Chapter 2: Supersymmetry

2.1 Introduction and Overview
- What is SUSY
- How can we find/measure it?

2.2 SUSY Theory/Phenomenology
- SUSY Lagrangian, MSSM
- SUSY interactions, masses, SUSY breaking

2.3 SUSY searches/measurements at experiments
- past and running experiments
- LHC / future linear collider

2.4 Searches for MSSM Higgs bosons
Available on the web:

• S. Martin, “A Supersymmetry Primer”, hep-ph/97093

• D.I. Kazakov, „Beyond the Standard Model“, CERN school 2004

• J. Ellis, Supersymmetry for Alp Hikers

Lehrbücher:

• H.Baer, X. Tata, „Weak Scale Supersymmetry“, 2006

• Drees, Godbole, Roy, „Theory and Phenomenology of Sparticles“, 2004
What is Supersymmetry (SUSY)?

SUSY is an extension of the Standard Model (since ~ 1970) that introduces a new symmetry between fermions and bosons:

Spin-$\frac{1}{2}$ matter particles (fermions) $\leftrightarrow$ Spin-1 force particles (bosons)

SUSY transformation (operator Q):

\begin{align*}
Q |\text{Fermion}\rangle & \sim |\text{Boson}\rangle \\
Q |\text{Boson}\rangle & \sim |\text{Fermion}\rangle
\end{align*}

→ SUSY doubles the number of particles
The SUSY Particle Spectrum
The SUSY Particle Spectrum

Particle
Spin-1/2
- quarks (L&R)
- leptons (L&R)
- neutrinos (L)

Sparticle (corresp. SUSY particle)
### The SUSY Particle Spectrum

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<tr>
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Extended Higgs sector: 2 complex Higgs doublets

$\rightarrow$ Degrees of freedom: 8 - 3 (Goldstone bosons) = 5 Higgs bosons: $h^0, H^0, A^0, H^\pm$
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→ Degrees of freedom: 8 - 3 (Goldstone bosons) = 5 Higgs bosons: \(h^0, H^0, A^0, H^\pm\)
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Extended Higgs sector: 2 complex Higgs doublets

→ Degrees of freedom: 8 - 3 (Goldstone bosons) = 5 Higgs bosons: $h^0, H^0, A^0, H^{\pm}$

After Mixing

4 neutralinos
The SUSY Particle Spectrum

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Extended Higgs sector: 2 complex Higgs doublets
→ Degrees of freedom: 8 - 3 (Goldstone bosons) = 5 Higgs bosons: h^0, H^0, A^0, H^±
Neutralino and Chargino Mixing

- Physical neutralinos and charginos are mixtures of Wino, Bino, Higgsinos

- Charginos:
  \[
  \begin{pmatrix}
  \chi_1^+ \\
  \chi_2^+
  \end{pmatrix}
  =
  \begin{pmatrix}
  M_2 & \sqrt{2}m_W \sin \beta \\
  \sqrt{2}m_W \cos \beta & \mu
  \end{pmatrix}
  \begin{pmatrix}
  \tilde{W}^+
  \end{pmatrix}
  \]

- Neutralinos:
  \[
  \begin{pmatrix}
  \chi_1^0 \\
  \chi_2^0 \\
  \chi_3^0 \\
  \chi_4^0
  \end{pmatrix}
  =
  \begin{pmatrix}
  M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\
  0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\
  -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\
  m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0
  \end{pmatrix}
  \begin{pmatrix}
  \tilde{B} \\
  \tilde{W}^3 \\
  \tilde{H}_1^0 \\
  \tilde{H}_2^0
  \end{pmatrix}
  \]

Mass eigenstates depend on:
- \(M_1, M_2, \tan \beta, \mu\) SUSY masses and breaking parameters
- \(m_Z, \sin^2 \theta_W\) EWSB (mixing: \(B^0, W^0 \rightarrow Z, g\)
Deep within the atomic supercollider, the search continues for the elusive elephantino.
## Superfields

<table>
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<tr>
<th></th>
<th>superfields</th>
<th>fermion fields</th>
<th>boson fields</th>
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<td><strong>Matter sector</strong></td>
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<td>squarks, quarks</td>
<td>$\hat{Q}_i$</td>
<td>$(\nu_{L,i})$</td>
<td>$(\bar{u}_{L,i})$</td>
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<td>$\bar{u}_{R,i}^+$</td>
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<td>$\hat{G}^a$</td>
<td>$\tilde{\lambda}_G^a$</td>
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<td>winos, W bosons</td>
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<td>$\tilde{\lambda}_W^i$</td>
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<td>bino, B boson</td>
<td>$\hat{B}$</td>
<td>$\tilde{\lambda}_B$</td>
<td>$B_\mu$</td>
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Problem: These couplings lead to proton decay

Unacceptably high rate compared to experimental limits
(proton lifetime $> 10^{33}$ years)

$\rightarrow$ Strong limits on product of couplings

- Introduce multiplicative quantum number:

$$R_p = (-1)^{3(B-L)+2S}$$

= $+1$ for SM particles
= $-1$ for SUSY particles

- Impose $R_p$ conservation:
  - Sparticles produced in pairs
  - Lightest SUSY particle (LSP) stable
SUSY Interactions: Some Examples

The coupling constants are the same as in SM (strong, electroweak)

“Recipe”: Obtain SUSY interactions by exchanging at a vertex two SM legs by corresponding SUSY legs.

The coupling constants are the same as in SM (strong, electroweak).
Motivation for SUSY
Reasons for SUSY (1) : Hierarchy Problem

- Reminder:
  In the SM, Higgs mass diverges due to quantum corrections.

- The symmetry between bosons and fermions, which contribute with different sign (statistics), can cure this problem:

\[ \Delta m_H = f(m_B^2 - m_f^2) \]

→ terms cancel one-by-one if SUSY perfect symmetry (i.e. if \( m(\text{particle}) = m(\text{sparticle}) \)). Since this is not the case, sparticles mustn’t be too heavy (\( M_{\text{SUSY}} < \sim 1 \text{ TeV} \)).
Reasons for SUSY (2) : Grand Unification

Due to quantum corrections, e.g.

slope is changed due to contributions from SUSY particles
Reasons for SUSY (3): Dark Matter in our Universe

Evidence from:

- **Rotational curves of galaxies**
- **Gravitational lensing**
- **Cosmic microwave background (CMB)**
Excursion: Dark Matter in Galaxies

- Gravitation \(\sim \frac{1}{r^2}\) \(\rightarrow\) Rotation curves \(\text{à la Kepler}\)

\[\begin{align*}
\text{Spiral Galaxy} & \quad \text{NGC6503} \\
\text{Solar System} & \\
\text{Orbital Speed [km/s]} & \quad \text{Distance from Sun [AU]} \\
\text{NGC 6503} & \quad \text{Radius (kpc)}
\end{align*}\]
Excursion: Gravitational Lensing

Contribution from dark matter?!
Excursion: Dark Matter & Colliding Galaxies

Here is the Hubble Space Telescope Image:

analysis of Bradac, Clowe, Gonzalez, Marshall, Forman, Jones, Markevitch, Randall, and Schrabback

From talk by M. Peskin (SLAC)
Here is the mass distribution reconstructed from gravitational lensing

From talk by M. Peskin (SLAC)

J. Dingfelder u. M. Schumacher  Higgs-Physik und BSM-Phäneomenologie  Uni. Freiburg / SoSe09
Excursion: Dark Matter & Colliding Galaxies

The atomic matter is mainly in hot gas, emitting X-rays. The Chandra satellite measures this component (red).

The gravitating mass is elsewhere (blue)!

From talk by M. Peskin (SLAC)
Dark Matter Properties

Dark-Matter properties:

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

→ Unambiguous evidence for new physics!
Reasons for SUSY (3): Dark Matter

- SUSY has a weakly interacting massive particle (WIMP), if R-parity is conserved:
  - the lightest supersymmetric particle
- LSP = lightest neutralino, gravitino (depending on SUSY model)
Reasons for SUSY (4): EW Measurements

SUSY is compatible with electroweak precision measurements

Leads to even tighter upper limit on Higgs mass: $m_h < \sim 130$ GeV
($h =$ lightest MSSM Higgs; it is expected to be similar to the SM Higgs)
The Problem: SUSY Breaking
• Supersymmetry is not an exact symmetry, since particle and sparticle masses are not the same. A selectron with the mass of an electron would certainly have been seen by now.

• Need model for “SUSY breaking”: SUSY breaking occurs in a hidden sector and is transmitted to visible sector (where MSSM particles live) via certain mechanisms. Particles in hidden sector are neutral to SM gauge group.

• SUSY breaking leads to additional parameters
  - Unconstrained models (>100 parameters: masses, couplings, phases)
  - Constrained models (e.g. mSUGRA, cMSSM: 5 parameters)
- Assumptions to reduce number of free parameters: "Unification at high energies"

- Assume universal masses for all bosons and all fermions at GUT scale, unification of couplings at GUT scale

- An example: mSUGRA (minimal SUper GRAvity)
  - SUSY breaking is mediated by gravity

- Remaining 5 parameters in mSUGRA:
  - $m_0$: universal boson (scalar, spin-0) mass at GUT scale
  - $m_{1/2}$: universal gaugino (spin-$1/2$) mass at GUT scale
  - $A_0$: universal trilinear coupling at GUT scale
  - $\tan\beta$: ratio of the two Higgs vacuum expectation values
  - $\text{sign}(\mu)$: sign of the higgsino mass parameter
Some Models for SUSY Breaking

- **mSUGRA**: Gravity-mediated
  \[ \text{LSP = lightest neutralino} \]

- **GMSB**: Gauge-mediated
  \[ \text{LSP = gravitino} \]

- **AMSB**: Anomaly-mediated
  \[ \text{LSP = lightest neutralino} \]
**SUSY Masses in mSUGRA**

**Evolution of SUSY masses:**

- **Gaugino masses:**
  \[
  \frac{M_1}{\alpha_1} = \frac{M_2}{\alpha_2} = \frac{M_3}{\alpha_3}
  \]

- \(M_3 \equiv M_{\tilde{g}} \approx 2.7m_{1/2}\), **gluino**
- \(M_2(M_Z) \approx 0.8m_{1/2}\), **wino**
- \(M_1(M_Z) \approx 0.4m_{1/2}\), **bino**

- **Sfermion masses:**
  \[m_{\tilde{l}} < m_{\tilde{q}} \approx M_{\tilde{g}}\]

- **Higgs masses:**
  - \(m_h < 130 \text{ GeV}\)
  - \(m_{H,A,H^\pm}^2 \approx m_A^2 + m_W^2\)

**“Renormalization Group Equations (RGE)”**
Typical examples for three different SUSY models

Example SUSY Mass Spectra
SUSY Constraints from Experiments
Direct Searches at LEP & TeVatron

- **Slepton & Chargino/Neutralino** searches at LEP ($e^+e^-$, $E_{cm} \sim 200$ GeV)
  - Excluded up to masses of 80 … 104 GeV

- **Squark and gluino** searches at TeVatron ($p\bar{p}$, $E_{cm} \sim 2$ TeV)
  - Excluded up to masses of $\sim 400$ GeV
Indirect SUSY Searches

- Measure branching fractions of rare decays or search for forbidden decays.
  → Potentially enhanced by SUSY particles “in loops”:

- Measurement of \( \mu \) anomalous magnetic moment \((g_\mu -2)\): Brookhaven
• Observed dark-matter abundance and properties of dark-matter particle annihilation and co-annihilation processes constrain SUSY parameters

(1) Assume new heavy particle in thermal equilibrium:
\[ \chi\chi \leftrightarrow f\bar{f} \]

(2) The Universe cools:
\[ \chi\chi \rightarrow f\bar{f} \quad \chi\gamma \rightarrow f\bar{f} \]

(3) Chi freezes out
\[ \chi\chi \leftrightarrow f\bar{f} \]

High Temp.  Low Temp.
• mSUGRA param. strongly constrained by cosmology (“blue bands”)
• Annihilation and co-annihilation of dark-matter particles, etc.

SUSY Dark Matter Constraints

- mSUGRA parameters strongly constrained by cosmology (“blue bands”)
- Annihilation and co-annihilation of dark-matter particles, etc.

'Focus point' region: significant h component to LSP enhances annihilation to gauge bosons

'Bulk' region: t-channel slepton exchange - LSP mostly Bino.

Slepton Co-annihilation region: LSP ~ pure Bino. Small slepton-LSP mass difference makes measurements difficult.

Also 'rapid annihilation funnel' at Higgs pole at high tan(β),
• $b \rightarrow s \gamma$ excluded

• $g_\mu -2$ favored

• Dark matter favored

SUSY already quite confined, but there are still many possibilities
→ Need discovery at LHC
Studying SUSY Points

- Particle physicists use Monte Carlo simulations to study SUSY and to discover new physics by comparing data with simulation.
- But SUSY parameter space is huge! The most sensitive parameters are the SUSY masses (determined by $m_0, m_{1/2}$ in mSUGRA).
- Need to choose some strategical “points” in parameter space to generate simulated events (later perform scans of other par.’s).

Example of choice of SUSY points inspired by cosmological constraints.
SUSY at the LHC
Production and Decay
• Squarks and gluinos produced via strong processes → large rates

![Diagram showing squark and gluino production via strong processes.]

<table>
<thead>
<tr>
<th>$M$ (GeV)</th>
<th>$\sigma$ (pb)</th>
<th>Evts/yr</th>
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<tbody>
<tr>
<td>500</td>
<td>100</td>
<td>$10^6$-$10^7$</td>
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<td>1000</td>
<td>1</td>
<td>$10^4$-$10^5$</td>
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<td>2000</td>
<td>0.01</td>
<td>$10^2$-$10^3$</td>
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</tbody>
</table>

• Charginos, neutralinos, sleptons via direct electroweak production → much smaller rates

![Diagram showing chargino and neutralino production via electroweak processes.]

$\sigma \approx 1$ pb for $m_\chi \approx 150$ GeV

• $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, $\tilde{g}\tilde{g}$ production are dominant SUSY processes at LHC
• Charginos/Neutralinos mostly from decays of squarks or gluinos
IV.25 Sparticle Production at LHC

Quark-gluon fusion

Quark annihilation

\[ g + g \rightarrow \tilde{g} + \tilde{g} \]

\[ q + g \rightarrow \tilde{q} + \tilde{g} \]

\[ g + q \rightarrow \tilde{g} + \tilde{q} \]

\[ \tilde{q} + \tilde{q} \rightarrow g + g \]

\[ \tilde{q} + \tilde{q} \rightarrow q + q \]

\[ \tilde{q} + \tilde{q} \rightarrow \tilde{g} + \tilde{g} \]

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SUSY Cross Sections (An Example)

\[ \sigma \ (pb) \]

\[ \sigma_{tot}[pb]: \, pp \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{t}_1\tilde{t}_1, \tilde{\chi}_2^0\tilde{\chi}_1^+, \tilde{\nu}\tilde{\nu}, \tilde{\chi}_2^0\tilde{\chi}_2^0, \tilde{\chi}_2^0\tilde{\chi}_2^- \]

\[ \sqrt{s} = 14 \, \text{TeV} \]

- Solid line: NLO
- Dashed line: LO

\[ M \ (\text{GeV}) \]

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SUSY Decay Cascade

- Long, complex decay chains (at the end: SM particles and LSP’s)
- Two SUSY decay chains per event (pair production due to $R_p$)
- Missing energy from LSP’s

Example:
Gluino production
- 3 isolated leptons
- 6 jets
- 2 b-quark jets
- $E_{\text{miss}}$

Huge combinatorial background from second SUSY decay in event → “dominant background to SUSY is SUSY itself”

Typical final states: jets + $E_{\text{miss}}$ (+ leptons)
## SUSY Final States ... there are many

<table>
<thead>
<tr>
<th>Process</th>
<th>Final States</th>
</tr>
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<tbody>
<tr>
<td>$p (q)$</td>
<td>$l \nu \chi^0_1 \chi^0_1 \chi^0_1 \chi^0_1$</td>
</tr>
<tr>
<td>$p (\bar{q})$</td>
<td>$l \nu \chi^0_1 \chi^0_1 \chi^0_1 \chi^0_1$</td>
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<td>$p (q_i)$</td>
<td>$2\ell \nu \chi^0_1 \chi^0_1 \chi^0_1 \chi^0_1$</td>
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<td>$p (\bar{q}_i)$</td>
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J. Dingfelder u. M. Schumacher Higgs-Physik und BSM-Phäneomenologie Uni. Freiburg / SoSe09
SUSY Final States ... there are many
Simulated SUSY Event in ATLAS

Missing transverse momentum

Jets

Leptons

Heavy quarks
SUSY Searches at LHC
Strategy for SUSY Searches

- **Step 1: Discovery**
  - Look for deviations from the Standard Model

- **Step 2: Mass scale**
  - Establish the approximate SUSY mass scale

- **Step 3: Measurements**
  - Determine masses, branching fractions, etc.

- **Step 4: Parameter studies**
  - Study underlying theory / SUSY model
Inclusive Searches – Mass Scale

- Select: > 4 jets, $E_{T,\text{miss}}$
- Reconstruct effective mass

$$M_{\text{eff}} = \sum_{i=1}^{4} |P_{T,i}| + |E_{T,\text{miss}}|$$

Look at multi-jet and $E_{T,\text{miss}}$ final states

From Simulation

At high $M_{\text{eff}}$ SUSY signal above SM

Inclusive signature for squarks and gluinos

Peaking $M_{\text{eff}}$ distribution correlates well with $M_{\text{SUSY}}$
Experimental Challenge: $E_T^{\text{miss}}$

- One of the most important SUSY signatures: $E_T^{\text{miss}}$ from the LSP’s
- Difficult to measure and is very sensitive to instrumental effects
- Lesson learned from the TeVatron experiments:

Partial List:
- Machine background
- Beam-gas events
- Hot cells
- Regions with poor jet response
- Displaced vertices
- And many more ...
Simulated event in detector showing **fake** missing energy (jet leakage into muon system)
Example: 10 fb⁻¹, m(squark) = 1 TeV

jets + E_T^{miss}

- jet+E_T^{miss} final states are the key for SUSY discovery
- Signal/bkg ratio can be improved by identifying leptons in the decay, e.g.

jets + E_T^{miss} + 1 lepton

→ Lower background, but also much fewer events!
LHC Reach for SUSY Masses

jets + $E_T^{\text{miss}}$

add. lepton(s)
Determining SUSY Masses: The Basic Idea

- Reconstruct SUSY masses in decay chain, e.g.
- Cannot reconstruct masses directly due to undetected LSP
- Study invariant masses for different combinations of particles in decay chain

\[ m_{ll} = m_{ll}^{\text{max}} \sqrt{1 - \cos \theta} / 2 \]

angle between leptons

\( m_{ll} \) is maximal when leptons are back-to-back in slepton rest frame

Enpoint of inv. mass spectrum:

\[ (m_{ll}^{\text{max}})^2 = \left( m_{\tilde{\chi}^0_2}^2 - m_{\tilde{l}_R}^2 \right) \left( m_{\tilde{l}_R}^2 - m_{\tilde{\chi}^0_1}^2 \right) / m_{\tilde{l}_R}^2 \]
Determining SUSY Masses

\[ M_{ll}^{\text{max}} = M_{\tilde{\chi}_2^0} \sqrt{1 - \frac{M_{l_R}^2}{M_{\tilde{\chi}_2^0}^2}} \sqrt{1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{l_R}^2}} \]

\[ M_{lq}^{\text{max}} = \left( \frac{M_{\tilde{q}_L}^2 - M_{\tilde{\chi}_2^0}^2}{M_{\tilde{\chi}_2^0}^2} \right) \left( \frac{M_{\tilde{\chi}_2^0}^2 - (M_{l_R}^2)}{M_{\tilde{\chi}_2^0}^2} \right) \]

\[ M_{qq}^{\text{max}} = \ldots \]

Determine SUSY masses from endpoints of \( M_{ll}, M_{lq} \) and \( M_{lqq} \) ...
Mass Determinations: Overview

Try various decay chains

Look for sensitive variables (inv. masses, many of them)

Extract masses