Where to go next ?

--After the discovery of the Higgs boson--

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DESY (2016)

- We have many particles;

(5* + 10 +1)x3 + Higgs + Gauge Fields

48 quarks/leptons

Why do we have so many particles ?

1. String theories -→ many many fields

   But, we can not explains why we have three families of quarks and leptons

2. Composite quarks and leptons

It is however very difficult to have massless composite fermions.

But, we have massless composite bosons which are Nambu-Goldstone bosons.

Then, if we have SUSY the NG bosons have fermion partners which are nothing but massless composite fermions.

We may identify those with quarks/ leptons

Buchmuller, Peccei, Love , Yanagida (1982)

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)

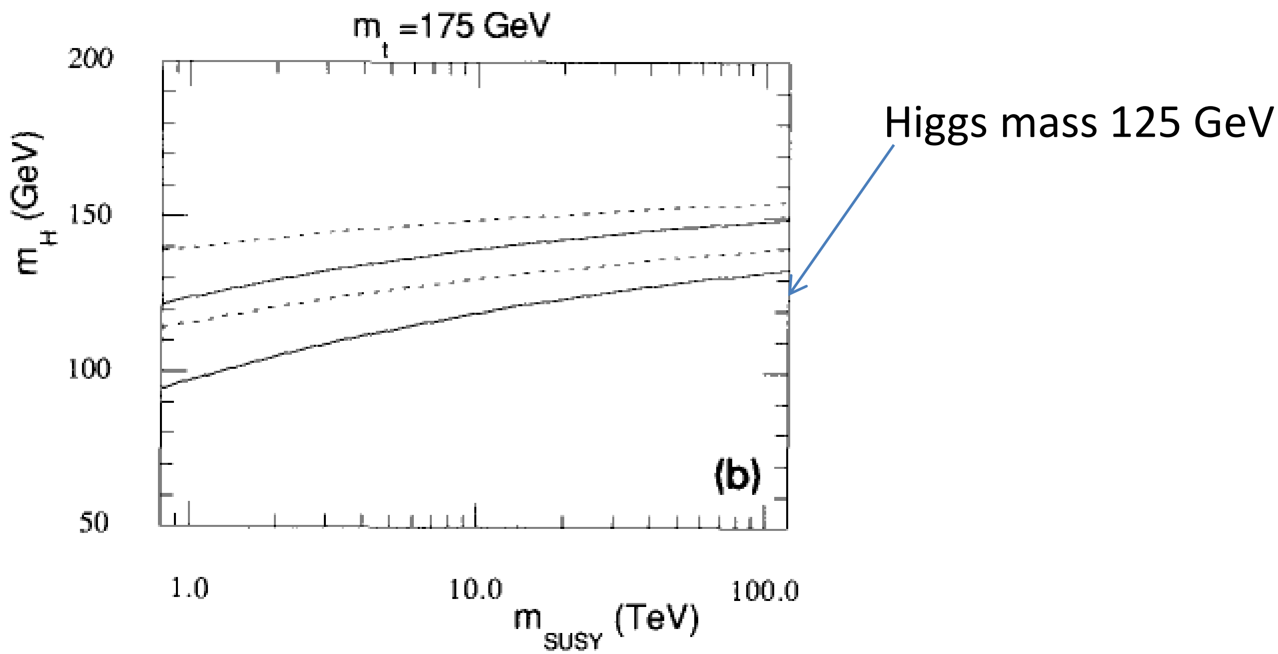
$$m_{\mathrm{H}}^2 \simeq m_{\mathrm{Z}}^2 \cos^2(2\beta) + \Delta m_{\mathrm{H}}^2$$

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

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

mass of scalar top quark

Our prediction of Higgs mass :



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

SUSY GUT

- Gauge coupling unification

- m_higgs =125 GeV → High Scale SUSY

(m_3/2 =100 TeV)

Consistent with non discovery of SUSY particles at LHC !!!

Pure Gravity Mediation

Ibe, Moroi and Yanagida (2006)
Ibe and Yanagida (2011)

- No cosmological gravitino problem

  $m_{3/2} = O(100)$ TeV → the gravitinos decay before BBN

- No cosmological Polonyi problem

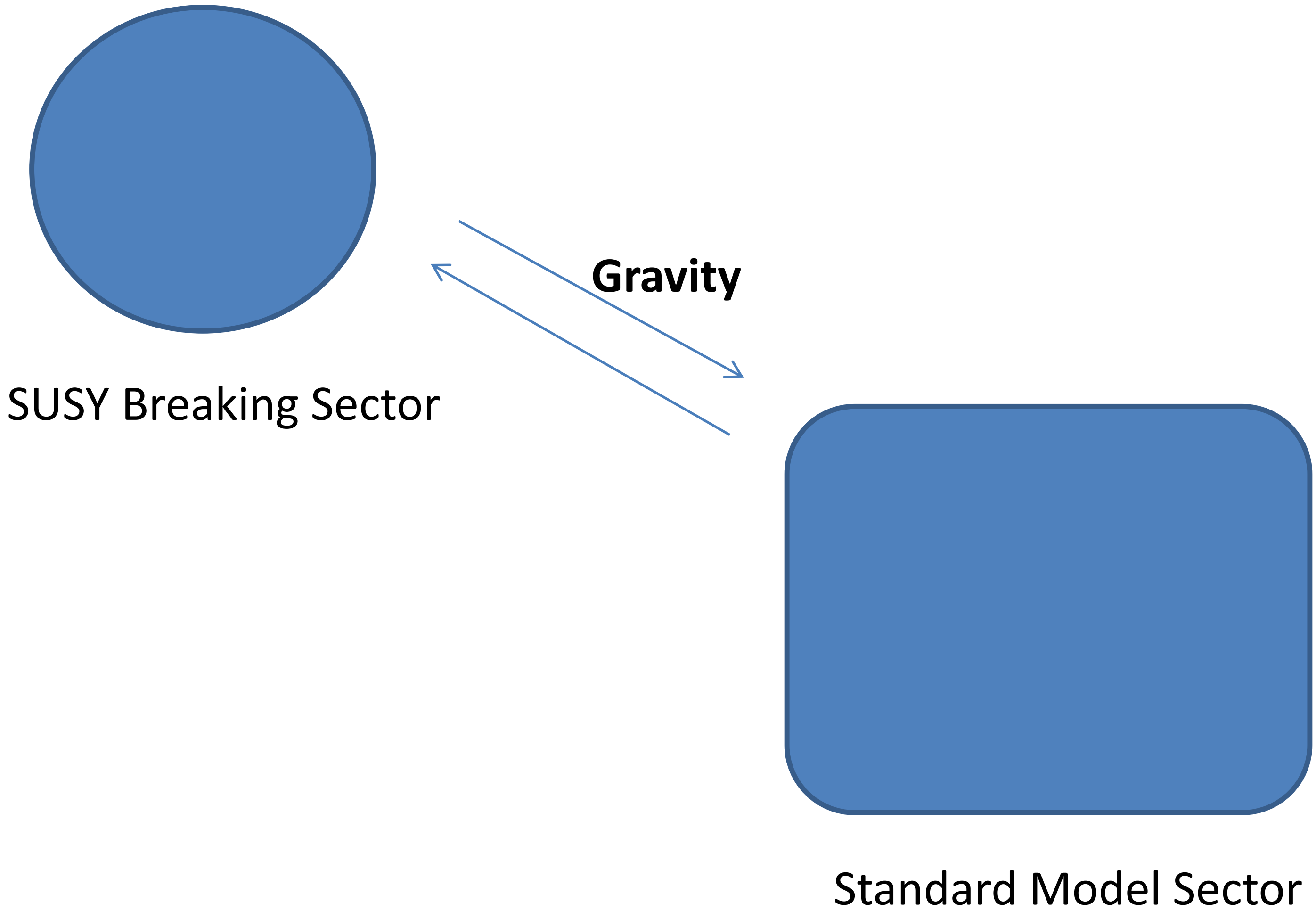
We do not need the Polonyi field to give the gaugino masses, since they get masses through the anomaly mediation

$$m_{1/2} = (e^2) m_{3/2} = O(1) \text{ TeV}$$

- No FCNC problem

Pure Gravity Mediation

Ibe, Moroi, Yanagida (2007)



Wino is the DM of mass O(1) TeV

Indirect detection of the wino annihilation
in cosmic ray experiments will be the next step

Where to go in particle-physics theory ?

Family Problem

- Why the quarks/leptons are **5*** + **10** of SU(5) ?
- Why we have three families ?
- What determines their Yukawa couplings ?

Quasi Nambu-Goldstone Fermions

Buchmuller, Love, Peccei and Yanagida (1982)

- NG bosons are always accompanied by massless fermions in supersymmetric non-linear sigma model
- Properties and number of NG bosons are determined by a given G/H
- We identify the quasi NG fermions with the observed quarks and leptons

- NG chiral multiplets are given by G/H and hence for a given G/H we can determine properties and number of quasi NG fermions , that is, quarks and leptons

We can answer to one of the most fundamental questions in particle physics;

Why do we have three families ?

Search for G/H

- G/H must be Kahler manifold in SUSY theories
- SU(6)/SU(5)xU(1) → NG multiplet =**5***
- SO(10)/SU(5)xU(1) → NG multiplet = **10**
- E_6/SO(10)xU(1) → NG multiplet =**16** of SO(10); **16** = **5*** + **10** +**1** (one family)
- Exceptional groups are very interesting to have family structure !

- E_7/SU(5)xU(1)^3→

NG multiplets = 3x(**5***+**10**+**1**) + **5**

Three families, Kugo and Yanagida (1983)

E_8/SU(5)xU(1)^4 →

NG multiplets = 4x(**5***+**10**+**1**) + 1x(**5**+**10***+**1**) +…

Three families !

We concluded the maximal number of families is 3 !!!

(E_8 is the maximal exceptional group)

SUSY Non-Linear Sigma Model

- G/H must be a Kahler (complex) manifold

⇓

Nambu-Gldstone multiplets are Chiral

The simplest example is CP^(1) =SU(2)/U(1)

The NG multiplet is phi(+1)

We do not have phi(-1)

SU(2) generators: T, X^+, X^-

[T,X^+] = X^+, [T,X^-]=-X^-, [x^+,X^-] =2T

One NG chiral multiplet ; phi(+1)

[T,phi]=+phi, [X^+, phi]= phixphi, [X^-,phi]=1

SU(2) invariant Kahler potential ;

K= log(1+ phixphi*)

*K → K + phi + phi**

Integration of ¥theta gives invariance !

BUT

There is a problem to couple to supergravity,

since K→ K +F(phi) + F*(phi*)

Witten and Bagger (1992)

We can solve this problem by introducing a singlets Z and the invariant Kahler potential is K=G(K+Z+Z*)

Z--→ -F(phi)

E_7 has 133 generators;

T^i_j (**63**) +E_{ijkl} (**70**) of **SU(8)**

Consider the Kahler manifold E_7/ SU(5)xSU(3)xU(1)

The broken generators are

T^a_i (**5*,3**); E_{ab}{ij} (**10, 3***); E_{ijkl} (**5,1**) and their conjugates

NG multiplets are

phi(**5*, 3**, +2) + phi(**10, 3***, +1) + phi(**5,1**,+3)

We should add a **X(5*,1)** multiplet to cancel non-linear sigma model anomalies

We have massless three families of quarks and leptons !!!

Mass hierarchy

Explicit breaking of E_7 gives Yukawa couplings;

Suppose $E_7 \rightarrow E_6 \rightarrow E_5$ (SO(10) $\rightarrow E_4$(SU(5)) explicitly

We obtain the mass hierarchy as

$m_t : m_c : m_u = 1 : \epsilon^2 : \epsilon^4$
$m_b : m_s : m_d = 1 : \epsilon : \epsilon^3$

We have a large neutrino mixing !

Is the NG hypothesis consistent ?

Why E_7 ?

Is the NG hypothesis consistent ?

- The squarks and sleptons are all massless at the GUT scale
- The Higgs multiplets are NOT NG multiplets and they have soft SUSY breaking masses of the order of $m_{3/2} \sim 100$ TeV
- Higgs loop diagrams give negative soft masses^2 for squarks and sleptons (tachyonic)
- ***Our vacuum is no longer stable !!***

If the soft SUSY breaking masses^2 of Higgs bosons are negative, the masses^2 of squarks and sleptons are positive !!!

Yin, Yokozaki (2016)

Higgs bosons have positive masses^2

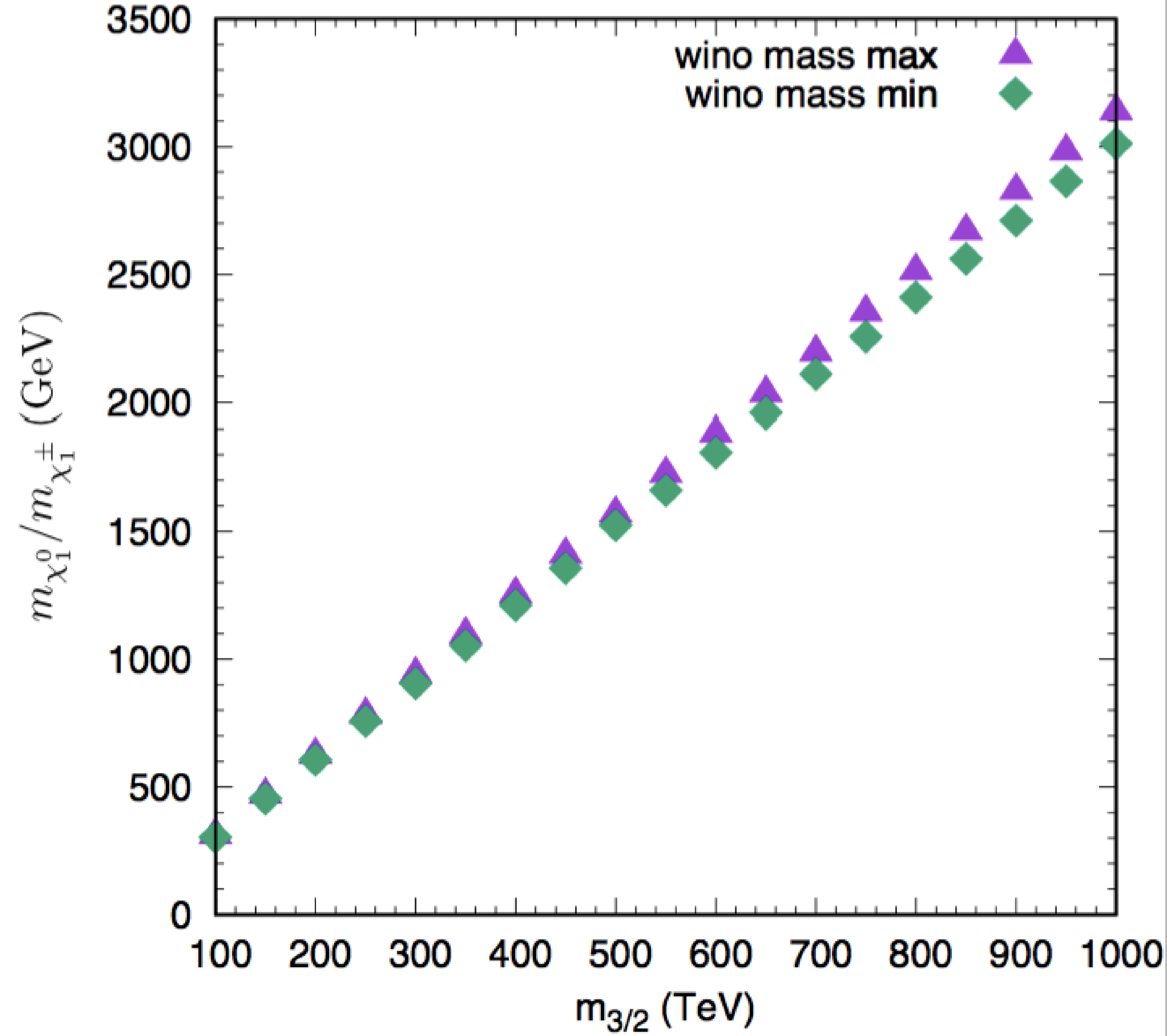
=|¥mu|^2 +m^2(soft) >0

Our Vacuum is Stable !!!

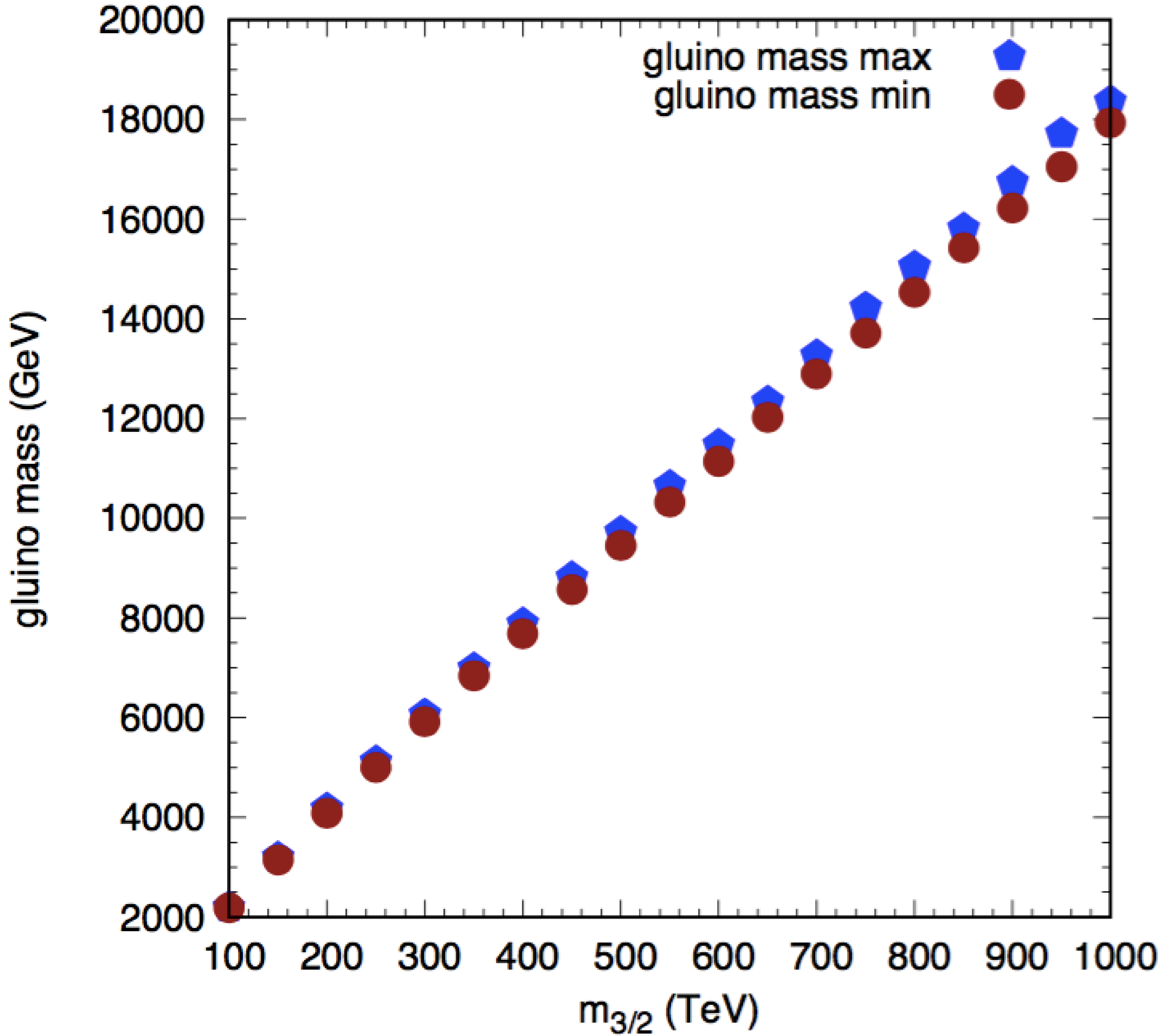
Stop mass = O(10) TeV explaining the Higgs boson mass =125 GeV

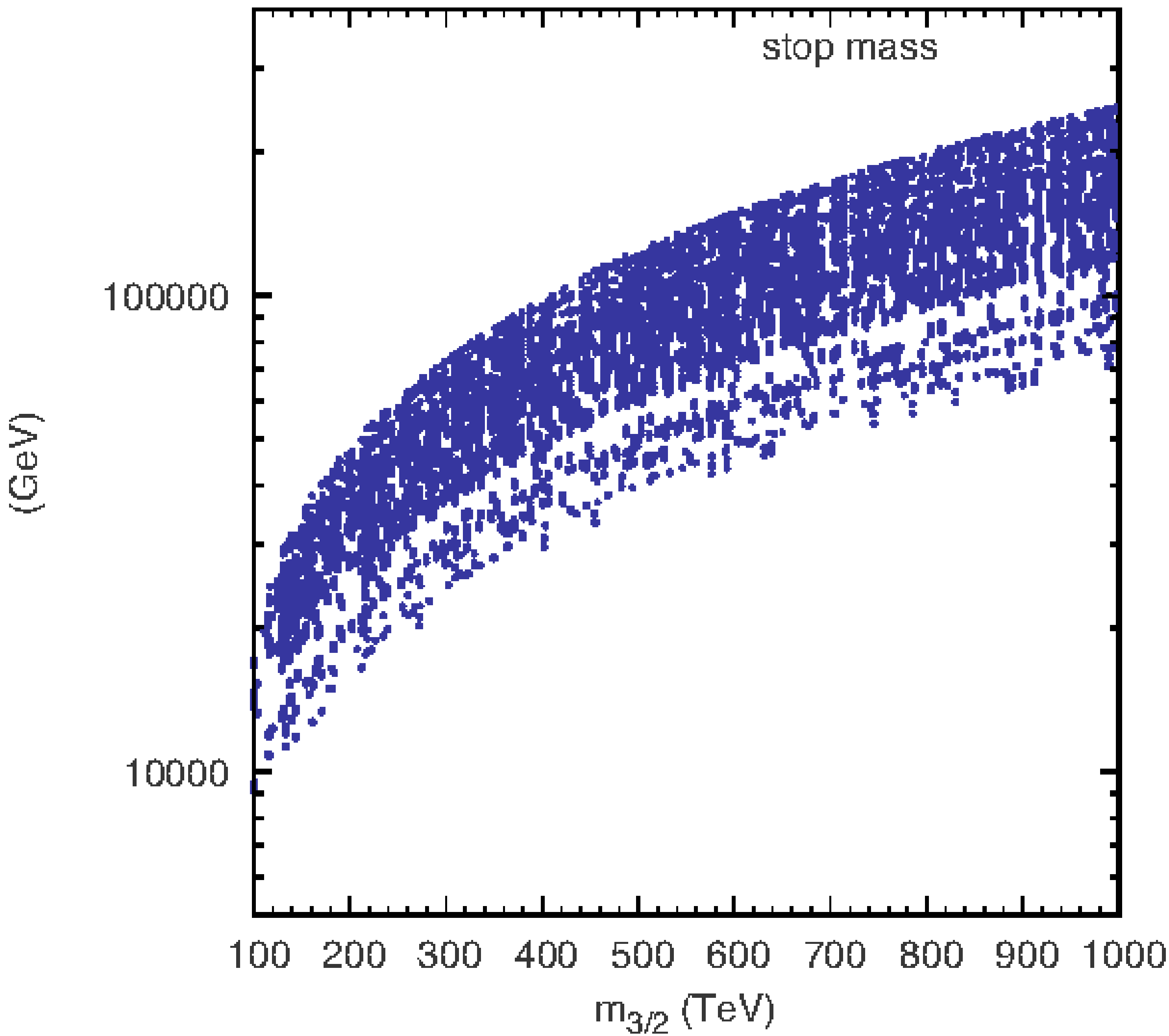
Squark (u,d,s,c) and slepton masses = O(1) TeV, since their Yukawa couplings are small

There is a parameter region where we can explain the muon g-2 anomaly

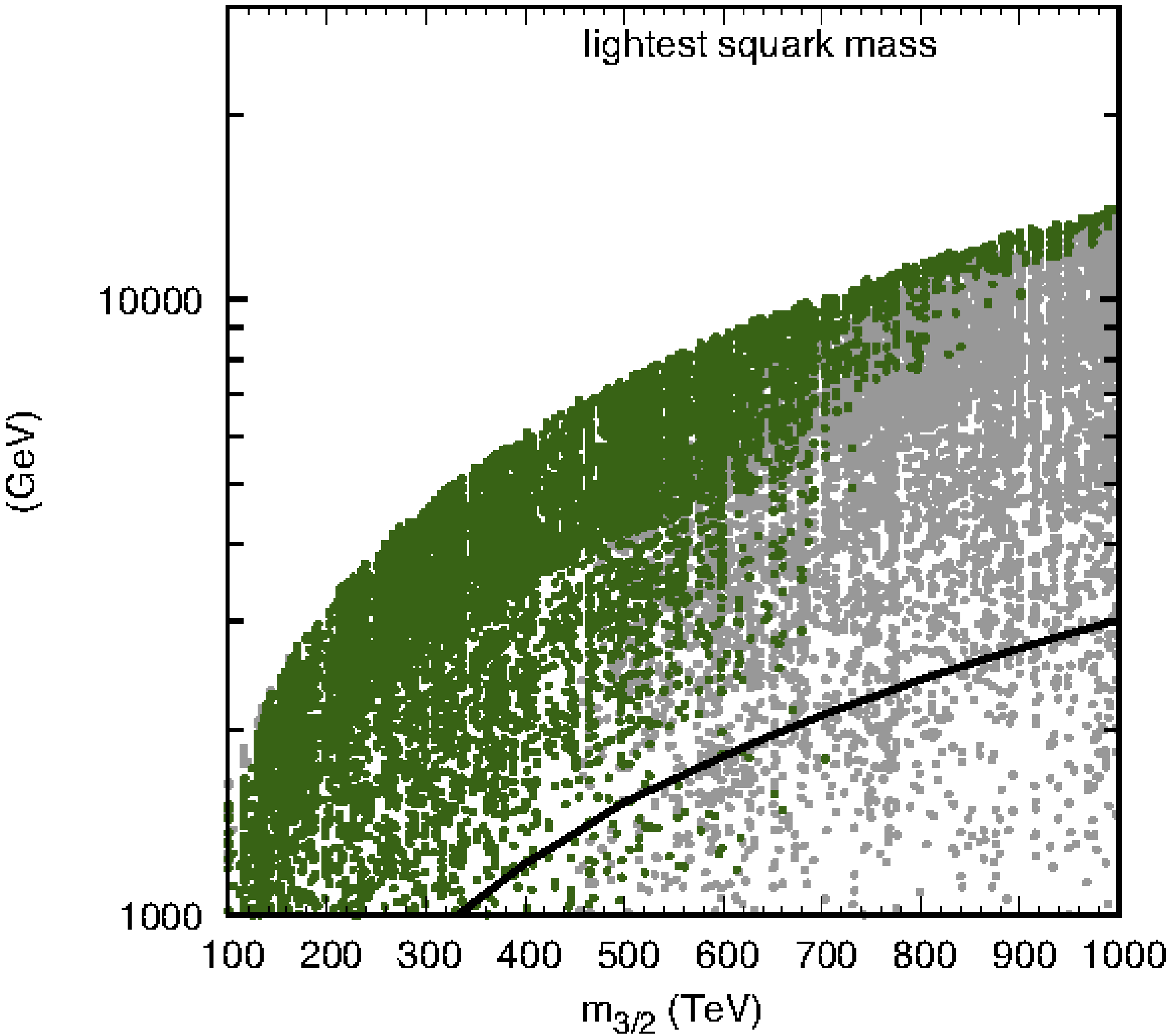


3500
3000
2500
2000
1500
1000
500
0
100
200
300
400
500
600
700
800
900
1000
wino mass max
wino mass min
$m_{\chi_1^0}/m_{\chi_1^\pm}$ (GeV)
$m_{3/2}$ (TeV)

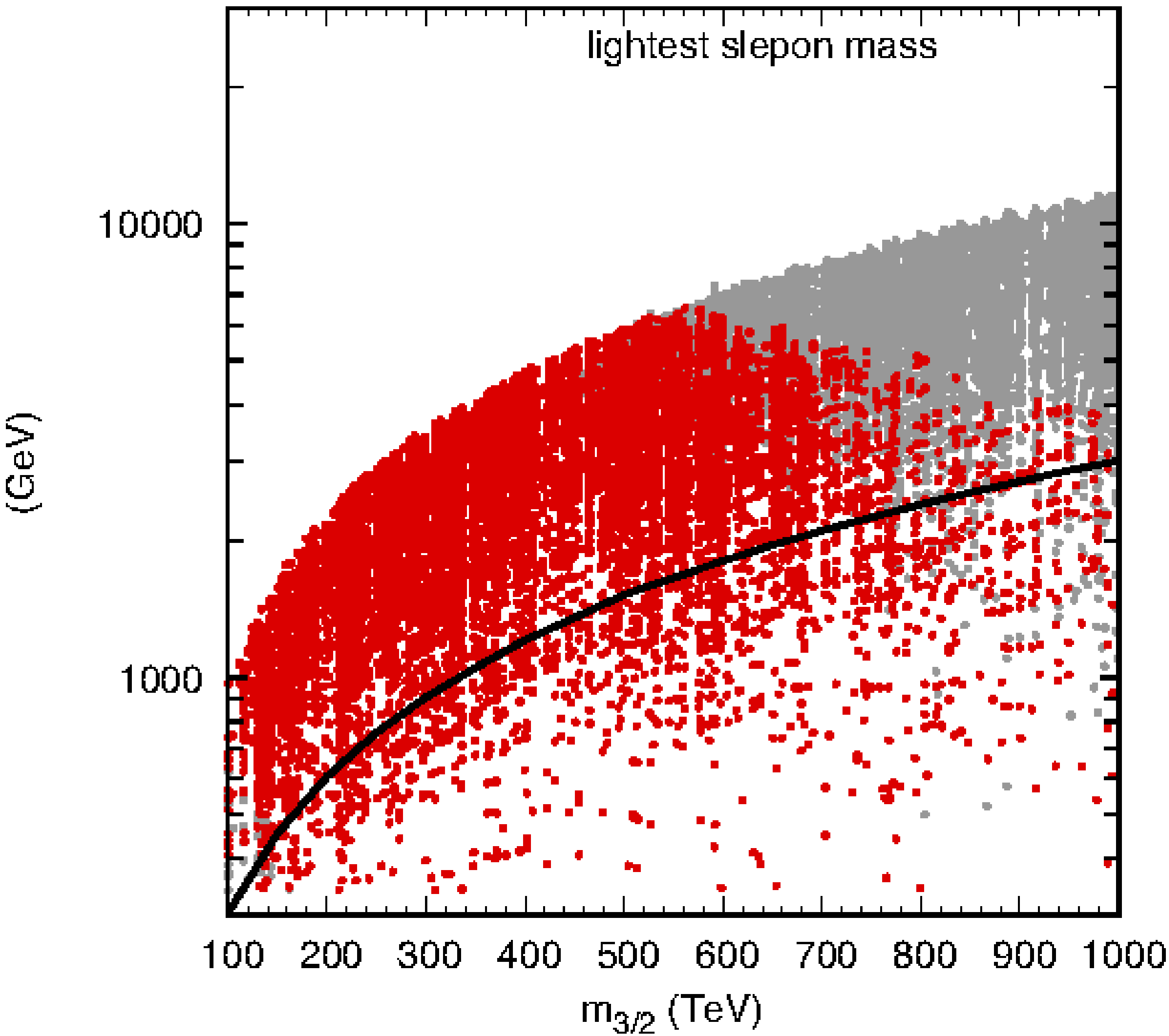

gluino mass max
gluino mass min
gluino mass (GeV)
$m_{3/2}$ (TeV)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
100
200
300
400
500
600
700
800
900
1000



stop mass
(GeV)
100000
10000
100
200
300
400
500
600
700
800
900
1000
$m_{3/2}$ (TeV)



lightest squark mass
(GeV)
10000
1000
100
200
300
400
500
600
700
800
900
1000
$m_{3/2}$ (TeV)


lightest slepon mass
10000
1000
(GeV)
100
200
300
400
500
600
700
800
900
1000
$m_{3/2}$ (TeV)

The Nambu-Goldstone hypothesis for squarks and sleptons is consistent with all observations so far

Yanagida, Yin, Yokozaki (2016)

Why Does Nature Choose 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

Assume [SU(2)x 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
and eight SU(2)'-doublet preons Q'^j_b ; J=1-8 and b=1,2

Here we have a global SU(8) x SU(8)'

Consider Mesons; M^{ij} = Q^iQ^j and M'_{ij} =Q'_iQ'_j
and superpotential W=M^{ij}M'_{ij}

We have a global SU(8)

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

Seiberg (1996)

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

Dimofte, Gaiotto (2012)

This may be the origin of our E_7

8 fundamental preons Q and {¥bar Q}

The theory has an IR fixed point, on which we have an enhanced symmetry E_7

Quarks and Leptons can be identified with massless quasi-NG fermions, which are bound states of the preons

The presence of SU(8) may be a crucial in N=8 Supergravity

conclusion

- The higgs mass 125 GeV suggests high scale SUSY…….. m_3/2=100-300 TeV, m_sq=O(100) TeV and m_gluino=2-6 TeV
- But, NG hypothesis for squarks and sleptons still survive from all experimental data
- This suggests that m_sq in the 1^{st} and 2d generations = 1-4 TeV and m_gluino=2-6 TeV which may be tested in future LHC