Quarks and Leptons as Quasi Nambu Goldstone Fermions
--- 33 Years Later ---

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Kavli IPMU September 9, 2015

~ 1980

1977; Peccei-Quinn Mechanism

Peccei and Quinn (1977)

1978; Baryogenesis

Yoshimura (1978)
Ignatiev, Krasnikov, Kuzmin, Tavkhelidze (1978)

1979; Supersymmetry (cancellation of quadratic divergence)

Maiani (1979); Veltman (1981)

1979; Seesaw Mechanism for Neutrino Mass

Minkowski (1977)
Yanagida (1979); Gell-Mann, Ramond and Slansky (1979)

1980; Naturalness

‘t Hooft (1980)

1981; Inflation Universe

Guth (1981)
Linde(1982) ; Albrecht and Steinhardt (1982)

Composite Model for Quarks and Leptons

Why are they so light ?

They are Quasi Nambu-Goldstone Fermions !!!

Buchmuller, Love, Peccei and Yanagida (1982)

Suppose some global symmetry G at a preon level and it is broken down to some subgroup H

Then, we have massless Nambu-Goldstone bosons, G/H, which are composite bound states of preons

In SUSY theory, the NG bosons are always accompanied with fermion partners, which we called Quasi-NG Fermions

They are nothing but massless fermion bound states, which we identified with Quarks and Leptons

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QUASI GOLDSTONE FERMIONS

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Received 17 May 1982

We discuss a mechanism by which, in theories with an explicitly broken supersymmetry, we can obtain calculable fermion masses, provided certain softly broken R symmetries are incorporated. The corresponding fermion representations are determined by the pattern of internal symmetry breakdown. This mechanism is explicitly studied in a simple U(1) model. Prospects and limitations of this idea for constructing realistic fermion spectra are discussed.

I will show in this talk
why this old fashioned idea has become very interesting now

The most important discovery in particle physics in the last 30 years is the standard-model like Higgs boson which was observed at the ATLAS and CMS experiments

Its mass is about 125 GeV !!!

The Higgs boson in the Standard Model

$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

$$<\Phi>= \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \quad ; \quad v = \sqrt{\mu^2/\lambda}$$

$$m_H = \sqrt{2\lambda}v \quad ; \quad v \simeq 246\mathrm{GeV}$$

The Higgs boson mass is **a free parameter** in the Standard Model

Are there any theories which predict
the Higgs boson mass ?

⟹ YES !!!!

Supersymmetry (SUSY)

The *coupling* is given by $\lambda = \frac{g_2^2 + g_1^2}{4}$ ⟵ SUSY

Then, we predict

$$m_{\mathrm{H}} \simeq m_Z \cos(2\beta) \leq m_Z \leq 91\mathrm{GeV}$$

$$\tan(\beta) = \frac{< H_u >}{< H_d >}$$

Is the SUSY Standard Model excluded ?

No!

125 GeV Higgs boson mass is
what we predicted about 24 years ago !!!

One –loop corrections at the quantum level are non negligible

Okada, Yamaguchi, Yanagida (1991)
J. Ellis et al (1991)
H. Haber et al (1991)

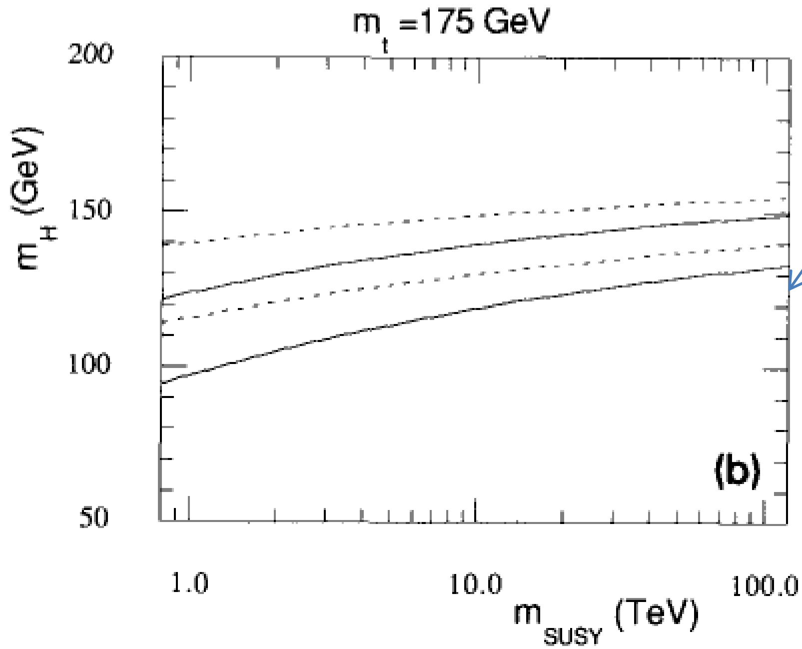
$$m_{\rm H}^2 \simeq m_{\rm Z}^2 \cos^2(2\beta) + \Delta m_{\rm H}^2$$

The quantum corrections are given by one-loop top quark and scalar top quark diagrams

$$m_{\rm light} \leq \sqrt{m_{Z^0}^2 \cos^2 2\theta + \frac{6}{(2\pi)^2}\left(\log \frac{m^2 + {m_t}^2}{{m_t}^2}\right)\frac{{m_t}^4}{v^2}}$$

mass of scalar top quark

Our prediction of Higgs mass :



Higgs mass 125 GeV

Okada, Yamaguchi, Yanagida (1991)

We have calculated the mass of the lightest Higgs boson in the minimal SUSY standard model postulating the SUSY breaking scale is much larger than the Fermi scale. Our results can be used to probe the SUSY breaking scale, with the situation where both m_t and m_{H^0} are given. For example, when $m_t = 150$ GeV, the existence of the Higgs boson below 70 GeV strongly suggests the presence of the SUSY below 1 TeV (see the lower solid line in fig. 1a). On the other hand, if the Higgs boson turns out to be heavier than 125 GeV, the SUSY breaking scale must be larger than

$$\Rightarrow \quad m_{\rm SUSY} = m_{stop} \geq O(10)\mathrm{TeV}$$

There were various motivations to consider the large SUSY breaking scale,

$$m_{\rm SUSY} = m_{stop} \geq O(10){\rm TeV}$$

I. Gravitino over-production problem
II. Polonyi (Moduli) problem
III. Flavor-changing neutral current problem
IV. CP-violation problem

Solutions to each problems suggest the large SUSY breaking

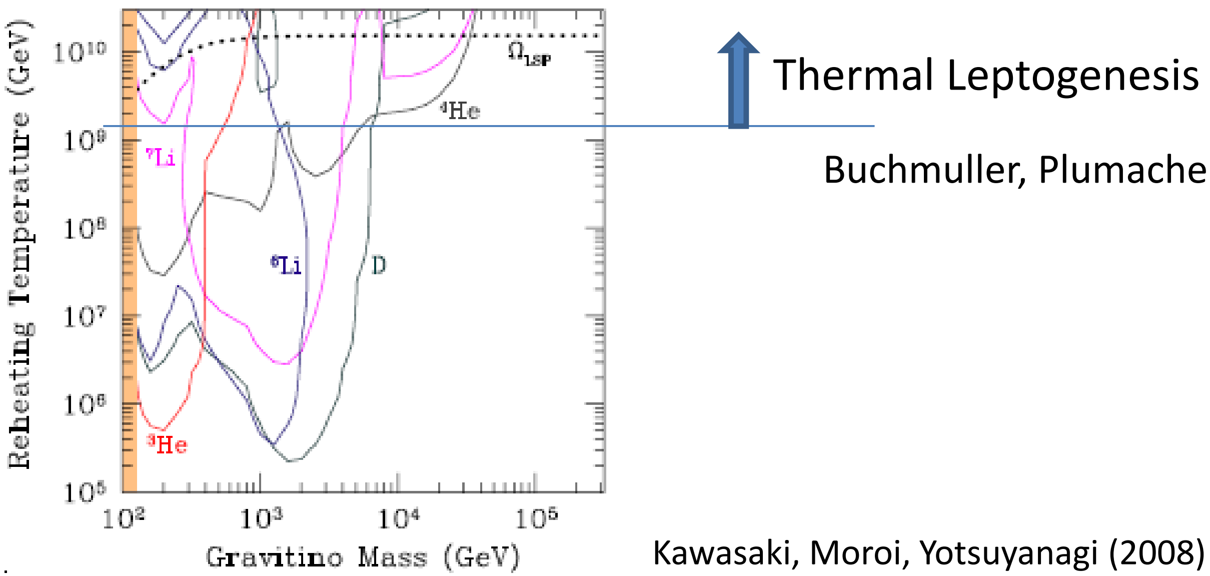
$$m_{3/2} \simeq m_{\rm SUSY} \geq O(10){\rm TeV}$$

gravitino mass

I. Gravitino over-production problem

S. Weinberg (1982)
J. Ellis et al (1982)

The gravitinos are produced by particle scattering in thermal bath in the early universe. They decay after the BBN and destroy the light elements produced by the BBN. We have constraints on T_R and m_3/2 not to disturb the BBN (big bang nucleosynthesis).



Buchmuller, Plumacher (1997)

Kawasaki, Moroi, Yotsuyanagi (2008)

The thermal leptogenesis predicts $m_{3/2} \simeq m_{\rm SUSY} \geq O(10)\mathrm{TeV}$!!!

Higgs boson mass m_h = 125 GeV

↓

m_3/2 ~ m_stop > 10 TeV

+ ***GUT !!***

m_3/2 ~ m_squark~ m_slepton > 10 TeV

But, we have a PROBLEM !!!

The Muon g-2

a(muon) = (1/2)(g-2) _exp =11659 2080 (63) x10^{-11}

Bennett et al (2004)

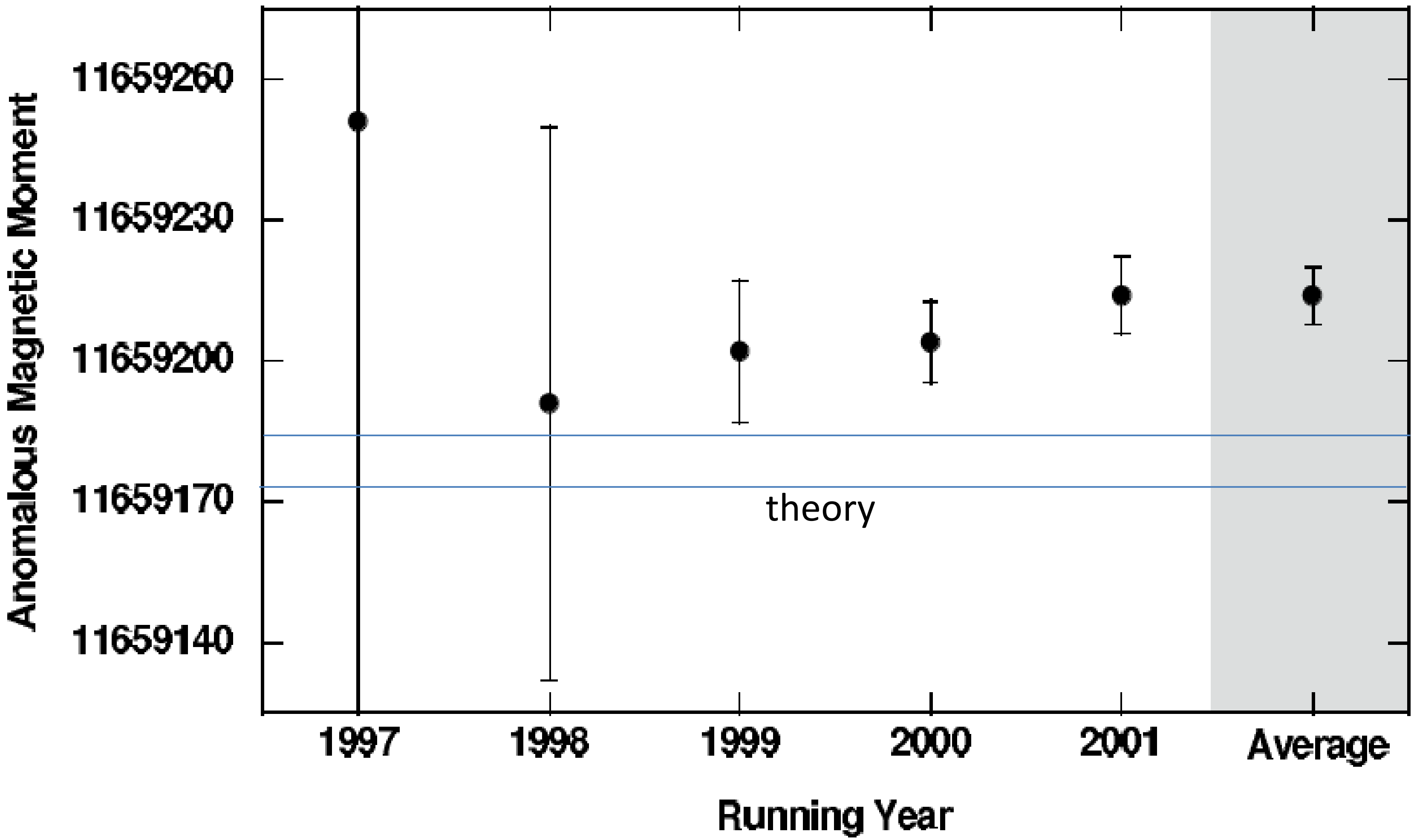
a(muon)_theor = 11659 1785 (61) x10^{-11}

We find a 3.4 sigma discrepancy

Miller, Rafael, Roberts (2007)

Table 1. Measurements of the muon anomalous magnetic moment. When the uncertainty on the measurement is the size of the next term in the QED expansion, or the hadronic or weak contributions, the term is listed under "sensitivity". The "?" indicates a result that differs by greater than two standard deviations with the Standard Model. For completeness, we include the experiment of Henry, et al.,[46], which is not discussed in the text.

$\pm$	**Measurement**	σ_{a_μ}/a_μ	**Sensitivity**	**Reference**
μ^+	$g = 2.00 \pm 0.10$		$g = 2$	Garwin *et al*[30], Nevis (1957)
μ^+	$0.001\,13^{+0.00016}_{-0.00012}$	12.4%	$\frac{\alpha}{\pi}$	Garwin *et al*[33], Nevis (1959)
μ^+	0.001 145(22)	1.9%	$\frac{\alpha}{\pi}$	Charpak *et al*[34] CERN 1 (SC) (1961)
μ^+	0.001 162(5)	0.43%	$(\frac{\alpha}{\pi})^2$	Charpak *et al*[35] CERN 1 (SC) (1962)
$\mu^\pm$	0.001 166 16(31)	265 ppm	$(\frac{\alpha}{\pi})^3$	Bailey *et al*[36] CERN 2 (PS) (1968)
μ^+	0.001 060(67)	5.8%	$\frac{\alpha}{\pi}$	Henry *et al*[46] solenoid (1969)
$\mu^\pm$	0.001 165 895(27)	23 ppm	$(\frac{\alpha}{\pi})^3$ + Hadronic	Bailey *et al*[37] CERN 3 (PS) (1975)
$\mu^\pm$	0.001 165 911(11)	7.3 ppm	$(\frac{\alpha}{\pi})^3$ + Hadronic	Bailey *et al*[38] CERN 3 (PS) (1979)
μ^+	0.001 165 919 1(59)	5 ppm	$(\frac{\alpha}{\pi})^3$ + Hadronic	Brown *et al*[48] BNL (2000)
μ^+	0.001 165 920 2(16)	1.3 ppm	$(\frac{\alpha}{\pi})^4$ + Weak	Brown *et al*[49] BNL (2001)
μ^+	0.001 165 920 3(8)	0.7 ppm	$(\frac{\alpha}{\pi})^4$ + Weak + ?	Bennett *et al*[50] BNL (2002)
μ^-	0.001 165 921 4(8)(3)	0.7 ppm	$(\frac{\alpha}{\pi})^4$ + Weak + ?	Bennett *et al*[51] BNL (2004)
$\mu^\pm$	0.001 165 920 80(63)	0.54 ppm	$(\frac{\alpha}{\pi})^4$ + Weak + ?	Bennett *et al*[51, 26] BNL WA (2004)


11659260
11659230
11659200
11659170
11659140
Anomalous Magnetic Moment
theory
1997
1998
1999
2000
2001
Average
Running Year

The standard model contributions to the muon g-2

- *Leptonic QED Contributions*

$$a_\mu(\mathrm{QED}) = (116\ 584\ 718.09 \pm 0.14_{\mathrm{5loops}} \pm 0.08_\alpha \pm 0.04_{\mathrm{masses}}) \times 10^{-11}$$

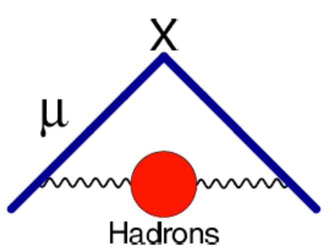
- *Electroweak Contributions*

$$a_\mu[EW] = (154 \pm 2 \pm 1) \times 10^{-11}$$

- *Hadronic Contributions*
  - *Hadronic Vacuum Polarization with EM-Data*

    From the two most recent determinations in Table 9, which take into account the new data on e^+e^- annihilation into hadrons, we get

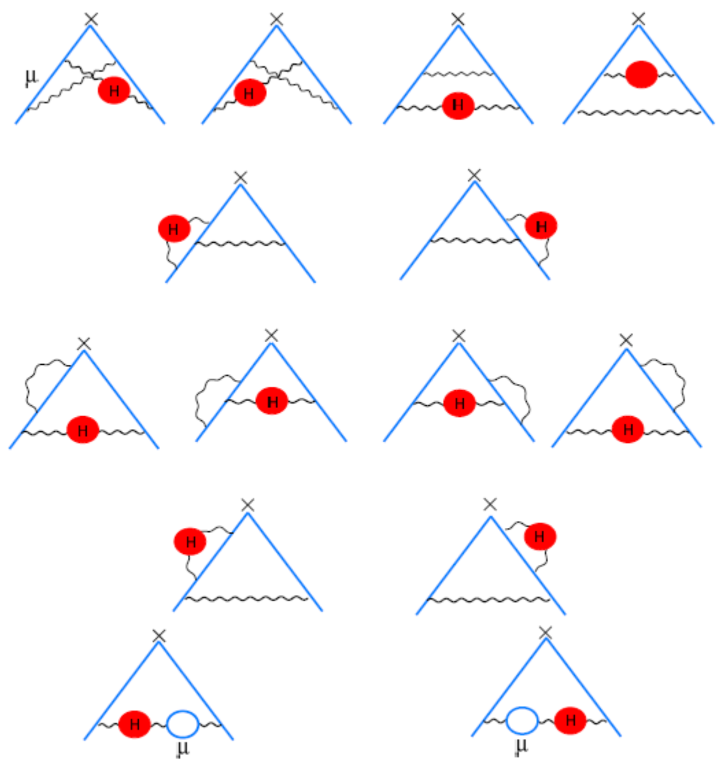
$$a_\mu[\mathrm{HVP(06)}] = (6901 \pm 42_{\mathrm{exp}} \pm 19_{\mathrm{rad}} \pm 7_{\mathrm{QCD}}) \times 10^{-11}\,, \qquad (158)$$

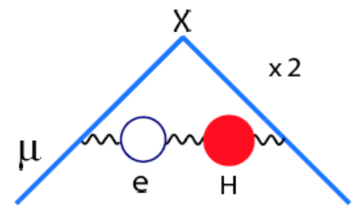


$$a_\mu^{\mathrm{exp}} = 11\ 659\ 2\underline{080}\ (63) \times 10^{-11}$$

– *Higher-Order Hadronic Vacuum Polarization with EM-Data*

$$a_\mu[\text{HVP h.o.}] = (-97.9 \pm 0.9_{\text{exp}} \pm 0.3_{\text{rad}}) \times 10^{-11}$$





Uncertainty comes from **hadron light by light contributions**

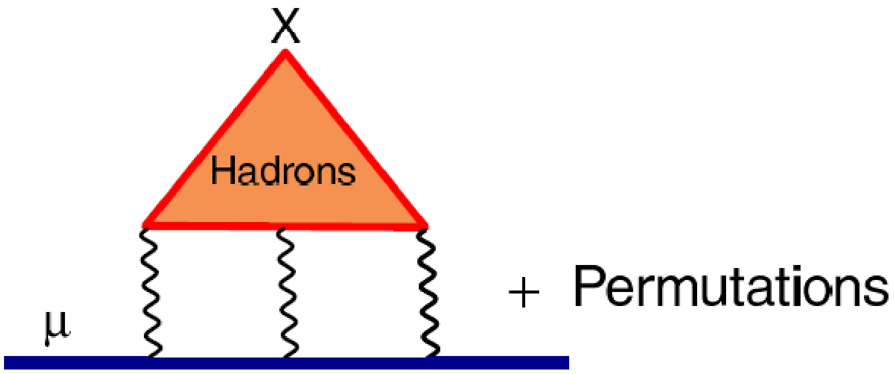


Figure 52. Hadronic Light-by-Light Contributions

The leading terms are given by the pion reducible diagrams

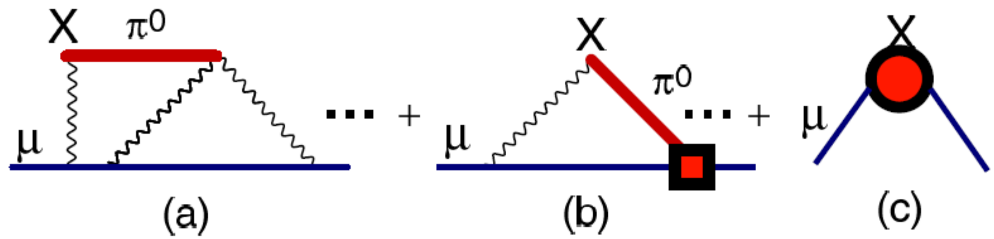


Figure 53. One Goldstone Reducible Diagrams in Chiral Perturbation Theory

$$a_\mu^{(6)}(\pi^0)_{\rm lxl} = (5.8 \pm 1.0) \times 10^{-10}\,,$$

$$a_\mu^{(6)}(\pi^0 + \eta + \eta')_{\rm lxl} = (8.3 \pm 1.2) \times 10^{-10}$$

– *Hadronic Light-by-Light Scattering*

$$a_\mu[\mathrm{HLLS}] = (110 \pm 40) \times 10^{-11}$$

Contributions from above the 1 GeV scale physics are suppressed as (m(pion)/1 GeV)^2 =O(0.01) !!!

The sum of these contributions, using the HVP06 result in Equation (158) and adding experimental and theoretical errors in quadrature, gives then a total

$$a_\mu^{\mathrm{SM}(06)} = 11\ 659\ 1\underline{785}\ (61) \times 10^{-11}\,. \tag{162}$$

These determinations are to be compared to the experimental world average in Equation (21)

$$a_\mu^{\mathrm{exp}} = 11\ 659\ \underline{2080}\ (63) \times 10^{-11}\,. \tag{163}$$

Therefore, we conclude that, with the input for the Standard-Model contributions discussed above, one finds at present a 3.4 σ discrepancy.

If contributions from hadronic light by light processes are 3 times bigger we may explain the experiments !!!

But, who believe it ?

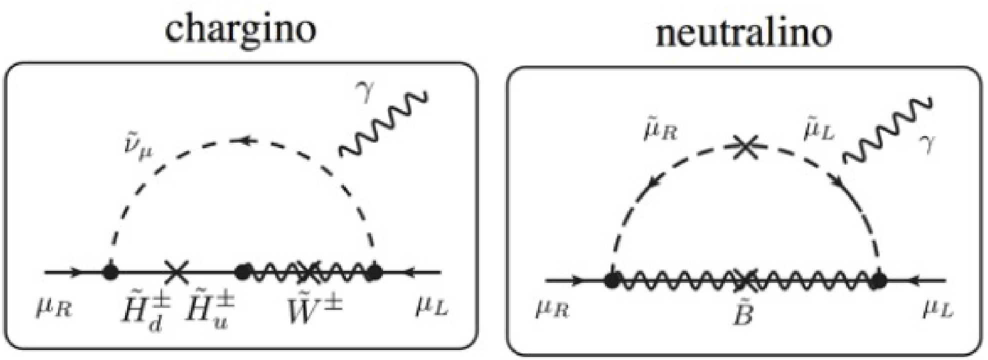
Main Message

muon g-2

$$a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0) \cdot 10^{-10}$$

> 3σ deviation !

low scale (<TeV) SUSY で説明出来る！



TeV 以下の chargino/neutralino and smuon が必要

Talk by Hamaguchi

⇒ **smuon mass < 1 TeV !**

In general, m_h=125 GeV -------> stop mass >10 TeV

The muon g-2 anomaly -------> smuon mass <1 TeV

Why smuon mass << stop mass ?

The quasi NG fermion hypothesis gives us a solution !!!

Quark Lepton Mass Hierarchy

m_u , m_c << m_t ; m_d, m_s << m_b ; m_e, m_{mu} << m_{tau}

Y_u, Y_c << Y_t ; Y_d, Y_s << Y_b ; Y_e, Y_{mu} << Y_{tau}

Yukawa coupling hierarchy

If Q_i and L_i are NG chiral multiplets, their Yukawa couplings =0 !
We can explain the small Yukawa couplings for 1st and 2nd generations

The quarks and leptons in the first and second generations may be the quasi NG fermions !!!

Buchmuller, Love, Peccei, Yanagida (1982)

What is G/H ?

this context, it appears interesting that the adjoint representation of E_6, **78** transforms with respect to the SO(10) subgroup as

$$\mathbf{78} = \mathbf{45} + \mathbf{16} + \mathbf{16}^* + 1. \tag{11}$$

Thus a spontaneous breakdown of E_6 to SO(10) would generate precisely one left-handed and one right-handed family of fermions ‡5.

The reality of the quasi Goldstone fermion representations appears unfortunate, however, since the observed fermions in nature transform according to complex representations. Although there is no a priori reason why quasi Goldstone fermions transforming according to complex conjugate representation should acquire *precisely* the same calculable mass, we have not been able to find a model where a sizable asymmetry in the calculable masses in complex conjugate representations arises naturally.

A second disturbing feature accompanies the generalization of this mechanism to larger groups; namely, the presence of pseudo Goldstone excitations. When one constructs a supersymmetric lagrangian which is invariant under a group G and which still possesses softly broken R symmetries, one in general finds that the potential has a larger invariance. When the group G is gauged, the invariance under the larger group is lost and pseudo Goldstone bosons and fermions emerge. The same approximate R-symmetries which protect the quasi Goldstone fermions from acquiring a divergent mass also protect the pseudo Goldstone fermions. Thus it is no longer true that one can, by direct group theory, deduce which representations of calculable fermions appear in the theory – irrespective of the initial field content of the model. This feature also makes a more realistic application of our idea more challenging.

‡5 Note also that the adjoint representation of E_8, **248** transforms with respect to the subgroup SO(16) as **248** = 120 + 128, where the **128** contains 4 left-handed and 4 right-handed **16**'s of SO(10) (i.e. 4 mirror families). In order for this mechanism to give rise to a realistic fermion spectrum, it is necessary that the fermions associated with further symmetry breakdowns acquire sufficiently heavy masses

One of us (RDP) enjoyed a fruitful discussion on this topic with A. Salam and G. Veneziano.

References

[1] G. 't Hooft, in: Recent developments in gauge theories, eds. G. 't Hooft et al. (Plenum, New York, 1980) p. 135.
[2] W.A Bardeen and V. Višnjič, Nucl. Phys. B194 (1982) 422.
[3] W.A. Bardeen, O. Piguet and K. Sibold, Phys. Lett. 72B (1977) 231.
[4] L. O'Raifeartaigh, Nucl. Phys. B96 (1975) 331.

$E_6/SO(10) \times U(1)$; One 16

$E_7/SO(10) \times U(1) \times U(1)$; Two 16's + 10 Kugo , Yanagida (1984)

The first two generations + one Higgs

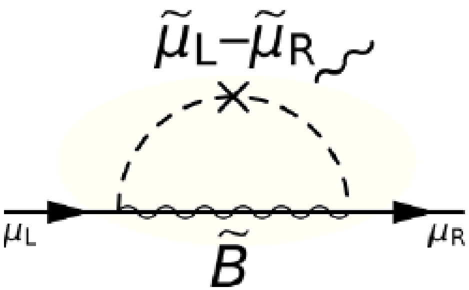
We introduce quarks and leptons in the third generation as matter multiplets and SUSY breaking soft masses for squarks and sleptons in the third generation is naturally unsuppressed of $O(m_{3/2})$

But, squarks and sleptons in the first and second generations are pseudo NG bosons and hence their soft masses are very suppressed; $m_0 \ll m_{3/2}$

We naturally predict the required mass hierarchy, smuon mass << stop mass !!!

We took m_3 = 10 TeV, m_0= (0-500) GeV, M_1/2=free at the GUT scale and calculated ¥delta a_mu for the muon (g-2)

Ibe, Yanagida, Yokozaki (2013)



$$\boxed{\frac{g_Y^2 m_\mu^2}{8\pi^2}\frac{\mu\tan\beta}{M_1^3}\cdot F_b\left(\frac{m_{\tilde{\mu}_L}}{M_1},\frac{m_{\tilde{\mu}_R}}{M_1}\right)}$$

- 通称：pure-bino contribution
- 特徴：μ tanβ に比例する。

Talk by S. Iwamoto

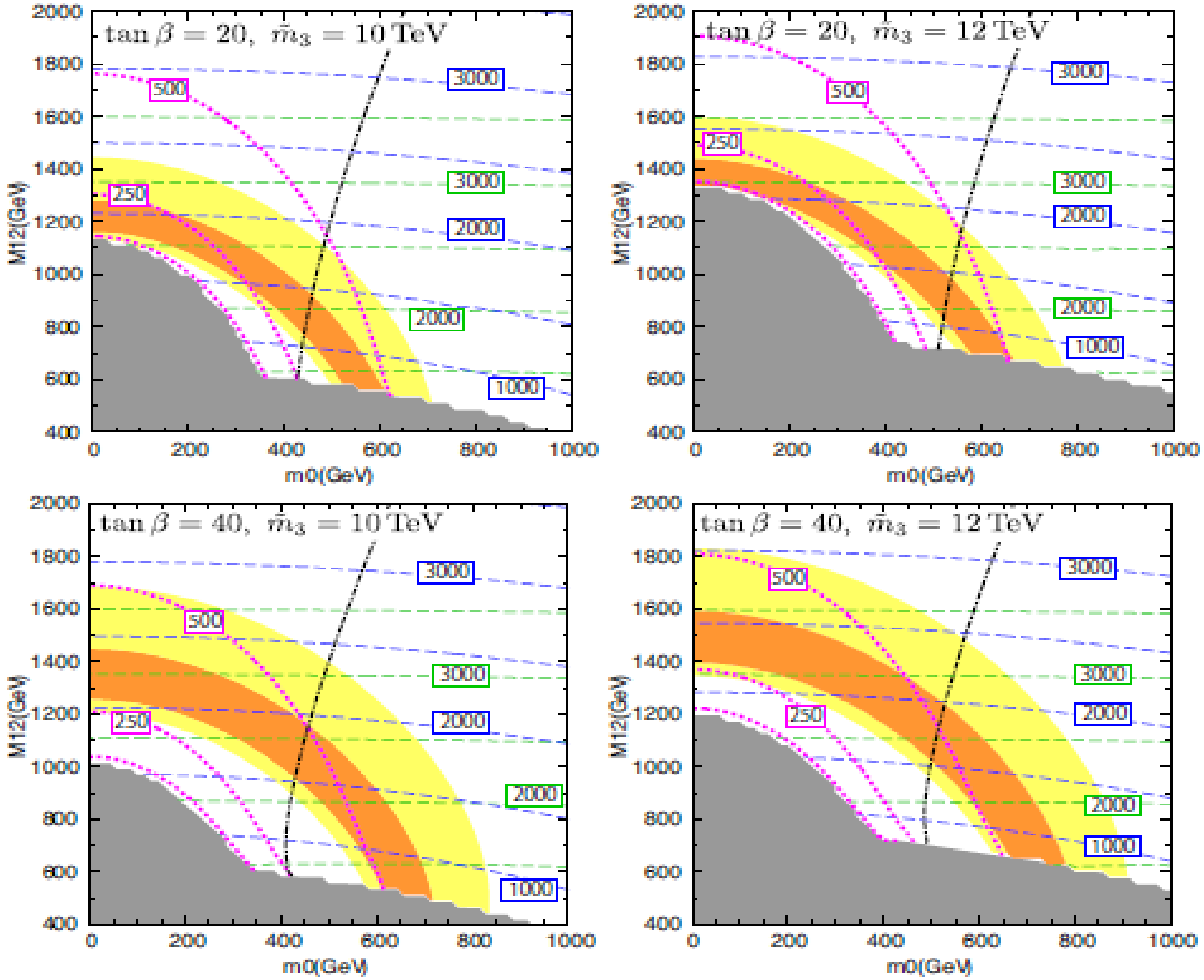


Figure 1: *Contours of δa_μ, the squark mass, the gluino mass, and the lightest slepton mass (the masses are shown in the unit of GeV) on $m_0 - M_{1/2}$ plane. The blue (green) dash-lines correspond to the squark (gluino) masses. The magenta dotted lines show the contours of the lightest slepton masses (from top to bottom, 500 GeV, 250 GeV, 100 GeV). In the orange (yellow) region, δa_μ is explained within $1\,\sigma$ ($2\,\sigma$) level. On the left region of the black dot-dashed line, the LSP is a slepton. The stop mass is $\simeq 8.5\,(10)$ TeV for $m_3 = 10\,(12)$ TeV.*

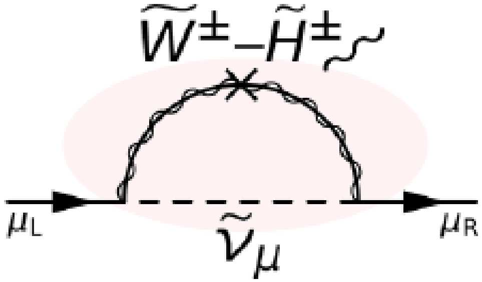
m_0, m_3	400 GeV, 10 TeV	m_0, m_3	600 GeV, 12 TeV
$M_{1/2}$	1000 GeV	$M_{1/2}$	1100 GeV
$\tan\beta$	20	$\tan\beta$	40
μ	7.7 TeV	μ	9.1 TeV
$m_{\rm stop}$	8.5 TeV	$m_{\rm stop}$	10 TeV
δa_μ	2.0×10^{-9}	δa_μ	1.9×10^{-9}
$m_{\rm gluino}$	2294 GeV	$m_{\rm gluino}$	2512 GeV
$m_{\rm squark}$	1613 GeV	$m_{\rm squark}$	1756 GeV
$m_{\tilde{e}_L}(m_{\tilde{\mu}_L})$	610 GeV	$m_{\tilde{e}_L}(m_{\tilde{\mu}_L})$	747 GeV
$m_{\tilde{e}_R}(m_{\tilde{\mu}_R})$	349 GeV	$m_{\tilde{e}_R}(m_{\tilde{\mu}_R})$	568 GeV
$m_{\chi_1^0}$	414 GeV	$m_{\chi_1^0}$	469 GeV
$m_{\chi_1^\pm}$	810 GeV	$m_{\chi_1^\pm}$	896 GeV

Table 1: Sample mass spectra for case I. The SUSY contributions to δa_μ is also shown.

Ibe, Yanagida, Yokozaki (2013)

The squarks and gluino will be discovered soon at LHC !!!

The other case ;



$$\boxed{\frac{g_2^2 m_\mu^2}{8\pi^2}\frac{M_2\mu\tan\beta}{m_{\widetilde{\nu}_\mu}^4}\cdot F_a\left(\frac{M_2}{m_{\widetilde{\nu}_\mu}},\frac{\mu}{m_{\widetilde{\nu}_\mu}}\right)}$$

- 通称：chargino contribution
- 特徴：唯一の “chargino”。$\tan\beta$ に比例。

Talk by S. Iwamoto

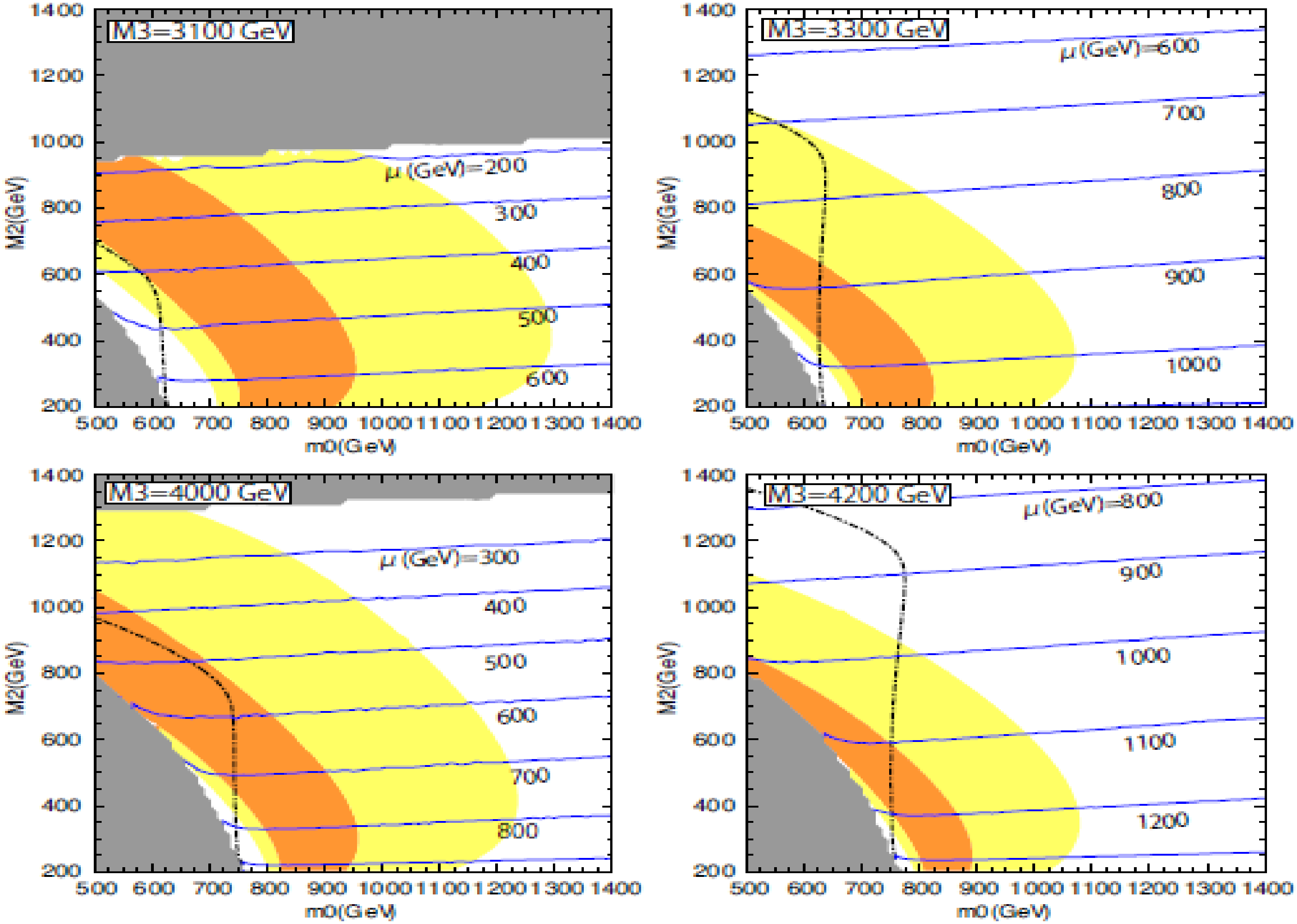


Figure 3: The contours of the Higgsino mass in the unit of GeV (blue) on $m_0 - M_2$ plane for given M_3. In the orange (yellow) region, δa_μ is explained within 1σ (2σ) level. Here, $\tan\beta = 50$, $M_1/M_2 = 1.7$. The third generation sfermion mass is taken as $m_3 = 10$ (12) TeV on upper (lower) two panels. In the orange (yellow) region, δa_μ is explained within 1σ (2σ) level. The upper gray shaded region is excluded by unsuccessful electroweak symmetry breaking, while the lower gray region is excluded due to the tachyonic slepton. On the left region of the black dot-dashed line, the LSP is a sneutrino.

Ibe, Yanagida, Yokozaki (2013)

$m_0,\, m_3$	$900\,\mathrm{GeV},\ 12\,\mathrm{TeV}$	$m_0,\, m_3$	$600\,\mathrm{GeV},\ 12\,\mathrm{TeV}$
$M_1,\, M_2$	$820\,\mathrm{GeV},\ 500\,\mathrm{GeV}$	$M_1,\, M_2$	$1360\,\mathrm{GeV},\ 800\,\mathrm{GeV}$
M_3	$4000\,\mathrm{GeV}$	M_3	$4000\,\mathrm{GeV}$
$\tan\beta$	50	$\tan\beta$	50
μ	$701\,\mathrm{GeV}$	μ	$519\,\mathrm{GeV}$
$m_{\rm stop}$	$9.9\,\mathrm{TeV}$	$m_{\rm stop}$	$9.9\,\mathrm{TeV}$
δa_μ	1.8×10^{-9}	δa_μ	2.3×10^{-9}
Ωh^2	0.09	Ωh^2	–
$m_{\rm gluino}$	8.2 TeV	$m_{\rm gluino}$	8.2 TeV
$m_{\rm squark}$	6.7 TeV	$m_{\rm squark}$	6.7 TeV
m_A	2.5 TeV	m_A	2.3 TeV
$m_{\tilde{e}_L}(m_{\tilde{\mu}_L})$	614 GeV	$m_{\tilde{\nu}_L},\, m_{\tilde{e}_L}$	$355\,\mathrm{GeV},\ 363\,\mathrm{GeV}$
$m_{\tilde{e}_R}(m_{\tilde{\mu}_R})$	845 GeV	$m_{\tilde{e}_R}(m_{\tilde{\mu}_R})$	649 GeV
$m_{\chi_1^0}$	335 GeV	$m_{\chi_1^0}$	495 GeV
$m_{\chi_1^\pm}$	358 GeV	$m_{\chi_1^\pm}$	508 GeV

Table 2: Sample mass spectra, δa_μ and the relic density of the lightest neutralino Ωh^2 for case II.

The charginos may be discovered at 13 TeV LHC !!!

The Conclusion

The present model is most likely tested at the LHC

Why E_7 ?

N=8 Supergravity

Gravity multiplet; one graviton (2), 8 gravitinos (3/2), 28 vector bosons (1)
56 Majorana spinors (1/2), 70 real scalar boson (0)

70 scalar boson = Nambu-Goldston bosons on $E_{7,7}/SU(8)$

Cremmer, Julia (1978)
De Wit, Nicolai (1981)

The maximal subgroup of E_7 is $SU(8)$:

E_7 generators (133) = $\mathbf{T^i{}_j}$ (63) + $\mathbf{E_{I,j,k,l}}$ (70)

SU(8) generators (i,j=1-8)

$E_7/SU(8)$ has 70 NG bosons !!

This hidden $E_{7,7}$ may be the origin of our effective E_7 ?

When N=8 → N=1 SUSY , G/H must be a Kahler manifold
But, E_7/SU(8) is NOT a Kahler manifold

We need rethinking

N=8 supergravity has a local SO(8) symmetry
and a hidden local SU(8) symmetry Nicolai (1982)

Let us assume some of the symmetries survive the breaking of the N=8 supergravity down to N=1 supergravity

Take SU(2) x SU(8)

A subgroup of SO(8)

Preon Model

Consider eight SU(2)-doublet preons Q^i_a, ; i=1-8 and a=1,2

Here we have SU(2) x SU(8)

Consider the strong coupling limit of the SU(2) gauge theory
which has an infrared fixed point

Seiberg (1996)

On the fixed point we have an enhanced global symmetry that is E_7 !!!

Dimofte, Gaiotto (2012)

Conclusion

Higgs boson mass = 125 GeV $\Longrightarrow$ **Scalar top mass > 10 TeV**

The muon g-2 anomaly $\Longrightarrow$ **Scalar muon mass < 1 TeV**

The suppression of FCNC $\Longrightarrow$ **Scalar mass degeneracy in 1st and 2nd generations**

Scalar masses in 1st and 2nd generations << scalar masses in 3d generation

The scalar quarks and leptons in the 1st and 2nd generations may be pseud Nambu-Goldstone bosons

Buchmuller, Love, Peccei, Yanagida in Munich (1982)

m(squarks) , m(gluino) = 1.5-3 TeV !!!

will be discovered at LHC soon

E_7/SO(10)xU(1)xU(1) has two 16 + 10 as NG multiplets

One of U(1)'s has QCD anomaly and must be broken spontaneously in supergravity:
It can be identified with Peccei-Quinn symmetry

The E_7 can be realized as an enhanced symmetry on an infrared fixed point of a strongly interacting SU(2) gauge theory !!!

Dimofte, Gaiotto (2012)

Our world may be very close to Super-Conformal Theory !!!