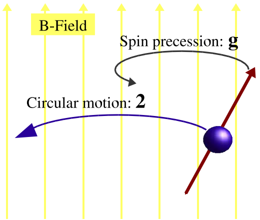
Magnetic moment $(g-2)_\mu$ and new physics

Dominik Stöckinger, TU Dresden

Heidelberg, November 2012

Muon magnetic moment

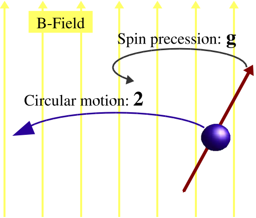


$$H_{\text{magnetic}} = -2(1 + a_\mu)\frac{e}{2m_\mu}\vec{B} \cdot \vec{S}$$

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

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

Muon magnetic moment



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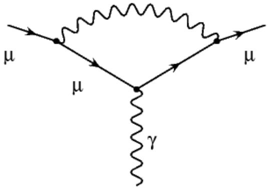
Quantum field theory:



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

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

Outline

1. $a_\mu^{\rm SM}$ — status?
2. Impact on New Physics in general
3. SUSY
   - Can explain the deviation — a_μ constraints
   - LHC vs a_μ
   - Subleading contributions
4. Alternatives to SUSY
5. Conclusions

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

(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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'96-'05	e.w. contributions:	2L full

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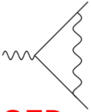
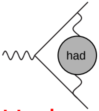
'01–'06	BNL exp.:	weak cont. needed, not confirmed!

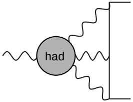
SM prediction a_μ^{SM} $[10^{-10}]$ [Miller, de Rafael, Roberts, DS '12]



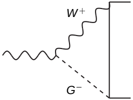
QED: $11\,658\,471.8 \quad (0.0)$



Had vp: $682.5 \quad (4.2)$



Had lbl: $10.5 \quad (2.6)$



Weak: $15.3 \quad (0.1)$

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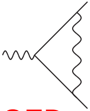
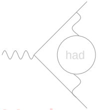


QED: 11 658 471.8 (0.0)



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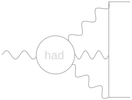

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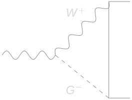

Weak:

QED:

- complete 5-loop result

  [Aoyama, Hayakawa, Kinoshita, Nio ’12]

- QED uncertainty 10^{-12}
- dominated by α

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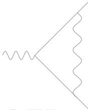
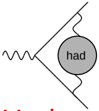
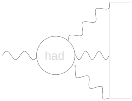


QED:



Had vp: 682.5 (4.2)



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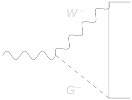


Weak:

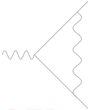
Hadronic vacuum polarization:

$\leftrightarrow e^+e^- \to \gamma^* \to$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 '12]



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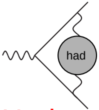

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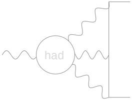

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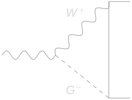

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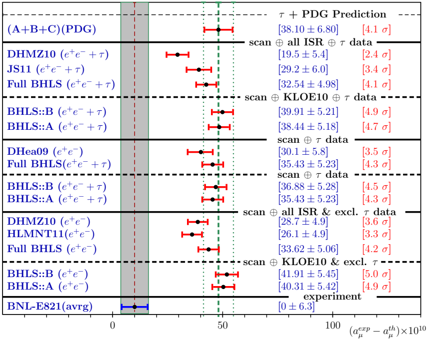

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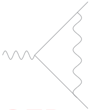

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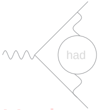

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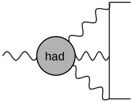

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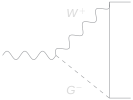

Weak:

Hadronic light-by-light:

- 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

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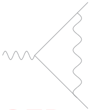

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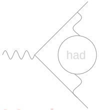

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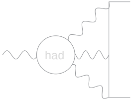

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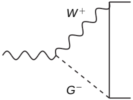

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Weak:

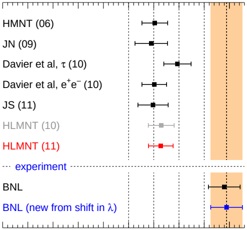
- 2-loop result ($M_H \to \infty$)

  [Czarnecki, Krause, Marciano '95]
- with full Higgs mass dependence

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

$\Rightarrow$ current M_H constraints fix $a_\mu^{\rm weak}$

Current status: SM prediction



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

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)
MdRRS12:	. . . 180.1(4.9)	(3.6σ)
BDDJ12:	. . . 170.8(5.2)	(4.7σ)

largest uncertainty from e^+e^- data
smaller from lbl
both will improve in future

Exp:

BNL06: . . . 208.9(6.3)

Muon $g-2$ experiment at Brookhaven

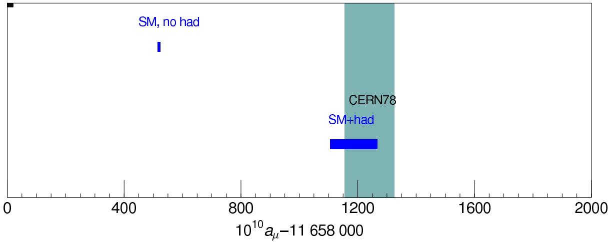
$$a_\mu^{\rm exp} = (11\,659\,208.9(5.4)_{\rm stat}(3.3)_{\rm syst}(6.3)_{\rm tot}) \times 10^{-10}$$

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

Theory confronts experiment

'68–'78 CERN measurement:	hadronic cont. needed, confirmed!
'01–'06 BNL measurement:	weak cont. needed, not confirmed!

Legacy of the CERN experiment



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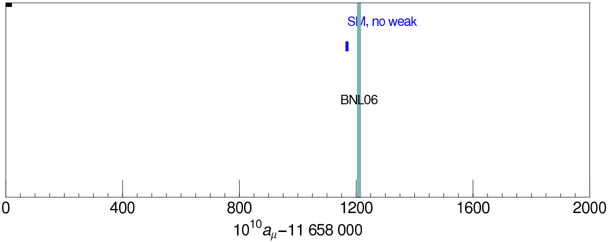

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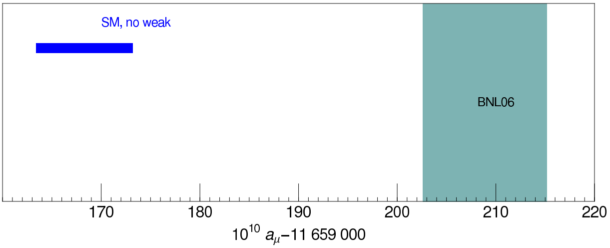

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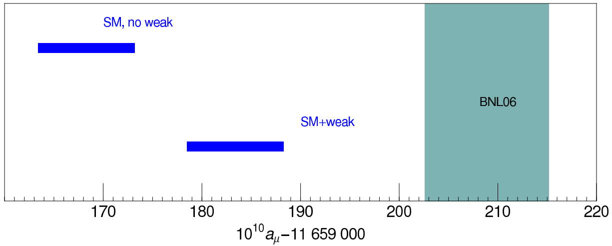


Discrepancy

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

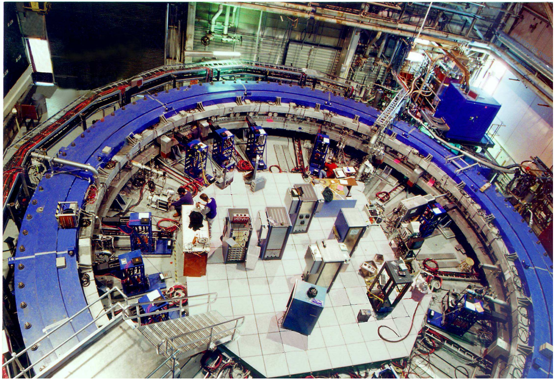
Note: discrepancy twice as large as $a_\mu^{\mathrm{SM,weak}}$

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

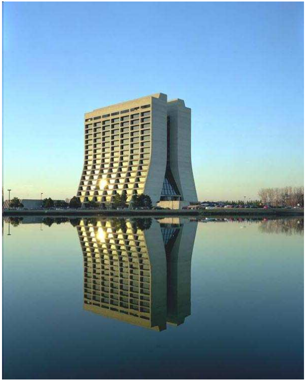
Future experiments at Fermilab and JParc (N. Saito)

	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

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

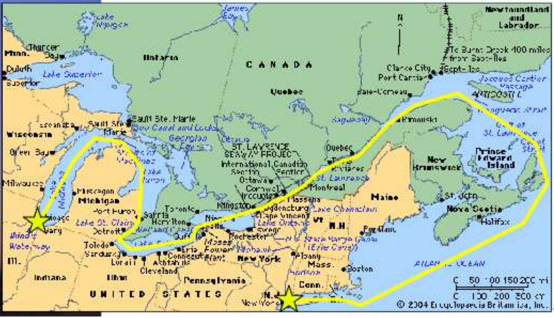
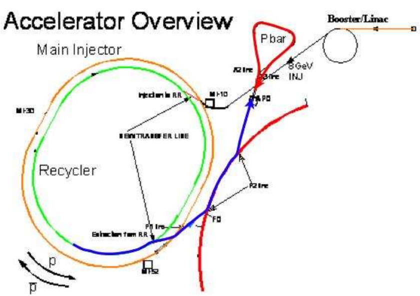


Photo from 29/09/12

Official CD-0 approval September 2012

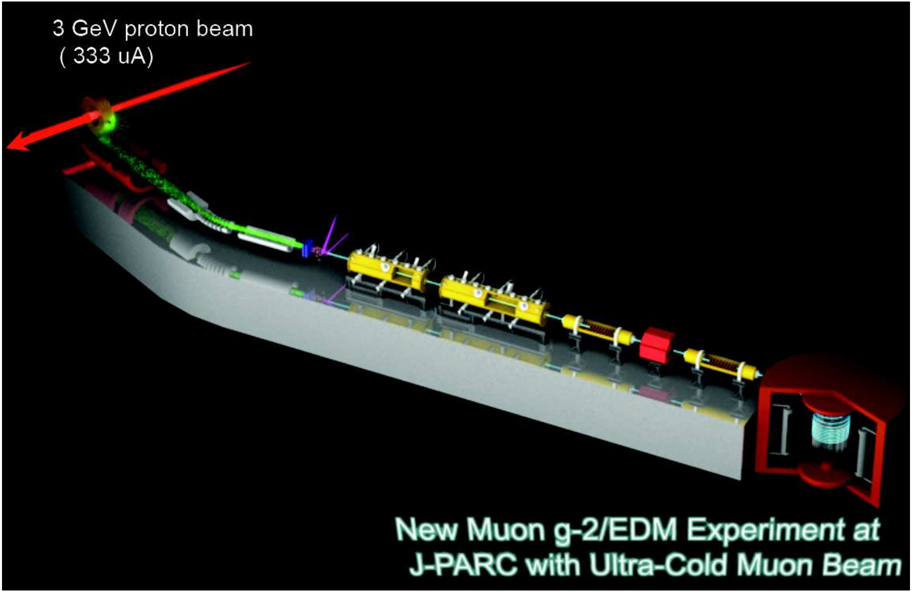
Advantages of Fermilab



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

Complementary experiment at JParc (N. Saito)



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

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

Data in $\sim$ 4–5 years

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

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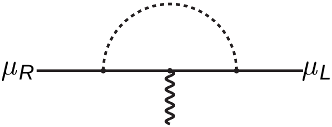
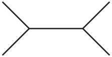
Why is a_μ special?



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

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

EWPO



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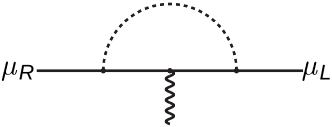

CP- and Flavour-conserving, chirality-flipping, loop-induced

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

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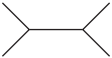

Note relation to m_μ

Very different contributions to a_μ

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

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

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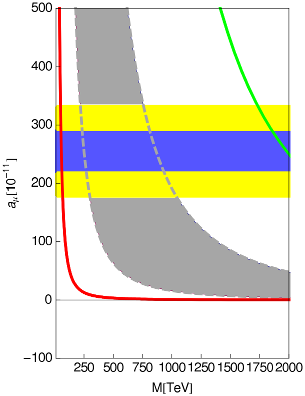

$\mathcal{O}(1)$	
$\mathcal{O}(\frac{\alpha}{4\pi} \ldots)$	
$\mathcal{O}(\frac{\alpha}{4\pi})$	Z', W', UED, Littlest Higgs (LHT)...

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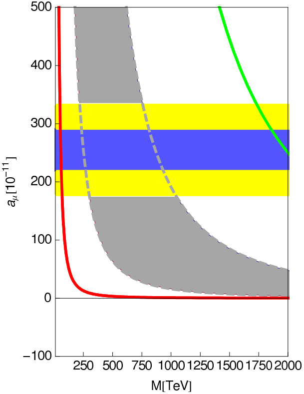
classify new physics: C **very** model-dependent



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

Very different contributions to a_μ

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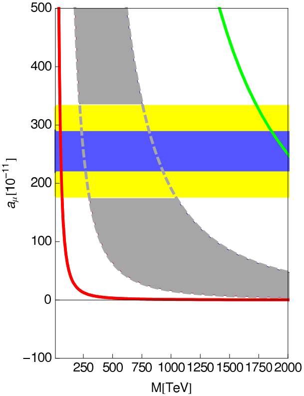

$\mathcal{O}(1)$	radiative muon mass generation ... [Czarnecki,Marciano '01] [Crivellin, Girrbach, Nierste '11][Dobrescu, Fox '10]
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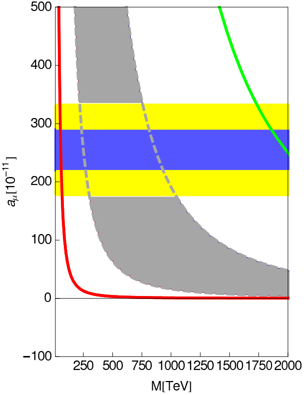
classify new physics: C **very** model-dependent

Very useful constraints on new physics



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Outline

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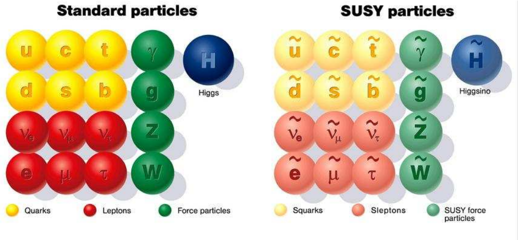
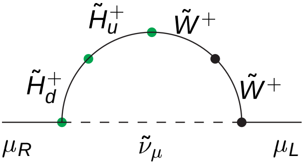
SUSY and the MSSM

- MSSM:



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

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



Each diagram

$$\propto \lambda_\mu, \text{ some vev}$$

Note

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

Hence, some terms

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

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

$g - 2$ in the MSSM

numerically

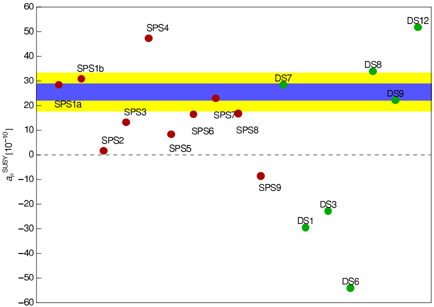
$$a_\mu^{\mathrm{SUSY}} \approx 12 \times 10^{-10} \tan\beta \,\mathrm{sign}(\mu) \left(\frac{100\mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^2$$

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

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

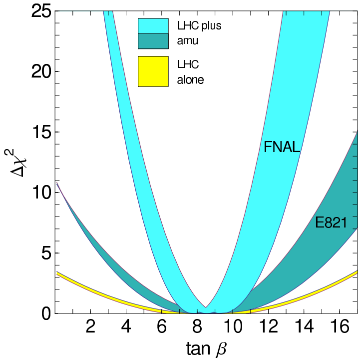
Precise analysis justified!

a_μ central complement for SUSY parameter analyses



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

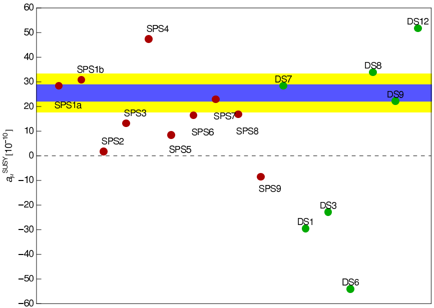
LHC Inverse Problem ($300 fb^{-1}$) can't be distinguished at LHC [Sfitter: Adam, Kneur, Lafaye, Plehn, Rauch, Zerwas '10]



[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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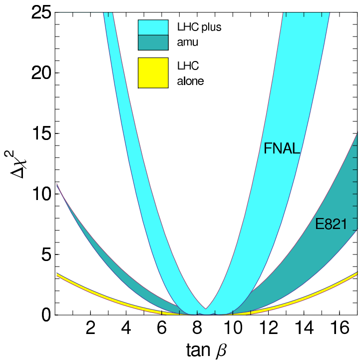


[Hertzog, Miller, de Rafael, Roberts, DS '07]

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

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

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

- also: dark matter, b-physics, FCNC/CP-constraints

Constrained models I

a_μ vs LHC-bounds on squarks/gluinos vs potential m_h-measurement

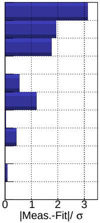
CMSSM: link $m_{\tilde{q}}$–$m_{\tilde{\mu}}$–m_h

- incompatible

FITTINO SUSY SPRING 2012

CMSSM, LHC, m_h=126 GeV

$a_\mu - a_\mu^{SM}$	$(2.9 \pm 0.8 \pm 0.2)$E-9	0.3E-9
$BR(b \to s\gamma)$	$(3.55 \pm 0.26 \pm 0.23)$E-4	2.88E-4
$BR(B \to \tau\nu)$	(1.67 ± 0.39)E-4	0.99E-4
$BR(B_s \to \mu^+\mu^-)$	$<(4.50 \pm 0.30)$E-9	3.61E-9
Δm_s (ps^{-1})	$17.78 \pm 0.12 \pm 5.20$	20.58
$\sin^2\theta^l_{eff}$	0.23113 ± 0.00021	0.23138
m_W (GeV)	$80.385 \pm 0.015 \pm 0.010$	80.386
m_h (GeV)	$126.0 \pm 2.0 \pm 3.0$	124.4
LHC		
$\Omega_{CDM}h^2$	$0.1123 \pm 0.0035 \pm 0.0112$	0.1112
σ^{SI} (pb)		2.44E-11



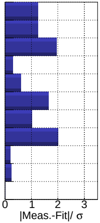
NUHM1: m_h^{soft} independent

- marginally compatible
- finetuning?

FITTINO SUSY SPRING 2012

NUHM1, LHC, m_h=126 GeV

$a_\mu - a_\mu^{SM}$	$(2.9 \pm 0.8 \pm 0.2)$E-9	1.8E-9
$BR(b \to s\gamma)$	$(3.55 \pm 0.26 \pm 0.23)$E-4	3.12E-4
$BR(B \to \tau\nu)$	(1.67 ± 0.39)E-4	0.91E-4
$BR(B_s \to \mu^+\mu^-)$	$<(4.50 \pm 0.30)$E-9	4.59E-9
Δm_s (ps^{-1})	$17.78 \pm 0.12 \pm 5.20$	20.88
$\sin^2\theta^l_{eff}$	0.23113 ± 0.00021	0.23148
m_W (GeV)	$80.385 \pm 0.015 \pm 0.010$	80.367
m_h (GeV)	$126.0 \pm 2.0 \pm 3.0$	118.8
LHC		
$\Omega_{CDM}h^2$	$0.1123 \pm 0.0035 \pm 0.0112$	0.1094
σ^{SI} (pb)		1.81E-10



Constrained models II

"Natural SUSY" [Barger, Huang, Ishida, Keung '12]...

- 1st, 2nd generation very heavy, light $\tilde{t}$ $\to$ FCNC, finetuning ok
- $a_\mu \approx 0$, would need $m_{\tilde{\mu}} \ll m_{\tilde{q}}$

Gauge-mediated SUSY breaking (FCNC ok) + extra matter

- increase m_h, lower $m_{\tilde{q},\tilde{\mu}}$
- reconcile a_μ, m_h, LHC-bounds [Endo, Hamaguchi, Iwamoto, Yokozaki '11]...

Compressed SUSY [Martin, LeCompte '11]

- hidden at LHC for $m_{\tilde{q},\tilde{g}} >\sim 600\text{GeV}$
- compatible with a_μ

Still tension/models might be be ruled out soon!

Alternative: radiative muon mass in SUSY

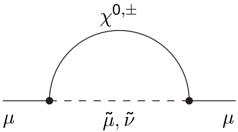
$$m_\mu^{\text{tree}} = \lambda_\mu v_d$$

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]

Status of SUSY prediction

1-Loop

$\propto \tan\beta$



[Fayet '80],. . .

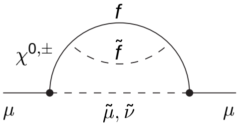
[Kosower et al '83],[Yuan et al '84],. . .

[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

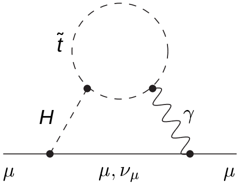
$(\tan\beta)^2$

aim: full calculation

(65000 diagrams)

2-Loop (SM 1L)

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



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

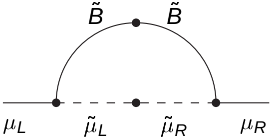
[Heinemeyer,DS,Weiglein '03]

[Heinemeyer,DS,Weiglein '04]

complete

Physics of subleading contributions (examples)

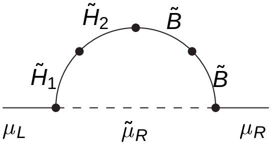
1-loop bino



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

$\to$ large μ-parameter

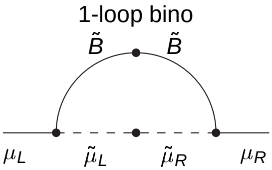
1-loop $\tilde{\mu}_R$



$\propto$ other sign!

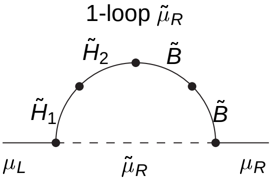
$\to$ Use if $\mu M_2 < 0$, light $\tilde{\mu}_R$

Physics of subleading contributions (examples)



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

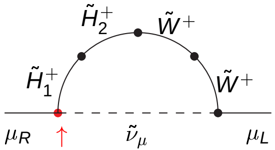
$\to$ large μ-parameter
$\to$ radiative muon mass, $\lambda_\mu = 0$



$\propto$ other sign!

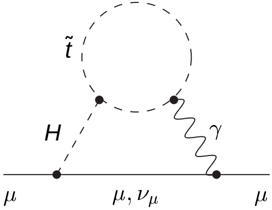
$\to$ Use if $\mu M_2 < 0$, light $\tilde{\mu}_R$

2-loop $\tan^2\beta$



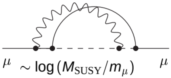
$\frac{\lambda_\mu}{1-\sim\mu\tan\beta} \approx \lambda_\mu(1+\sim\mu\tan\beta)$

2-loop $\tilde{t}, \tilde{\chi}$

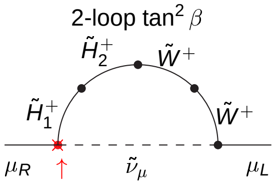


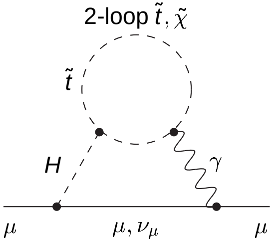
$\sim m_t\mu/M_H m_{\tilde{t}}$

Photonic 2-loop



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





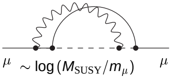
$\frac{\lambda_\mu}{1-\sim\mu\tan\beta} \approx \lambda_\mu(1+\sim\mu\tan\beta)$

$\sim m_t\mu/M_H m_{\tilde{t}}$

Allows limit $\tan\beta \to \infty$! Wrong sign!

Dominant for heavy smuons!

Photonic 2-loop



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

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2 Impact on New Physics in general

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EWSB Models

Large a_μ possible?

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

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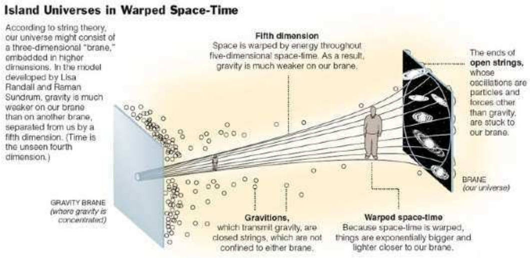

Randall Sundrum

- 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]

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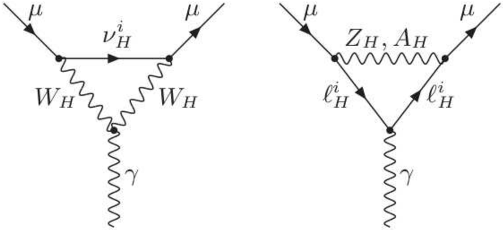

Littlest Higgs + T-Parity

[Cheng, Low '03]
[Hubisz, Meade, Noble, Perelstein '06]

- Tiny a_μ from Z_H, W_H contributions

  [Blanke et al '07]

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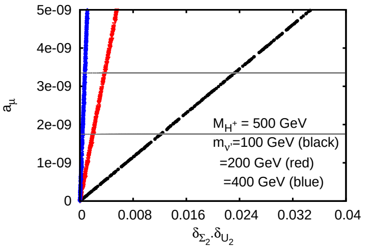


2-Higgs doublet model + 4th generation

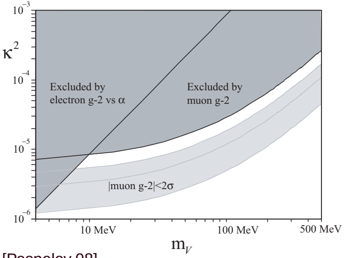
[Bar-Shalom, Nandi, Soni '11]

- Large contributions from ν'–$H^{\pm}$ possible
- in agreement with LFV, FCNC constraints

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



[Pospelov 08]

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

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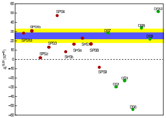
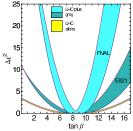
Conclusions

- Currently $a_\mu^{\text{Exp}} - a_\mu^{\text{SM}} \approx (30 \pm 8) \times 10^{-10}$ — reliable, tantalizing
- New measurements within next 5 years — very promising!
- $a_\mu^{\text{N.P.}}$ very model-dependent, typically $\mathcal{O}(\pm 1 \ldots 50) \times 10^{-10}$
  - constraints, model discriminator, unique properties
  - break degeneracies
    measure central parameters
    complementary to LHC





If large a_μ-deviation is real: tension rising between LHC-bounds, a_μ, finetuning, Higgs mass; difficult to find alternatives to SUSY
Promising future!!