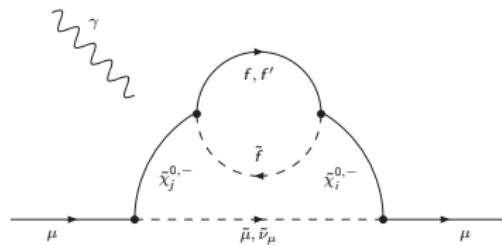


# Magnetic moment $(g - 2)_\mu$

Dominik Stöckinger

TU Dresden



UK HEP Forum “Anomalies and Deviations — Clues for new physics”,  
November 2015

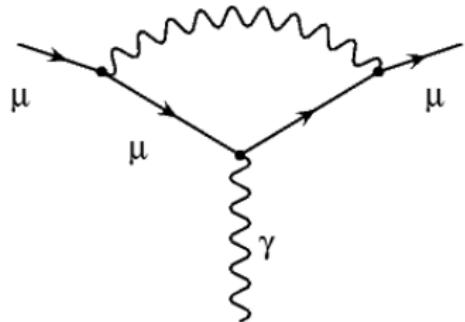
# Outline

- 1  $a_\mu$ -deviation: SM and experimental status
- 2 Clues from  $a_\mu$  on New Physics
- 3 Clues from  $a_\mu$  (and other data) in specific models

# Outline

## 1 $a_\mu$ -deviation: SM and experimental status

# Muon ( $g - 2$ ) in SM



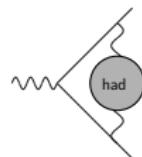
$$a_\mu = \frac{\alpha(0)}{2\pi} + \dots$$

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

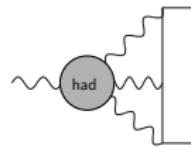
[Miller, de Rafael, Roberts, DS, Ann.Rev.Nucl.Part. (2012) 62.]



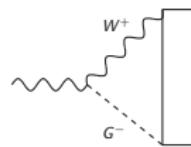
QED: 11 658 471.8 (0.0)



Had vp: 682.5 (4.2)



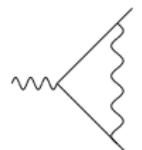
Had lbl: 10.5 (2.6)



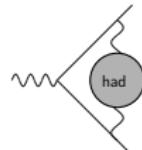
Weak: 15.3 (0.1)

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

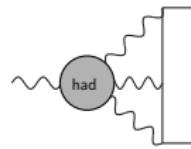
[Miller, de Rafael, Roberts, DS, Ann.Rev.Nucl.Part. (2012) 62.]



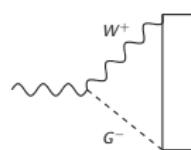
**QED:** 11 658 471.8 (0.0)



**Had vp:** 682.5 (4.2)



**Had lbl:** 10.5 (2.6)



**Weak:** 15.3 (0.1)

## Progress:

- **QED:** complete 5-loop [Kinoshita et al '12], checks [Steinhauser et al '14]
- **Hadronic vacuum polarization:** New  $e^+e^-$  data [BESIII, more to come from Siberia], resolution of  $\tau$ -puzzle [Jegerlehner; Benayoun et al]
- **Hadronic light-by-light:** new approaches (lattice, dispersion relations, more data) [Blum; Colangelo; Vanderhaegen; Nyffeler; et al]
- **Weak:** re-analysis with measured  $M_H$  and consistent combination of 2-loop, 3-loop results [Gnendiger, DS, Stöckinger-Kim '13]

# Muon $g - 2$ at Brookhaven $\longrightarrow$ Fermilab

$$a_{\mu}^{\text{exp}} = (11\,659\,208.9 \quad (6.3)_{\text{tot}}) \times 10^{-10}$$

$$a_{\mu}^{\text{FNAL}} = (\text{?????????}) \quad (1.6)_{\text{tot}} \times 10^{-10}$$

3–4  $\sigma$  deviation from  $a_{\mu}^{\text{SM}}$



new experiment at Fermilab!



# arrived at Fermilab and powered up!



... New data expected within 2–3 years... should clarify deviation

(Further, complementary experiment planned at JParc)

SM prediction too low by  $\approx (30 \pm 8) \times 10^{-10}$   
(twice as large as  $a_\mu^{\text{SM weak}}$ )

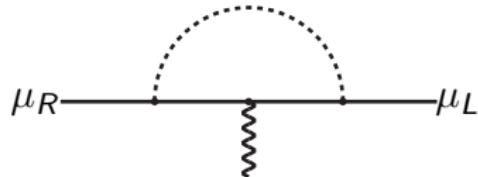
Can be due to new physics!

# Outline

## ② Clues from $a_\mu$ on New Physics

- Overview of new physics contributions

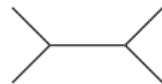
# Why is $a_\mu$ special?



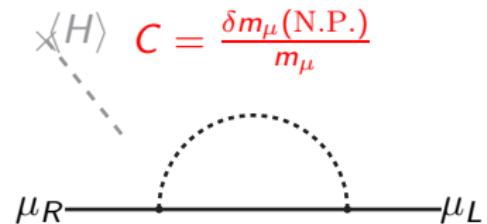
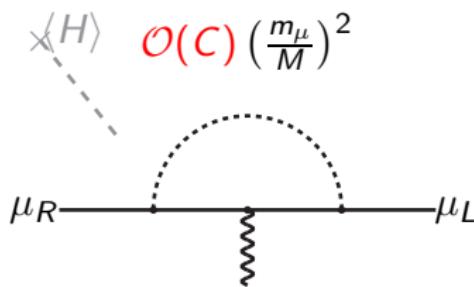
**CP- and Flavour-conserving, chirality-flipping, loop-induced**

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

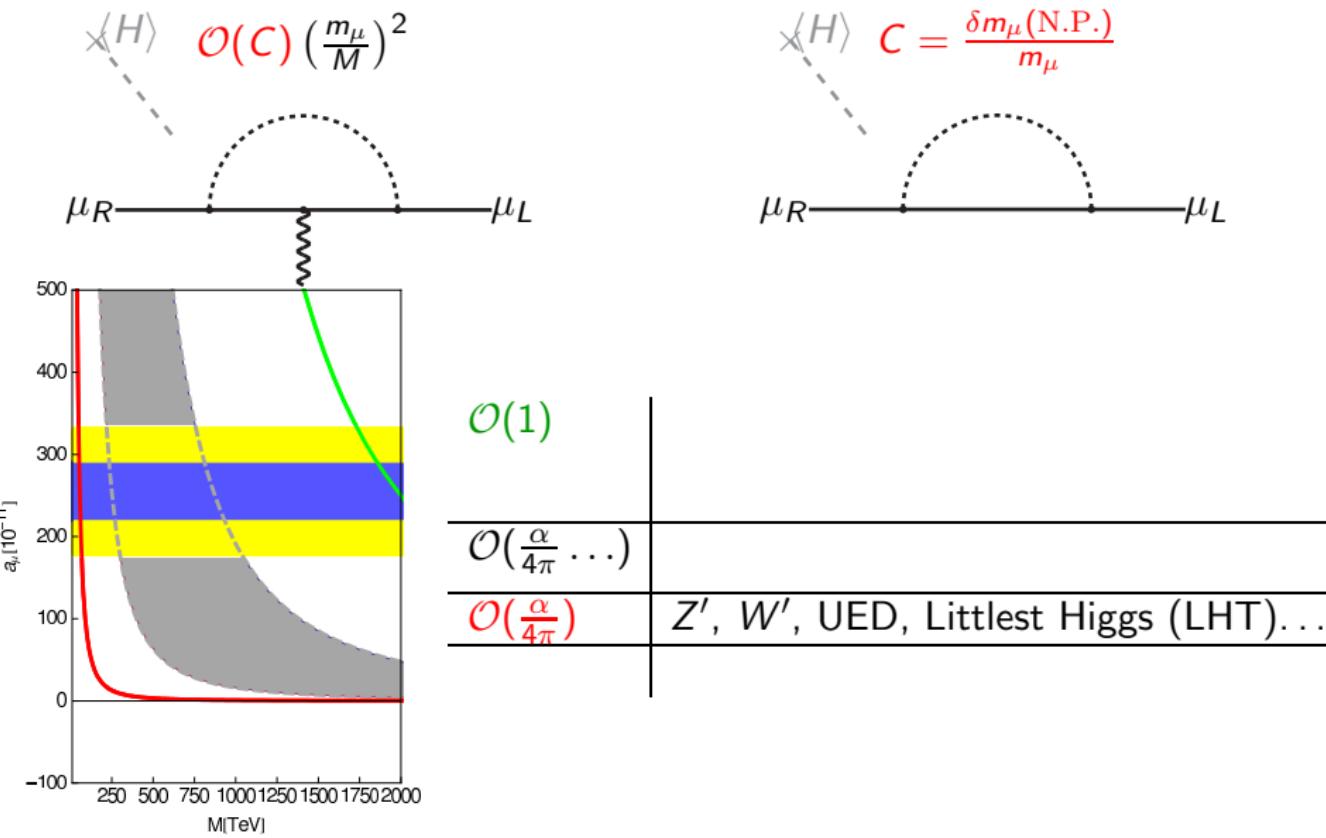
EWPO



# Very different contributions to $a_\mu$ : classify $\propto C$

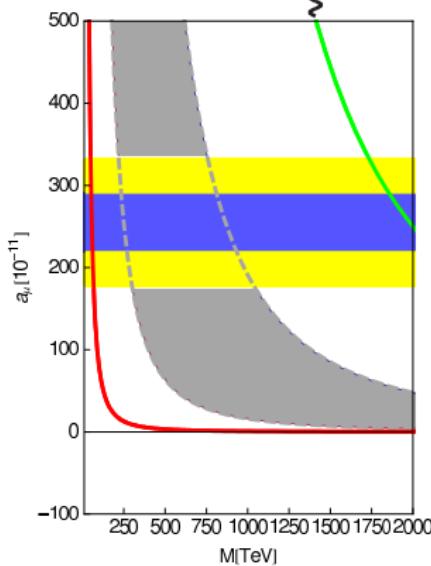
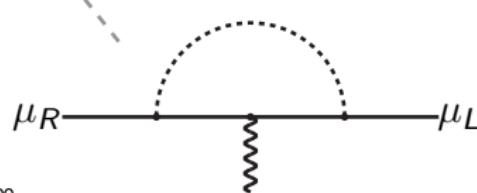


# Very different contributions to $a_\mu$ : classify $\propto C$

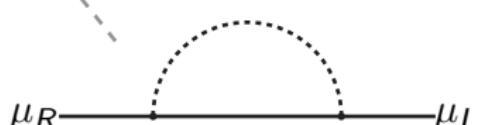


# Very different contributions to $a_\mu$ : classify $\propto C$

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



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



$\mathcal{O}(1)$

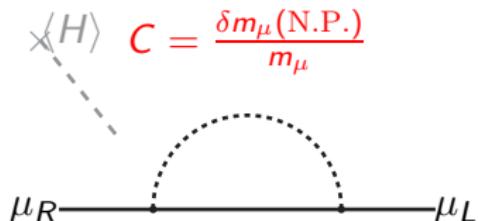
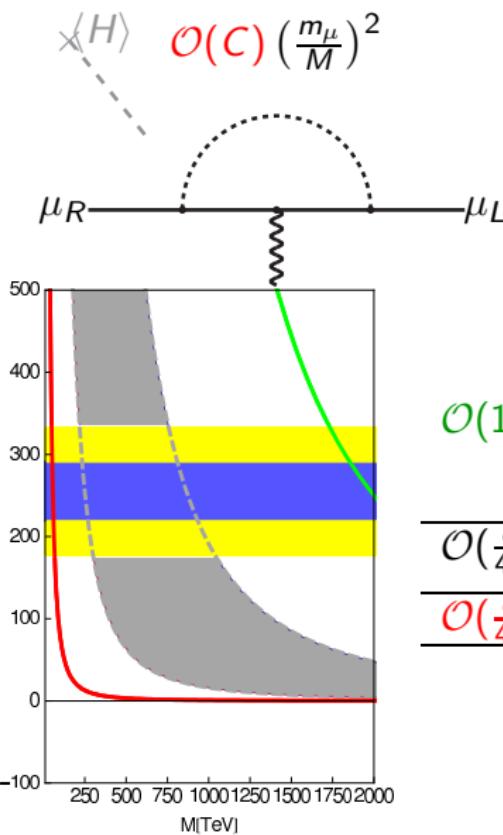
$\mathcal{O}\left(\frac{\alpha}{4\pi} \dots\right)$

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

supersymmetry ( $\tan \beta$ )

$Z'$ ,  $W'$ , UED, Littlest Higgs (LHT)...

# Very different contributions to $a_\mu$ : classify $\propto C$



$\mathcal{O}(1)$

radiative muon mass generation ...  
[Czarnecki, Marciano '01]

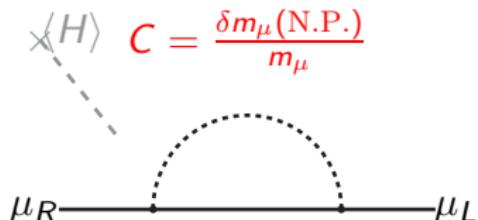
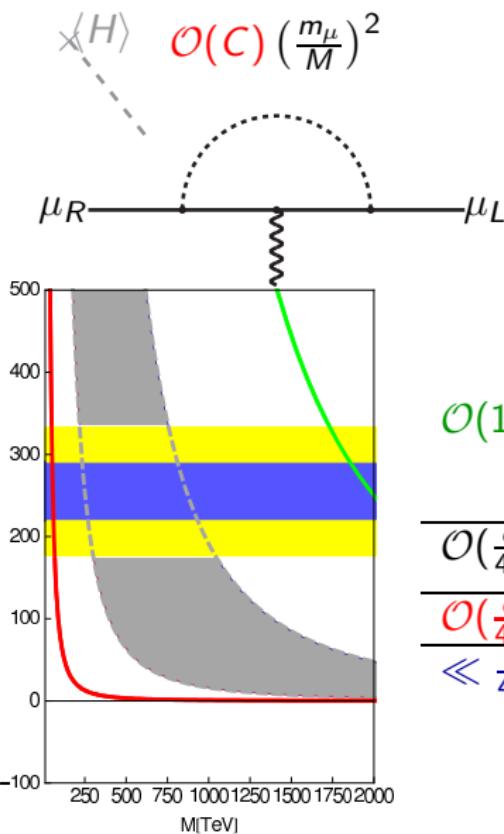
$\mathcal{O}(\frac{\alpha}{4\pi} \dots)$

[Crivellin, Girrbach, Nierste '11] [Dobrescu, Fox '10]  
supersymmetry ( $\tan \beta$ )

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

$Z'$ ,  $W'$ , UED, Littlest Higgs (LHT) ...

# Very different contributions to $a_\mu$ : classify $\propto C$



$\mathcal{O}(1)$	radiative muon mass generation ... [Czarnecki, Marciano '01]
$\mathcal{O}(\frac{\alpha}{4\pi} \dots)$	[Crivellin, Girrbach, Nierste '11] [Dobrescu, Fox '10] supersymmetry ( $\tan \beta$ )
$\mathcal{O}(\frac{\alpha}{4\pi})$	$Z'$ , $W'$ , UED, Littlest Higgs (LHT) ...
$\ll \frac{\alpha}{4\pi}$	dark photon ...

# Outline

- ③ Clues from  $a_\mu$  (and other data) in specific models
  - Non-SUSY
  - SUSY: many different scenarios

Examples: dark photons, two-Higgs doublet model

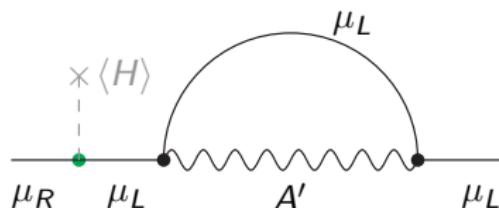
### Possibility:

Some models are theoretically well motivated  
and explain  $a_\mu$ -deviation “accidentally” in some part of the parameter space

~ tested/constrained by existing and future data!

# Dark photon: “second most promising scenario” [Marciano]

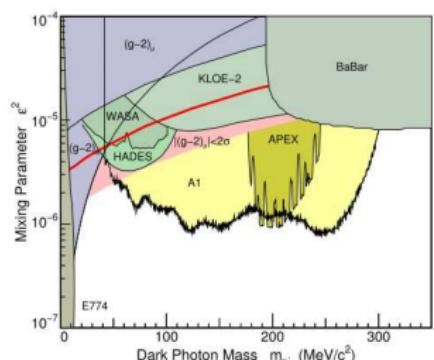
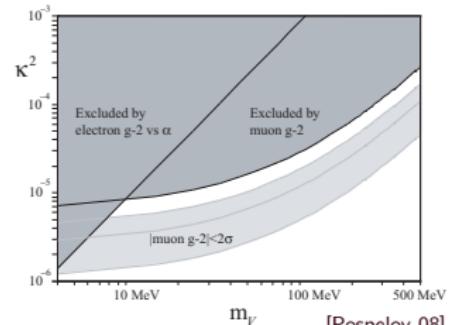
- very light/weakly interacting



- theory motivation: new U(1) group (from GUTs, ...)
- $a_\mu$ -explanation now almost completely excluded!!

generalization: “dark Z”  
with more general couplings,  
also strongly constrained

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

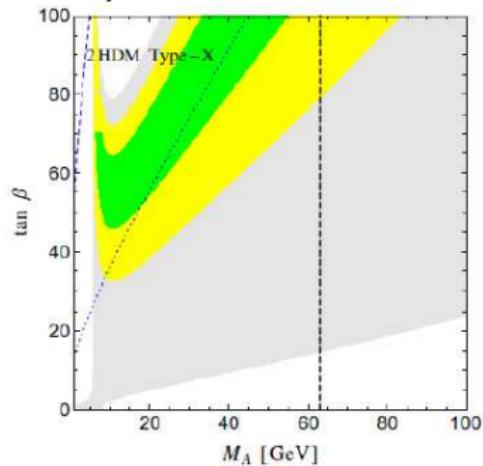
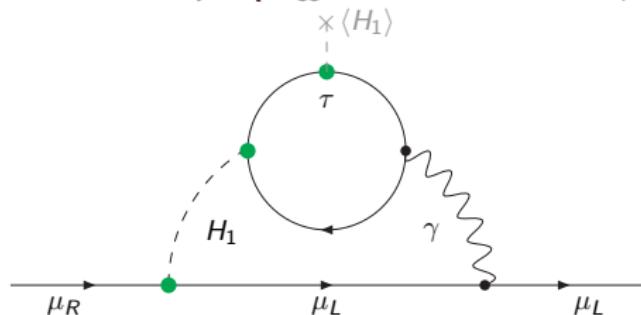


[A1/Mainz '14]

# Two-Higgs Doublet Model

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

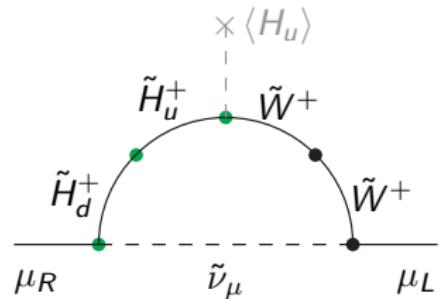
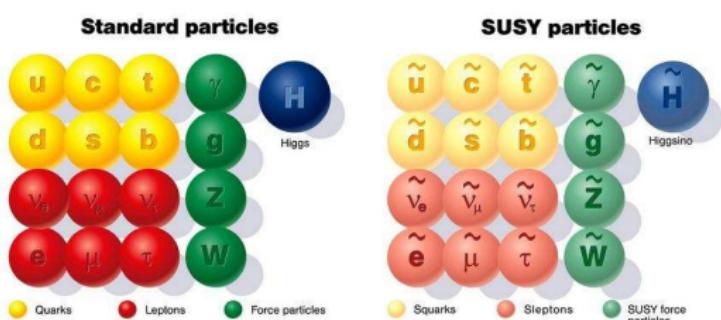
recent analyses: [Broggio, Chun, Passera, Patel, Vempati '14, Illisie '15]



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

In SUSY, the  $a_\mu$ -deviation can be explained in a large, “natural” part of parameter space

# MSSM contributions to $a_\mu$



- MSSM: superpartners for all SM fields, two Higgs doublets

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

SUSY could be the origin of the observed  $(30 \pm 8) \times 10^{-10}$  deviation if, e.g.,  $\tan \beta \sim 50$  and  $M_{\text{SUSY}} \sim 500$  GeV!

Code: Gm2Calc [Athron et al '15]

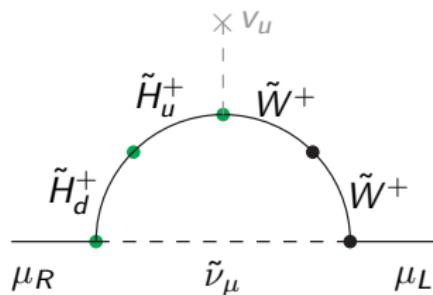
# Chirality flip and $\tan \beta$ -enhancement

Detailed mass dependence:

$$\propto \frac{\mu M_{\tilde{W}, \tilde{B}}}{M_{\text{SUSY}}^4}, \text{ where } M_{\text{SUSY}} \in \{M_{\tilde{W}, \tilde{B}, \tilde{\nu}, \tilde{\mu}}, \mu\}$$

Origin of  $\tan \beta$ :

$$\frac{y_\mu \langle H_u \rangle}{m_\mu} = \frac{y_\mu \langle H_u \rangle}{y_\mu \langle H_d \rangle} = \tan \beta$$



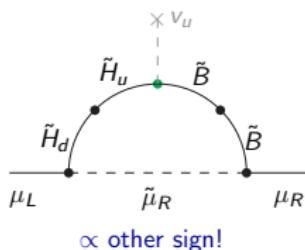
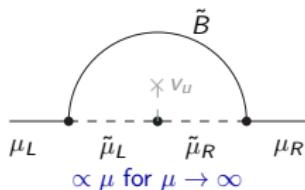
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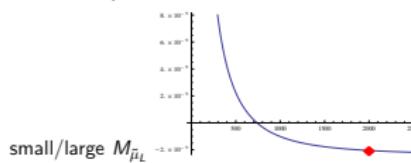
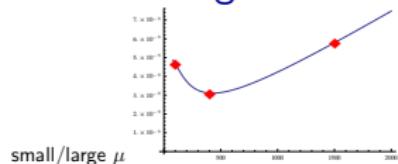
$$\propto \frac{\mu M_{\tilde{W}, \tilde{B}}}{M_{\text{SUSY}}^4}, \text{ where } M_{\text{SUSY}} \in \{M_{\tilde{W}, \tilde{B}, \tilde{\nu}, \tilde{\mu}}, \mu\}$$

Origin of  $\tan \beta$ :

$$\frac{y_\mu \langle H_u \rangle}{m_\mu} = \frac{y_\mu \langle H_u \rangle}{y_\mu \langle H_d \rangle} = \tan \beta$$



Further diagrams: same generic dependence, different details



[Fargnoli, Gnendiger, Passeehr, DS, Stöckinger-Kim '13]

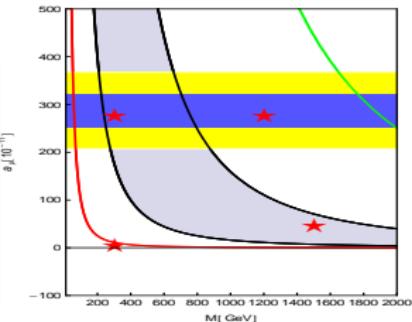
# The first possibility within SUSY

Possible conclusion 1:

LHC-data motivate specific SUSY scenarios/models

⇒ often:  $a_\mu$  negligible

⇒ will be tested at new  $a_\mu$ -experiments!



# The first possibility within SUSY

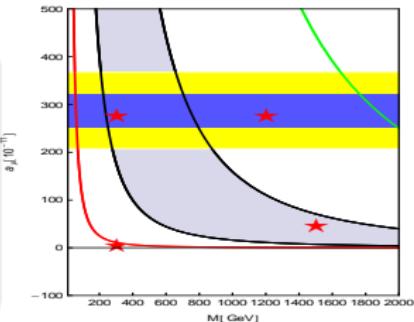
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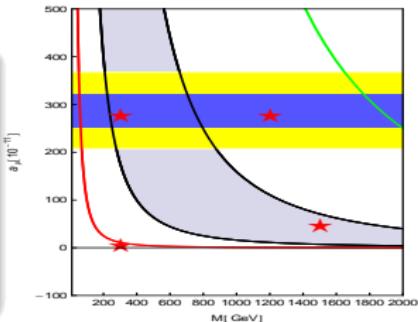
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e.g. "Constrained MSSM": masses heavy,  $a_\mu \approx 0$



e.g. R-symmetry, MRSSM [Kribs, Poppitz, Weiner '08]: (conserved R-charge)

- motivated: naturally satisfies flavour constraints, suppresses LHC cross sections, lighter sparticles viable [Kribs, Martin '10]
- compatible with Higgs and LEP constraints [Diessner, Kalinowski, Kotlarski, DS '14, '15]
- kills  $g - 2$  (no  $\tan \beta$  enhancement)

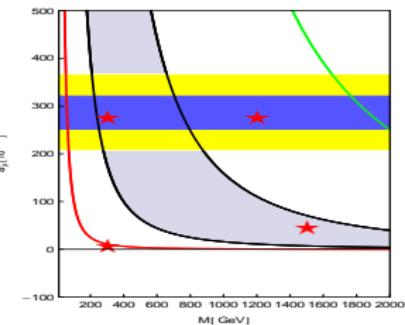
# Second possibility within SUSY

Possible conclusion 2:

MSSM is correct **and**  $a_\mu$ -deviation is real

⇒ construct models/scenarios which reconcile this with LHC-data!

Such models will eventually be tested by LHC



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Possible conclusion 2:

MSSM is correct **and**  $a_\mu$ -deviation is real

$\Rightarrow$  construct models/scenarios which reconcile this with LHC-data!

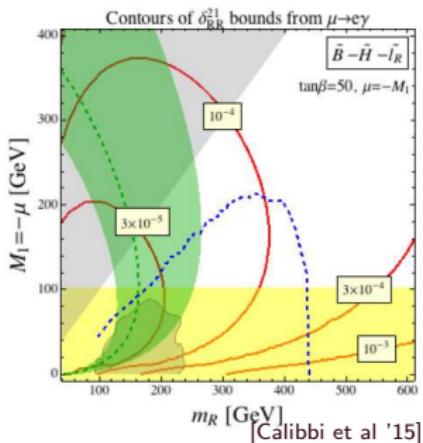
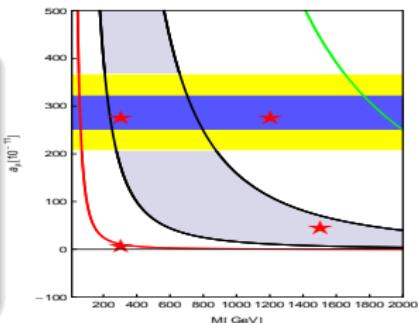
Such models will eventually be tested by LHC

Easy! Only three light sparticles needed

model building studies, e.g. strong  $\gg$  weak or compact spectra

[Endo, Hamaguchi, Ibe, Yanagida, D.P. Roy, ...]

dedicated LHC studies [Endo; Yanagida; Roy; Calibbi; Roszkowski...]

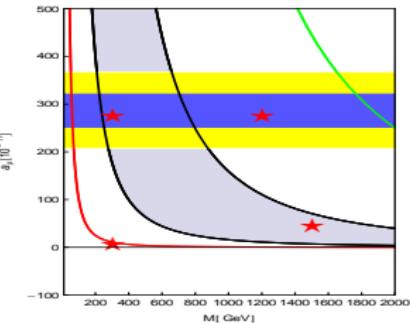


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Possible conclusion 2:

MSSM is correct **and**  $a_\mu$ -deviation is real  
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Another idea: heavy SUSY,  $\tan \beta \rightarrow \infty$ ,  $v_d \rightarrow 0$

[Dobrescu, Fox '10]  
[Altmannshofer, Straub '10]  
[Bach, Park, DS, Stöckinger-Kim, '15]

In  $a_\mu$ -formula: replace  $\tan \beta \rightarrow \frac{y_\mu v_u}{m_\mu} = \underbrace{\frac{y_\mu v_u}{y_\mu v_d + y_\mu v_u \Delta_\mu^{\text{red}}}}_{\rightarrow 0} \rightarrow \frac{1}{\Delta_\mu^{\text{red}}}$

# Large $a_\mu$ in MSSM for $\tan \beta \rightarrow \infty$ ,

[Bach, Park, DS, Stöckinger-Kim, '15]

Generally:  $a_\mu^{\text{SUSY}} \rightarrow \frac{a_\mu^{\text{red}}}{\Delta_\mu^{\text{red}}}$

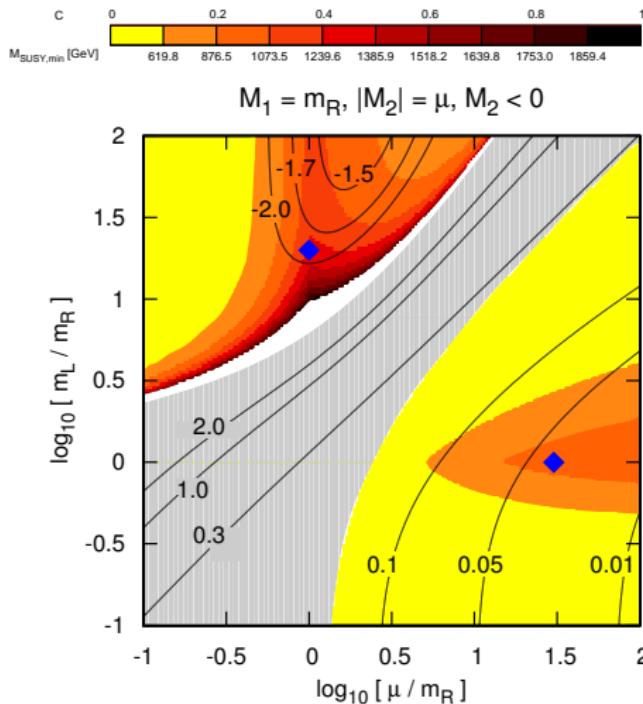
coloured:  $a_\mu$  positive

Sample TeV-scale masses:

$\mu$	$M_1$	$M_2$	$m_L$	$m_R$	$a_\mu / 10^{-9}$
15	1	-1	1	1	3.01
1.3	1.3	-1.3	26	1.3	2.90

Experimental constraints ok: B-physics,

Higgs-physics, vacuum stability



# Summary: $a_\mu$ and clues for new physics

- Progress on  $a_\mu^{\text{SM}}$  and experiment
  - ▶  $a_\mu^{\text{Exp}} - a_\mu^{\text{SM}} \approx (30 \pm 8) \times 10^{-10}$
- $a_\mu^{\text{SUSY}}$  very model-dependent
  - ▶ can be  $\mathcal{O}(\pm 1 \dots 50) \times 10^{-10}$
  - ▶ special SUSY scenarios  
 $\tan \beta \rightarrow \infty$ , R-symmetry
- Preliminary possible conclusions

