Supersymmetry breaking and superspace higher derivatives

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SUSY 2014

- Supersymmetry can offer answers to long-standing theoretical questions in particle physics.
- If it is a symmetry of the elementary particles it has to be broken.
- Various mechanisms and ideas have been proposed to achieve this.
- Here we will see a new mechanism for SUSY breaking.

Outline

Supersymmetry breaking

Supersymmetry breaking from superspace higher derivatives

Embedding in effective field theory?

Conclusions

Superspace

- Supersymmetry is better formulated by utilizing a space with auxiliary anti-commuting coordinates.
- This construction allows us to built manifestly supersymmetric Lagrangians.
- In $4D$, $\mathcal{N} = 1$ all we need is

$$\begin{aligned} \{D_\alpha, \bar{D}_{\dot\alpha}\} &= -2i\sigma^a_{\alpha\dot\alpha}\partial_a \\ \{D_\alpha, D_\beta\} &= 0 \\ \{\bar{D}_{\dot\alpha}, \bar{D}_{\dot\beta}\} &= 0 \\ [D_\alpha, \partial_a] &= [\bar{D}_{\dot\alpha}, \partial_a] = 0. \end{aligned} \tag{1}$$

- Superfields contain the various components of the supersymmetric multiplets.

A simple supersymmetry-breaking Lagrangian is

$$\begin{aligned} \mathcal{L}_{break} &= \int d^4\theta\, K(\Phi,\bar{\Phi}) + \int d^2\theta\, f\,\Phi + c.c. \\ &= F\bar{F} + f\,F + f\,\bar{F} + \cdots \qquad (\langle K_{A\bar{A}}\rangle = 1) \end{aligned} \tag{2}$$

When is SUSY spontaneously broken?

- EOM for the auxiliary field: $F = f$
- Existence of a massless fermion G_α: Goldstino.
- Supersymmetry becomes a shift for the Goldstino:

$$< \delta G_\alpha > \sim \xi_\alpha < F >$$

- Positive energy vacuum: $< H > \sim < P^0 > \sim < |Q|^2 > \neq 0$
- Existence of a massive scalar, the sGoldstino.

Decoupling the sGoldstino and constrined superfields

- Supersymmetry is broken and it can not protect the sGoldtino from becoming very heavy.
- In the formal limit $m_{sg} \to \infty$ the equations of motion of the sGoldtino become a constraint which enforces

$$X^2 = 0 \tag{3}$$

- The SUSY breaking sector can be described effectively by a constrained chiral superfield X with Lagrangian

$$\mathcal{L}_X = \int d^4\theta \, X\bar{X} + \int d^2\theta \, f \, X + c.c. \tag{4}$$

- On-shell this is the Akulov-Volkov model.

Duals to chiral multiplets: complex linear superfields

- Consider the action

$$\mathcal{L}_D = -\int d^4\theta \left(\Sigma\bar{\Sigma} + \Phi\Sigma + \bar{\Phi}\bar{\Sigma}\right) \tag{5}$$

where Φ is chiral and Σ is unconstrained.

- Integrate out Σ to find

$$\mathcal{L}_\Phi = \int d^4\theta \Phi\bar{\Phi} \tag{6}$$

- Integrate out Φ to find

$$\mathcal{L}_\Sigma = -\int d^4\theta\, \Sigma\bar{\Sigma} \tag{7}$$

with

$$\bar{D}^2\Sigma = 0 \tag{8}$$

Complex linear superfields may give new insight to supersymmetry breaking.

Superspace higher derivatives

- We consider the following Lagrangian

$$\mathcal{L}_{SHD} = -\int d^4\theta \Sigma\bar{\Sigma} + \int d^4\theta \, \frac{1}{64 f^2} \, D^{\alpha}\Sigma D_{\alpha}\Sigma \bar{D}_{\dot{\alpha}}\bar{\Sigma}\bar{D}^{\dot{\alpha}}\bar{\Sigma} \quad (9)$$

- This higher derivative theory does not give rise to any instability.
- It may lead to SUSY breaking.

The properties of this model can not be captured by Kähler potential-superpotential.

Bosonic sector

- The bosonic part of the full Lagrangian turns out to be

$$\begin{aligned}\mathcal{L}^B =&\mathcal{L}^B_\Sigma + \mathcal{L}^B_{SHD}\\ =&-F\bar{F} + A\partial^2\bar{A} + \frac{1}{2}P_m\bar{P}^m\\ &+\frac{1}{64f^2}\left(P^mP_m\bar{P}^n\bar{P}_n + 4P_m\bar{P}^mF\bar{F} + 16F^2\bar{F}^2\right)\end{aligned} \quad (10)$$

- From the equations of motion for the complex auxiliary vector we find that

$$P_m = 0 \quad (11)$$

leading to

$$\mathcal{L}^B = -F\bar{F} + A\partial^2\bar{A} + \frac{1}{4f^2}F^2\bar{F}^2 \quad (12)$$

A SUSY model with two branches

- The equations of motion for the auxiliary scalar turn out to be

$$F\left(1 - \frac{1}{2f^2} F\bar{F}\right) = 0 \tag{13}$$

- There are now two solutions:

$$\begin{array}{llll} (i) & F = 0 & \rightarrow & \text{supersymmetric branch.} \\ (ii) & F\bar{F} = 2\,f^2 & \rightarrow & \text{supersymmetry is broken.} \end{array}$$

- The superspace equations of motion give equivalently

$$\begin{array}{llll} (i) & \Sigma = \bar{\Phi} & \rightarrow & \text{supersymmetric branch.} \\ (ii) & \Sigma = X + \bar{\Phi} & \rightarrow & \text{supersymmetry is broken.} \end{array}$$

Essential hierarchy

- Let us now introduce a higher order correction

$$\mathcal{L}_F = -F\bar{F} + \frac{1}{2f^2}F^2\bar{F}^2 + \frac{1}{f'^4}F^3\bar{F}^3 + \cdots \tag{14}$$

and then (14) for the breaking solution becomes

$$\mathcal{L}_F = -\frac{1}{2}f^2 + f^2\left(\frac{f}{f'}\right)^4 + \cdots \tag{15}$$

- If we consider

$$\frac{1}{f} \lesssim \frac{1}{f'} \quad \leftrightarrow \quad \frac{f}{f'} \gtrsim 1 \tag{16}$$

we can not trust the breaking branch.

- The other limiting case is the existence of a large hierarchy

$$\frac{1}{f} >> \frac{1}{f'} \quad \leftrightarrow \quad \frac{f}{f'} << 1 \tag{17}$$

where the beaking branch is valid.

Massive gauged complex linear & massive $U(1)$

- We consider the following superspace Lagrangian

$$\begin{aligned}\mathcal{L} &= -\int d^4\theta\,\bar{\Sigma}e^{gV}\Sigma + \int d^4\theta\,\bar{\Phi}e^{gV}\Phi \\ &+ \int d^2\theta\,W^2(V) + c.c.\int d^4\theta\,M^2V^2 \qquad (18)\end{aligned}$$

- Gauge invariant (renormalizable) model.
- The vacuum structure is determined by

$$\mathcal{L}^{vac} = -F\bar{F} + N\bar{N} + \mathrm{D}(-gA\bar{A} + M^2C) + \mathrm{D}^2 \qquad (19)$$

thus no tree-level supersymmetry breaking

$$< F > = < N > = < \mathrm{D} > = 0 \qquad (20)$$

Effective action

We calculate the effective action for the background field Σ_0

$$
\begin{aligned}
\mathcal{L}_{\Sigma_0,eff} \quad = \quad & -\mathcal{T}\int d^4\theta\,\bar{\Sigma}_0\Sigma_0 - \mathcal{P}\frac{g^2}{M^2}\int d^4\theta\Sigma_0^2\bar{\Sigma}_0^2 \\
& -\mathcal{Q}\frac{g^4}{M^4}\int d^4\theta\Sigma_0^3\bar{\Sigma}_0^3 \\
& +\mathcal{R}\frac{g^4}{16\pi^2M^4}\int d^4\theta D^2(\Sigma_0\bar{\Sigma}_0)\bar{D}^2(\Sigma_0\bar{\Sigma}_0) \\
& +\mathcal{S}\frac{g^4}{16\pi^2M^4}\int d^4\theta D^2(\bar{\Sigma}_0^2)\bar{D}^2(\Sigma_0^2) \qquad (21)
\end{aligned}
$$

Here we have set external momenta to zero.

Off-shell effective potential

- The non-derivative scalar part of the effective Lagrangian is

$$\mathcal{L}^{vac}_{\Sigma,eff} = -F\bar{F}\left[\mathcal{T} + \frac{4g^2}{M^2}\,\mathcal{P}\,A\bar{A} + \frac{9g^4}{M^4}\,\mathcal{Q}\,A^2\bar{A}^2\right] + \frac{g^4\,\mathcal{R}}{16\pi^2 M^4}F^2\bar{F}^2$$

- The equations of motion for the auxiliary scalar turn out to be (for $\langle A\rangle = 0$)

$$\left[\frac{g^4\,\mathcal{R}}{8\pi^2 M^4}\,F\bar{F} - \mathcal{T}\right]\bar{F} = 0$$

- Higher order in g loop corrections are of the same order

$$\mathcal{L}_{\text{higher order}} \sim (-1)^n g^{2n}\frac{1}{M^{2n-4}}\left(F\bar{F}\right)^n \tag{22}$$

- No hierarchy $\rightarrow$ the supersymmetry breaking solutions can not be trusted.

Summary

- Higher dimension operators mediate the supersymmetry breaking, but they may also trigger it.
- This supersymmetry breaking can not be captured by the Kähler potential or the superpotential.
- These superspace higher derivatives are always present in supersymmetric effective theories.
- Is there a perturbative or non-perturbative mechanism for these superspace higher derivatives to be generated including a hierarchy?

Thank you!