Physics at Hadron Colliders

Part 4

Physics Beyond the Standard Model

• Supersymmetry
  (Tevatron and LHC)

• Other Extensions of the Standard Model
  - Extra dimensions
  - Extra gauge bosons
  - Leptoquarks ….
Why?

1. Gravity is not yet incorporated in the Standard Model
2. Dark Matter not accomodated
3. Many open questions in the Standard Model
   - Hierarchy problem: $m_W$ (100 GeV) → $m_{\text{Planck}}$ ($10^{19}$ GeV)
   - Unification of couplings
   - Flavour / family problem
   - ....

All this calls for a more fundamental theory of which the Standard Model is a low energy approximation → New Physics

Candidate theories: Supersymmetry
Extra Dimensions
Technicolor

Many extensions predict new physics at the TeV scale !!

Strong motivation for LHC, mass reach ~ 3 TeV
Supersymmetry

Extends the Standard Model by predicting a new symmetry
Spin $\frac{1}{2}$ matter particles (fermions) $\Leftrightarrow$ Spin 1 force carriers (bosons)

New Quantum number: R-parity:

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

+1 SM particles
-1 SUSY particles
Experimental consequences of R-parity conservation:

• SUSY particles are produced in pairs

• Lightest Supersymmetric Particle (LSP) is stable.

LSP is only weakly interacting:
LSP = \chi^0_1 (lightest neutralino, in many models)

→ LSP behaves like a \nu → it escapes detection

→ E_T^{miss} (typical SUSY signature)
Why do we like SUSY so much?

1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided

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

(Hierarchy or naturalness problem)

2. Unification of coupling constants of the three interactions seems possible

3. SUSY provides a candidate for dark matter

The lightest SUSY particle (LSP)

4. A SUSY extension is a small perturbation, consistent with the electroweak precision data

\[ m_{\text{SUSY}} \sim 1 \text{ TeV} \]
Link to the Dark Matter in the Universe?

Parameters of the SUSY model \( \Rightarrow \) predictions for the relic density of dark matter

Interpretation in a simplified model

cMSSM
(constrained Minimal Supersymmetric Standard Model)

Five parameters:
- \( m_0, m_{1/2} \): particle masses at the GUT scale
- \( A_0 \): common coupling term
- \( \tan \beta \): ratio of vacuum expectation value of the two Higgs doublets
- \( \mu \) (sign \( \mu \)): Higgs mass term

\[ \rho \sim m \rho \sim \frac{1}{\sigma_{\text{ann}}(\chi\chi \rightarrow \cdots)} \]

regions of parameter space which are consistent with the measured relic density of dark matter (WMAP,.....)
The **masses of the SUSY particles** are not predicted; Theory has many additional new parameters (on which the masses depend)

However, charginos/neutralinos are usually lighter than squarks/sleptons/gluinos.

**Present mass limits**

- $m$ (sleptons, charginos) $> 90-103$ GeV LEP II
- $m$ (squarks, gluinos) $> \sim 350$ GeV Tevatron
- $m$ (LSP, lightest neutralino) $> \sim 45$ GeV LEP II

LEP-II limit on the mass of the lightest SUSY particle

assumption:

lightest neutralino = LSP
Search for Supersymmetry at the LHC

• If SUSY exists at the electroweak scale, a discovery at the LHC should be easy

• Squarks and Gluinos are strongly produced

They decay through cascades to the lightest SUSY particle (LSP)

1. Step: Look for deviations from the Standard Model
   Example: Multijet + $E_T^{\text{miss}}$ signature

2. Step: Establish the SUSY mass scale use inclusive variables, e.g. effective mass distribution

3. Step: Determine model parameters (difficult)
   Strategy: select particular decay chains and use kinematics to determine mass combinations
Squarks and Gluinos

If R-parity conserved, cascade decays produce distinctive events: multiple jets, leptons, and $E_T^{miss}$

Typical selection: $N_{jet} > 4$, $E_T > 100, 50, 50, 50$ GeV, $E_T^{miss} > 100$ GeV

Define: $M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$ (effective mass)

LHC reach for Squark- and Gluino masses:
- $0.1 \text{ fb}^{-1} \Rightarrow M \sim 750$ GeV
- $1 \text{ fb}^{-1} \Rightarrow M \sim 1350$ GeV
- $10 \text{ fb}^{-1} \Rightarrow M \sim 1800$ GeV

Deviations from the Standard Model due to SUSY at the TeV scale can be detected fast!

Example: mSUGRA, point SU3 (bulk region)
- $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV
- $\tan \beta = 6$, $A_0 = -300$ GeV, $\mu > 0$
...additional potential: inclusive searches with leptons

SU3, 4 jets + 0 lepton final states

- Smaller signal rates, but better S:B conditions
- Discovery potential is more robust, in particular at the beginning, when systematic uncertainties on the backgrounds are large
- Similar analyses with $\tau$ lepton and b quark final states

SU3, 4 jets + 1 lepton final states

4 jets + 1 lepton final states for other benchmark points
Example: search for final states with $E_{T}^{\text{miss}}$ and two b-jets
$h \rightarrow bb$: 

CMS 

important if $\chi^0_2 \rightarrow \chi^0_1 h$ is open; bb peak can be reconstructed in many cases

Could be a Higgs discovery mode!

SM background can be reduced by applying a cut on $E_T^{\text{miss}}$
LHC reach in the $m_0 - m_{1/2}$ mSUGRA plane:

Multijet + $E_T^{\text{miss}}$ signature

SUSY cascade decays give also rise to many other inclusive signatures: leptons, b-jets, $\tau$'s

- Tevatron reach can be extended with early data
- Expect multiple signatures for TeV-scale SUSY
- Long term mass reach (300 fb⁻¹): 2.5 – 3 TeV
How can the underlying theoretical model be identified?

Measurement of the SUSY spectrum $\rightarrow$ Parameter of the theory

LHC: strongly interacting squarks and gluinos
ILC / CLIC: precise investigation of electroweak SUSY partners
LHC Strategy: End point spectra of cascade decays

Example: \( \tilde{q} \rightarrow q\tilde{\chi}_2^0 \rightarrow q\ell^+\ell^- \rightarrow q\ell^+\ell^-\tilde{\chi}_1^0 \)

\[
M_{\ell^+\ell^-}^{\text{max}} = \frac{\sqrt{(m_{\tilde{\chi}_2^0}^2 - m_{\ell^+}^2)(m_{\ell^-}^2 - m_{\tilde{\chi}_1^0}^2)}}{m_{\ell^-}}
\]

\[
M_{\ell^+\ell^-q}^{\text{max}} = \frac{\sqrt{(m_{\tilde{\chi}_2^0}^2 - m_{\ell^+}^2)(m_{\tilde{q}}^2 - m_{\tilde{\chi}_2^0}^2)}}{m_{\tilde{\chi}_2^0}}
\]

Results for point 01:

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>LHC + ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta m_{\tilde{\chi}_1^0} )</td>
<td>4.8</td>
<td>0.05 (input)</td>
</tr>
<tr>
<td>( \Delta m_{\tilde{\chi}_2^0} )</td>
<td>4.8</td>
<td>0.05 (input)</td>
</tr>
<tr>
<td>( \Delta m_{\tilde{\chi}_2} )</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>( \Delta m_{\tilde{\chi}_R} )</td>
<td>8.7</td>
<td>4.9</td>
</tr>
<tr>
<td>( \Delta m_{\tilde{\chi}_L} )</td>
<td>11.8</td>
<td>10.9</td>
</tr>
<tr>
<td>( \Delta m_{\tilde{\chi}_2^0} )</td>
<td>8.0</td>
<td>6.4</td>
</tr>
<tr>
<td>( \Delta m_{\tilde{\chi}_1} )</td>
<td>7.5</td>
<td>5.7</td>
</tr>
<tr>
<td>( \Delta m_{\tilde{\chi}_2} )</td>
<td>7.9</td>
<td>6.2</td>
</tr>
<tr>
<td>( \Delta m_{\tilde{\chi}_4} )</td>
<td>5.0</td>
<td>0.2 (input)</td>
</tr>
<tr>
<td>( \Delta m_{\tilde{\chi}_3} )</td>
<td>5.1</td>
<td>2.23</td>
</tr>
</tbody>
</table>

\( L = 300 \text{ fb}^{-1} \)
The LHC and the ILC (International Linear Collider, in study/planning phase) are complementary in SUSY searches

Number of observable SUSY particles:

*) Study by J. Ellis et al., hep-ph/0202110
Strategy in SUSY Searches at the LHC:

• Search for multijet + $E_T^{\text{miss}}$ excess
• If found, select SUSY sample (simple cuts)
• Look for special features (\(\gamma\)'s, long lived sleptons)
• Look for $\ell^\pm$, $\ell^+ \ell^-$, $\ell^\pm \ell^\pm$, b-jets, $\tau$'s
• End point analyses, global fit $\rightarrow$ SUSY model parameters
Importance for the interplay between direct and indirect Dark Matter searches

• Following a discovery of New Physics at the LHC (deviation from the Standard Model) the LHC will aim to test the Dark Matter hypothesis
• Estimation of relic density in a simple model-dependent scenario will be the first goal
• Less model-dependent scenarios will follow, detailed studies probably require the ILC
• Conclusive result is only possible in conjunction with astroparticle physics experiments
• Ultimate goal: observation of LSP at the LHC, confirmed by a signal in a direct dark matter experiment with predicted mass and cross-section
The Search for

SUSY at the Tevatron
The two classical signatures

1. **Search for Squarks and Gluinos:** \( \text{Jet} + E_T^{\text{miss}} \) signature produced via QCD processes

2. **Search for Charginos and Neutralinos:** \( \text{Multilepton} + E_T^{\text{miss}} \) signature produced via electroweak processes (associated production)

\[ \tilde{\chi}_2^0 \tilde{\chi}_1^{\pm} \rightarrow l^\pm l'^\pm \tilde{\chi}_1^0 \tilde{\chi}_1^0 X \]

\[ q \rightarrow W^+ \tilde{\chi}_2 \tilde{\chi}_1^{0} \]

\[ \bar{q} \rightarrow W^- \tilde{\chi}_2 \tilde{\chi}_1^{0} \]
Search for Squarks and Gluinos

- Three different analyses, depending on squark / gluinos mass relations:

(i) dijet analysis
   small $m_0$, $m(\text{squark}) < m(\text{gluino})$

(ii) 3-jet analysis
   intermediate $m_0$ $m(\text{squark}) \approx m(\text{gluino})$

(iii) Gluino analysis
   large $m_0$, $m(\text{squark}) > m(\text{gluino})$

- Main backgrounds: $Z \rightarrow \nu\nu + \text{jets}$, $tt$, $W + \text{jet production}$

- Event selection:
  * require at least 2, 3 or 4 jets with $P_T > 60 / 40 / 30 / 20$ GeV
  * veto on isolated electrons and muons
  * isolation of $E_T^{\text{miss}}$ and all jets
  * optimization of the final cuts $\rightarrow$ discriminating variables
Search for Squarks and Gluinos (cont.)

No excess above background from Standard Model processes

→ No evidence for SUSY (yet)  →  Set limits on masses of SUSY particles

<table>
<thead>
<tr>
<th>samples</th>
<th>2-jets</th>
<th>3-jets</th>
<th>4-jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD</td>
<td>$4.37 \pm 2.01$</td>
<td>$13.34 \pm 4.67$</td>
<td>$15.26 \pm 7.60$</td>
</tr>
<tr>
<td>top</td>
<td>$1.35 \pm 1.22$</td>
<td>$7.56 \pm 3.85$</td>
<td>$22.14 \pm 7.29$</td>
</tr>
<tr>
<td>$Z \rightarrow \nu\nu$+jets</td>
<td>$3.95 \pm 1.09$</td>
<td>$5.39 \pm 1.74$</td>
<td>$2.74 \pm 0.95$</td>
</tr>
<tr>
<td>$Z \rightarrow ll$+jets</td>
<td>$0.09 \pm 0.04$</td>
<td>$0.16 \pm 0.11$</td>
<td>$0.14 \pm 0.08$</td>
</tr>
<tr>
<td>$W \rightarrow l\nu$+jets</td>
<td>$6.08 \pm 2.15$</td>
<td>$10.69 \pm 3.84$</td>
<td>$7.68 \pm 2.85$</td>
</tr>
<tr>
<td>WW/WZ/ZZ</td>
<td>$0.21 \pm 0.19$</td>
<td>$0.35 \pm 0.17$</td>
<td>$0.49 \pm 0.34$</td>
</tr>
<tr>
<td>tot SM</td>
<td>$16 \pm 5$</td>
<td>$37 \pm 12$</td>
<td>$48 \pm 17$</td>
</tr>
</tbody>
</table>

Observed events in data:

<table>
<thead>
<tr>
<th>Region</th>
<th>Observed data</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-jets</td>
<td>45</td>
</tr>
<tr>
<td>3-jets</td>
<td>38</td>
</tr>
<tr>
<td>2-jets</td>
<td>18</td>
</tr>
</tbody>
</table>
Excluded regions in the m(squark) vs. m(gluino) plane

Exclusion limits (incl. systematic uncertainties)*:
- m(gluino) > 290 GeV/c²
- m(squark) > 375 GeV/c²

*) uncertainties from structure functions, change of renormalization and factorization scale $\mu$ by a factor of 2, NLO calculation, default choice: $\mu = m(\text{gluino}), m(\text{squark})$ or $\frac{1}{2}(m(\text{gluino})+m(\text{squark}))$ for gg, qq, qg production
Search for Charginos and Neutralinos
- the tri-lepton channel-

- Gaugino pair production via electroweak processes
  (small cross sections, ~0.1 – 0.5 pb, however, small expected background)

- For small gaugino masses (~100 GeV/c²)
  one needs to be sensitive to low $P_T$ leptons

![Diagram showing processes involving $W$, $Z$, gauginos, and leptons.](image)
Analysis:

• Search for different (\ell\ell\ell) + like-sign \(\mu\mu\) final states with missing transverse momentum
• In order to gain efficiency, no lepton identification is required for the 3\textsuperscript{rd} lepton, select: two identified leptons + a track with \(p_T > 4\) GeV/c

mSUGRA interpretation

For specific scenarios: sensitivity / limits above LEP limits; e.g., \(M(\chi^\pm) > 140\) GeV/c\(^2\) for the 3l-max scenario
Can LHC probe extra dimensions?

- Much recent theoretical interest in models with extra dimensions
  (Explain the weakness of gravity (or hierarchy problem) by extra dimensions)

- New physics can appear at the TeV-mass scale,
  i.e. accessible at the LHC

Example: Search for direct Graviton production

\[ gg \rightarrow gG, \quad qg \rightarrow qG, \quad q\bar{q} \rightarrow Gg \]
\[ q\bar{q} \rightarrow G\gamma \]

⇒ Jets or Photons with \( E_T^{\text{miss}} \)
Search for escaping gravitons:

Jet + $E_T^{\text{miss}}$ search:

\[ G_N^{-1} = 8\pi R^\delta M_D^{2+\delta} \]

\( \delta : \# \text{ extra dimensions} \)
\( M_D = \text{scale of gravitation} \)
\( R = \text{radius (extension)} \)

\[ M_D^{\text{max}} = 9.1, 7.0, 6.0 \text{ TeV} \]
\[ \delta = 2, 3, 4 \]

LHC experiments are sensitive, but conclusions on the underlying theory are difficult and require a detailed measurement program.

Main backgrounds:
- jet+Z($\rightarrow\nu\nu$), jet+W$\rightarrow$jet+(e,$\mu$,$\tau$)$\nu$
More ideas?

1. New resonances decaying into lepton pairs

   examples: $W'$ and $Z'$ or Graviton resonances (extra dimensions)

   use again leptonic decay mode to search for them: $W' \rightarrow \ell \nu$
   $Z' \rightarrow \ell \ell$

2. Leptoquarks?

   Particles that decay into leptons and quarks
   (violate lepton and baryon number; appear in Grand Unified theories)

   here: search for low mass Leptoquarks (TeV scale)
Fermilab Search for New Resonances in High Mass Di-leptons

- **Neutral Gauge Boson** Z' assume SM-like couplings
- **Randall-Sundrum narrow Graviton** resonances decaying to di-lepton appear in Extra Dim. Scenarios

Main background from Drell-Yan pairs
Search for New Resonances in High Mass Di-leptons

Data are consistent with background from SM processes. No excess observed.

<table>
<thead>
<tr>
<th>Z’ mass limits (SM couplings)</th>
<th>ee</th>
<th>μμ</th>
<th>ττ</th>
</tr>
</thead>
<tbody>
<tr>
<td>95% C.L.</td>
<td>CDF/D0: 965</td>
<td>835</td>
<td>394 GeV/c^2</td>
</tr>
</tbody>
</table>
Early Surprises at the LHC??

- as already mentioned, the experiments must be open for surprises /
  unknowns /
  unexpected discoveries

- requires unbiased measurements of
  - inclusive lepton spectra
  - dileptons spectra......
  - $E_T^{\text{miss}}$ spectrum.......  
  - ......
One example of many….

$Z' \rightarrow e^+e^-$ with SM-like couplings ($Z_{SSM}$)

Discovery window above Tevatron limits

$m \sim 1$ TeV, perhaps even in 2011... (?)
Search for $W' \rightarrow e\nu$

- $W'$: additional charged heavy vector boson
- Appears in theories based on the extension of the gauge group
- E.g. Left-right symmetric models: $SU(2)_R \ W_R$
- Assume: the neutrino from $W'$ decay is light and stable.

**Signature:** high $p_T$ electron + high $E_T^{\text{miss}}$

→ Peak in transverse mass distribution

**MC only**
Search for $W' \rightarrow e\nu$

Data:

consistent with one well known $W$ + background

Limit: $M(W') > 842 \text{ GeV/c}^2$

(assuming Standard Model couplings)
Search for Scalar Leptoquarks (LQ)

- **Production:** pair production via QCD processes (qq and gg fusion)

- **Decay:** into a lepton and a quark

\[ \beta = \text{LQ branching fraction to charged lepton and quark} \]

\[ N = \text{generation index} \]

Leptoquarks of 1., 2., and 3. generation

**Experimental Signatures:**

- two high \( p_T \) isolated leptons + jets .OR.

- one isolated lepton + \( P_T^{\text{miss}} \) + jets .OR.

- \( P_T^{\text{miss}} \) + jets
1st, 2nd and 3rd generation Leptoquarks

channels: ee jj, e+jj

channels: μμjj, εjj, ννjj

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>CDF (Run II)</td>
<td>235 GeV/c^2</td>
<td>224 GeV/c^2</td>
<td>129 GeV/c^2</td>
</tr>
<tr>
<td>D0 (Run I + II)</td>
<td>256 GeV/c^2</td>
<td>200 GeV/c^2 (Run I)</td>
<td>129 GeV/c^2</td>
</tr>
<tr>
<td></td>
<td>30 fb⁻¹</td>
<td>100 fb⁻¹</td>
<td></td>
</tr>
<tr>
<td>-------------------------</td>
<td>------------------------------</td>
<td>------------------------------</td>
<td></td>
</tr>
<tr>
<td><strong>Excited Quarks</strong></td>
<td>M (q⁺) ~ 3.5 TeV</td>
<td>M (q⁺) ~ 6 TeV</td>
<td></td>
</tr>
<tr>
<td>Q⁺ → qγ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Leptoquarks</strong></td>
<td>M (LQ) ~ 1 TeV</td>
<td>M (LQ) ~ 1.5 TeV</td>
<td></td>
</tr>
<tr>
<td>Z' → ℓℓ, jj</td>
<td>M (Z') ~ 3 TeV</td>
<td>M (Z') ~ 5 TeV</td>
<td></td>
</tr>
<tr>
<td>W' → ℓν</td>
<td>M (W') ~ 4 TeV</td>
<td>M (W') ~ 6 TeV</td>
<td></td>
</tr>
<tr>
<td><strong>Compositeness</strong></td>
<td>Λ ~ 25 TeV</td>
<td>Λ ~ 40 TeV</td>
<td></td>
</tr>
<tr>
<td>(from Di-jet)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

\[ \int L \, dt = 100 \text{ fb}^{-1} \]
Sensitivity to New Physics with jets in Early LHC data

• Even with JES uncertainties expected with early data and an int. luminosity of only 10 pb\(^{-1}\) compositeness scales of \(\sim 3\) TeV can be reached

(close to the present Tevatron reach of \(\Lambda > 2.7\) TeV)

• Resonances decaying into two jets:

Discovery sensitivity around 2 TeV (Spin-1 \(Z^\prime\) like resonance) for \(~200\) pb\(^{-1}\)

Present Tevatron limits: \(320 < m < 740\) GeV
Conclusions

1. Experiments at Hadron Colliders have a huge discovery potential
   - SM Higgs: full mass range, already at low luminosity;
     Vector boson fusion channels improve the sensitivity significantly
   - MSSM Higgs: parameter space covered
   - SUSY: discovery of TeV-scale SUSY should be easy,
     determination of model parameters is more difficult
   - Exotics: experiments seem robust enough to cope with new scenarios

2. Experiments have also a great potential for precision measurements
   - \( m_W \) to \(~10 - 15\) MeV
   - \( m_t \) to \(~1\) GeV
   - \( \Delta m_H / m_H \) to \(0.1\% \) (100 - 600 GeV)
   + gauge couplings and measurements in the top sector .......
End of lectures

• In case you have any questions: please do not hesitate to contact me: karl.jakobs@uni-freiburg.de

• Transparencies will be made available as .pdf files on the web (school pages)