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

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Introduction

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (28.6 \pm 8) \times 10^{-10}$$
$$\to (?? \pm 1.6^{\rm exp} \pm 3^{\rm th}) \times 10^{-10}$$

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

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

Outline

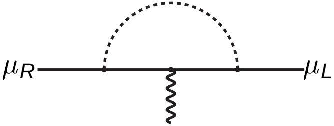
- New physics contributions to a_μ in general
    - Different types of new physics lead to very different a_μ(N.P.)
- SUSY
    - compare with LHC, subleading contributions
- Alternatives: Extra dimensions, light particles, …

Outline

1. Impact on New Physics in general
2. SUSY
   - Can explain the deviation — a_μ constraints
   - LHC vs a_μ
   - Subleading contributions
3. Alternatives to SUSY
4. Conclusions
5. Backup

New physics contributions to a_μ

$g - 2$ = chirality-flipping interaction

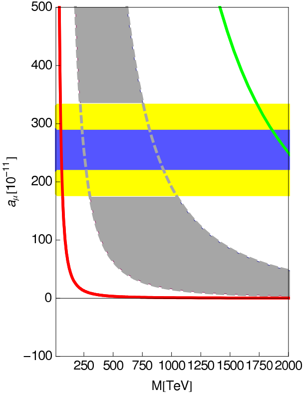


m_μ = chirality-flipping interaction as well

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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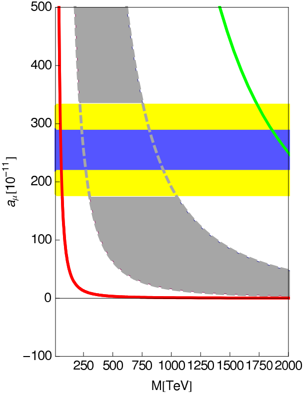

$\mathcal{O}(1)$	
$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	
$\mathcal{O}(\frac{\alpha}{4\pi})$	Z', W', UED, Littlest Higgs (LHT)...

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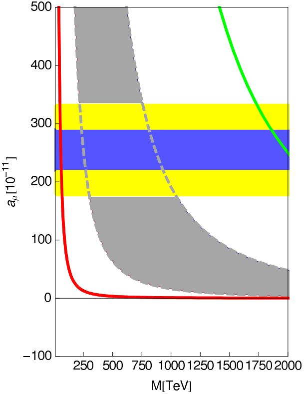

$\mathcal{O}(1)$	
$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	supersymmetry (tan β), unparticles [Cheung, Keung, Yuan '07] extra dim. (ADD/RS) (n_c)... [Davioudasl, Hewett, Rizzo '00] [Graesser,'00][Park et al '01][Kim et al '01]
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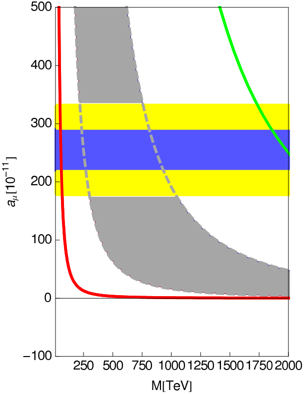

$\mathcal{O}(1)$	radiative muon mass generation . . . [Czarnecki,Marciano '01] [Crivellin, Girrbach, Nierste '11][Dobrescu, Fox '10]
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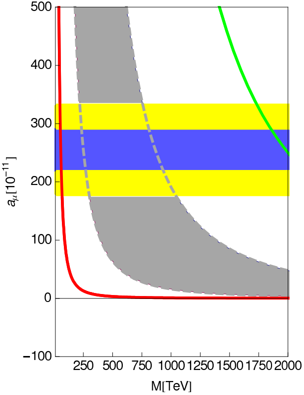
classify new physics: *C* **very** model-dependent

Very useful constraints on new physics



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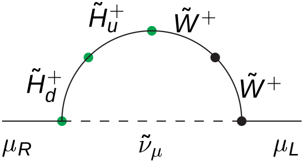
$g-2$ in the MSSM: chirality flips, λ_μ, and H_u



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

some terms

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

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

$g-2$ in the MSSM

numerically

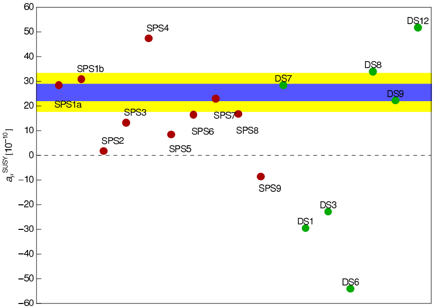
$$a_\mu^{\rm SUSY} \approx 12\times 10^{-10}\,\tan\beta\,{\rm sign}(\mu)\left(\frac{100{\rm GeV}}{M_{\rm SUSY}}\right)^2$$

SUSY could be the origin of the observed $(28.6\pm 8)\times 10^{-10}$ deviation!

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

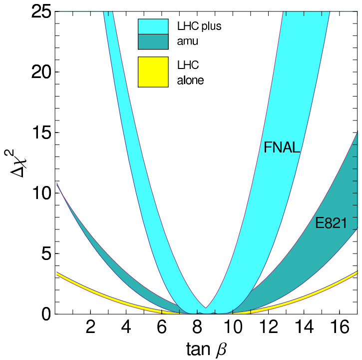
Precise analysis justified!

a_μ central complement for SUSY parameter analyses



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

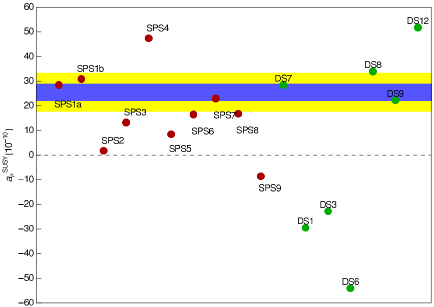
LHC Inverse Problem (300fb^{-1})
can't be distinguished at LHC
[Sfitter: Adam, Kneur, Lafaye, Plehn, Rauch, Zerwas '10]



[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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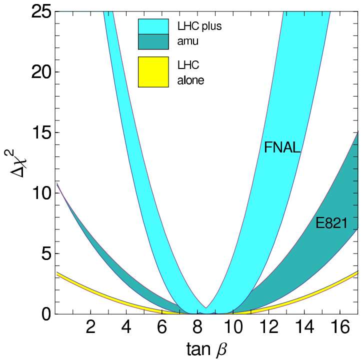


[Hertzog, Miller, de Rafael, Roberts, DS '07]

- a_μ sharply distinguishes SUSY models
- helps measure parameters

Next: Tension in SUSY models — subleading contributions

The tension is increasing

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

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

Constrained models I

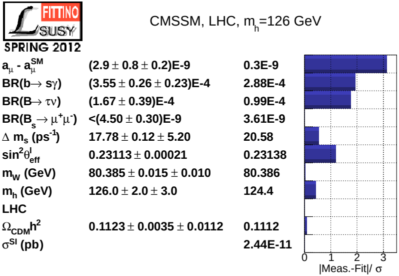
a_μ vs LHC-bounds on squarks/gluinos vs potential m_h-measurement

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

- incompatible

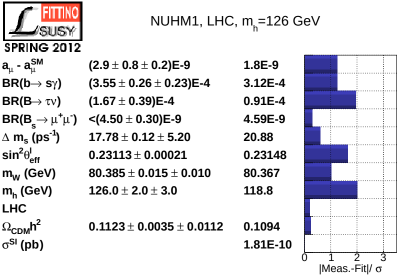
NUHM1: $m_h^{\rm soft}$ independent

- marginally compatible
- finetuning?



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, 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 $m_{\tilde{q},\tilde{g}} >\sim 600$GeV
- compatible with a_μ

Still tension/models might be be ruled out soon!

Alternative: radiative muon mass in SUSY

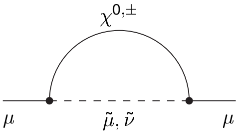
$$m_\mu^{\text{tree}} = \lambda_\mu v_d$$

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],. . .

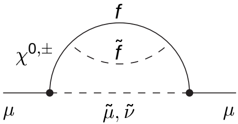
[Kosower et al '83],[Yuan et al '84],. . .

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

complete

2-Loop (SUSY 1L)

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



[Degrassi,Giudice '98]

[Marchetti, Mertens, Nierste, DS '08]

[Schäfer, Stöckinger-Kim,

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photonic

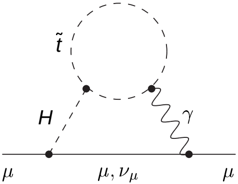
$(\tan\beta)^2$

aim: full calculation

(65000 diagrams)

2-Loop (SM 1L)

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



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

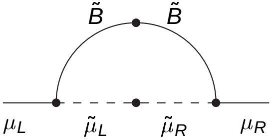
[Heinemeyer,DS,Weiglein '03]

[Heinemeyer,DS,Weiglein '04]

complete

Physics of subleading contributions (examples)

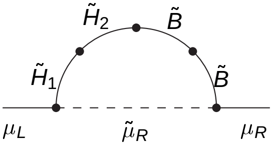
1-loop bino



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

→ large μ-parameter

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



$\propto$ other sign!

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

Physics of subleading contributions (examples)

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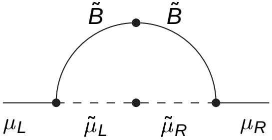

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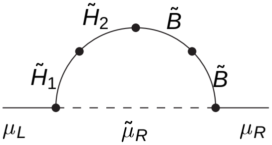
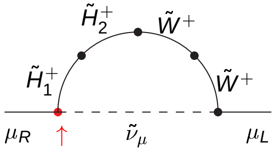


$\propto$ other sign!

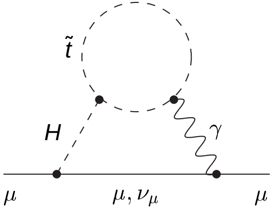
→ large μ-parameter
→ radiative muon mass, $\lambda_\mu = 0$

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



2-loop $\tan^2\beta$

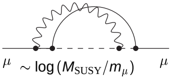
$\frac{\lambda_\mu}{1-\sim\mu\tan\beta} \approx \lambda_\mu(1+\sim\mu\tan\beta)$



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

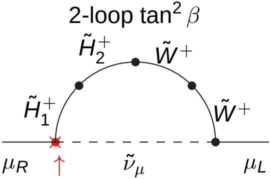
$\sim m_t \mu / M_H m_{\tilde{t}}$

Photonic 2-loop



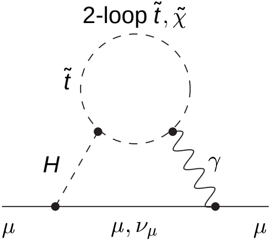
$\sim \log(M_{\rm SUSY}/m_\mu)$

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



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

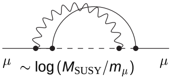
Allows limit $\tan\beta \to \infty$! Wrong sign!



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

Dominant for heavy smuons!

Photonic 2-loop



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

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EWSB Models

- Randall Sundrum → large contributions possible [Kim, Kim, Song'01]
  However, challenged by electroweak precision data [Hewett et al '00] + $\gamma\gamma \to \gamma\gamma$ unitarity [Kim,Kim,Song]
- Littlest Higgs + T-Parity ("Bosonic SUSY") [Cheng, Low '03] [Hubisz, Meade, Noble, Perelstein '06]
  →Tiny a_μ from Z_H, W_H contributions [Blanke et al '07]
- 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 models

Hide new particles at colliders$\rightsquigarrow$large a_μ possible

- Dark forces [Pospelov, Ritz. . .]
  very light, weakly interacting, invisible at LHC
  ($C \propto 10^{-8}$, $M < 1$GeV)
- Light “Z'” from gauged $L_\mu - L_\tau$ [Ma,Roy,Roy ’02][Heeck,Rodejohann ’11]
  flavour-dependent couplings, hidden at LEP
  $C \sim C_{SM,weak}$, $M_{Z'} \sim M_Z$

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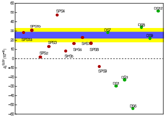
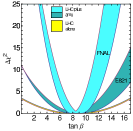
Conclusions

- Currently $a_\mu^{\text{Exp}} - a_\mu^{\text{SM}} \approx (28.6 \pm 8) \times 10^{-10}$ — 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!!

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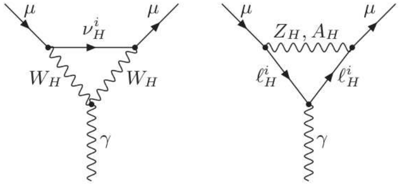
Littlest Higgs (with T-parity)

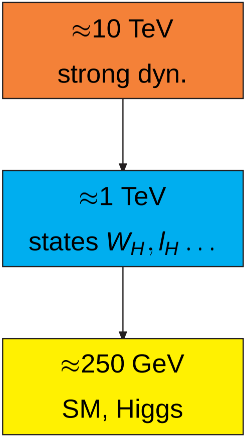
[Georgi; Arkani-Hamed,Cohen,Georgi]
Concrete LHT model: [Cheng, Low '03]
[Hubisz, Meade, Noble, Perelstein '06]

Bosonic SUSY

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



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



≈10 TeV
strong dyn.

≈1 TeV
states $W_H, l_H \ldots$

≈250 GeV
SM, Higgs

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

[Blanke, Buras, et al '07]

Clear-cut prediction, sharp distinction from SUSY possible

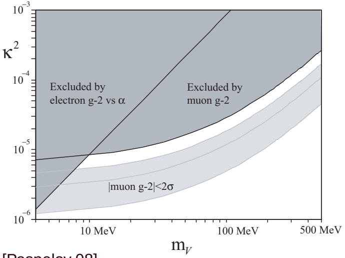
What if the LHC does not find new physics —

“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]

Flavour-dependent Z'?

Yet another possibility to hide new physics at colliders

Gauged $L_\mu - L_\tau$ [Ma,Roy,Roy '02][Heeck,Rodejohann '11]

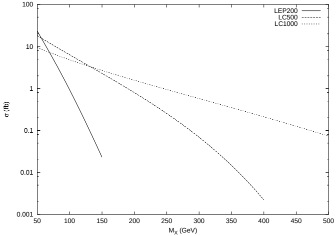
- flavour-dependent Z'
- hidden at LEP, even for $g' = 1$, $M_{Z'} = 200$ GeV

- reach for $g' = 1$:
  - LHC (10fb^{-1}): 130GeV
  - LHC (100fb^{-1}): 350GeV

    [Heeck,Rodejohann '11]
  - LC (0.5TeV): 300GeV

$C \sim C_{SM,weak}$, $M_{Z'} \sim M_Z$

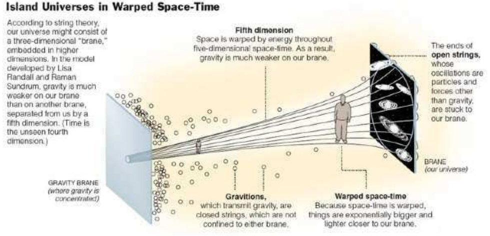
- explains a_μ for $M_{Z'}/g' \approx 200$ GeV



[Ma,Roy,Roy '01]

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}



Island Universes in Warped Space-Time

According to string theory, our universe might consist of a three-dimensional "brane," embedded in higher dimensions. In the model developed by Lisa Randall and Raman Sundrum, gravity is much weaker on our brane than on another brane, separated from us by a fifth dimension. (Time is the unseen fourth dimension.)

Fifth dimension Space is warped by energy throughout five-dimensional space-time. As a result, gravity is much weaker on our brane.

The ends of **open strings,** whose oscillations are particles and forces other than gravity, are stuck to our brane.

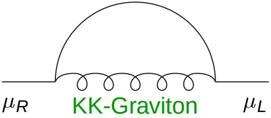
Gravitons, which transmit gravity, are closed strings, which are not confined to either brane.

Warped space-time Because space-time is warped, things are exponentially bigger and lighter closer to our brane.

TeV-scale determined by:

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

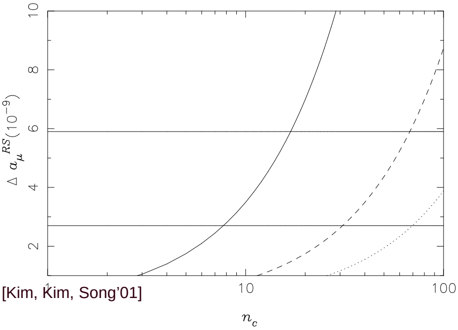
theory breaks down at scale $\sim \Lambda_\pi$, n_c KK-gravitons up to that scale



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

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

$g-2$ 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

However, might be excluded by electroweak precision data [Hewett et al '00] + $\gamma\gamma \to \gamma\gamma$ unitarity [Kim,Kim,Song]

Challenge: is there non-SUSY calculable TeV-scale model that can accommodate the current a_μ?