# Physics at LHC:
## ***SUperSYmmetry***

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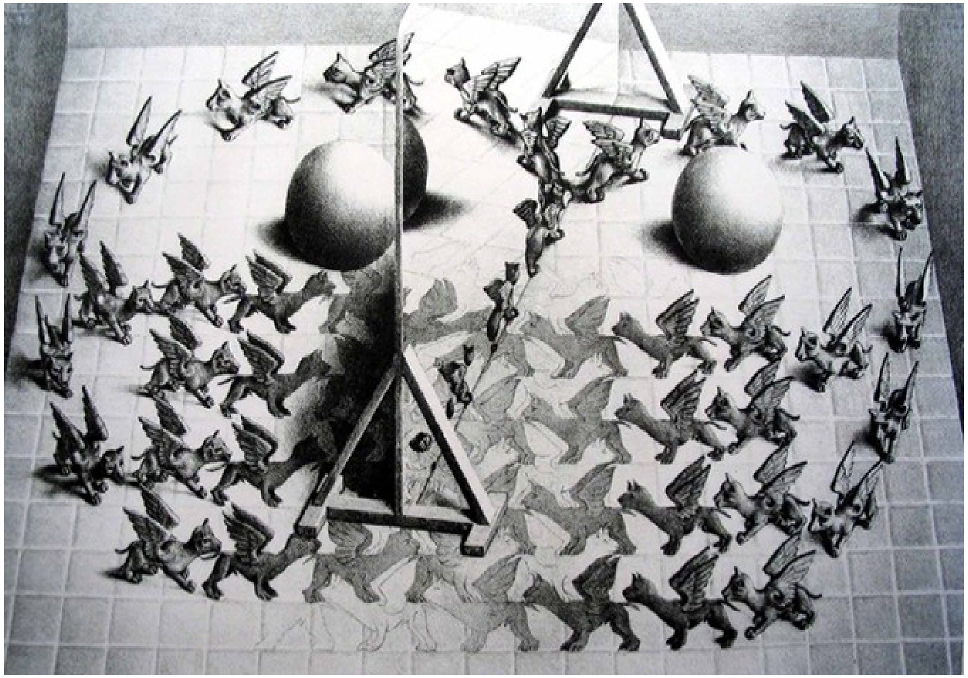

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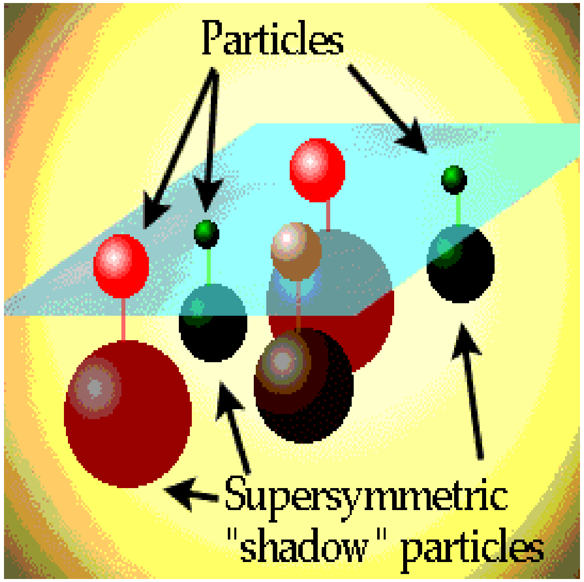
# Outline

- *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
- “A supersymmetry primer” S. P. Martin, arxiv:hep-ph/9709356

# *Brief introduction & Motivations*



# **Supersymmetry:** Introduction words

"Generalize" the spin of known fields

**SUperSYmmetry :** spin particle ½ ↔ spin partner 0
spin particle 1 ↔ spin partner ½

| Names | | spin 0 | spin 1/2 |
|---|---|---|---|
| squarks, quarks (×3 families) | $Q$ | $(\widetilde{u}_L \;\; \widetilde{d}_L)$ | $(u_L \;\; d_L)$ |
| | $\overline{u}$ | $\widetilde{u}^*_R$ | $u^\dagger_R$ |
| | $\overline{d}$ | $\widetilde{d}^*_R$ | $d^\dagger_R$ |
| sleptons, leptons (×3 families) | $L$ | $(\widetilde{\nu} \;\; \widetilde{e}_L)$ | $(\nu \;\; e_L)$ |
| | $\overline{e}$ | $\widetilde{e}^*_R$ | $e^\dagger_R$ |
| Higgs, higgsinos | $H_u$ | $(H^+_u \;\; H^0_u)$ | $(\widetilde{H}^+_u \;\; \widetilde{H}^0_u)$ |
| | $H_d$ | $(H^0_d \;\; H^-_d)$ | $(\widetilde{H}^0_d \;\; \widetilde{H}^-_d)$ |

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

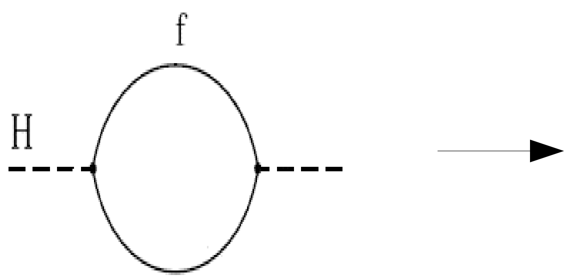
Observed SUSY particles with same mass than Standard-Model partners ? No !

**SUSY : A broken symmetry !**
**Physical sParticles: Mixture of super-partners**

- Charginos ($\chi^\pm$) / Neutralinos ($\chi^0$) : Bino/Wino ↔ 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 GeV/c$^2$**
- **Consider Higgs mass correction from fermionic loop:**



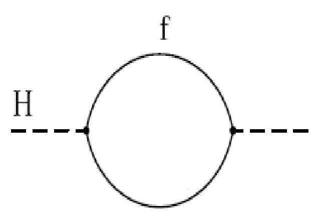

$$\Delta m_H^2 = \frac{\lambda_f^2}{16\pi^2} \cdot \left[-2\Lambda_{UV}^2 + \ldots\right]$$

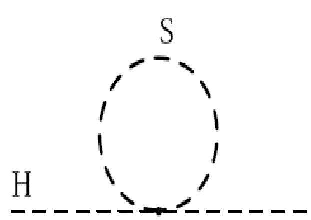
$\Lambda_{UV}$: Energy-scale at which new physics alters the Standard-Model (momentum cut-off regulating the loop-integral)

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

And all Standard-Model masses indirectly sensitive to $\Lambda_{UV}$ !!!

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




$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2} \cdot \left[\Lambda_{UV}^2 - \ldots\right]$$

$\Delta m^2_H$ quadratic divergence cancelled :

**Hierarchy problem naturally solved !**

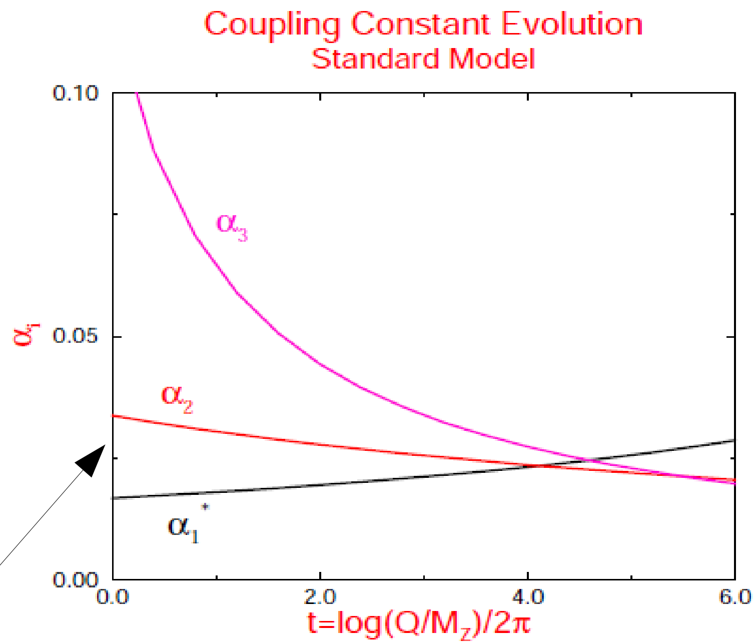
# **Supersymmetry** & Coupling constants

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

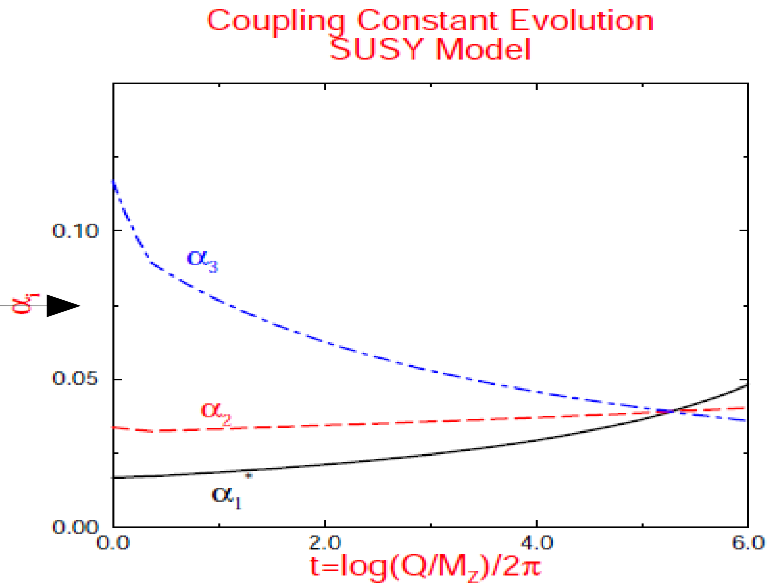
$$\mathbf{1/\alpha_i(Q) = 1/\alpha_i(M_Z) + (b_i/2)\log[M_Z/Q]}$$

$b_i$: 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 !

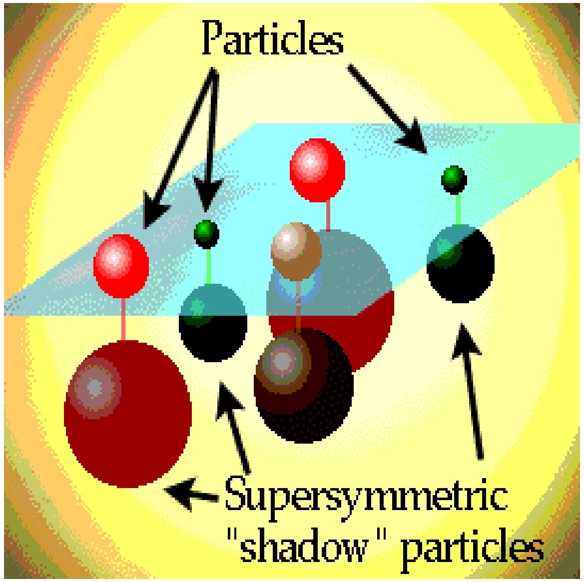
**Now if** sParticles were to exist at TeV scale:
Such interactions very seriously restricted by experimental observation !

In SUSY: $N_{B,L}$ conservation *can* be "protected" by new symmtery $R_P$:

- **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 $\chi^0$ (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** : ~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

$$\mathbf{L_{EW} = L_{free+interaction} + L_{gauge} + L_{higgs} + L_{yukawa}}$$

# **SM Lagrangian:** Free & Interaction parts

$$\mathbf{L_{free+interaction} = \Sigma_f\, i\, [\bar{\psi}_f^{\,L}\, \gamma^\mu\, D^L_\mu\, \psi_f^{\,L} + \bar{\psi}_f^{\,R}\, \gamma^\mu\, D^R_\mu\, \psi_f^{\,R}]}$$

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

→ Gauge-invariant derivatives:

$$D^L_\mu = \delta_\mu - i\, g\, (\tau_a/2)\, W^a_\mu - i\, g'\, (Y_L/2)\, B_\mu$$

$$D^R_\mu = \delta_\mu - i\, g'\, (Y_R/2)\, B_\mu$$

→ $g$, $g'$: Weak-isospin & -hypercharge couplings

→ $W^a_\mu$, $B_\mu$: Weak-isospin & -hypercharge fields

→ $\tau_a$, $Y_{L,R}$: Weak-isospin & -hypercharge quantum numbers, matrices

# **SM Lagrangian:** The gauge part

$$\mathbf{L_{gauge} = -(1/4)\, W^a_{\mu\nu} W^{a\mu\nu} - (1/4)\, B_{\mu\nu} B^{\mu\nu}}$$

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

$$W^a_{\mu\nu} = \delta_\mu W^a_\nu - \delta_\nu W^a_\nu + g\, \varepsilon_{abc}\, W^b_\mu W^c_\nu$$

$$B_{\mu\nu} = \delta_\mu B_\nu - \delta_\nu B_\nu$$

2nd term of $W^a_{\mu\nu}$: 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

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

$D_\mu$ : Same gauge-invariant derivatives as before

→ 1st term: Higgs↔Boson interaction:

Gives Boson masses

Gives Higgs↔Boson couplings

→ $V(\phi)$: Pure Higgs interaction:

Mass: $m_H = \sqrt{-2\mu^2} = \sqrt{2\lambda v^2}$

Coupling: Calculate :-D

The lagrangian has to be SU(2)xU(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

$$\mathbf{L_{yukawa} = -G_d\,(\bar{u},\bar{d})_L\,(\phi^+,\phi^0)\,d_R - G_u\,(\bar{u},\bar{d})_L\,(-\bar{\phi}^0,\phi^-)\,u_R}$$

$$\mathbf{+\ hermitian\text{-}conjugate}$$

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

Once Higgs sector is EW-broken:

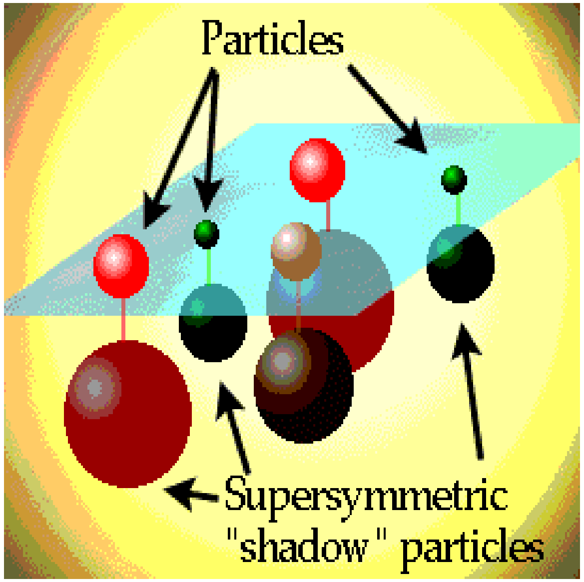
$\phi = (1/\sqrt{2})(0,v+H) \rightarrow$ "Confers" mass to fermions:

$L_{yukawa} = -m_d\,\bar{d}_L d_R\,(1+H/v) - m_u\,\bar{u}_L u_R\,(1+H/v)$

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

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

# *“Constructing” the SUSY 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**

$$Q = \begin{pmatrix} u \\ d \end{pmatrix}_L \longrightarrow \tilde{Q} = \begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix} \quad \begin{matrix} \overline{u}_R \\ \overline{d}_R \end{matrix} \quad \begin{matrix} \tilde{u}^*_R \\ \tilde{d}^*_R \end{matrix}$$

$$L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \longrightarrow \tilde{L} = \begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix} \quad \overline{e}_R \quad \tilde{e}^*_R$$

**SM** **MSSM**

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

**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 | $\frac{1}{6}$ | $(u_L, d_L)$, $(\tilde{u}_L, \tilde{d}_L)$ |
| $\hat{U}^c$ | $\overline{3}$ | 1 | $-\frac{2}{3}$ | $\overline{u}_R$, $\tilde{u}^*_R$ |
| $\hat{D}^c$ | $\overline{3}$ | 1 | $\frac{1}{3}$ | $\overline{d}_R$, $\tilde{d}^*_R$ |
| $\hat{L}$ | 1 | 2 | $-\frac{1}{2}$ | $(\nu_L, e_L)$, $(\tilde{\nu}_L, \tilde{e}_L)$ |
| $\hat{E}^c$ | 1 | 1 | 1 | $\overline{e}_R$, $\tilde{e}^*_R$ |
| $\hat{H}_1$ | 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:**

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

- Interaction-specific quantum number
- $S_i$: Scalar fields: Squarks & Sleptons
- $\psi_i$: Higgsinos
- $\lambda_A$: Gauge fermions

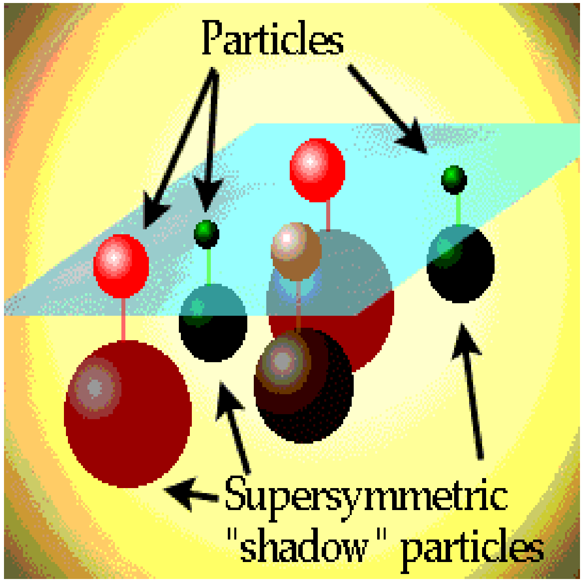
**The gauge invariant derivative part: Same as introduced in SM, but generalized to superfields**

**The kinetic part:**

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

| Fermion | Scalar | Gauge field |
|---|---|---|
| **SM** | | |
| $i\,\bar{f}\,\gamma^{\mu}\,D_{\mu}\,f\;+$ | $(D_{\mu}\,\phi)^{+}(D^{\mu}\,\phi)$<br>SM: Higgs | $-\;(1/4)\,F_{\mu\nu}F^{\mu\nu}$ |
| **MSSM** (includes what is above) | | |
| $i\,\bar{\psi}\,\gamma^{\mu}\,D_{\mu}\,\psi\;+$<br>MSSM: Higgsinos | $(D_{\mu}\,S_{i})^{+}(D^{\mu}\,S_{i})$<br>Squarks & Sleptons | $-\;(1/4)\,F_{\mu\nu}F^{\mu\nu}$<br>Same as above |
| $+(i/2)\,\bar{\lambda}_{A}\,\gamma^{\mu}\,D_{\mu}\,\lambda_{A}$<br>Gauge fermions | | |

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



# SUSY breaking

**<u>How is it broken</u> ? 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
- $m_{½}$ : Fermion mass
- $\mu$: Higgs parameter ($\mu H_1 H_2$)
- A: Tri-linear squark/slepton mixing term
- $\tan\beta = \langle H^0{}_2 \rangle / \langle H^0{}_1 \rangle$

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

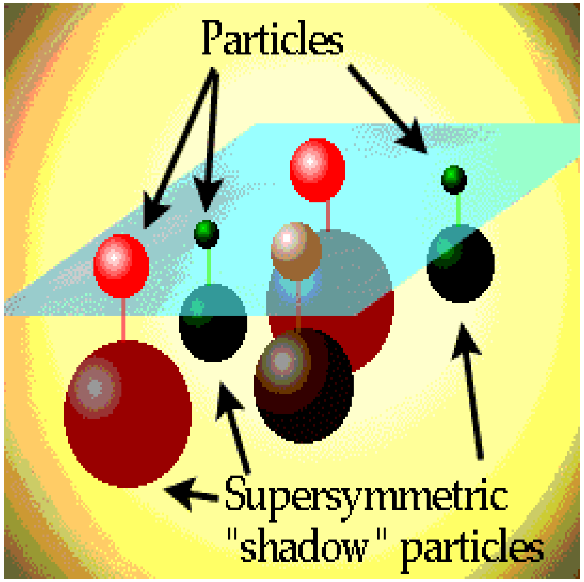
# **MSSM:** Effective Lagrangian

- 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

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

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

## ***Squark & Slepton sector***



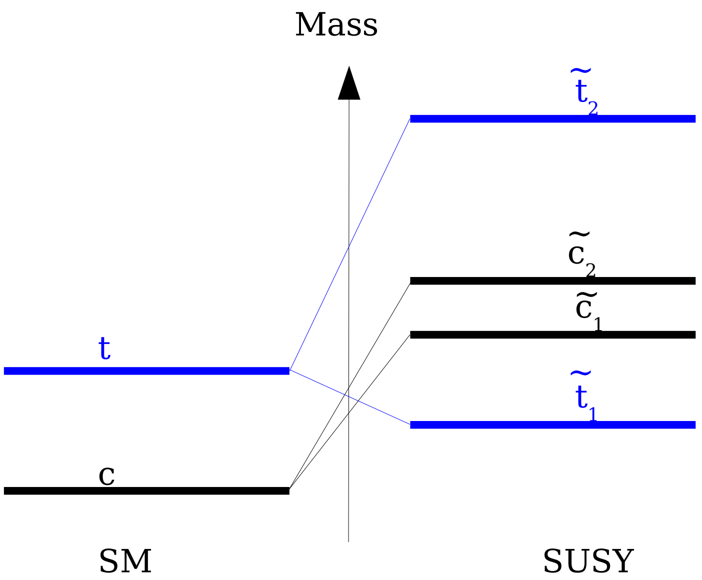
# **MSSM:** Squark & Slepton sector

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

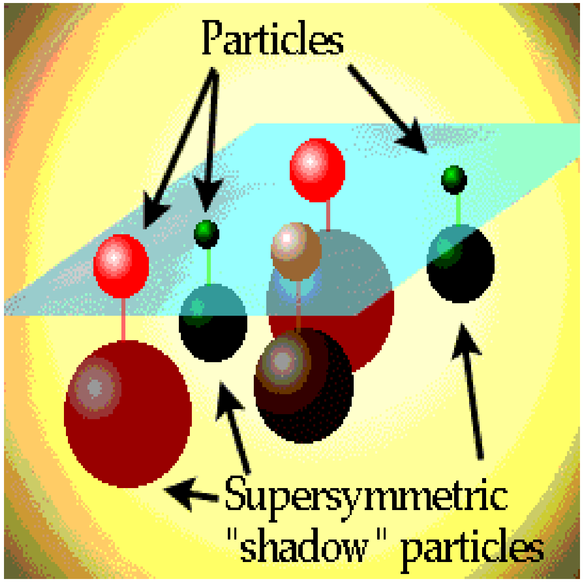
Let's pick-up example of the top sector: If $[f_L - f_R]$ chiral basis:

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

- $\tilde{M}_Q$: 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
- $\mu$: Higgs (bilinear) mixing parameter
- $\beta$: 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:

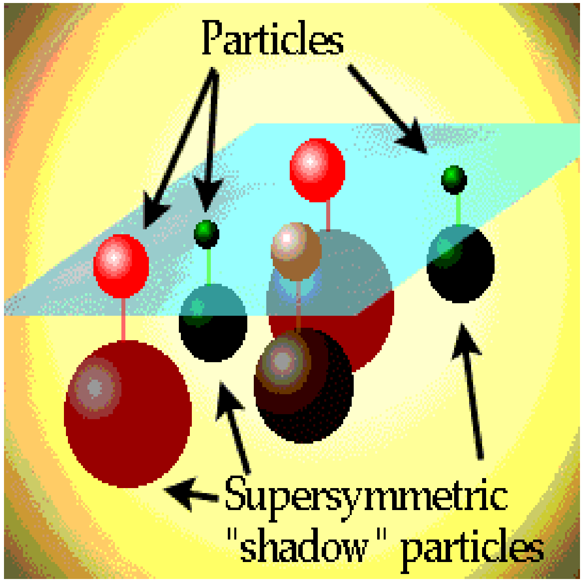
$$M_{\tilde{\chi}^{\pm}} = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & -\mu \end{pmatrix}$$

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

Comments:

- The more $M_2$ » 1: The more the charginos are wino-like
- The more μ » 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:

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

- $M_1$: Mass of the bino
- $M_2$: Mass of the wino
- $\mu$: 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

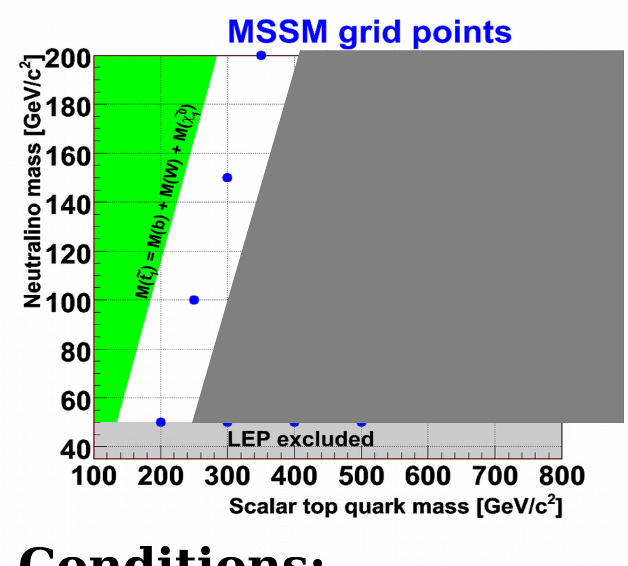
For 2i) & 2ii), let's pick-up:

→ The lightest neutralino
→ The chargino
→ The lightest stop and stau
→ The lighest Higgs

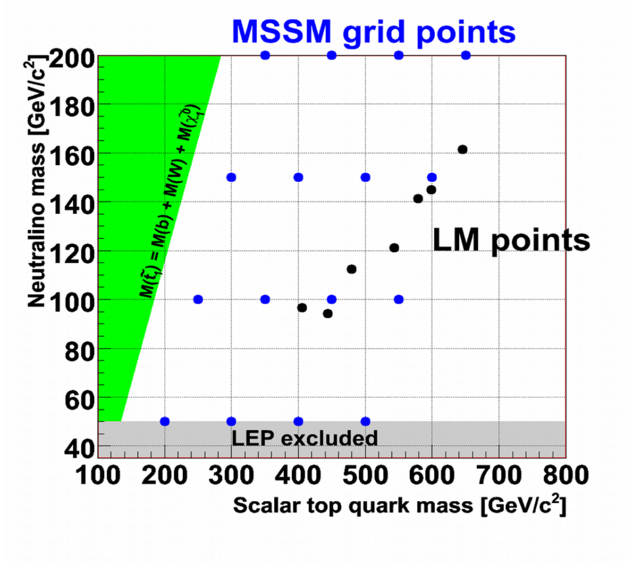
3/ Once your fingers are well warmed-up with pMSSM, produce the points on the following page :-D

# **Stop decays:** Different diagrams for different domains

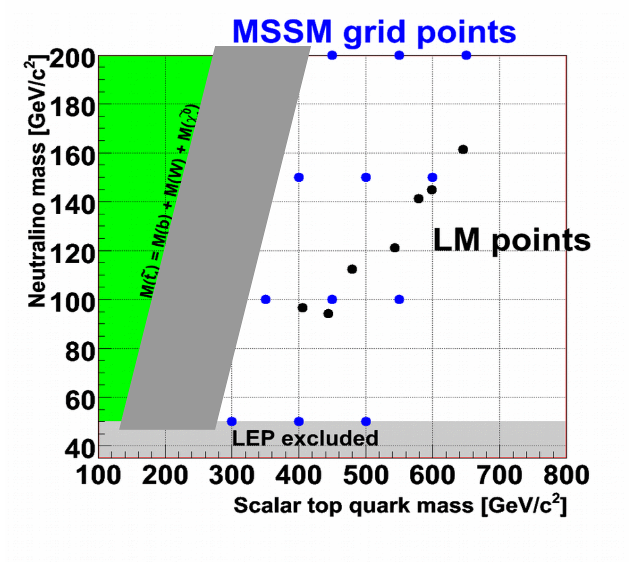
**$\tilde{t}_1 \rightarrow b\,W^+\,\tilde{\chi}_1^{\,0}$**




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




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




**Conditions:**

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

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

Close $\tilde{t}_1$ -> $t+\tilde{\chi}_1^{\,0}$

← Not exclusive: Will co-exist →

**"Dominance" conditions:**

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

Make $\tilde{\chi}^+_1$ virtual | Privilege vs $b\,\tilde{\chi}_1^{\,+}$