu^{\text{weak}} \propto \frac{\alpha}{4\pi} \left(\frac{m_\mu}{M_W} \right)^2$$

- New physics: y_μ very different? E.g. $y_\mu^{\text{SUSY}} \approx \tan\beta \, y_\mu^{\text{SM}}$

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

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



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

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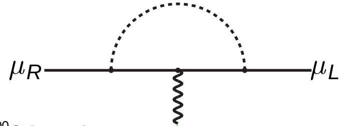

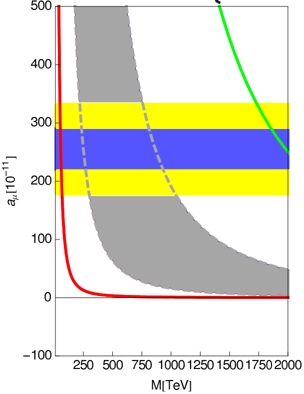

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$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	
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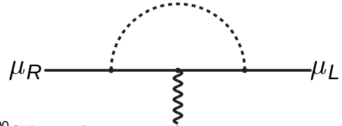

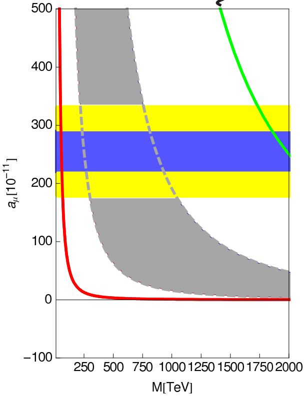

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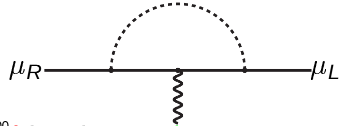

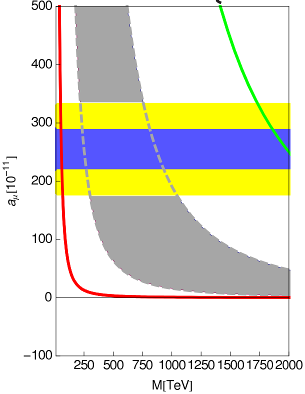

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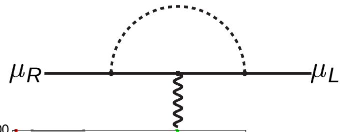

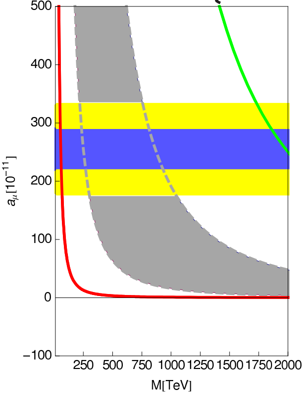

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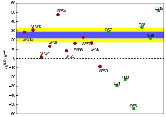
$\mathcal{O}(\frac{\alpha}{4\pi})$	Z', W', UED, Littlest Higgs (LHT)...

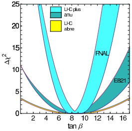
Conclusions

- Currently $a_\mu^{\mathrm{Exp}} - a_\mu^{\mathrm{SM}} \approx (26.1 \pm 6.3 \pm 5.0) \times 10^{-10}$

- Experimental progress in sight: $6.3 \to 1.6$

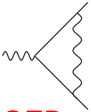
- a_μ^{SUSY} is very important constraint on physics beyond the SM



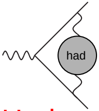


Needed: Improvements on SM prediction

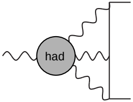
Outlook/Tasks: Further SM improvements



QED: 11 658 471.8 (0.0) — check 4-,5-loop, positronium?

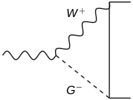


Had vp: 685.1 (4.3) — reduce error? higher order contributions?



Had lbl: 10.5 (2.6) — reduce error?

- from first principles
- hadronic models
- experimental data



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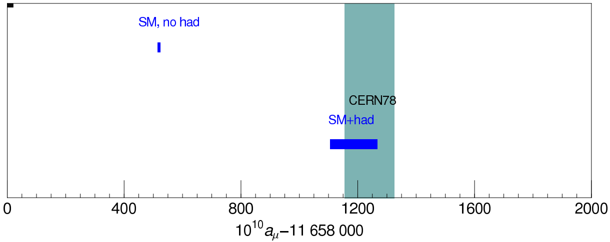
Legacy of the CERN experiment



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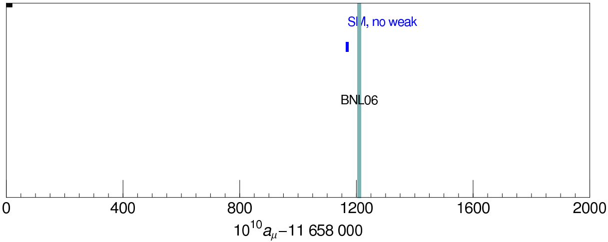

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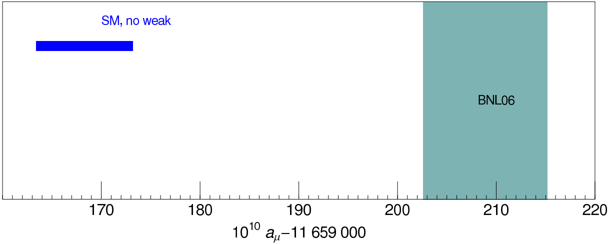

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'01–'06 BNL measurement:	weak cont. needed, **not confirmed!**

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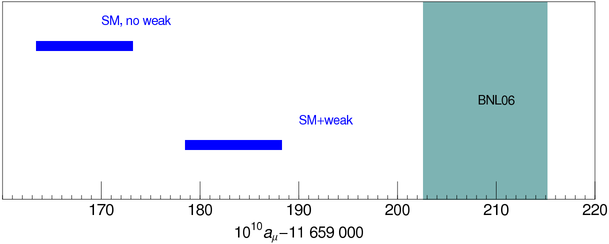
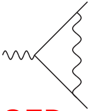


SM prediction $a_\mu^{\rm SM}$ $[10^{-10}]$ [Miller, de Rafael, Roberts, DS, Ann.Rev.Nucl.Part. (2012) 62.]



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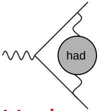
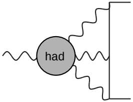


Had vp: $682.5 \quad (4.2)$



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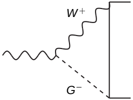
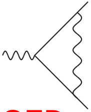
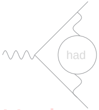


Weak: $15.3 \quad (0.1)$

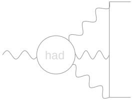
SM prediction a_μ^{SM} $[10^{-10}]$ [Miller, de Rafael, Roberts, DS, Ann.Rev.Nucl.Part. (2012) 62.]



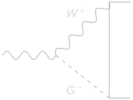
QED: 11 658 471.8 (0.0)



Had vp:



Had lbl:



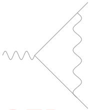
Weak:

QED:

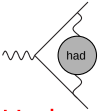
- Schwinger (1947): first loop calculation!
- complete 5-loop result

  [Aoyama, Hayakawa, Kinoshita, Nio '12]
- QED uncertainty 10^{-12}
- dominated by α

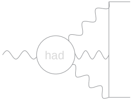
SM prediction $a_\mu^{\rm SM}$ $[10^{-10}]$ [Miller, de Rafael, Roberts, DS, Ann.Rev.Nucl.Part. (2012) 62.]



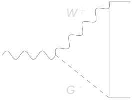
QED:



Had vp: 682.5 (4.2)



Had lbl:



Weak:

Hadronic vacuum polarization:

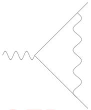
$\leftrightarrow e^+e^- \to \gamma^* \to$hadrons

- depends on exp data (e^+e^-, also τ-decays)
  - SND, CMDII (energy scan)
  - KLOE08, KLOE10, Babar (rad return)
- convergence of theoretical determinations
- most recent: “EFT induced interpolation” $\to$ slightly lower result

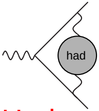
[Benayoun, David, DelBuono, Jegerlehner ’12]

SM prediction $a_\mu^{\rm SM}$ $[10^{-10}]$

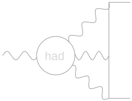
[Miller, de Rafael, Roberts, DS, Ann.Rev.Nucl.Part. (2012) 62.]



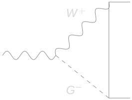
QED:



Had vp: 682.5 (4.2)



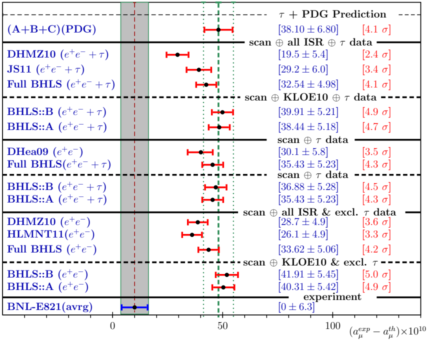
Had lbl:



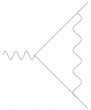
Weak:

Hadronic vacuum polarization:

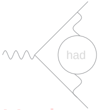
[Benayoun, David, DelBuono, Jegerlehner '12]



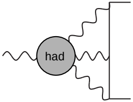
SM prediction a_μ^{SM} $[10^{-10}]$ [Miller, de Rafael, Roberts, DS, Ann.Rev.Nucl.Part. (2012) 62.]



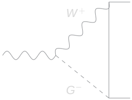
QED:



Had vp:



Had lbl: 10.5 (2.6)



Weak:

Hadronic light-by-light:

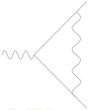
- difficult QFT problem
- not from first principles $\to$ models

[Bijnens, Prades ’07]	10.0 ± 4.0
[Melnikov, Vainshtein ’03]	13.6 ± 2.5
[Jegerlehner ’08]	11.4 ± 3.8
[Jegerlehner, Nyffeler ’09]	11.6 ± 4.0
[Prades, Vainshtein, de Rafael ’08]	10.5 ± 2.6

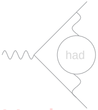
- “Glasgow” consensus: combine methods, inflate errors
- Promising new approaches: **lattice**, Dyson-Schwinger

SM prediction a_μ^{SM} $[10^{-10}]$

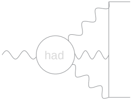
[Miller, de Rafael, Roberts, DS, Ann.Rev.Nucl.Part. (2012) 62.]



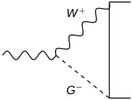
QED:



Had vp:



Had lbl:



Weak: 15.3 (0.1)

Weak:

- first SM 2-loop result ($M_H \to \infty$)

  [Czarnecki, Krause, Marciano '95]

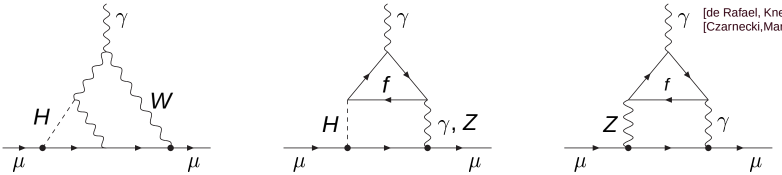
- with full Higgs mass dependence

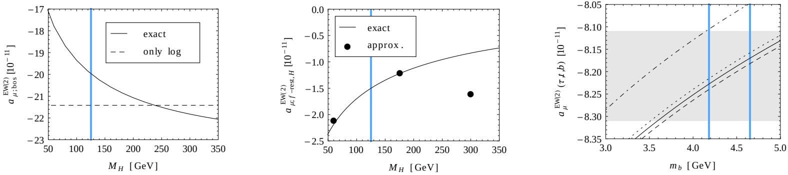
  [Heinemeyer, DS, Weiglein '04][Czarnecki, Gribouk '05]

$\Rightarrow$ current M_H constraints fix a_μ^{weak}

Re-evaluation of a_μ(weak) [Gnendiger, DS, Stöckinger-Kim '13]

[de Rafael, Knecht, et al '95–'02]
[Czarnecki,Marciano,Vainshtein '03]



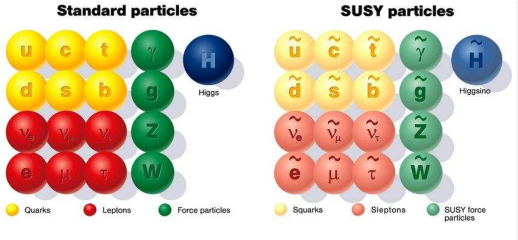


- exact evaluation of M_H-dependent parts
- consistent parametrization of 1-, 2-, 3-loop $\propto G_F \alpha^{n-1}$
- final result: $(15.36 \pm 0.10) \times 10^{-10}$

Outline

SUSY and the MSSM

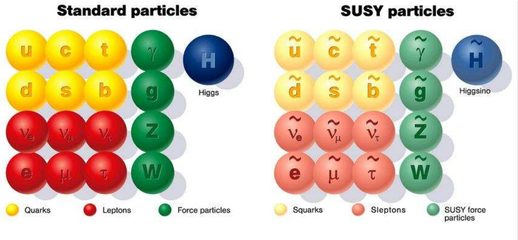
- MSSM:



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

SUSY and the MSSM

- MSSM:



- 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!

LHC-data! The tension is increasing . . .

LHC: $m_{\tilde{q},\tilde{g}} >\sim$ 1TeV	a_μ $m_{\tilde{\mu},\chi} <\sim$ 700GeV
$m_h = 126$ GeV $m_{\tilde{t}} >\sim$ 1TeV	finetuning $m_{\tilde{t}}, \mu$ small

Alternative: radiative muon mass in SUSY

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

1. $\lambda_\mu = 0$
   generate m_μ via $A'_\mu \tilde{\mu}_L \tilde{\mu}_R H_u$ [Borzumati et al '99][Crivellin et al '11]
2. $v_d \to 0$, $\tan\beta \to \infty$
   generate m_μ via coupling to v_u [Dobrescu, Fox '10][Altmannshofer, Straub '10]

$g-2$ in the MSSM: general behaviour

$g-2$ = chirality-flipping interaction

$$\frac{a_\mu}{m_\mu}\bar{\mu}_L\sigma_{\mu\nu}q^\nu\mu_R$$

How is this generated in SUSY?

$g-2$ in the MSSM: general behaviour

$g-2$ = chirality-flipping interaction

$$\frac{a_\mu}{m_\mu}\bar{\mu}_L \sigma_{\mu\nu} q^\nu \mu_R$$

How is this generated in SUSY?

In SM or MSSM: chirality flips governed by λ_μ, $m_\mu = \lambda_\mu \langle H_1 \rangle$

In MSSM: second Higgs doublet H_2 important!

$g - 2$ in the MSSM

numerically

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

- $\propto \tan\beta \, \mathrm{sign}(\mu)$
- $\propto 1/M_{\mathrm{SUSY}}^2$, but complicated dependence on individual masses

$g - 2$ in the MSSM

numerically

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

$\tan\beta = 8, \quad M_{\mathrm{SUSY}} = 200$ GeV
$\tan\beta = 50, \quad M_{\mathrm{SUSY}} = 500$ GeV: $\quad a_\mu^{\mathrm{SUSY}} = 24 \times 10^{-10} \quad (\mu > 0)$

$\tan\beta = 50, \quad M_{\mathrm{SUSY}} = 250$ GeV: $\quad a_\mu^{\mathrm{SUSY}} = -96 \times 10^{-10} \quad (\mu < 0)$

$g-2$ in the MSSM

numerically

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

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

positive μ, large $\tan\beta$/small $M_{\rm SUSY}$ preferred
however, beware of the fine print. . .

Precise analysis justified!

$g-2$ in the MSSM

numerically

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

- 1-loop and most 2-loop contributions known
- remaining theory uncertainty of SUSY prediction: [DS '06]

$$\delta a_\mu^{\mathrm{SUSY}} \approx 3 \times 10^{-10}$$

$g - 2$ in the MSSM

numerically

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

- 1-loop and most 2-loop contributions known
- remaining theory uncertainty of SUSY prediction: [DS '06]

$$\delta a_\mu^{\mathrm{SUSY}} \approx 3 \times 10^{-10}$$

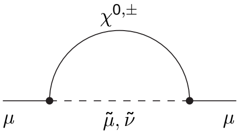
Aim in Dresden: reduce error to $1 \times 10^{-10} \Rightarrow$ full computation!

$\Rightarrow$ It is worthwhile to look at the details

Status of SUSY prediction

1-Loop

$\propto \tan\beta$



[Fayet '80],. . .

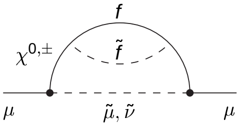
[Kosower et al '83],[Yuan et al '84],. . .

[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]

photonic

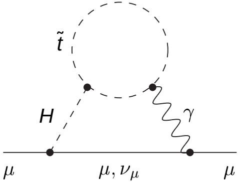
$(\tan\beta)^2$

aim: full calculation

(65000 diagrams)

2-Loop (SM 1L)

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



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

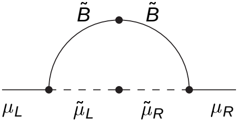
[Heinemeyer,DS,Weiglein '03]

[Heinemeyer,DS,Weiglein '04]

complete

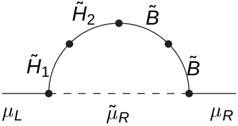
Physics of subleading contributions (examples)

1-loop bino



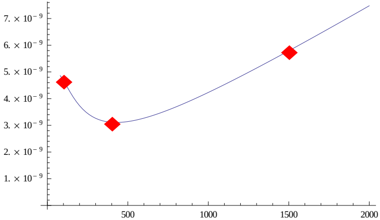
$\propto \mu$ for $\mu \to \infty$

1-loop $\tilde{\mu}_R$

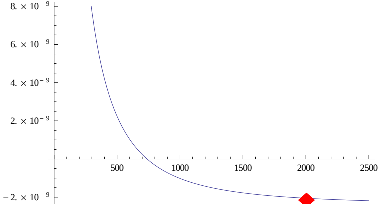


$\propto$ other sign!

small/large μ

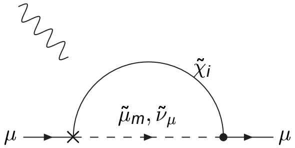


small/large $M_{\tilde{\mu}_L}$

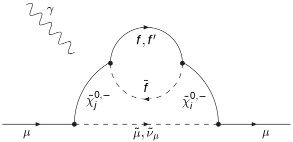


New calculation of class $f\tilde{f}$: contains large logs, $\Delta\rho$

[H. Fargnoli, C. Gnendiger, S. Passehr, DS, H. Stöckinger-Kim '13]

1. 

$\rightarrow a_\mu^{1L} \times \Delta\rho$

2. 

$\rightarrow a_\mu^{1L} \times \log(m_{\tilde{f}})$

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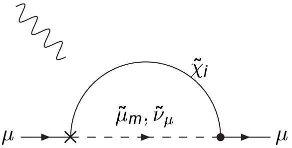
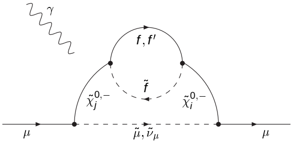
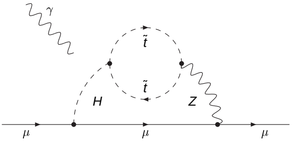
1. 

$\rightarrow a_\mu^{1L} \times \Delta\rho$

2. 

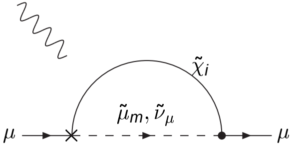
$\rightarrow a_\mu^{1L} \times \log(m_{\tilde{f}})$

Old

3. 

$\rightarrow a_\mu^{1L} \times \frac{1}{m_{\tilde{f}}^2}$

Contributions involving $\Delta\rho$

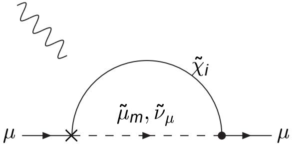


$$= a_\mu^{1L} \times \left(\ldots + \frac{\delta(e^2/s_W^2)}{e^2/s_W^2} \right)$$
$$= a_\mu^{1L} \times \left(\Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \ldots \right)_{f,\tilde{f}\text{-loops}}$$

One-loop ambiguity

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

Contributions involving $\Delta\rho$



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

One-loop ambiguity

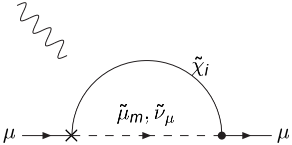
Fixed by full $2Lf\tilde{f}$ calculation

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

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

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

Contributions involving $\Delta\rho$



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

One-loop ambiguity

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

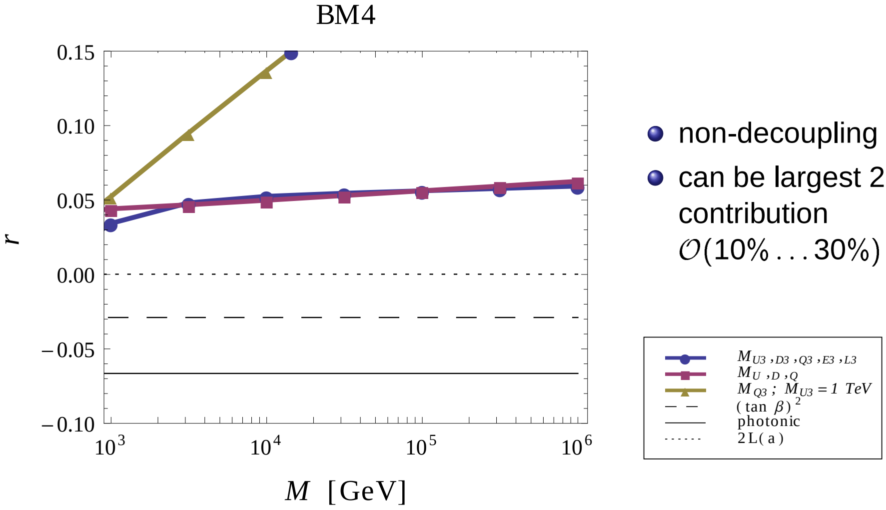
differ by $\Delta\alpha$, $\Delta\rho$: 2L$f\tilde{f}$-terms

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

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

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

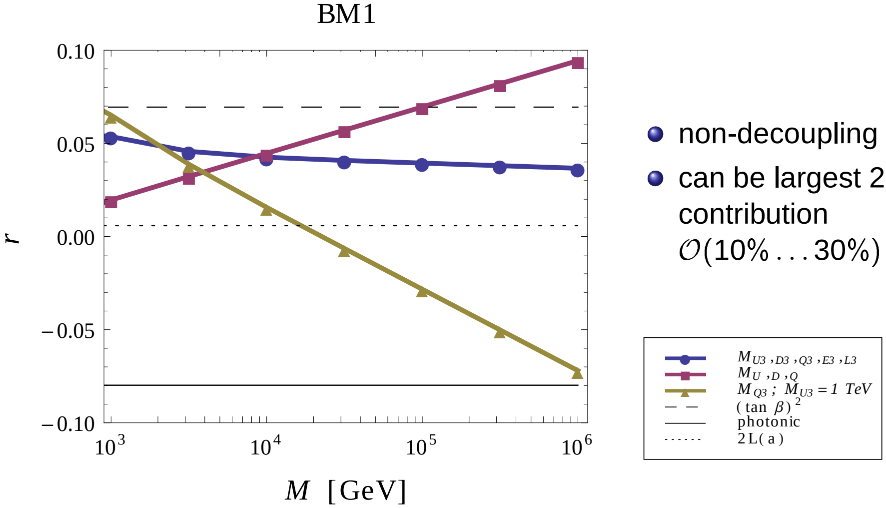
Results for $f\tilde{f}$-loops: Large contributions from heavy squarks [Fargnoli, Gnendiger, Passehr, DS, Stöckinger-Kim ’13]



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

$\mu = -160$, $M_1 = 140$, $m_{\tilde{\mu}_R} = 200$, $M_2 = m_{\tilde{\mu}_L} = 2000$ GeV, $\tan\beta = 50$

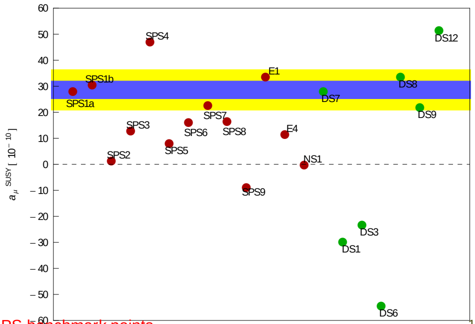
Results for $f\tilde{f}$-loops: Large contributions from heavy squarks [Fargnoli, Gnendiger, Passehr, DS, Stöckinger-Kim '13]



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

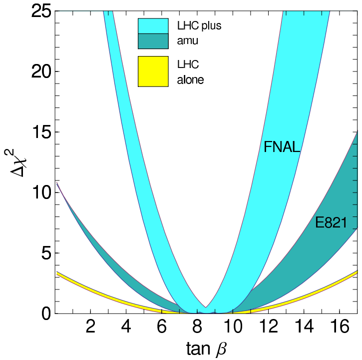
$\mu = 350$, $M_2 = 2M_1 = 300$, $m_{\tilde{\mu}_{R,L}} = 400$ GeV, $\tan\beta = 40$

a_μ central complement for SUSY parameter analyses



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

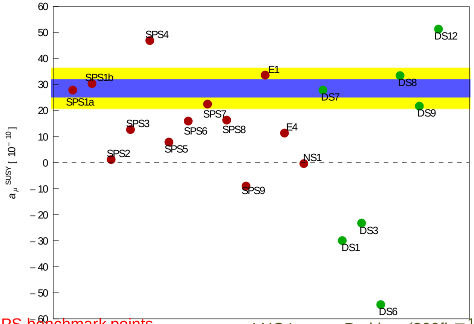
LHC Inverse Problem (300fb^{-1}) can't be distinguished at LHC
[Sfitter: Adam, Kneur, Lafaye, Plehn, Rauch, Zerwas '10]



[Hertzog, Miller, de Rafael, Roberts, DS '07]

- a_μ sharply distinguishes SUSY models
- helps measure parameters

a_μ central complement for SUSY parameter analyses



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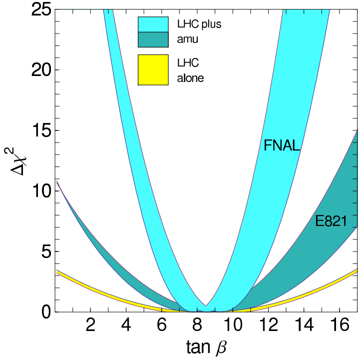


[Hertzog, Miller, de Rafael, Roberts, DS '07]

vision: test universality of $\tan\beta$, like for $\cos\theta_W = \frac{M_W}{M_Z}$ in the SM:

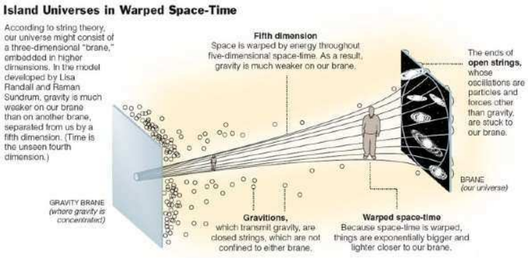
$$(t_\beta)^{a_\mu} = (t_\beta)^{\text{LHC,masses}} = (t_\beta)^H = (t_\beta)^b?$$

Outline

EWSB Models

Large a_μ possible?

- Randall Sundrum
- Littlest Higgs + T-Parity ("Bosonic SUSY")
- 2-Higgs doublet model + 4th generation



Randall Sundrum

- KK-gravitons $\rightarrow$ large [Kim, Kim, Song'01]
- However, challenged by electroweak precision data [Hewett et al '00] and $\gamma\gamma \rightarrow \gamma\gamma$ unitarity [Kim,Kim,Song '01]
- non-graviton contributions small

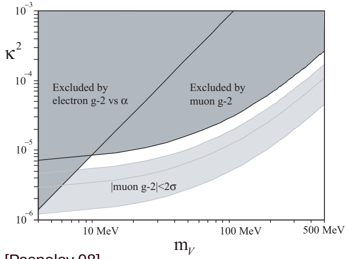
[Beneke, Dey, Rohrwild '12]

Other types of new physics

What if the LHC does not find new physics?
Hide new particles at colliders $\rightsquigarrow$ large a_μ possible

- "Dark force"? [Pospelov, Ritz...]
  very light, weakly interacting
  $C \propto 10^{-8}$, $M < 1\text{GeV}$

- Light "Z'" from gauged $L_\mu - L_\tau$
  [Ma, Roy, Roy '02][Heeck, Rodejohann '11]
  flavour-dependent couplings,
  hidden at LEP
  (but see [Altmannshofer, Gori, Pospelov, Yavin '14])
  $C \sim C_{\text{SM,weak}}$, $M_{Z'} \sim M_Z$



[Pospelov 08]