Non-universal gaugino mass, Higgs mass and muon g-2

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Harigaya, Yanagida and Yokozaki (arXiv:1501.07447)
Harigaya, Ibe and Suzuki (arXiv: 1505.05024)

Plan of talk

- Motivation of supersymmetry
- In compatibility of universal gaugino mass with low-energy SUSY
- Higgs mass and muon g-2 with non-universal gaugino mass

Supersymmetry

Less divergences

Only wave functions are renormalized

$$\mathcal{L} = Z(H^\dagger \partial^2 H + i\tilde{H}^\dagger \sigma \partial \tilde{H}) + m^2 |H|^2 + m\tilde{H}\tilde{H}$$

No large radiative corrections to Higgs mass !

$$\cancel{\delta m^2 \sim M_{\rm PL}^2, M_{\rm GUT}^2}$$

EWSB by dimensional transmutation

In minimal SUSY standard model (MSSM),

$$V_{\mathrm{SUSY}} = |\mu|^2(|H_u|^2 + |H_d|^2) + \cdots$$

$$\Delta V = -m^2_{\cancel{\mathrm{SUSY}}}|H_u^2| + \cdots$$

~~SUSY~~ by gauge dynamics → dynamical origin of EWSB

Dark matter Candidate

Assume R parity

	Boson	Fermion
$Q, \bar{u}, \bar{d}, L, \bar{e}$	$-$	$+$
H_u, H_d	$+$	$-$
Gauge	$+$	$-$

Higgsino, Bino, Wino can be dark matter

Coupling unification ?

In MSSM, gauge coupling constants unify around $10^{16}\,\mathrm{GeV}$

Consistent with SU(5) GUT
Considered to be the motivation of SUSY

↓

We often assume universal gaugino mass

GUT and low energy SUSY

How natural non-universal gaugino mass is

R symmetry

The only symmetry to control the negative potential

$$V = |F_{\rm SUSY}|^2 - 3|W_0|^2$$

If it is largely broken, low energy SUSY is hopeless

ex. minimal SU(5)

$$W = m\mathbf{24}^2 + \lambda\mathbf{24}^3$$

$$m_{3/2} \sim M_{\rm GUT}^3/M_{\rm pl}^2 \sim 10^{12}{\rm GeV}$$

R symmetry and GUT

In GUT model with universal gaugino mass,
R symmetry breaking is mandatory !

Goodmann, Witten (1986)
Fallbasher, Ratz, Vaudrevange (2011)
Harigaya, Ibe, Suzuki (2015)

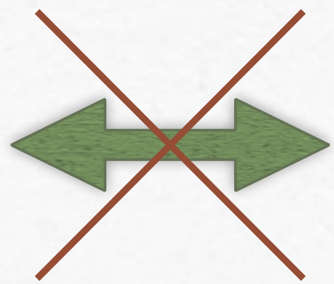
$$SU(3)_c \times SU(2)_L \times U(1)_Y \subset SU(5) \subset G_{\rm GUT}$$

$G_{\rm GUT}$: e.g. $SU(5), SU(5) \times SU(5), SO(10), \cdots$

R symmetry and GUT

Assume

GUT breaking fields
gauginos



Higgs, quarks, leptons

No mass mixing

In principle mixing may be possible,
but requires many/higher representation fields,
leads to blow up…

R symmetry and GUT

Consider anomaly matching:

Harigaya, Ibe, Suzuki (2015)

	above GUT		below GUT	
	$R\text{-}SU(5)\text{-}SU(5)$	$= R\text{-}SU(3)\text{-}SU(3)$		$= R\text{-}SU(2)\text{-}SU(2)$
gaugino		6		4

only Z_{2R} may remain unbroken….

Non-universal gaugino mass

product GUT e.g. $SU(5) \times SU(3) \times U(1)$

$$SU(3)_c \subset SU(3)_{\text{in } SU(5)} \times SU(3)$$
$$SU(2)_L = SU(2)_{\text{in } SU(5)}$$

evade the no-go-theorem

Non-universal gaugino mass

Unification of quarks and leptons is maintained

Higgs mass and muon g-2 with non-universal gaugino mass

$m_{\text{SM-higgs}} < m_Z$

$$m_h^2 = \lambda v^2$$

λ : determined by SUSY

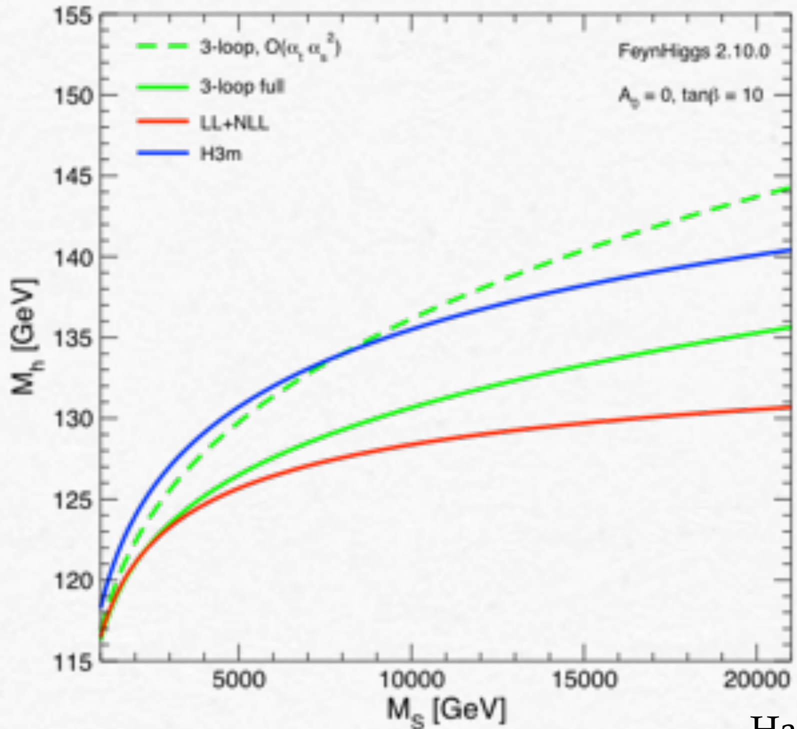
$$\lambda < \frac{1}{4}(g^2 + g'^2)$$

$$m_h < m_Z \sim 90 \text{ GeV}$$

Raising m_h

Large SUSY breaking raises higgs mass

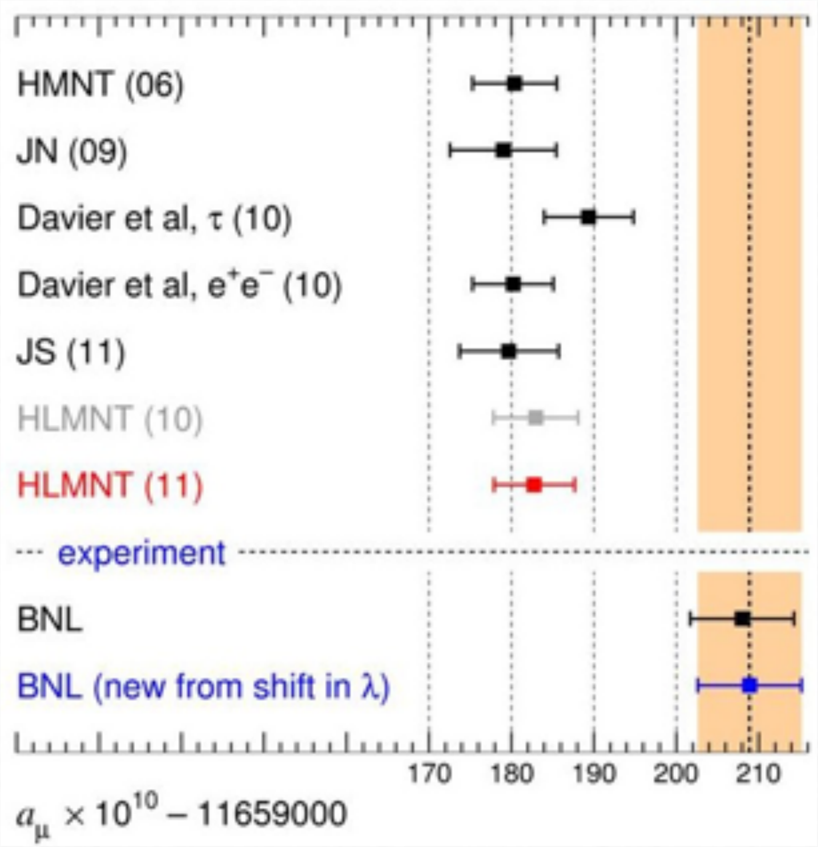
Okada, Yamaguchi, Yanagida (1991)
Ellis, Ridolfi, Zwirner (1991)
Haber, Hempfling (1991)



$$m_{\tilde{t}} > \text{few TeV}$$

Hahn, Heinemeyer, Hollik, Rzehak, Weiglein (2013)

Long-standing puzzle of muon g-2



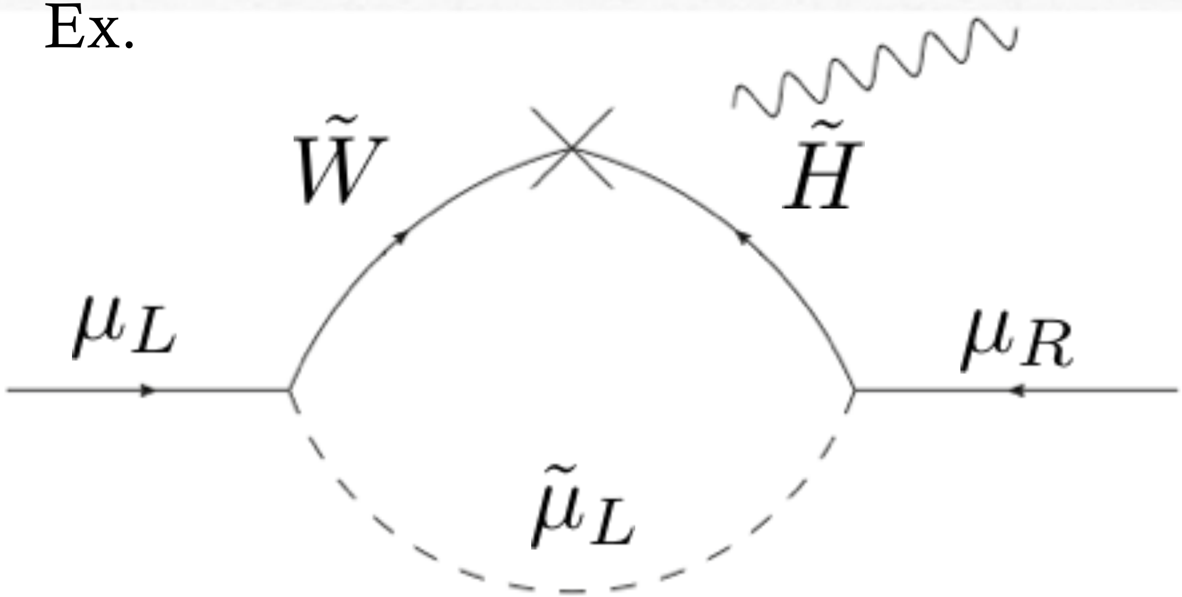
Hagiwara, Liao, Martin, Nomura, Teubner (2011)

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \times 10^{-10}$$

g-2 in SUSY

Moroi (1995)

Ex.



$$\Delta a_\mu \sim \frac{\alpha_{2,Y}}{4\pi} \frac{m_\mu^2}{m_{\rm SUSY}^2} \tan\beta \quad = O(1\text{-}10) \times 10^{-9} \frac{\tan\beta}{10} \left(\frac{100\text{GeV}}{m_{\rm SUSY}} \right)^2$$

muon g-2 and higgs mass

$m_{\tilde{t}} > \text{few TeV}$

SU(5) relation, flavor-universality

$\Downarrow$

$m_{\text{SUSY},g-2} > O(100)\ \text{GeV}$

It is difficult to explain g-2

Ways out

- Beyond MSSM (Extra tree λ, Extra loop corrections)

NMSSM: Ellwanger, Hugonie, Teixeira (Review, 2009)

Extra matter: Moroi and Okada (1992) U(1)’: Langacker, Polonsk, Wang (1999)

- Light 2nd generation, Heavy 3rd generation

Ibe, Yanagida, Yokozaki (2013)

- Departure from SU(5): heavy squark, light slepton

Ibe, Matsumoto, Yanagida, Yokozaki (2012)

Non-universal gaugino mass !

Gaugino mediation

Kaplan, Krib, Schmaltz (1999)
Chacko, Luty, Nelson,Ponton (1999)

Assume

SUSY breaking field Z ⟷ (tree) Gaugino, higgs

↓ quantum correction

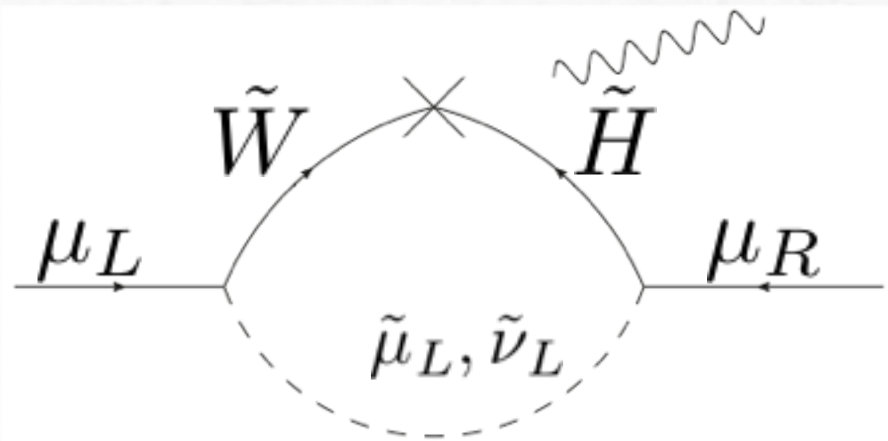
Squark, slepton

- Higher dimensional theory
- Structure of Kahler manifold e.g. CP^N
- Other possibilities ?

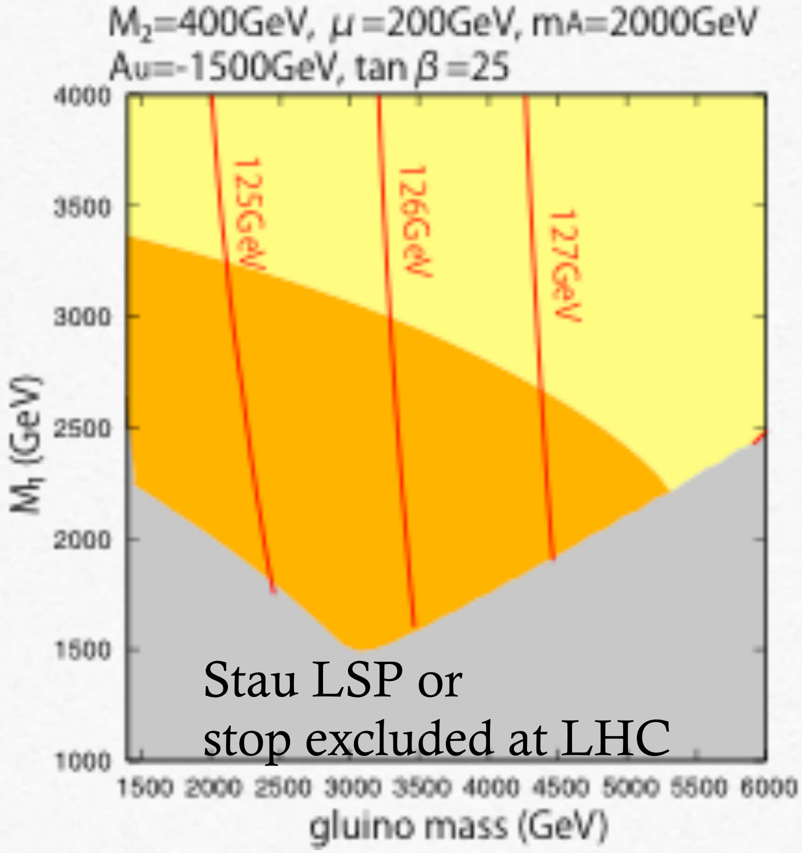
Flavor structure of soft mass aligned with Yukawa

No flavor problem

Light higgsino case

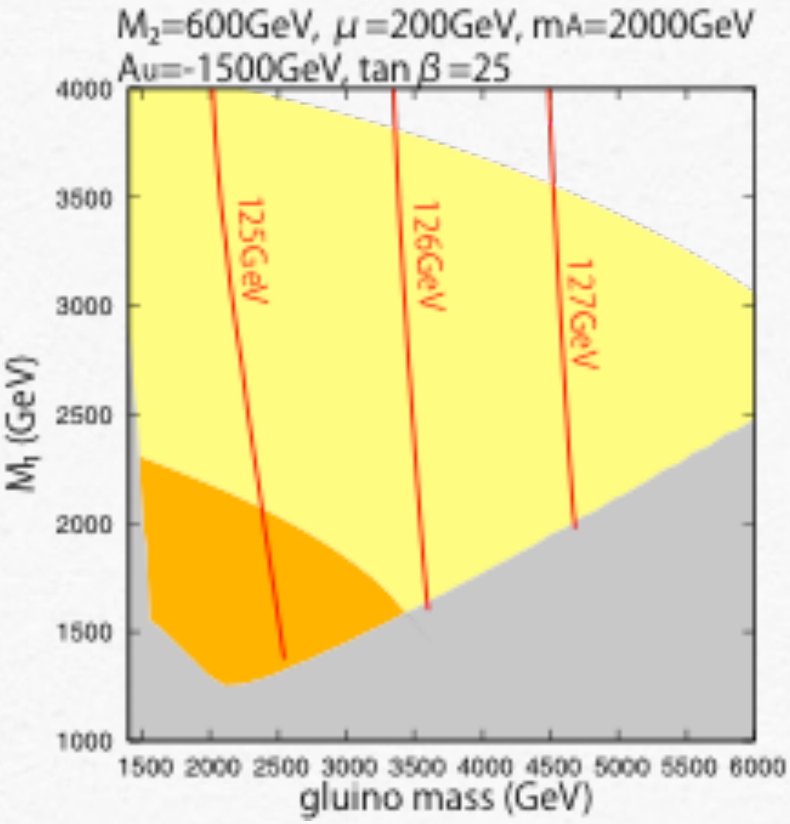


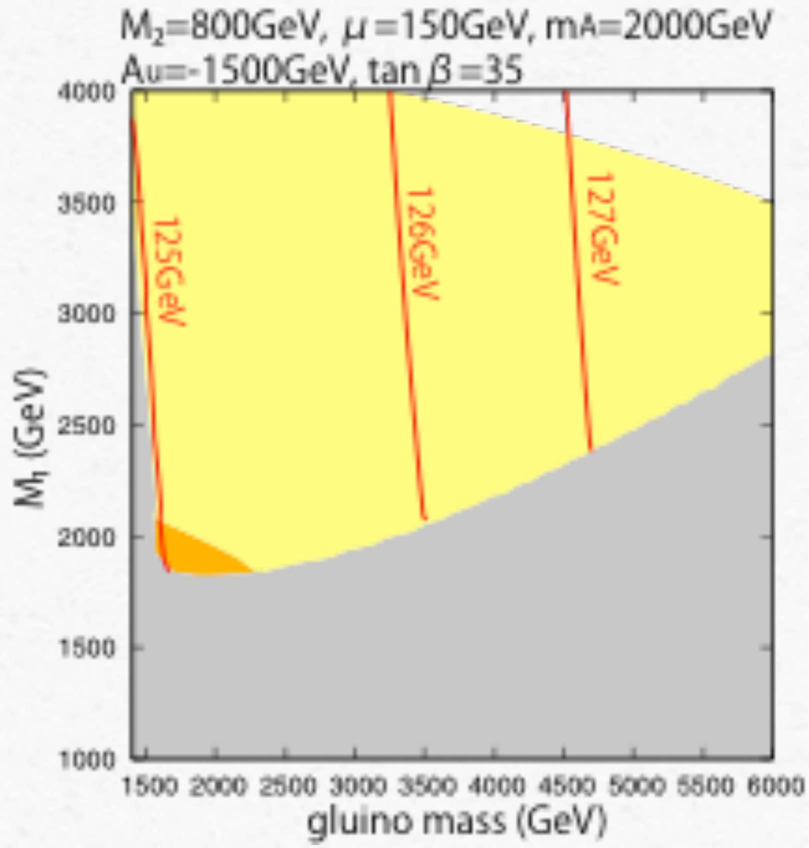
(Heavy bino raises right-handed slepton mass)



Harigaya, Yanagida, Yokozaki (2015)

Light higgsino case

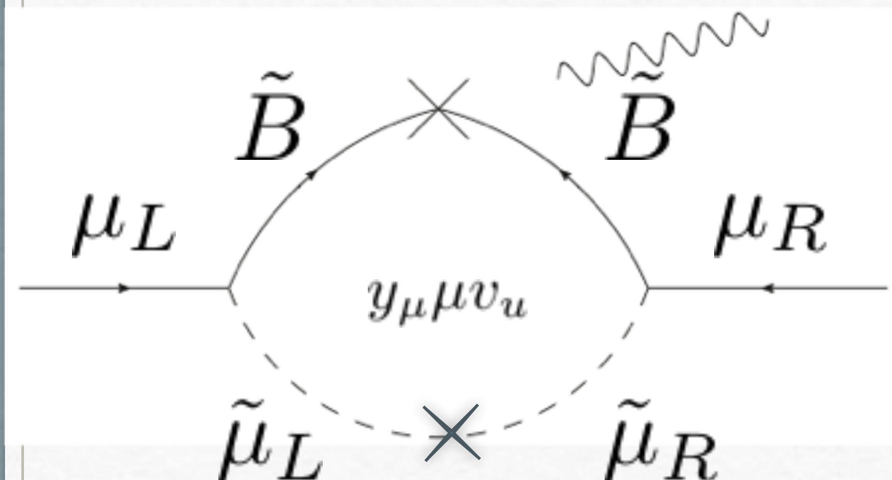




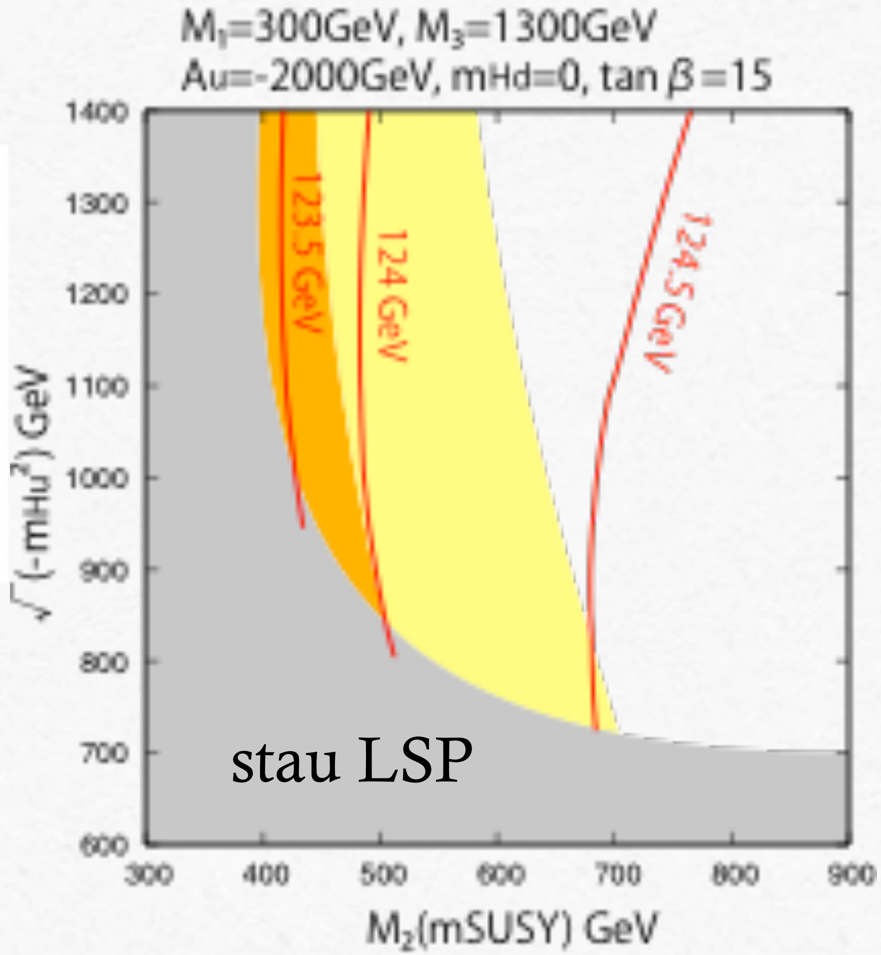
Reference points

m_{gluino}	2.4 TeV	m_{gluino}	3.0 TeV
$m_{\tilde{q}}$	2.1 TeV	$m_{\tilde{q}}$	2.6 TeV
$m_{\tilde{t}_{1,2}}$	1.4, 1.8 TeV	$m_{\tilde{t}_{1,2}}$	1.8, 2.2 TeV
$m_{\tilde{e}_L}(m_{\tilde{\mu}_L})$	450 GeV	$m_{\tilde{e}_L}(m_{\tilde{\mu}_L})$	573 GeV
$m_{\tilde{e}_R}(m_{\tilde{\mu}_R})$	836 GeV	$m_{\tilde{e}_R}(m_{\tilde{\mu}_R})$	721 GeV
$m_{\tilde{\tau}_1}$	361 GeV	$m_{\tilde{\tau}_1}$	174 GeV
$m_{\chi_1^0}$, $m_{\chi_2^0}$	179, 210 GeV	$m_{\chi_1^0}$, $m_{\chi_2^0}$	145, 159 GeV
$m_{\chi_3^0}$, $m_{\chi_4^0}$	342, 935 GeV	$m_{\chi_3^0}$, $m_{\chi_4^0}$	602, 806 GeV
$m_{\chi_1^\pm}$, $m_{\chi_2^\pm}$	184, 343 GeV	$m_{\chi_1^\pm}$, $m_{\chi_2^\pm}$	151, 602 GeV
m_h	124.5 GeV	m_h	125.3 GeV
Δa_μ	2.20×10^{-9}	Δa_μ	1.97×10^{-9}
$\Delta \text{Br}(b \to s\gamma)$	-2.9×10^{-5}	$\Delta \text{Br}(b \to s\gamma)$	-2.5×10^{-5}

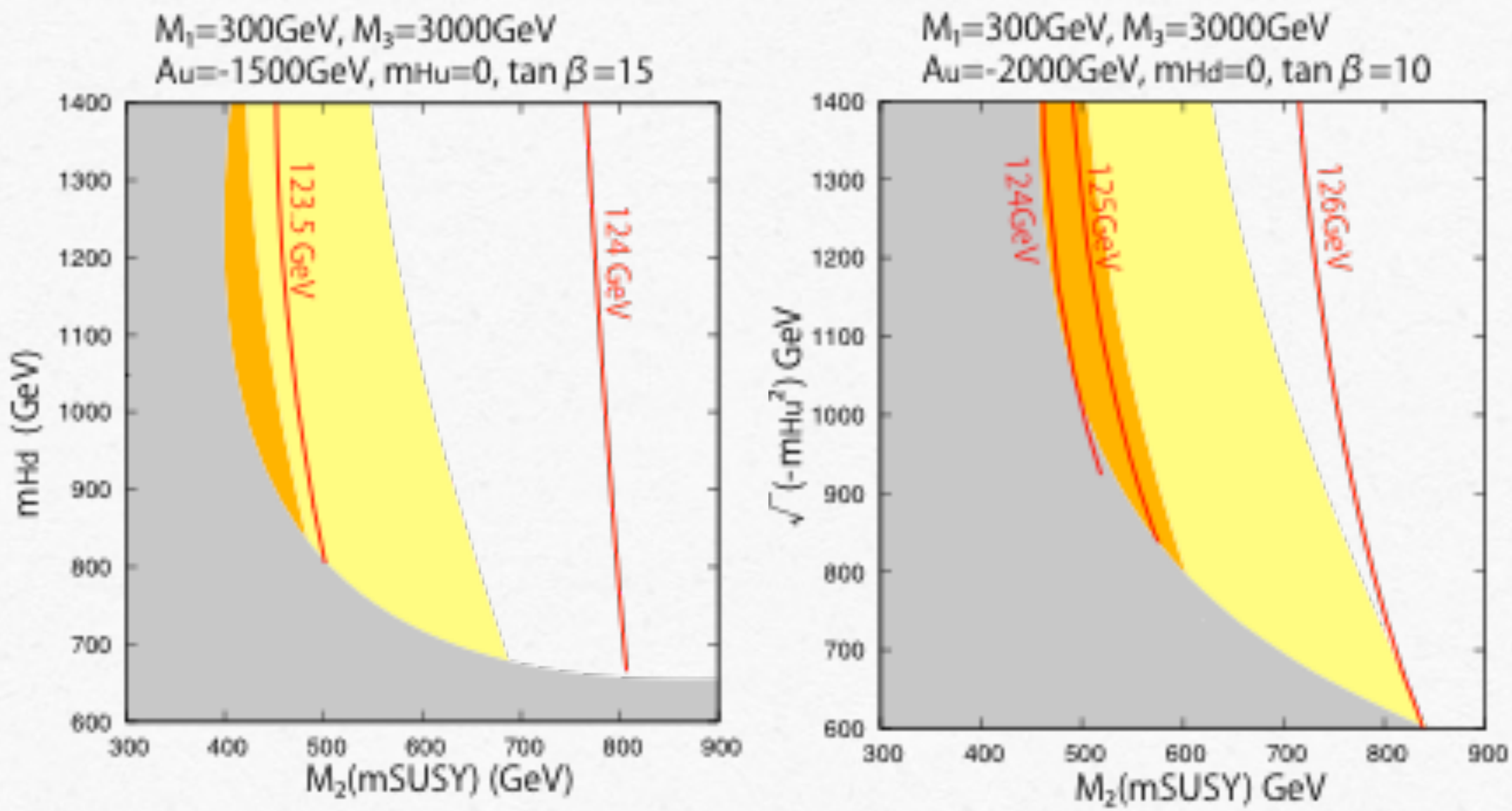
Heavy higgsino case



Negatively large up-type
Higgs mass raises stau mass



Heavy higgsino case



Reference points

m_{gluino}	2.8 TeV	m_{gluino}	6.1 TeV
$m_{\tilde{q}}$	2.5 TeV	$m_{\tilde{q}}$	5.2 TeV
$m_{\tilde{t}_{1,2}}$	1.9, 2.2 TeV	$m_{\tilde{t}_{1,2}}$	4.4, 4.9 TeV
$m_{\tilde{e}_L}(m_{\tilde{\mu}_L})$	471 GeV	$m_{\tilde{e}_L}(m_{\tilde{\mu}_L})$	423 GeV
$m_{\tilde{e}_R}(m_{\tilde{\mu}_R})$	212 GeV	$m_{\tilde{e}_R}(m_{\tilde{\mu}_R})$	218 GeV
$m_{\tilde{\tau}_1}$	120 GeV	$m_{\tilde{\tau}_1}$	118 GeV
$m_{\chi_1^0}$, $m_{\chi_2^0}$	118, 609 GeV	$m_{\chi_1^0}$, $m_{\chi_2^0}$	107, 606 GeV
$m_{\chi_1^\pm}$, $m_{\chi_2^\pm}$	609, 2006 GeV	$m_{\chi_1^\pm}$, $m_{\chi_2^\pm}$	606, 3671 GeV
m_h	124.3 GeV	m_h	125.2 GeV
Δa_μ	1.40×10^{-9}	Δa_μ	1.88×10^{-9}

Summary

- SUSY is attractive
- Non-universal gaugino mass is well-motivated from GUT
- It explains higgs mass & muon g-2

Harigaya, Yanagida and Yokozaki (arXiv:1501.07447)
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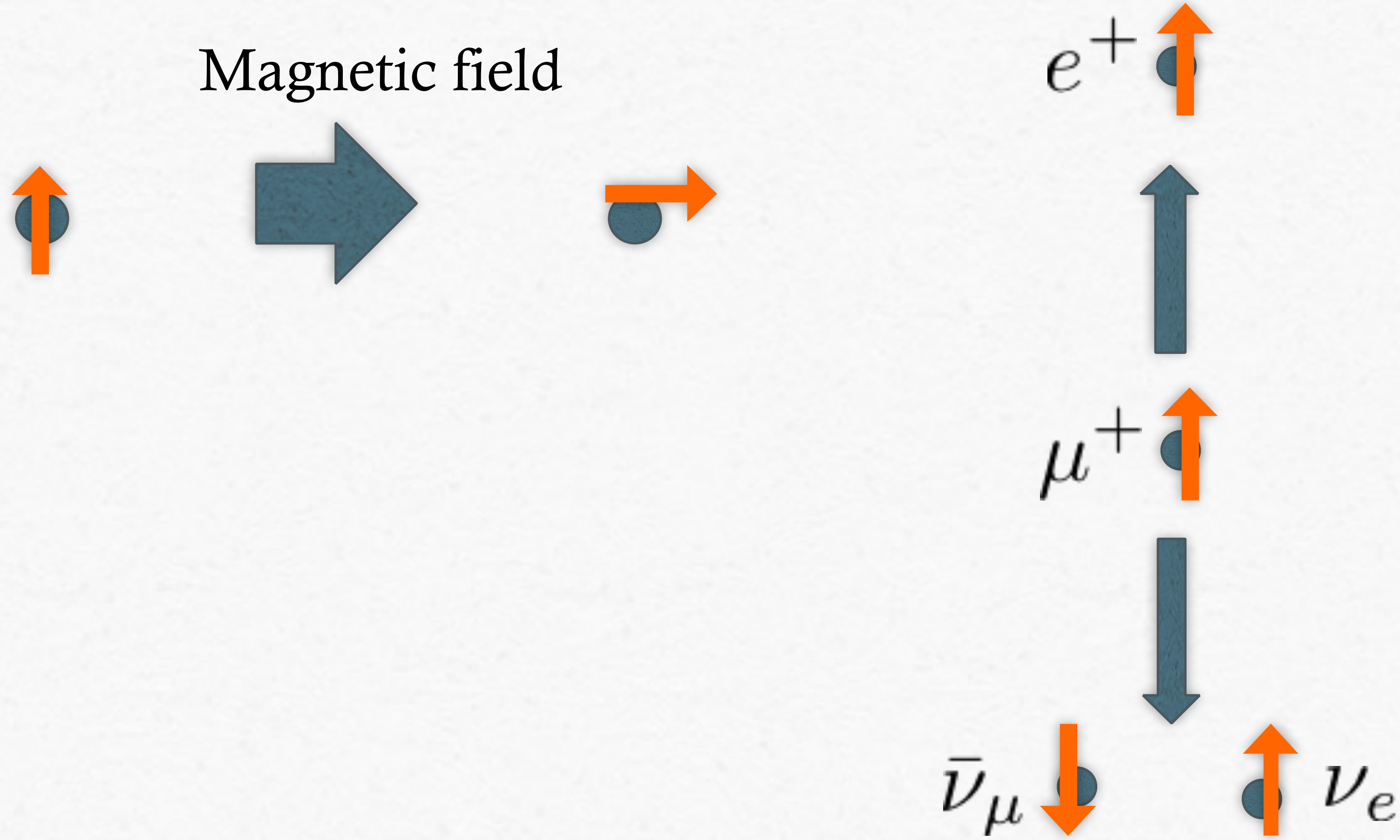
Backup

Measurement of g-2



g-2 ?

$$H = -g\frac{q}{2m}\vec{s}\cdot\vec{B}$$

$$g = 2 + \text{quantum corrections}$$

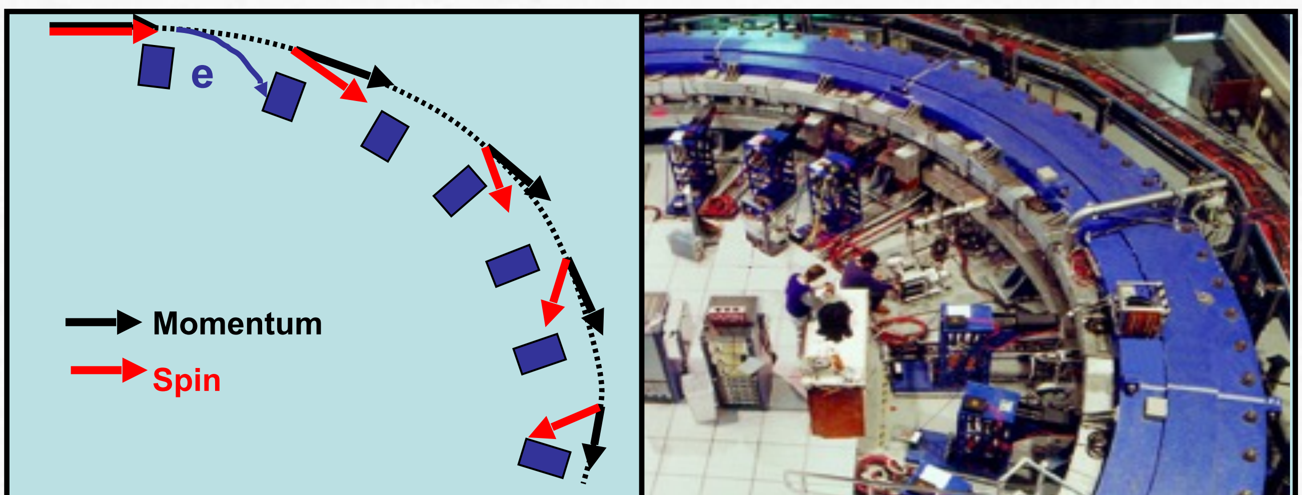
$$a \equiv \frac{g-2}{2}$$

$$\mathcal{L}_{g-2} = \frac{q}{4m}a\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}$$

Measurement of g-2

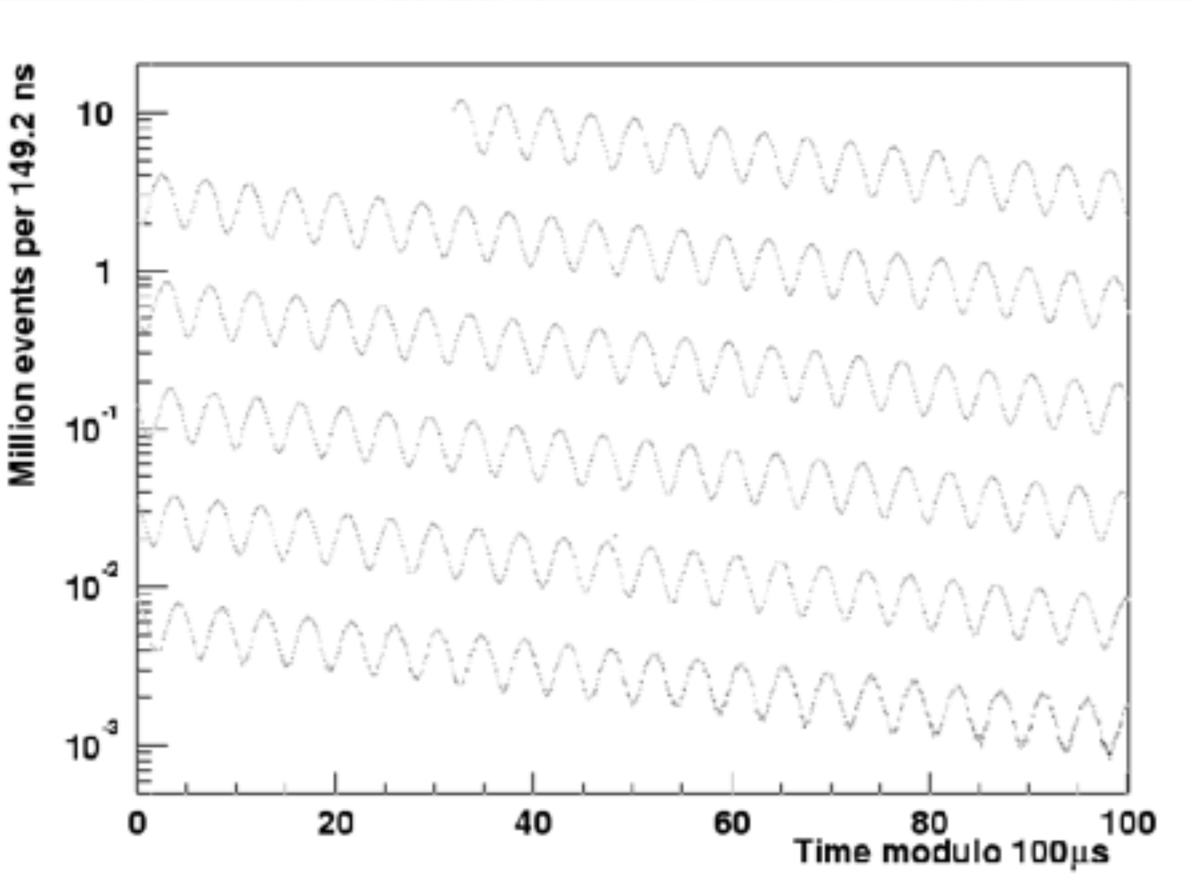
$$\omega_{\text{mom}} = -\frac{eB}{m} \qquad \omega_{\text{spin}} = \frac{g}{2}\frac{eB}{m}$$

$$\Delta\omega_{\text{spin}} = \frac{g-2}{2}\frac{eB}{m}$$



Herzog, tau06

Measurement of g-2



Muon (g-2) collaboration (2006)

Prediction on g-2

$$a_\mu = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm had}$$

$$a_\mu^{\rm QED} = 116584718.08(15) \times 10^{-11}$$

$$a_\mu^{\rm EW} = (154 \pm 2) \times 10^{-11}$$

$$a_\mu^{\rm had,VP,LO} = 6949(43) \times 10^{-11}$$

$$a_\mu^{\rm had,VP,HO} = -98.4(0.7) \times 10^{-11}$$

$$a_\mu^{\rm had,LbL} = [(80\text{-}140) \pm (10\text{-}40)] \times 10^{-11}$$

QED

$$a_\mu^{\mathrm{QED}} = 116584718.08(15) \times 10^{-11}$$

4 – loop !

Electro weak

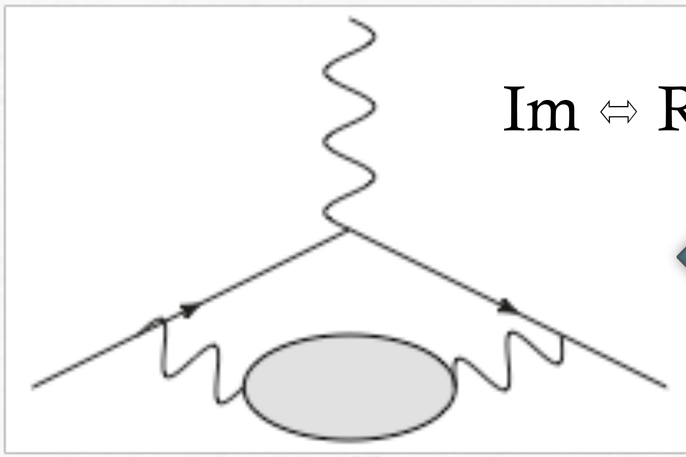
$$a_\mu^{\mathrm{EW}} = (154 \pm 2) \times 10^{-11}$$

2-loop

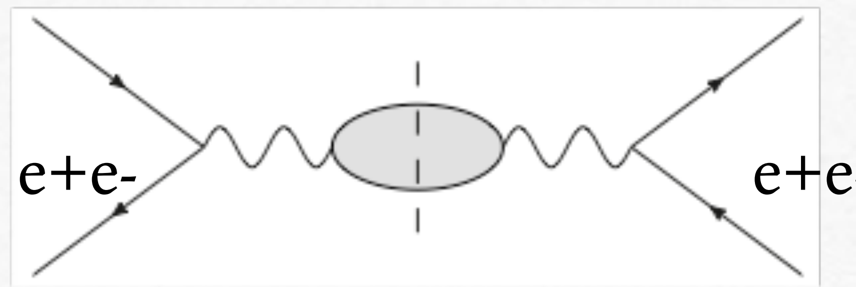
Hadronic, VP

Vacuum polarization

Im ⇔ Re by the dispersion relation



$$a_\mu^{\mathrm{had,VP,LO}} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} \mathrm{d}s\,\sigma_{\mathrm{had}}(s)K(s)$$

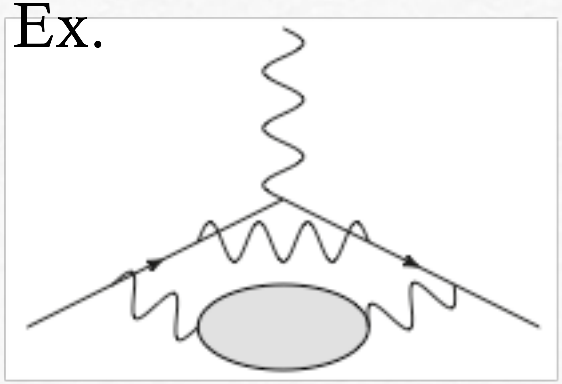


$$a_\mu^{\mathrm{had,VP,LO}} = 6949(43) \times 10^{-11}$$

Hadronic, VP

Vacuum polarization, higher order

Ex.

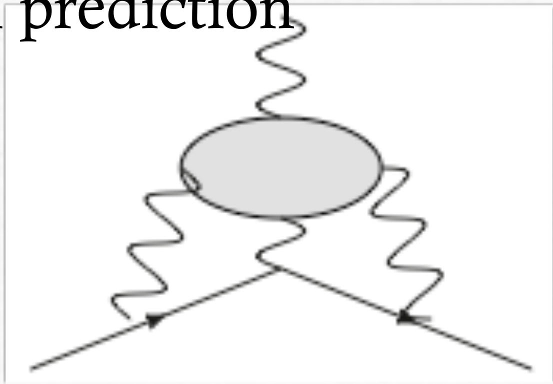


$$a_\mu^{\mathrm{had,VP,HO}} = -98.4(0.7) \times 10^{-11}$$

Hadronic, LbL

Light-by-Light

Dominate the theoritical error in SM prediction



Using effective field theories of mesons,

$$a_\mu^{\mathrm{had,LbL}} = [(80\text{-}140) \pm (10\text{-}40)] \times 10^{-11}$$

Higgs mass calc.

Feynhiggs2.10.2

Borowka, Hahn, Heinemeyer, Hienrich, Hollik (2014)

- Full one-loop
- Two-loop $O(\alpha_t^2, \alpha_t\alpha_s, \alpha_s^2)$ for zero-momentum
- Two-loop $O(\alpha_t\alpha_s)$ for non-zero-momentum
- Large logs resummed

2-3 GeV error from uncalculated quantum corrections

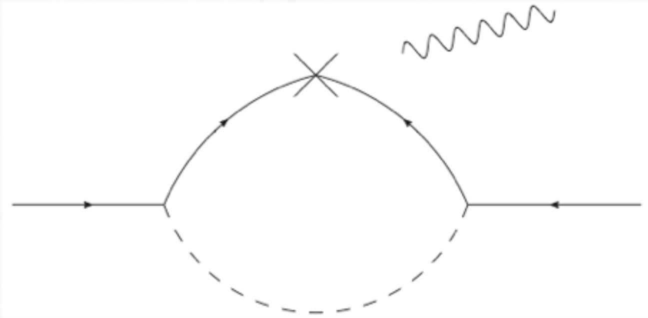
Other issues

- Flavor violation from SUSY particles
- CP violations from SUSY particles

Especially,
the g-2 diagram contributes to electron EDM,
by muon ➔ electron

$$\theta_{\rm CP} < 10^{-3} \left(\frac{m_{\rm SUSY}}{300\ {\rm GeV}} \right)^2 \frac{10}{\tan\beta}$$

Pokorski, Rosiek, Savoy (1999)
ACME collaboration (2014)



CP safe

Iwamoto, Yanagida, Yokozaki (2014)

Assume the shift symmetry

$$Z \to Z + iC$$

$$K(Z + Z^\dagger, QQ^\dagger) \quad \text{Real coefficients}$$

$$W = W_0 + \mu H_u H_d + W_{\text{yukawa}}$$

Made Real by R-rot PQ-rot

$$kZW^\alpha W_\alpha \quad \text{Real k}$$

No CP phases beyond yukawa

About renormalization

Gaugino mass, gauge interaction ➔ positive scalar masses
Scalar masses, yukawa interaction ➔ negative scalar masses