Physics at Hadron Colliders

Lecture 4

Search for Physics Beyond the Standard Model

• Supersymmetry
• Heavy particles decaying into di-leptons
• What if there are extra dimensions?

Why do we think about extensions of the Standard Model?
see lecture by E. Kiritsis

1. Gravity is not incorporated yet in the Standard Model
2. 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

All predict new physics at the TeV scale !!

Strong motivation for LHC mass reach ~ 3 TeV
The Search for Supersymmetry

1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided
   \[ \Delta m_H = f(m_B^2 - m_f^2) \rightarrow m_{\text{SUSY}} \sim 1 \text{ TeV} \]
   (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
the only problem:……

No experimental evidence for SUSY so far! (except that about half of the particles are already discovered)

Either SUSY does not exist

OR

\[ m_{\text{SUSY}} \text{ large (}>> 100 \text{ GeV)} \rightarrow \text{not accessible at present machines} \]

LHC should say “final word” about (low energy) SUSY since theory predicts \[ m_{\text{SUSY}} \leq \text{a few TeV} \]

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**The Minimal Supersymmetric Standard Model (MSSM)**

Symmetry between fermions (matter) and bosons (forces)

For each particle \( p \) with spin \( s \), there exists a SUSY partner \( \tilde{p} \) with spin \( \Delta s = 1/2 \).

Ex. : \( q \) (s=1/2) \( \rightarrow \) \( \tilde{q} \) (s=0) squarks

\( g \) (s=1) \( \rightarrow \) \( \tilde{g} \) (s=1/2) gluino

Many new particles predicted!

Here: Minimal Supersymmetric extension of the Standard Model (MSSM) which has minimal particle content
MSSM particle spectrum:

5 Higgs bosons: h, H, A, H^±

- quarks → squarks
- leptons → sleptons
- W^± → winos
- H^± → charged higgsino
- γ → photino
- Z → zino
- h, H → neutral higgsino
- g → gluino

,...

SUSY phenomenology

There is a multiplicative quantum number:

\[ R_p = +1 \text{ Standard Model particles} - 1 \text{ SUSY particles} \]

which is conserved in most popular models (considered here).

Consequences:

- SUSY particles are produced in pairs
- Lightest Supersymmetric Particle (LSP) is stable.
  In most models LSP is also weakly interacting: \( LSP = \chi^0_1 \)

→ LSP is a good candidate for cold dark matter
→ LSP behaves like a ν → it escapes detection
→ \( E_T^{miss} \) (typical SUSY signature)
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

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Mass Limit</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>(sleptons, charginos)</td>
<td>&gt; 90-103 GeV</td>
<td>LEP II</td>
</tr>
<tr>
<td>(squarks, gluinos)</td>
<td>&gt; ~ 250 GeV</td>
<td>Tevatron Run 1</td>
</tr>
<tr>
<td>(LSP, lightest neutralino)</td>
<td>&gt; ~ 45 GeV</td>
<td>LEP II</td>
</tr>
</tbody>
</table>

[Graph showing mass limits with LEP-II limit on the mass of the lightest SUSY particle with assumption: lightest neutralino = LSP]

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**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)

  \[ \Rightarrow \text{combination of Jets, Leptons, } E_{T}\text{miss} \]

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**

- Strongly produced, cross sections comparable to QCD cross sections at the same mass scale
- If R-parity conserved, cascade decays produce distinctive events: multiple jets, leptons, and $E_T^{\text{miss}}$
- Typical selection: $N_{\text{jet}} > 4$, $E_T > 100, 50, 50, 50$ GeV, $E_T^{\text{miss}} > 100$ GeV
- Define: $M_{\text{eff}} = p_T^{\text{miss}} + p_T^1 + p_T^2 + p_T^3 + p_T^4$ (effective mass)

**LHC reach for Squark- and Gluino masses:**
- $1 \text{ fb}^{-1} \Rightarrow M \sim 1500$ GeV
- $10 \text{ fb}^{-1} \Rightarrow M \sim 1900$ GeV
- $100 \text{ fb}^{-1} \Rightarrow M \sim 2500$ GeV

TeV-scale SUSY can be found quickly!

**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

Expect multiple signatures for TeV-scale SUSY
**Determination of model parameters**

- **Invisible LSP** \( \Rightarrow \) no mass peaks, but kinematic endpoints 
  \( \Rightarrow \) mass combinations

- **Simplest case**: \( \chi_0^2 \rightarrow \chi_1^0 \ell^+ \ell^- \) endpoint: 
  \[ M_{\ell \ell} = M(\chi_2^0) - M(\chi_1^0) \]
  (significant mode if no \( \chi_2^0 \rightarrow \chi_1^0 Z, \chi_1^0 h, \ell \ell \) decays)

- **Require**: 2 isolated leptons, multiple jets, and large \( E_T^{\text{miss}} \)

Modes can be distinguished using shape of \( \ell \ell \)-spectrum

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h \( \rightarrow \) bb:

**CMS**

important if \( \chi_2^0 \rightarrow \chi_1^0 h \) 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 \( E_T^{\text{miss}} \)
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

Status of SUSY Searches at the Tevatron
- a few examples-

1. Search for Charginos and Neutralinos
   - These particles can decay via $W^* / Z^*$ or sleptons into Leptons + $P_T^{\text{miss}}$
   - Example: associated $\chi_0^2\chi_1^\pm$ production

   $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \rightarrow l^\pm l^\mp l^\pm l^\mp \tilde{\chi}_1^0 \tilde{\chi}_1^0 X$

   - Small background from Standard Model processes (striking signature), but also a small signal cross section
   - Leptonic branching ratios are enhanced if slepton masses are close to gaugino masses
Analysis: Search for $5\ell\ell\ell +$ like-sign di-muon final states with missing transverse momentum

<table>
<thead>
<tr>
<th>Selection</th>
<th>background expected</th>
<th># obs. events</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee+l</td>
<td>0.21±0.12</td>
<td>0</td>
</tr>
<tr>
<td>eµ+l</td>
<td>0.31±0.13</td>
<td>0</td>
</tr>
<tr>
<td>µµ+l</td>
<td>1.75±0.57</td>
<td>2</td>
</tr>
<tr>
<td>µ²µ²</td>
<td>0.64±0.38</td>
<td>1</td>
</tr>
<tr>
<td>eτ+l</td>
<td>0.58±0.14</td>
<td>0</td>
</tr>
<tr>
<td>µτ+l</td>
<td>0.36±0.13</td>
<td>1</td>
</tr>
<tr>
<td>SUM</td>
<td>3.85±0.75</td>
<td>4</td>
</tr>
</tbody>
</table>

mSUGRA interpretation

For specific scenarios: sensitivity / limits above LEP limits

K. Jakobs, Universität Freiburg

CERN Summer Student Lectures, Aug. 2005

(2) Search for Squarks and Gluinos

- Copiously produced (QCD production)

- Cascade decays into multi-jet + $P_T^{miss}$ final states
  (2,3 or 4 jets, depending on squark / gluino mass relations)

Limits beyond LEP mSUGRA reach for $m(\text{squark}) \sim m(\text{gluino})$

K. Jakobs, Universität Freiburg

CERN Summer Student Lectures, Aug. 2005
The Reach for SUSY at the Tevatron

SUSY:
Extend reach for SUSY particle masses
(for 10 fb⁻¹)
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

\[ gg \rightarrow gG, \; qg \rightarrow qG, \; q\bar{q} \rightarrow G\bar{g} \]

\[ q\bar{q} \rightarrow G\gamma \]

\( \Rightarrow \) Jets or Photons with \( E_T^{\text{miss}} \)

Search for escaping gravitons:

Jet + \( E_T^{\text{miss}} \) search:

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

\( \delta \): # extra dimensions

\[ M_D = \text{scale of gravitation} \]

\( R = \text{radius (extension)} \)

\[ M_D^{\text{max}} = 9.1, 7.0, 6.0 \text{ TeV} \]

\( \delta = 2, 3, 4 \)

Extension: \( 10^{-5}, 10^{-10}, 10^{-12} \text{ m} \)

"LHC experiments are also sensitive to this field of physics" \( \rightarrow \) robust detectors
More ideas?

1. What about heavy new resonances decaying into lepton pairs

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

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

   Increased sensitivity in the Tevatron Run II

2. What about 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)

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Fermilab Search for New Resonances in High Mass Di-leptons

- Neutral Gauge Boson $Z'$
  - SM Coupling assumed

- 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>ee+μμ</th>
<th>ττ</th>
</tr>
</thead>
<tbody>
<tr>
<td>95% C.L.</td>
<td>CDF: 750 735 815 394 GeV/c²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DØ: 780 680</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Search for W’ → eν

- 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 WR
- assume: the neutrino from W’ decay is light and stable.
- signature:
  high p_T electron + high P_T^{miss}
  → peak in transverse mass distribution
Search for $W' \rightarrow e\nu$

**Data:**
consistent with one well known $W$ + background

Limit: $M(W') > 842$ GeV/c² (assuming Standard Model couplings)

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Search for Scalar Leptoquarks (LQ)

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

- **Decays:** 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 + $P_T^{miss}$ + jets .OR.
- $P_T^{miss}$ + jets
1st, 2nd and 3rd generation Leptoquarks

channels: $e\bar{e}jj, e\nu jj$

channels: $\mu\mu jj, \epsilon\nu jj, \nu\nu jj$

<table>
<thead>
<tr>
<th>95% C.L.</th>
<th>1st Generation</th>
<th>2nd Generation</th>
<th>3rd Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Limits</td>
<td>LQ</td>
<td>LQ</td>
<td>LQ</td>
</tr>
<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></td>
</tr>
</tbody>
</table>

LHC reach for other BSM Physics

(a few examples for 30 and 100 fb$^{-1}$)

<table>
<thead>
<tr>
<th></th>
<th>30 fb$^{-1}$</th>
<th>100 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excited Quarks</td>
<td>$M(q^*) \sim 3.5$ TeV</td>
<td>$M(q^*) \sim 6$ TeV</td>
</tr>
<tr>
<td>Leptoquarks</td>
<td>$M(LQ) \sim 1$ TeV</td>
<td>$M(LQ) \sim 1.5$ TeV</td>
</tr>
<tr>
<td>$Z' \rightarrow \ell\ell, jj$</td>
<td>$M(Z') \sim 3$ TeV</td>
<td>$M(Z') \sim 5$ TeV</td>
</tr>
<tr>
<td>$W' \rightarrow \ell\nu$</td>
<td>$M(W') \sim 4$ TeV</td>
<td>$M(W') \sim 6$ TeV</td>
</tr>
<tr>
<td>Compositeness</td>
<td>$\Lambda \sim 25$ TeV</td>
<td>$\Lambda \sim 40$ TeV</td>
</tr>
</tbody>
</table>
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 ~15 MeV
   - $m_{top}$ to ~ 1 GeV
   - $\Delta m_H / m_H$ to 0.1% (100 - 600 GeV)
   + gauge couplings and measurements in the top sector

LHC: most difficult and ambitious high-energy physics project ever realized
(human and financial resources, technical challenges, complexity, ....)

It has a crucial role in physics: can say the final word about

--- SM Higgs mechanism
--- low-energy SUSY and other TeV-scale predictions

It will most likely modify our understanding of Nature
There are very exciting times ahead of us!!

We hope that many of you will join us in the discovery enterprise

• 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
  (official summer school pages)

End of lectures