Non-linear supersymmetry and brane dynamics

I. Antoniadis

CERN

QUARKS-2010

Kolomna, Russia, 6-12 June 2010

1. Introduction and motivations
2. $N = 1$: goldstino couplings to matter

   I.A.-Tuckmantel '04; Komargodski-Seiberg '09

   Non-linear MSSM — I.A.-Dudas-Ghilencea-Tziveloglou to appear
3. Extended supersymmetry and brane dynamics

   Bagger-Galperin '97; I.A.-Derendinger-Maillard '08

   Ambrosetti-I.A.-Derendinger-Tziveloglou '09 + '10

Non-linear supersymmetry $\Rightarrow$ goldstino mode χ

Volkov-Akulov '73

Why study goldstino interactions:

- Effective field theory of SUSY breaking at low energies $m_\chi << m_{susy}$

  e.g. gauge mediation dominant vs gravity mediation

  χ: longitudinal gravitino with $m_\chi << m_{soft} << m_{susy}$

- Brane dynamics: half SUSY of the bulk broken but NL realized

  $\Rightarrow$ e.g. strongly constrain coupling of brane to bulk fields

  exact NL susy in the large volume limit

  broken by the orientifold projection at finite volume

  $\Rightarrow$ important for large volume compactifications, e.g. low scale strings

Non-linear SUSY transformations: [5]

$$\delta\chi_\alpha = \frac{\xi_\alpha}{\kappa} + \kappa\,\Lambda^\mu_\xi\,\partial_\mu\chi_\alpha \qquad \Lambda^\mu_\xi = -i\left(\chi\sigma^\mu\bar{\xi} - \xi\sigma^\mu\bar{\chi}\right)$$

κ: goldstino decay constant (SUSY breaking scale) $\kappa = (\sqrt{2}m_{susy})^{-2}$

Goldstino interactions: 3 formulations

- Standard realization

  Volkov-Akulov '73, Clark-Love '96, Clark-Lee-Love-Wu '98

- Superfield formalism Ivanov-Kapustnikov '78, Samuel-Wess '83

  Brignole-Feruglio-Zwirner '97, Luty-Ponton '98, I.A.-Tuckmantel '04

- Constrained superfields

  Rocek-Tseytlin '78, Lindstrom-Rocek '79, Komargodski-Seiberg '09

Standard realization

Define the 'metric': $G_\mu^\nu = \delta_\mu^\nu + \kappa^2\, t_\mu^\nu \qquad t_\mu^\nu = i\chi \overleftrightarrow{\partial}_\mu \sigma^\nu \bar{\chi}$

$\delta(\det G) = \kappa\, \partial_\mu \left(\Lambda_\xi^\mu \det G \right) \Rightarrow$ invariant action:

$$S_{VA} = -\frac{1}{2\kappa^2} \int d^4x \det G = -\frac{1}{2\kappa^2} - \frac{i}{2} \chi \sigma^\mu \overleftrightarrow{\partial}_\mu \bar{\chi} + \dots$$

Generalization to matter and gauge fields:

$S_{eff} = \int d^4x \det G\, \mathcal{L}_{SM}(\phi)$ invariant if $\delta\phi = \kappa\, \Lambda_\xi^\mu \partial_\mu \phi$ and so $\mathcal{L}_{SM}$

However problem with derivatives $\Rightarrow$ define SUSY covariant ones:

$$\mathcal{D}_\mu \phi \equiv \left(G^{-1}\right)_\mu^\nu D_\nu \phi \qquad \mathcal{F}_{\mu\nu} \equiv \left(G^{-1}\right)_\mu^\lambda \left(G^{-1}\right)_\mu^\rho F_{\lambda\rho}$$

$$\mathcal{L}_{eff} = \det G\, \mathcal{L}_{SM}(\phi, \mathcal{D}_\mu \phi) = \mathcal{L}_{SM}(\phi, D_\mu \phi) + \kappa^2\, t^{\mu\nu}\, T_{\mu\nu} + \dots$$

universal coupling to stress-tensor but NOT the most general inv action

Superfield formalism

Recipe: $\phi(x) \to \Phi(x,\theta,\bar\theta) \equiv \phi(\tilde x)$ $\qquad \tilde x^\mu = x^\mu + \Lambda^\mu_\theta(\tilde x)$ [3] [8]

$$= \phi(x) + \kappa\Lambda^\mu_\theta \partial_\mu \phi + \ldots \quad \Rightarrow$$

Goldstino (spinor) superfield: $\mathcal{G}_\alpha = \frac{\theta_\alpha}{\kappa} + \chi_\alpha(\tilde x)$

space-time derivatives: use the 'metric' $G(\tilde x)$

$$\text{e.g. } \mathcal{F}_{\mu\nu}(x,\theta,\bar\theta) \equiv \left[\left(G^{-1}\right)^\lambda_\mu \left(G^{-1}\right)^\rho_\mu F_{\lambda\rho}\right](\tilde x)$$

$$O = \int d^2\theta d^2\bar\theta\, \mathcal{O} = \sum_{n\geq 0} \kappa^n O^{(n)}$$ even/odd $n \leftrightarrow$ even/odd number of χ's

dims: $[\mathcal{O}] = d \geq 0 \Rightarrow [O] = d+2\,,\ [O^{(n)}] = d+2+2n$

Effective operators of dimension $\leq 8 \Rightarrow\ d \leq 2\,,\ n \leq 2$

List of lowest dim operators

2 operators of dim 6 linear in χ [12]

$$S_1 = C_1 \int d^4x \; \kappa \, F_{\mu\nu} \psi \sigma^\mu \partial^\nu \bar{\chi} + h.c. \qquad S_2 = C_2 \int d^4x \; \kappa \, (\psi \partial_\alpha \chi) D^\alpha \phi + h.c.$$

Quadratic in χ: 1 operator of dim 7

$$S_7 = C_7 \int d^4x \; \kappa^{3/2} \phi_1 \phi_2 \; \partial_\mu \chi J^{\mu\nu}_{(\frac{1}{2},0)} \partial_\nu \chi + h.c. \qquad J^{\mu\nu}_{(\frac{1}{2},0)} = \frac{i}{4} \sigma^{[\mu} \bar{\sigma}^{\nu]}$$

$+$ 5 operators of dim 8

$$S_3 = C_3 \int d^4x \, \kappa^2 (\psi_1 \partial^\mu \chi)(\bar{\psi}_2 \partial_\mu \bar{\chi}) + h.c. \quad S_4 = C_4 \int d^4x \, \kappa^2 (\psi_1 \psi_2)(\partial_\mu \chi \partial^\mu \chi) + h.c.$$

$$S_5 = C_5 \int d^4x \, \kappa^2 \phi_1 \overleftrightarrow{D}_\mu \phi_2 i \partial_\alpha \chi \sigma^\mu \partial^\alpha \bar{\chi} + h.c.$$

$$S_6 = C_6 \int d^4x \, \kappa^2 \partial^\alpha \chi \sigma^\mu \partial^\nu \bar{\chi} \partial_\alpha F_{\mu\nu} + h.c.$$

$$S_8 = C_8 \int d^4x \, \kappa^2 \phi_1 \phi_2 \phi_3 (\partial_\mu \chi J^{\mu\nu}_{(\frac{1}{2},0)} \partial_\nu \chi) + h.c.$$

Constrained superfields

spontaneous global $S\!\!\!/USY$: no supercharge but still conserved supercurrent

$\Rightarrow$ superpartners exist in operator space (not as 1-particle states)

$\Rightarrow$ constrained superfields: 'eliminate' superpartners

Goldstino: chiral superfield X_{NL} satisfying $X_{NL}^2 = 0 \Rightarrow$ [22]

$$X_{NL}(y) = \frac{\chi^2}{2F} + \sqrt{2}\theta\chi + \theta^2 F \qquad y^\mu = x^\mu + i\theta\sigma^\mu\bar{\theta}$$

$$= F\Theta^2 \qquad \Theta = \theta + \frac{\chi}{\sqrt{2}F}$$

$$\mathcal{L}_{NL} = \int d^4\theta X_{NL}\bar{X}_{NL} - \frac{1}{\sqrt{2}\kappa}\left\{\int d^2\theta X_{NL} + h.c.\right\} = \mathcal{L}_{VA}$$

$$F = \frac{1}{\sqrt{2}\kappa} + \dots$$

Goldstino couplings to matter

Coupling to superfields: $m_{soft} << E << m_{susy} \sim 1/\sqrt{\kappa}$

replace auxiliary superfield spyrion $S = m_{soft}\theta^2$ by $\sqrt{2}\kappa m_{soft} X_{NL}$ [15]

Coupling to (non-SUSY) matter: $E << m_{soft}, m_{susy}$

$\rightarrow$ constrained matter superfelds

- Fermions: Q_{NL} satisfying $Q_{NL} X_{NL} = 0$ (eliminate sfermions) $\Rightarrow$

$$Q_{NL} = \sqrt{2}\left(\psi - \frac{F_Q \chi}{F}\right)\Theta + F_Q \Theta^2$$

- Complex scalars: H_{NL} with $X_{NL}\bar{H}_{NL} =$ chiral (eliminate 'higgsinos') [5]

$$\Rightarrow H_{NL} = H(\hat{y}) \qquad \hat{y} = y^\mu + i\sqrt{2}\theta\sigma^\mu\bar{\chi}(\hat{y})/\bar{F}(\hat{y})$$

- Real scalars: A_{NL} with $X_{NL}\bar{A}_{NL} = X_{NL} A_{NL}$

$$\Rightarrow \mathrm{Im}A = \tfrac{1}{2F\bar{F}}\left(\chi\sigma^\mu\bar{\chi}\right)\partial_\mu \mathrm{Re}A + \ldots$$

- Gauge fields: V_{NL}

gauge transformations: $\delta V = \Omega + \bar{\Omega}$ with $X_{NL}(\Omega_{NL} + \bar{\Omega}_{NL}) = 0$

e.g. charged matter $H_{NL} = e^{iR_{NL}}$; $X_{NL}(R_{NL} - \bar{R}_{NL}) = 0$: $\delta R_{NL} = i\Omega_{NL}$

$\Rightarrow$ convenient gauge choice $X_{NL} V_{NL} = 0$

eliminate gaugino: $X_{NL} W_{NL} = 0$ field strength $W = -\frac{1}{4}\bar{D}^2 DV$

$$\Rightarrow V_{NL} = -\Theta\left(\sigma^m V_m + \frac{D}{|F|^2}\chi\bar{\chi}\right)\bar{\Theta} + \frac{1}{2}\Theta^2\bar{\Theta}^2 D + \text{derivatives}$$

D-brane dynamics

Type II (closed) strings on $4d$ Minkowski $M_4 \times X_6$ internal $6d$ manifold

X_6 flat $\Rightarrow N = 8$ SUSY ; X_6 Calabi-Yau $\Rightarrow N = 2$ SUSY

Single stack of N Dp-branes $\Rightarrow$ half SUSY is spontaneously broken $p \geq 3$

$(p-3)$ dims wrapped around cycles in $X_6 \Rightarrow 4d$ effective field theory

- Gauge group: $G = U(N)$ (generically)
- SUSY: half remains unbroken Q_e ; other half NL realized Q_o

  broken SUSY commutes with $G \Rightarrow$ goldstino $= U(1)$ gaugino of Q_e

Intersecting branes: useful framework for model building

Standard Model embedding

Two D-brane stacks: N_1 Dp_1 and N_2 Dp_2

$\Rightarrow$ bifundamental matter on their intersections: chiral fermions

L-SUSY: generally broken but preserved for special intersection angles

e.g. for $X_6 = T^2 \times T^2 \times T^2$ when $\theta_1 + \theta_2 + \theta_3 = 0$

NL-SUSY: generally all (both $U(1)_1 \times U(1)_2$ gauginos = goldstinos)

special angles $\Rightarrow$ only a linear combination

Remark: string consistency (e.g. tadpole cancellation) $\Rightarrow$ need orientifolds

non-dynamical planes $\Rightarrow$ break half-SUSY explicitly

$\Rightarrow$ goldstino gets a volume suppressed mass

NL-SUSY only locally $\rightarrow$ restored in the large volume limit [19]

Intersecting D-brane models

I.A.-Tuckmantel '04

1) Goldstino decay constant: sum of brane tensions

$$\frac{1}{2\kappa^2} = T_1 + T_2 \qquad T_i = \frac{M_s^4}{4\pi^2 g_i^2} N_i$$

2) Goldstino couplings: only 3 non-vanishing up to order κ^2 [6]

$$C_1 = \sqrt{2} \quad ; \quad C_2 = 2 \quad ; \quad C_3 = 2$$

- universal coefficients independent of brane-angles
- C_3: fixes the field theory ambiguity of 4-fermion operator

  Brignole-Feruglio-Zwirner '97, I.A.-Benakli-Laugier '01

- $C_{1,2}$: dim 6 operators linear in χ can be written as

  $\mathcal{L}_{\rm linear} = \frac{\kappa}{\sqrt{2}} J^\mu \partial_\mu \chi + h.c.$ $\quad J^\mu$: $N = 1$ supercurrent of linear SUSY

  present in the intersection if massless scalars

Phenomenological analysis in the Standard Model

$$\mathcal{L}_\chi = -\frac{i}{2}\chi\sigma^\mu \overleftrightarrow{\partial}_\mu \bar{\chi} + i\kappa^2(\chi \overleftrightarrow{\partial}^\mu \sigma^\nu \bar{\chi}) T_{\mu\nu} + \delta\mathcal{L}_\chi$$

$$\delta\mathcal{L}_\chi = i\sqrt{2}\kappa F_{\mu\nu}\psi\sigma^\mu\partial^\nu\bar{\chi} + 2\kappa D_\mu\phi(\psi\partial^\mu\chi) + h.c.$$
$$+2\kappa^2(\partial_\mu\chi\psi_1)(\partial^\mu\bar{\chi}\bar{\psi}_2) + \mathcal{O}(\kappa^3)$$

- 1st term: hypercharge + fermion singlet
- 2nd term: higgs + lepton doublets I.A.-Tuckmantel-Zwirner '04

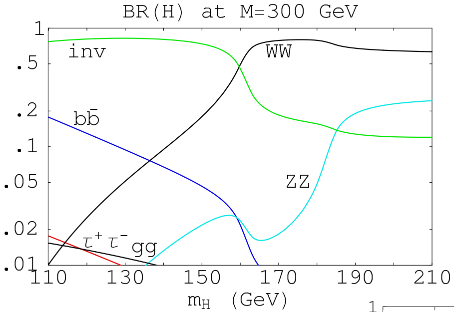
  preserves lepton number if $L(\chi) = -1$

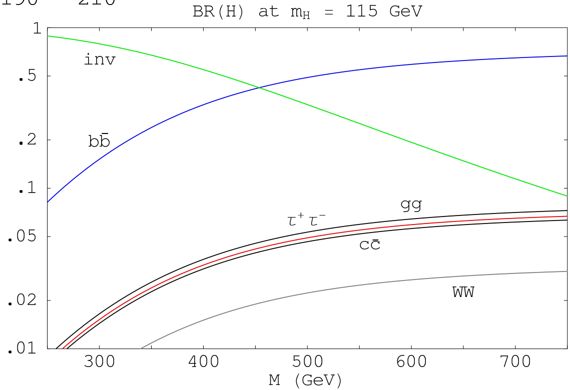
  $Z, H \to \nu\chi$ $W^\pm \to l^\pm\chi \Rightarrow$ $M = m_{susy}\,|\sqrt{2}/C_2|^{1/2} \simeq M_s/2$

  - bounds: $M \gtrsim 270$ GeV $\Rightarrow M_s \gtrsim 500$ GeV (e.g. invisible Z width)

  - signal: invisible Higgs decay

    dominant or non-negligible in a large range of (M, m_H)


BR(H) at M=300 GeV
inv
WW
bb̄
ZZ
τ+τ− gg
1
.5
.2
.1
.05
.02
.01
110
130
150
170
190
210
mH (GeV)


BR(H) at mH = 115 GeV
inv
bb̄
gg
τ+τ−
cc̄
WW
1
.5
.2
.1
.05
.02
.01
300
400
500
600
700
M (GeV)

Phenomenological analysis in the MSSM [8]

$E \sim m_{soft} >> m_\chi$ **I.A.-Dudas-Ghilencea-Tziveloglou to appear**

Higgs potential is modified:

$$V = V_{MSSM} + 2\kappa^2 \left| m_1^2 |h_1|^2 + m_2^2 |h_2|^2 + B\mu h_1 h_2 \right|^2 + \mathcal{O}(\kappa^4) \quad \Rightarrow$$

$m_{1,2}, B\mu$: soft mass parameters, μ: higgsino mass

classical value of light higgs mass can be increased above the LEP bound

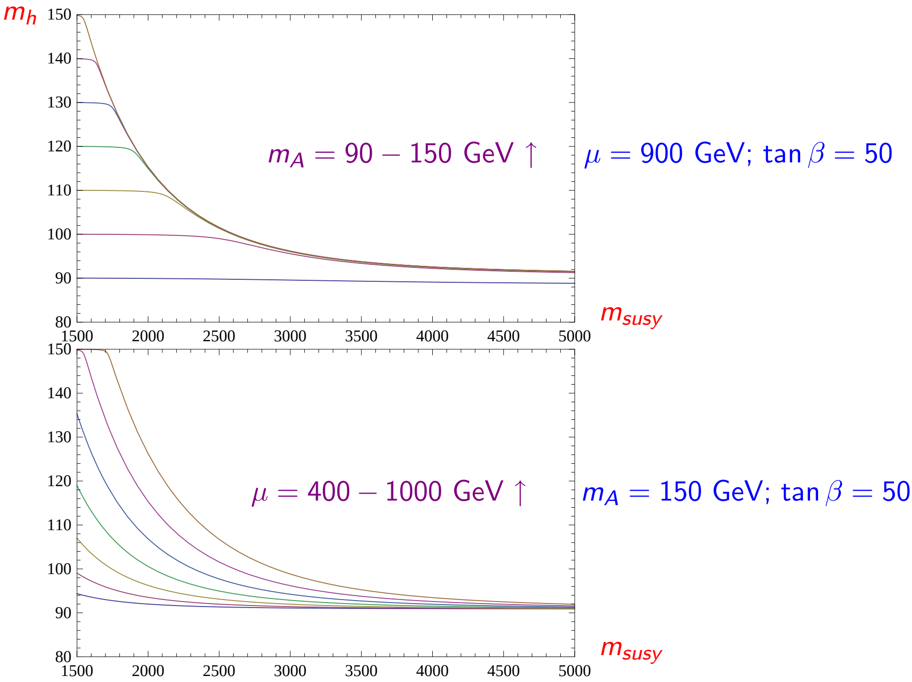
large $\tan\beta$ limit: $m_h^2 = m_Z^2 + \frac{v^2}{2m_{susy}^2}(2\mu^2 + m_Z^2)^2 + \cdots$

$\rightarrow$ e.g. $\mu = 900$ GeV, $m_{susy} = 2$ TeV $\Rightarrow$ $m_h = 114.4$ GeV

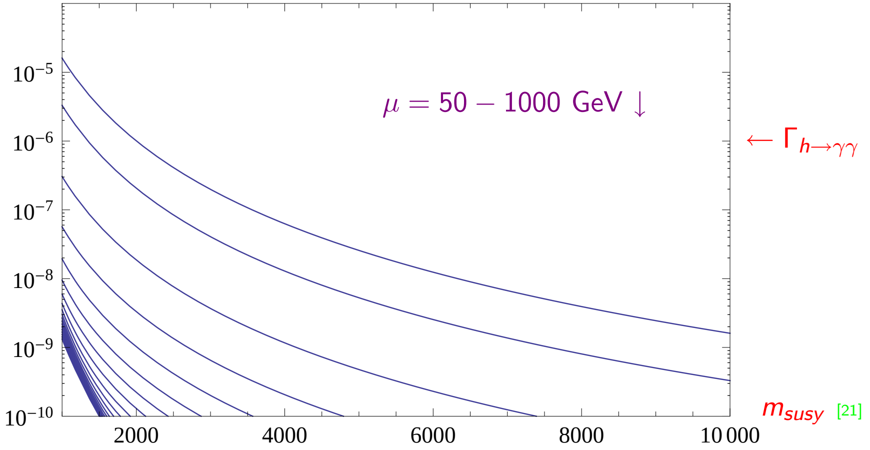
Quartic higgs coupling increases for large soft masses $\Rightarrow$

MSSM 'little' fine tuning is alleviated

New couplings $\Rightarrow$ invisible higgs decay $h \rightarrow \chi +$ NLSP


m_h
150
140
130
120
110
100
90
80
1500
2000
2500
3000
3500
4000
4500
5000
$m_A = 90 - 150$ GeV ↑
$\mu = 900$ GeV; $\tan\beta = 50$
m_{susy}
$\mu = 400 - 1000$ GeV ↑
$m_A = 150$ GeV; $\tan\beta = 50$
m_{susy}

$\Gamma_{h\to\chi+\mathrm{NLSP}}$ $m_A = 150$ GeV; $\tan\beta = 50$; $(m_{\lambda_1}, m_{\lambda_2}) = (70, 150)$ GeV



Conclusions

Non-linear supersymmetry: powerful tool for studying:

- low energy SUSY breaking $E << m_{SUSY} \sim 1/\sqrt{\kappa}$

  Volkov-Akulov action and goldstino χ couplings to matter

  standard coupling to stress-tensor *not* the most general

  $\rightarrow$ detailed analysis $\Rrightarrow$ dim 6 operators linear in χ

  $E >> m_{soft} \Rrightarrow$ goldstino $\equiv$ spurion coupled to supermultiplets

  $\rightarrow$ Non-linear MSSM

  $E << m_{soft} \Rrightarrow$ goldstino coupling to Standard Model fields

- brane effective actions $\Rrightarrow$ brane dynamics

  $N = 1$ string computation: 3 independent couplings up to dim 8

Brane supersymmetry breaking

I.A.-Dudas-Sagnotti, Aldazabal-Uranga '99

Stable configurations of branes with orientifolds

- absence of tachyons
- bulk susy breaking suppressed by (transverse) volume

	D	$\bar{\mathrm{D}}$	O	$\bar{\mathrm{O}}$
RR charge	$+$	$-$	$-$	$+$
tension	$+$	$+$	$-$	$-$
linear SUSY	Q_e	Q_o	Q_e	Q_o
NL SUSY	Q_o	Q_e		

Model I: DO or $\bar{\mathrm{D}}\bar{\mathrm{O}}$ $\Rightarrow$ local charge conservation, brane SUSY (locally)

Model II: $\bar{\mathrm{D}}$O or D$\bar{\mathrm{O}}$ $\Rightarrow$ brane SUSY breaking (linear), NL SUSY

- Model I: N Dp-branes on Op-plane $\Rightarrow$ $SO(2N)$ SUSY
- Model II: N Dp branes on $\bar{\mathrm{O}}p$-plane $\Rightarrow$ $SO(2N)$ with fermions in the symmetric representation $=$ traceless $+$ trace $\leftarrow$ goldstino

  Dudas-Mourad, Pradisi-Riccioni '01

  orientifold: antisymmetrizes bosons but symmetrizes fermions

  $\Rightarrow$ breaks SUSY
- Model III: D-branes away from O-plane $\Rightarrow$ $U(N)$ SUSY $\leftarrow$ L $+$ NL

  partial breaking $N = 2 \rightarrow N = 1$ $U(1)$: goldstino multiplet [11]

NL extended supersymmetry $N = 1_L + 1_{NL}$

Goldstino in multiplet of $N = 1$ SUSY: vector or chiral?

brane dynamics $\Rightarrow$ Maxwell goldstino multiplet

gauge chiral multiplet$\big|_{N=2}$ $\mathcal{W} =$ (vector W + chiral $X)_{N=1}$

$$\mathcal{W}(y,\theta,\tilde\theta) = X(y,\theta) + i\sqrt{2}\tilde\theta W(y,\theta) - \tilde\theta^2\left[\tfrac{1}{4}\overline{DDX}(y,\theta) + \tfrac{1}{2\kappa}\right]$$

allow partial SUSY breaking $N = 2 \to N = 1$

$\delta^* X = i\sqrt{2}\eta^\alpha W_\alpha \qquad \delta^* W_\alpha = \frac{i}{\sqrt{2}\kappa}\eta_\alpha + \dots \leftarrow$ linear SUSY

$$\mathcal{L}^{N=2}_{Maxwell} = -\frac{1}{8}\int d^2\theta\, d^2\tilde\theta\, \mathcal{W}^2 + h.c. = \int d^2\theta \left[\frac{1}{2}W^2 - \frac{1}{4}X\overline{DDX} - \frac{1}{2\kappa}X\right] + h.c.$$

Partial SUSY breaking: non trivial prepotential $f(\mathcal{W})$

I.A.-Partouche-Taylor '96

Non-linear $N = 2$ constraint: $\mathcal{W}_{NL}^2 = 0$

$$\Rightarrow \quad X^2 = 0 \quad , \quad XW_\alpha = 0 \quad , \quad WW - \frac{1}{2}X\overline{DDX} = \frac{1}{\kappa}X \text{ [7]}$$

$$X = \kappa W^2 - \kappa^3 \bar{D}^2 \frac{W^2\overline{W}^2}{1+A_+ + \sqrt{1+2A_+ + A_-^2}} \qquad A_\pm = \frac{\kappa^2}{2}\left(D^2W^2 \pm \bar{D}^2\overline{W}^2\right) = \pm A_\pm^*$$

$$\Rightarrow \mathcal{L}_{NL}^{N=2} = \frac{1}{4\kappa}\int d^2\theta X + h.c.$$

$$= \frac{1}{8\kappa^2}\left(1 - \sqrt{-\det(\eta_{\mu\nu} + 2\sqrt{2}\kappa F_{\mu\nu})}\right) + \ldots = \mathcal{L}_{\rm DBI} \leftarrow \text{D-brane}$$

The FI-term is also invariant under NL SUSY

$$\mathcal{L}_{FI} = \xi\int d^4\theta V; \quad W = -\frac{1}{4}\bar{D}^2 DV; \quad \delta^* V = \frac{i}{2\kappa}\left(\eta D + \bar{\eta}\bar{D}\right)\theta^2\bar{\theta}^2 + \ldots$$

$$\Rightarrow \mathcal{L}_{Max}^{NL} = \mathcal{L}_{NL}^{N=2} + \mathcal{L}_{FI} \text{ [24]}$$

Coupling to bulk hypermultiplets e.g. the universal dilaton

at least one isometry $\rightarrow$ single-tensor multiplet (RR 2-forms)

$N = 2$ tensor $\mathcal{Y} = (\text{tensor } L + \text{chiral } \Phi)_{N=1}$ $\qquad D^2 L = \bar{D}^2 L = 0$

general action: $\mathcal{L}_{ST} = \int d^4\theta \mathcal{H}(L, \Phi, \bar{\Phi})$ with $\left(\partial_L^2 + 2\partial_\Phi \partial_{\bar{\Phi}}\right) \mathcal{H} = 0$

$L = D^\alpha \ell_\alpha + h.c.$ $\qquad \ell_\alpha$: chiral spinor superfield

off-shell $N = 2 \Rightarrow$ add auxiliary chiral superfield $Y \sim \theta^2 \epsilon \cdot C_4 \leftarrow$ 4-form

$$\mathcal{Y}(y, \theta, \tilde{\theta}) = Y(y, \theta) + i\sqrt{2}\,\tilde{\theta}\,\ell(y, \theta) - \tfrac{i}{2}\tilde{\theta}^2\,\Phi(y, \theta)$$

coupling to $N = 2$ vector $\mathcal{W}$: Chern-Simons interaction:

$$\mathcal{L}_{CS} \sim g \int d^2\theta d^2\tilde{\theta}\,\mathcal{Y}\,\mathcal{W} = g \int d^2\theta \left(\ell^\alpha W_\alpha + \frac{1}{2}\Phi X - \frac{i}{2\kappa} Y\right) + h.c.$$

$\Rightarrow$ global SUSY limit of D-brane coupling to bulk hypermultiplets

$N=2$ NL QED and novel super-higgs mechanism

General action: $\mathcal{L}_{tot}^{NL} = \mathcal{L}_{CS} + \mathcal{L}_{Max}^{NL}(W) + \mathcal{L}_{ST}(L,\Phi) \Rightarrow$ [22]

superhiggs mechanism without gravity:

Maxwell goldstino $\mathcal{W}_{NL}(W)$ is 'absorbed' by $N=2$ tensor $\mathcal{Y}(L,\Phi)$

$\rightarrow N=1$ massive vector (W,L) + massless chiral Φ:

- tensor of L + vector of $W \rightarrow$ massive vector
- scalar of $L \in$ same massive vector multiplet
- goldstino + fermion of $L \rightarrow$ Dirac spinor

System identical to Higgs phase of $N=2$ NL QED (up to $\mathcal{L}_{ST}$)

$\Phi \sim Q_1 Q_2$ $\quad L \sim |Q_1|^2 - |Q_2|^2$ $\quad (Q_1, Q_2)$: charged hypermultiplet

adding mass-term $m\int d^2\theta\,\Phi \Rightarrow$ also Coulomb phase for $\xi = 0$

Vacuum structure of $N = 2$ NL QED

3 parameters: κ, ξ, m

- $m = 0$: Higgs phase and super-higgs without gravity

  $\langle Q_1 \rangle = v$ (real) arbitrary $\qquad \langle Q_2 \rangle = \sqrt{\xi + v^2}$

- $m \neq 0, \xi = 0$: Coulomb phase with $N = 2$ NL SUSY unbroken
- $m \neq 0, \xi \neq 0$: $N = 1$ (linear) SUSY is also broken [18]

Ambrosetti-I.A.-Derendinger-Tziveloglou '09