Physics at Hadron Colliders

Lecture 4

Search for Physics Beyond the Standard Model

• Supersymmetry

• Other Extensions of the Standard Model
  - Extra dimensions
  - Extra gauge bosons
  - Leptoquarks ….
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) $\rightarrow$ $m_{\text{Planck}}$ ($10^{19}$ 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 $\rightarrow$ New Physics

Candidate theories: Supersymmetry
Extra Dimensions
Technicolor
…….

All predict new physics at the TeV scale!!

Strong motivation for LHC mass reach $\sim 3$ TeV
The Search for Supersymmetry
Supersymmetry

Extends the Standard Model by predicting a new symmetry
Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

New Quantum number: R-parity:

\[ R_p = (-1)^{B+L+2s} = \begin{cases} +1 & \text{SM particles} \\ -1 & \text{SUSY particles} \end{cases} \]
Experimental consequences of R-parity conservation:

• SUSY particles are produced in pairs

• Lightest Supersymmetric Particle (LSP) is stable. In most models LSP is also weakly interacting:
  \[ \text{LSP} = \chi^0_1 \text{ (lightest neutralino)} \]

  \[ \rightarrow \text{LSP is a good candidate for cold dark matter} \]

  \[ \rightarrow \text{LSP behaves like a } \nu \rightarrow \text{it escapes detection} \]

  \[ \rightarrow E_T^{\text{miss}} \text{ (typical SUSY signature)} \]
Why do we like her so much?

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

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

LHC should say “final word” about (low energy)
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:**
- $m \text{ (sleptons, charginos)} > 90-103 \text{ GeV}$ LEP II
- $m \text{ (squarks, gluinos)} > \sim 250 \text{ GeV}$ Tevatron Run 1
- $m \text{ (LSP, lightest neutralino)} > \sim 45 \text{ GeV}$ LEP II
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)

⇒ 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 $E_T^{miss}$

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

- 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:

\[
\begin{align*}
1 \text{ fb}^{-1} & \Rightarrow M \sim 1500 \text{ GeV} \\
10 \text{ fb}^{-1} & \Rightarrow M \sim 1900 \text{ GeV} \\
100 \text{ fb}^{-1} & \Rightarrow M \sim 2500 \text{ GeV}
\end{align*}
\]

TeV-scale SUSY can be found quickly!

example: mSUGRA

\[
\begin{align*}
m_0 &= 100 \text{ GeV}, \ m_{1/2} = 300 \text{ GeV} \\
\tan \beta &= 10, \ A_0 = 0, \ \mu > 0
\end{align*}
\]
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: $\chi^0_2 \rightarrow \chi^0_1 \ell^+ \ell^-$ endpoint: $M_{\ell\ell} = M(\chi^0_2) - M(\chi^0_1)$

  (significant mode if no $\chi^0_2 \rightarrow \chi^0_1 Z, \chi^0_1 h, \ell\ell$ decays)

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

Modes can be distinguished using shape of $\ell\ell$-spectrum
$h \rightarrow bb$: 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 $E_T^{miss}$
work backwards the decay chain: 
example: 

\[ pp \rightarrow \tilde{q}_L \tilde{q}_R: \]

\[ \tilde{q}_R \rightarrow \tilde{\chi}_1^0 q \]

\[ \tilde{q}_L \rightarrow \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h q \rightarrow \tilde{\chi}_1^0 b \bar{b} q \]

combine \( h \rightarrow bb \) with jets to determine other masses

\[ \bar{q} \rightarrow \tilde{\chi}_1^0 h q \] endpoint

---

**Strategy in SUSY Searches at the LHC:**

- Search for multijet + \( E_T^{miss} \) excess
- If found, select SUSY sample (simple cuts)
- Look for special features (\( \gamma \)'s, long lived sleptons)
- Look for \( \ell^\pm, \ell^+ \ell^- \), b-jets, \( \tau \)'s
- End point analyses, global fit \( \rightarrow \) SUSY model parameters
The Search for

SUSY at the Tevatron
The two classical signatures

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

2. Search for Charginos and Neutralinos: Multilepton + $E_T^{\text{miss}}$ signature produced via electroweak processes (associated production)
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 \( P_T > 60 / 40 / 30 / 20 \text{ GeV} \)
  * veto on isolated electrons and muons
  * isolation of \( P_T^{\text{miss}} \) and all jets
  * optimization of the final cuts \( \rightarrow \) discriminating variables
Search for Squarks and Gluinos (cont.)

DØ analysis \( L = 310 \text{ pb}^{-1} \)

Example: 3 jet + \( E_T^{\text{miss}} \) search

Discriminating variable:

- \( H_T = \sum E_T(\text{jets}) \)

Comparison between data and expected background:

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Total background</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Dijet”</td>
<td>6</td>
<td>4.8 +4.4 -2.0 (stat) +1.1 -0.8 (sys)</td>
</tr>
<tr>
<td>“3 jets”</td>
<td>4</td>
<td>3.9 +1.3 -1.0 (stat) +0.7 -0.8 (sys)</td>
</tr>
<tr>
<td>“Gluino”</td>
<td>10</td>
<td>10.3 +1.5 -1.4 (stat) +1.9 -2.5 (sys)</td>
</tr>
</tbody>
</table>

No excess above background from Standard Model processes found
→ NO evidence for SUSY (yet) → Set limits on masses of SUSY particles
Excluded regions in the $m$(squark) vs. $m$(gluino) plane

Excluded mass values:

$m$(gluino), $m$(squark) > ~ 330 GeV for equal masses

major systematic uncertainties:

- renormalization scale - vary $m$(gluino)/2 < $\mu$ < 2 $m$(gluino) -
- parton density functions (gluon distribution at large $x$) qg-processes
- jet energy scale,....
Future Prospects for Squark and Gluino Searches

With 8 fb⁻¹: explore mass range up to ~ 400 GeV/c²
Search for Charginos and Neutralinos - the tri-lepton channel -

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

- For small gaugino masses (\(\sim 100\) GeV/c\(^2\)) one needs to be sensitive to low \(P_T\) leptons
Analysis:

- Search for five different (ℓℓℓ) + like-sign μμ final states with missing transverse momentum
- In order to gain efficiency, no lepton identification is required for the 3rd lepton, select: two id. Leptons + a track with \( P_T > 4 \text{ GeV/c} \)

For specific scenarios: sensitivity / limits above LEP limits; e.g., \( M(χ^±) > 140 \text{ GeV/c}^2 \) for the 3l-max scenario
Excluded \( σ \times \text{BR} \): 0.08 pb

<table>
<thead>
<tr>
<th></th>
<th>Lum. (fb(^{-1}))</th>
<th>Data</th>
<th>Total background</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee+l</td>
<td>1.2</td>
<td>0</td>
<td>0.76 ±0.67 (stat)</td>
</tr>
<tr>
<td>μμ+l</td>
<td>0.3</td>
<td>2</td>
<td>1.75 ±0.57 (stat)</td>
</tr>
<tr>
<td>εμ+l</td>
<td>0.3</td>
<td>0</td>
<td>0.31 ±0.13 (stat)</td>
</tr>
<tr>
<td>SS μμ</td>
<td>0.9</td>
<td>1</td>
<td>1.10 ±0.40 (stat)</td>
</tr>
<tr>
<td>ετ+l</td>
<td>0.3</td>
<td>0</td>
<td>1.58 ±0.14 (stat)</td>
</tr>
<tr>
<td>μτ+l</td>
<td>0.3</td>
<td>1</td>
<td>0.36 ±0.13 (stat)</td>
</tr>
</tbody>
</table>

mSUGRA interpretation

DØ Run II Preliminary, 0.3-1.1 fb\(^{-1}\)

\( M(χ^1_1)=M(χ^0_2)=2M(χ^0_1); M(χ^1_1)+M(χ^0_2) \)
\( \tan β=3, \mu>0, \) no slepton mixing

- Observed Limit
- Expected Limit

σ(χ\(^{±}\)) x BR(3l) (pb)

Chargino Mass (GeV)
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

\[ gg \rightarrow gG, \quad qq \rightarrow qG, \quad q\bar{q} \rightarrow Gg \]

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

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

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

\[ G_N^{-1} = 8\pi R^\delta M_D^{2+\delta} \]
\( \delta : \# \text{ extra dimensions} \)
\( M_D = \text{scale of gravitation} \)
\( R = \text{radius (extension)} \)

Main backgrounds:

jet+Z($\rightarrow$\nu\nu), jet+W$\rightarrow$jet+(e,\mu,\tau)$\nu$

\( M_D^{\text{max}} = 9.1, 7.0, 6.0 \text{ TeV} \)

for

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

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)
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

Di-electron Invariant Mass

Di-muon Invariant Mass

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

Z' mass limits (SM couplings)  
95% C.L.  

<table>
<thead>
<tr>
<th></th>
<th>CDF /D0:</th>
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<tbody>
<tr>
<td>ee</td>
<td>850</td>
</tr>
<tr>
<td>(\mu\mu)</td>
<td>835</td>
</tr>
<tr>
<td>(\tau\tau)</td>
<td>394 GeV/c^2</td>
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K. Jakobs, Universität Freiburg            CERN Summer Student Lectures, Aug. 2006
• **W'**: additional charged heavy vector boson
• appears in theories based on the extension of the gauge group
• e.g. Left-right symmetric models: $SU(2)_R \times W_R$
• assume: the neutrino from W' decay is light and stable.
• signature:

  high $p_T$ electron + high $P_T^{\text{miss}}$

  $\rightarrow$ peak in transverse mass distribution
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)

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

\[ LQ_N \rightarrow l_N^\beta, \quad q_N^{1-\beta} \]

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

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

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
1\textsuperscript{st}, 2\textsuperscript{nd} and 3\textsuperscript{rd} generation Leptoquarks

channels: $\text{eejj}, \text{evjj}$

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<tr>
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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></td>
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</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>
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</thead>
<tbody>
<tr>
<td><strong>Excited Quarks</strong></td>
<td></td>
<td></td>
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<tr>
<td>Q* → q γ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M (q*) ~ 3.5 TeV</td>
<td></td>
<td>M (q*) ~ 6 TeV</td>
</tr>
<tr>
<td><strong>Leptoquarks</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M (LQ) ~ 1 TeV</td>
<td></td>
<td>M (LQ) ~ 1.5 TeV</td>
</tr>
<tr>
<td><strong>Z' → ℓℓ, jj</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M (Z') ~ 3 TeV</td>
<td></td>
<td>M (Z') ~ 5 TeV</td>
</tr>
<tr>
<td>M (W') ~ 4 TeV</td>
<td></td>
<td>M (W') ~ 6 TeV</td>
</tr>
<tr>
<td><strong>Compositeness</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(from Di-jet)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Λ ~ 25 TeV</td>
<td>Λ ~ 40 TeV</td>
<td></td>
</tr>
</tbody>
</table>

\[ \int L dt = 100 \text{ fb}^{-1} \]
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 $\sim 15$ MeV
   - $m_{\text{top}}$ to $\sim 1$ 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

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• 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