Why Supersymmetry? Physics Beyond the Standard Model

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Another name for this requirement is Naturalness Principle.

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There is enhanced symmetry even at the quantum level as $\alpha \to 0$.

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It is 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: $m_\mu \sim 200\ m_e$, $m_\tau \sim 3500\ m_e$, ..., $m_{top} \sim 3.4 \times 10^{11}\ m_e$. Effect of heavier fermions is decoupled.

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No decoupling of the heavy mass scale from the low mass scale theory.
Even in the limit $m_L \to 0$, this correction does not go away.

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$$m_{Higgs} = \sqrt{\lambda} v, \;\; m_W = \frac{gv}{2}, \;\; m_Z = \frac{gv}{2\cos\theta_W}, \;\; m_f = \frac{Y_f v}{\sqrt{2}}.$$

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No enhancement of symmetry in the limit $v \to 0$ at the quantum level.

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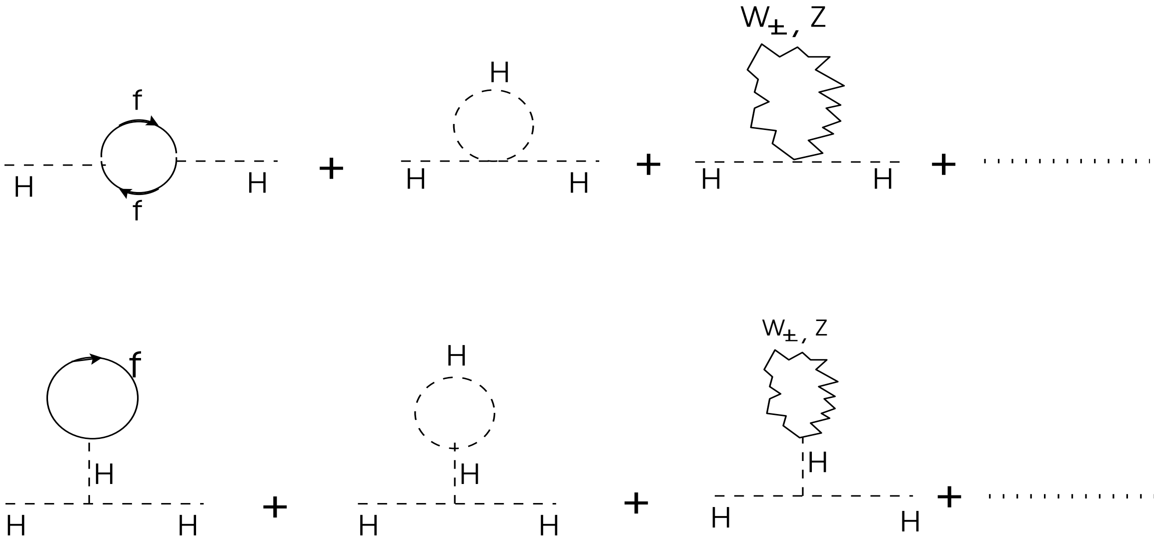

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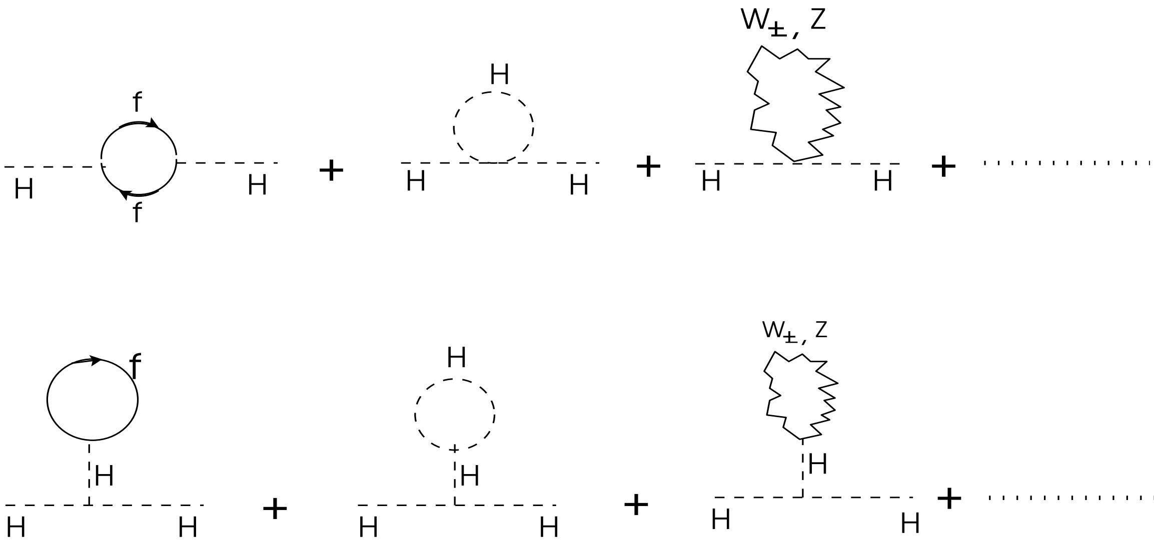

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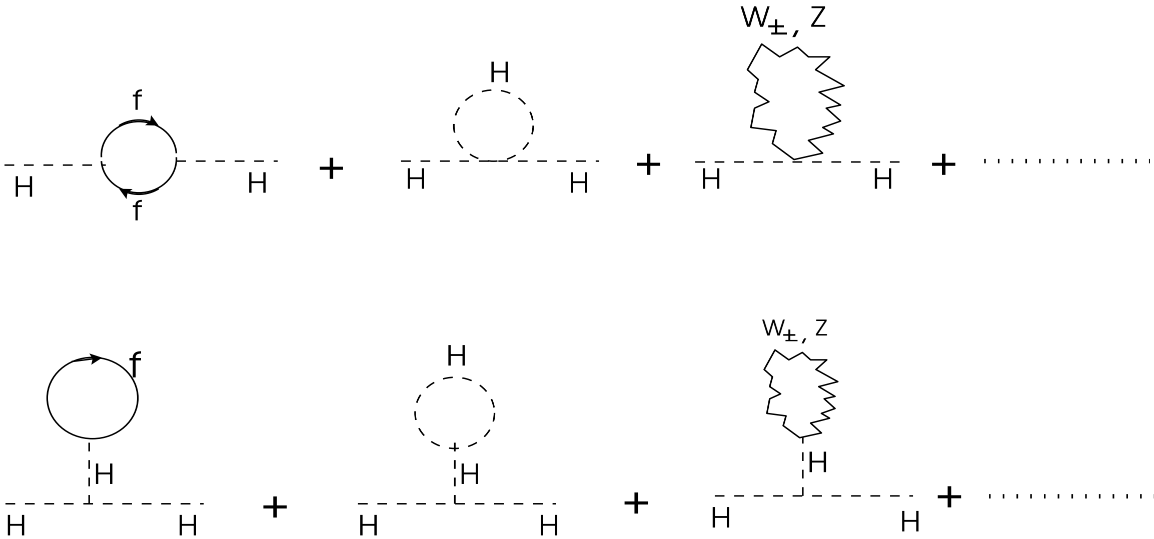

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But if there were a much heavier particle in Nature, such as in a GUT, the radiative corrections to Higgs mass would be controlled by this heavy scale and hence very large.

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This leads to the naturalness breakdown scale for EW theory to be: $\Lambda_N \sim 1 \; TeV$.

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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 ($\sim f^2$).

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

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These come from the mixed light-heavy field interaction terms of the type ($\langle\Phi\rangle_{vac} = F$ and $\langle\phi\rangle_{vac} = f;\ \ F \gg f$):

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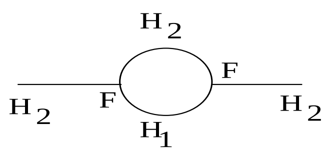

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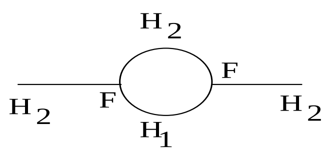

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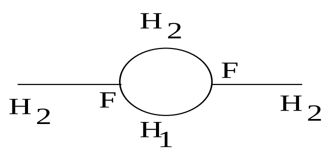

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There has to be some new physics beyond $1\,TeV$ such that the SM with its characteristic scale of $100\,GeV$ stays natural beyond this scale.

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This is what supersymmetry does indeed provide.

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In a SUSY theory with two distinctly different scales F and f associated with sequential gauge symmetry breaking through vevs of two sets of scalar fields, the hierarchy $f^2/F^2 \ll 1$ is radiatively maintained even by quantum corrections; the quadratic divergences as well as the large log divergences are absent.

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(iii) RKK and P. Majumdar: CTS-TIFR preprint Sept 1981 (TIFR-TH-81-34), Nucl. Phys. (1982):

(a) In a SUSY theory with anomalous $U(1)$ gauge invariance $(\sum Q_{U(1)} \neq 0)$, quadratic divergences are not absent; but in a theory which is anomaly free $(\sum Q_{U(1)} = 0)$, these are absent.

(b) In a SUSY theory with anomaly free $SU(2) \times U(1)$ gauge invariance, quadratic divergences are absent.

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(iv) RKK: CTS preprint October 1981 (Print-81-0867):

Two Solutions to the Naturalness Problem, INSA Lecture Book (1982):

Technicolour and SUSY solutions of the Naturalness Problem of SM are reviewed.

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(iv) RKK: CTS preprint October 1981 (Print-81-0867):

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(v) RKK: CTS preprint Feb. 1982 (Print-82-0161), Pramana (1982):

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(vi) Govindarajan, RKK, Vijayalakshmi: CTS-IIT Kanpur preprint Jan 1983, J. Phys. G (1983):

In SUSY theories with spontaneous broken $U(1)$ gauge symmetry even when trace of $U(1)$ charges is zero, the D term can get one loop corrections, but these are only logarithmically divergent.

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One such model known as constrained Minimal SUSY Model (cMSSM), has only a few extra free parameters, five in all.

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Hopefully, more results from the LHC will provide this discriminating guidance that will finally result in the correct SUSY model.

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LI implies that we can make an arbitrary large boost transformation which would result in Lorentz contraction of lengths to arbitrary small values.

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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.

Lorentz non-invariance

This violation of LI reflects itself through a change of the dispersion relations for the particles:

[Gambini and Pullin, PRD 1999; Alfaro et al , PRL 2000 and PRD 2002;
Sahlmann and Theimann, Class. Quan. Grav. 2006;
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But not in theories with elementary scalar fields.

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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 $c = 1$.

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Thus $\xi \neq 0$ *would be a measure of low energy violation LI.*

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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.

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The correction to scalar two-point function is:

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

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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 $\xi_S = 0$.

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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.

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

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

$$\frac{-i(\gamma^\mu k_\mu - m_{low})}{(k^2 - m_{low}^2)} \rightarrow \frac{-i(\gamma^\mu k_\mu - m_{low})}{(k^2 - m_{low}^2)} f(|\vec{k}|/\Lambda)$$

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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).

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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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But at high energy (Planck scale), $k^2 \sim \Lambda^2$*, the violation is large.*

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[Collins, Perez, Sudarsky, Urrutia, and Vucetich, PRL, 2004;

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But SUSY is broken at a scale M_{SUSY}. *Bose-Fermi cancellation will not be exact, but will happen upto:* $\xi_S \sim y^2 \left(M^2_{SUSY}/M^2_{Pl}\right) \ln \left(M^2_{Pl}/M^2_{SUSY}\right)$.

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Present day observational/exptal limits on violation of LI:

$\frac{\Delta c}{c} \left(\sim \xi/4 + O(\xi^2)\right) < 10^{-20}$.

Conclusion

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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.

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Hopefully, experimental discovery of SUSY, though very likely 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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Thank You !