Physics at LHC: SUperSYmmetry

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LIP 18/04/2018
Outline

➢ Reminders of last time: Different physical SUSY sectors
➢ Higgs sector
➢ Getting into experimental feedback
➢ Exercises

Advised readings:
➢ “SUSY & Such” S. Dawson, arxiv:hep-ph/9612229v2
Quick reminders of last time
MSSM: Effective Lagrangian

- We don't know how SUSY is broken, but can write the most general broken effective Lagrangian
- Maximal dimension of soft operators: $\leq 3 \rightarrow$ Mass terms, Bilinear & Trilinear terms

\begin{align*}
-L_{\text{soft}} &= m_1^2 |H_1|^2 + m_2^2 |H_2|^2 - B \mu \epsilon_{ij} (H_i^i H_j^j + \text{h.c.}) + \tilde{M}_Q^2 (\tilde{u}_L^* \tilde{u}_L + \tilde{d}_L^* \tilde{d}_L) \\
&\quad + \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{\epsilon}_L^* \tilde{\epsilon}_L + \tilde{\nu}_L^* \tilde{\nu}_L) + \tilde{M}_e^2 \tilde{\epsilon}_R^* \tilde{\epsilon}_R \\
&\quad + \frac{1}{2} \left[ 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^* \\
&\quad + \frac{M_u}{\sin \beta} A_u H_2^i \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{align*}

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

\[
M_t^2 = \left( \frac{\tilde{M}_Q^2 + M_T^2 + M_Z^2(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W)}{M_T(A_T + \mu \cot\beta)} \cos 2\beta \right) \left( \frac{M_T(A_T + \mu \cot\beta)}{M_U^2 + M_T^2 + \frac{2}{3}M_Z^2\sin^2\theta_W \cos 2\beta} \right)
\]

- \(\tilde{M}_Q\): 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
**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
- \(\mu\): 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
- \(\beta\): Not playing a role in mixing
**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:

$$ M_{\tilde{X}_1^0} = \begin{pmatrix} M_1 & 0 & -M_Z \cos \beta \sin \theta_W & M_Z \sin \beta \sin \theta_W \\ 0 & M_2 & M_Z \cos \beta \sin \theta_W & -M_Z \sin \beta \cos \theta_W \\ -M_Z \cos \beta \sin \theta_W & M_Z \cos \beta \sin \theta_W & 0 & \mu \\ M_Z \sin \beta \sin \theta_W & -M_Z \sin \beta \cos \theta_W & \mu & 0 \end{pmatrix} $$

- $M_1$: 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
**Higgs sector:**
"Richer" than others...
MSSM: Higgs sector

2 Higgs complex doublets:

\[ V_H = \left( | \mu |^2 + m_1^2 \right) | H_1 |^2 + \left( | \mu |^2 + m_2^2 \right) | H_2 |^2 - \mu B \epsilon_{ij} (H_1^i H_2^j + \text{h.c.}) \]
\[ + \frac{g^2 + g'^2}{8} \left( | H_1 |^2 - | H_2 |^2 \right)^2 + \frac{1}{2} g^2 | H_1^* H_2 |^2 \]

8 degrees of freedom – 3 (massive gauge bosons) = 5 physical Higgs fields: 
\[ h / H / H^\pm / A \text{ (CP-odd)} \]

2 VEVs:

\[ \langle H_1^0 \rangle \equiv v_1 \]
\[ \langle H_2^0 \rangle \equiv v_2 \]

→ Key MSSM parameter:

\[ \tan \beta \equiv \frac{v_2}{v_1} \]

\[ \tan 2\alpha = \frac{(M_A^2 + M_Z^2) \sin 2\beta}{(M_A^2 - M_Z^2) \cos 2\beta + \epsilon_h / \sin^2 \beta} \]

3 parameters to describe the MSSM Higgs sector:

Once \( v_{1,2} \) are fixed such that:

\[ M_W^2 = \frac{g^2}{2} (v_1^2 + v_2^2) \]

This whole sector is described by (only) 2 other parameters:

→ \( \tan \beta \)
→ \( M_A \)
**MSSM: Higgs mass & squarks / Limit**

Equation governing lightest Higgs mass:

\[
M_{h,H}^2 = \frac{1}{2} \left\{ M_A^2 + M_Z^2 + \frac{\epsilon_h}{\sin^2 \beta} \pm \left[ \left( M_A^2 - M_Z^2 \right) \cos 2\beta + \frac{\epsilon_h}{\sin^2 \beta} \right]^2 + \left( M_A^2 + M_Z^2 \right)^2 \sin^2 2\beta \right\}^{1/2}
\]

with: \( \epsilon_h = \frac{3G_F}{\sqrt{2}\pi^2} M_T^4 \log \left( \frac{\tilde{m}^2}{M_T^2} \right) \)

- **Contribution of 1-loop correction only !**
- **Squark masses: Higgs mass particularly sensitive to \( \sim t_{1,2} \) system**

Upper bound:

\[
M_h^2 < M_Z^2 \cos^2 2\beta + \epsilon_h
\]

Here: No mixing.

- M(h) can go higher if stop-sector mixing larger

→ The “well-known” \( M_h < 135 \text{ GeV}/c^2 \)

limit for any-SUSY lightest Higgs
→ ...is dependent on
→ 2-loop calculations
→ Renormalization calculations which can evolve...
**MSSM: Higgs mass & squarks / Limit**

Equation governing lightest Higgs mass:

\[
M_{h,H}^2 = \frac{1}{2} \left\{ M_A^2 + M_Z^2 + \frac{\varepsilon_h}{\sin^2 \beta} \pm \left[ \left( M_A^2 - M_Z^2 \right) \cos 2\beta + \frac{\varepsilon_h}{\sin^2 \beta} \right]^2 + M_A^2 \right\}^{1/2}
\]

with: \[\varepsilon_h \equiv \frac{3G_F}{\sqrt{2}\pi^2} M_T^4 \log \left( \frac{\tilde{m}^2}{M_T^2} \right)\]

**Contribution of 1-loop correction only!**

Squark masses: Higgs mass particularly sensitive to \( \sim t_{1,2} \) system

**Upper bound:** When \( M_A \to \infty \)

\[
M_h^2 = M_A^2 - f(M_A^4)
\]

\[
M_H^2 = M_A^2 + f(M_A^4)
\]

**Just to know:**

→ With richer Higgs structure: Can also have \( M_h^{\text{max}} > 130 \text{ GeV/c}^2 \)

→ \( \mu \)B perturbative up to Planck-scale:

**For any SUSY:** \( M_h^{\text{max}} \sim 150 \text{ GeV/c}^2 \)

**And m(lightest Higgs) = 125 GeV/c^2**

Does this mean that it is a Susy Higgs? ;-)
MSSM: Higgs couplings to bosons

Let's look at couplings:

\[
Z^\mu Z^\nu h : \frac{ig M_Z}{\cos \theta_W} \sin(\beta - \alpha) g^{\mu \nu}
\]

\[
Z^\mu Z^\nu H : \frac{ig M_Z}{\cos \theta_W} \cos(\beta - \alpha) g^{\mu \nu}
\]

\[
W^\mu W^\nu h : ig M_W \sin(\beta - \alpha) g^{\mu \nu}
\]

SM couplings

Similar for coupling to γ & fermions

**Exercise:** Demonstrate the 2 relations above

**It is possible that:**

1/ Light h “SM like”:
   → Mass: Rather low
   → ~All branching ratios: Like in SM

2/ \{H, H^\pm, A\} much heavier & degenerate
   → Couplings of lightest Higgs to fermions/γ/W/Z ~ Like in SM
   → Couplings of “additional” Higgs to fermions/γ/W/Z ~ 0

**This is called the decoupled regime:**
1/ The lightest Higgs field is a) rather light b) behaves *a la* SM
2/ The “new” physical Higgs fields are (much ?) higher in mass
MSSM: Higgs couplings to fermions

Let's plug in $L_{\text{yukawa}}$ the full MSSM Higgs fields & the SM fermions:

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

Then break EW with $\phi = (1/\sqrt{2})(0, v_{1,2} + \text{Higgs}) \leftarrow \text{"Rapid" notation}$

Then re-rewrite things in terms of coupling:

$$L = -\frac{g m_i}{2 M_W} \left[ C_{f f h} \bar{f}_i f_i h + C_{f f H} \bar{f}_i f_i H + C_{f f A} \bar{f}_i \gamma_5 f_i A \right]$$

- **Coupling to same fermions:**  
  “Opposite” behaviors of 2 lightest neutral higgs $h$ and $H$

- **Coupling to the same Higgs:**  
  “Opposite” behaviors of $u/d$ quarks

- Let's see what the 2nd case graphically means...

$$\tan 2\alpha = \frac{(M_A^2 + M_Z^2) \sin 2\beta}{(M_A^2 - M_Z^2) \cos 2\beta + \varepsilon_h / \sin^2 \beta}$$
MSSM: Higgs couplings to fermions

Let's find the different effects
MSSM: Higgs couplings to fermions

- Opposite behaviours versus $M_A$: See couplings: $C_{ddh} \propto \frac{1}{\cos \beta} \propto \tan \beta$
- Different behaviours versus $\tan \beta$: See couplings
- Down/Up quark couplings: Always bigger/smaller than 1
  - MSSM Higgs hunters are interested in final states with $b$, $\tau$!
    - Only interesting @ high $\tan \beta$ AND low $M_A$
- High $M_A$: All $h$-fermion coupling $\rightarrow 1$
  - **In decoupled regime**: No enhancement effect for down quarks. Things are pretty “democratic” across quark generations
    - Guess what's the present experimental picture...
Do present Higgs search limits "exclude MSSM"?

- $M_A$ has no (dynamic) reason to be $< 500, 700$ GeV/c$^2$
  - High $M_A$ region still quite open
- Be careful: Do not interpret this plot as a “probability density plot for something to exist”: **IF SUSY exists, it will be in 1 given spot**
  - Could be here
- **Now one thing is sure:** **IF SUSY exists, $M_A$ pretty high:** Decoupled regime seems preferred

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The 1$^{st}$ M in MSSM means Minimal: We are dealing with 124 parameters here... “Not constrained at all” framework
Motivation for the $\tilde{t}_1$: Special relations with the Higgs

Stop/Higgs yukawa coupling

\[ M(h) = f \{ M(\tilde{q}, \tilde{t}_{1,2}) \} \]

\[ M_{h,H}^2 = \frac{1}{2} \left\{ M_A^2 + M_Z^2 + \frac{\epsilon_h}{\sin^2 \beta} \pm \left[ \left( M_A^2 - M_Z^2 \right) \cos 2\beta + \frac{\epsilon_h}{\sin^2 \beta} \right]^2 + \left( M_A^2 + M_Z^2 \right)^2 \sin^2 2\beta \right\}^{1/2} \]

with:
\[ \epsilon_h \equiv \frac{3G_F}{\sqrt{2}\pi^2} M_T^4 \log \left( \frac{\tilde{m}^2}{M_T^2} \right) \]

Squark masses: Higgs mass particularly sensitive to $\sim t_{1,2}$ system

LHC: Higgs & stop searches can constraint each other

Stop masses

Higgs masses

Demina et al., PRD 62, 35011
Experimental feedbacks, Hints (?)...
Looking for SUSY in EW data

Why did-we not get any hint of SUSY in EW Data ?

→ When looking at sector other than Higgs: Such SUSY contributions are suppressed \( \alpha \left[ \frac{M_W}{M_{\text{SUSY}}} \right]^2 \) where \( M_{\text{SUSY}} \) is the scale SUSY particles

What about performing a global fit to the EW data and try to fix SUSY spectrum ?

→ No stringent limit on physical masses
  → Not really astonishing: Try to fit with 124 degrees of freedom...
→ There “seems” to be information about \( \tan \beta \): Two “preferred” values:
  → \( \tan \beta \sim 2 \): Well, this is more & more suppressed by Higgs searches
  → \( \tan \beta \sim 30 \): ...
    → What to think about this ? Probably better to look more directly for SUSY particles
Looking “a bit more” directly: $\text{Br}(b \to s \ X)$

Famous “on the edge of SM” measurement:

$BR(B \to X_s \gamma) = (2.32 \pm 0.67) \times 10^{-4}$

Out of SM… ?

→ Either statistical fluctuation
→ Or new physics around corner

Let's plug-in SUSY: Let's draw a SUSY diagram allowing such a process
Looking “a bit more” directly: $\text{Br}(b \rightarrow s \, X)$

Famous “on the edge of SM” measurement:

\[ \text{Out of SM... ?} \]
\[ \rightarrow \text{Either statistical fluctuation} \]
\[ \rightarrow \text{Or new physics around corner} \]

Let's plug-in SUSY: $b \rightarrow \text{Loop} \{\chi_1^-, t_1\} \rightarrow s$

\[
\frac{\text{BR}(b \rightarrow s \gamma)}{\text{BR}(b \rightarrow c e \bar{\nu})} \sim \frac{\left| V_{ts} V_{tb} \right|^2}{\left| V_{cb} \right|^2} \frac{6 \alpha}{\pi} \left\{ C + \text{tan} \beta \right\}^2
\]

SM prediction: Slightly above measurement $\rightarrow$ Indication of $A_{t\mu} < 0$

Depending on $\text{tan} \beta$: This probes $t_1$ masses in $[100,300]$ GeV/c$^2$ region

Let's look at the of $A_{t\mu} < 0$ issue...
Looking “a bit more” directly: Indications?

Stop masses

Higgs masses

\[
A_{\mu} < 0: \text{Compatible with:}
\]

1/ $M(h) > 115, 120 \text{ GeV/c}^2$
2/ $M(t_1) < 500 \text{ GeV/c}^2$

Other thoughts?
Exercises
Let's start from the bottom of the SUSY scale...

\[ \chi_2^0 \rightarrow l^+ l^- \chi_1^0 \]
\[ \chi_1^\pm \rightarrow l^\pm \nu \chi_1^0 \]

@LHC: Give a production process for lightest chargino production
Then give the full diagram

\[ t_1 \rightarrow b \chi_1^\pm \]
\[ t_1 \rightarrow t \chi_1^0 \]
\[ t_1 \rightarrow c \chi_1^0 \]
SUSY diagrams

Let's start from the bottom of the SUSY scale...

\[
\begin{align*}
\chi^0_2 & \rightarrow l \bar{l} \chi^0_1 \\
\chi^\pm_1 & \rightarrow l^\pm \nu \chi^0_1
\end{align*}
\]

@LHC: Give a production process for lightest chargino production
Then give the full diagram

\[
\begin{align*}
t_1 & \rightarrow b \chi^\pm_1 \\
t_1 & \rightarrow t \chi^0_1 \\
t_1 & \rightarrow c \chi^0_1 \\
t_1 & \rightarrow b W \chi^0_1
\end{align*}
\]

@LHC: Give an example of simplest production mode for \( t_1 \)
Now push it to the semi-leptonic final state via \( b \chi^\pm_1 \) scenario
SUSY diagrams

@LHC: Give an example of simplest production mode for:
   → squarks
   → gluino
   → squark+gluino production

Simplest diagram for $t_1$ production via gluino pair-production
SUSY diagrams

t₁ production via – give each time the mass condition(s):

→ Simplest squark production
→ Simplest sbottom production
→ Squark production with intermediate slepton
→ t₂ production