Magnetic moment $(g-2)_\mu$ and new physics

Dominik Stöckinger, TU Dresden

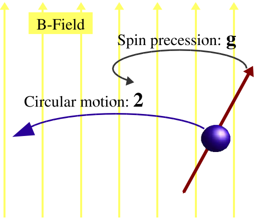
Sussex, November 2011

Outline

1. Introduction
   - Motivation and Prehistory
   - Legacy of Brookhaven measurement: 3σ deviation
2. New $g-2$ experiments at Fermilab and JParc
3. Impact on New Physics in general
4. SUSY could explain the deviation
   - General behaviour
   - Two-loop contributions
   - a_μ, parameter measurements and model discrimination
5. Alternatives to SUSY
6. Conclusions

Outline

Muon magnetic moment



$$H_{\text{magnetic}} = -2(1 + a_\mu)\frac{e}{2m_\mu}\vec{B}\cdot\vec{S}$$

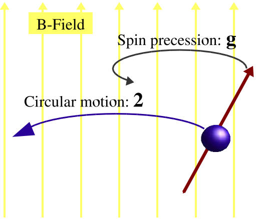
Measurement:

circular motion: $\omega_c = -\frac{e}{m_\mu}B$

spin precession: $\omega_s = -\frac{2(1+a_\mu)e}{2m_\mu}B$

$\rightarrow$ measure $\omega_a = \omega_s - \omega_c = -a_\mu \frac{e}{m_\mu}B$

Muon magnetic moment



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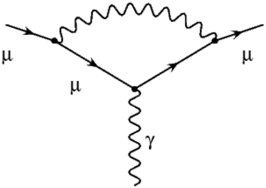
Quantum field theory:

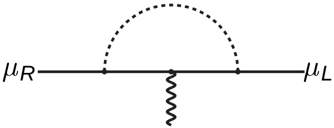


$$\tilde{=}\bar{u}(p')\left[\gamma_\mu F_1 + \frac{i}{2m_\mu}\sigma_{\mu\nu}q^\nu a_\mu\right]u(p)$$

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

Why is a_μ special?

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

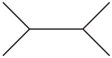


Beautifully simple “textbook” quantity, very precise

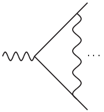
CP- and Flavour-conserving, chirality-flipping, loop-induced

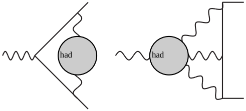
compare: EDMs, $b \to s\gamma$, $B \to \tau\nu$, $\mu \to e\gamma$

EWPO

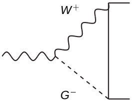


Classification of SM contributions

QED:  $\sim 10^{-3}$

had: 

$\sim 10^{-7}$

weak: 

$\sim 10^{-9}$

(Pre)history

'49 Schwinger: QED 1L: $\frac{\alpha}{2\pi}$

'57 Garwin et al: $g_\mu \approx 2 \Rightarrow$ Muon=Dirac particle!

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'80-'11 Theory developments:	QED, hadronic,
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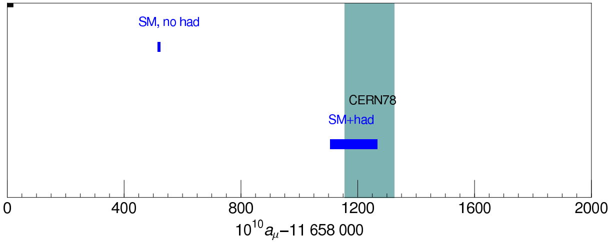
Legacy of the CERN experiment



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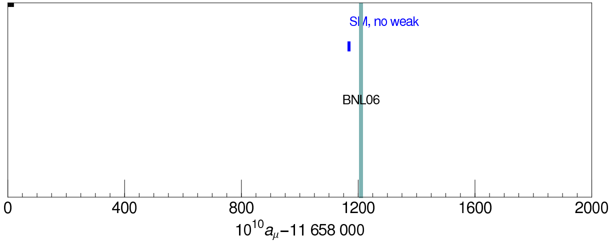

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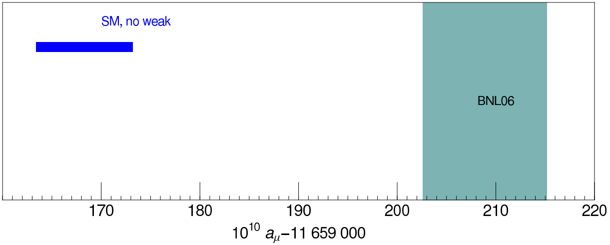

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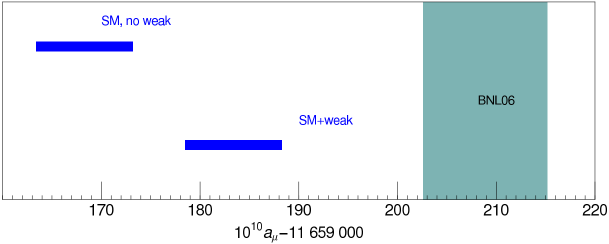
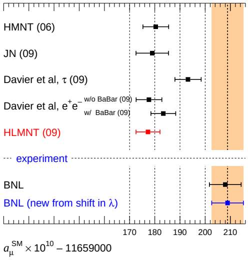
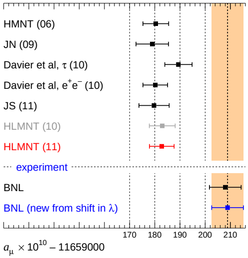


Era of the muon $g - 2$ experiment at Brookhaven

$$a_\mu^{\exp} = (11\,659\,208.9 \pm 6.3) \times 10^{-10}$$

Current status: SM prediction





Full SM: $a_\mu \times 10^{10} - 11659000$

dR08:	. . . 178.5(5.1)	(3.6σ)
JN09:	. . . 179.0(6.5)	(3.2σ)
HLMNT09:	. . . 177.3(4.8)	(4.0σ)
Detal09:	. . . 183.4(4.9)	(3.2σ)
JS11:	. . . 179.7(6.0)	(3.3σ)
HLMNT11:	. . . 182.8(4.9)	(3.3σ)
BDDJ11:	. . . 175.4(5.3)	(4.1σ)

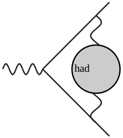
Exp:

BNL06: . . . 208.9(6.3)

3σ deviation established

Current status: SM prediction

Hadronic vacuum polarization contributions:



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

Recent progress:

- new exp data (CMD2, SND, KLOE, B-factories)

  $\Rightarrow$ significantly more precise!
- possible explanations of τ-based results

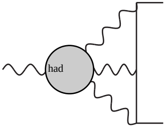
  $\rightarrow$ confirmation of e^+e^--based evaluations

  [Benayoun et al '07][Jegerlehner, Szafron '11]
- assume e^+e^- data different

  $\Rightarrow$ contradiction to Higgs mass bounds! [Marciano, Passera, Sirlin '08]

Current status: SM prediction

Hadronic light-by-light contributions



new estimates with correct sign,
using different approximations

[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

Cannot be computed from first principles — Error difficult to assess!

Promising new approaches: lattice, Dyson-Schwinger, perturbative

Discrepancy

SM prediction too low by $\approx (25 \pm 8) \times 10^{-10}$

Why?

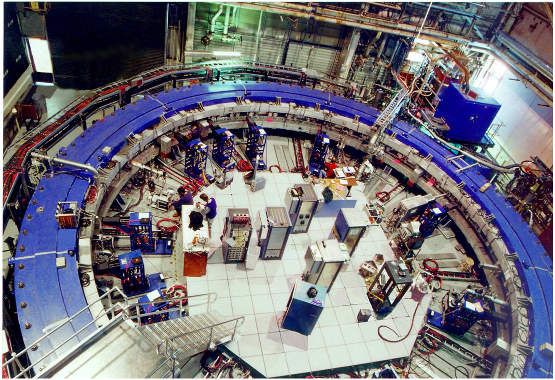
Confirmation needed!

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

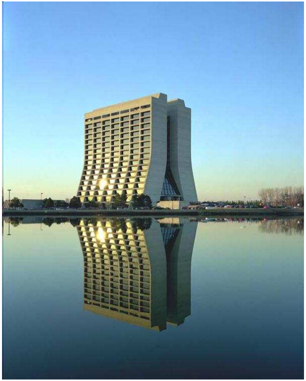
but we expect: $a_\mu^{\mathrm{NP}} \sim a_\mu^{\mathrm{SM,weak}} \times \left(\frac{M_W}{M_{\mathrm{NP}}}\right)^2 \times$ couplings

Outline

The Opportunity



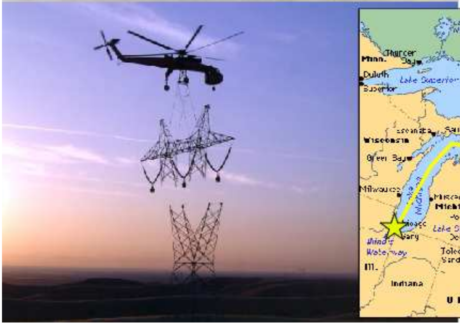
$\Rightarrow$

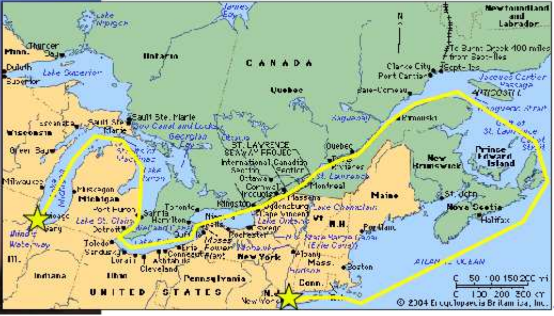


The Opportunity

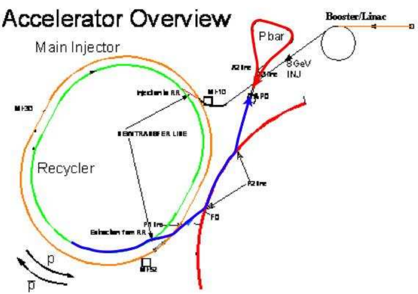
Barge around St. Lawrence

- Airlift coils to barge off Long Island
- Estimated barge cost \$1M to transport yoke steel and coils
- Ship through St Lawrence -> Great Lakes -> Calumet SAG
- Airlift from somewhere around Romeoville, IL to Fermilab





Advantages of Fermilab



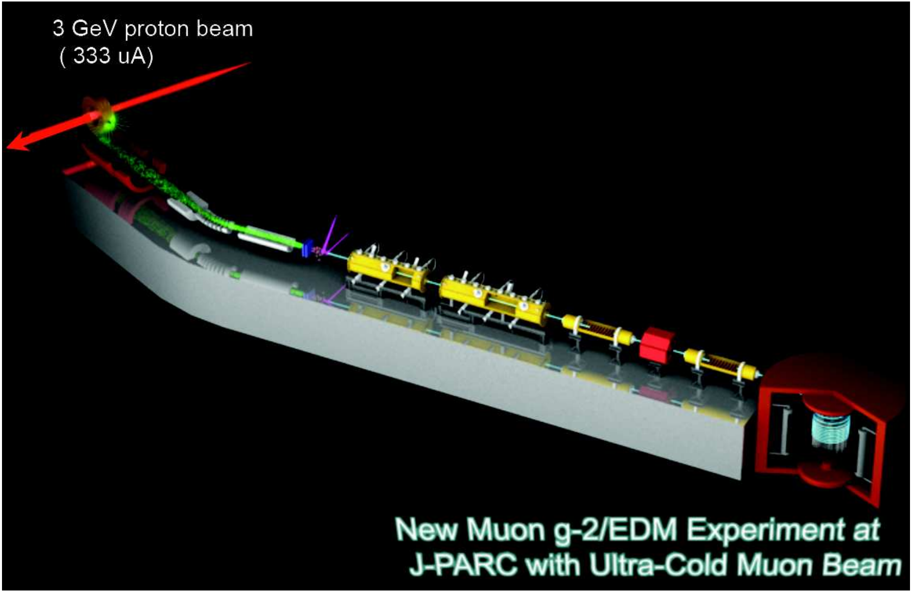
π decay length 900m vs 88m

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

The Collaboration

First collaboration meeting after approval in March

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

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

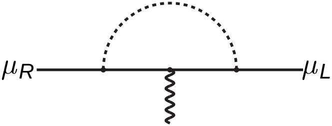
$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (255?? \pm 16^{\rm Exp} \pm 34^{\rm Th}??) \times 10^{-11}$$

Data in $\sim$ 4–5 years

- Tremendously useful complement of LHC (and flavour physics experiments), independent of final value [Hertzog, Miller, de Rafael, Roberts, DS ’07]
- Benchmark for any new physics scenario
- Timely, complementary constraints
- This will be demonstrated in the following

Outline

Why is a_μ special?



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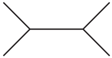
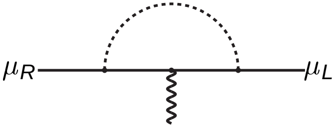


New physics contributions to a_μ

$g - 2$ = chirality-flipping interaction



m_μ = chirality-flipping interaction as well

are the two related?

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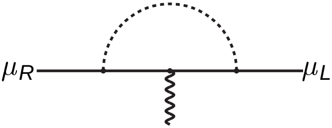

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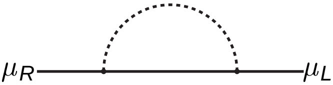

are the two related?

New physics loop contributions to a_μ, m_μ related by chiral symmetry

[Czarnecki, Marciano '01]

generally: $$\delta a_\mu(\mathrm{N.P.}) = \mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2, \quad C = \frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}$$

Very different contributions to a_μ

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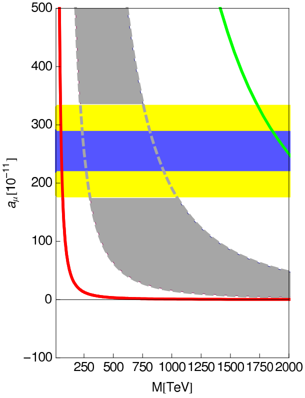
classify new physics: C **very** model-dependent



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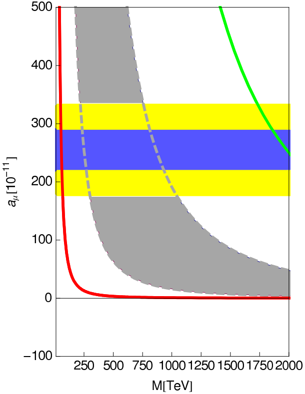

$\mathcal{O}(1)$	
$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	
$\mathcal{O}(\frac{\alpha}{4\pi})$	Z', W', UED, Littlest Higgs (LHT)...

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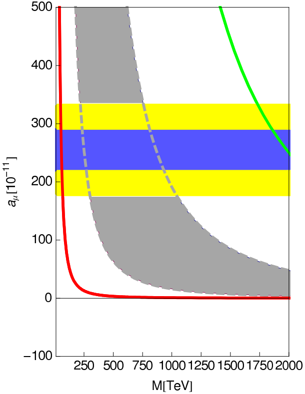

$\mathcal{O}(1)$	
$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	supersymmetry ($\tan\beta$), unparticles [Cheung, Keung, Yuan '07] extra dim. (ADD/RS) (n_c)... [Davioudasl, Hewett, Rizzo '00] [Graesser,'00][Park et al '01][Kim et al '01]
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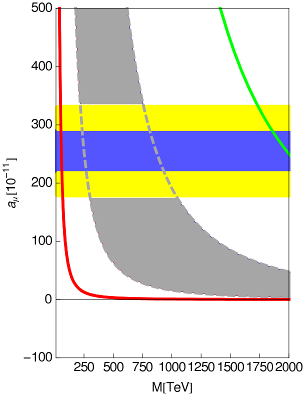

$\mathcal{O}(1)$	radiative muon mass generation … [Czarnecki,Marciano '01]
$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	supersymmetry ($\tan\beta$), unparticles [Cheung, Keung, Yuan '07] extra dim. (ADD/RS) (n_c)… [Davioudasl, Hewett, Rizzo '00] [Graesser,'00][Park et al '01][Kim et al '01]
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a_μ and new physics

Different types of new physics lead to very different δa_μ(N.P.)

- SUSY, RS, ADD, . . . : strong parameter constraints
- Z', UED, LHT, . . . : ruled out if deviation confirmed

If new physics found at LHC:

- a_μ constitutes a benchmark for new physics models
- can sharply distinguish between different types of models
- timely, complementary constraints, parameter measurements

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Now illustrate general points with examples

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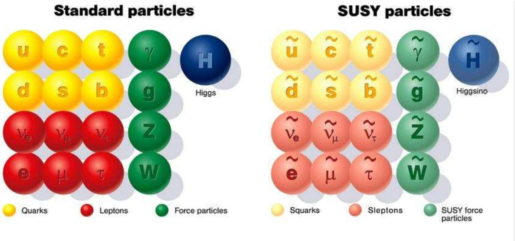
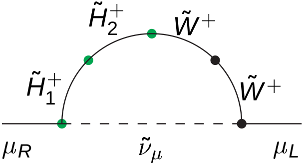
SUSY and the MSSM

- MSSM:



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

$g-2$ in the MSSM: chirality flips, λ_μ, and H_2



$\tan\beta = \frac{\langle H_2\rangle}{\langle H_1\rangle}$, $\quad \mu = H_2 - H_1$ transition

some terms

$$\propto \lambda_\mu \langle H_1\rangle = m_\mu \qquad \rightarrow a_\mu^{\rm SUSY} \propto \frac{m_\mu^2}{M_{\rm SUSY}^2}$$

some terms

$$\propto \lambda_\mu\, \mu \langle H_2\rangle = m_\mu\ \mu\ \tan\beta \qquad \rightarrow a_\mu^{\rm SUSY} \propto \tan\beta\, \mathrm{sign}(\mu)\, \frac{m_\mu^2}{M_{\rm SUSY}^2}$$

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

$g - 2$ in the MSSM

numerically

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

SUSY could be the origin of the observed $(25 \pm 8) \times 10^{-10}$ deviation!

a_μ significantly restricts the SUSY parameters

$\rightarrow$ generically, positive μ, large $\tan\beta$/small M_{SUSY} preferred

Precise analysis justified!

$g - 2$ in the MSSM

numerically

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

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

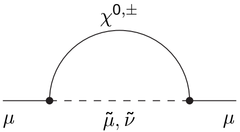
$$\delta a_\mu^{\rm SUSY} \approx 3 \times 10^{-10}$$

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

Status of SUSY prediction

1-Loop

$\propto \tan\beta$



[Fayet '80],...

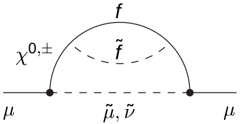
[Kosower et al '83],[Yuan et al '84],...

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

complete

2-Loop (SUSY 1L)

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



[Degrassi,Giudice '98]

[Marchetti, Mertens, Nierste, DS '08]

[Schäfer, Stöckinger-Kim,

v. Weitershausen, DS '10]

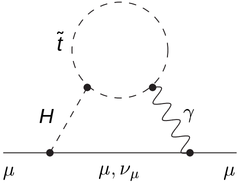
photonic

$(\tan\beta)^2$

rest under investigation

2-Loop (SM 1L)

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



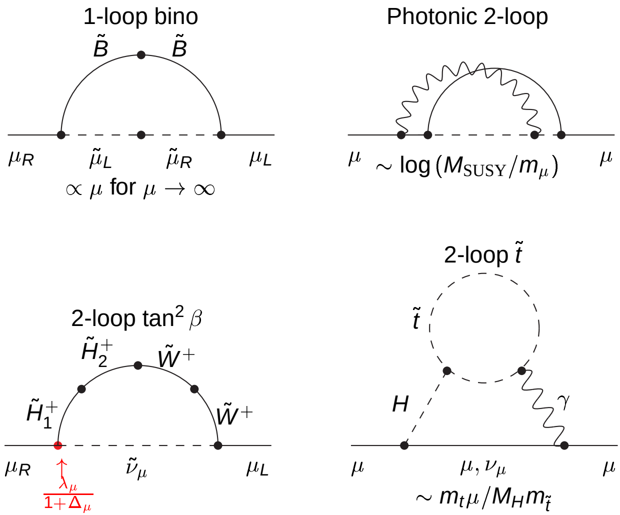
[Chen,Geng'01][Arhib,Baek '02]

[Heinemeyer,DS,Weiglein '03]

[Heinemeyer,DS,Weiglein '04]

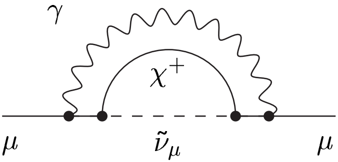
complete

Physics of subleading contributions (examples)



Important for drawing precise conclusions from confronting SUSY-prediction with $a_\mu^{\rm Exp-SM}$

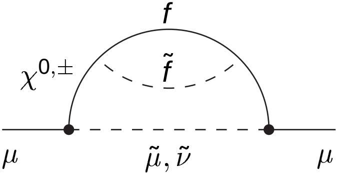
Technical details: Photon loops



All SUSY 1-loop diagrams with additional photon loop

- leading log: $-7 \ldots -9\%$ [Degrassi, Giudice '98]
- full result: subleading logs, $\log(m_\chi/m_{\tilde{\nu}_\mu})$, non-log terms
- additional terms $\mathcal{O}(1\%)$
- full result more precise [v. Weitershausen, Schäfer, Stöckinger-Kim, DS '09]
- technically difficult but useful: contains all infrared divergences

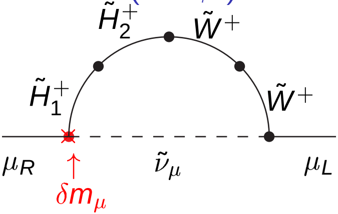
Technical details: $f/\tilde{f}$-loops



All SUSY 1-loop diagrams with additional $f/\tilde{f}$-loop (3rd generation)

- finite, gauge invariant class of contributions
- enhanced by top/bottom Yukawa coupling
- partial results [Drechsel, Gnendiger, Passehr, Schäfer, Stöckinger-Kim, DS] [Fargnoli, Stöckinger-Kim]
- typically $\mathcal{O}(1\%)$

Technical details: $(\tan\beta)^2$ enhanced corrections



$a_\mu^{\rm SUSY} \propto$ chirality flip $\propto \lambda_\mu$

However, one-loop coupling to "wrong" Higgs doublet induces shift

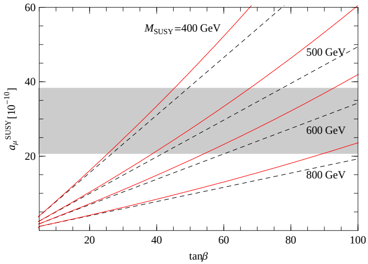
$$\lambda_\mu \to \frac{\lambda_\mu}{1+\Delta_\mu} \qquad \text{or} \qquad \delta m_\mu^{\rm OS} = \frac{m_\mu}{1+\Delta_\mu} + \ldots$$

Corresponding 2-loop shift in $a_\mu^{\rm SUSY}$

[Marchetti, Mertens, Nierste, DS '08]

$$a_\mu^{\rm SUSY} \to \frac{a_\mu^{\rm SUSY}}{1+\Delta_\mu}$$

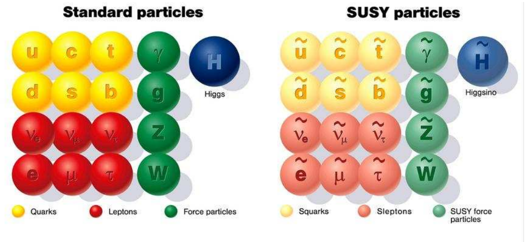
Technical details: leading two-loop corrections



$$a_\mu^{\rm SUSY} = a_\mu^{\rm SUSY,1L}\left(1 - \frac{4\alpha}{\pi}\log\frac{M_{\rm SUSY}}{m_\mu}\right)\left(\frac{1}{1+\Delta_\mu}\right)$$

- QED-logs: $-7\ldots-9\%$
- $(\tan\beta)^2$: $+1\ldots+15\%$, $\Delta_\mu(M_{\rm SUSY}) \approx -0.0018\ \tan\beta\ \mathrm{sign}(\mu)$

SUSY and a_μ

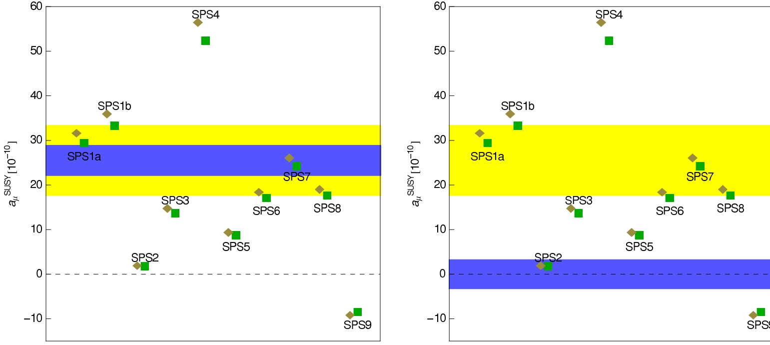


$$a_\mu^{\rm SUSY} \approx 12 \times 10^{-10} \tan\beta \; {\rm sign}(\mu) \left(\frac{100{\rm GeV}}{M_{\rm SUSY}}\right)^2$$

$\tan\beta = \frac{v_2}{v_1}$, $\mu = H_1$-H_2 transition — central for EWSB

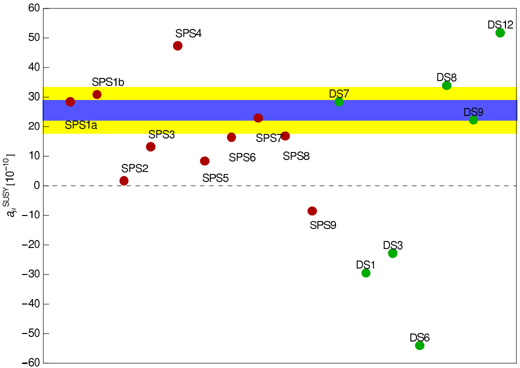
If SUSY signals at LHC:
a_μ complementary for: model selection, parameter measurements
$\rightarrow$ understand EWSB, link to GUT scale . . .

a_μ central complement for SUSY parameter analyses



- a_μ sharply distinguishes SUSY models
- breaks LHC degeneracies

a_μ central complement for SUSY parameter analyses



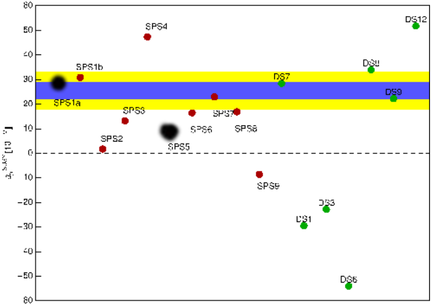
SPS benchmark points

LHC Inverse Problem (300fb^{-1})

can't be distinguished at LHC

- a_μ sharply distinguishes SUSY models
- breaks LHC degeneracies

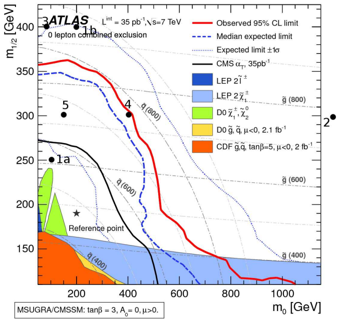
a_μ central complement for SUSY parameter analyses



SPS benchmark points

LHC Inverse Problem (300fb^{-1})

can't be distinguished at LHC [Sfitter: Adam, Kneur, Lafaye, Plehn, Rauch, Zerwas '10]



[ATLAS jets+0lepton 02/11]

- LHC already rules out small masses in CMSSM
- $\Rightarrow$ large tan β (SPS1b,4)? Non-CMSSM (heavier squarks)?
- $a_\mu^{\rm SUSY}$ smaller?

Ways to reconcile the LHC bounds with a_μ

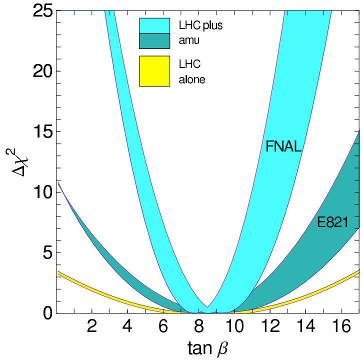
LHC mainly constrains squarks/gluinos

- Even within the CMSSM: heavy masses + large $\tan\beta$
- Beyond the CMSSM: sleptons lighter than squarks

Don't worry, SUSY still viable — but the LHC—*b*-decays—a_μ tensions start preferring some parameter regions

- If SUSY exists, a_μ will be even important to measure parameters

a_μ central complement for SUSY parameter analyses



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

$\tan\beta = \frac{v_2}{v_1}$
central for understanding EWSB

LHC: $(\tan\beta)^{\mathrm{LHC,masses}} = 10 \pm 4.5$ bad
[Sfitter: Lafaye, Plehn, Rauch, Zerwas '08, assume SPS1a]

a_μ improves $\tan\beta$ considerably

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

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

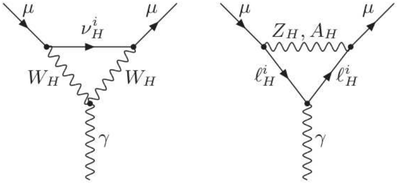
Outline

Littlest Higgs (with T-parity)

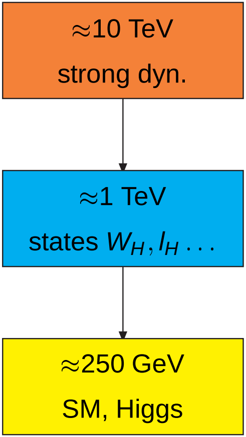
[Georgi; Arkani-Hamed,Cohen,Georgi]
Concrete LHT model: [Cheng, Low '03]
[Hubisz, Meade, Noble, Perelstein '06]

Bosonic SUSY

- partner states, same spin
- cancel quadratic div.s
- T-parity⇒lightest partner stable



no enhancement of $\frac{\alpha}{4\pi}\left(\frac{m_\mu}{M}\right)^2$



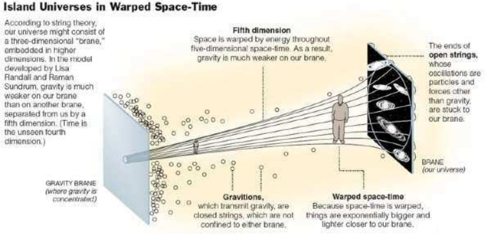
$$a_\mu^{\mathrm{LHT}} < 1.2 \times 10^{-10}$$

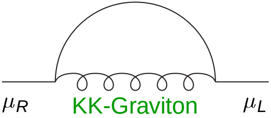
[Blanke, Buras, et al '07]

Clear-cut prediction, sharp distinction from SUSY possible

Randall-Sundrum models

Big question: Where does the hierarchy $M_{\rm Pl} : M_W \sim 10^{17}$ come from?
Answer: beautifully explained by warp factor e^{-kL}





Gravity propagates in extra dimension
each KK-Graviton contributes equally, weakly, **no decoupling!**

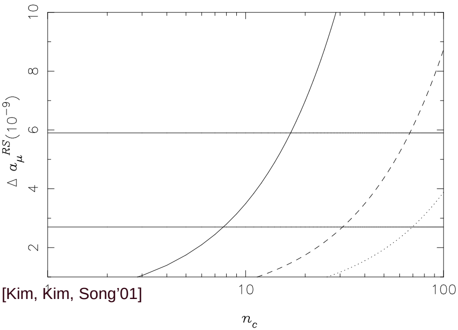
TeV-scale determined by:

- coupling $k/M_{\rm Pl}$
- scale $\Lambda_\pi = e^{-kL} M_{\rm Pl}$

theory breaks down at scale $\sim \Lambda_\pi$, n_c KK-gravitons up to that scale

$$\to a_\mu^{\rm RS} \sim \frac{5 n_c}{16\pi^2} \frac{m_\mu^2}{\Lambda_\pi^2}$$

$g-2$ and Randall-Sundrum models



[Kim, Kim, Song'01]

Complementarity: LHC

- lowest KK-modes
- masses

a_μ from KK-loops

- feels all KK-modes
- e.g. $C_{\rm Grav} \propto M^2$, $C_{\rm H} \sim 1$
- guides model building of full theory

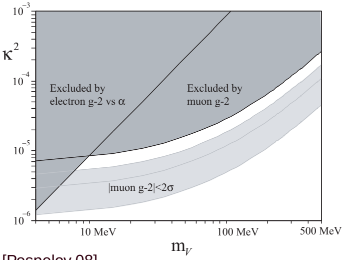
Other types of new physics

What if the LHC does not find new physics — "Dark force"? [Pospelov, Ritz...]

$C \propto 10^{-8}$, $M < 1\text{GeV}$

- a_μ can be large
- could be "seen" by a_μ-exp.

- very light new vector boson
- very weak coupling
- motivated e.g. by dark matter, not by EWSB



[Pospelov 08]

Outline

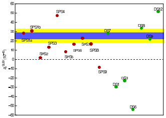
Conclusions

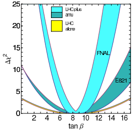
- Currently $a_\mu^{\rm Exp} - a_\mu^{\rm SM} \approx (25 \pm 8) \times 10^{-10}$ — tantalizing

- New Fermilab measurement will start soon — very promising!

- $a_\mu^{\rm N.P.}$ very model-dependent, typically $\mathcal{O}(\pm 1 \ldots 50) \times 10^{-10}$
  - Benchmark, model discriminator
  - unique properties

- New measurement of a_μ will
  - sharply distinguish models, even with similar LHC signatures
  - break degeneracies
    measure central parameters





a_μ will provide essential complementary input in the quest to understand TeV-scale physics — no matter what the result
BSM physics can look forward to the new a_μ measurement!!