Naturalness: Why Supersymmetry? Physics Beyond the Standard Model

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Introduction

All the elementary particles that were known to exist in Nature till recently were only spin half fermions and spin one gauge particles.

Discovered in 2012 at the LHC, Higgs is the first elementary spin zero particle that has been discovered.

An elementary scalar field, such as the Higgs field, introduces a completely new feature in quantum field theories containing such a field.

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This decoupling requirement is a reasonable expectation so that whatever low mass scale quantum theory we have can describe the physics at that scale reliably.

Another name for this requirement is *Naturalness Principle.*

A qft containing *only spin half fermions and gauge fields* exhibits precisely this decoupling. Such theories are called *Natural theories and the masses and the gauge couplings are Natural parameters*.

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Naturalness

Examples of Natural theories are QED and QCD.

The notion of Naturalness emerged in the late 1970's from the work of Wilson, Gildener and Weinberg, and 't Hooft.

A concise formulation:

't Hooft's Doctrine of Naturalness (1979-80): *A parameter $\alpha(\mu)$ at any energy scale μ in the description of physical reality can be small, if and only if, there is an enhanced symmetry in the limit $\alpha(\mu) \to 0$.*

This implies a rule of thumb:

Quantum corrections to a parameter α (mass or and coupling) should be proportional to a positive power of that parameter itself:

$$(\Delta\alpha)_{quantum} \sim \alpha^n, \quad n \geq 1.$$

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$$\mathcal{L}_{QED} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\lambda}\left[i\gamma^{\mu}\left(\partial_{\mu} - ieq_f A_{\mu}\right) - m_e\right]\lambda$$

Various parameters here, the em coupling e, electron mass m_e, can be naturally small.

$m_e \to 0$ leads to chiral sym: separate conservation of the number of left and right handed electrons. $(\Delta m_e^2)_{1\ loop} \sim e^2\ m_e^2 \ln\Lambda$

$e \to 0$ also results in enhanced symmetry: no interaction; particle number of each type is conserved. $(\Delta e)_{1\ loop} \sim e^3\ \ln\Lambda$.

It is for this reason that atomic physics described by the interactions of electrons and photons is not disturbed by the fact there are other heavier charged fermions in Nature: $m_\mu \sim 200\ m_e$, $m_\tau \sim 3500\ m_e$, ...
$m_{top} \sim 3.4 \times 10^{11}\ m_e$. Effects of heavier fermions are decoupled.

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Naturalness and scalar fields

Elementary scalar fields spoil heavy-light decoupling: *QFTs with scalar fields are not natural*.

$$\mathcal{L} = \frac{1}{2}\,\partial^\mu\phi\,\partial_\mu\phi - \frac{1}{2}\,m_L^2\phi^2 + \bar{\lambda}\,(i\gamma^\mu\partial_\mu - m_H)\,\lambda + y\bar{\lambda}\lambda\phi\,; \quad m_H \gg m_L$$

Scalar mass m_L is not a natural parameter.

Smallness of m_L can not be protected by any approx symmetry against perturbative quantum corrections involving heavy fermions in the loops.

In fact, such corrections to m_L^2 appear with quadratic divergences and *are not proportional to m_L^2:*

$$\Delta m_L^2 \sim -y^2\int d^4k\,\frac{k^2+m_H^2}{(k^2-m_H^2+i\epsilon)^2} \sim -y^2 m_H^2 \ln\left(m_H^2/\mu^2\right)$$

(by dimensional regularization and minimal subtraction)

No decoupling of the heavy mass scale . *Notice that even in the limit $m_L \to 0$, this correction does not go away*.

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Naturalness of Electro-weak theory

SM has an elementary scalar particle, the Higgs particle: *its mass is not protected by any quantum symmetry against large radiative corrections.*

Tree level masses in SM: $m_{Higgs} = \sqrt{\lambda} v, \quad m_W = \frac{gv}{2},$
$$m_Z = \frac{gv}{2\cos\theta_W}, \quad m_f = \frac{Y_f \; v}{\sqrt{2}}.$$

Notice, the limit $v \to 0$ does enhance *classical* symmetry: (i) scale invariance of the classical theory, (ii) weak gauge bosons are massless: restored $SU(2)$ gauge symmetry, and (iii) chiral symmetry due to zero masses of the fermions.

Yet, v is not a natural parameter; consequently, masses of the Higgs particle, weak gauge bosons and fermions are not natural.

This is so, because of the Coleman-Weinberg mechanism of radiative breaking of symmetry: Quantum fluctuations generate a non-zero quantum v.e.v. for the scalar field even when classically v is zero, breaking all these symmetries.

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Tree level masses in SM: $m_{Higgs} = \sqrt{\lambda} v, \quad m_W = \frac{gv}{2},$
$$m_Z = \frac{gv}{2\cos\theta_W}, \quad m_f = \frac{Y_f \ v}{\sqrt{2}}.$$

Notice, the limit $v \to 0$ does enhance *classical* symmetry:
(i) scale invariance of the classical theory, (ii) weak gauge bosons are massless: restored $SU(2)$ gauge symmetry, and (iii) chiral symmetry due to zero masses of the fermions.

Yet, v is not a natural parameter; consequently, masses of the Higgs particle, weak gauge bosons and fermions are not natural.

This is so, because of the Coleman-Weinberg mechanism of radiative breaking of symmetry: Quantum fluctuations generate a non-zero quantum v.e.v. for the scalar field even when classically v is zero, breaking all these symmetries.

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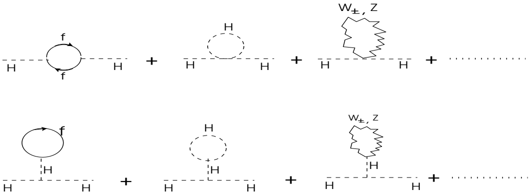

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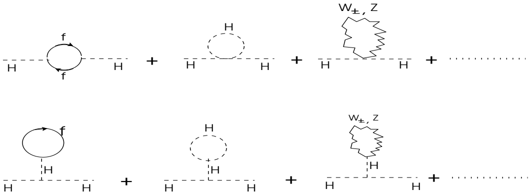

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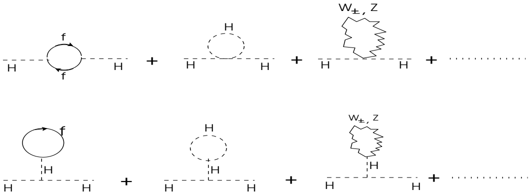

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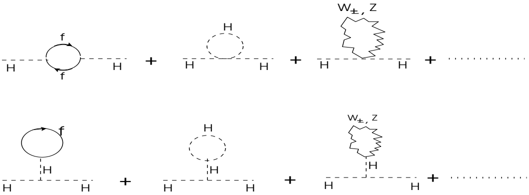

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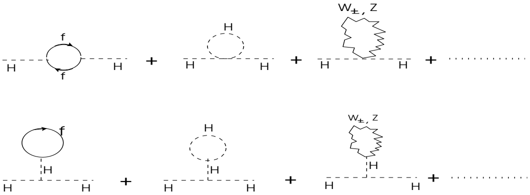

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Largest mass particle in the loops gives the dominant correction: top quark is the heaviest particle in the SM:

$$\Delta m^2_{Higgs} \sim -\alpha \, m_t^2 \, \ln(m_t^2/\mu^2).$$

Now, for top mass $m_t = 175 \ GeV$, and $\alpha \sim 1/100$, this radiative contribution is still small for $m_{Higgs} = 125 \ GeV$.

But if there were a much heavier particle in Nature, such as in a GUT (with a scale $10^{15} \ GeV$), the radiative corrections to Higgs mass would be controlled by this heavy scale and hence very large.

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Naturalness breakdown scale of the SM

One-loop correction to Higgs boson mass due to quantum fluctuations of a size characterised by the scale Λ may be written as: $\Delta m^2_{Higgs} \sim \alpha\, \Lambda^2$.

The masses of vector bosons $W^{\pm}$ and Z^0 and also fermions would obtain similar corrections.

For coupling $\alpha \sim (100)^{-1}$ and $m_{Higgs} \sim 100\ GeV$, if we require that the radiative corrections to this mass do not exceed its value, $\Delta m^2_{Higgs} \sim m^2_{Higgs}$, we have:

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Large log div corrections in GUTs

Not only are the quadratic divergent graphs with heavy mass fields going around the loops responsible for destabilizing the lower mass scale, there are also some log divergent graphs which contribute to this phenomenon.

These graphs appear generically in any GUT.

Consider a gauge theory based on a gauge group G which is spontaneously broken at two stages:

$$G \xrightarrow{F} G_1 \xrightarrow{f} G_2 \; ; \qquad F \gg f$$

This is achieved through v.e.v.'s of two scalar fields:

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Quadratically divergent graphs for the two-point correlations of light scalar fields give large corrections ($\sim F^2$) to its M_2^2 ($\sim f^2$).

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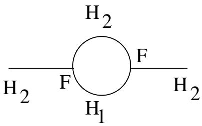

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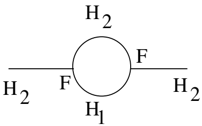

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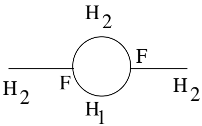

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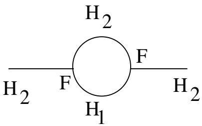
which is a large correction to the small mass from a log divergent graph.

Large log div corrections *(RKK: Phys. Letts.: vol. B109, 1982, 19)*



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$$\mathcal{L}_{int} \sim \kappa \Phi^2 \phi^2 = \kappa \left(H_1 + F\right)^2 \left(H_2 + f\right)^2$$
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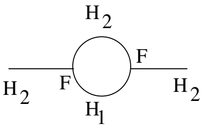

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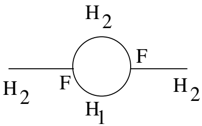

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Perturbative quantum corrections tend to draw the smaller electro-weak scale towards the GUT scale ($M_{GUT} \sim 10^{16}$ GeV).

Yet another physical mass scale $M_{Pl} = 10^{19}$ GeV in Nature associated with quantum gravity.

Radiative corrections would draw the masses of EW theory to this high scale and hence their natural values would be $\sim 10^{19}$ GeV and not the physical values characterised by the SM scale of 100 GeV!

There has to be some new physics beyond 1 TeV such that the SM with its characteristic scale of 100 GeV stays natural beyond this scale.

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Supersymmetric solution

SUSY theories with non-Abelian gauge invariances are always free of quadratic divergences.

Those with $U(1)$ gauge invariance have quad div radiative corrections $\propto$ the sum of $U(1)$ charges of all the fields.

If the $U(1)$ charges sum to zero, no quadratic divergences.

Supersymmetrized Standard Model is one such theory.

Also for theories with two widely separated scales such as a susy GUT, the large logarithmic divergences are also separately absent.

In SUSY theories with spontaneously broken gauge symmetries through non-zero VEV of elementary scalar fields, the limit VEV $\to 0$ does lead to an enhanced symmetry even at the quantum level,(provided, in presence of a $U(1)$ gauge symmetry, $\sum Q_{U(1)} = 0$).

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Simplest SUSY model: the *Minimal-Supersymmetric-Standard-Model* (MSSM) where every SM particle has a superpartner with opposite statistics:

photon $\sim$ *photino; electron* $\sim$ *selectron; quarks* $\sim$ *squarks; etc.*

Exact SUSY: all properties, except the spin, of particles in a supermultiplet are the same:
Masses are equal and so are the couplings; electroweak and colour quantum numbers are identical.

SUSY can not be an exact symmetry of Nature: $M_{part} \neq M_{spart}$.

Yet naturalness violating quad divergences should not appear.

This indeed happens if SUSY is spontaneously broken or broken by so called soft-terms in the action at a scale $M_{SUSY} \sim 1\ TeV$.

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SUSY can not be an exact symmetry of Nature: $M_{part} \neq M_{spart}$.

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MSSM with all possible soft SUSY breaking terms has a whole variety of new interactions: a large number of new free parameters (~ 100).

This makes it difficult to make any robust and easily verifiable predictions.

An important requirement for model building is the suppression of FCNC, which otherwise are present in large sizes.

Sometimes, people make certain assumptions about the nature of these new interactions which reduces the number of these extra parameters.

Different possible choices of these parameters lead to predictions with different possible masses and also different decay patterns.

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There has been no evidence from the first run of LHC with 8 *TeV* data.

From the present second run with energy up to 13 *Tev* no news has emerged so far. This may change over time.

But, it is perfectly possible that the simplest form of SUSY Model, *i.e.*, cMSSM is not the right picture.

More involved SUSY models may have to be explored.

A MSSM with more parameters, or a next-to-minimal SUSY Standard-Model (NMSSM) *[Fayet (1975), RKK-Majumdar (1982)]* or even a non-minimal model with more structure may be required.

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Besides the radiative stability of mass scales, there are two other reasons offered for SUSY:

(i) In the supersymmetrized SM, there is sufficient new matter content that allows for a more precise unification of the gauge coupling constants;

(ii) Models with $R-$parity allow for the possibility of stable particles (neutralinos) which could be the sought after candidates for weakly interacting massive particle (WIMP) as the dark matter.

These additional properties are not really that compelling.

It is important to realize that, except for the compelling naturalness argument which predicts SUSY as operative at about 1000 GeV, so far there is really no strong theoretical or experimental guidance that can lead us to the right SUSY model.

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Other non-decoupling problems

There can be many other physical contexts where the same non-decoupling problem due to elementary scalar fields can arise.

Large quantum fluctuations in the gravitational field would introduce granularity of space at extremely short distances ($\sim \ell_{Planck} = 10^{-33}\ cm$)

This would imply a minimum spatial length beyond which no physical process can take us. This is in tension with Lorentz invariance (LI).

The reason is very simple: special theory of relativity allows us to have a boost of any large size with consequent contraction of the length of a rod to aribitrarily small size.

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This violation of LI reflects itself through a change of the dispersion relation for a particle:

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But, do these Planck scale effects decouple from low energy physics?

In a quantum field theory of fermions and gauge fields only where low-high mass scale decoupling holds, this would indeed be realized.

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LI implies a unique form of the dispersion relation for a particle: $E^2 - \vec{p}^2 - m^2 = 0$, in units where velocity of light $c = 1$.

A Lorentz non-invariance would change the dispersion relation to: $E^2 - \vec{p}^2 - m^2 - \Pi(E, \vec{p}) = 0$.

Π represents the result of all the self energy graphs with a possible small Lorentz violating contribution from the quantum gravity effects.

Parametrize low energy the Lorentz violation through a dimensionless parameter: $\xi = \lim_{p \to 0} \left[\left(\frac{\partial}{\partial p^0} \frac{\partial}{\partial p^0} + \frac{\partial}{\partial |\vec{p}|} \frac{\partial}{\partial |\vec{p}|} \right) \Pi(p) \right]$

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Say, in the Yukawa theory of a fermion and a scalar field with their masses given by the low scale m_{low}, we may compute the contribution to ξ for the scalar field due to a fermion loop.

The correction to scalar two-point function $\Pi(p_0, \vec{p})$ is:

$$\Pi(p) = -4iy^2 \int \frac{d^4k}{(2\pi)^4} \frac{k.(k+p) + m_{low}^2}{(k^2 - m_{low}^2 + i\epsilon)\left[(p+k)^2 - m_{low}^2 + i\epsilon\right]}$$

The integral has quad divergence which gets converted into a log divergence in ξ.

$$\xi = -16iy^2 \int \frac{d^4k}{(2\pi)^4} \frac{k_0^2 + \frac{1}{3}\vec{k}^2}{(k^2 - m_{low}^2 + i\epsilon)^3}\left[1 + \frac{4m_{low}^2}{k^2 - m_{low}^2 + i\epsilon}\right]$$

This integral can be evaluated by Euclidean continuation of k_0 to imaginary values ik_4

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$$\xi = 16y^2 \int \frac{(d^4k)_E}{(2\pi)^4} \frac{k_4^2 - \frac{1}{3}\vec{k}^2}{(k^2 + m_{low}^2)^3} \left[1 - \frac{4m_{low}^2}{k^2 + m_{low}^2}\right]$$

We may use a ultraviolet cut off Λ for the Euclidean internal loop momentum $k = \sqrt{k^\mu k_\mu} = \sqrt{k_4^2 + \vec{k}^2}$ which is invariant under four dimensional Euclidean rotations. It is straight forward to check that such a calculation yields the Lorentz symmetric answer $\xi = 0$.

However due to the possible Lorentz violations from the Planck scale physics, the free fermion propagator used here would get significantly modified at high scales.

The momentum cut-off would have to be Lorentz violating introducing different cut-offs for the k_0 and $|\vec{k}|$ integrations.

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One way to introduce this order one non-invariance is by introducing a Lorentz non-invariant cut-off by multiplying the free fermion propagator by a smooth function $f(|\vec{k}|/\Lambda)$.

The cut off scale here $\Lambda \sim \ell_{min}^{-1}$ is characterized by the size ℓ_{min} $(\sim \ell_P)$ of the granularity of space due the quantum gravity effects.

The cut-off function $f(|\vec{k}|/\Lambda)$ is such that for the momenta much below the Planck-scale cut-off Λ $(\sim M_{Pl})$ goes to 1, $f(0) = 1$, (low energy propagator stays largely unaffected), and for high momenta this function goes to zero, $f(\infty) = 0$ (tames the ultraviolet behaviour in a Lorentz non-invariant manner).

An example of such a cut-off function: $f(|\vec{k}|/\Lambda) = \left(1 + (\vec{k}^2/\Lambda^2)\right)^{-1}$.

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$$\textit{Fermion propagator}: \; \frac{-i(\gamma^{\mu}k_{\mu} - m_{low})}{(k^2 - m_{low}^2)} \;\rightarrow\; \frac{-i(\gamma^{\mu}k_{\mu} - m_{low})}{(k^2 - m_{low}^2)}\, f(|\vec{k}|/\Lambda)$$

Such a fermion propagator radiatively induces a large Lorentz violation for the scalar field at low energies as can be seen by evaluating ξ from the one-loop contribution to the scalar two-point correlation $\Pi_S(p)$:

$$\Pi_S(p) = -4iy^2 \int \frac{d^4k}{(2\pi)^4} \frac{\left[k.(k+p) + m_{low}^2\right] f\left(\frac{|\vec{k}|}{\Lambda}\right) f\left(\frac{|\vec{k}+\vec{p}|}{\Lambda}\right)}{(k^2 - m_{low}^2 + i\epsilon)\left[(p+k)^2 - m_{low}^2 + i\epsilon\right]}$$

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$$\xi_S = \frac{y^2}{3\pi^2}\int_0^\infty dx\, x\,(f'(x))^2 + O\left(\frac{m^2_{low}}{\Lambda^2}\right) \sim \mathcal{O}(y^2)$$

with, for example $f(x) = (1+x^2)^{-1}$

The leading effect is independent of the Planck-scale cut-off Λ ($\sim M_{Pl}$): no m^2_{low}/M^2_{Pl} factor in the leading term.

Only a coupling constant suppression. No decoupling!

[Collins, Perez, Sudarsky, Urrutia, and Vucetich, PRL, 2004; Polchinski, Class. Quantum Grav., 2012.]

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It is again the quadratically divergent graphs for the two-point scalar correlation which result in this non-decoupling behaviour.

Obviously, SUSY provides a protection mechanism: there are no quadratic divergences in the scalar self-energy graphs in SUSY theories.

Exact SUSY will completely cancel out contributions from graphs with bosonic fields going around the loops with those with fermionic fields going around the loops. [Pankaj Jain and John P. Ralston, PLB 2005].

But SUSY is broken at a scale M_{SUSY}.

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This implies:

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Present day observational/exptal limits on violation of LI:

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Lorentz non-invariance

Radiative stability of the Higgs mass requires: $M_{SUSY} \sim 10^3\ GeV$.

This implies:

$$\xi_S \sim y^2 \ (M^2_{SUSY}/M^2_{Pl}) \sim (100)^{-1}\ (10^3/10^{19})^2 \sim 10^{-34}$$

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Conclusion

QFT's with elementary scalar fields do not exhibit low-high energy decoupling behaviour: such theories are not Natural.

The various low mass parameters are not stable under quantum radiative corrections which tend to drag them to the highest mass scale.

The Naturalness Problem of the SM has proven to be an ideational fountain head for a whole variety of new Beyond-Standard-Model (BSM) ideas over last several decades.

SUSY is the most promising of these.

Now is the time to confront these with experiments at LHC.

Hopefully, experimental discovery of SUSY, not necessarily in the simplest version as represented by the cMSSM, but a more general MSSM framework, or even perhaps in a non-minimal form, may happen in near future.

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Conclusion

Non-decoupling of the (possible) Planck scale violation of LI due to quantum gravity effects in theories with elementary scalar fields has the same origin.

SUSY again can ensure decoupling of this Planck scale violation from the low energy physics.

This implies a suppressed low energy violation of LI of a size

$$\xi \sim 4\,(\Delta c/c) \sim y^2 \,\left(M_{SUSY}^2/M_{Pl}^2\right) \sim 10^{-34}$$

for a SUSY breaking scale of $M_{SUSY} \sim 10^3\ GeV$ (which is required by the radiative stability of the 100 GeV scale of electro-weak theory).

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Thank you!