33 Jahre danach …. in Muenchen

Tsutomu Yanagida

Herzlichen Glueckwunsch zum Geburtstag, lieber Wilfried !!

DESY July 9, 2015

I met Wilfried in Autumn in 1981

That is the time Roberto had started to construct a new particle-physics theory group at Max-Planck Institute in Munich
Both of us were chosen as Post Docs and joined Roberto's group at MPI

That was the first time for me to go outside of Japan
and hence I knew nothing about life in Europa
Wilfried spent his precious time for helping me and my family
I did not know, for example, how to buy a used car
Wilfried took me several places where selling used cars were located
and he taught me a way how to find a better car and how to buy it

We (even Roberto) were very young and very much interested in many new ideas proposed in that time

Our collaboration started !

~ 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 Quai 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

W BUCHMÜLLER, S.T. LOVE [1], R.D. PECCEI and T. YANAGIDA [2]
Max-Planck-Institut für Physik und Astrophysik
– Werner Heisenberg Institut für Physik –
Munich, Fed. Rep. Germany

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 taste 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 CMS and ATLAS 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)

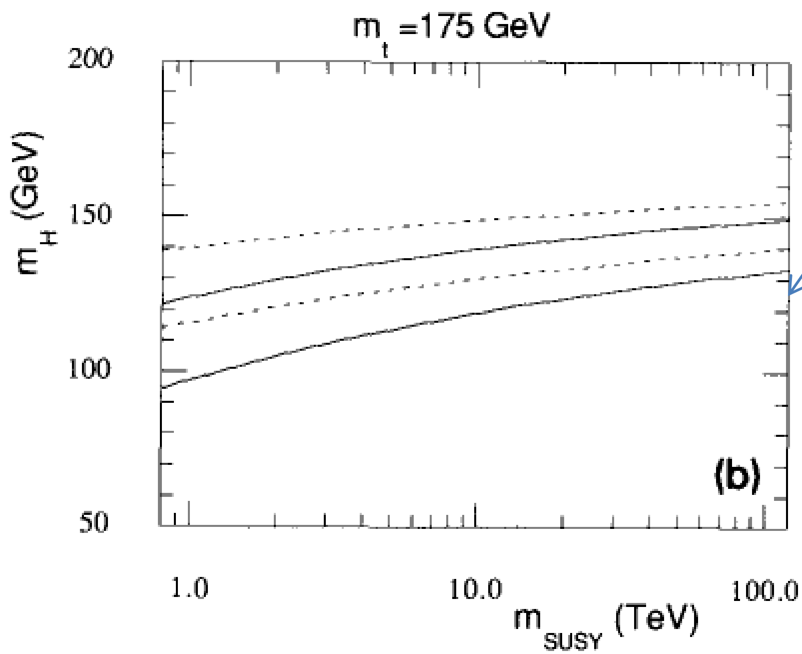
$$m_{\mathrm{H}}^2 \simeq m_{\mathrm{Z}}^2 \cos^2(2\beta) + \Delta m_{\mathrm{H}}^2$$

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

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

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

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

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

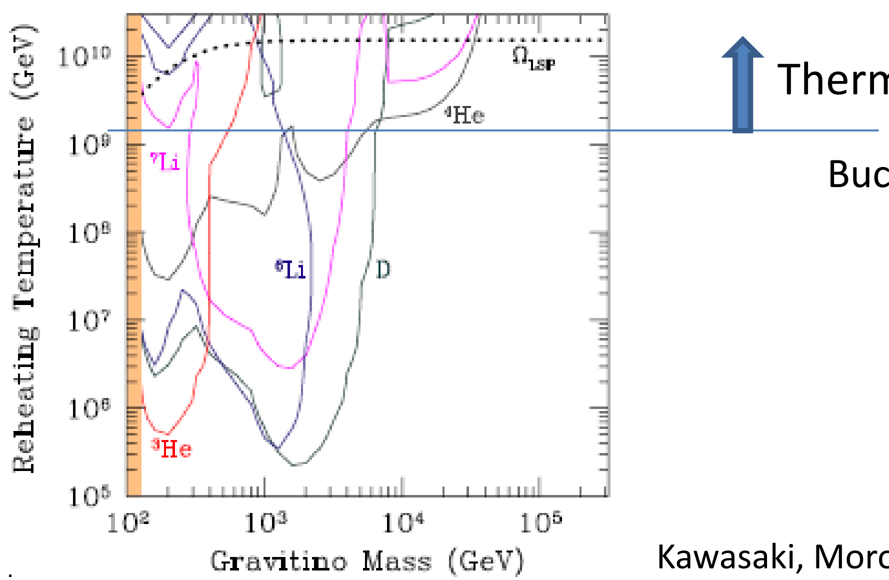
$$m_{3/2} \simeq m_{\rm SUSY} \geq O(10){\rm TeV}$$

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

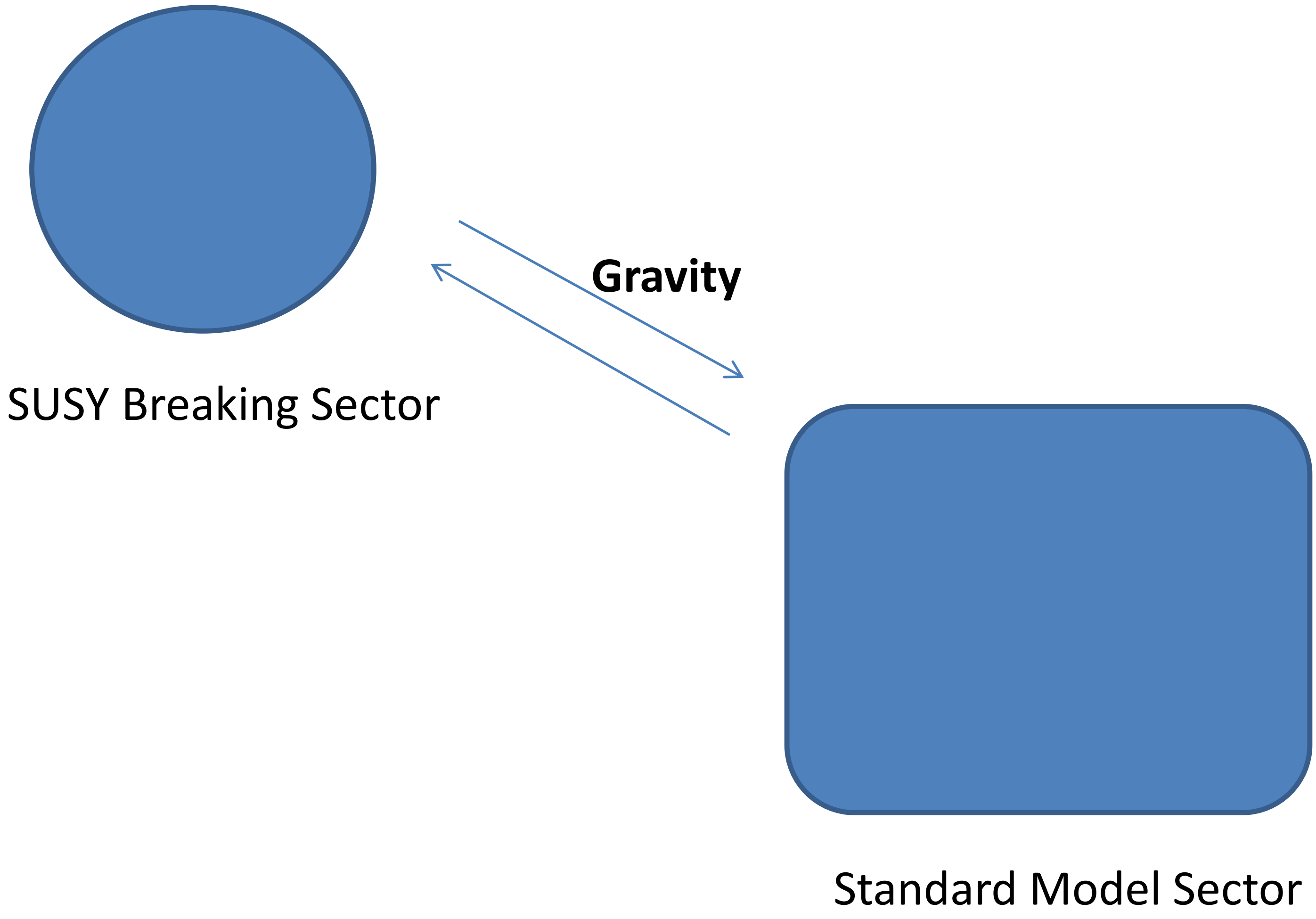
Encouraged by the LHC discovery of the Higgs boson mass about 125 GeV, we proposed a New Theoretical Scheme of the SUSY breaking mediation

Pure Gravity Mediation

Ibe, Yanagida (2011)
N. Arkani-Hamed (2011)

Pure Gravity Mediation

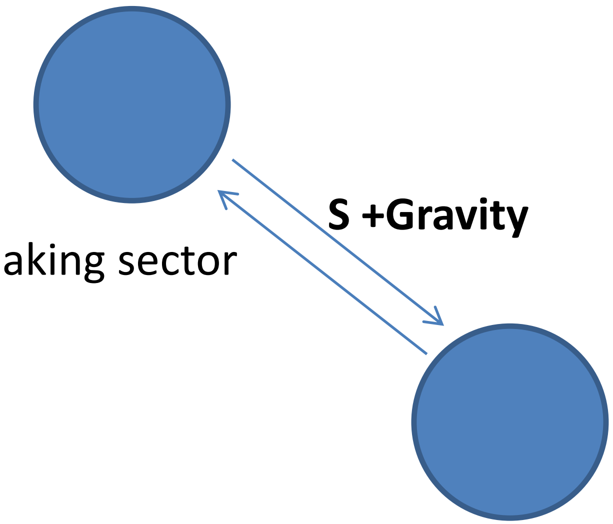
Ibe, Moroi, Yanagida (2007)



Minimal Gravity Mediation:

The minimal gravity mediation of SUSY breaking assumes
a Polonyi field S to generate masses for gauginos and Higgsino

The S has a SUSY-breaking F term;



$$m_{\text{gaugino}} \simeq \frac{F_S}{M_{\text{Planck}}} \qquad m_{\text{Higgsino}} \simeq \frac{F_S^\dagger}{M_{\text{Planck}}}$$

Giudice, Masiero (1988)

We considered, for long time, that the Polonyi field S
is needed for constructing a realistic world

Two important theoretical facts were observed in the 90th

I. The gaugino masses can be generated by quantum corrections without the Polonyi field in supergravity

H. Murayama et al (1998)
Randall, Sundrum (1999)

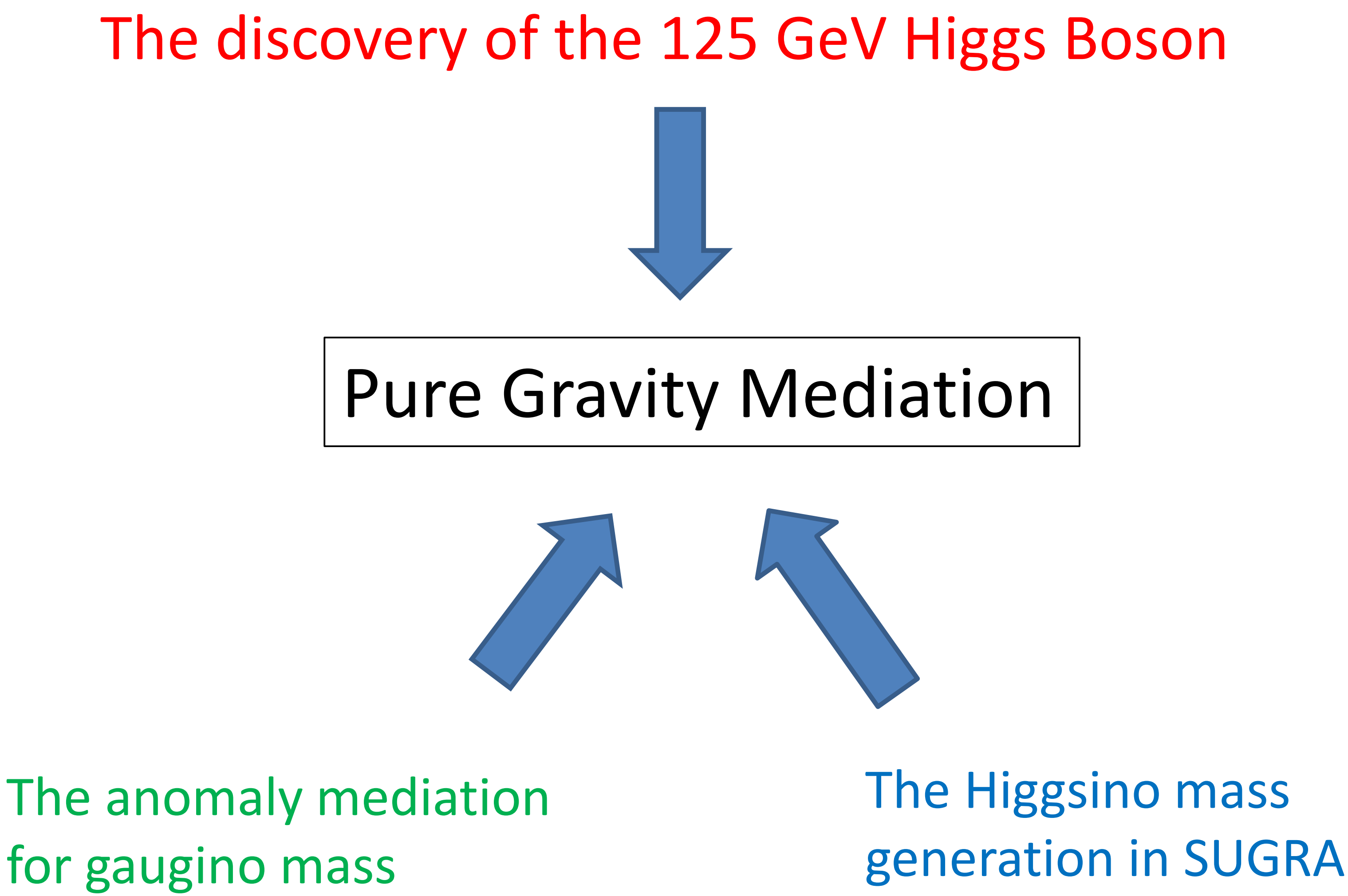
Anomaly mediation:

$$
\begin{aligned}
m_{\rm bino} &\simeq 10^{-2} m_{3/2} ,\\
m_{\rm wino} &\simeq 3 \times 10^{-3} m_{3/2} ,\\
m_{\rm gluino} &\simeq (2-3) \times 10^{-2}\, m_{3/2} .
\end{aligned}
$$

II. The Higgsino mass can be generated by the supergravity effects without the Polonyi field at the classical level

Inoue, Kawasaki, Yamaguchi, Yanagida (1992)

$$m_{\rm Higgsino} = \mu \simeq m_{3/2}$$


The discovery of the 125 GeV Higgs Boson
Pure Gravity Mediation
The anomaly mediation
for gaugino mass
The Higgsino mass
generation in SUGRA

- Higgsino loops give additional non negligible contributions to the wino and bino masses if $\mu \simeq m_{3/2}$

H. Murayama et al (1998)
T. Gherghetta et al (1999)
M. Ibe et al (2007)

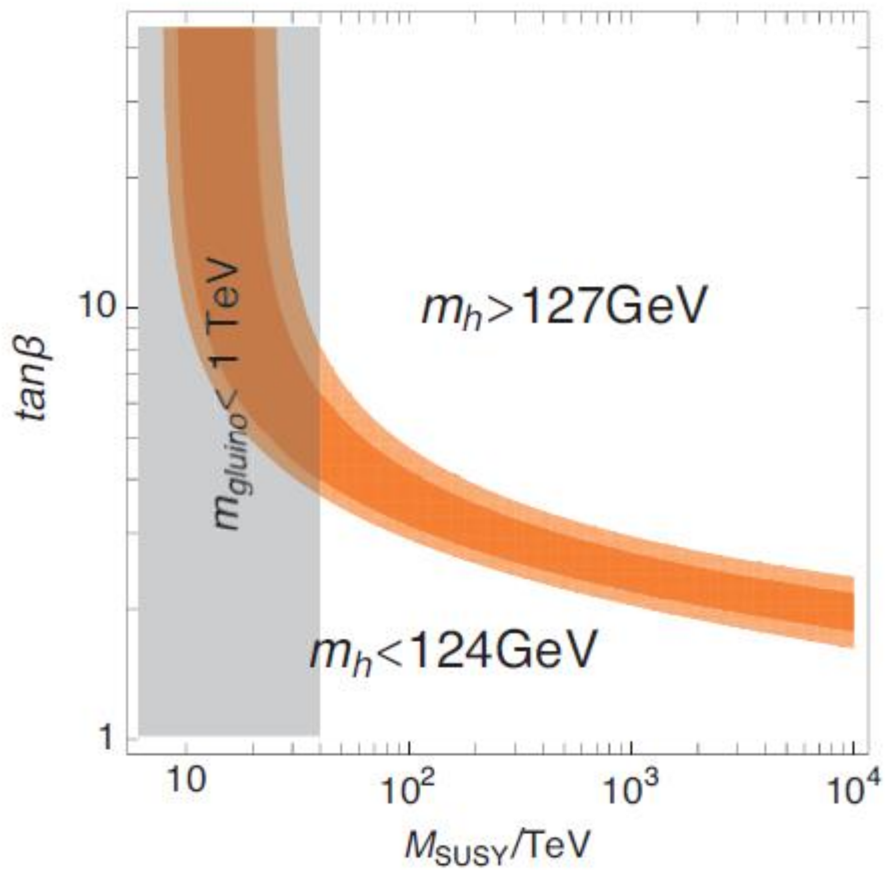
$$
\begin{aligned}
M_1 &= \frac{33}{5}\frac{g_1^2}{16\pi^2}\left(m_{3/2} + \frac{1}{11}L\right) , \\
M_2 &= \frac{g_2^2}{16\pi^2}\left(m_{3/2} + L\right) , \\
M_3 &= -3\frac{g_3^2}{16\pi^2}m_{3/2} .
\end{aligned}
$$

$$L \simeq O(1) \quad \text{for} \quad \mu \simeq m_{3/2}$$

- $\tan\beta \simeq O(1)$ for $\mu \simeq m_{3/2}$

The Higgs mass about 125 GeV can be explained for small

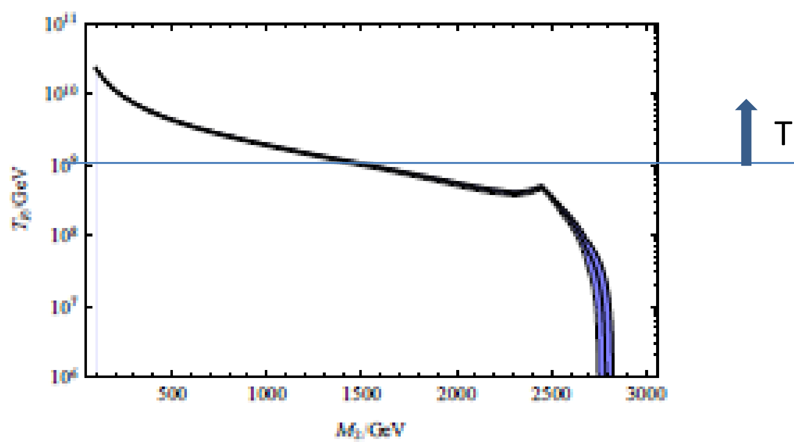
$\tan\beta \simeq O(1)$



m_higgs =125 GeV → m_3/2 = 100-1000 TeV

Wino is the LSP and the mass M_wino =O(1) TeV

The thermal relic Wino DM requires M_wino = 2.8 TeV !!



Buchmuller, Plumacher (1997)

Figure 3: *The required reheating temperature of universe as a function of the wino mass for the consistent dark matter density. We have used the thermal relic density given in Refs. [14, 15]. The color bands correspond to the 1σ error of the observed dark matter density, $\Omega h^2 = 0.1126 \pm 0.0036$ [29]. For a detailed discussion see also Ref. [10].*

Summary

	Standard Model	Pure Gravity Mediation
125 GeV Higgs Boson	▲	☺
Polonyi Problem	☺	☺
Gravitino Problem	☺	☺
FCNC /CP Problem	☺	☺
Dark Matter	✗	☺
GUT Unification	✗	☺
Fine Tuning Problem	✗ ✗ ✗ ✗ ✗	✗

Pure Gravity Mediation is a very simple and consistent model !!

m(squraks; sleptons; higgsino) =O(100-1000) TeV

m(wino) =O(1) TeV ; m(gluino)=3-30 TeV

BUT

A PROBLEM !!!

The Muon g-2

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

Bennett et al (2004)

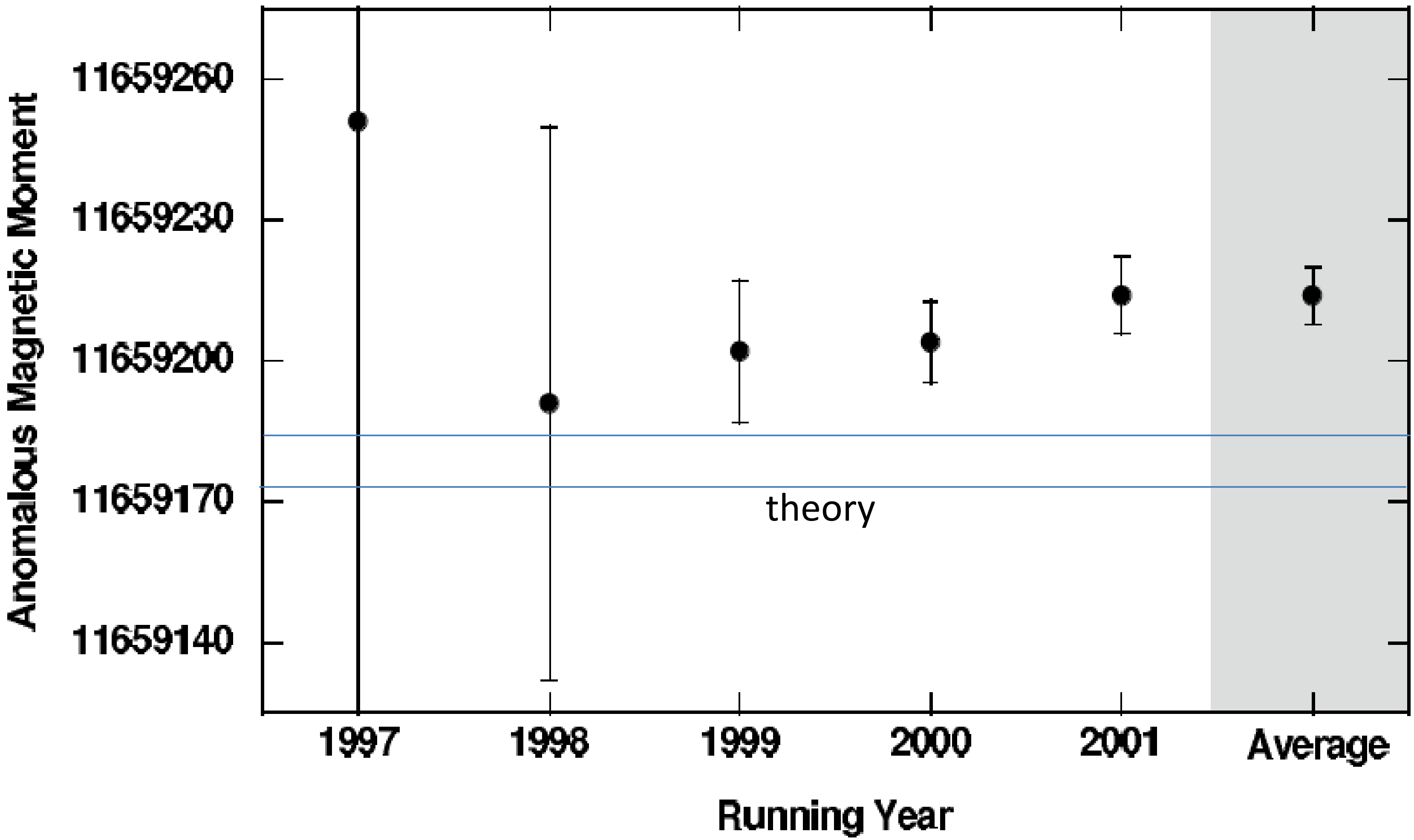
a(muon)_theor = 11659 1785 (61) x10^{-11}

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

Dominant uncertainty comes from **hadron light by light contributions**

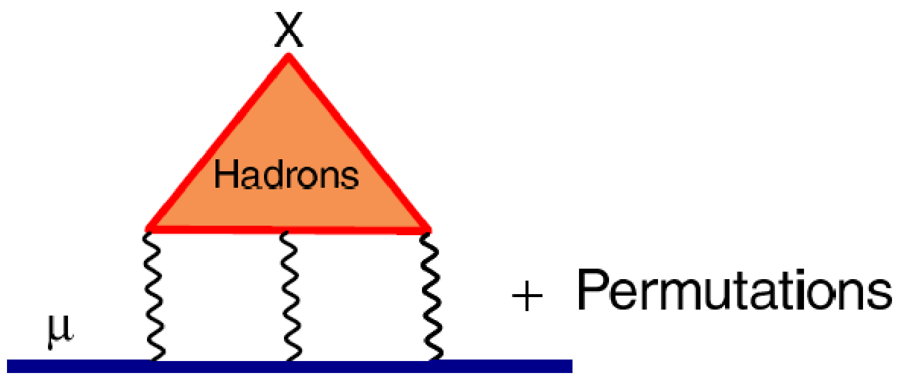


Figure 52. Hadronic Light-by-Light Contributions

The leading terms are given by the pion reducible diagrams

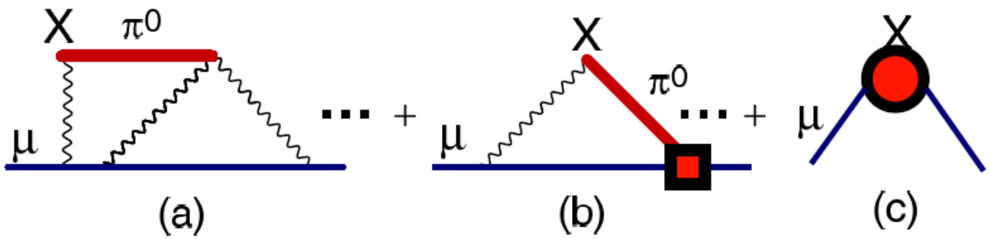


Figure 53. One Goldstone Reducible Diagrams in Chiral Perturbation Theory

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

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

We need comparable contributions from 1 GeV scale physics
But they are suppressed as (m(pion)/1 GeV)^2 =O(0.01) !!!

Main Message

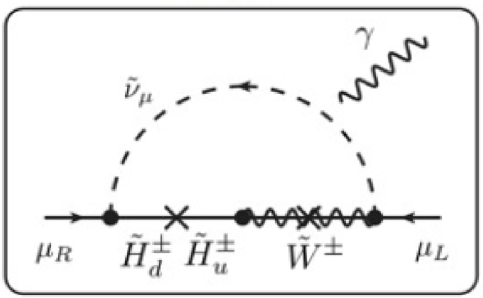
muon g-2

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

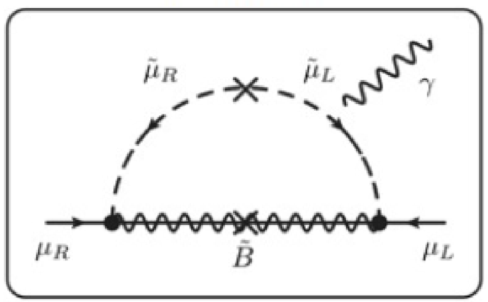
> 3σ deviation !

low scale (<TeV) SUSY で説明出来る！

chargino



neutralino



TeV 以下の
chargino/neutralino
and smuon が必要

Talk by Hamaguchi

→ **smuon mass < 1 TeV !**

Pure Gravity Mediation predicts the smuon mass =O(100) 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 1^{st} and 2^{nd} 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

$$\mathbf{78} = \mathbf{45} + \mathbf{16} + \mathbf{16}^* + 1. \qquad (11)$$

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)xU(1) ; One 16

E_7/SO(10)xU(1)xU(1); Two 16's + 10

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 << 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)

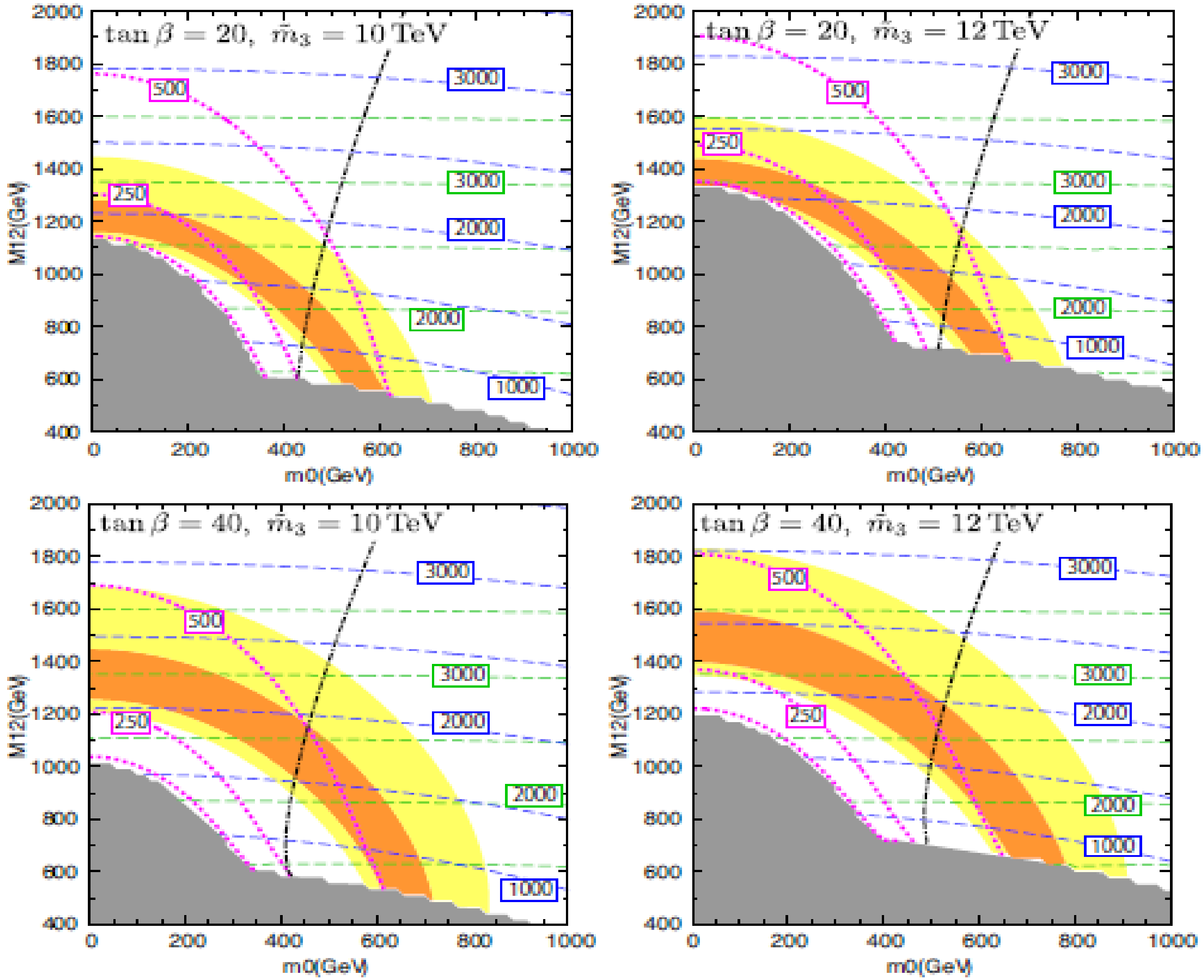


Figure 1: *Contours of δa_μ, the squark mass, the gluino mass, and the lightest slepton mass (the masses are shown in the unit of GeV) on $m_0 - M_{1/2}$ plane. The blue (green) dash-lines correspond to the squark (gluino) masses. The magenta dotted lines show the contours of the lightest slepton masses (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	$400\,\mathrm{GeV}, 10\,\mathrm{TeV}$	m_0, m_3	$600\,\mathrm{GeV}, 12\,\mathrm{TeV}$
$M_{1/2}$	1000 GeV	$M_{1/2}$	1100 GeV
$\tan\beta$	20	$\tan\beta$	40
μ	7.7 TeV	μ	9.1 TeV
m_{stop}	8.5 TeV	m_{stop}	10 TeV
δa_μ	2.0×10^{-9}	δa_μ	1.9×10^{-9}
m_{gluino}	2294 GeV	m_{gluino}	2512 GeV
m_{squark}	1613 GeV	m_{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 !!!

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 → **Scalar top mass > 10 TeV**

The muon g-2 anomaly → **Scalar muon mass < 1 TeV**

The suppression of FCNC → **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 !!!