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
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

$$-\mathcal{L}_{\text{soft}} = m_1^2 |H_1|^2 + m_2^2 |H_2|^2 - B \mu \epsilon_{ij} (H_1^i H_2^j + \text{h.c.}) + \tilde{M}_Q^2 (\bar{u}_L^* \tilde{u}_L + \bar{d}_L^* \tilde{d}_L) + \tilde{M}_u \bar{u}_R \tilde{u}_R + \tilde{M}_d \bar{d}_R \tilde{d}_R + \tilde{M}_L (\bar{e}_L^* \tilde{e}_L + \bar{\nu}_L^* \tilde{\nu}_L) + \tilde{M}_e \bar{e}_R^* \tilde{e}_R$$

$$+ \frac{1}{2} \left[ M_3 \bar{g} \bar{g} + M_2 \bar{\omega}_i \bar{\omega}_i + M_1 \bar{b} \bar{b} \right] + \frac{g}{\sqrt{2} M_W} \epsilon_{ij} \left[ \frac{M_d}{\cos \beta} A_d H_1^i \tilde{Q}^j \tilde{d}_R^* + \frac{M_u}{\sin \beta} A_u H_2^i \tilde{u}_R^* + \frac{M_e}{\cos \beta} A_e H_1^i \tilde{L}^j \tilde{e}_R^* + \text{h.c.} \right].$$

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:

\[
M_t^2 = \begin{pmatrix}
M_Q^2 + M_T^2 + M_Z^2 \left( \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) \cos 2 \beta & M_T (A_T + \mu \cot \beta) \\
M_T (A_T + \mu \cot \beta) & M_T^2 + M_T^2 + \frac{2}{3} M_Z^2 \sin^2 \theta_W \cos 2 \beta
\end{pmatrix}
\]

- \(\widetilde{M}_Q\): Left squark mass
- \(\widetilde{M}_U\): 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

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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:

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

- \( M_1 \): Mass of the bino
- \( M_2 \): Mass of the wino
- \( \mu \): 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: \( h / H / H^\pm / A \) (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: \( \epsilon_h \equiv \frac{3G_F}{\sqrt{2}\pi^2} M_T^4 \log \left( \frac{\bar{m}^2}{M_T^2} \right) \)

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

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? ;-(
Let's look at couplings:

\[
\begin{align*}
Z^\mu Z^\nu h : & \quad \frac{ig M_Z}{\cos \theta_W} \sin(\beta - \alpha) g^{\mu \nu} \\
Z^\mu Z^\nu H : & \quad \frac{ig M_Z}{\cos \theta_W} \cos(\beta - \alpha) g^{\mu \nu} \\
W^\mu W^\nu h : & \quad ig M_W \sin(\beta - \alpha) g^{\mu \nu}
\end{align*}
\]

Similar for coupling to $\gamma$ & fermions

**Exercise:** Demonstrate the 2 relations above

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**It is possible that:**

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

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

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

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:

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

- **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 2\textsuperscript{nd} case graphically means...*
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 $\to 1$!
  - **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

Stop/Higgs yukawa coupling

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

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

with: \[ \epsilon_h \equiv \frac{3G_F}{\sqrt{2} \pi^2} M_T^4 \log \left( \frac{\tilde{m}_2^2}{M_T^2} \right) \]

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: $\text{Br}(b \rightarrow s \ X)$

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:

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

Out of SM... ?

$\rightarrow$ Either statistical fluctuation

$\rightarrow$ Or new physics around corner

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

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

SM prediction:
Whether above/below measurement $\rightarrow$ Indication of sign of $\mu$

Depending on $\tan \beta$: This probes $t_1$ masses in $[100,300]$ GeV/c$^2$ region
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
@LHC: Give an example of simplest production mode for:
→ squarks
→ gluino
→ squark+gluino production

Simplest diagram for $t_1$ production via gluino pair-production
t_1 \text{ production via } \rightarrow \text{ give each time the mass condition(s):}

→ Simplest squark production
→ Simplest sbottom production
→ Squark production with intermediate slepton
→ t_2 \text{ production}