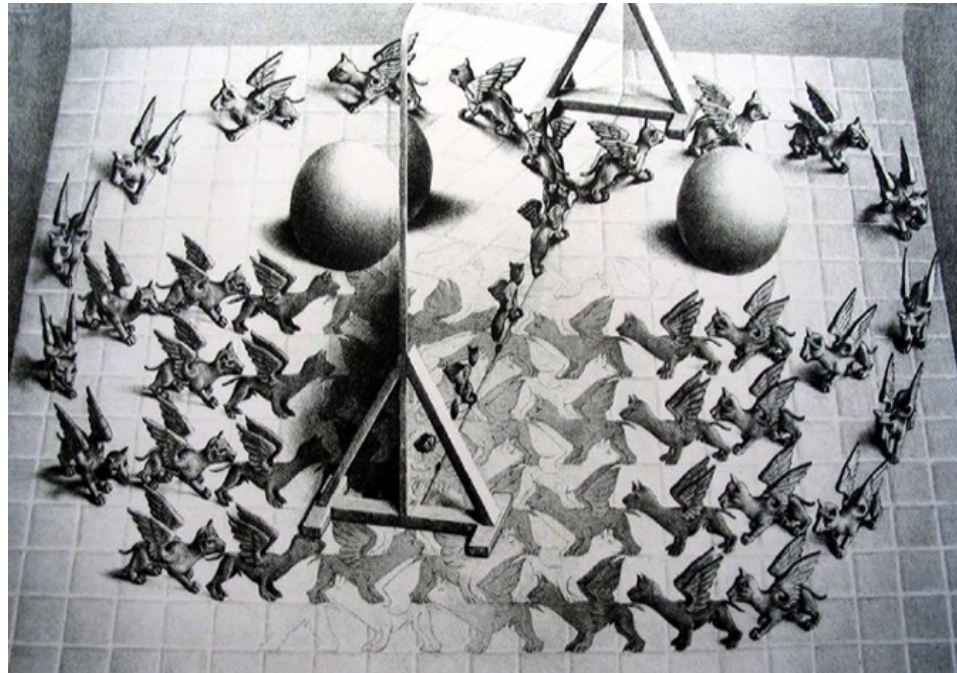


Physics at LHC: *SUperSYmmetry*

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LIP 22/04/2019

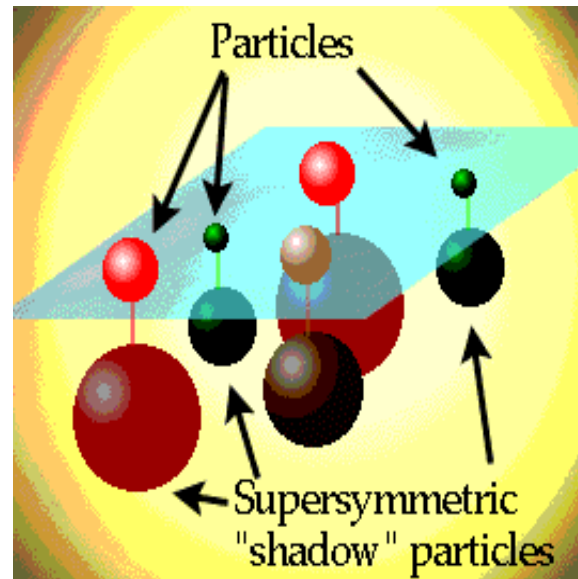
Outline

- *SUperSYmmetry: Brief introduction & Motivations*
- *Reminder of Standard Model (SM) Lagrangian*
- *SUSY phenomenology: Deeper look*
 - *“Constructing” the SUSY Lagrangian*
 - *Different sectors of MSSM:*
 - *Squark & Slepton*
 - *Chargino*
 - *Neutralino*
 - *Higgs*

Advised readings:

- *“SUSY & Such” S. Dawson, [arxiv:hep-ph/9612229v2](https://arxiv.org/abs/hep-ph/9612229v2)*
- *“A supersymmetry primer” S. P. Martin, [arxiv:hep-ph/9709356](https://arxiv.org/abs/hep-ph/9709356)*

Brief introduction & Motivations



Supersymmetry: Introduction words

“Generalize” the spin of known fields

SUPERSymmetry : spin particle $1/2 \leftrightarrow$ spin partner 0
 spin particle 1 \leftrightarrow spin partner $1/2$

Names		spin 0	spin 1/2
squarks, quarks ($\times 3$ families)	Q	$(\tilde{u}_L \ \tilde{d}_L)$	$(u_L \ d_L)$
	\bar{u}	\tilde{u}_R^*	u_R^\dagger
	\bar{d}	\tilde{d}_R^*	d_R^\dagger
sleptons, leptons ($\times 3$ families)	L	$(\tilde{\nu} \ \tilde{e}_L)$	$(\nu \ e_L)$
	\bar{e}	\tilde{e}_R^*	e_R^\dagger
Higgs, higgsinos	H_u	$(H_u^+ \ H_u^0)$	$(\tilde{H}_u^+ \ \tilde{H}_u^0)$
	H_d	$(H_d^0 \ H_d^-)$	$(\tilde{H}_d^0 \ \tilde{H}_d^-)$

Names	spin 1/2	spin 1
gluino, gluon	\tilde{g}	g
winos, W bosons	$\tilde{W}^\pm \ \tilde{W}^0$	$W^\pm \ W^0$
bino, B boson	\tilde{B}^0	B^0

Observed SUSY particles with same mass than Standard-Model partners ? No !

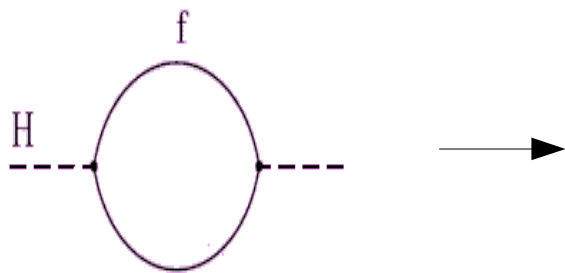
SUSY : A broken symmetry !

Physical sParticles:
Mixture of super-partners

- Charginos (χ^\pm) / Neutralinos (χ^0) :
 Bino/Wino \leftrightarrow Higgs (charged/neutral)
- Squarks, Sleptons : Mixture of $f_L \leftrightarrow f_R$

Supersymmetry: The natural cure of Hierarchy problem

- Discovery of a Higgs Boson:
 - $m_H = 125 \text{ GeV}/c^2$
- Consider Higgs mass correction from fermionic loop:

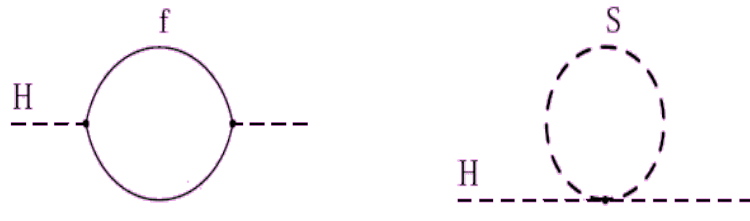


$$\Delta m_H^2 = \frac{\lambda_f^2}{16\pi^2} \cdot [-2\Lambda_{UV}^2 + \dots]$$

Λ_{UV} : Energy-scale at which new physics alters the Standard-Model (momentum cut-off regulating the loop-integral)

If $\Lambda_{UV} \sim M_P \rightarrow \Delta m_H^2 \sim O(10^{30})$ larger than m_H !!!

And all Standard-Model masses indirectly sensitive to Λ_{UV} !!!



$$\Delta m_H^2 = \frac{\lambda_s}{16\pi^2} \cdot [\Lambda_{UV}^2 - \dots]$$

Δm_H^2 quadratic divergence cancelled :

Hierarchy problem naturally solved !

Supersymmetry & Coupling constants

In Gauge theories :
 Predict coupling constants at a scale Q once we measured them at another:

$$1/\alpha_i(Q) = 1/\alpha_i(M_Z) + (b_i/2) \log[M_Z/Q]$$

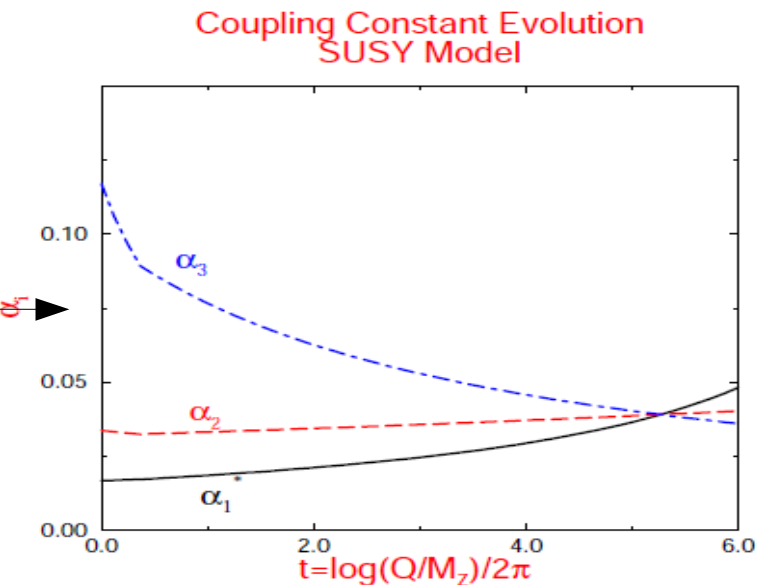
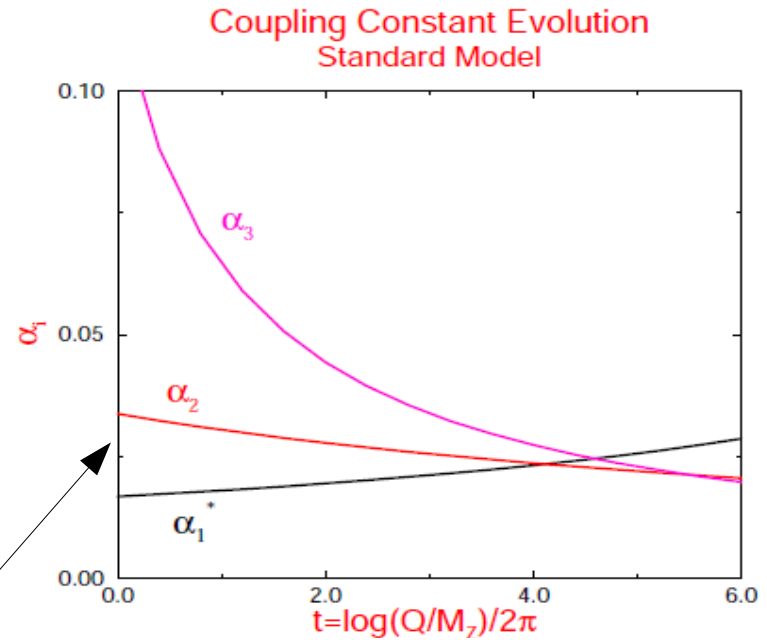
b_i : Function of $N_g (=3)$ and N_H (Number of Higgs doublets)

In Standard-Model : $N_H = 1$
 -> b_i 's such that ...

In SUSY: $N_H = 2$ + New particles contributing to a different evolution of coupling constants

-> b_i 's such that !

SUSY can naturally be incorporated into Grand Unified Theories



Supersymmetry & Dark Matter

Most general SUSY lagrangian allows interactions leading to Baryon- & Lepton-number violation !

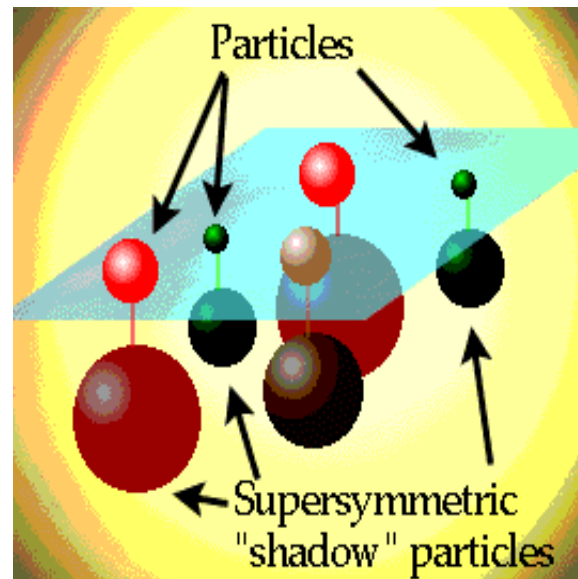
Now if sParticles were to exist at TeV scale:
Such interactions very seriously restricted by experimental observation !

In SUSY: $N_{B,L}$ conservation *can* be “protected” by new symmetry R_p :

- **Eigenvalue: $(-1)^{3(B-L)+s}$**
 - +1 / -1 for SM / SUSY particles
- **If R_p conserved: Lightest Supersymmetric Particle (LSP) is stable**
In most SUSY scenarios, LSP is either:
 - The lightest neutralino $\tilde{\chi}^0$ (mixture of neutral Higgsinos / Bino / Wino)
 - Scalar neutrinos
- ...In all cases a weakly interacting neutral particle

SUSY can have a natural candidate for the observed Cold Dark Matter : $\sim 25\%$ of mass of universe

Revisiting SM Lagrangian



SM Lagrangian

Let's put the QCD part aside & have a look at the EW part only

$$\mathbf{L}_{EW} = \mathbf{L}_{\text{free+interaction}} + \mathbf{L}_{\text{gauge}} + \mathbf{L}_{\text{higgs}} + \mathbf{L}_{\text{yukawa}}$$

SM Lagrangian: Free & Interaction parts

$$\mathbf{L}_{\text{free+interaction}} = \sum_f \mathbf{i} [\bar{\psi}_f^L \boldsymbol{\gamma}^\mu \mathbf{D}_\mu^L \psi_f^L + \bar{\psi}_f^R \boldsymbol{\gamma}^\mu \mathbf{D}_\mu^R \psi_f^R]$$

→ $\psi_f^{L,R}$: Left and Right fermion, CC, Dirac spinors

→ Gauge-invariant derivatives:

$$\mathbf{D}_\mu^L = \delta_\mu - i \mathbf{g} (\boldsymbol{\tau}_a/2) \mathbf{W}_\mu^a - i \mathbf{g}' (\mathbf{Y}_L/2) \mathbf{B}_\mu$$

$$\mathbf{D}_\mu^R = \delta_\mu - i \mathbf{g}' (\mathbf{Y}_R/2) \mathbf{B}_\mu$$

→ \mathbf{g}, \mathbf{g}' : Weak-isospin & -hypercharge couplings

→ $\mathbf{W}_\mu^a, \mathbf{B}_\mu$: Weak-isospin & -hypercharge fields

→ $\boldsymbol{\tau}_a, \mathbf{Y}_{L,R}$: Weak-isospin & -hypercharge quantum numbers, matrices

SM Lagrangian: The gauge part

$$\mathbf{L}_{\text{gauge}} = -\frac{1}{4} \mathbf{W}_{\mu\nu}^a \mathbf{W}^{a\mu\nu} - \frac{1}{4} \mathbf{B}_{\mu\nu} \mathbf{B}^{\mu\nu}$$

→ Gauge-invariant Weak-isospin & -hypercharge fields:

$$\mathbf{W}_{\mu\nu}^a = \delta_{\mu}^{\nu} \mathbf{W}_{\nu}^a - \delta_{\nu}^{\mu} \mathbf{W}_{\mu}^a + g \varepsilon_{abc} \mathbf{W}_{\mu}^b \mathbf{W}_{\nu}^c$$

$$\mathbf{B}_{\mu\nu} = \delta_{\mu}^{\nu} \mathbf{B}_{\nu} - \delta_{\nu}^{\mu} \mathbf{B}_{\mu}$$

2nd term of $\mathbf{W}_{\mu\nu}^a$: Self-interacting character of Weak-isospin interaction → *This is the term allowing tri-boson couplings in SM*

A similar term exists in QCD sector of SM: QCD is also non-abelian → Allows self-coupling

SM Lagrangian: The Higgs part

$$\mathbf{L}_{\text{Higgs}} = (D_{\mu} \phi)^{\dagger} (D^{\mu} \phi) - V(\phi)$$

D_{μ} : Same gauge-invariant derivatives as before

→ 1st term: Higgs↔Boson interaction:

Gives Boson masses

Gives Higgs↔Boson couplings

→ $V(\phi)$: Pure Higgs interaction:

$$\text{Mass: } m_{\text{H}} = \sqrt{-2\mu^2} = \sqrt{2\lambda v^2}$$

Coupling: Calculate :-D

The lagrangian has to be $SU(2) \times U(1)$ invariant

→ 4 scalar real fields: $\phi = (\phi^+, \phi^0)$

$$\phi^+ = (1/\sqrt{2})(\phi_1 + i\phi_2)$$

$$\phi^0 = (1/\sqrt{2})(\phi_3 + i\phi_4)$$

SM Lagrangian: Yukawa

$$\mathbf{L}_{\text{yukawa}} = -\mathbf{G}_d (\bar{\mathbf{u}}, \bar{\mathbf{d}})_L (\phi^+, \phi^0) \mathbf{d}_R - \mathbf{G}_u (\bar{\mathbf{u}}, \bar{\mathbf{d}})_L (-\bar{\phi}^0, \phi^-) \mathbf{u}_R \\ + \text{hermitian-conjugate}$$

(u,d): Up & Down doublets of quarks / leptons

Once Higgs sector is EW-broken:

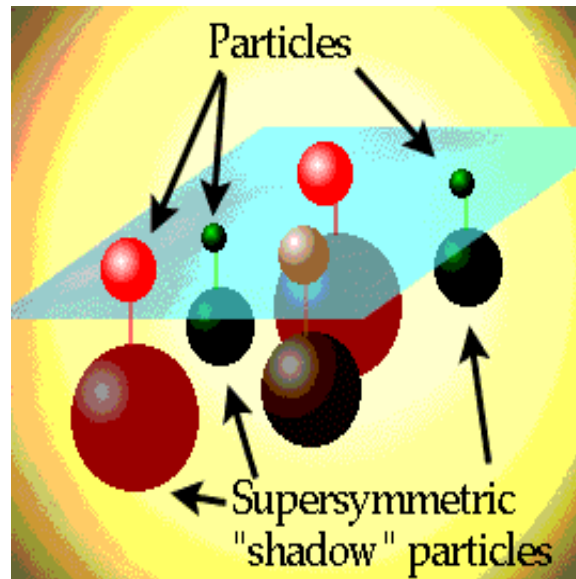
$\phi = (1/\sqrt{2})(0, v+H) \rightarrow$ “Confers” mass to fermions:

$$\mathbf{L}_{\text{yukawa}} = -m_d \bar{\mathbf{d}}_L \mathbf{d}_R (1+H/v) - m_u \bar{\mathbf{u}}_L \mathbf{u}_R (1+H/v)$$

because: $m_f = G_f v/\sqrt{2}$

For neutrinos: $m = G_v v/\sqrt{2} \sim 0$

“Constructing” the SUSY Lagrangian



MSSM: Writing the Lagrangian

Recipe to build the particle content and Lagrangian:

- Each SM fermion f has 2 chiral superpartners: f_L & f_R
- SM fermions and SUSY sfermions are regrouped in **superfields**

$Q = \begin{pmatrix} u \\ d \end{pmatrix}_L \longrightarrow \tilde{Q} = \begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix} \quad \bar{u}_R \quad \tilde{u}_R^* \\ \bar{d}_R \quad \tilde{d}_R^*$
$L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \longrightarrow \tilde{L} = \begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix} \quad \bar{e}_R \quad \tilde{e}_R^*$

SM

MSSM

- Gauge superfields:** “Simply” containing the SM gauge fields and their SUSY partners
- Gauge superfields: Respecting the $SU(3) \times SU_L(2) \times U(1)$

MSSM: Writing the Lagrangian

Superfields of Gauge & Matter, by definition, respect the gauge symmetries extended from the SM

Superfield	SU(3)	$SU(2)_L$	$U(1)_Y$	Particle Content
\hat{Q}	3	2	$\frac{1}{6}$	$(u_L, d_L), (\tilde{u}_L, \tilde{d}_L)$
\hat{U}^c	$\bar{3}$	1	$-\frac{2}{3}$	\bar{u}_R, \tilde{u}_R^*
\hat{D}^c	$\bar{3}$	1	$\frac{1}{3}$	\bar{d}_R, \tilde{d}_R^*
\hat{L}	1	2	$-\frac{1}{2}$	$(\nu_L, e_L), (\tilde{\nu}_L, \tilde{e}_L)$
\hat{E}^c	1	1	1	\bar{e}_R, \tilde{e}_R^*
\hat{H}_1	1	2	$-\frac{1}{2}$	(H_1, \tilde{h}_1)
\hat{H}_2	1	2	$\frac{1}{2}$	(H_2, \tilde{h}_2)

Superfield	SU(3)	$SU(2)_L$	$U(1)_Y$	Particle Content
\hat{G}^a	8	1	0	g, \tilde{g}
\hat{W}^i	1	3	0	$W_i, \tilde{\omega}_i$
\hat{B}	1	1	0	B, \tilde{b}

MSSM: Writing the Lagrangian

The interaction part:

$$\mathcal{L}_{int} = -\sqrt{2} \sum_{i,A} g_A \left[S_i^* T^A \bar{\psi}_{iL} \lambda_A + \text{h.c.} \right] - \frac{1}{2} \sum_A \left(\sum_i g_A S_i^* T^A S_i \right)^2$$

- Interaction-specific quantum number
- S_i : Scalar fields: Squarks & Sleptons
- ψ_i : Higgsinos
- λ_A : Gauge fermions

The gauge invariant derivative part: Same as introduced in SM, but generalized to superfields

The kinetic part:

$$\mathcal{L}_{KE} = \sum_i \left\{ (D_\mu S_i^*) (D^\mu S_i) + i \bar{\psi}_i D \psi_i \right\} + \sum_A \left\{ -\frac{1}{4} F_{\mu\nu}^A F^{\mu\nu A} + \frac{i}{2} \bar{\lambda}_A D \lambda_A \right\}$$

MSSM: SM \leftrightarrow MSSM correspondance

Fermion

Scalar

Gauge field

SM

$$i \bar{f} \gamma^\mu D_\mu f +$$

$$(D_\mu \phi)^\dagger (D^\mu \phi)$$

SM: Higgs

$$- (1/4) F_{\mu\nu} F^{\mu\nu}$$

MSSM (includes what is above)

$$i \bar{\psi} \gamma^\mu D_\mu \psi +$$

MSSM: Higgsinos

$$(D_\mu S_i)^\dagger (D^\mu S_i)$$

Squarks & Sleptons

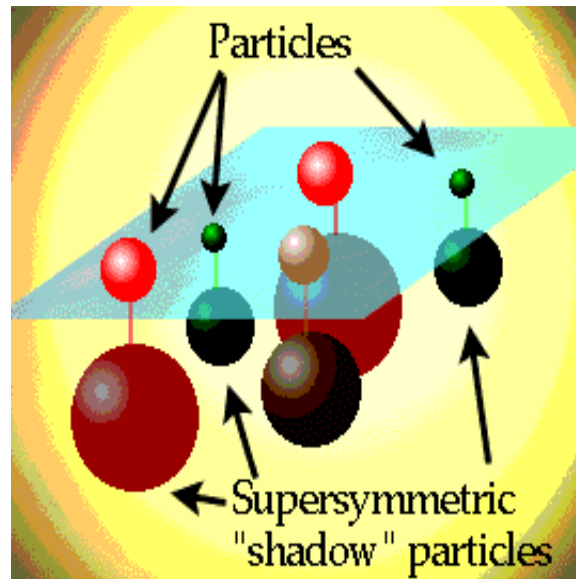
$$- (1/4) F_{\mu\nu} F^{\mu\nu}$$

Same as above

$$+ (i/2) \bar{\lambda}_A \gamma^\mu D_\mu \lambda_A$$

Gauge fermions

***SUSY: Let's minimally break it:
Broken & effective MSSM***



SUSY breaking

How is it broken ? We don't know... did not discover it (yet)...

How we *think* it's broken: Models/Implications by/for the theorists/experimentalists

mSUGRA Spontaneous Super-Gravity breaking: **More constrained** → 5 parameters @ breaking scale → RGEs → Our mass spectrum

- m_0 : Scalar mass
- $m_{1/2}$: Fermion mass
- μ : Higgs parameter ($\mu H_1 H_2$)
- A : Tri-linear squark/slepton mixing term
- $\tan\beta = \langle H_2^0 \rangle / \langle H_1^0 \rangle$

MSSM Parametrizing our ignorance of SUSY breaking, i.e. no hypothesis: **Un-constrained** → 124 parameters

- $\tan\beta / \mu / M_A$ (pseudoscalar Higgs boson mass)
- $M_{L1,2,3}$: Controls slepton masses
- $M_{Q1,2,3}$: Controls squark masses
- $M_{1,2}$: Controls neutralino/chargino sectors
- ...

This is the most general Lagrangian we can write, hence the large number of unknowns: Only the spin hypothesis has been made

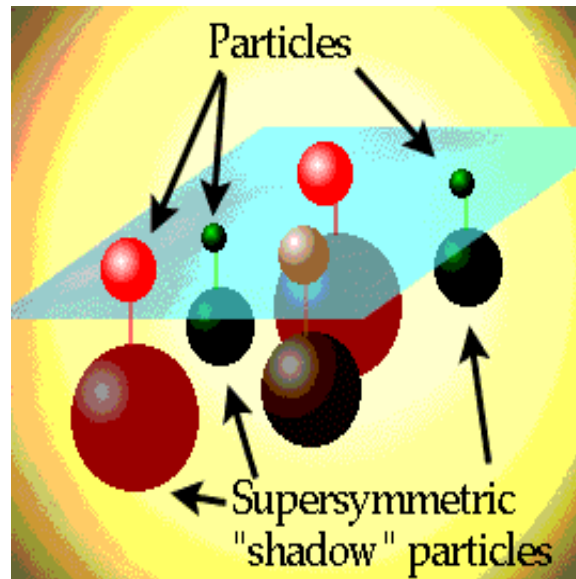
MSSM: Effective Lagrangian

- We don't know how SUSY is broken, but can write the **most general broken effective Lagrangian**
- Soft: The breaking of the symmetry is taken care of by introducing “soft” mass terms for scalars & gauginos: Soft because no re-introduction of quadratic divergence
- Maximal dimension of soft operators: $\leq 3 \rightarrow$ Mass terms, **Bilinear** & **Trilinear** terms

$$\begin{aligned}
 -\mathcal{L}_{\text{soft}} = & \boxed{m_1^2 |H_1|^2 + m_2^2 |H_2|^2} - \boxed{B\mu\epsilon_{ij}(H_1^i H_2^j + \text{h.c.})} + \boxed{\tilde{M}_Q^2(\tilde{u}_L^* \tilde{u}_L + \tilde{d}_L^* \tilde{d}_L)} \\
 & \boxed{+ \tilde{M}_u^2 \tilde{u}_R^* \tilde{u}_R + \tilde{M}_d^2 \tilde{d}_R^* \tilde{d}_R + \tilde{M}_L^2(\tilde{e}_L^* \tilde{e}_L + \tilde{\nu}_L^* \tilde{\nu}_L) + \tilde{M}_e^2 \tilde{e}_R^* \tilde{e}_R} \\
 & + \frac{1}{2} \left[\boxed{M_3 \tilde{g} \tilde{g} + M_2 \tilde{\omega}_i \tilde{\omega}_i + M_1 \tilde{b} \tilde{b}} \right] + \frac{g}{\sqrt{2} M_W} \epsilon_{ij} \left[\frac{M_d}{\cos \beta} A_d H_1^i \tilde{Q}^j \tilde{d}_R^* \right. \\
 & \left. + \frac{M_u}{\sin \beta} A_u H_2^j \tilde{Q}^i \tilde{u}_R^* + \frac{M_e}{\cos \beta} A_e H_1^i \tilde{L}^j \tilde{e}_R^* + \text{h.c.} \right] .
 \end{aligned}$$

Specificity of SUSY: Writing the most general Lagrangian, generalizing the spins of fields, SUCH that quadratic divergences are always shut down

Squark & Slepton sector



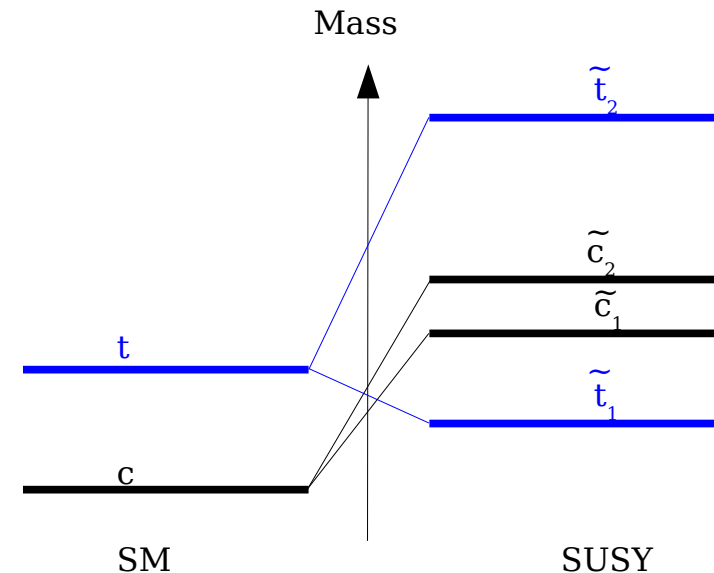
MSSM: Squark & Slepton sector

Physical states are 2 scalar mass-eigenstates: Mixtures of left- & -right chiral superpartners (scalars) of SM quark and leptons

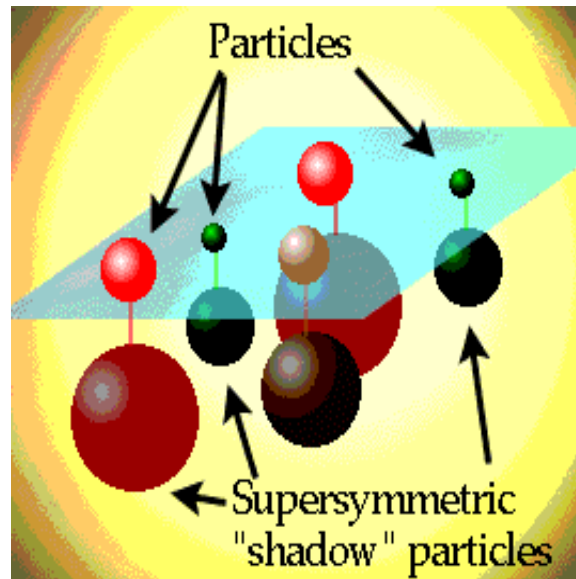
Let's pick-up example of the top sector: If $[f_L - f_R]$ chiral basis:

$$M_{\tilde{t}}^2 = \begin{pmatrix} \tilde{M}_Q^2 + M_T^2 + M_Z^2 \left(\frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) \cos 2\beta & M_T (A_T + \mu \cot \beta) \\ M_T (A_T + \mu \cot \beta) & \tilde{M}_U^2 + M_T^2 + \frac{2}{3} M_Z^2 \sin^2 \theta_W \cos 2\beta \end{pmatrix}$$

- \tilde{M}_Q : Left squark mass
- \tilde{M}_U : Right squark mass
- A_T : Trilinear coupling specific to the top sector
- $M_Q = M_T$: Mass of the SM particle
- μ : Higgs (bilinear) mixing parameter
- β : Higgs vev-specific parameter (see in a couple of slides): **Plays a role in the mixing**



Chargino sector



MSSM: Chargino sector

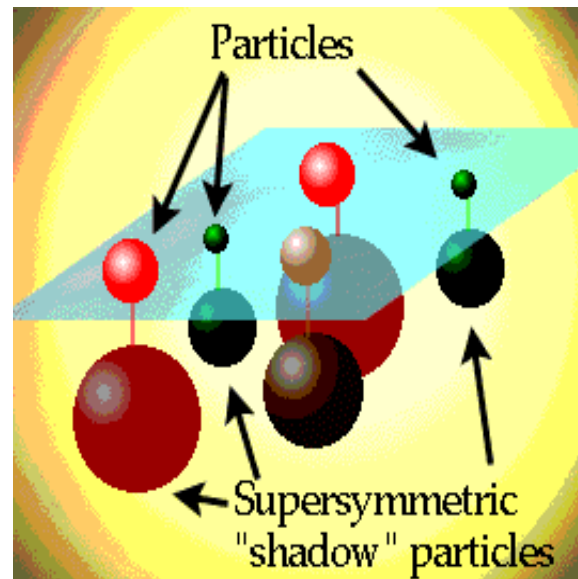
Physical states are 2 fermionic mass-eigenstates: Mixtures of charged winos and charged higgsinos, which are SUSY eigenstates

In the charged [wino - higgsino] basis:

$$M_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & \sqrt{2}M_W \sin \beta \\ \sqrt{2}M_W \cos \beta & -\mu \end{pmatrix}$$

- M_2 : Mass of the wino
 - μ : Higgs (bilinear) mixing parameter
- Comments:
- The more $M_2 \gg 1$: The more the charginos are wino-like
 - The more $\mu \gg 1$: The more the charginos are higgsino-like
 - β : Not playing a role in mixing

Neutralino sector



MSSM: Neutralino sector

Physical states are 4 fermionic mass-eigenstates: Mixtures of neutral winos w^0 , bino b , and 2 neutral higgsinos, which are SUSY eigenstates

In the neutral $[b - w^0 - h^0_1 - h^0_2]$ basis:

$$M_{\tilde{\chi}_i^0} = \begin{pmatrix} M_1 & 0 & -M_Z \cos \beta \sin \theta_W & M_Z \sin \beta \sin \theta_W \\ 0 & M_2 & M_Z \cos \beta \cos \theta_W & -M_Z \sin \beta \cos \theta_W \\ -M_Z \cos \beta \sin \theta_W & M_Z \cos \beta \sin \theta_W & 0 & \mu \\ M_Z \sin \beta \sin \theta_W & -M_Z \sin \beta \cos \theta_W & \mu & 0 \end{pmatrix}$$

- M_1 : Mass of the bino
- M_2 : Mass of the wino
- μ : Higgs (bilinear) mixing parameter

Exercise: Qualitatively gauge the influence of each parameters in the mass-matrix above on the “type” of neutralinos

EXERCISES

1/ Install the SuSpect software on your computer: This one of the only SUSY spectrum calculators with parametrized MSSM (pMSSM) parameters as input: You don't have 124, but 27 parameters to play with ;-)

2/ Just play with different parameters and follow evolution of the generated masses

2i) What are the most sensitive parameters for different types of particles ?

2ii) Once you get an idea for 2i): For a set of frozen parameters, produce plots showing evolution of the physical masses, say , as function of pMSSM parameters

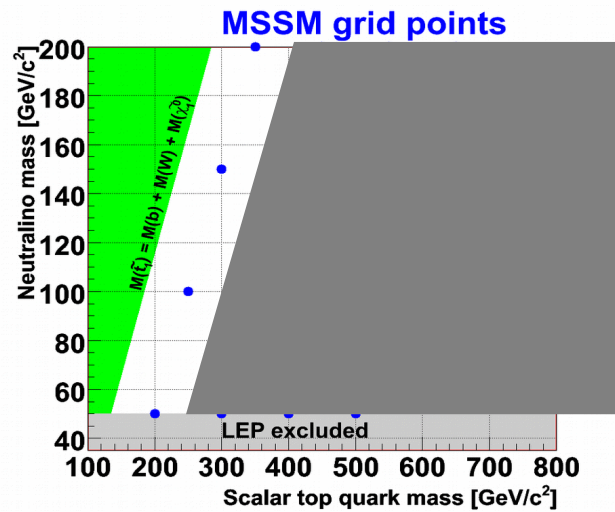
For 2i) & 2ii), let's pick-up:

- The lightest neutralino
- The chargino
- The lightest stop and stau
- The lightest Higgs

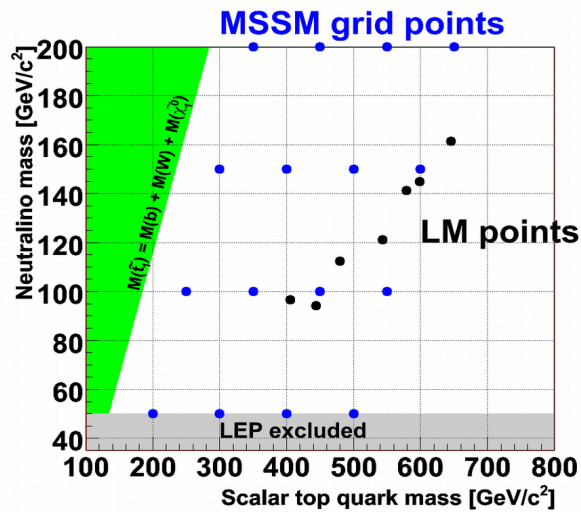
3/ Once your fingers are well warmed-up with pMSSM, produce the points on the following page :-D

Stop decays: Different diagrams for different domains

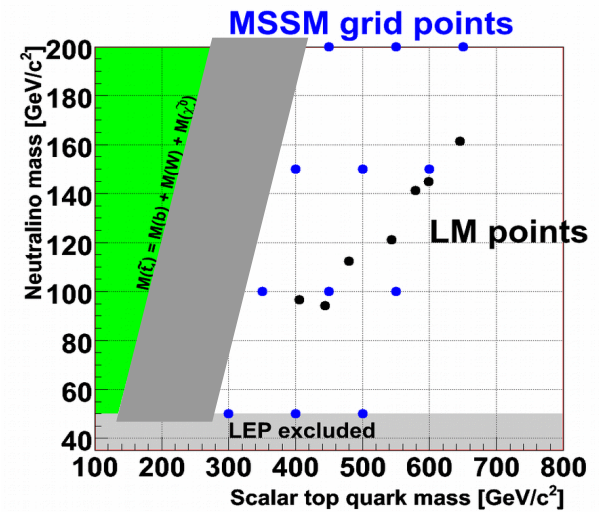
$$\tilde{t}_1 \rightarrow b W^+ \tilde{\chi}_1^0$$



$$\tilde{t}_1 \rightarrow b \tilde{\chi}_1^+$$



$$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$$



Conditions:

$$b + W + \tilde{\chi}_1^0 < \tilde{t}_1$$

$$\tilde{t}_1 < t + \tilde{\chi}_1^0 :$$

$$\text{Close } \tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$$

“Dominance” conditions:

$$\tilde{t}_1 < \tilde{\chi}_1^+ + b :$$

Make $\tilde{\chi}_1^+$ virtual

$$b + W + \tilde{\chi}_1^0 < \tilde{t}_1$$

$$W + \tilde{\chi}_1^0 < \tilde{\chi}_1^+ < \tilde{t}_1 - b$$

← Not exclusive: Will co-exist →

$$t + \tilde{\chi}_1^0 < \tilde{t}_1$$

$$t + \tilde{\chi}_1^0 < \tilde{\chi}_1^+ + b :$$

Privilege vs $b \tilde{\chi}_1^+$