Corfu Summer Institute
14th Hellenic School and Workshops on Elementary Particle Physics and Gravity
Corfu, Greece 2014
DUBNA

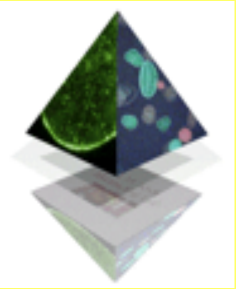
Supersymmetry in Particle Physics

1. Basics of SUSY
2. Supersymmetric SM

Dmitri Kazakov
JINR

Summer School and Workshop
on the Standard Model and Beyond
3 - 14 September 2014

What is SUSY?



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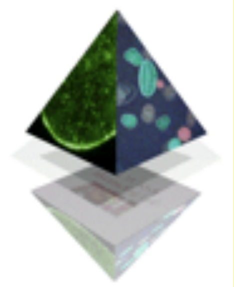

- **Supersymmetry** is a boson-fermion symmetry that is aimed to unify all forces in Nature including gravity within a singe framework

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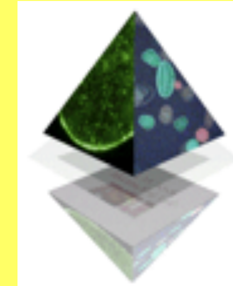

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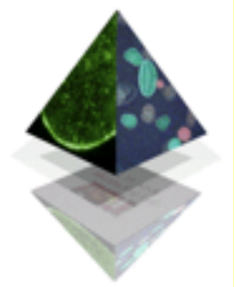

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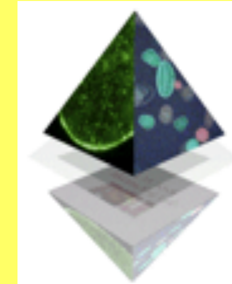

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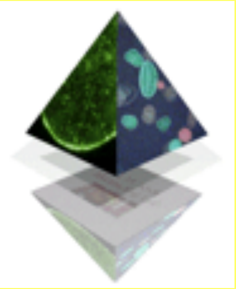

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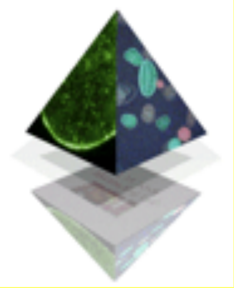
• Modern views on supersymmetry in particle physics are based on string paradigm, though low energy manifestations of SUSY can be found (?) at modern colliders and in non-accelerator experiments

What is SUSY?



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$Q|\,boson>=|\,f$ $n>$

$[b,b]$ $(\sigma^{\mu})_{\alpha\dot{\beta}}P_{\mu}$

First papers in 1971-1974

No evidence in particle physics yet

• Moder in particle physics
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Superalgebra

Superalgebra

Poincare Algebra

$$[P_\mu, P_\nu] = 0,$$
$$[P_\mu, M_{\rho\sigma}] = i(g_{\mu\rho}P_\sigma - g_{\mu\sigma}P_\rho),$$
$$[M_{\mu\nu}, M_{\rho\sigma}] = i(g_{\nu\rho}M_{\mu\sigma} - g_{\nu\sigma}M_{\mu\rho} - g_{\mu\rho}M_{\nu\sigma} + g_{\mu\sigma}M_{\nu\rho})$$

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Poincare Algebra

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New Genarators $Q_i, \ \bar{Q}_i$

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Poincare Algebra

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New Genarators $Q_i, \ \bar{Q}_i$

$$\begin{aligned}
[P_\mu, Q^I_\alpha] &= c_1(\sigma_\mu)_{\alpha\dot\alpha}\bar{Q}^{\dot\alpha I}, \\
[P_\mu, \bar{Q}^I_{\dot\alpha}] &= c_2(\tilde\sigma_\mu)_{\dot\alpha\alpha}Q^{\alpha I}, \\
[M_{\mu\nu}, Q^I_\alpha] &= c_3(\sigma_{\mu\nu})_\alpha^\beta Q^I_\beta, \\
[M_{\mu\nu}, \bar{Q}^I_{\dot\alpha}] &= c_4(\tilde\sigma_{\mu\nu})_{\dot\alpha}^{\dot\beta} Q^I_{\dot\beta}, \\
\{Q^I_\alpha, Q^J_\beta\} &= c_5\epsilon_{\alpha\beta}Z^{IJ} + \tilde{c}_5(\sigma^{\mu\nu})_{\alpha\beta}M_{\mu\nu}X^{IJ}, \\
\{\bar{Q}^I_{\dot\alpha}, \bar{Q}^J_{\dot\beta}\} &= c_6\epsilon_{\dot\alpha\dot\beta}\bar{Z}^{IJ} + \tilde{c}_6(\tilde\sigma^{\mu\nu})_{\dot\alpha\dot\beta}M_{\mu\nu}\bar{X}^{IJ}, \\
\{Q^I_\alpha, \bar{Q}^J_{\dot\alpha}\} &= 2c_7(\sigma^\mu)_{\alpha\dot\alpha}P\mu\delta^{IJ}
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New Genarators $Q_i, \ \bar{Q}_i$ Jacobi Identities

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$$
\begin{aligned}
[B_1,[B_2,B_3]] + [B_2,[B_3,B_1]] + [B_3,[B_1,B_2]] &= 0, \\
[B,\{F_1,F_1\}] + \{F_1,[F_2,B]\} - \{F_2,[B,F_1]\} &= 0, \\
[B_1,[B_2,F]] + [B_2,[F,B_1]] + [F,[B_1,B_2]] &= 0, \\
[F_1,\{F_2,F_3\}] + [F_2,\{F_3,F_1\}] + [F_3,\{B_1,B_2\}] &= 0
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[B,\{F_1,F_1\}] + \{F_1,[F_2,B]\} - \{F_2,[B,F_1]\} &= 0, \\
[B_1,[B_2,F]] + [B_2,[F,B_1]] + [F,[B_1,B_2]] &= 0, \\
[F_1,\{F_2,F_3\}] + [F_2,\{F_3,F_1\}] + [F_3,\{B_1,B_2\}] &= 0
\end{aligned}$$

$$c_1 = c_2 = \tilde{c}_5 = \tilde{c}_6 = 0, \ c_3 = c_4 = i,$$
$$c_5 = c_6 = c_7 = 1, \ X^{IJ} = \bar{X}^{IJ} = 0$$

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Super Poincare Algebra

$$
\begin{aligned}
&[Q^i_\alpha, P_\mu] = [\bar{Q}^i_{\dot\alpha}, P_\mu] = 0,\\
&[Q^i_\alpha, M_{\mu\nu}] = \tfrac{1}{2}(\sigma_{\mu\nu})^\beta_\alpha Q^i_\beta, \qquad [\bar{Q}^i_{\dot\alpha}, M_{\mu\nu}] = -\tfrac{1}{2}\bar{Q}^i_{\dot\beta}(\bar\sigma_{\mu\nu})^{\dot\beta}_{\dot\alpha},\\
&\{Q^i_\alpha, \bar{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta}P_\mu,\\
&\{Q^i_\alpha, Q^j_\beta\} = 2\epsilon_{\alpha\beta}Z^{ij}, \qquad Z^{ij} = Z^+_{ij},\\
&\{\bar{Q}^i_{\dot\alpha}, \bar{Q}^j_{\dot\beta}\} = -2\epsilon_{\dot\alpha\dot\beta}Z^{ij}, \quad [Z_{ij}, anything] = 0,\\
&\alpha, \dot\alpha = 1, 2 \qquad i, j = 1, 2, \ldots, N.
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Quantum States

Quantum states: Vacuum = $|E,\lambda>$ $Q|E,\lambda>=0$

Energy helicity

$$[Q^i_\alpha, P_\mu] = [\bar{Q}^i_{\dot{\alpha}}, P_\mu] = 0$$

State	Expression	# of states
vacuum	$\|E,\lambda>$	1
1-particle	$\overline{Q_i}\|E,\lambda>=\|E,\lambda+1/2>$	$\binom{N}{1}=N$
2-particle	$\overline{Q_i}\,\overline{Q_j}\|E,\lambda>=\|E,\lambda+1>$	$\binom{N}{2}=\frac{N(N-1)}{2}$
...	...	...
N-particle	$\overline{Q_1}\,\overline{Q_2}...\overline{Q_N}\|E,\lambda>=\|E,\lambda+N/2>$	$\binom{N}{N}=1$

Quantum States

Quantum states: Vacuum = $|E,\lambda>$ $\quad Q|E,\lambda>=0$

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Energy (E), helicity (λ)

State	Expression	# of states
vacuum	$\vert E,\lambda>$	1
1-particle	$\overline{Q_i}\vert E,\lambda>=\vert E,\lambda+1/2>$	$\begin{pmatrix} N \\ 1 \end{pmatrix} = N$
2-particle	$\overline{Q_i}\,\overline{Q_j}\vert E,\lambda>=\vert E,\lambda+1>$	$\begin{pmatrix} N \\ 2 \end{pmatrix} = \frac{N(N-1)}{2}$
...	...	...
N-particle	$\overline{Q_1}\,\overline{Q_2}...\overline{Q_N}\vert E,\lambda>=\vert E,\lambda+N/2>$	$\begin{pmatrix} N \\ N \end{pmatrix} = 1$

Total # of states: $\sum_{k=0}^{N} = 2^N = 2^{N-1}\ bosons + 2^{N-1}\ fermions$

SUSY Multiplets

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Chiral multiplet $N = 1,\ \lambda = 0$

helicity	-1/2	0	1/2
# of states	1	2	1

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(φ, ψ)

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(φ, ψ)

Vector multiplet $N = 1,\ \lambda = 1/2$

helicity	-1	-1/2	1/2	1
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(λ, A_μ) — spinor, vector

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Extended supersymmetry

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Vector multiplet $N = 1,\ \lambda = 1/2$

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(λ, A_μ) — spinor, vector

Members of a supermultiplet are called **superpartners**

Extended supersymmetry

N=4	SUSY YM	helicity	-1	–1/2	0	1/2	1				
	λ = -1	# of states	1	4	6	4	1				
N=8	SUGRA	helicity	-2	–3/2	–1	–1/2	0	1/2	1	3/2	2
	λ = -2	# of states	1	8	28	56	70	56	28	8	1

SUSY Multiplets

Chiral multiplet $N=1,\ \lambda=0$

helicity	-1/2	0	1/2
# of states	1	2	1

scalar spinor

(φ, ψ)

Vector multiplet $N=1,\ \lambda=1/2$

helicity	-1	-1/2	1/2	1
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(λ, A_μ)

spinor vector

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Extended supersymmetry

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$N \leq 4S$ ← spin

$N \leq 4$ For renormalizable theories (YM)

$N \leq 8$ For (super)gravity

Superspace

Superspace

$$\begin{array}{ccc} Space & \Rightarrow & Superspace \\ x_\mu & & x_\mu, \theta_\alpha, \bar{\theta}_{\dot{\alpha}} \end{array}$$

Superspace

$$Space \quad \Rightarrow \quad Superspace$$

$$x_\mu \qquad\qquad x_\mu, \theta_\alpha, \bar{\theta}_{\dot{\alpha}}$$

Grassmannian parameters

$\alpha, \dot{\alpha} = 1, 2$

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$$\{\theta_\alpha, \theta_\beta\} = 0, \{\bar\theta_{\dot\alpha}, \bar\theta_{\dot\beta}\} = 0, \theta_\alpha^2 = 0, \bar\theta_{\dot\alpha}^2 = 0$$

$$\theta^2 = \theta^\alpha\theta_\alpha = \epsilon_{\alpha\beta}\theta^\alpha\theta^\beta = \theta_1\theta_2 = -\theta_2\theta_1$$

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Differentiation

Superspace

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Grassmannian parameters

$\alpha, \dot{\alpha} = 1, 2$

$$\{\frac{\partial}{\partial\theta^\alpha}, \frac{\partial}{\partial\theta^\beta}\} = 0$$

<u>Differentiation</u> $\frac{\partial}{\partial\theta^\alpha}\theta^\beta = \delta_\alpha^\beta, \ \frac{\partial}{\partial\theta^\alpha}(\theta^\beta\theta^\gamma) = \delta_\alpha^\beta\theta^\gamma - \delta_\alpha^\gamma\theta^\beta$

$$(\frac{\partial}{\partial\theta^\alpha})^2 = 0$$

Superspace

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<u>Integration</u>

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$$\{\frac{\partial}{\partial\theta^\alpha}, \frac{\partial}{\partial\theta^\beta}\} = 0$$
$$(\frac{\partial}{\partial\theta^\alpha})^2 = 0$$

Integration $\int d\theta_\alpha\theta^\beta = \delta_\alpha^\beta, \qquad d^2\theta = \frac{1}{4}\epsilon^{\alpha\beta}d\theta_\alpha d\theta_\beta, \qquad \int d^2\theta\theta^2 = 1,$

Superspace

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$$x_\mu \qquad\qquad x_\mu, \theta_\alpha, \bar\theta_{\dot\alpha}$$

Grassmannian parameters

$\alpha, \dot\alpha = 1, 2$

$$\{\theta_\alpha, \theta_\beta\} = 0, \{\bar\theta_{\dot\alpha}, \bar\theta_{\dot\beta}\} = 0, \theta_\alpha^2 = 0, \bar\theta_{\dot\alpha}^2 = 0$$

$$\theta^2 = \theta^\alpha\theta_\alpha = \epsilon_{\alpha\beta}\theta^\alpha\theta^\beta = \theta_1\theta_2 = -\theta_2\theta_1$$

$$\{\frac{\partial}{\partial\theta^\alpha}, \frac{\partial}{\partial\theta^\beta}\} = 0$$

<u>Differentiation</u> $\frac{\partial}{\partial\theta^\alpha}\theta^\beta = \delta_\alpha^\beta, \; \frac{\partial}{\partial\theta^\alpha}(\theta^\beta\theta^\gamma) = \delta_\alpha^\beta\theta^\gamma - \delta_\alpha^\gamma\theta^\beta$

$$(\frac{\partial}{\partial\theta^\alpha})^2 = 0$$

<u>Integration</u> $\int d\theta_\alpha\theta^\beta = \delta_\alpha^\beta, \qquad d^2\theta = \frac{1}{4}\epsilon^{\alpha\beta}d\theta_\alpha d\theta_\beta, \qquad \int d^2\theta\theta^2 = 1,$

$$\int d\theta_\alpha F = \partial_\alpha F, \; \int d^2\theta\partial_\alpha F = 0,$$

Superspace

$$\begin{array}{ccc} Space & \Rightarrow & Superspace \\ x_\mu & & x_\mu, \theta_\alpha, \bar{\theta}_{\dot{\alpha}} \end{array}$$

Grassmannian parameters $\quad \alpha, \dot{\alpha} = 1, 2$

$$\{\theta_\alpha, \theta_\beta\} = 0, \{\bar{\theta}_{\dot{\alpha}}, \bar{\theta}_{\dot{\beta}}\} = 0, \theta_\alpha^2 = 0, \bar{\theta}_{\dot{\alpha}}^2 = 0$$

$$\theta^2 = \theta^\alpha \theta_\alpha = \epsilon_{\alpha\beta}\theta^\alpha\theta^\beta = \theta_1\theta_2 = -\theta_2\theta_1$$

$$\{\frac{\partial}{\partial\theta^\alpha}, \frac{\partial}{\partial\theta^\beta}\} = 0$$

<u>Differentiation</u> $\quad \frac{\partial}{\partial\theta^\alpha}\theta^\beta = \delta_\alpha^\beta, \; \frac{\partial}{\partial\theta^\alpha}(\theta^\beta\theta^\gamma) = \delta_\alpha^\beta\theta^\gamma - \delta_\alpha^\gamma\theta^\beta$

$$(\frac{\partial}{\partial\theta^\alpha})^2 = 0$$

<u>Integration</u> $\quad \int d\theta_\alpha \theta^\beta = \delta_\alpha^\beta, \quad d^2\theta = \frac{1}{4}\epsilon^{\alpha\beta}d\theta_\alpha d\theta_\beta, \quad \int d^2\theta\theta^2 = 1,$

$$\int d\theta_\alpha F = \partial_\alpha F, \; \int d^2\theta \partial_\alpha F = 0,$$

$$\int d^2\theta\theta^2 F(\theta) = \int d^2\theta\theta^2(a + b_\alpha\theta^\alpha + c\theta^2) = \int d^2\theta\theta^2 a = a\int d^2\theta\theta^2 = a = F(0)$$

Superspace

$$Space \Rightarrow Superspace$$
$$x_\mu \qquad x_\mu, \theta_\alpha, \bar{\theta}_{\dot{\alpha}}$$

Grassmannian parameters

$\alpha, \dot{\alpha} = 1, 2$

$$\{\theta_\alpha, \theta_\beta\} = 0, \{\bar{\theta}_{\dot{\alpha}}, \bar{\theta}_{\dot{\beta}}\} = 0, \theta_\alpha^2 = 0, \bar{\theta}_{\dot{\alpha}}^2 = 0$$

$$\theta^2 = \theta^\alpha \theta_\alpha = \epsilon_{\alpha\beta}\theta^\alpha\theta^\beta = \theta_1\theta_2 = -\theta_2\theta_1$$

<u>Differentiation</u>

$$\frac{\partial}{\partial\theta^\alpha}\theta^\beta = \delta_\alpha^\beta, \quad \frac{\partial}{\partial\theta^\alpha}(\theta^\beta\theta^\gamma) = \delta_\alpha^\beta\theta^\gamma - \delta_\alpha^\gamma\theta^\beta$$

$$\{\frac{\partial}{\partial\theta^\alpha}, \frac{\partial}{\partial\theta^\beta}\} = 0$$

$$(\frac{\partial}{\partial\theta^\alpha})^2 = 0$$

<u>Integration</u>

$$\int d\theta_\alpha \theta^\beta = \delta_\alpha^\beta, \qquad d^2\theta = \frac{1}{4}\epsilon^{\alpha\beta} d\theta_\alpha d\theta_\beta, \qquad \int d^2\theta\theta^2 = 1,$$

$$\int d\theta_\alpha F = \partial_\alpha F, \quad \int d^2\theta \partial_\alpha F = 0,$$

$$\delta^2(\theta) = \theta^2, \delta^2(\theta)|_{\theta=0} = 0$$

$$\int d^2\theta\theta^2 F(\theta) = \int d^2\theta\theta^2(a + b_\alpha\theta^\alpha + c\theta^2) = \int d^2\theta\theta^2 a = a\int d^2\theta\theta^2 = a = F(0)$$

SUSY Transformation

SUSY Transformation

$F(x, \theta, \bar{\theta})$ Superfield

SUSY Transformation

$F(x, \theta, \bar{\theta})$ Superfield

Grassmannian expansion

$$F(x,\theta,\bar\theta) = A(x) + \theta^\alpha \psi_\alpha(x) + \bar\theta_{\dot\alpha}\bar\phi^{\dot\alpha}(x) + \theta^2 F(x) + \bar\theta^2 G(x)$$
$$+(\theta\sigma^\mu\bar\theta)A_\mu(x) + \bar\theta^2\theta^\alpha\lambda_\alpha(x) + \theta^2\bar\theta_{\dot\alpha}\bar\eta^{\dot\alpha}(x) + \theta^2\bar\theta^2 D(x)$$

SUSY Transformation

$F(x,\theta,\bar{\theta})$ Superfield

Grassmannian expansion

$$F(x,\theta,\bar{\theta}) = A(x) + \theta^\alpha \psi_\alpha(x) + \bar{\theta}_{\dot{\alpha}} \bar{\phi}^{\dot{\alpha}}(x) + \theta^2 F(x) + \bar{\theta}^2 G(x)$$
$$+(\theta\sigma^\mu\bar{\theta})A_\mu(x) + \bar{\theta}^2\theta^\alpha\lambda_\alpha(x) + \theta^2\bar{\theta}_{\dot{\alpha}}\bar{\eta}^{\dot{\alpha}}(x) + \theta^2\bar{\theta}^2 D(x)$$

Supertranslation

$$x_\mu \to x_\mu + i\theta\sigma_\mu\bar{\xi} - i\xi\sigma_\mu\bar{\theta},$$
$$\theta \to \theta + \xi,$$
$$\bar{\theta} \to \bar{\theta} + \bar{\xi}$$

SUSY Transformation

$F(x,\theta,\bar{\theta})$ Superfield

Grassmannian expansion

$$F(x,\theta,\bar{\theta}) = A(x) + \theta^{\alpha}\psi_{\alpha}(x) + \bar{\theta}_{\dot{\alpha}}\bar{\phi}^{\dot{\alpha}}(x) + \theta^2 F(x) + \bar{\theta}^2 G(x)$$
$$+(\theta\sigma^{\mu}\bar{\theta})A_{\mu}(x) + \bar{\theta}^2\theta^{\alpha}\lambda_{\alpha}(x) + \theta^2\bar{\theta}_{\dot{\alpha}}\bar{\eta}^{\dot{\alpha}}(x) + \theta^2\bar{\theta}^2 D(x)$$

Supertranslation

$$x_{\mu} \to x_{\mu} + i\theta\sigma_{\mu}\bar{\xi} - i\xi\sigma_{\mu}\bar{\theta},$$
$$\theta \to \theta + \xi,$$
$$\bar{\theta} \to \bar{\theta} + \bar{\xi}$$

Scalar Superfield $F'(x',\theta',\bar{\theta}') = F(x,\theta,\bar{\theta})$

$$\delta F(x,\theta,\bar{\theta}) = i(\epsilon^{\alpha}Q_{\alpha} + \bar{\epsilon}_{\dot{\alpha}}\bar{Q}^{\dot{\alpha}})F(x,\theta,\bar{\theta})$$

SUSY Transformation

$F(x,\theta,\bar{\theta})$ Superfield

Grassmannian expansion

$$F(x,\theta,\bar{\theta}) = A(x) + \theta^{\alpha}\psi_{\alpha}(x) + \bar{\theta}_{\dot{\alpha}}\bar{\phi}^{\dot{\alpha}}(x) + \theta^2 F(x) + \bar{\theta}^2 G(x)$$
$$+(\theta\sigma^{\mu}\bar{\theta})A_{\mu}(x) + \bar{\theta}^2\theta^{\alpha}\lambda_{\alpha}(x) + \theta^2\bar{\theta}_{\dot{\alpha}}\bar{\eta}^{\dot{\alpha}}(x) + \theta^2\bar{\theta}^2 D(x)$$

Supertranslation

$$x_{\mu} \to x_{\mu} + i\theta\sigma_{\mu}\bar{\xi} - i\xi\sigma_{\mu}\bar{\theta},$$
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$$\delta F(x,\theta,\bar{\theta}) = i(\epsilon^{\alpha}Q_{\alpha} + \bar{\epsilon}_{\dot{\alpha}}\bar{Q}^{\dot{\alpha}})F(x,\theta,\bar{\theta})$$

SUSY Generators

$$\{Q_{\alpha},Q_{\beta}\} = 0, \{\bar{Q}_{\dot{\alpha}},\bar{Q}_{\dot{\beta}}\} = 0,$$
$$\{Q_{\alpha},\bar{Q}_{\dot{\alpha}}\} = 2(\sigma^{\mu})_{\alpha\dot{\alpha}}P_{\mu}$$

SUSY Transformation

$F(x,\theta,\bar{\theta})$ Superfield

Grassmannian expansion

$$F(x,\theta,\bar{\theta}) = A(x) + \theta^{\alpha}\psi_{\alpha}(x) + \bar{\theta}_{\dot{\alpha}}\bar{\phi}^{\dot{\alpha}}(x) + \theta^2 F(x) + \bar{\theta}^2 G(x)$$
$$+(\theta\sigma^{\mu}\bar{\theta})A_{\mu}(x) + \bar{\theta}^2\theta^{\alpha}\lambda_{\alpha}(x) + \theta^2\bar{\theta}_{\dot{\alpha}}\bar{\eta}^{\dot{\alpha}}(x) + \theta^2\bar{\theta}^2 D(x)$$

Supertranslation

$$x_{\mu} \to x_{\mu} + i\theta\sigma_{\mu}\bar{\xi} - i\xi\sigma_{\mu}\bar{\theta},$$
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$$\{Q_{\alpha},Q_{\beta}\} = 0, \{\bar{Q}_{\dot{\alpha}},\bar{Q}_{\dot{\beta}}\} = 0,$$
$$\{Q_{\alpha},\bar{Q}_{\dot{\alpha}}\} = 2(\sigma^{\mu})_{\alpha\dot{\alpha}}P_{\mu}$$

Supertranslation $G(x,\theta,\bar{\theta}) = e^{i(-x^{\mu}P_{\mu} + \theta Q + \bar{\theta}\bar{Q})}.$

SUSY Transformation

$F(x,\theta,\bar\theta)$ Superfield

Grassmannian expansion

$$F(x,\theta,\bar\theta) = A(x) + \theta^\alpha\psi_\alpha(x) + \bar\theta_{\dot\alpha}\bar\phi^{\dot\alpha}(x) + \theta^2 F(x) + \bar\theta^2 G(x)$$
$$+(\theta\sigma^\mu\bar\theta)A_\mu(x) + \bar\theta^2\theta^\alpha\lambda_\alpha(x) + \theta^2\bar\theta_{\dot\alpha}\bar\eta^{\dot\alpha}(x) + \theta^2\bar\theta^2 D(x)$$

Supertranslation

$$x_\mu \to x_\mu + i\theta\sigma_\mu\bar\xi - i\xi\sigma_\mu\bar\theta,$$
$$\theta \to \theta + \xi,$$
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Scalar Superfield $F'(x',\theta,'\bar\theta') = F(x,\theta,\bar\theta)$

$$\delta F(x,\theta,\bar\theta) = i(\epsilon^\alpha Q_\alpha + \bar\epsilon_{\dot\alpha}\bar Q^{\dot\alpha})F(x,\theta,\bar\theta)$$

SUSY Generators

$$\{Q_\alpha, Q_\beta\} = 0, \{\bar Q_{\dot\alpha}, \bar Q_{\dot\beta}\} = 0,$$
$$\{Q_\alpha, \bar Q_{\dot\alpha}\} = 2(\sigma^\mu)_{\alpha\dot\alpha}P_\mu$$

Supertranslation

$$G(x,\theta,\bar\theta) = e^{i(-x^\mu P_\mu + \theta Q + \bar\theta\bar Q)}.$$

$$Q_\alpha = \frac{\partial}{\partial\theta_\alpha} - i\sigma^\mu_{\alpha\dot\alpha}\bar\theta^{\dot\alpha}\partial_\mu, \quad \bar Q_{\dot\alpha} = -\frac{\partial}{\partial\bar\theta_{\dot\alpha}} + i\theta_\alpha\sigma^\mu_{\alpha\dot\alpha}\partial_\mu.$$

Matter (Chiral) Superfield

Matter (Chiral) Superfield

$F(x, \theta, \bar{\theta})$ General superfield - reducible representation

Matter (Chiral) Superfield

$F(x,\theta,\bar{\theta})$ General superfield - reducible representation

$$F(x,\theta,\bar{\theta}) = \Phi(y,\theta) + \bar{\Phi}(y,\theta) + V(x,\theta,\bar{\theta})$$

Matter (Chiral) Superfield

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$$F(x, \theta, \bar{\theta}) = \Phi(y, \theta) + \bar{\Phi}(y, \theta) + V(x, \theta, \bar{\theta})$$

Chiral superfield

Matter (Chiral) Superfield

$F(x, \theta, \bar{\theta})$ General superfield - reducible representation

$$F(x, \theta, \bar{\theta}) = \Phi(y, \theta) + \bar{\Phi}(y, \theta) + V(x, \theta, \bar{\theta})$$ ← Real superfield

↗ Chiral superfield

Matter (Chiral) Superfield

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$$F(x, \theta, \bar{\theta}) = \Phi(y, \theta) + \bar{\Phi}(y, \theta) + V(x, \theta, \bar{\theta})$$ ← Real superfield

Chiral superfield

$$\partial^{\dot{\alpha}} \Phi(x, \theta, \bar{\theta}) = 0$$

Matter (Chiral) Superfield

$F(x,\theta,\bar\theta)$ General superfield - reducible representation

$$F(x,\theta,\bar\theta) = \Phi(y,\theta) + \bar\Phi(y,\theta) + V(x,\theta,\bar\theta)$$ ← Real superfield

Chiral superfield ↗

$$\partial^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0 \quad \longrightarrow \quad \bar D^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0$$

Matter (Chiral) Superfield

$F(x,\theta,\bar\theta)$ General superfield - reducible representation

$F(x,\theta,\bar\theta) = \Phi(y,\theta) + \bar\Phi(y,\theta) + V(x,\theta,\bar\theta)$ ← Real superfield

Chiral superfield

SUSY covariant derivative

$\partial^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0$ → $\bar D^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0$

Matter (Chiral) Superfield

$F(x,\theta,\bar{\theta})$ General superfield - reducible representation

$$F(x,\theta,\bar{\theta}) = \Phi(y,\theta) + \bar{\Phi}(y,\theta) + V(x,\theta,\bar{\theta})$$ ← Real superfield

Chiral superfield

SUSY covariant derivative

$$\partial^{\dot{\alpha}}\Phi(x,\theta,\bar{\theta}) = 0 \rightarrow \bar{D}^{\dot{\alpha}}\Phi(x,\theta,\bar{\theta}) = 0$$

$$D_\alpha = \frac{\partial}{\partial\vartheta_\alpha} + i\sigma^\mu_{\alpha\dot{\alpha}}\bar{\vartheta}^{\dot{\alpha}}\partial_\mu$$

$$\bar{D}_{\dot{\alpha}} = -\frac{\partial}{\partial\bar{\theta}_{\dot{\alpha}}} - i\theta_{\dot{\alpha}}\sigma^\mu_{\alpha\dot{\alpha}}\partial_\mu$$

Matter (Chiral) Superfield

$F(x,\theta,\bar\theta)$ General superfield - reducible representation

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Chiral superfield

SUSY covariant derivative

$\partial^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0$ → $\bar D^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0$

$$D_\alpha = \frac{\partial}{\partial\vartheta_\alpha} + i\sigma^\mu_{\alpha\dot\alpha}\bar\vartheta^{\dot\alpha}\partial_\mu$$

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$\Phi(x,\theta,\bar\theta) = e^{i\theta\sigma_\mu\bar\theta}\Phi(x,\theta) = \Phi(y,\theta)$ $(y = x + i\theta\sigma\bar\theta)$

Matter (Chiral) Superfield

$F(x,\theta,\bar{\theta})$ General superfield - reducible representation

$F(x,\theta,\bar{\theta}) = \Phi(y,\theta) + \bar{\Phi}(y,\theta) + V(x,\theta,\bar{\theta})$ ← Real superfield

Chiral superfield

SUSY covariant derivative

$\partial^{\dot{\alpha}}\Phi(x,\theta,\bar{\theta}) = 0 \rightarrow \bar{D}^{\dot{\alpha}}\Phi(x,\theta,\bar{\theta}) = 0$

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$\Phi(x,\theta,\bar{\theta}) = e^{i\theta\sigma_\mu\bar{\theta}}\Phi(x,\theta) = \Phi(y,\theta)$ $(y = x + i\theta\sigma\bar{\theta})$

Expansion over Grassmannian parameter

$\theta^2 = \theta_1\theta_2, \quad \theta_1^2 = \theta_2^2 = 0!$

Matter (Chiral) Superfield

$F(x,\theta,\bar\theta)$ General superfield - reducible representation

$F(x,\theta,\bar\theta) = \Phi(y,\theta) + \bar\Phi(y,\theta) + V(x,\theta,\bar\theta)$ ← Real superfield

Chiral superfield

SUSY covariant derivative

$\partial^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0$ → $\bar D^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0$

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$\Phi(x,\theta,\bar\theta) = e^{i\theta\sigma_\mu\bar\theta}\Phi(x,\theta) = \Phi(y,\theta)$ $\quad (y = x + i\theta\sigma\bar\theta)$

Expansion over Grassmannian parameter

$\theta^2 = \theta_1\theta_2, \quad \theta_1^2 = \theta_2^2 = 0!$

$$\Phi(y,\theta) = A(y) + \sqrt{2}\theta\psi(y) + \theta\theta F(y)$$
$$= A(x) + i\theta\sigma^\mu\bar\theta\partial_\mu A(x) + \tfrac{1}{4}\theta\theta\bar\theta\bar\theta\Box A(x)$$
$$+ \sqrt{2}\theta\psi(x) - i/\sqrt{2}\theta\theta\partial_\mu\psi(x)\sigma^\mu\bar\theta + \theta\theta F(x)$$

Matter (Chiral) Superfield

$F(x,\theta,\bar\theta)$ General superfield - reducible representation

$F(x,\theta,\bar\theta) = \Phi(y,\theta) + \bar\Phi(y,\theta) + V(x,\theta,\bar\theta)$ ← Real superfield

Chiral superfield

SUSY covariant derivative

$\partial^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0 \rightarrow \bar D^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0$

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$\Phi(x,\theta,\bar\theta) = e^{i\theta\sigma_\mu\bar\theta}\Phi(x,\theta) = \Phi(y,\theta)$ $(y = x + i\theta\sigma\bar\theta)$

Expansion over Grassmannian parameter

$\theta^2 = \theta_1\theta_2, \quad \theta_1^2 = \theta_2^2 = 0!$

superfield →

$$\Phi(y,\theta) = A(y) + \sqrt{2}\theta\psi(y) + \theta\theta F(y)$$
$$= A(x) + i\theta\sigma^\mu\bar\theta\partial_\mu A(x) + \tfrac{1}{4}\theta\theta\bar\theta\bar\theta\Box A(x)$$
$$+\sqrt{2}\theta\psi(x) - i/\sqrt{2}\theta\theta\partial_\mu\psi(x)\sigma^\mu\bar\theta + \theta\theta F(x)$$

Matter (Chiral) Superfield

$F(x,\theta,\bar\theta)$ General superfield - reducible representation

$F(x,\theta,\bar\theta) = \Phi(y,\theta) + \bar\Phi(y,\theta) + V(x,\theta,\bar\theta)$ ← Real superfield

Chiral superfield

SUSY covariant derivative

$\partial^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0 \rightarrow \bar D^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0$

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$\Phi(x,\theta,\bar\theta) = e^{i\theta\sigma_\mu\bar\theta}\Phi(x,\theta) = \Phi(y,\theta) \quad (y = x + i\theta\sigma\bar\theta)$

Expansion over Grassmannian parameter

$\theta^2 = \theta_1\theta_2, \quad \theta_1^2 = \theta_2^2 = 0!$

superfield →

$$\Phi(y,\theta) = A(y) + \sqrt{2}\theta\psi(y) + \theta\theta F(y)$$

$$= A(x) + i\theta\sigma^\mu\bar\theta\partial_\mu A(x) + \tfrac{1}{4}\theta\theta\bar\theta\bar\theta\Box A(x)$$

$$+ \sqrt{2}\theta\psi(x) - i/\sqrt{2}\theta\theta\partial_\mu\psi(x)\sigma^\mu\bar\theta + \theta\theta F(x)$$

component fields

Matter (Chiral) Superfield

$F(x,\theta,\bar\theta)$ General superfield - reducible representation

$$F(x,\theta,\bar\theta) = \Phi(y,\theta) + \bar\Phi(y,\theta) + V(x,\theta,\bar\theta)$$ ← Real superfield

Chiral superfield

SUSY covariant derivative

$$\partial^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0 \rightarrow \bar D^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0$$

$$D_\alpha = \frac{\partial}{\partial\vartheta_\alpha} + i\sigma^\mu_{\alpha\dot\alpha}\bar\vartheta^{\dot\alpha}\partial_\mu$$

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$$\Phi(x,\theta,\bar\theta) = e^{i\theta\sigma_\mu\bar\theta}\Phi(x,\theta) = \Phi(y,\theta) \qquad (y = x + i\theta\sigma\bar\theta)$$

Expansion over Grassmannian parameter

$$\theta^2 = \theta_1\theta_2, \quad \theta_1^2 = \theta_2^2 = 0!$$

superfield →

$$\Phi(y,\theta) = A(y) + \sqrt{2}\theta\psi(y) + \theta\theta F(y)$$

$$= A(x) + i\theta\sigma^\mu\bar\theta\partial_\mu A(x) + \tfrac{1}{4}\theta\theta\bar\theta\bar\theta\Box A(x)$$

$$+ \sqrt{2}\theta\psi(x) - i/\sqrt{2}\theta\theta\partial_\mu\psi(x)\sigma^\mu\bar\theta + \theta\theta F(x)$$

spin=0

component fields

Matter (Chiral) Superfield

$F(x,\theta,\bar\theta)$ General superfield - reducible representation

$F(x,\theta,\bar\theta) = \Phi(y,\theta) + \bar\Phi(y,\theta) + V(x,\theta,\bar\theta)$ ← Real superfield

Chiral superfield

SUSY covariant derivative

$\partial^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0 \rightarrow \bar D^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0$

$$D_\alpha = \frac{\partial}{\partial\vartheta_\alpha} + i\sigma^\mu_{\alpha\dot\alpha}\bar\vartheta^{\dot\alpha}\partial_\mu$$

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$\Phi(x,\theta,\bar\theta) = e^{i\theta\sigma_\mu\bar\theta}\Phi(x,\theta) = \Phi(y,\theta)$ $(y = x + i\theta\sigma\bar\theta)$

Expansion over Grassmannian parameter

$\theta^2 = \theta_1\theta_2, \quad \theta_1^2 = \theta_2^2 = 0!$

superfield →

$$\Phi(y,\theta) = A(y) + \sqrt{2}\theta\psi(y) + \theta\theta F(y)$$
$$= A(x) + i\theta\sigma^\mu\bar\theta\partial_\mu A(x) + \tfrac{1}{4}\theta\theta\bar\theta\bar\theta\Box A(x)$$
$$+ \sqrt{2}\theta\psi(x) - i/\sqrt{2}\theta\theta\partial_\mu\psi(x)\sigma^\mu\bar\theta + \theta\theta F(x)$$

component fields: spin=0, spin=1/2

Matter (Chiral) Superfield

$F(x,\theta,\bar\theta)$ General superfield - reducible representation

$F(x,\theta,\bar\theta) = \Phi(y,\theta) + \bar\Phi(y,\theta) + V(x,\theta,\bar\theta)$ ← Real superfield

Chiral superfield

SUSY covariant derivative

$\partial^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0 \rightarrow \bar D^{\dot\alpha}\Phi(x,\theta,\bar\theta) = 0$

$$D_\alpha = \frac{\partial}{\partial\vartheta_\alpha} + i\sigma^\mu_{\alpha\dot\alpha}\bar\vartheta^{\dot\alpha}\partial_\mu$$

$$\bar D_{\dot\alpha} = -\frac{\partial}{\partial\bar\theta_{\dot\alpha}} - i\theta_{\dot\alpha}\sigma^\mu_{\alpha\dot\alpha}\partial_\mu$$

$\Phi(x,\theta,\bar\theta) = e^{i\theta\sigma_\mu\bar\theta}\Phi(x,\theta) = \Phi(y,\theta)$ $(y = x + i\theta\sigma\bar\theta)$

Expansion over Grassmannian parameter

$\theta^2 = \theta_1\theta_2, \quad \theta_1^2 = \theta_2^2 = 0!$

superfield →

$$\Phi(y,\theta) = A(y) + \sqrt{2}\theta\psi(y) + \theta\theta F(y)$$

$$= A(x) + i\theta\sigma^\mu\bar\theta\partial_\mu A(x) + \tfrac{1}{4}\theta\theta\bar\theta\bar\theta\Box A(x)$$

$$+ \sqrt{2}\theta\psi(x) - i/\sqrt{2}\theta\theta\partial_\mu\psi(x)\sigma^\mu\bar\theta + \theta\theta F(x)$$

component fields: spin=0, spin=1/2, spin=0

SUSY Transformation

Chiral superfield

$$\delta\Phi = i(\epsilon^\alpha Q_\alpha + \bar{\epsilon}_{\dot{\alpha}}\bar{Q}^{\dot{\alpha}})\Phi$$

parameter of SUSY transformation (spinor)

spin=0 → $\delta_\varepsilon A = \sqrt{2}\varepsilon\psi$,

spin=1/2 → $\delta_\varepsilon \psi = i\sqrt{2}\sigma^\mu \bar{\varepsilon}\partial_\mu A + \sqrt{2}\varepsilon F$,

$\delta_\varepsilon F = i\sqrt{2}\bar{\varepsilon}\sigma^\mu \partial_\mu \psi$

Auxiliary field

(unphysical d.o.f. needed to close SYSY algebra)

SUSY Transformation

Chiral superfield

$$\delta\Phi = i(\epsilon^{\alpha} Q_{\alpha} + \bar{\epsilon}_{\dot{\alpha}} \bar{Q}^{\dot{\alpha}})\Phi$$

parameter of SUSY transformation (spinor)

spin=0 → $\delta_{\varepsilon} A = \sqrt{2}\varepsilon\psi,$

spin=1/2 → $\delta_{\varepsilon}\psi = i\sqrt{2}\sigma^{\mu}\bar{\varepsilon}\partial_{\mu}A + \sqrt{2}\varepsilon F,$

$\delta_{\varepsilon} F = i\sqrt{2}\bar{\varepsilon}\sigma^{\mu}\partial_{\mu}\psi$

Auxiliary field

(unphysical d.o.f. needed to close SYSY algebra)

F-component transforms as a total derivative

SUSY Transformation

Chiral superfield $\delta\Phi = i(\epsilon^\alpha Q_\alpha + \bar{\epsilon}_{\dot{\alpha}}\bar{Q}^{\dot{\alpha}})\Phi$

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SUSY Transformation

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Auxiliary field

(unphysical d.o.f. needed to close SYSY algebra)

F-component transforms as a total derivative → $\Phi\big|_{\theta\theta}$ is SUSY invariant

Superpotential - chiral superfield

$$\mathcal{W}(\Phi_i) = \mathcal{W}(A_i + \sqrt{2}\theta\psi_i + \theta\theta F)$$

$$= \mathcal{W}(A_i) + \frac{\partial\mathcal{W}}{\partial A_i}\sqrt{2}\theta\psi_i + \theta\theta\left(\frac{\partial\mathcal{W}}{\partial A_i}F_i - \frac{1}{2}\frac{\partial^2\mathcal{W}}{\partial A_i\partial A_j}\psi_i\psi_j\right)$$

SUSY Transformation

Chiral superfield

$$\delta\Phi = i(\epsilon^\alpha Q_\alpha + \bar{\epsilon}_{\dot{\alpha}}\bar{Q}^{\dot{\alpha}})\Phi$$

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$$\delta_\varepsilon F = i\sqrt{2}\bar{\varepsilon}\sigma^\mu\partial_\mu\psi$$

Auxiliary field

(unphysical d.o.f. needed to close SYSY algebra)

F-component transforms as a total derivative → $\Phi|_{\theta\theta}$ is SUSY invariant

Superpotential - chiral superfield

$\mathcal{W}|_{\theta\theta}$ is SUSY invariant

$$\mathcal{W}(\Phi_i) = \mathcal{W}(A_i + \sqrt{2}\theta\psi_i + \theta\theta F)$$

$$= \mathcal{W}(A_i) + \frac{\partial\mathcal{W}}{\partial A_i}\sqrt{2}\theta\psi_i + \theta\theta\left(\frac{\partial\mathcal{W}}{\partial A_i}F_i - \frac{1}{2}\frac{\partial^2\mathcal{W}}{\partial A_i\partial A_j}\psi_i\psi_j\right)$$

Gauge superfields

Gauge superfield

$$V(x,\theta,\bar\theta) = C(x) + i\theta\chi(x) - i\bar\theta\bar\chi(x) + i\theta\theta M(x) - i\bar\theta\bar\theta M^{+}(x)$$
$$-\theta\sigma^{\mu}\bar\theta v_{\mu}(x) + i\theta\theta\bar\theta[\bar\lambda(x) + i\bar\sigma^{\mu}\partial_{\mu}\chi(x)] - i\bar\theta\bar\theta\theta[\lambda(x) + i\sigma^{\mu}\partial_{\mu}\bar\chi(x)]$$
$$+\tfrac{1}{2}\theta\theta\bar\theta\bar\theta[D(x) + \tfrac{1}{2}\Box C(x)]$$

Gauge superfields

Gauge superfield

$$V(x,\theta,\bar{\theta}) = C(x) + i\theta\chi(x) - i\bar{\theta}\bar{\chi}(x) + i\theta\theta M(x) - i\bar{\theta}\bar{\theta}M^{+}(x)$$

$$-\theta\sigma^{\mu}\bar{\theta}v_{\mu}(x) + i\theta\theta\bar{\theta}[\bar{\lambda}(x) + i\bar{\sigma}^{\mu}\partial_{\mu}\chi(x)] - i\bar{\theta}\bar{\theta}\theta[\lambda(x) + i\sigma^{\mu}\partial_{\mu}\bar{\chi}(x)]$$

$$+\tfrac{1}{2}\theta\theta\bar{\theta}\bar{\theta}[D(x) + \tfrac{1}{2}\Box C(x)]$$

SUSY transformation

$$\begin{aligned}
\delta C &= \sqrt{2}\epsilon^{\alpha}\chi_{\alpha}, \\
\delta\chi_{\alpha} &= i\sqrt{2}(\sigma^{\mu})_{\alpha\dot{\alpha}}\bar{\epsilon}^{\dot{\alpha}}\partial_{\mu}C + \sqrt{2}\epsilon_{\alpha}M, \\
\delta M &= i\sqrt{2}\bar{\epsilon}^{\dot{\alpha}}(\tilde{\sigma}^{\mu})_{\dot{\alpha}\alpha}\partial_{\mu}\chi^{\alpha} + i2C\bar{\epsilon}^{\dot{\alpha}}\bar{\lambda}_{\dot{\alpha}}, \\
\delta v_{\mu} &= -i\bar{\lambda}^{\dot{\alpha}}(\tilde{\sigma}_{\mu})_{\dot{\alpha}\alpha}\epsilon^{\alpha} + i\bar{\epsilon}^{\dot{\alpha}}(\tilde{\sigma}_{\mu})_{\alpha\dot{\alpha}}\lambda^{\alpha}, \\
\delta\lambda_{\alpha} &= (\sigma^{\mu\nu})_{\alpha\dot{\alpha}}\bar{\epsilon}^{\dot{\alpha}}v_{\mu\nu} + i\epsilon_{\alpha}D, \\
\delta D &= \bar{\epsilon}^{\dot{\alpha}}(\tilde{\sigma}^{\mu})_{\dot{\alpha}\alpha}\partial_{\mu}\lambda^{\alpha} - \epsilon^{\alpha}(\sigma^{\mu})_{\alpha\dot{\alpha}}\partial_{\mu}\bar{\lambda}^{\dot{\alpha}}
\end{aligned}$$

Gauge superfields

Gauge superfield

$$V(x,\theta,\bar\theta) = C(x) + i\theta\chi(x) - i\bar\theta\bar\chi(x) + i\theta\theta M(x) - i\bar\theta\bar\theta M^{+}(x)$$
$$-\theta\sigma^{\mu}\bar\theta v_{\mu}(x) + i\theta\theta\bar\theta[\bar\lambda(x) + i\bar\sigma^{\mu}\partial_{\mu}\chi(x)] - i\bar\theta\bar\theta\theta[\lambda(x) + i\sigma^{\mu}\partial_{\mu}\bar\chi(x)]$$
$$+\tfrac{1}{2}\theta\theta\bar\theta\bar\theta[D(x) + \tfrac{1}{2}\Box C(x)]$$

SUSY transformation

$$\begin{aligned}
\delta C &= \sqrt{2}\epsilon^{\alpha}\chi_{\alpha}, \\
\delta\chi_{\alpha} &= i\sqrt{2}(\sigma^{\mu})_{\alpha\dot\alpha}\bar\epsilon^{\dot\alpha}\partial_{\mu}C + \sqrt{2}\epsilon_{\alpha}M, \\
\delta M &= i\sqrt{2}\bar\epsilon^{\dot\alpha}(\tilde\sigma^{\mu})_{\dot\alpha\alpha}\partial_{\mu}\chi^{\alpha} + i2C\bar\epsilon^{\dot\alpha}\bar\lambda_{\dot\alpha}, \\
\delta v_{\mu} &= -i\bar\lambda^{\dot\alpha}(\tilde\sigma_{\mu})_{\dot\alpha\alpha}\epsilon^{\alpha} + i\bar\epsilon^{\dot\alpha}(\tilde\sigma_{\mu})_{\alpha\dot\alpha}\lambda^{\alpha}, \\
\delta\lambda_{\alpha} &= (\sigma^{\mu\nu})_{\alpha\dot\alpha}\bar\epsilon^{\dot\alpha}v_{\mu\nu} + i\epsilon_{\alpha}D, \\
\delta D &= \bar\epsilon^{\dot\alpha}(\tilde\sigma^{\mu})_{\dot\alpha\alpha}\partial_{\mu}\lambda^{\alpha} - \epsilon^{\alpha}(\sigma^{\mu})_{\alpha\dot\alpha}\partial_{\mu}\bar\lambda^{\dot\alpha}
\end{aligned}$$

D-component transforms as a total derivative

Gauge superfields

Gauge superfield

$$V(x,\theta,\bar{\theta}) = C(x) + i\theta\chi(x) - i\bar{\theta}\bar{\chi}(x) + i\theta\theta M(x) - i\bar{\theta}\bar{\theta} M^{+}(x)$$

$$-\theta\sigma^{\mu}\bar{\theta} v_{\mu}(x) + i\theta\theta\bar{\theta}[\bar{\lambda}(x) + i\bar{\sigma}^{\mu}\partial_{\mu}\chi(x)] - i\bar{\theta}\bar{\theta}\theta[\lambda(x) + i\sigma^{\mu}\partial_{\mu}\bar{\chi}(x)]$$

$$+\tfrac{1}{2}\theta\theta\bar{\theta}\bar{\theta}[D(x) + \tfrac{1}{2}\Box C(x)]$$

SUSY transformation

$$\begin{aligned}
\delta C &= \sqrt{2}\epsilon^{\alpha}\chi_{\alpha}, \\
\delta\chi_{\alpha} &= i\sqrt{2}(\sigma^{\mu})_{\alpha\dot{\alpha}}\bar{\epsilon}^{\dot{\alpha}}\partial_{\mu}C + \sqrt{2}\epsilon_{\alpha}M, \\
\delta M &= i\sqrt{2}\bar{\epsilon}^{\dot{\alpha}}(\tilde{\sigma}^{\mu})_{\dot{\alpha}\alpha}\partial_{\mu}\chi^{\alpha} + i2C\bar{\epsilon}^{\dot{\alpha}}\bar{\lambda}_{\dot{\alpha}}, \\
\delta v_{\mu} &= -i\bar{\lambda}^{\dot{\alpha}}(\tilde{\sigma}_{\mu})_{\dot{\alpha}\alpha}\epsilon^{\alpha} + i\bar{\epsilon}^{\dot{\alpha}}(\tilde{\sigma}_{\mu})_{\alpha\dot{\alpha}}\lambda^{\alpha}, \\
\delta\lambda_{\alpha} &= (\sigma^{\mu\nu})_{\alpha\dot{\alpha}}\bar{\epsilon}^{\dot{\alpha}}v_{\mu\nu} + i\epsilon_{\alpha}D, \\
\delta D &= \bar{\epsilon}^{\dot{\alpha}}(\tilde{\sigma}^{\mu})_{\dot{\alpha}\alpha}\partial_{\mu}\lambda^{\alpha} - \epsilon^{\alpha}(\sigma^{\mu})_{\alpha\dot{\alpha}}\partial_{\mu}\bar{\lambda}^{\dot{\alpha}}
\end{aligned}$$

D-component transforms as a total derivative $D\big|_{\theta\theta\bar{\theta}\bar{\theta}}$ is SUSY invariant

Gauge superfields

Gauge transformation $V \to V + \Phi + \overline{\Phi}$

$C \to C + A + A^*$
$\chi \to \chi - i\sqrt{2}\psi$
$M \to M - 2iF$
$v_\mu \to v_\mu - i\partial_\mu (A - A^*)$
$\lambda \to \lambda$
$D \to D$

Wess-Zumino gauge

$$C = \chi = M = 0$$

physical fields

Field strength tensor

$$W_\alpha = -\tfrac{1}{4}\overline{D}^2 e^V D_\alpha e^{-V}$$

$$\bar{W}_{\dot{\alpha}} = -\frac{1}{4} D^2 e^V \bar{D}_{\dot{\alpha}} e^{-V}$$

in WZ gauge

$$W_\alpha = -i\lambda_\alpha + \theta_\alpha D - \tfrac{i}{2}(\sigma^\mu \overline{\sigma}^\nu \theta)_\alpha F_{\mu\nu} + \theta^2 \sigma^\mu D_\mu \overline{\lambda}$$

$\bar{D} W_\alpha = 0, \; D\bar{W}_{\dot{\alpha}} = 0$ Chiral (anti-chiral) fields

$$W^\alpha W_\alpha|_{\theta\theta} = -2i\lambda\sigma^\mu D_\mu \bar{\lambda} - \frac{1}{2} F_{\mu\nu}F^{\mu\nu} + \frac{1}{2} D^2 + i\frac{1}{4} F^{\mu\nu}F^{\rho\sigma}\epsilon_{\mu\nu\rho\sigma}$$

The usual kinetic terms for the gauge field and its spinor superpartner

D-term has no derivative

SUSY Lagrangians

Superfields

$$L = \Phi_i^+ \Phi \,|_{\theta\theta\bar{\theta}\bar{\theta}} + [(\lambda_i \Phi_i + \tfrac{1}{2} m_{ij} \Phi_i \Phi_j + \tfrac{1}{3} y_{ijk} \Phi_i \Phi_j \Phi_k)\,|_{\theta\theta} + h.c.]$$

SUSY Lagrangians

Superfields

$$L = \Phi_i^+ \Phi \Big|_{\theta\theta\bar{\theta}\bar{\theta}} + [(\lambda_i \Phi_i + \tfrac{1}{2} m_{ij} \Phi_i \Phi_j + \tfrac{1}{3} y_{ijk} \Phi_i \Phi_j \Phi_k) \Big|_{\theta\theta} + h.c.]$$

Components

SUSY Lagrangians

Superfields

$$L = \Phi_i^+ \Phi \big|_{\theta\theta\bar{\theta}\bar{\theta}} + [(\lambda_i \Phi_i + \tfrac{1}{2} m_{ij} \Phi_i \Phi_j + \tfrac{1}{3} y_{ijk} \Phi_i \Phi_j \Phi_k) \big|_{\theta\theta} + h.c.]$$

Components

$$L = i\partial_\mu \bar{\psi}_i \bar{\sigma}^\mu \psi_i + A_i^* \Box A_i + F_i^* F_i$$
$$+ [\lambda_i F_i + m_{ij}(A_i F_j - \tfrac{1}{2}\psi_i \psi_j) + y_{ijk}(A_i A_j F_k - \psi_i \psi_j A_k) + h.c.]$$

SUSY Lagrangians

Superfields

$$L = \Phi_i^+ \Phi \big|_{\theta\theta\bar{\theta}\bar{\theta}} + [(\lambda_i \Phi_i + \tfrac{1}{2} m_{ij} \Phi_i \Phi_j + \tfrac{1}{3} y_{ijk} \Phi_i \Phi_j \Phi_k) \big|_{\theta\theta} + h.c.]$$

Components

$$L = i\partial_\mu \bar{\psi}_i \bar{\sigma}^\mu \psi_i + A_i^* \Box A_i + F_i^* F_i$$

no derivatives

$$+ \ [\lambda_i F_i + m_{ij}(A_i F_j - \tfrac{1}{2}\psi_i \psi_j) + y_{ijk}(A_i A_j F_k - \psi_i \psi_j A_k) + h.c.]$$

SUSY Lagrangians

Superfields

$$L = \Phi_i^+ \Phi \,|_{\theta\theta\bar{\theta}\bar{\theta}} + [(\lambda_i \Phi_i + \tfrac{1}{2} m_{ij} \Phi_i \Phi_j + \tfrac{1}{3} y_{ijk} \Phi_i \Phi_j \Phi_k)\,|_{\theta\theta} + h.c.]$$

Components

$$L = i\partial_\mu \bar{\psi}_i \bar{\sigma}^\mu \psi_i + A_i^* \Box A_i + F_i^* F_i$$

no derivatives

$$+ \; [\lambda_i F_i + m_{ij}(A_i F_j - \tfrac{1}{2}\psi_i \psi_j) + y_{ijk}(A_i A_j F_k - \psi_i \psi_j A_k) + h.c.]$$

Constraint

SUSY Lagrangians

Superfields

$$L = \Phi_i^{+}\Phi\,|_{\theta\theta\bar{\theta}\bar{\theta}} + [(\lambda_i\Phi_i + \tfrac{1}{2}m_{ij}\Phi_i\Phi_j + \tfrac{1}{3}y_{ijk}\Phi_i\Phi_j\Phi_k)\,|_{\theta\theta} + h.c.]$$

Components

$$L = i\partial_\mu\bar{\psi}_i\bar{\sigma}^\mu\psi_i + A_i^*\Box A_i + F_i^*F_i$$

← no derivatives

$$+ \; [\lambda_i F_i + m_{ij}(A_i F_j - \tfrac{1}{2}\psi_i\psi_j) + y_{ijk}(A_i A_j F_k - \psi_i\psi_j A_k) + h.c.]$$

Constraint $\dfrac{\delta L}{\delta F_k} = F_k^* + \lambda_k + m_{ik}A_i + y_{ijk}A_iA_j = 0$

SUSY Lagrangians

Superfields

$$L = \Phi_i^+ \Phi |_{\theta\theta\bar{\theta}\bar{\theta}} + [(\lambda_i \Phi_i + \tfrac{1}{2} m_{ij} \Phi_i \Phi_j + \tfrac{1}{3} y_{ijk} \Phi_i \Phi_j \Phi_k)|_{\theta\theta} + h.c.]$$

Components

$$L = i\partial_\mu \bar{\psi}_i \bar{\sigma}^\mu \psi_i + A_i^* \Box A_i + F_i^* F_i$$ ← no derivatives

$$+ \ [\lambda_i F_i + m_{ij}(A_i F_j - \tfrac{1}{2}\psi_i \psi_j) + y_{ijk}(A_i A_j F_k - \psi_i \psi_j A_k) + h.c.]$$

Constraint $\frac{\delta L}{\delta F_k} = F_k^* + \lambda_k + m_{ik} A_i + y_{ijk} A_i A_j = 0$ → F_k

SUSY Lagrangians

Superfields

$$L = \Phi_i^+ \Phi \big|_{\theta\theta\bar\theta\bar\theta} + [(\lambda_i \Phi_i + \tfrac{1}{2} m_{ij} \Phi_i \Phi_j + \tfrac{1}{3} y_{ijk} \Phi_i \Phi_j \Phi_k) \big|_{\theta\theta} + h.c.]$$

Components

$$L = i\partial_\mu \bar\psi_i \bar\sigma^\mu \psi_i + A_i^* \Box A_i + F_i^* F_i$$

← no derivatives

$$+ \; [\lambda_i F_i + m_{ij}(A_i F_j - \tfrac{1}{2}\psi_i \psi_j) + y_{ijk}(A_i A_j F_k - \psi_i \psi_j A_k) + h.c.]$$

Constraint $\dfrac{\delta L}{\delta F_k} = F_k^* + \lambda_k + m_{ik} A_i + y_{ijk} A_i A_j = 0$ → F_k

$$L = i\partial_\mu \bar\psi_i \bar\sigma^\mu \psi_i + A_i^* \Box A_i - \tfrac{1}{2} m_{ij} \psi_i \psi_j - \tfrac{1}{2} m_{ij}^* \bar\psi_i \bar\psi_j$$

$$- \; y_{ijk} \psi_i \psi_j A_k - y_{ijk}^* \bar\psi_i \bar\psi_j A_k^* - V(A_i, A_j)$$

SUSY Lagrangians

Superfields

$$L = \Phi_i^+ \Phi |_{\theta\theta\bar{\theta}\bar{\theta}} + [(\lambda_i \Phi_i + \tfrac{1}{2} m_{ij} \Phi_i \Phi_j + \tfrac{1}{3} y_{ijk} \Phi_i \Phi_j \Phi_k) |_{\theta\theta} + h.c.]$$

Components

$$L = i\partial_\mu \bar{\psi}_i \bar{\sigma}^\mu \psi_i + A_i^* \Box A_i + F_i^* F_i$$

← no derivatives

$$+ \ [\lambda_i F_i + m_{ij}(A_i F_j - \tfrac{1}{2}\psi_i \psi_j) + y_{ijk}(A_i A_j F_k - \psi_i \psi_j A_k) + h.c.]$$

Constraint $\frac{\delta L}{\delta F_k} = F_k^* + \lambda_k + m_{ik} A_i + y_{ijk} A_i A_j = 0$ → F_k

$$L = i\partial_\mu \bar{\psi}_i \bar{\sigma}^\mu \psi_i + A_i^* \Box A_i - \tfrac{1}{2} m_{ij} \psi_i \psi_j - \tfrac{1}{2} m_{ij}^* \bar{\psi}_i \bar{\psi}_j$$

$$- \ y_{ijk} \psi_i \psi_j A_k - y_{ijk}^* \bar{\psi}_i \bar{\psi}_j A_k^* - V(A_i, A_j)$$

$$V = F_k^* F_k$$

Superfield Lagrangians

$$Action = \int d^4x\, L \;\Longrightarrow\; \int d^4x\, d^4\theta\, L$$

Grassmannian integration in superspace $\int d\theta_\alpha = 0, \int \theta_\beta\, d\theta_\alpha = \delta_{\alpha\beta}$

Superfield Lagrangians

$$Action = \int d^4x\, L \quad \Longrightarrow \quad \int d^4x\, d^4\theta\, L$$

Grassmannian integration in superspace $\quad \int d\theta_\alpha = 0, \int \theta_\beta\, d\theta_\alpha = \delta_{\alpha\beta}$

Matter fields

$$L = \int d^2\theta\, d^2\overline{\theta}\; \Phi_i^+ \Phi_i + \int d^2\theta\; (\lambda_i \Phi_i + \tfrac{1}{2} m_{ij} \Phi_i \Phi_j + \tfrac{1}{3} y_{ijk} \Phi_i \Phi_j \Phi_k) + h.c.]$$

Superfield Lagrangians

$$Action = \int d^4x\, L \;\Longrightarrow\; \int d^4x\, d^4\theta\; L$$

Grassmannian integration in superspace $\int d\theta_\alpha = 0,\ \int \theta_\beta\, d\theta_\alpha = \delta_{\alpha\beta}$

Matter fields

$$L = \int d^2\theta\, d^2\bar{\theta}\; \Phi_i^+ \Phi_i + \int d^2\theta\; \underbrace{(\lambda_i \Phi_i + \tfrac{1}{2} m_{ij} \Phi_i \Phi_j + \tfrac{1}{3} y_{ijk} \Phi_i \Phi_j \Phi_k)}_{\text{Superpotential}} + h.c.]$$

Superfield Lagrangians

$$Action = \int d^4x\, L \quad \Longrightarrow \quad \int d^4x\, d^4\theta\, L$$

Grassmannian integration in superspace $\int d\theta_\alpha = 0,\ \int \theta_\beta d\theta_\alpha = \delta_{\alpha\beta}$

Matter fields

$$L = \int d^2\theta\, d^2\bar{\theta}\ \Phi_i^+\Phi_i + \int d^2\theta\ (\lambda_i\Phi_i + \tfrac{1}{2} m_{ij}\Phi_i\Phi_j + \tfrac{1}{3} y_{ijk}\Phi_i\Phi_j\Phi_k) + h.c.]$$

Superpotential

Gauge fields

$$L = \tfrac{1}{4}\int d^2\theta\ W^\alpha W_\alpha + \int d^2\bar{\theta}\ \bar{W}^{\dot{\alpha}}\bar{W}_{\dot{\alpha}} = \tfrac{1}{2}D^2 - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} - i\lambda\sigma^\mu D_\mu\bar{\lambda}$$

Superfield Lagrangians

$$Action = \int d^4x\, L \quad \Rightarrow \quad \int d^4x\, d^4\theta\, L$$

Grassmannian integration in superspace $\int d\theta_\alpha = 0,\ \int \theta_\beta\, d\theta_\alpha = \delta_{\alpha\beta}$

Matter fields

$$L = \int d^2\theta\, d^2\bar{\theta}\ \Phi_i^+ \Phi_i + \int d^2\theta\ (\lambda_i \Phi_i + \tfrac{1}{2} m_{ij} \Phi_i \Phi_j + \tfrac{1}{3} y_{ijk} \Phi_i \Phi_j \Phi_k) + h.c.]$$

Superpotential

Gauge fields

$$L = \tfrac{1}{4}\int d^2\theta\ W^\alpha W_\alpha + \int d^2\bar{\theta}\ \bar{W}^{\dot{\alpha}} \bar{W}_{\dot{\alpha}} = \tfrac{1}{2} D^2 - \tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} - i\lambda\sigma^\mu D_\mu \bar{\lambda}$$

Gauge transformation $\Phi \to e^{-ig\Lambda}\Phi,\ \Phi^+ \to \Phi^+ e^{ig\Lambda^+},\ V \to V + i(\Lambda - \Lambda^+)$

Superfield Lagrangians

$$Action = \int d^4x\, L \quad \Rightarrow \quad \int d^4x\, d^4\theta\, L$$

Grassmannian integration in superspace $\quad \int d\theta_\alpha = 0,\ \int \theta_\beta\, d\theta_\alpha = \delta_{\alpha\beta}$

Matter fields

$$L = \int d^2\theta\, d^2\bar{\theta}\ \Phi_i^+ \Phi_i + \int d^2\theta\ \underbrace{(\lambda_i \Phi_i + \tfrac{1}{2} m_{ij} \Phi_i \Phi_j + \tfrac{1}{3} y_{ijk} \Phi_i \Phi_j \Phi_k)}_{\text{Superpotential}} + h.c.]$$

Gauge fields

$$L = \tfrac{1}{4}\int d^2\theta\ W^\alpha W_\alpha + \int d^2\bar{\theta}\ \bar{W}^{\dot{\alpha}} \bar{W}_{\dot{\alpha}} = \tfrac{1}{2} D^2 - \tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} - i\lambda\sigma^\mu D_\mu \bar{\lambda}$$

Gauge transformation $\quad \Phi \to e^{-ig\Lambda}\Phi,\ \Phi^+ \to \Phi^+ e^{ig\Lambda^+},\ V \to V + i(\Lambda - \Lambda^+)$

Gauge invariant interaction $\quad \Phi^+\Phi \to \Phi^+ e^{gV} \Phi$

Gauge Invariant SUSY Lagrangian

Gauge Invariant SUSY Lagrangian

Super-fields

$$L_{SUSY\ YM} = \frac{1}{4}\int d^2\theta\ \mathrm{Tr}(W^{\alpha}W_{\alpha}) + \frac{1}{4}\int d^2\bar{\theta}\ \mathrm{Tr}(\overline{W}^{\alpha}\overline{W}_{\alpha})$$

$$+\int d^2\theta d^2\bar{\theta}\ \overline{\Phi}_{ia}(e^{gV})^a_b\Phi^b_i + \int d^2\theta\ \mathcal{W}(\Phi_i) + \int d^2\bar{\theta}\ \overline{\mathcal{W}}(\overline{\Phi}_i)$$

Gauge Invariant SUSY Lagrangian

Super-fields

$$L_{SUSY\ YM} = \frac{1}{4}\int d^2\theta\ \mathrm{Tr}(\mathrm{W}^{\alpha} W_{\alpha}) + \frac{1}{4}\int d^2\overline{\theta}\ \mathrm{Tr}(\overline{\mathrm{W}}^{\alpha}\overline{W}_{\alpha})$$
$$+\int d^2\theta d^2\overline{\theta}\ \overline{\Phi}_{ia}(e^{gV})^a_b \Phi^b_i + \int d^2\theta\ \mathcal{W}(\Phi_i) + \int d^2\overline{\theta}\ \overline{\mathcal{W}}(\overline{\Phi}_i)$$

Components

$$\begin{aligned} & \mathcal{L}_{SUSY\ YM} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - i\lambda^a\sigma^\mu D_\mu\bar{\lambda}^a + \frac{1}{2}D^aD^a \\ + \quad & (\partial_\mu A_i - igv^a_\mu T^a A_i)^\dagger(\partial_\mu A_i - igv^{a\mu}T^a A_i) - i\bar{\psi}_i\bar{\sigma}^\mu(\partial_\mu\psi_i - igv^{a\mu}T^a\psi_i) \\ - \quad & D^aA^\dagger_i T^a A_i - i\sqrt{2}A^\dagger_i T^a\lambda^a\psi_i + i\sqrt{2}\bar{\psi}_i T^a A_i\bar{\lambda}^a + F^\dagger_i F_i \\ + \quad & \frac{\partial W}{\partial A_i}F_i + \frac{\partial\bar{W}}{\partial A^\dagger_i}F^\dagger_i - \frac{1}{2}\frac{\partial^2 W}{\partial A_i\partial A_j}\psi_i\psi_j - \frac{1}{2}\frac{\partial^2\bar{W}}{\partial A^\dagger_i\partial A^\dagger_j}\bar{\psi}_i\bar{\psi}_j \end{aligned}$$

Gauge Invariant SUSY Lagrangian

Super-fields

$$L_{SUSY\ YM} = \frac{1}{4}\int d^2\theta\ \mathrm{Tr}(W^\alpha W_\alpha) + \frac{1}{4}\int d^2\bar\theta\ \mathrm{Tr}(\overline{W}^\alpha \overline{W}_\alpha)$$
$$+\int d^2\theta d^2\bar\theta\ \overline{\Phi}_{ia}(e^{gV})^a_b \Phi^b_i + \int d^2\theta\ \mathcal{W}(\Phi_i) + \int d^2\bar\theta\ \overline{\mathcal{W}}(\overline{\Phi}_i)$$

Components

$$\begin{aligned}
\mathcal{L}_{SUSY\ YM} &= -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - i\lambda^a\sigma^\mu D_\mu\bar\lambda^a + \frac{1}{2}D^a D^a \\
+ \quad & (\partial_\mu A_i - igv^a_\mu T^a A_i)^\dagger(\partial_\mu A_i - igv^{a\mu}T^a A_i) - i\bar\psi_i\bar\sigma^\mu(\partial_\mu\psi_i - igv^{a\mu}T^a\psi_i) \\
- \quad & D^a A^\dagger_i T^a A_i - i\sqrt{2}A^\dagger_i T^a\lambda^a\psi_i + i\sqrt{2}\bar\psi_i T^a A_i\bar\lambda^a + F^\dagger_i F_i \\
+ \quad & \frac{\partial W}{\partial A_i}F_i + \frac{\partial\bar W}{\partial A^\dagger_i}F^\dagger_i - \frac{1}{2}\frac{\partial^2 W}{\partial A_i\partial A_j}\psi_i\psi_j - \frac{1}{2}\frac{\partial^2\bar W}{\partial A^\dagger_i\partial A^\dagger_j}\bar\psi_i\bar\psi_j
\end{aligned}$$

Gauge Invariant SUSY Lagrangian

Super-fields

$$L_{SUSY\ YM} = \frac{1}{4}\int d^2\theta\ \mathrm{Tr}(W^{\alpha}W_{\alpha}) + \frac{1}{4}\int d^2\bar{\theta}\ \mathrm{Tr}(\overline{W}^{\alpha}\overline{W}_{\alpha})$$
$$+\int d^2\theta d^2\bar{\theta}\ \overline{\Phi}_{ia}(e^{gV})^a_b\Phi^b_i + \int d^2\theta\ \mathcal{W}(\Phi_i) + \int d^2\bar{\theta}\ \overline{\mathcal{W}}(\overline{\Phi}_i)$$

Compo-nents

$$\begin{aligned} \mathcal{L}_{SUSY\ YM} &= -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - i\lambda^a\sigma^\mu D_\mu\bar{\lambda}^a + \frac{1}{2}D^aD^a \\ &+ (\partial_\mu A_i - igv^a_\mu T^a A_i)^\dagger(\partial_\mu A_i - igv^{a\mu}T^aA_i) - i\bar{\psi}_i\bar{\sigma}^\mu(\partial_\mu\psi_i - igv^{a\mu}T^a\psi_i) \\ &- D^aA^\dagger_iT^aA_i - i\sqrt{2}A^\dagger_iT^a\lambda^a\psi_i + i\sqrt{2}\bar{\psi}_iT^aA_i\bar{\lambda}^a + F^\dagger_iF_i \\ &+ \frac{\partial W}{\partial A_i}F_i + \frac{\partial\bar{W}}{\partial A^\dagger_i}F^\dagger_i - \frac{1}{2}\frac{\partial^2 W}{\partial A_i\partial A_j}\psi_i\psi_j - \frac{1}{2}\frac{\partial^2\bar{W}}{\partial A^\dagger_i\partial A^\dagger_j}\bar{\psi}_i\bar{\psi}_j \end{aligned}$$

Potential

$$D^a = -gA^\dagger_iT^aA_i, \quad F_i = -\frac{\partial W}{\partial A_i} \quad \rightarrow \quad V = \frac{1}{2}D^aD^a + F^\dagger_iF_i$$

How to write SUSY Lagrangians

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1st step

Take your favorite Lagrangian written in terms of fields

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3rd step

Replace

$$Action = \int d^4x\, L(x) \quad \Rightarrow \quad \int d^4x\, d^4\theta\, L(x, \theta, \bar{\theta})$$

Grassmannian integration in superspace $\int d\theta_\alpha = 0,\ \int \theta_\beta\, d\theta_\alpha = \delta_{\alpha\beta}$

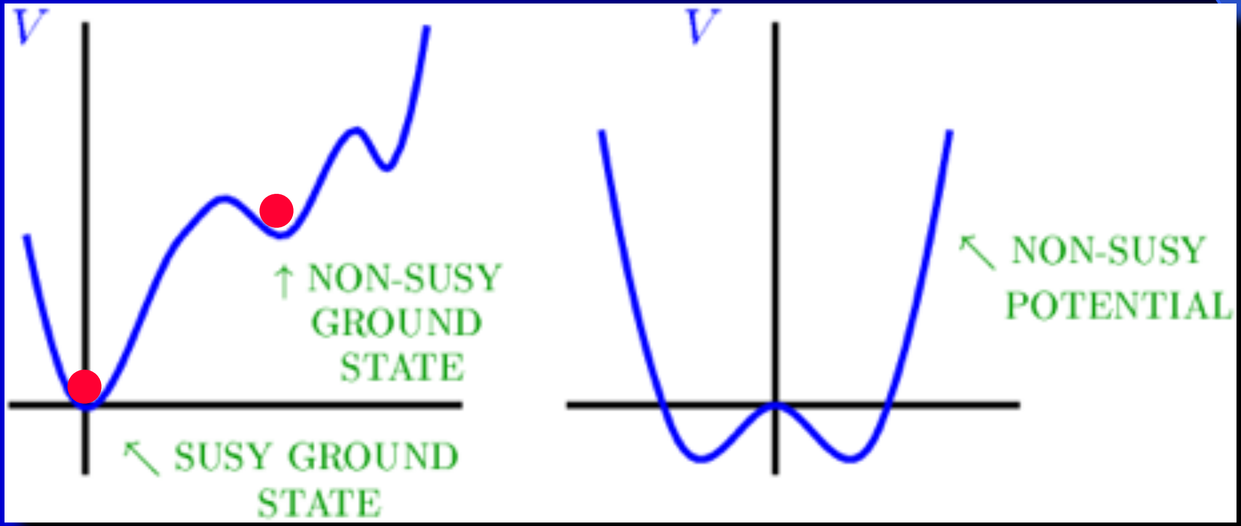
Spontaneous Breaking of SUSY

Energy $E = \langle 0 | H | 0 \rangle$

$$\{Q^i_\alpha, \overline{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta} P_\mu$$

$$E = \frac{1}{4}\sum_{\alpha=1,2} \langle 0 | \{Q^i_\alpha, \overline{Q}^j_\alpha\} | 0 \rangle = \frac{1}{4}\sum_\alpha | Q_\alpha | 0 \rangle |^2 \geq 0$$

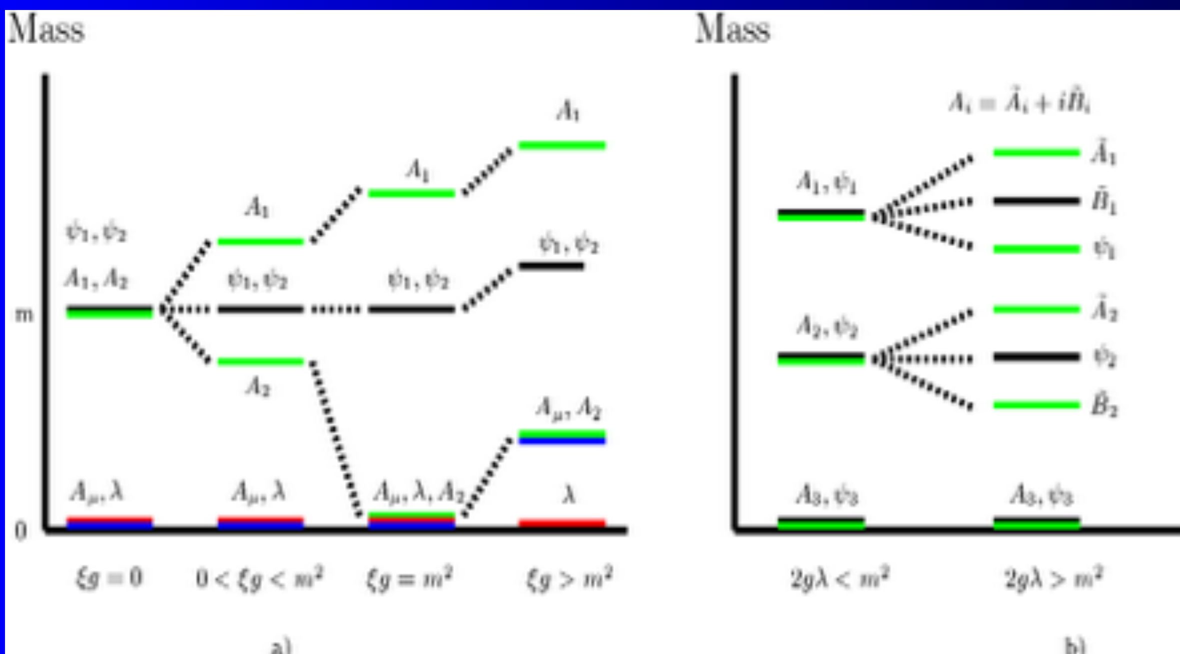
$E = \langle 0 | H | 0 \rangle \neq 0$ if and only if $Q_\alpha | 0 \rangle \neq 0$



Mechanism of SUSY Breaking

- Fayet-Iliopoulos (D-term) mechanism (in Abelian theory) $\Delta L = \xi V|_{\theta\theta\bar{\theta}\bar{\theta}} = \xi \int d^4\theta \; V = \xi D \neq 0$

- O'Raifertaigh (F-term) mechanism $W(\Phi) = \lambda\Phi_3 + m\Phi_1\Phi_2 + g\Phi_3\Phi_1^2$



$$F_1^* = mA_2 + 2gA_1A_2$$

$$F_2^* = mA_1$$

$$F_3^* = \lambda + gA_1^2$$

$\Rightarrow$ $< F_i > \neq 0$

$$\sum_{bosons} m_i^2 = \sum_{fermions} m_i^2$$

D-term F-term

Motivation for SUSY in Particle Physics

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Supersymmetry is a dream of a unified theory of all particles and interactions

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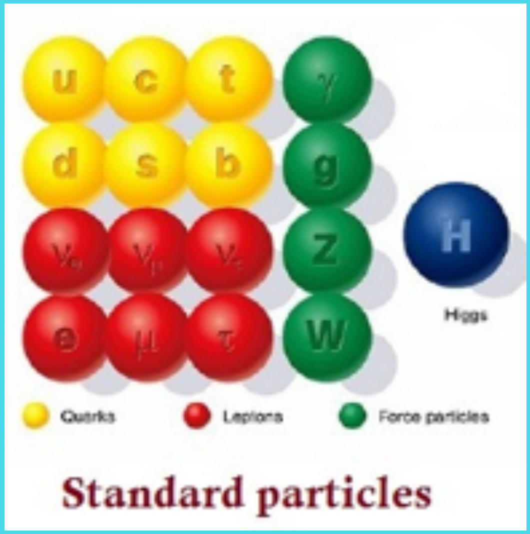

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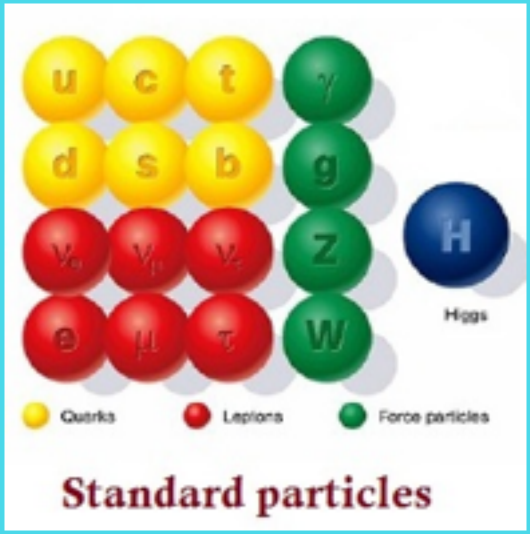

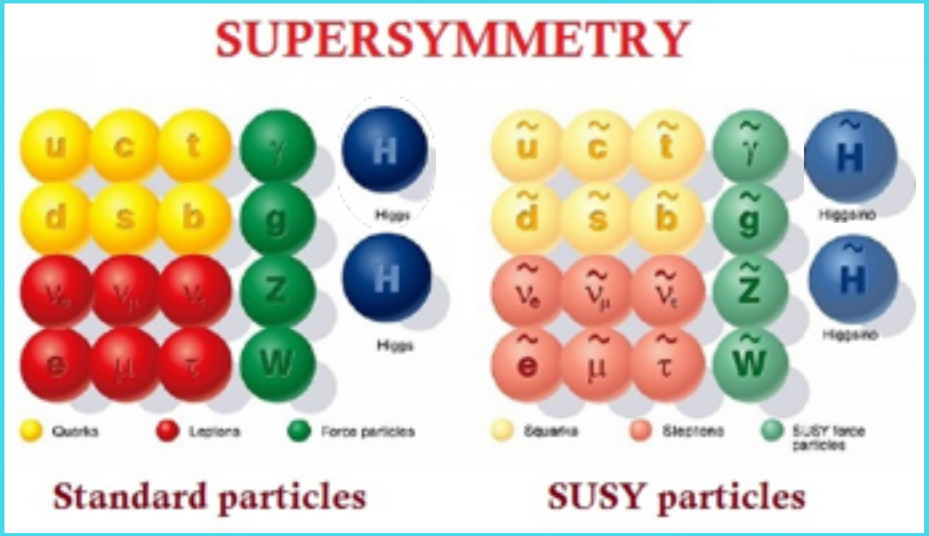

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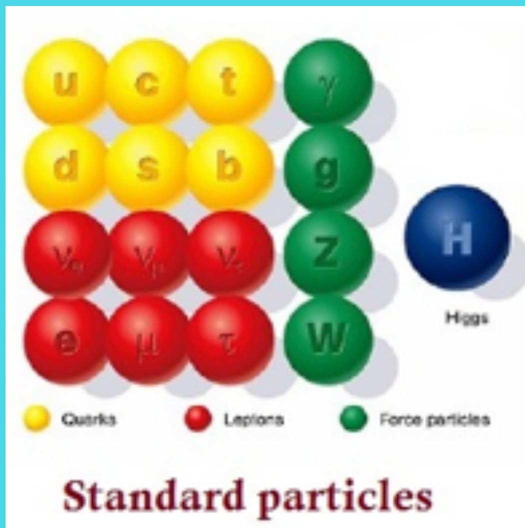

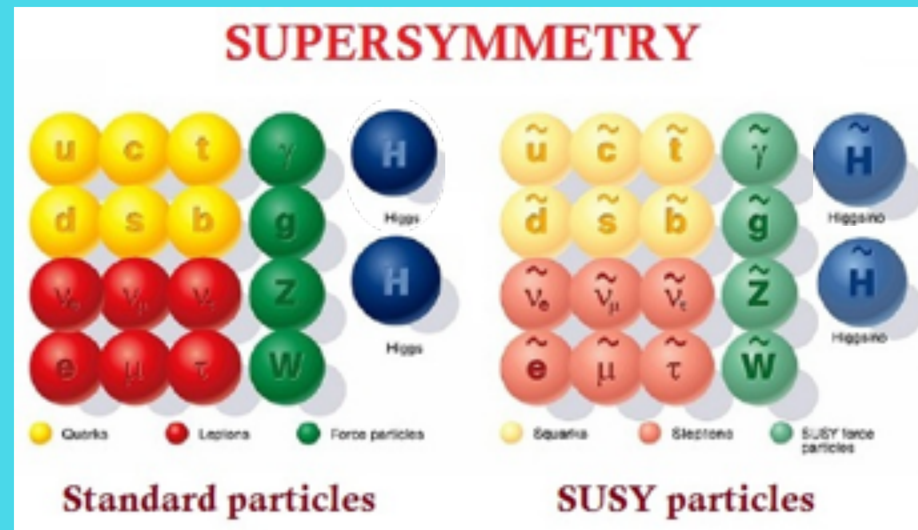

Why SUSY?

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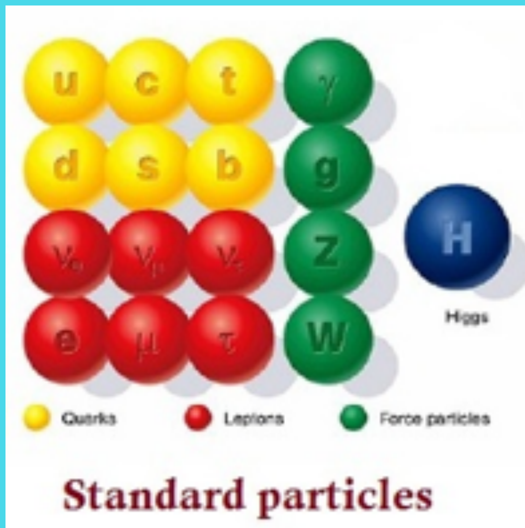

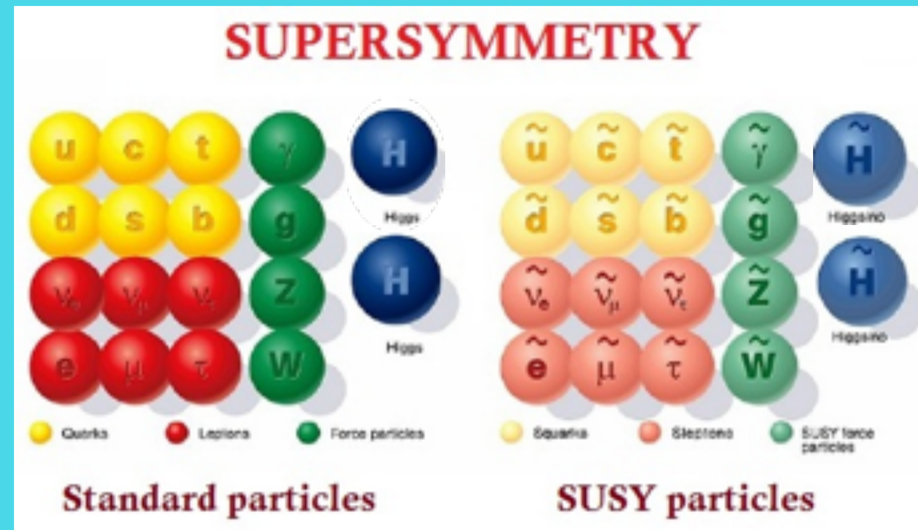

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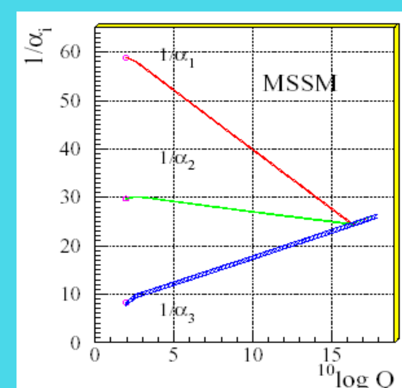

The basis of a grand Unified Theory

Motivation for SUSY in Particle Physics

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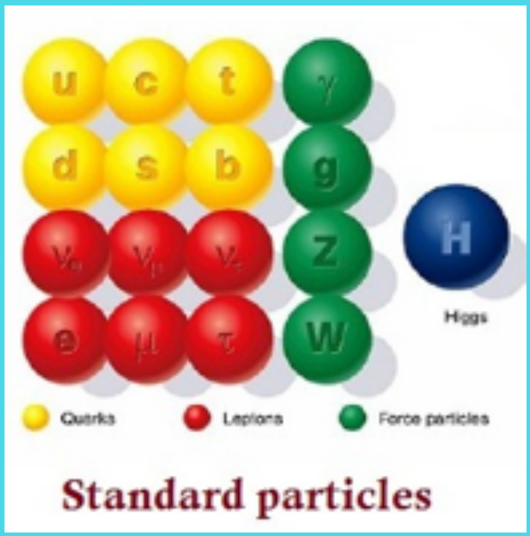
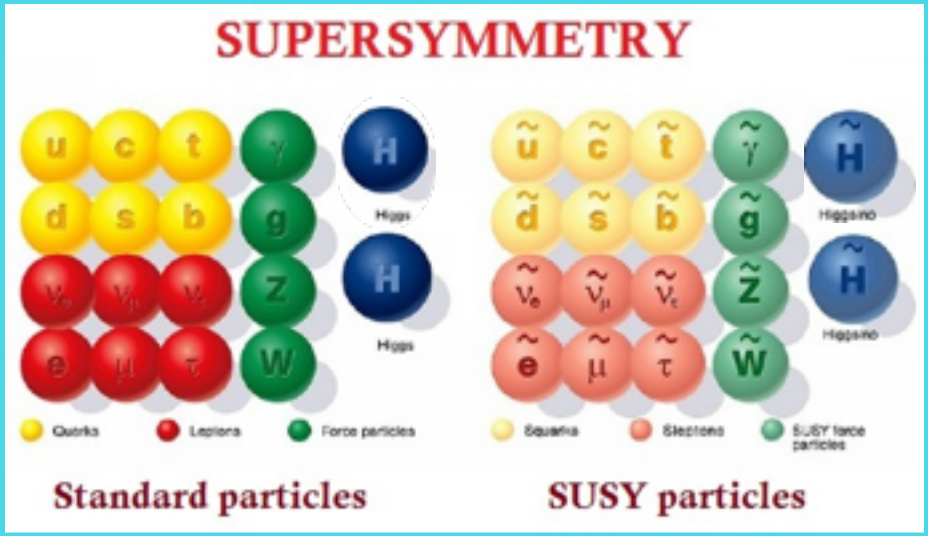
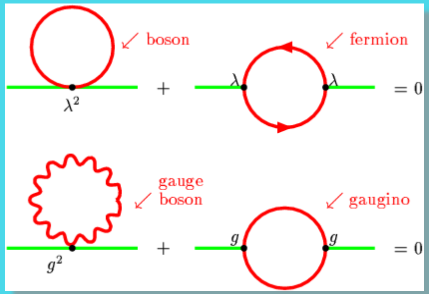




Why SUSY?

- Unification of the gauge couplings
- Solution of the hierarchy problem

Cancellations of corrections and stabilization of the Higgs potential



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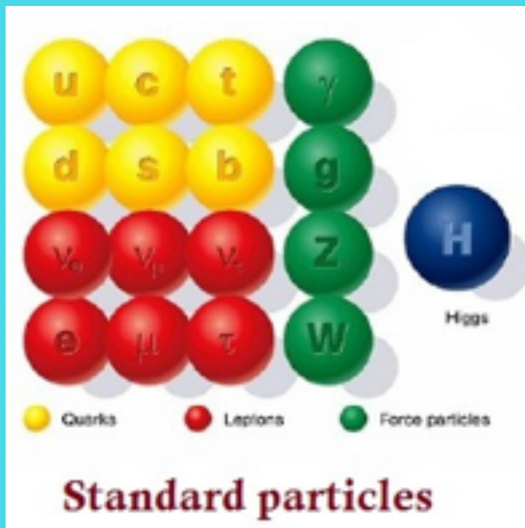

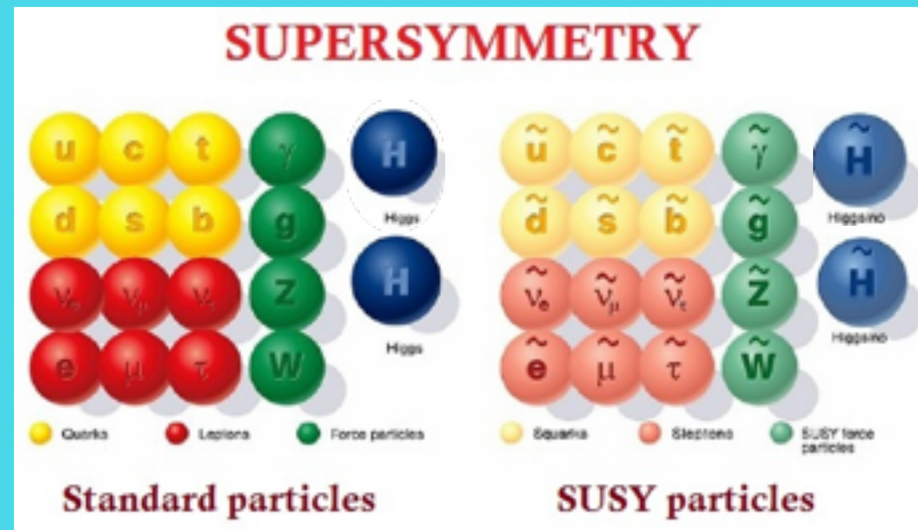

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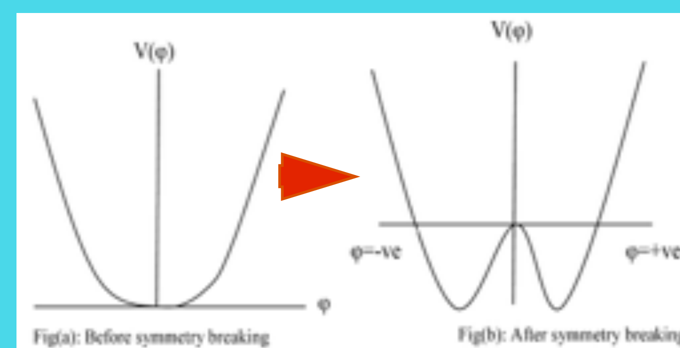

Violation of symmetry comes from radiative corrections

Motivation for SUSY in Particle Physics

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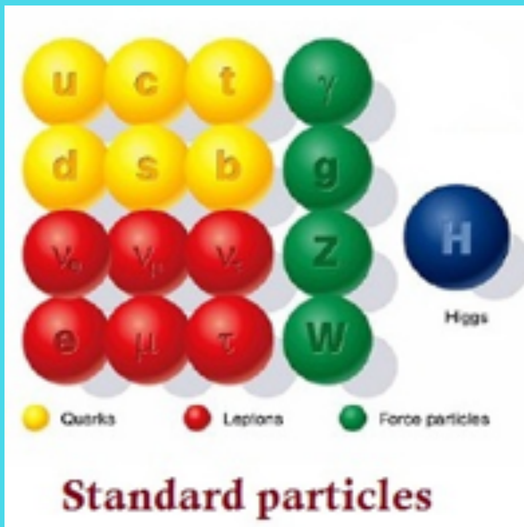
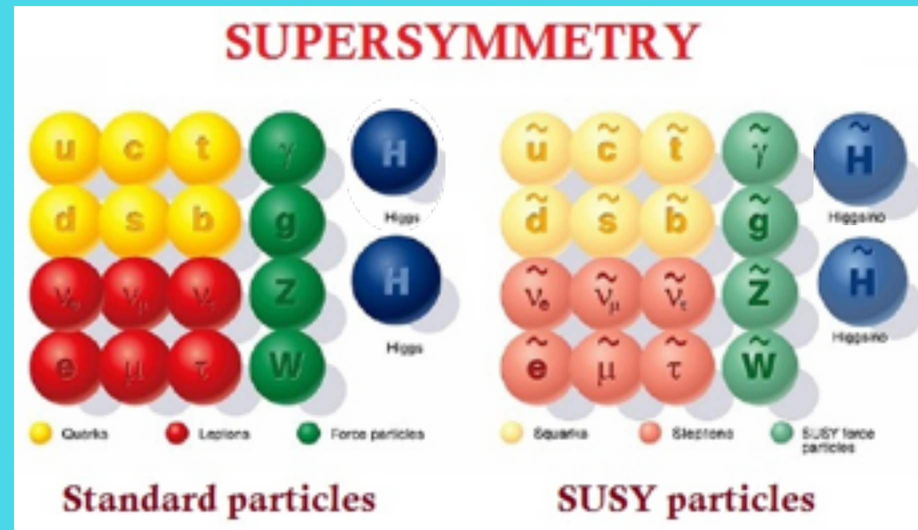




Why SUSY?

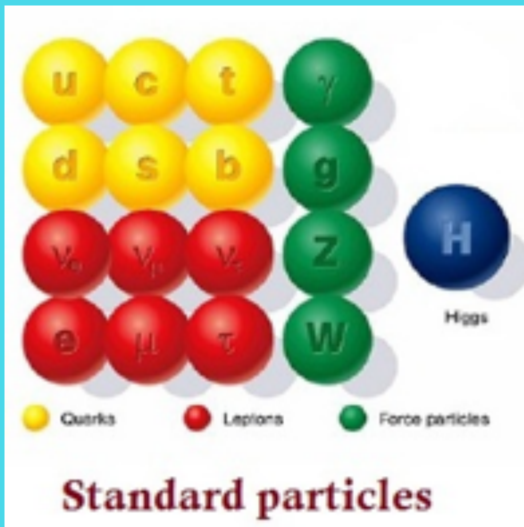
- Unification of the gauge couplings
- Solution of the hierarchy problem
- Explanation of the EW symmetry violation
- Provided the DM particle

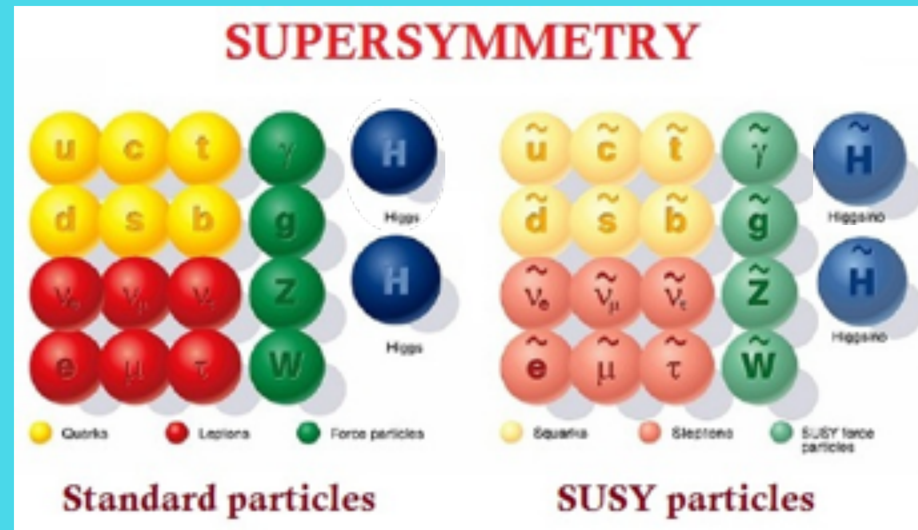
$$\tilde{\chi}^0 = N_1\tilde{\gamma} + N_2\tilde{z} + N_3\tilde{H}_1^0 + N_4\tilde{H}_2^0$$

Neutralino

Motivation for SUSY in Particle Physics

Supersymmetry is a dream of a unified theory of all particles and interactions





Why SUSY?

- Unification of the gauge couplings
- Solution of the hierarchy problem
- Explanation of the EW symmetry violation
- Provided the DM particle
- Unification with gravity!

$$\{Q^i_\alpha, \overline{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta} P_\mu \quad \Rightarrow \quad \{\delta_\varepsilon, \bar\delta_{\bar\varepsilon}\} = 2(\varepsilon\sigma^\mu\bar\varepsilon)P_\mu$$

$\varepsilon = \varepsilon(x)$ local coordinate transf. $\Rightarrow$ (super)gravity

Local supersymmetry = general relativity !

Simplest (N=1) SUSY Multiplets

Bosons and Fermions come in pairs

(φ, ψ) (λ, A_μ) $(\tilde{g}, g)$

Spin 0 Spin 1/2 Spin 1/2 Spin 1 Spin 3/2 Spin 2

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scalar chiral fermion majorana fermion vector

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scalar chiral fermion **majorana fermion** **vector** **gravitino**

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$$(\varphi, \psi) \qquad (\lambda, A_\mu) \qquad (\tilde{g}, g)$$

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Minimal Supersymmetric Standard Model (MSSM)

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$$Tr\ Y^3 = 3\left(\tfrac{1}{27}+\tfrac{1}{27}-\tfrac{64}{27}+\tfrac{8}{27}\right)-1-1+8=0$$

colour u_L d_L u_R d_R ν_L e_L e_R

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Higgsinos

-1+1=0

Particle Content of the MSSM

Superfield	Bosons		Fermions		$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge							
$\mathbf{G^a}$	gluon	g^a	gluino	$\tilde{g}^a$	8	0	0
$\mathbf{V^k}$	Weak	$W^k \quad (W^\pm, Z)$	wino, zino	$\tilde{w}^k \quad (\tilde{w}^\pm, \tilde{z})$	1	3	0
$\mathbf{V'}$	Hypercharge	$B\ (\gamma)$	bino	$\tilde{b}(\tilde{\gamma})$	1	1	0
Matter							
$\mathbf{L_i}$	sleptons	$\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons	$L_i = (\nu, e)_L$	1	2	-1
$\mathbf{E_i}$		$\tilde{E}_i = \tilde{e}_R$		$E_i = e_R$	1	1	2
$\mathbf{N_i}$		$\tilde{N}_i = \tilde{\nu}_R$		$N_i = \nu_R$	1	1	0
$\mathbf{Q_i}$	squarks	$\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks	$Q_i = (u, d)_L$	3	2	$1/3$
$\mathbf{U_i}$		$\tilde{U}_i = \tilde{u}_R$		$U_i = u_R^c$	3^*	1	$-4/3$
$\mathbf{D_i}$		$\tilde{D}_i = \tilde{d}_R$		$D_i = d_R^c$	3^*	1	$2/3$
Higgs							
$\mathbf{H_1}$	Higgses	H_1	higgsinos	$\tilde{H}_1$	1	2	-1
$\mathbf{H_2}$		H_2		$\tilde{H}_2$	1	2	1

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$\mathbf{L_i}$	sleptons	$\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons	$L_i = (\nu, e)_L$	1	2	−1
$\mathbf{E_i}$		$\tilde{E}_i = \tilde{e}_R$		$E_i = e_R$	1	1	2
$\mathbf{N_i}$		$\tilde{N}_i = \tilde{\nu}_R$		$N_i = \nu_R$	1	1	0
$\mathbf{Q_i}$	squarks	$\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks	$Q_i = (u, d)_L$	3	2	1/3
$\mathbf{U_i}$		$\tilde{U}_i = \tilde{u}_R$		$U_i = u_R^c$	3*	1	−4/3
$\mathbf{D_i}$		$\tilde{D}_i = \tilde{d}_R$		$D_i = d_R^c$	3*	1	2/3
Higgs							
$\mathbf{H_1}$	Higgses	H_1	higgsinos	$\tilde{H}_1$	1	2	−1
$\mathbf{H_2}$		H_2		$\tilde{H}_2$	1	2	1
$\mathbf{S}$	Singlet	s	singlino	s	1	1	0

Particle Content of the MSSM

Superfield	Bosons		Fermions		$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge							
$\mathbf{G^a}$	gluon	g^a	gluino	$\tilde{g}^a$	8	0	0
$\mathbf{V^k}$	Weak	$W^k \ (W^\pm, Z)$	wino, zino	$\tilde{w}^k \ (\tilde{w}^\pm, \tilde{z})$	1	3	0
$\mathbf{V'}$	Hypercharge	$B \ (\gamma)$	bino	$\tilde{b}(\tilde{\gamma})$	1	1	0
Matter							
$\mathbf{L_i}$	sleptons	$\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons	$L_i = (\nu, e)_L$	1	2	-1
$\mathbf{E_i}$		$\tilde{E}_i = \tilde{e}_R$		$E_i = e_R$	1	1	2
$\mathbf{N_i}$		$\tilde{N}_i = \tilde{\nu}_R$		$N_i = \nu_R$	1	1	0
$\mathbf{Q_i}$	squarks	$\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks	$Q_i = (u, d)_L$	3	2	$1/3$
$\mathbf{U_i}$		$\tilde{U}_i = \tilde{u}_R$		$U_i = u^c_R$	3^*	1	$-4/3$
$\mathbf{D_i}$		$\tilde{D}_i = \tilde{d}_R$		$D_i = d^c_R$	3^*	1	$2/3$
Higgs							
$\mathbf{H_1}$	Higgses	H_1	higgsinos	$\tilde{H}_1$	1	2	-1
$\mathbf{H_2}$		H_2		$\tilde{H}_2$	1	2	1
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NMSSM

The MSSM Lagrangian

$$L = L_{gauge} + L_{Yukawa} + L_{SoftBreaking}$$

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The Yukawa Superpotential

Superfields

$$W_R = y_U Q_L H_2 U_R + y_D Q_L H_1 D_R + y_L L_L H_1 E_R + \mu H_1 H_2$$

Yukawa couplings

Higgs mixing term

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$$W_{NR} = \lambda_L L_L L_L E_R + \lambda_L' L_L Q_L D_R + \mu' L_L H_2 + \lambda_B U_R D_R D_R$$

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Violate: Lepton number Baryon number

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These terms are forbidden in the SM

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Violate: Lepton number Baryon number

These terms are forbidden in the SM

$$\lambda_L, \lambda_L^{'} < 10^{-6}, \quad \lambda_B < 10^{-9}$$

R-parity

$$R = (-)^{3(B-L)+2S}$$

The Usual Particle : R = + 1
SUSY Particle : R = - 1

B - Baryon Number
L - Lepton Number
S - Spin

R-parity

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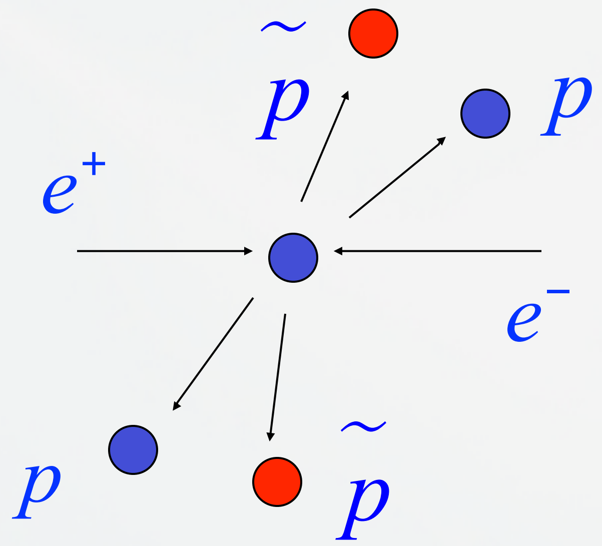
The consequences:

- The superpartners are created in pairs
- The lightest superparticle is stable



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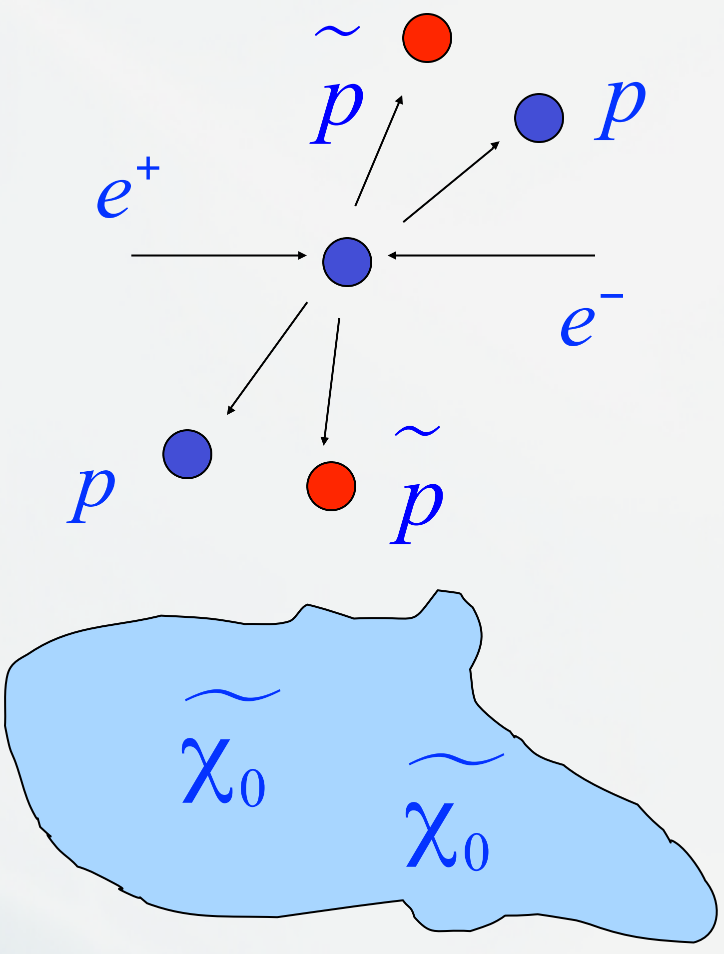
⇓

- The lightest superparticle (LSP) should be neutral - the best candidate is neutralino (photino or higgsino) $\tilde{\chi}_0$
- It can survive from the Big Bang and form the Dark matter in the Universe



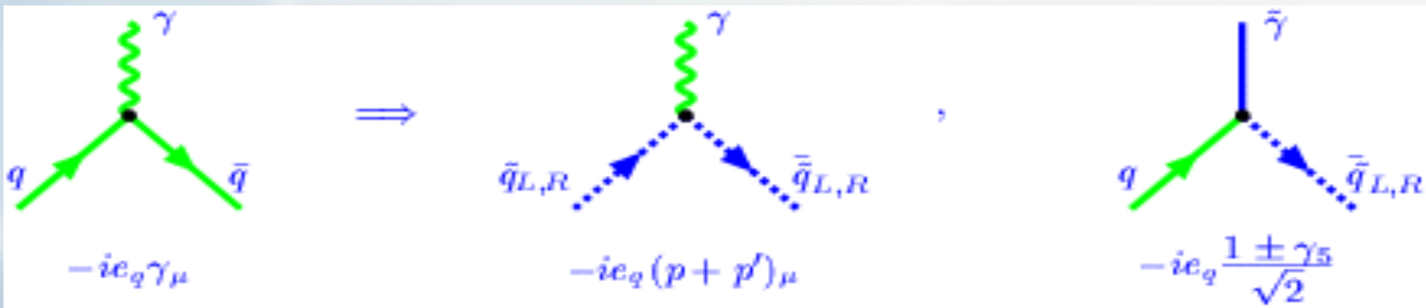
Interactions in the MSSM

SM → **MSSM**

Interactions in the MSSM

SM → **MSSM**

Vertices



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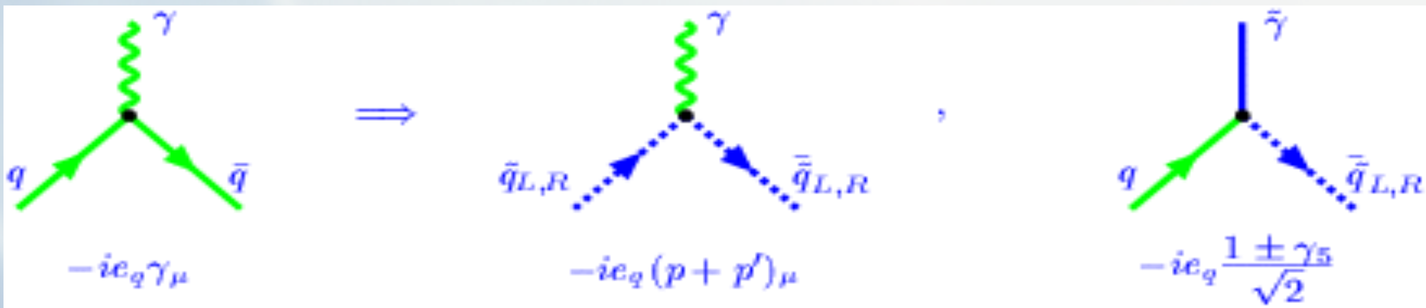

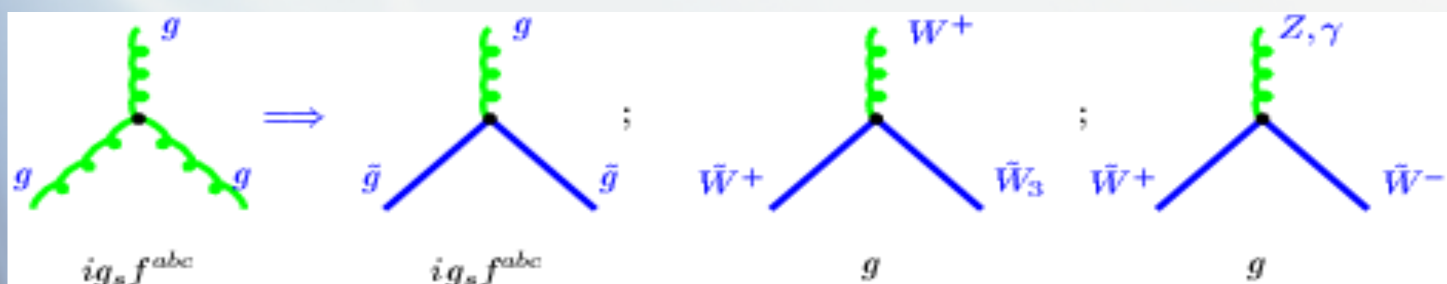

Interactions in the MSSM

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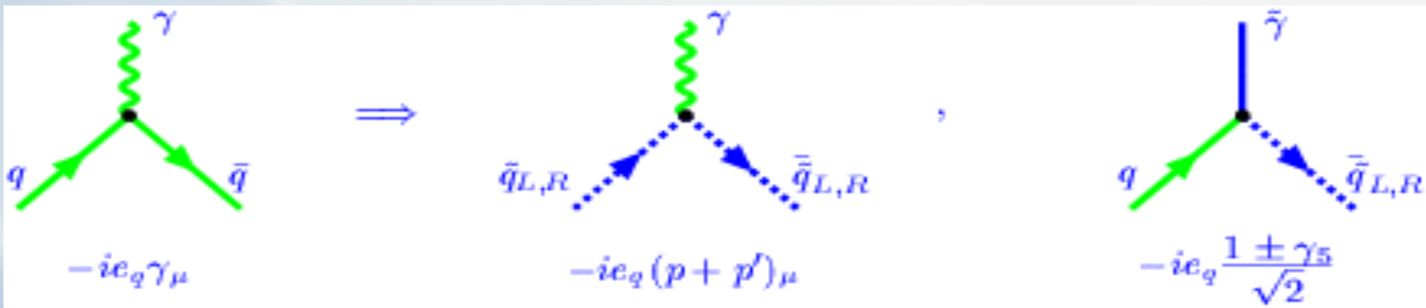
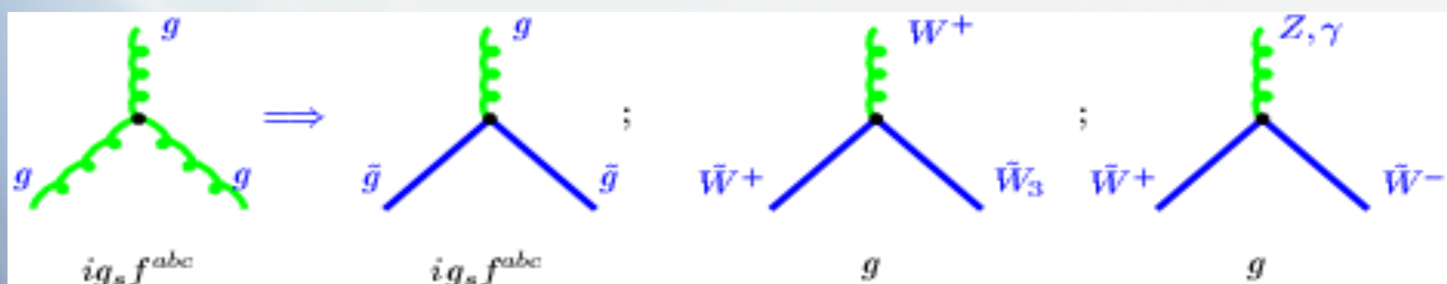
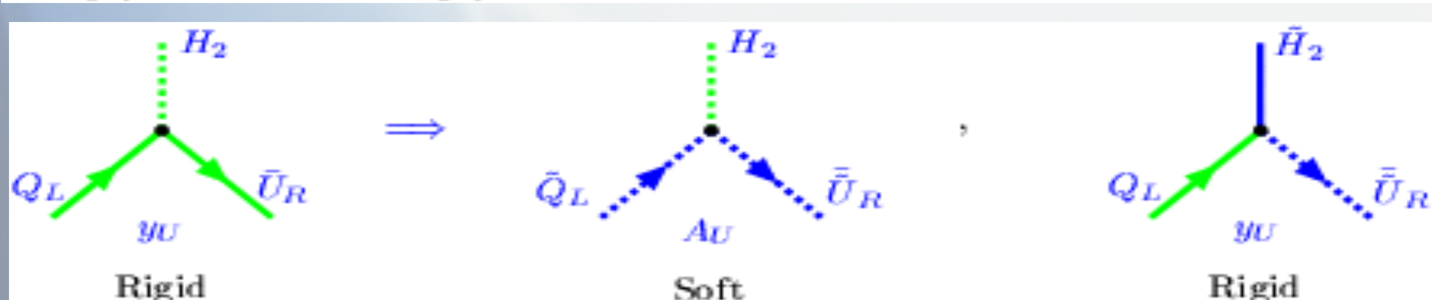
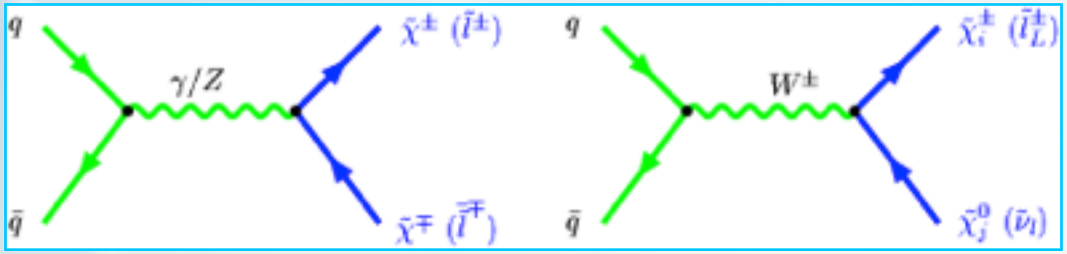




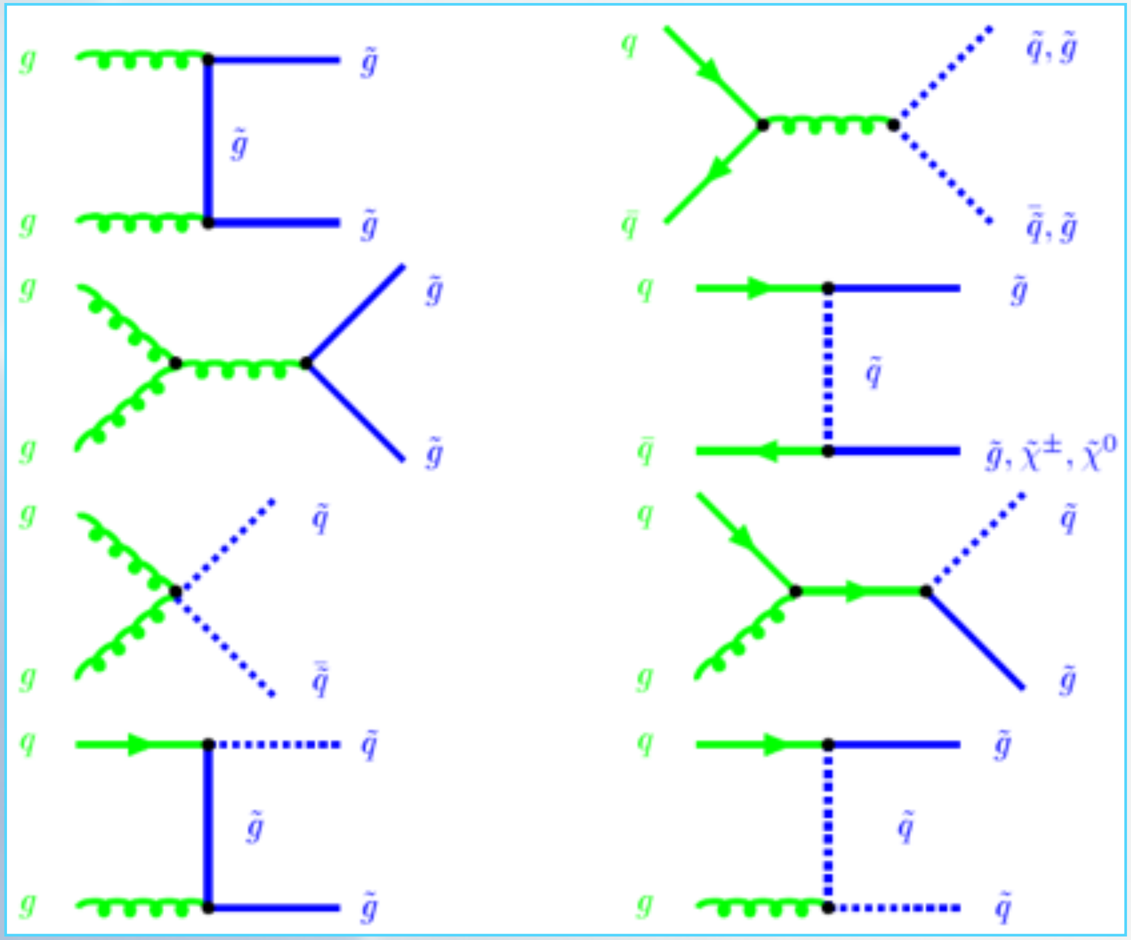


Superpartners Production at LHC

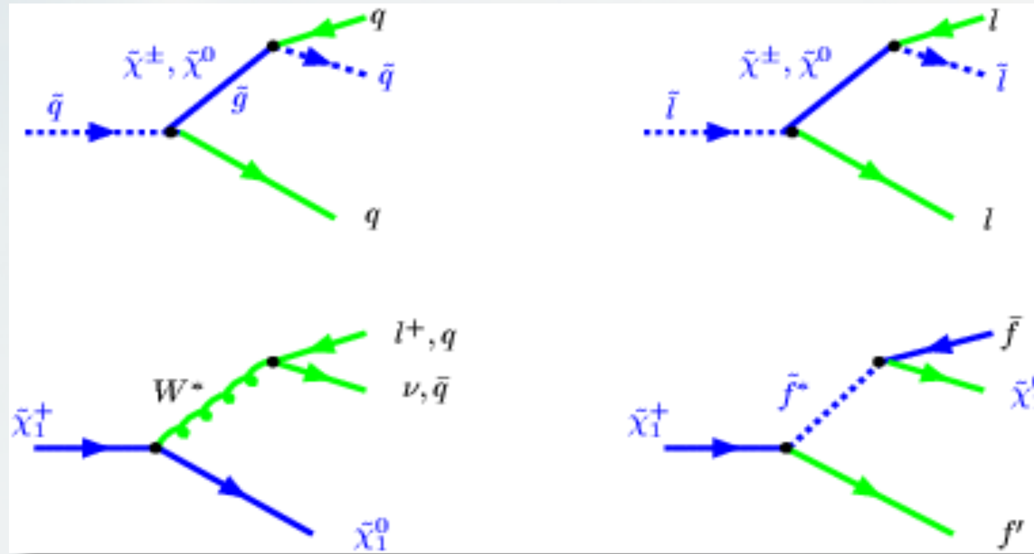
Annihilation



Quark- gluon Fusion



Decay of Superpartners



squarks

$$\tilde{q}_{L,R} \rightarrow q + \tilde{\chi}_i^0$$

$$\tilde{q}_{L} \rightarrow q' + \tilde{\chi}_i^{\pm}$$

$$\tilde{q}_{L,R} \rightarrow q + \tilde{g}$$

sleptons

$$\tilde{l} \rightarrow l + \tilde{\chi}_i^0$$

$$\tilde{l}_L \rightarrow \nu_l + \tilde{\chi}_i^{\pm}$$

chargino

$$\tilde{\chi}_i^{\pm} \rightarrow e + \nu_e + \tilde{\chi}_i^0$$

$$\tilde{\chi}_i^{\pm} \rightarrow q + \bar{q}' + \tilde{\chi}_i^0$$

gluino

$$\tilde{g} \rightarrow q + \bar{q} + \tilde{\gamma}$$

$$\tilde{g} \rightarrow g + \tilde{\gamma}$$

neutralino

$$\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 + l^+ + l^-$$

$$\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 + q + \bar{q}'$$

$$\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^{\pm} + l^{\pm} + \nu_l$$

$$\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 + \nu_l + \bar{\nu}_l$$

Final states

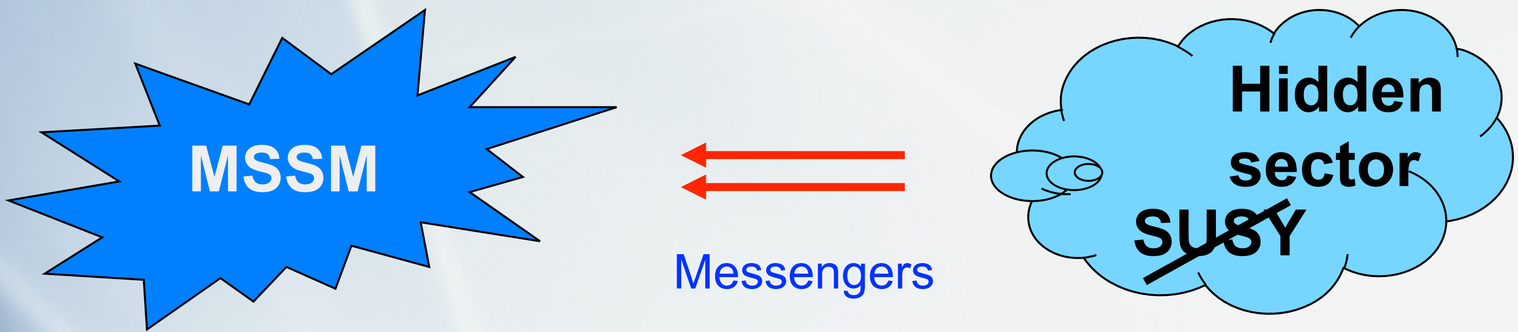
$l^+ l^- + \not{E}_T$

2 jets $+ \not{E}_T$

$\gamma + \not{E}_T$

$\not{E}_T$

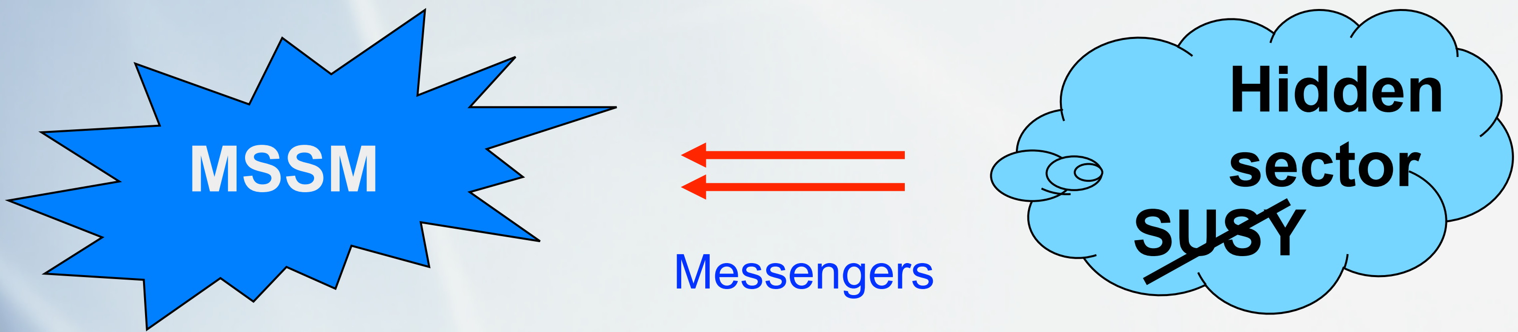
Soft SUSY Breaking



Gravitons, gauge, gauginos, etc

Breaking via F and D terms in a hidden sector

Soft SUSY Breaking



Gravitons, gauge, gauginos, etc

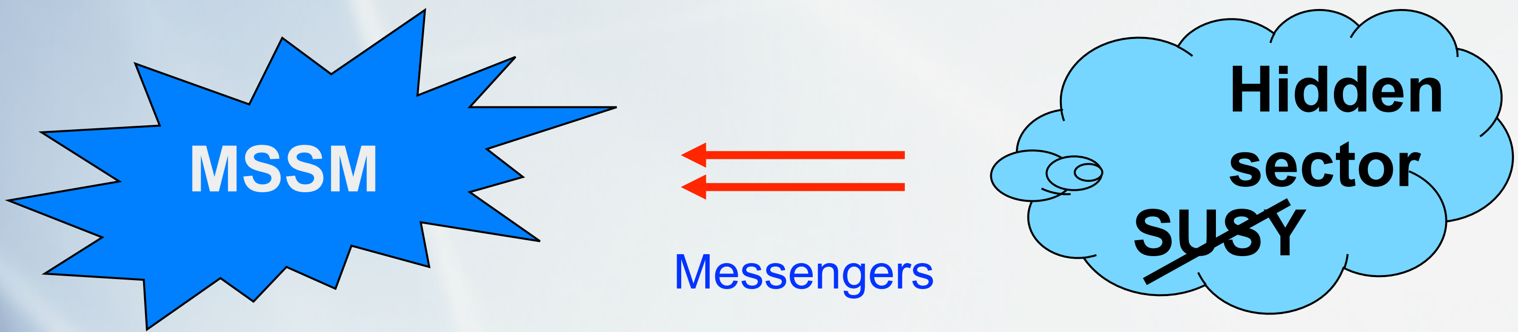
Breaking via F and D terms in a hidden sector

$$-L_{Soft} = \sum_{\alpha} M_i \widetilde{\lambda}_i \widetilde{\lambda}_i + \sum_i m_{0i}^2 \,|\, A_i \,|^2 + + \sum_{ijk} \mathrm{A}_{ijk} A_i A_j A_k + \sum_{ij} \mathrm{B}_{ij} A_i A_j$$

gauginos

scalar fields

Soft SUSY Breaking



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Over 100 of free parameters !

MSSM Parameter Space

- Three gauge couplings
- Three (four) Yukawa matrices
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Five universal soft parameters: $A,\ m_0,\ M_{1/2},\ B \leftrightarrow \tan\beta = v_2 / v_1$ and μ

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versus m and λ in the SM

Mass Spectrum (spin=1/2)

$$L_{gaugino-Higgsino} = -\frac{1}{2} M_3 \bar{\lambda}_a \lambda_a - \frac{1}{2} \bar{\chi} M^{(0)} \chi - (\bar{\psi} M^{(c)} \psi + h.c.)$$

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Chargino

$$\psi = \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}^+ \end{pmatrix}$$

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Neutralino

$$(\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0)$$

$$\Uparrow$$

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Mass Spectrum (spin=0)

Squarks & Sleptons

Mass Spectrum (spin=0)

$$\tilde{m}_t^2 = \begin{pmatrix} \tilde{m}_{tL}^2 & m_t(A_t - \mu \cot\beta) \\ m_t(A_t - \mu \cot\beta) & \tilde{m}_{tR}^2 \end{pmatrix}$$

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$$\tilde{m}_{tL}^2 = \tilde{m}_Q^2 + m_t^2 + \tfrac{1}{6}(4M_W^2 - M_Z^2)\cos 2\beta,$$

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$$\tilde{m}_{bL}^2 = \tilde{m}_Q^2 + m_b^2 - \tfrac{1}{6}(2M_W^2 + M_Z^2)\cos 2\beta,$$
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$$\tilde{m}_\tau^2 = \begin{pmatrix} \tilde{m}_{\tau L}^2 & m_\tau(A_\tau - \mu\tan\beta) \\ m_\tau(A_\tau - \mu\tan\beta) & \tilde{m}_{\tau R}^2 \end{pmatrix}$$

Mass Spectrum (spin=0)

Squarks & Sleptons

$$\tilde{m}_t^2 = \begin{pmatrix} \tilde{m}_{tL}^2 & m_t(A_t - \mu\cot\beta) \\ m_t(A_t - \mu\cot\beta) & \tilde{m}_{tR}^2 \end{pmatrix} \Rightarrow \begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix}$$

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$$\tilde{m}_{tL}^2 = \tilde{m}_Q^2 + m_t^2 + \tfrac{1}{6}(4M_W^2 - M_Z^2)\cos 2\beta,$$

$$\tilde{m}_{tR}^2 = \tilde{m}_U^2 + m_t^2 - \tfrac{2}{3}(M_W^2 - M_Z^2)\cos 2\beta,$$

$$\tilde{m}_{bL}^2 = \tilde{m}_Q^2 + m_b^2 - \tfrac{1}{6}(2M_W^2 + M_Z^2)\cos 2\beta,$$

$$\tilde{m}_{bR}^2 = \tilde{m}_D^2 + m_b^2 + \tfrac{1}{3}(M_W^2 - M_Z^2)\cos 2\beta,$$

$$\tilde{m}_{\tau L}^2 = \tilde{m}_L^2 + m_\tau^2 - \tfrac{1}{2}(2M_W^2 - M_Z^2)\cos 2\beta,$$

$$\tilde{m}_{\tau R}^2 = \tilde{m}_E^2 + m_\tau^2 + (M_W^2 - M_Z^2)\cos 2\beta.$$

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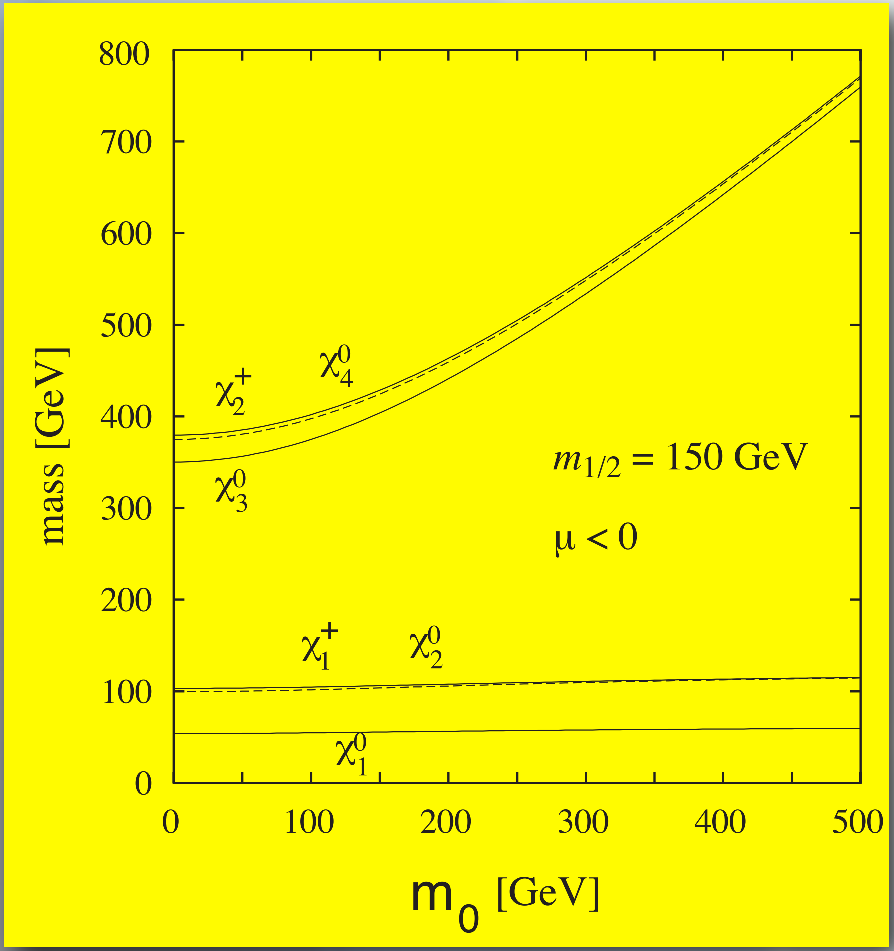
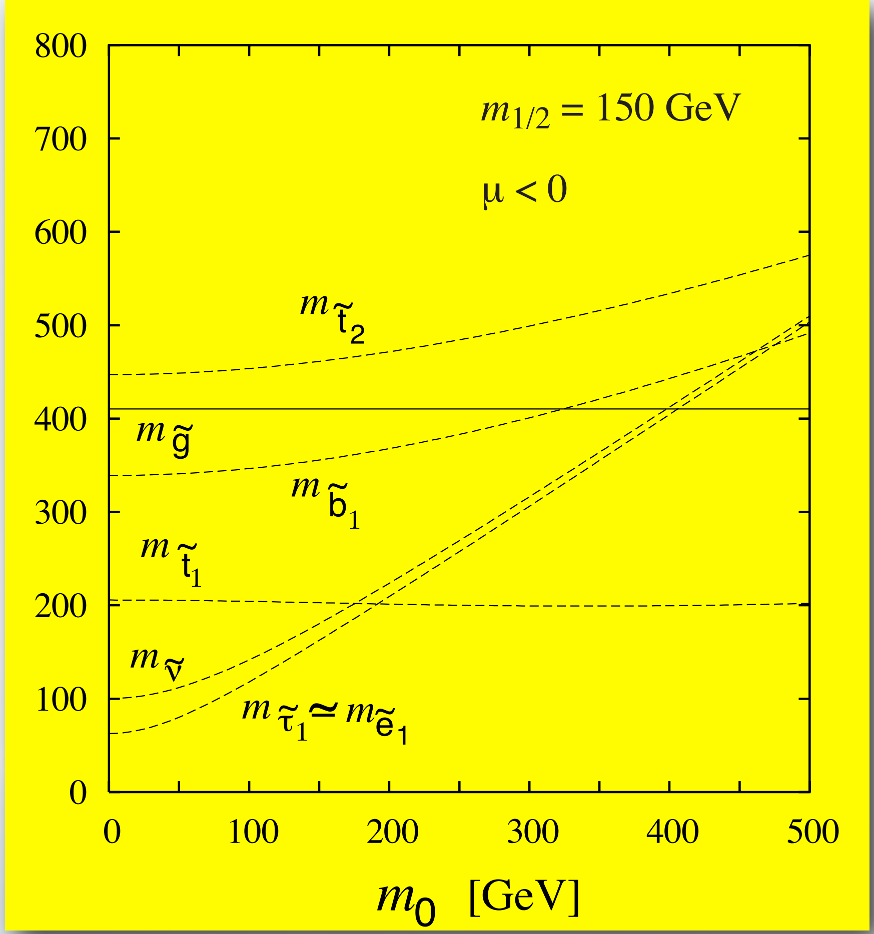
SUSY Masses in MSSM

Gauginos+Higgsinos



Squarks and Sleptons



SUSY Higgs Bosons

SUSY Higgs Bosons

SM

$$H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix} = \begin{pmatrix} v + \frac{S + iP}{\sqrt{2}} \\ H^- \end{pmatrix} = \exp\left(i \frac{\vec{\xi}\vec{\sigma}}{2}\right) \begin{pmatrix} v + \frac{S}{\sqrt{2}} \\ 0 \end{pmatrix}$$

SUSY Higgs Bosons

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$$H \to H' = \exp\left(i\frac{\vec{\alpha}\vec{\sigma}}{2}\right)H \xrightarrow{(\vec{\alpha} = -\vec{\xi})} H' = \begin{pmatrix} \mathrm{v} + \frac{S}{\sqrt{2}} \\ 0 \end{pmatrix}$$

SUSY Higgs Bosons

SM

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4=2+2=3+1

$$H \to H' = \exp\left(i\frac{\vec{\alpha}\vec{\sigma}}{2}\right)H \xrightarrow{(\vec{\alpha}=-\vec{\xi})} H' = \begin{pmatrix} v + \frac{S}{\sqrt{2}} \\ 0 \end{pmatrix}$$

SUSY Higgs Bosons

SM

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MSSM

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} = \begin{pmatrix} v_1 + \frac{S_1 + iP_1}{\sqrt{2}} \\ H_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} = \begin{pmatrix} H_2^+ \\ v_2 + \frac{S_2 + iP_2}{\sqrt{2}} \end{pmatrix},$$

$$v_1^2 + v_2^2 = v^2 \;, \quad v_2/v_1 \equiv \tan\beta$$

SUSY Higgs Bosons

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MSSM

8=4+4=3+5

$$H_1=\begin{pmatrix}H_1^0\\H_1^-\end{pmatrix}=\begin{pmatrix}v_1+\frac{S_1+iP_1}{\sqrt{2}}\\H_1^-\end{pmatrix},\quad H_2=\begin{pmatrix}H_2^+\\H_2^0\end{pmatrix}=\begin{pmatrix}H_2^+\\v_2+\frac{S_2+iP_2}{\sqrt{2}}\end{pmatrix},$$

$v_1^2+v_2^2=v^2$, $v_2/v_1 \equiv \tan\beta$

SUSY Higgs Bosons

SM

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NMSSM

SUSY Higgs Bosons

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NMSSM +2

SUSY Higgs Bosons

SM

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NMSSM +2 $S + P$

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NMSSM +2 $S + P$

The Higgs Potential

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$$V_{tree}(H_1, H_2) = m_1^2 |H_1|^2 + m_2^2 |H_2|^2 - m_3^2 (H_1 H_2 + h.c.)$$
$$+ \frac{g^2 + g'^2}{8} (|H_1|^2 - |H_2|^2)^2 + \frac{g^2}{2} |H_1^+ H_2|^2$$

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Minimization

$$\frac{1}{2}\frac{\delta V}{\delta H_1} = m_1^2 v_1 - m_3^2 v_2 + \frac{g^2 + g'^2}{4}(v_1^2 - v_2^2) v_1 = 0,$$
$$\frac{1}{2}\frac{\delta V}{\delta H_2} = m_2^2 v_2 - m_3^2 v_1 - \frac{g^2 + g'^2}{4}(v_1^2 - v_2^2) v_2 = 0.$$

$$< H_1 > \equiv v_1 = v \cos\beta, \quad < H_2 > \equiv v_2 = v \sin\beta,$$

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Solution

$$v^2 = \frac{4(m_1^2 - m_2^2\tan^2\beta)}{(g^2+g'^2)(\tan^2\beta - 1)},$$

$$\sin 2\beta = \frac{2m_3^2}{m_1^2 + m_2^2}$$

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$$v^2 = -\frac{4}{g^2+g'^2} m^2 < 0$$

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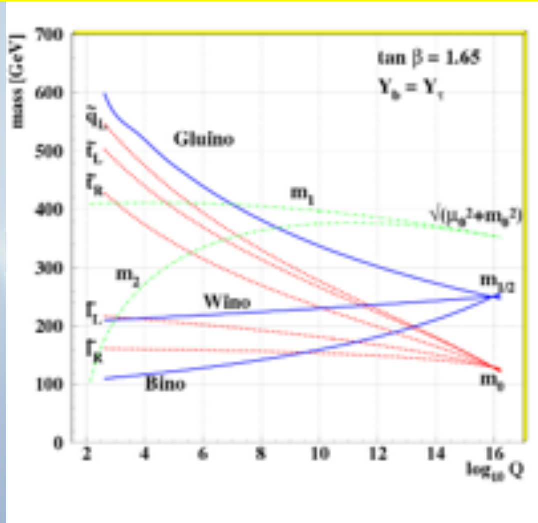
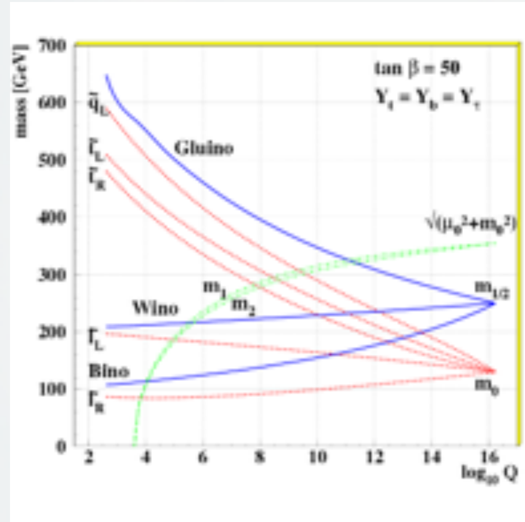
No SSB in SUSY theory !

Radiative EW Symmetry Breaking

Due to RG controlled running the mass terms from the Higgs potential may change sign and trigger the appearance of non-trivial minimum leading to spontaneous breaking of EW symmetry - this is called Radiative EWSB





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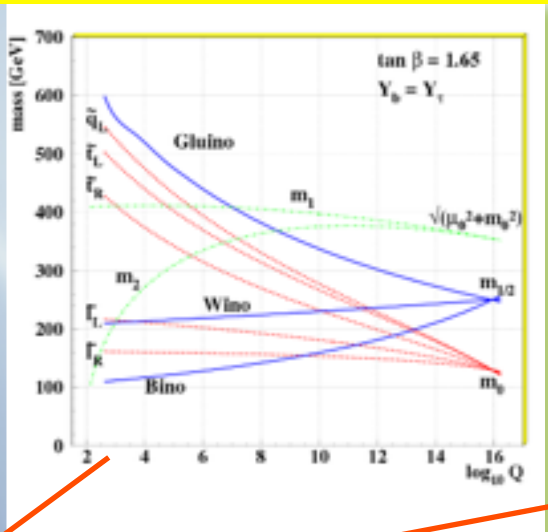

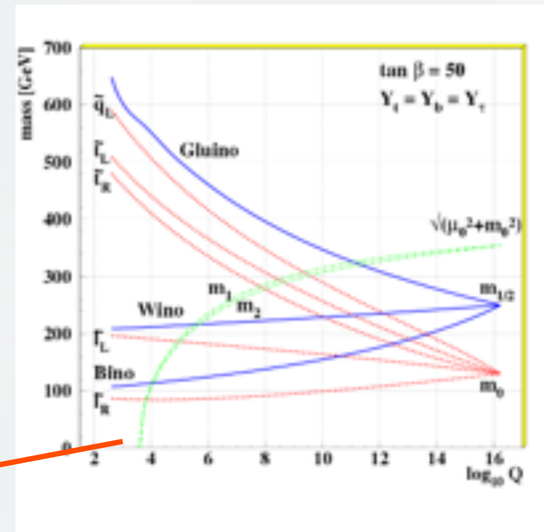

$$\frac{M_Z^2}{2} = -\mu^2 + \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1}$$

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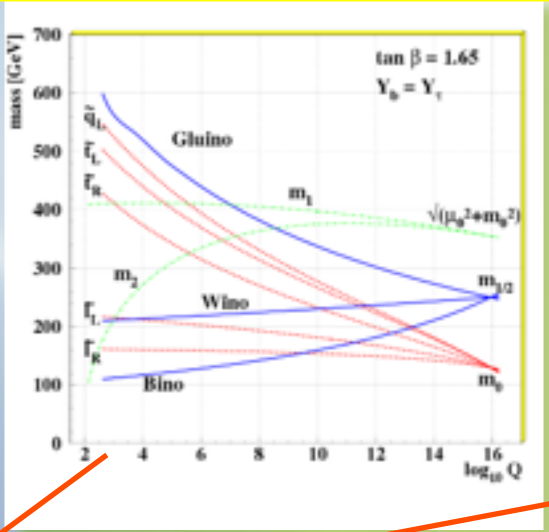

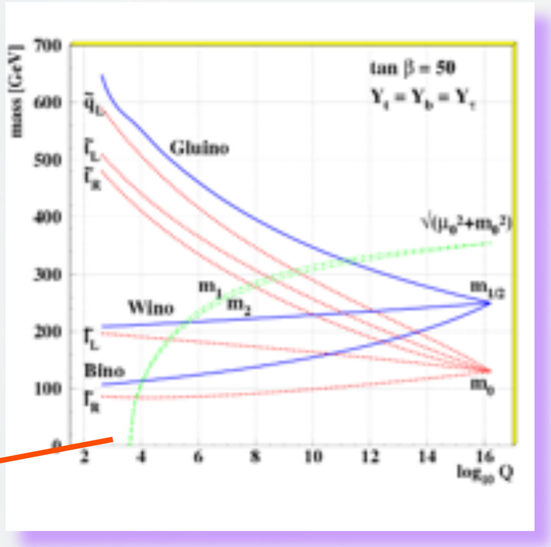

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$$m_{H_1} \sim m_{H_2} \sim m_0 \sim 1\ TeV$$

Soft SUSY parameters

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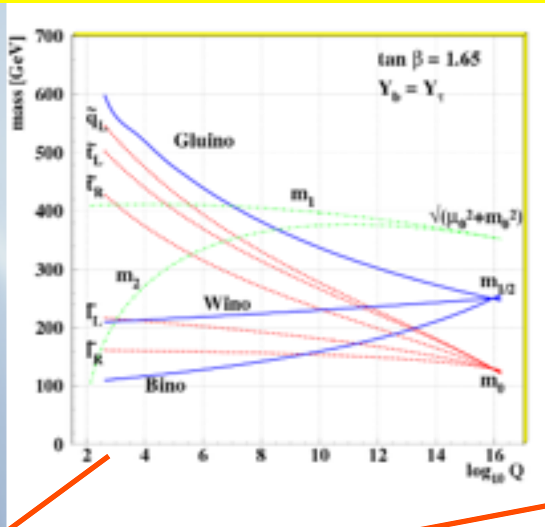

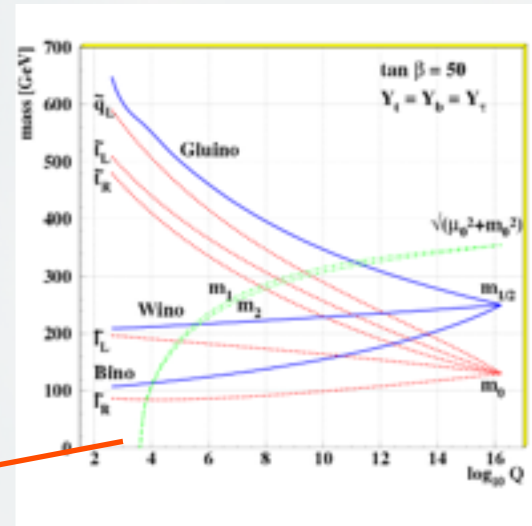

$$\frac{M_Z^2}{2} = -\mu^2 + \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1}$$

$$\mu^2 \quad \begin{cases} \text{For given } \tan\beta \\ m_0 \text{ and } m_{1/2} \end{cases}$$

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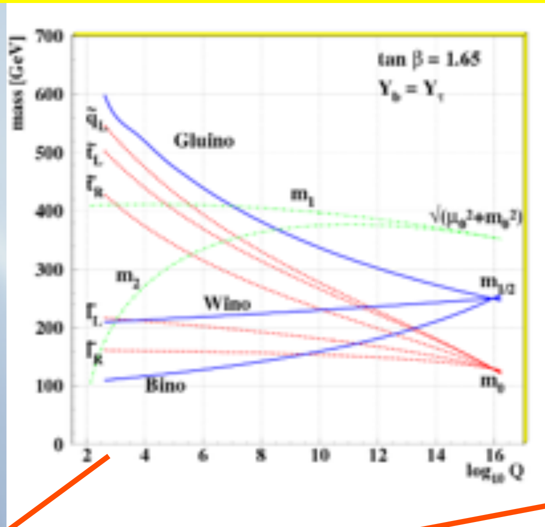

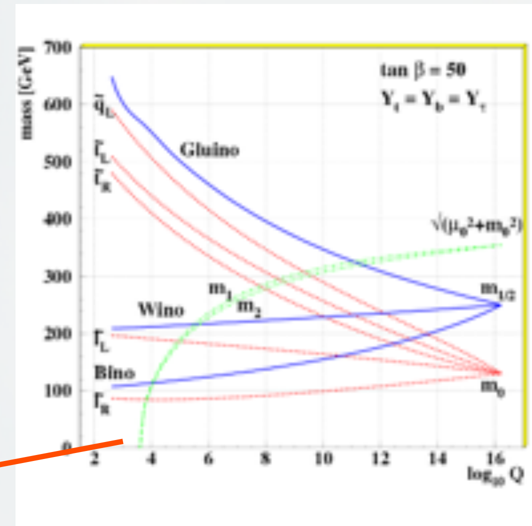

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$\Rightarrow$ μ^2 { For given $\tan\beta$; m_0 and $m_{1/2}$ }

$$m_{H_1} \sim m_{H_2} \sim m_0 \sim 1\ TeV$$

Soft SUSY parameters

$\Rightarrow$ $\mu \sim 1$ TeV

Hard SUSY parameter

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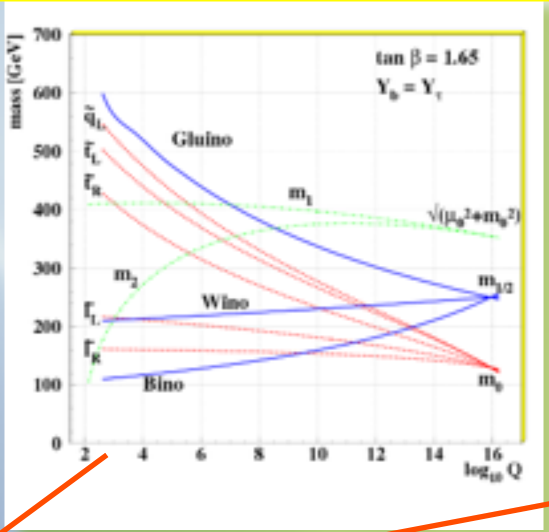

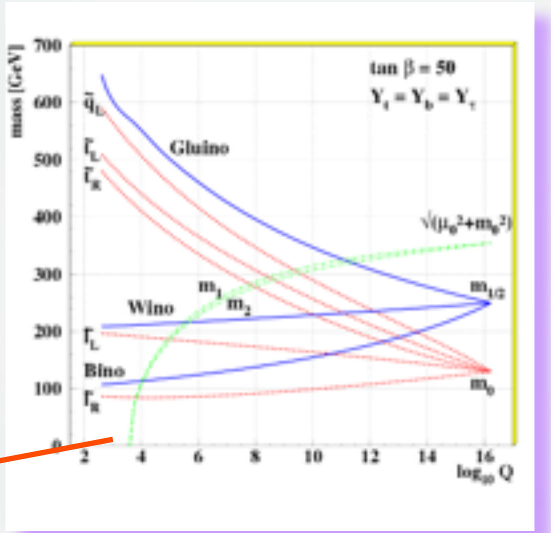

$$\frac{M_Z^2}{2} = -\mu^2 + \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1}$$

$\Rightarrow \mu^2$ { For given $\tan\beta$; m_0 and $m_{1/2}$ }

$$m_{H_1} \sim m_{H_2} \sim m_0 \sim 1\ TeV$$

Soft SUSY parameters

$\Rightarrow$ $\mu \sim 1$ TeV — μ - problem

Hard SUSY parameter

Higgs Boson's Masses

$$M^{odd} = \left.\frac{\partial^2 V}{\partial P_i \partial P_j}\right|_{H_i = v_i} = \begin{pmatrix} \tan\beta & 1 \\ 1 & \cot\beta \end{pmatrix} m_3^2$$

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$A = \sin\beta\, P_1 + \cos\beta\, P_2$	*Neutral* $CP = -1$ *Higgs*
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$h = -\sin\alpha\, S_1 + \cos\alpha\, S_2$	SM *Higgs boson* $CP = 1$
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$$\tan 2\alpha = \tan 2\beta \, \frac{m_A^2 + m_Z^2}{m_A^2 - m_Z^2}$$

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$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3 g^2 m_t^4}{16\pi^2 M_W^2} \log \frac{\tilde{m}_{t_1}^2 \tilde{m}_{t_2}^2}{m_t^4} + 2\ loops$$

The Higgs Mass Limit (MSSM)

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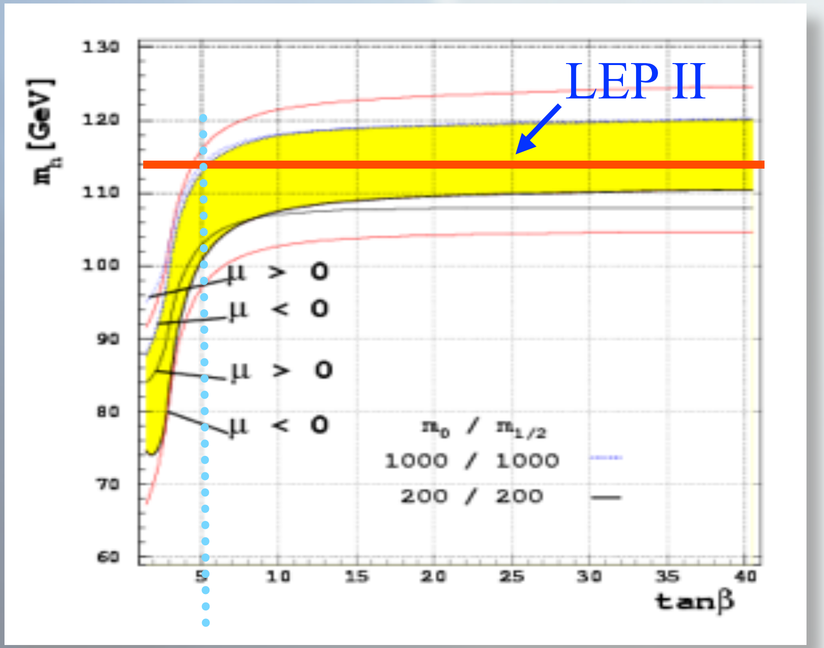

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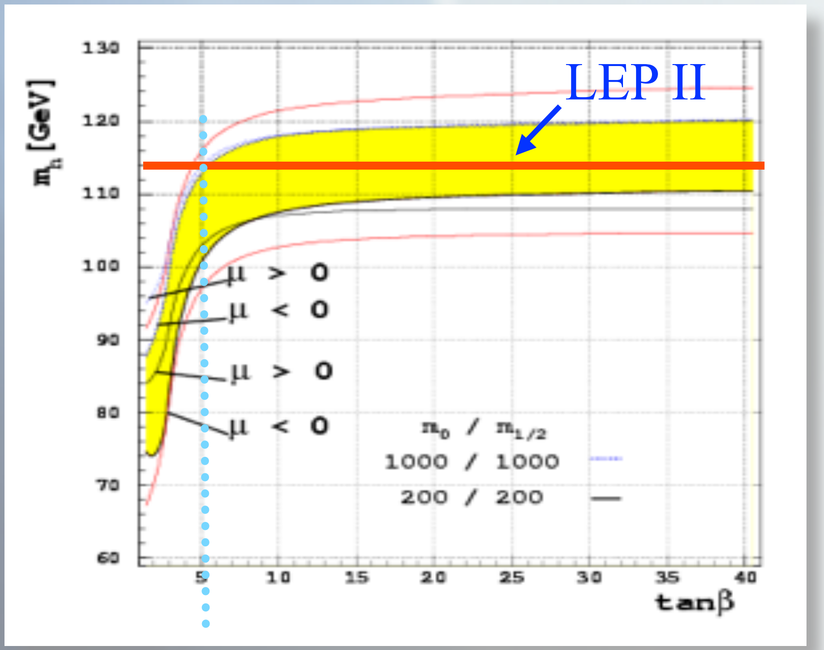

- MSSM Higgs $m_H \lesssim 130$ GeV

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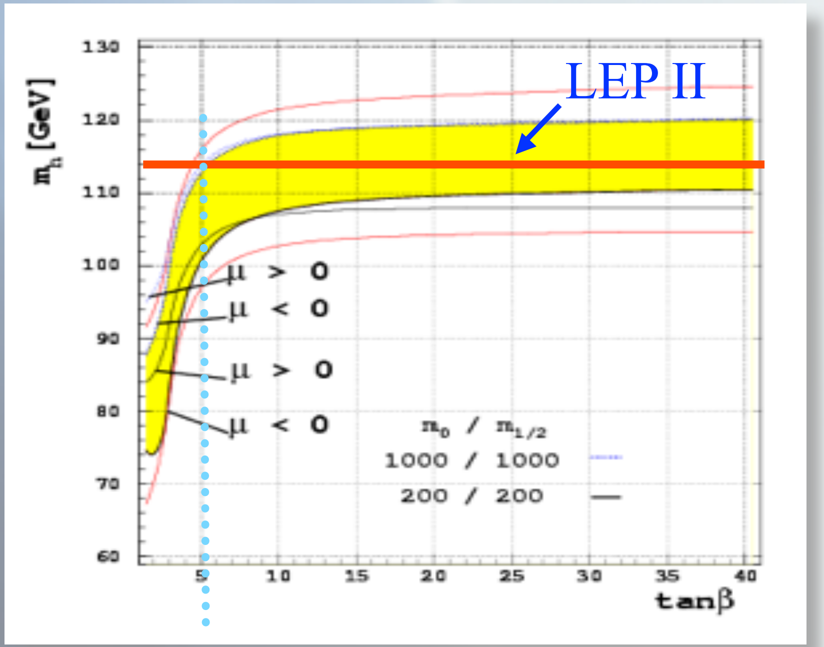

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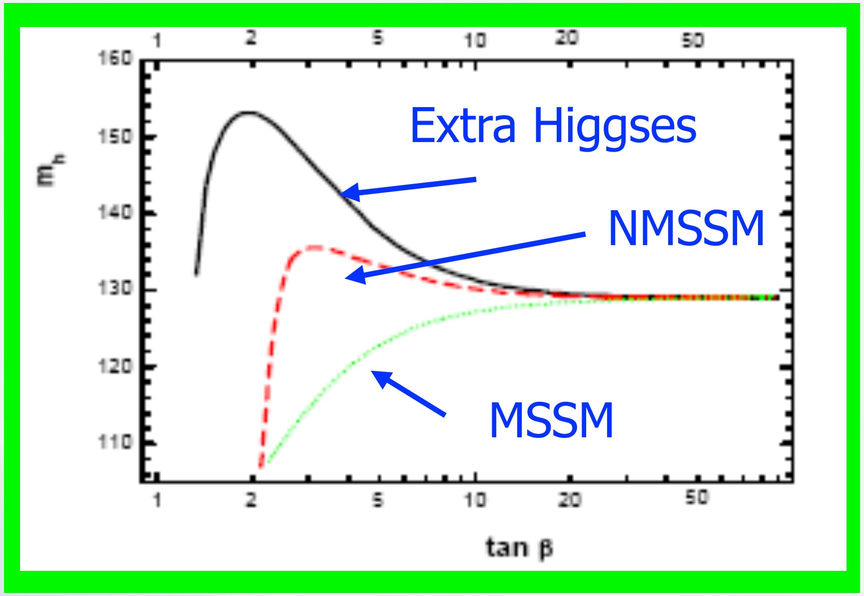
NMSSM



$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \ldots$$

The Higgs Sector: Alternatives

Model	Particle content
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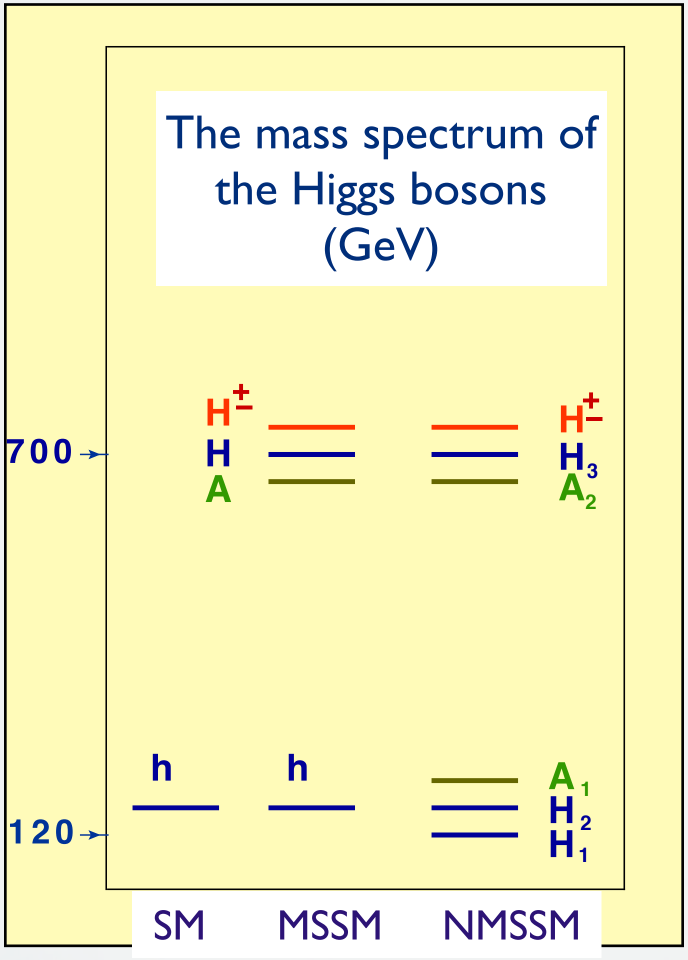

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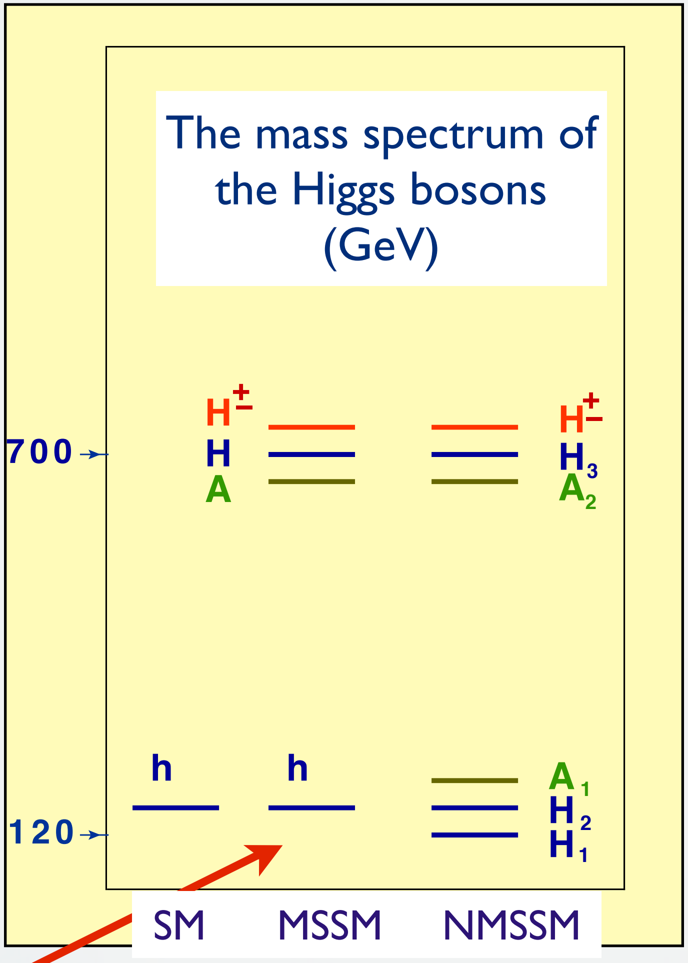

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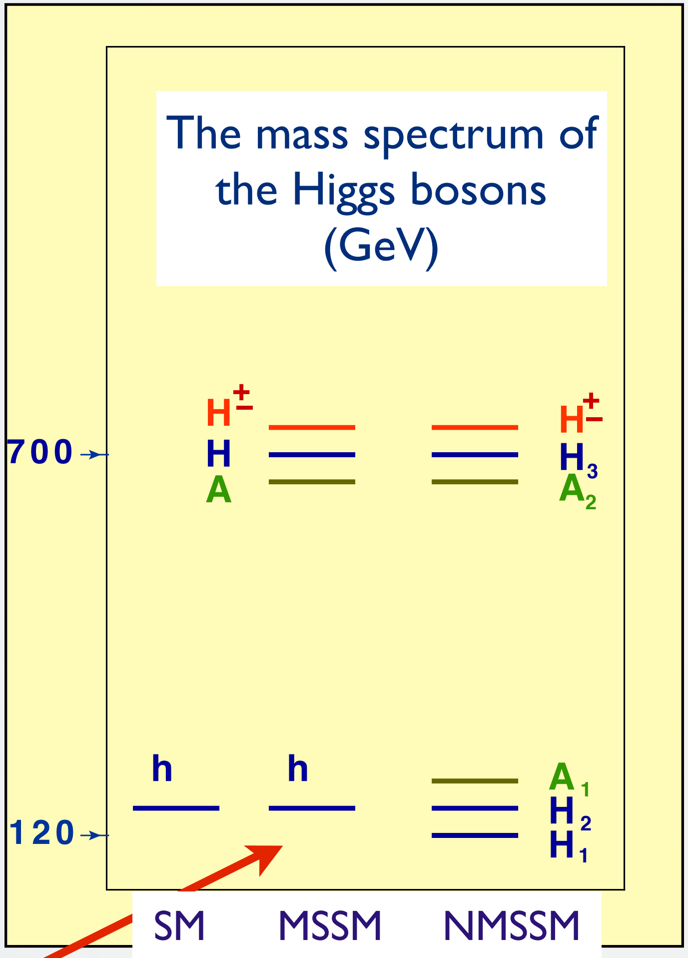

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One has to check the presence or absence of heavy Higgs bosons

The Lightest Superparticle

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		property	signature
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• R-parity violation LSP is unstable -> SM particles

Rare decays
Neutrinoless double β decay

Where is SUSY?

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Accelerators

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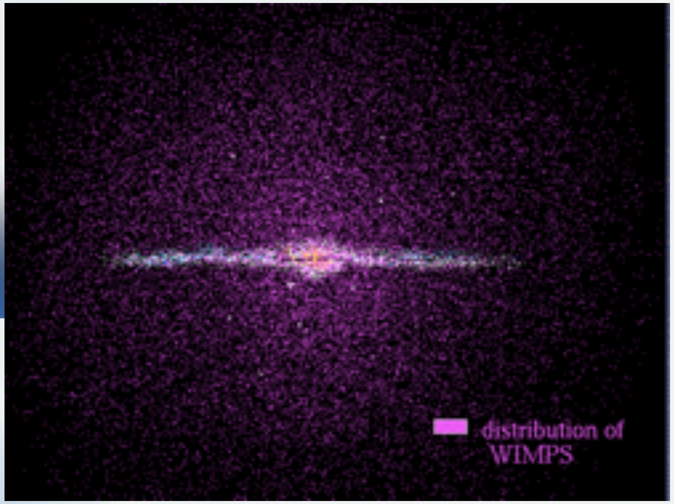
Telescopes



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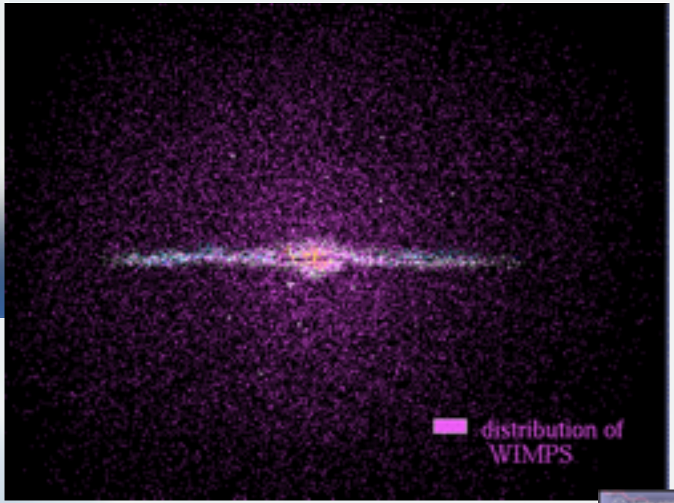

Underground
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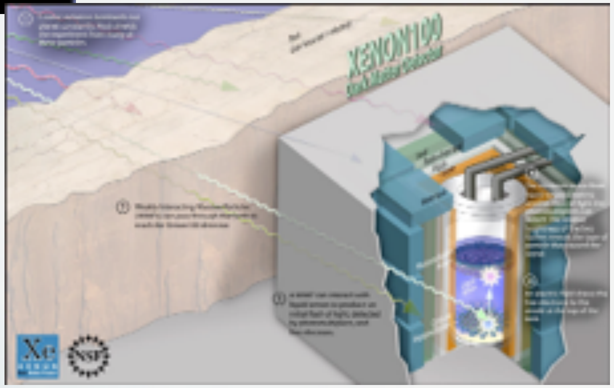
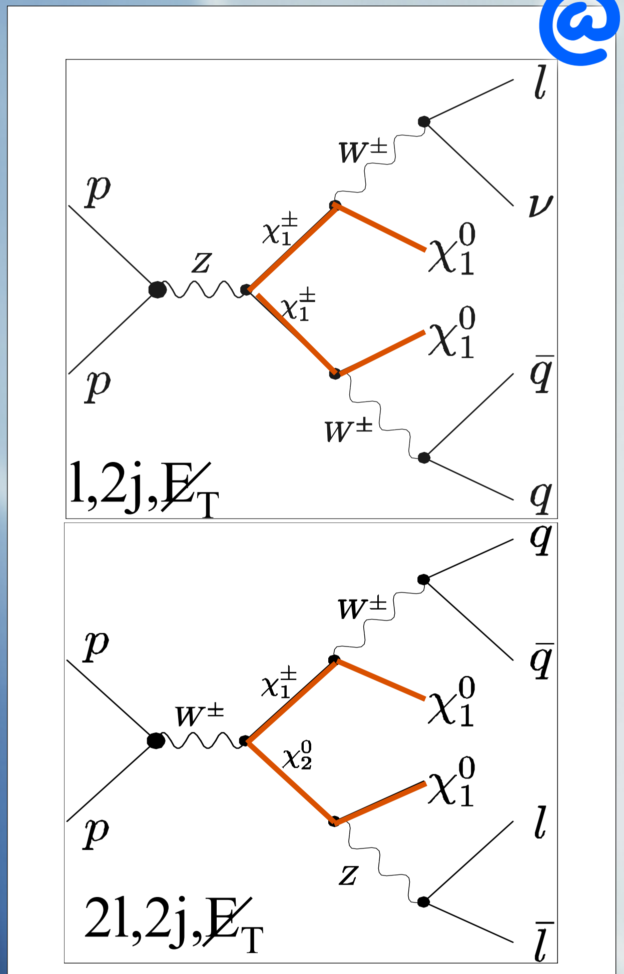
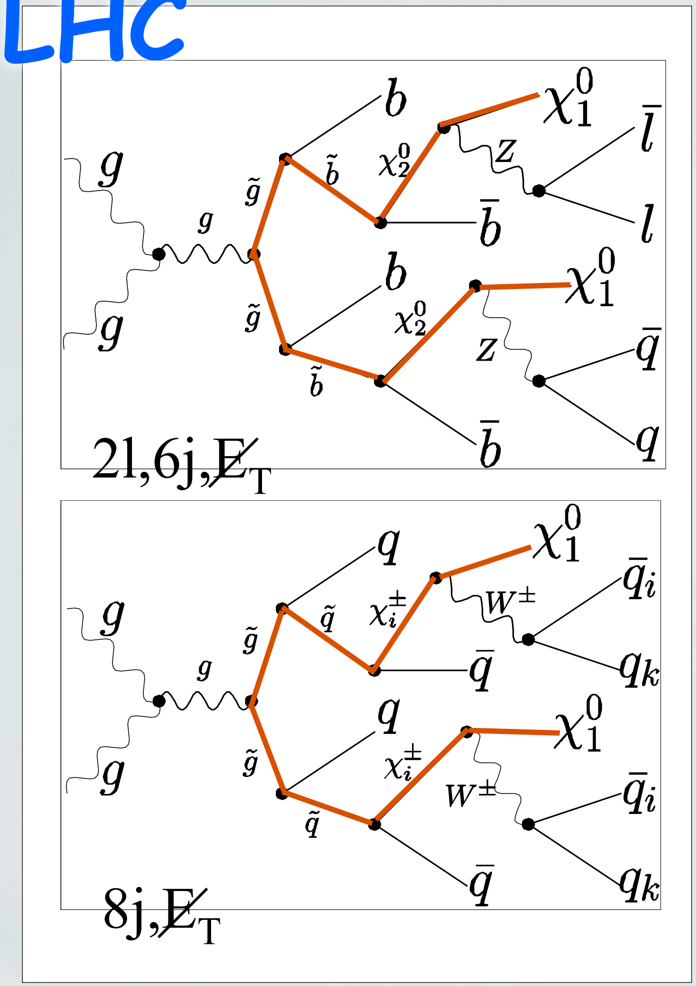


Creation and Decay of Superpartners @ LHC

weak int's





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Typical SUSY signature: missing energy and transverse momentum

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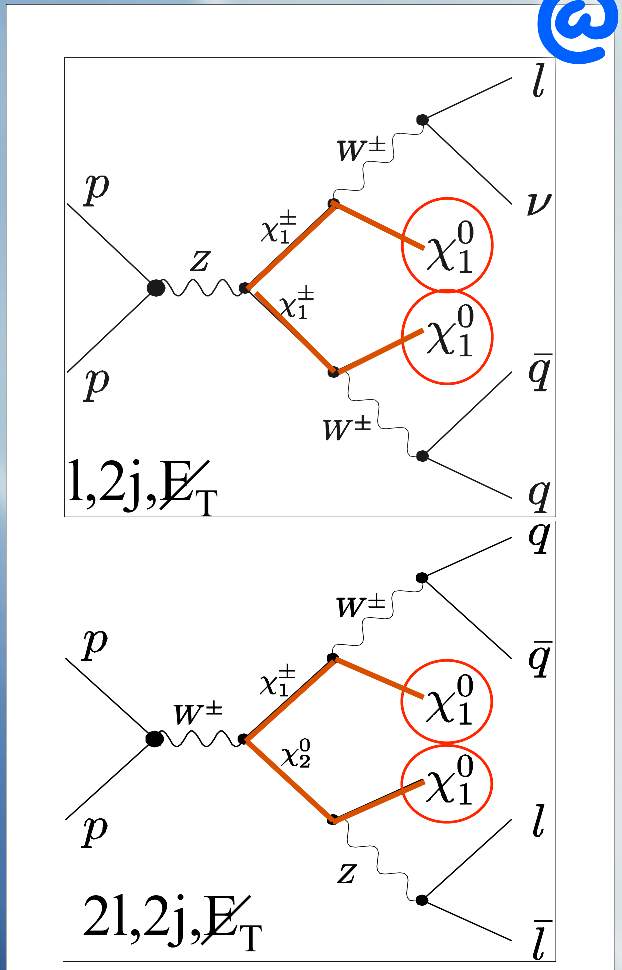

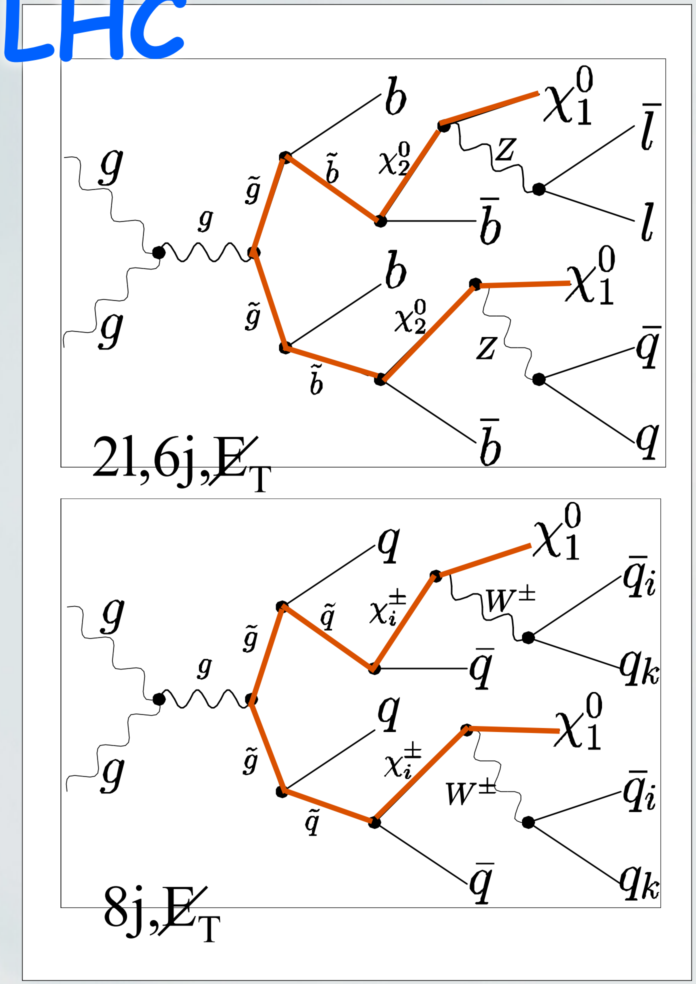

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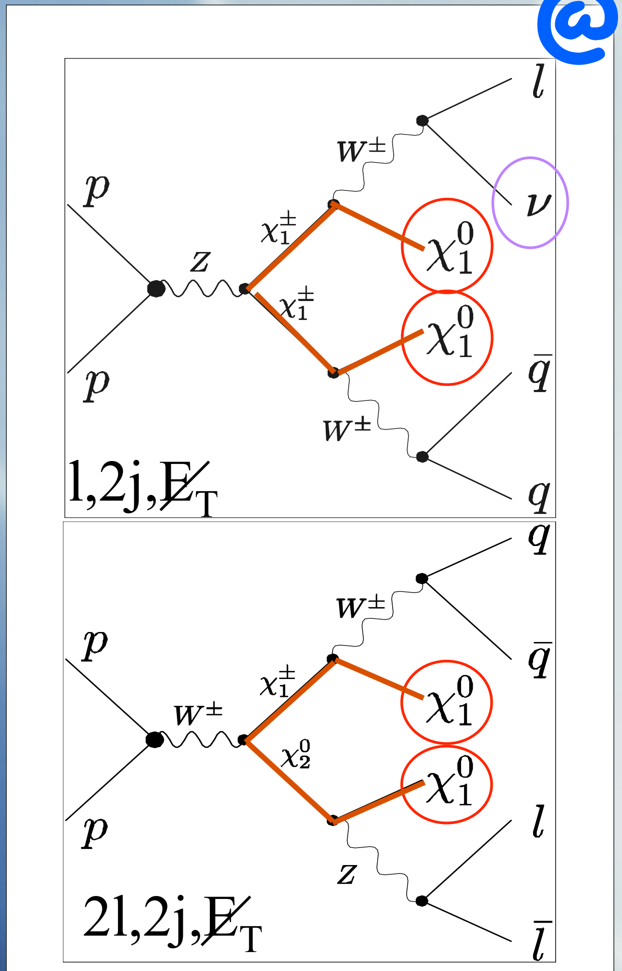

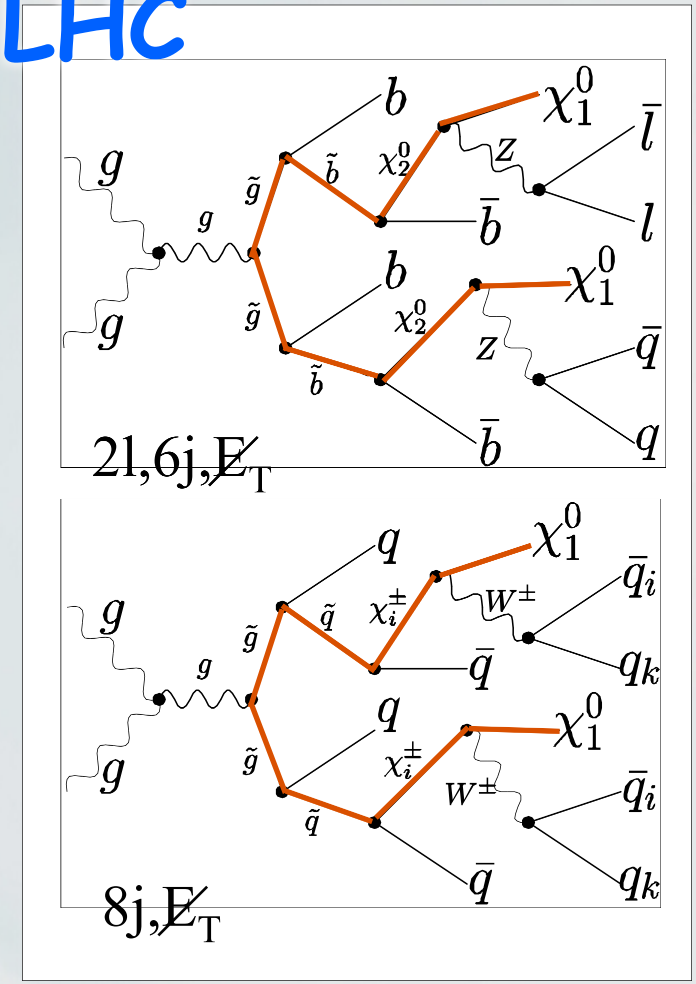

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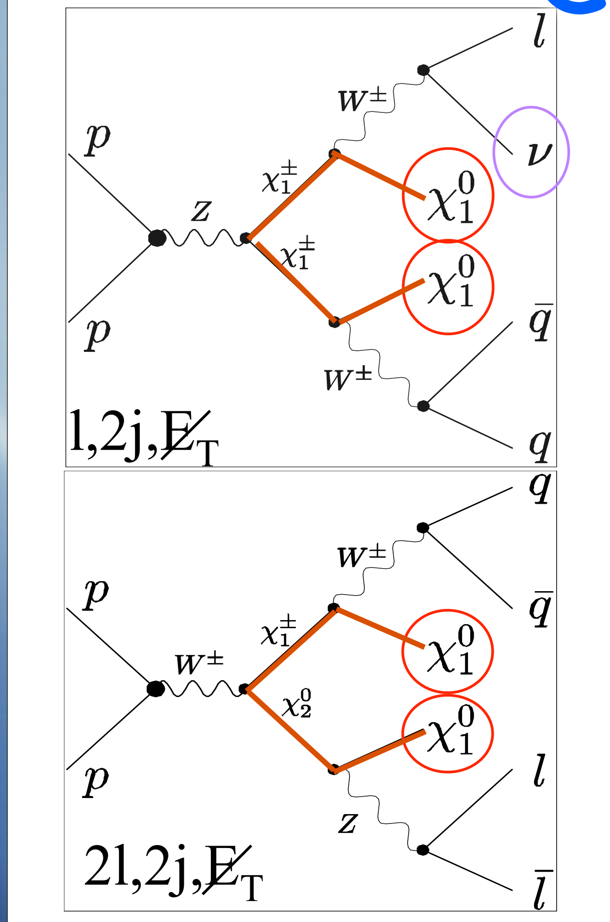

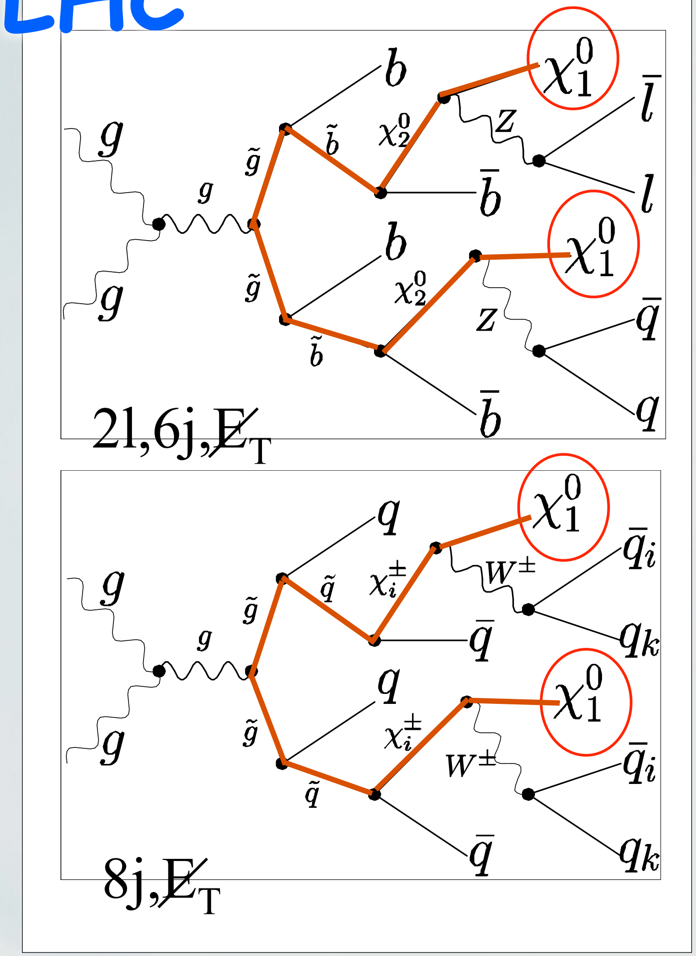

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- Leads to gauge coupling unification (GUT)
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