Physics at LHC: 
SUperSYmmetry

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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

$$-\mathcal{L}_{\text{soft}} = m_1^2 |H_1|^2 + m_2^2 |H_2|^2 - B \mu \epsilon_{ij}(H_i^i H_j^j + \text{h.c.}) + M_Q^2 (\bar{u}_L^* u_L + \bar{d}_L^* d_L)$$
  
  $$+ \tilde{M}_u^2 \bar{u}_R^* \bar{u}_R + \tilde{M}_d^2 \bar{d}_R^* \bar{d}_R + \tilde{M}_e^2 (\bar{e}_L^* \bar{e}_L + \bar{\nu}_L^* \bar{\nu}_L) + \tilde{M}_e^2 \bar{e}_R^* \bar{e}_R$$
  
  $$+ \frac{1}{2} \left[ M_3 \bar{g}^* \bar{g} + M_2 \bar{\omega}_i \bar{\omega}_i + M_1 \bar{b}^* \bar{b} \right] + \frac{g}{\sqrt{2} M_W} \epsilon_{ij} \left[ \frac{M_d}{\cos \beta} A_d H_1^i \bar{Q}_j^j \bar{d}_R^* \right.$$

$$\left. + \frac{M_u}{\sin \beta} A_u H_2^j \bar{Q}_i^i \bar{u}_R^* \right] + \frac{M_e}{\cos \beta} A_e H_1^i \bar{L}_j^j \bar{e}_R^* + \text{h.c.} .$$

**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:

\[
M^2_t = \begin{pmatrix}
\tilde{M}^2_Q + M^2_T + M^2_Z(1 - \frac{2}{3} \sin^2 \theta_W) \cos 2\beta \\
M_T (A_T + \mu \cot \beta)
\end{pmatrix}
\]

- \(\tilde{M}_Q\): 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
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:

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

- \( M_1 \): 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
Higgs sector: “Richer” than others...
MSSM: Higgs sector

2 Higgs complex doublets:

\[
V_H = \left( | \mu |^2 + m_1^2 \right) | H_1 |^2 + \left( | \mu |^2 + m_2^2 \right) | H_2 |^2 - \mu B \epsilon_{ij} (H^i_1 H^j_2 + \text{h.c.}) \\
+ \frac{g^2 + g'^2}{8} \left( | H_1 |^2 - | H_2 |^2 \right)^2 + \frac{1}{2} g^2 | H_1^* H_2 |^2 .
\]

8 degrees of freedom – 3 (massive gauge bosons) = 5 physical Higgs fields:

\[h / H / H^\pm / A\] (CP-odd)

2 VEVs:

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

→ 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

\[ \to \text{The “well-known” } M_h < 135 \text{ GeV/c}^2 \]

limit for any-SUSY lightest Higgs
\[ \to \text{...is dependent on} \]
\[ \to \text{2-loop calculations} \]
\[ \to \text{Renormalization calculations which can evolve...} \]
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: \( \epsilon_h \equiv \frac{3G_F}{\sqrt{2}\pi^2} M_T^4 \log \left( \frac{\tilde{m}^2}{M_T^2} \right) \)

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 \( m(\text{lightest Higgs}) = 125 \text{ GeV/c}^2 \)

Does this mean that it is a Susy Higgs? ;-)
Let's look at couplings:

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

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

$$W^\mu W^\nu h : \frac{ig M_W}{\cos \theta_W} \sin(\beta - \alpha) g^{\mu\nu}$$

Similar for coupling to $\gamma$ & fermions

**Exercise:** Demonstrate the 2 relations above

**It is possible that:**

1/ **Light $h$ “SM like”:**
   - Mass: Rather low
   - $\sim$All branching ratios: Like in SM

2/ **$\{H, H^\pm, A\}$ much heavier & degenerate**
   - Couplings of lightest Higgs to fermions/$\gamma/W/Z \sim$ Like in SM
   - Couplings of “additional” Higgs to fermions/$\gamma/W/Z \sim 0$

**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:

$$L_{\text{yukawa}} = -G_d (\bar{u},\bar{d})_L (\phi^+,\phi^0) d_R - G_u (\bar{u},\bar{d})_L (\phi_0^+,\phi^-) u_R + \text{hc}$$

Then break EW with $\phi = (1/\sqrt{2})(0,v_1,v_2 + \text{Higgs}) \leftarrow \text{“Rapid” notation}$

Then re-rewrite things in terms of coupling:

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

- **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...**

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

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

- Opposite behaviours versus $M_A$: See couplings: $C_{ddh} \propto 1/\cos\beta \propto \tan\beta$

- 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

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

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

Stop/Higgs yukawa coupling

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

with:

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

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

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Experimental feedbacks, Hints (?)...
Why did we not get any hint of SUSY in EW Data?

→ When looking at sector other than Higgs: Such SUSY contributions are suppressed as \( \alpha [M_W/M_{\text{SUSY}}]^2 \) 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: $\text{Br}(b \rightarrow s \ X)$

Famous “on the edge of SM” measurement:

$$BR(B \rightarrow X_s \gamma) = (2.32 \pm .67) \times 10^{-4}$$

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:

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

Out of SM...?

→ Either statistical fluctuation
→ Or new physics around corner

Let's plug-in SUSY: $b \rightarrow \text{Loop } \{\chi_1^- , t_1^1 \} \rightarrow s$

$$\frac{\text{BR}(b \rightarrow s \gamma)}{\text{BR}(b \rightarrow c e \overline{\nu})} \sim \frac{|V_{ts} V_{tb}|^2}{|V_{cb}|^2} \frac{6\alpha}{\pi} \left\{ C + \frac{M_T^2 A_T \mu}{\tilde{m}_T^4} \tan^2 \beta \right\}^2$$

**SM prediction**: Slightly above measurement → Indication of $A_t^u < 0$

Depending on $\tan \beta$: This probes $t_1^1$ masses in $[100,300]$ GeV/c$^2$ region

*Let's look at the of $A_t^u < 0$ issue...*
Looking “a bit more” directly: Indications?

Stop masses

Higgs masses

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

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

Other thoughts?
Exercises
SUSY diagrams

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...

\[ \chi^0_2 \rightarrow l^+l^- \chi^0_1 \]
\[ \chi^\pm_1 \rightarrow l^\pm \nu \chi^0_1 \]

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

\[ t_1 \rightarrow b \ \chi^\pm_1 \]
\[ t_1 \rightarrow t \ \chi^0_1 \]
\[ t_1 \rightarrow c \ \chi^0_1 \]
\[ t_1 \rightarrow b \ W^+ \chi^0_1 \]

@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

$t_1$ production via – give each time the mass condition(s):
  → Simplest squark production
  → Simplest sbottom production
  → Squark production with intermediate slepton
  → $t_2$ production